New NEO search technology using small telescopes and FPGA

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Abstract—**The Japan Aerospace Exploration Agency (JAXA) is developing a new observation technology for Near Earth Objects (NEOs). The technology employs a very different process compared to existing NEO survey programs such as Pan-Starrs and CSS, and could possibly innovate the current NEO survey concept. It uses many CCD images in which to detect faint and fast moving NEOs. The FPGA (field programmable gate array) board is used to reduce analysis time. We discovered two NEOs using 18-cm telescopes in January 2017. This marked Japan's first discovery of NEOs in about nine years.**

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1. INTRODUCTION

Finding Near Earth Objects (NEOs) that could potentially collide with Earth is among the most important issues to be addressed for the future prosperity of human beings. Although there are many survey programs for NEOs in the world, those programs use a similar observational strategy and analysis method, which could miss a particular NEO group. We would like to propose a new observation strategy

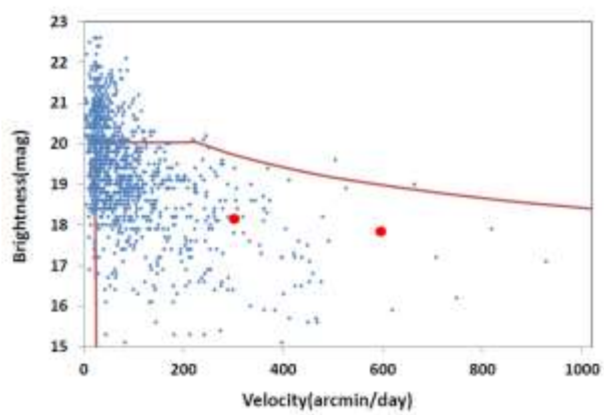

Figure 1. Distribution of PHA at initial discovery in the velocity and brightness space

that can efficiently detect an undiscovered NEO group at low cost. This new strategy could possibly innovate the existing NEO observation strategy. We discovered two new NEOs using the new observation strategy in January 2017. This paper describes the new analysis process in detail, the new observation strategy, including a comparison with the existing NEO survey programs, the test observations that discovered two NEOs, and the future plan.

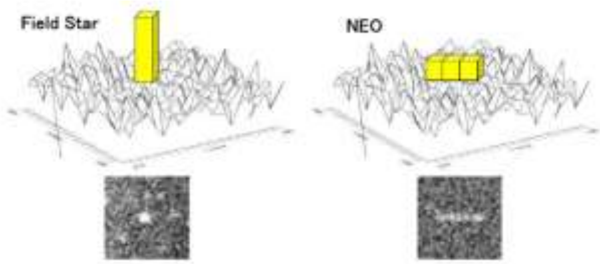

Figure 2. Example of trail loss

2. POSSIBLE GROUP OF UNDISCOVERED NEOS

There are many NEO survey programs such as Pan-STARRS and CSS in the world [1,2], which conduct observation night after night. However, those programs adopt almost the same observation strategy and data analysis process. Survey observation uses a 1- to 2-m-class telescope and a large CCD camera covering several square degrees in the sky. In order to detect NEOs, several CCD images with up to a few minutes of exposure time are taken and compared to detect moving NEOs among the field stars. The same observation strategy and analysis process may miss a particular group of NEOs due to the observation bias of that strategy and process. Figure 1 shows the distribution of one NEO group, PHAs (Potentially Hazardous Asteroids) at initial discovery in the velocity and brightness space. The X-axis represents the velocity of NEOs in arcminutes per day and expresses the brightness thereof in terms of visual magnitude. From the figure, we can see that the dark NEOs were only discovered at very slow speed. This is attributed to trail loss, which is caused by moving objects such as asteroids and comets that spread photons to the numerous

