SMALL NEO SEARCH TECHNOLOGIES USING SMALL TELESCOPES AND FPGA

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ABSTRACT

Most of NEOs from 10m to 100m in diameter have not been discovered. These NEOs have more chances to collide with the Earth than lager NEOs and may cause significant localized damages. We have developed a new survey system for such small NEOs at extraordinary low cost in comparison with the current survey systems and discovered 7 NEOs, including 2 in the test survey in Jan. 2017.

Although the existing NEO search programs uses 1-2m telescopes and large CCDs, our technology uses many CCD or CMOS frames from small telescopes of about 20cm to find out faint and fast moving NEOs in the frames. The FPGA (field programmable gate array) board is used to implement the sophisticated image processing algorithm and reduce analysis time. We are using 18cm telescopes at Mt.Nyukasa observatory in Japan and 25cm telescopes at the remote observation site in Australia for the technology. We are also considering space application of the technologies in the future. Spacecraft equipped with the technologies will discover more NEOs effectively. In this paper, the detail of the new technology, the comparison with the existing NEO survey, the observation in which new NEOs were discovered, and the space application will be explained.

1 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

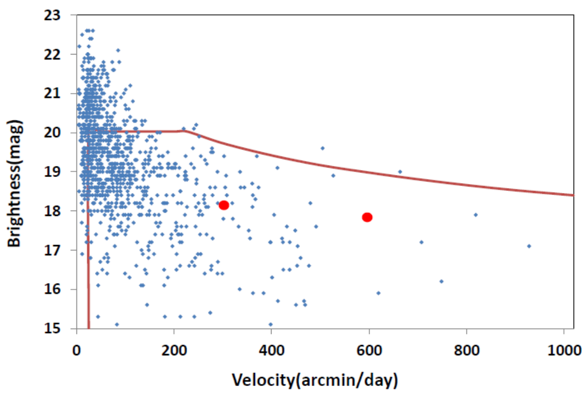

Figure 1. Distribution of PHA at initial discovery in the velocity and brightness space

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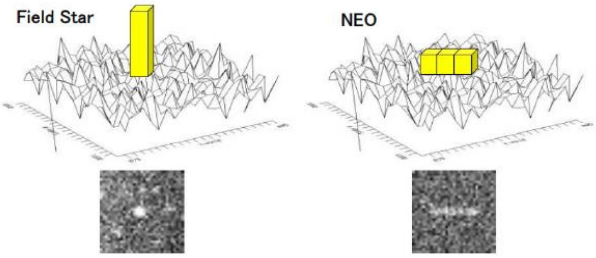

Figure 2. Example of trail loss

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 Y-axis 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 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.

2 NEW ANALYSIS PROCESS

In the previous section, we found that the existing observation strategy and analysis process miss fast

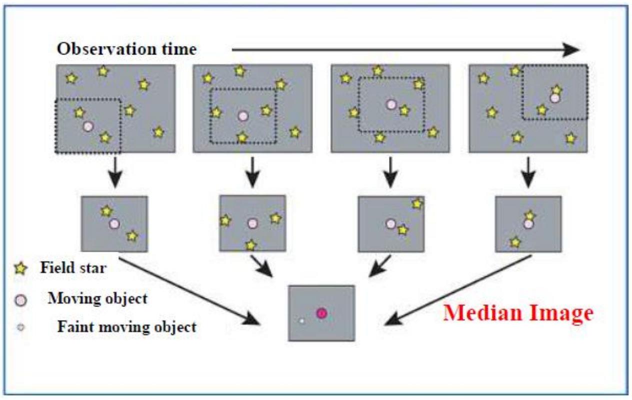

Figure 3. The new image processing algorithm

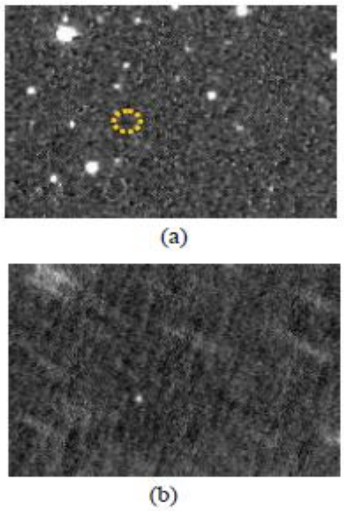

Figure 4. An asteroid detected using the algorithm

moving NEO groups that come very close to Earth. In order to cope with the situation, we have developed 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 figure 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 figure 4 (a), whereas the asteroid is bright and no field stars are visible in figure 4 (b).

A similar process was developed by Shao et al. [6]. They use add and mean instead of median. We use median

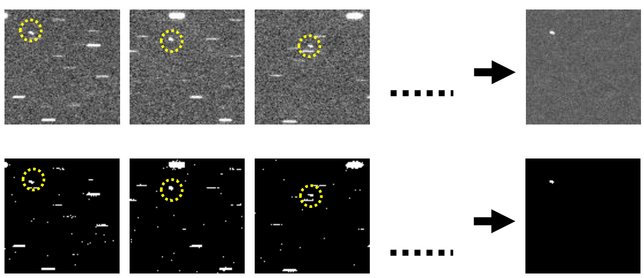

Figure 5. The difference between the original algorithm using median and the modified one using binarization

Figure 6. FPGA board developed for the algorithm

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 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.

