Comparison Between Four Detection Algorithms For GEO Objects

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ABSTRACT

In order to cope with the space debris problem, Four detection algorithms for GEO objects are being developed under the collaboration between Kyushu University, IHI corporation and JAXA. Each algorithm is designed to process CCD images to detect GEO objects. All four algorithms analyzed the same sets of data to evaluate their advantages and disadvantages. By comparing their analysis times and results, an optimum usage of these algorithms was considered.

1. INTRODUCTION

Solution of the space debris problem is one of the most important issues to secure the future space activities of our human beings. Observation technologies for space objects must be strengthened for this objective. We are focusing on the optical observation technologies especially on image processings as these are relatively cost-effective and it is easy to install to certain observation facilities and/or establish new observation systems by using them. Four detection algorithms for GEO objects are being developed under the collaboration between Kyushu University, IHI corporation and JAXA. Each algorithm is designed to process CCD images to detect GEO objects.

The first one is PC based stacking method which has been developed in JAXA since 2000. Numerous CCD images are used to detect faint GEO objects below the limiting magnitude of a single CCD image. Sub-images are cropped from many CCD image to fit the movement of the objects. A median image of all the sub-images is then created. Although this method has an ability to detect faint objects, it takes time to analyze.

The second one is the FPGA based stacking method which uses binalized images and a new algorithm installed in a FPGA board which reduce analysis time about one thousandth of PC based stacking method.

The third one is the line-identifying technique which also uses many CCD frames and finds any series of objects that are arrayed on a straight line from the first frame to the last frame. This can analyze data faster than the stacking method, but cannot detect faint objects as the PC and FPGA based stacking method.

The fourth one is the multi-pass multi-period algorithm developed by IHI corporation which uses the average instead of median to reduce analysis time. This has same analysis speed as the line-identifying technique and better detection capabilities in terms of the darkness.

By analyzing the same data set with four algorithms, advantages and disadvantages of each algorithm were extracted and optimal usages of these algorithms were considered. In section 2, the details of each algorithm are explained. Analyses and discussions are described in section 3 and 4, respectively.

2. FOUR DETECTION ALGORITHM

2.1. PC BASED STACKING METHOD

The PC based stacking method (hereafter PC stack) uses multiple CCD images to detect very faint objects that are undetectable on a single CCD image. We have been developing this image processing, investigating its effectiveness

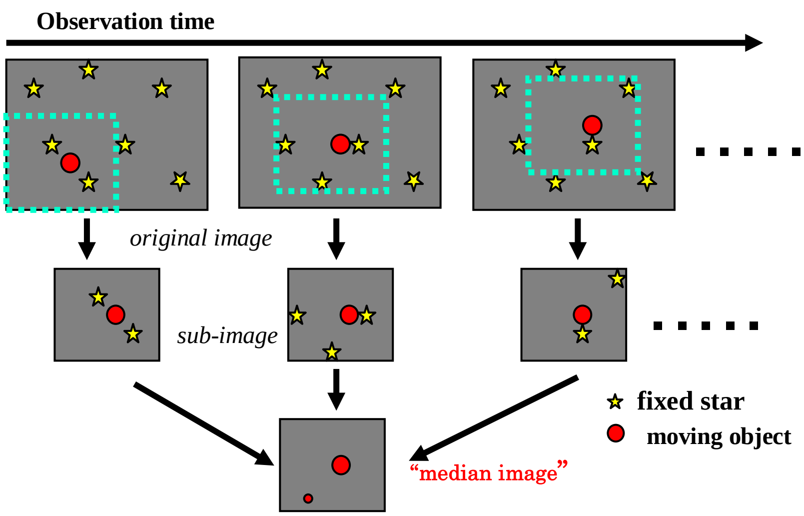
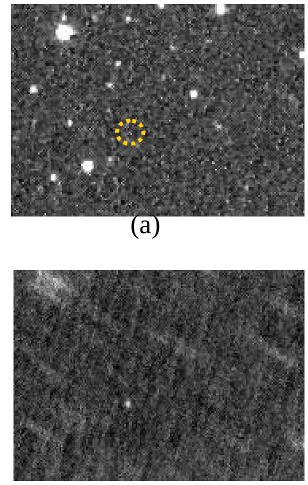