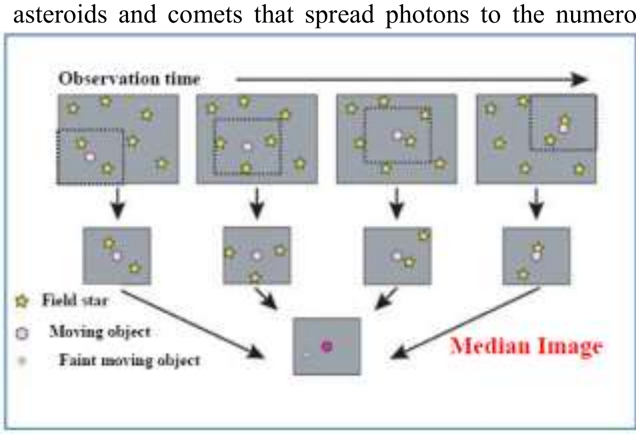

Figure 3. The new image processing algorithm

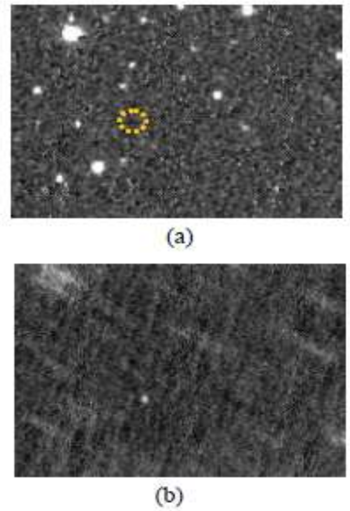

Figure 4. An asteroid detected using the algorithm

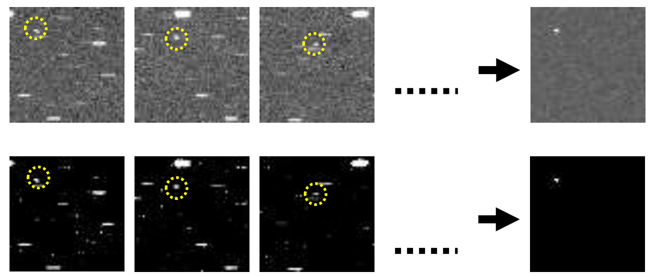

Figure 5. The difference between the original algorithm using median and the modified one using binarization

Figure 6. FPGA board developed for the algorithm

lined-pixels of such sensors as CCD. This degrades the signal-to-noise ratio of the objects. Figure 2 shows an example of trail loss. The left side shows the case of a field star. The right side shows the case of a moving NEO having almost the same brightness. While photons from the field star are concentrated to a few pixels, which significantly improves the signal-to-noise ratio, the photons from the NEO spread to many pixels, thereby making the NEO unrecognizable in the image. In order to detect an undiscovered NEOs with unknown motions, a telescope with the CCD must observe the sky in sidereal tracking mode. For this reason, faster NEOs cause more significant trail loss. In the case of small NEOs, it is even worse. From the above, the existing observation strategy and analysis process miss fast moving NEO groups that come very close to Earth.

so simple that we developed the field programmable gate array (FPGA) board shown in Fig. 6 for the algorithm, which further reduces the analysis time to one-twentieth. The analysis time is reduced to 14 minutes from 280 hours in total, and thus realistic for NEO observations.

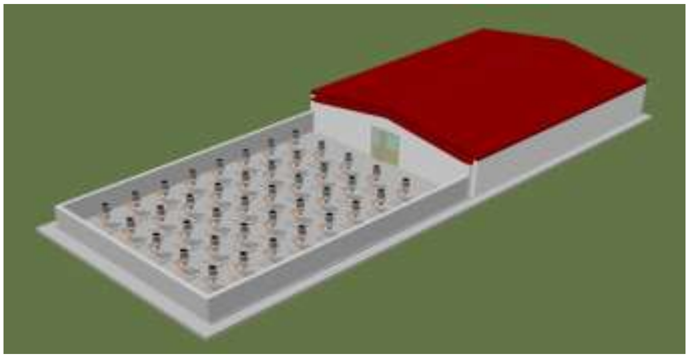

Figure 7. The concept of the new observation strategy

Figure 8. the devices of the test observations

3. NEW ANALYSIS PROCESS

In the previous section, we found that the existing observation strategy and analysis process miss fast moving NEO groups that come very close to Earth. In order to cope with the situation, we are developing a new image processing algorithm [3-5]. The algorithm basically uses numerous CCD images with a relatively short exposure time to reduce trail loss and enhance the signal-to-noise ratio. As illustrated in Fig. 3, the algorithm cuts out sub-images from many CCD images to follow the presumed motion of moving objects. Then the median image of these sub-images is created. The algorithm repeats this process for various presumed motions. When one presumed motion matches the motion of a NEO in the images, the algorithm can detect the NEO even if the NEO is invisible in a single CCD image due to its faintness. Figure 4 shows an example of an asteroid detected using the algorithm. Figure 4 (a) shows a part of one CCD image, and Fig, 4 (b) shows the same region of the final image after the running algorithm using forty images. It is impossible to confirm the presence of the asteroid in Fig. 4 (a), whereas the asteroid is bright and no field stars are visible in Fig. 4 (b).

A similar process was developed by Shao et al. [6]. They use add and mean instead of median. We use median because it can remove the effect of high noise caused by field stars and cosmic rays, which add and mean cannot. However, calculating median takes more time than add and mean. For example, the analysis time for 65,536 processing iterations of 32 1,024×1,024-pixel images, which are intended to detect objects moving within a 256×256-pixel area, is about 280 hours using a normal desktop computer, and thus not really practical. We found that image binarization combined with add gives almost the same result as median, while dramatically reducing the analysis time to one-sixtieth. Figure 5 shows the difference between the original algorithm using median and the modified one using binarization. Details of the modified algorithm are described in Yanagisawa and Kurosaki [7]. The modified algorithm is

4. NEW OBSERVATION STRATEGY

We would like to propose a new observation strategy using the new analysis process described in Section 2. Existing NEO survey programs adopt a strategy using a 1- to 2-m-class telescope and one large CCD camera. Conversely, our strategy uses many small telescopes and normal CCD cameras as depicted in Fig. 7.

There are many benefits of our new strategy. As both devices are commercially available, we need not design and develop a dedicated telescope and a CCD camera that would entail using a lot of budget and time. There are also certain risks that a newly developed telescope and CCD camera will not exhibit the expected performance. It is particularly difficult to design wide field optics and extract its capability. In contrast, the performance levels of paticular commercial telescopes and CCD cameras are guaranteed by many customers. We can adopt these devices.

Small telescopes have a relatively larger field of view (FOV) than large telescopes. Using many small telescope offers a great advantage with regard to sky coverage.

The limiting magnitude of small telescopes is smaller than that of large telescopes. As we solved the trail loss problem, we need not detect far NEOs that move slow and are dark. The new strategy can use small telescopes to detect near NEOs that move fast and are bright. The red line in Fig. 1 shows the detectable area of the strategy. Although the limiting magnitude is below 20th, the strategy can detect very fast NEOs that existing NEO survey programs cannot detect. The decline of the red line in the figure is caused by trail loss in the single CCD. NEOs faster than 226 arcmin/day make streaks in a single CCD frame in the setting of our 25-cm telescope, the CCD camera, and typical exposure time of 24 seconds. In order to avoid such streaks, the exposure time must be shorter. Moreover, the number of CCD frames must also be increased to compensate for signals from NEOs.