Fig.1. PC based stacking method



(b)

Fig.2. Asteroid detected by the PC based stacking method

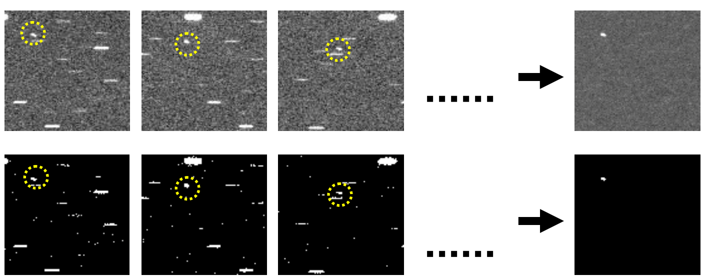


Fig.3. Deference between the original algorithm of the stacking method (upper) and the new algorithm using binarized images.

Fig.4. FPGA board H101-PCIXM manufactured by Nallatech

and trying to utilize actual GEO debris observation since 2000 [1][2]. The general idea of this method is described below, and details are available in the references.

As shown in Fig.1, sub-images are cropped from many CCD images to follow the presumed movement of space debris. A median image of all the sub-images is then created. In this method, photons from the space debris arrive on the same pixels of the sub-images, and field stars are removed by taking the median because they appear in different places on each sub-image. Fig.2 shows an example of an asteroid detected using this method. Fig.2 (a) shows a part of one CCD image, and Fig.2 (b) shows the same region of the final image after the process was carried out using forty images. It is impossible to confirm the presence of the asteroid in Fig.2 (a), whereas the asteroid is bright and no field stars are shown in Fig.2 (b). The discovery of many new asteroids has proven the effectiveness of this method. The method enhances the detection ability of the 35 cm telescope to equal that of a 1 m telescope.

The only weak point of the PC based stacking method is the time required to analyze the data when detecting an unseen object whose movement is not known, because a range of likely paths must be assumed and checked. Although main-belt asteroids and cataloged space debris whose movements can be estimated in some way are easy targets to detect, finding near-Earth objects and un-cataloged space debris is time-consuming work and not really practical. Using many PCs in parallel to reduce analysis time may be one solution. However, a hardware system purpose-built for this method such as a field programmable gate array (FPGA), would be the best solution for use with an upcoming large-format CCD camera.

2.2. FPGA BASED STACKING METHOD

In order to reduce analysis time of the PC based stacking method, FPGA based stacking method (hereafter FPGA stack) has been developed. Most time-consuming part of the PC based stacking method is calculating median values of each pixel from the sub-images. As FPGA is a kind of electrical circuits, it shows its power in simple calculations. More sophisticated and simplified algorithm is required for FPGA. We discovered that binarization of the sub-images with a proper threshold and calculating the sum of the binarized sub-image instead could derive almost the same consequence described in section 2.1. Fig.3 represents the difference between the original algorithm and the new algorithm. Calculating sum is much simpler than calculating median which has to sort individual value of each pixel and pick the median value, and very suitable for FPGA. Moreover, binarization itself reduces amount of data to one sixteenth which helps to reduce analysis time a lot. We developed FPGA boards executing this algorithm. Fig.4 shows the FPGA board which is H101-PCIXM manufactured by Nallatech. The FPGA board was shown to be able to reduce analysis time to about one thousandth of PC based stacking method.