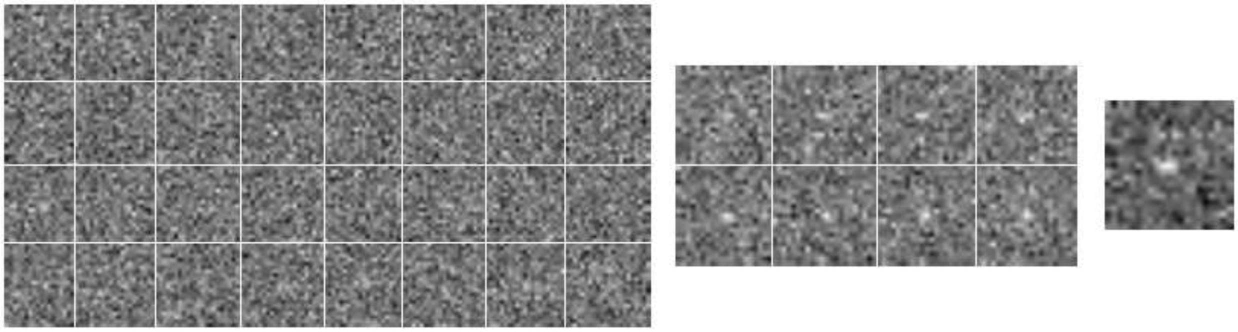

Figure 9. The images of detected NEO 2017 BK. (Left): combination of 32 raw images where the NEO should exist; (Center and Right): median images of 8 frames and 32 frames, respectively.

The new strategy is very robust against device malfunction. As many sets of telescopes and CCD cameras are used in the strategy, the failure of one set does not affect overall performance. If the failed set cannot be repaired, we can easily purchase another set of devices at low cost. Conversely, existing survey programs may experience a long-term suspension of observation and high repair cost in case a malfunction occurs.

5. TEST OBSERVATIONS

We carried out test observations to evaluate the effectiveness of the new strategy at Mount Nyukasa observatory in Nagano prefecture, Japan on January 17th, 25th, 26th, and 31st. Figure 8 shows the devices used for the test observations. Two 18-cm telescopes (Takahashi e180ED) pointing at consecutive regions in the sky were used. The CCD camera (FLI ML23042) and the CMOS camera (manufactured by Canon) were installed with each telescope. The FOV of the CCD and CMOS cameras are 3.5×3.5-degrees and 4.4×2.5-degrees, respectively. The exposure times for CCD and CMOS are 24 and 26 seconds, respectively, as the readout time of the CMOS is negligible. A total of 32 images was taken with each sensor per region. Telescopes pointed at 40 regions for one night with 15-minute intervals. Total sky coverage for one night was 930 square degrees. The CCD and CMOS cameras were each controlled by a dedicated Windows PC.

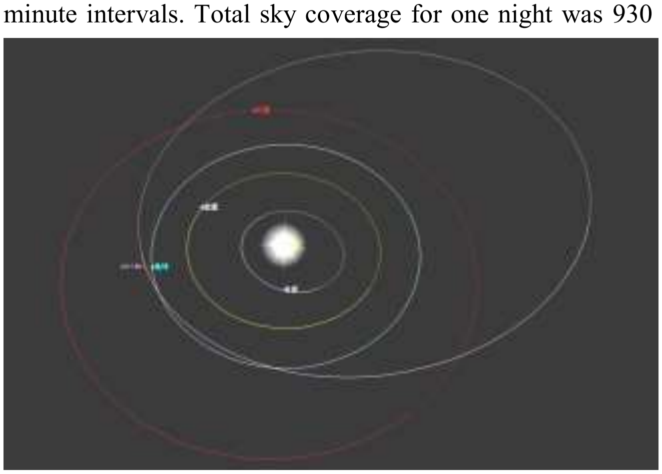

Figure 10. The orbit of NEO 2017 BK at its discovery

All the data from both sensors were stored on the NAS (network attached storage) device. Two FPGA-installed Linux PCs were used for the main analysis of each sensor. And nine Linux PCs controlled such initial analysis as dark frame subtraction, flat fielding, sky level adjustment, and binarization. Another Windows PC was used for confirming the detected NEOs and calculating their coordinates. As all the PCs and NAS device were connected with a LAN, the data and analysis results were transferred among them. A total of 32 images was produced every 15 minutes from one sensor, and all the processes were completed in two hours. As the nine Linux PCs used for initial analysis work in parallel, data from two sensors were processed on a quasi-real-time basis.

Table 1. Orbital elements and other parameters of NEO 2017 BK

Parameter	value
Epoch	2017-02-16.0
Semi-major axis	1.9107853 AU
Eccentricity	0.4902647
Inclination	6.64014-degree
Longitude of the ascending node	110.92190-degree
Argument of periapsis	39.62114-degree
Mean anomaly	0.82779-degree
Absolute magnitude	24.0
Slope parameter	0.15

As a result, two fast moving NEOs (2017 BK and 2017 BN92) were detected during the test observation on January 17th and 31st. A few hours after said detection, follow-up observations were carried out for both NEOs, with four positions for each NEO being reported to the minor planet center [8]. The absolute magnitudes of 2017 BK and 2017 BN92 were 24.0- and 25.6-magnitude, respectively. Figure 9 shows the images of detected NEO 2017 BK. The left shows a combination of 32 raw images where the NEO should exist. The center and the right show median images of 8 frames and 32 frames, respectively. Although the features of the NEO are almost invisible in the raw images, the features are clearly recognizable in the median images. Figure 10 depicts the orbit of NEO 2017 BK at its discovery. The lines of light blue, red, and pink represent the orbits of Earth, Mars and NEO 2017 BK, respectively. Table 1 lists the orbital elements and other parameters of the NEO. As we expected, the NEO was discovered at very close region to Earth where it moves very fast in the sky. Figure 1 shows the positions of the two NEOs with red circles. We have shown that the new strategy is able to detect fast moving NEOs, for which existing NEO survey programs have detection difficulties by this test observation. The discovery of NEOs in Japan marked the first time in about nine years.

6. Future Plan

From the discovery rate of NEOs in the test observations described in the previous section (two NEOs discovered by using two telescopes during four nights), there may be many yet to be discovered fast moving NEOs. We started to consider the large-scale observational network Janess (JAxa NEo Survey System) using multiple ground observation facilities and satellites. The principle concept of Janess is as follows: 20 sets of 25-cm telescopes and CCD or CMOS cameras will be installed in both hemispheres to cover the night side of Earth. Four satellites consisting of one set of devices will be injected into Sun-synchronous orbit to cover the day side of Earth. By using the detectable area of the strategy as shown in Fig. 1 and assuming that the distribution of NEOs in Fig. 1 is constant along the X-axis (velocity of the NEOs), the total expected number of NEOs using both the ground observation facilities and the satellites was estimated. The two ground observation facilities consisting of 40 sets of devices will detect about 4000 NEOs a year, assuming that the number of observable dates is limited to one-third due to poor weather conditions. The four satellites will detect about 3000 NEOs a year. Given the fact that about 2000 NEOs are currently discovered each year, Janess will contribute significantly to the discovery of more NEOs. The cost for the ground facilities and satellites will be about 8 and 130 million dollars, respectively. In view of such high cost, international collaboration would be the optimum solution.

6. Summary

JAXA is developing a new observation technology for NEOs. The technology employs a very different process than such existing NEO search programs as Pan-Starrs and CSS, and could possibly innovate the current NEO survey concept. We propose a new observation strategy using a new analysis process. The strategy uses many small telescopes and normal CCD cameras instead of one large telescope and one large CCD camera, which are typically used in existing NEO survey programs. And the strategy offers many advantages over existing NEO survey programs in terms of cost, FOV, robustness against malfunction, and other aspects. We carried out test observations to evaluate the effectiveness of the strategy. The discovery of two NEOs showed that the strategy can detect fast moving NEOs, for which existing NEO survey programs have detection difficulties. In the future, we would like to establish the large-scale observational network Janess (JAxa NEo Survey System) using multiple ground observation facilities and satellites. International collaboration will be needed to accomplish that objective.

Acknowledgements

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Biography

Toshifumi Yanagisawa *received Ph.D. in Astrophysics from the Nagoya University in 2000. He has been working on the observation technologies and the image-processing for space debris and near earth objects in Japan Aerospace Exploration Agency (JAXA) for 17 years. He is currently the chairman of the working group 1 (space debris observation) of the Inter-Agency Space Debris Coordination Committee (IADC).*

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