2.3. LINE-IDENTIFYING TECHNIQUE

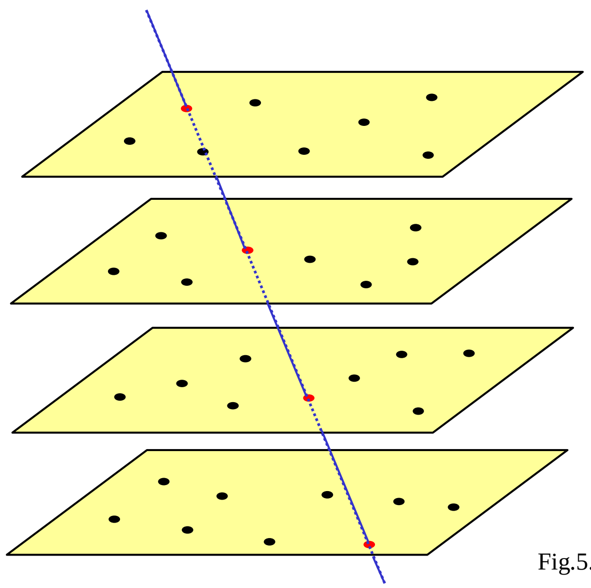


Fig.5. Line-identification technique

We developed the line-identifying technique (hereafter LINE) to complement the PC based stacking method. Fig. 5 sketches the technique. The line-identifying technique uses many CCD frames as the PC and FPGA based stacking method does. First, it detects candidate objects (black dots in Fig.5) using a threshold and a shape parameter. Then, it finds any series of objects that are arrayed on a straight line from the first frame to the last frame. Appearing on a straight line as shown in Fig.5 means that an object is moving across the field of view at a constant velocity. Using this technique enables us to detect near-Earth asteroids and unknown space debris whose movements are unpredictable. The technique does not need to presume any particular movements of a target, as the PC based stacking method does. The number of calculations depends on the number of candidates. For example, a commercial PC (DELL Precision 450) is able to analyze 18 frames with 400 candidates in each frame in 7 minutes, which is quite acceptable. The user can select an appropriate number of candidates in each frame by considering the capability of the PC and the number of frames. If a PC has sufficient power, the number of candidates can be increased by lowering the detection threshold, meaning that darker objects will be detectable.

Although the line-identifying technique works efficiently in a practical analysis time, its ability to detect faint objects does not measure up to the PC and FPGA based stacking method. Its analysis time increases exponentially with the number of candidates on each frame.

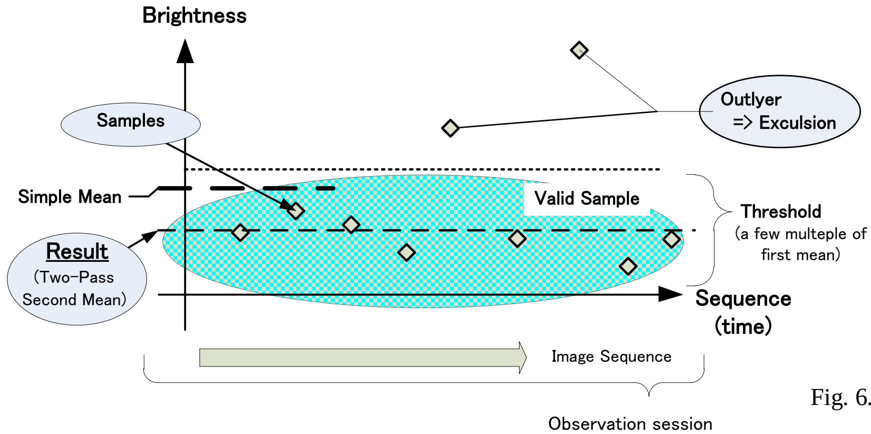


Fig. 6. Two-pass Outlier-excluded Mean

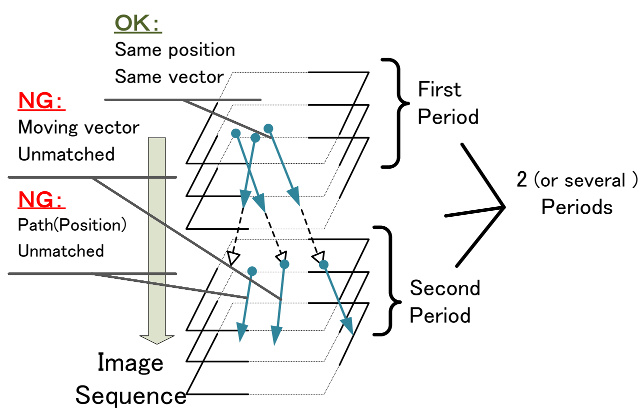


Fig. 7. Multi-Period Consistency Validation

2.4. MULTI-PASS MULTI-PERIOD ALGORITHM

We use Multi-Pass Multi-Period Denoising Algorithm (hereafter MPMP) to find moving low-brightness (invisible) faint object in the consecutive sky images with bright stars. This algorithm consists of four processes as follows.

In the first process, this algorithm eliminates bright star's trail by the background subtraction[3]. Each frame is subtracted to the following (or previous if current image is last image frame) one which is shifted by fixed star moving speed, because fixed star moves constant speed between image frames by Earth's rotation.

In the second process, same as the PC based stacking method, this algorithm stacks many frames under the various uniform motion shifts. This algorithm specifies shift values for the x- and y-axes of pixels and, once the shift values are determined, this process shifts each frame depending on the shift value, and Two-pass Outlier-excluded mean (mentioned bellow) are calculated from shifted images.

In the third process, to reduce noise, this algorithm calculates mean twice at the process (Fig. 6) .For first mean, this algorithm uses all stacking pixel (equal to number of frames). To obtain threshold, this algorithm calculates a few multiples of the first mean (e.g. Twice mean of the first).For the second mean, this algorithm chooses all pixels which is less than the threshold from stacking pixel, and calculates mean by chosen pixels as a denoised values. Denoised values are calculated for each pixel in an image frame.

In last process, this algorithm divides one observation to two (or several) periods(Fig. 7). First, for each period, this algorithm applies Tow-pass Outlier-excluded Mean, and find a bright point as debris candidate. And second, this algorithm validates consistency between first-period candidate and second-period candidate. To validate candidates, we use consistency in the speed vector and the pass of candidate pair.

Table. 1. The summary of analyses of the four algorithms

	PC stack	FPGA stack	LINE	MPMP
# of detection	91	146	87	121
Search area	416×600	1024×1024	—	800×800
# of search	3933	262,144	—	40,000
analysis time for one region(min)	353	30	7	9
time/one search(msec)	5385	6.87	—	13.5

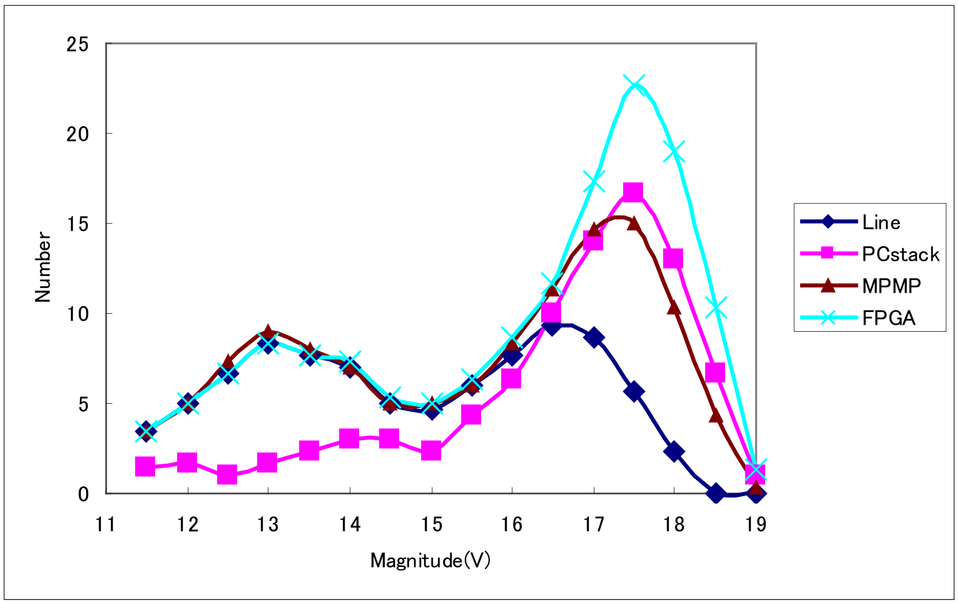


Fig. 8. Brightness distributions of detected objects for the four algorithms

3. ANALYSES AND RESULTS

In order to evaluate advantages and disadvantages of each algorithm, all the four algorithms analyzed the same data set. We carried out a collaborative observation with Taiwan to detect fragments created by the breakup of Titan 3C transtage in 1992. The detail of the observation is described by Uetsuhara et al [4]. For this observation, a 50cm telescope of TAOS [5] at Lulin observatory in Taiwan was used for 3 nights. In each night, the telescope observed about 60 regions to detect the fragments efficiently. In each region, about 30 frames with 6-second exposure were taken. 5625 frames in total were analyzed with the 4 algorithms. Table 1 and Fig. 8 show the summary of the analyses and the brightness distribution of detected objects for each algorithms, respectively.

Each column represents each algorithm. Search area means maximum motions of objects to be searched. For example, 1024×1024 of FPGA means objects which show the motion ±512 pixels in x- and y-axis at maximum were searched in FPGA based stacking method. # of search shows the actual calculation number. Some algorithms thin out calculations in their search area to reduce analysis time. Although analysis time for each algorithm is shown in the forth line, analysis speeds for the three algorithm, PC stack, FPGA stack and MPMP should be evaluated with the last line of Table. 1 (time/one search). Since LINE has very different way of analysis from other three algorithms, it does not have the concepts of "search area" and "# of search". It can detect all objects which show constant velocities in the frames.

From Fig. 8, three algorithms, LINE, MPMP and FPGA stack show almost same detection abilities around 16th magnitude. From 16th magnitude, MPMP and FPGA show the superiorities over LINE. From 16.5th magnitude, FPGA shows the superiority over MPMP. The inferiority of PC stack around bright region is due to relatively small

Table. 2. Advantages and disadvantages of the four algorithms

	PC stack	FPGA stack	Line	MPMP
detection of faint objects	very good	very good	fair	good
analysis speed	bad	good	good	good
detection of fast moving objects	bad	good	very good	good
cost	good	bad	good	fair

search area as compared with other three algorithm. Detection ability of PC stack overcomes MPMP around 17th magnitude.

4. DISCUSSIONS

Table. 2 shows advantages and disadvantages of each algorithm. PC stack has a very good detection ability for faint objects. Even with the small search area, it overcomes LINE and MPMP at 16.5th and 17th magnitude, respectively. However, its disadvantage on analysis speed is fatal. As a result, it can't detect fast moving objects as well. From these facts, PC stack is not feasible for the survey observation which tries to detect faint objects whose motions are not known. But it shows its ability of faint object detection when it is used for the observation of motion-known objects such as main-belt asteroids and breakup fragments caused by an identical event.

FPGA stack shows good performances except its cost. It is able to detect fainter objects than other three algorithms. By modifying pre-process before FPGA process, further improvement on analysis speed is expected. It is also suitable for larger format CCD and more frames by applying more powerful FPGA board. Although FPGA board is very expensive, using FPGA stack is much more effective than building a large telescope and a large CCD camera to get same results. Using a lot of FPGA boards at various observation site also help to reduce its cost.

LINE is not able to detect faint objects like other three algorithms. However its unique detection method enable it to detect fast moving objects which are not detectable for other three algorithms.

MPMP shows good performances on every aspect. Its analysis speed, detection ability of faint objects are very close to FPGA stack. Since its overall performance is relatively good and its cost is better than FPGA, building cost effective observation systems specialized for GEO debris observation using MPMPs and small telescopes may contribute to solving the space debris problem in GEO.

Taking into account the advantages and disadvantages of these algorithms, one optimum usage is considered. In order to maintain orbital accuracy of detected GEO objects, about 10 observation sites around the globe will be required. A few sites with relatively a large telescope and a large format CCD camera are dedicated to survey observation (survey site) using FPGA stack or MPMP. In addition, LINE is used to detect fast moving objects at those sites. The rest of sites are used to follow up (follow-up site) the detected objects at the sites mentioned above. In the survey sites, initial orbital determinations of detected objects are carried out using a technique described by Yanagisawa and Umehara [6]. The orbital elements are sent to the follow-up sites to track the objects. In the follow-up sites, PC stack is used for the analysis. The orbital elements inform the observers overall position and motion of the objects in the sky which means search area becomes very small. This situation is suitable for PC stack. Even for fast moving objects, PC stack is able to detect them if its overall motion is known. In the follow-up sites, a large telescope and a large format CCD camera are not required. Since overall position and motion of the objects in the sky are known, small CCD camera is enough to catch them in its small field of view ,and many CCD frames compensating with small aperture of the telescope does not increase analysis time so much.

SUMMARY

Advantages and disadvantages of four detection algorithms for GEO objects are evaluated by analyzing the same data set. By using each algorithm efficiently, it is possible to build a world wide observation network of GEO objects with relatively low cost. Such a observation network will greatly contribute to solving the space debris problem in the future.

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