3 NEW OBSERVATION SYSTEM

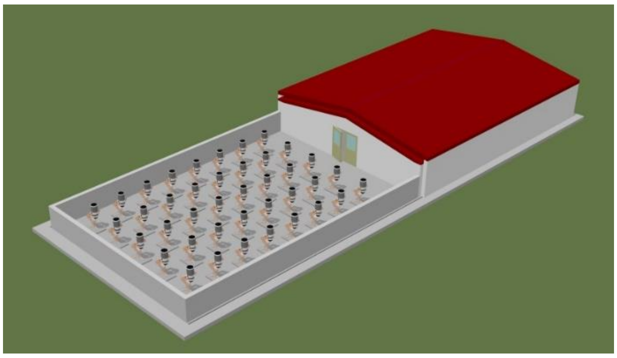

Figure 7. The concept of the new observation strategy

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

There are many advantages in our new system. As both devices are commercially available, we need not design and develop a dedicated telescope and a CCD camera that would require huge costs and time. There are also certain risks that a newly developed telescope and CCD camera will not show the expected performance. It is particularly difficult to design wide field optics and extract its capability. In contrast, the performance levels of particular 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 telescopes 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.

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

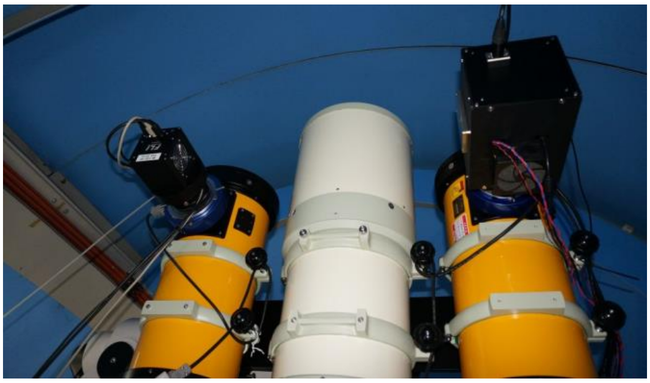

Figure 8. the devices of the test observations

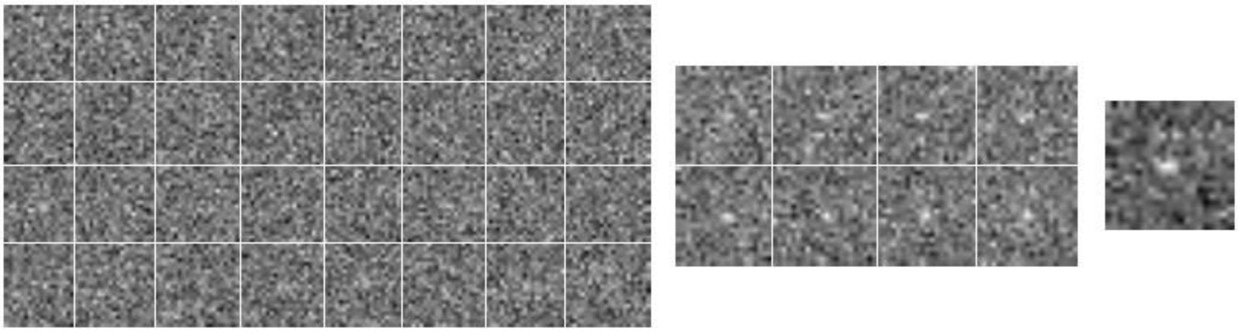

Figure 9. The images of detected NEO 2017 BK. (Left): combination of 32 raw images where the NEO should exist; (Center and Right): median images of 8 frames and 32 frames, respectively.

observation and high repair cost in case a malfunction occurs.

4 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.

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.

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 centre [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

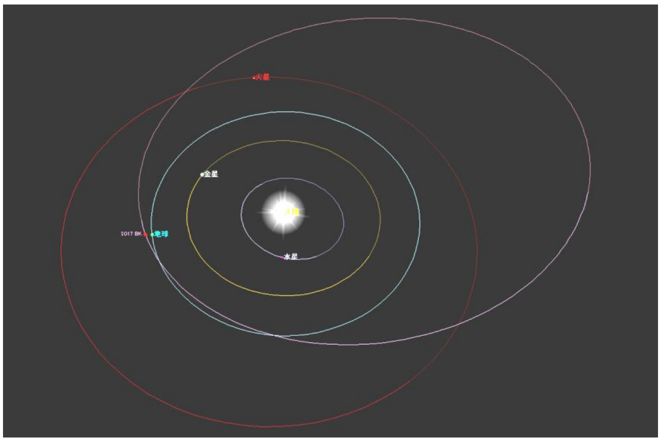

Figure 10. The orbit of NEO 2017 BK at its discovery

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

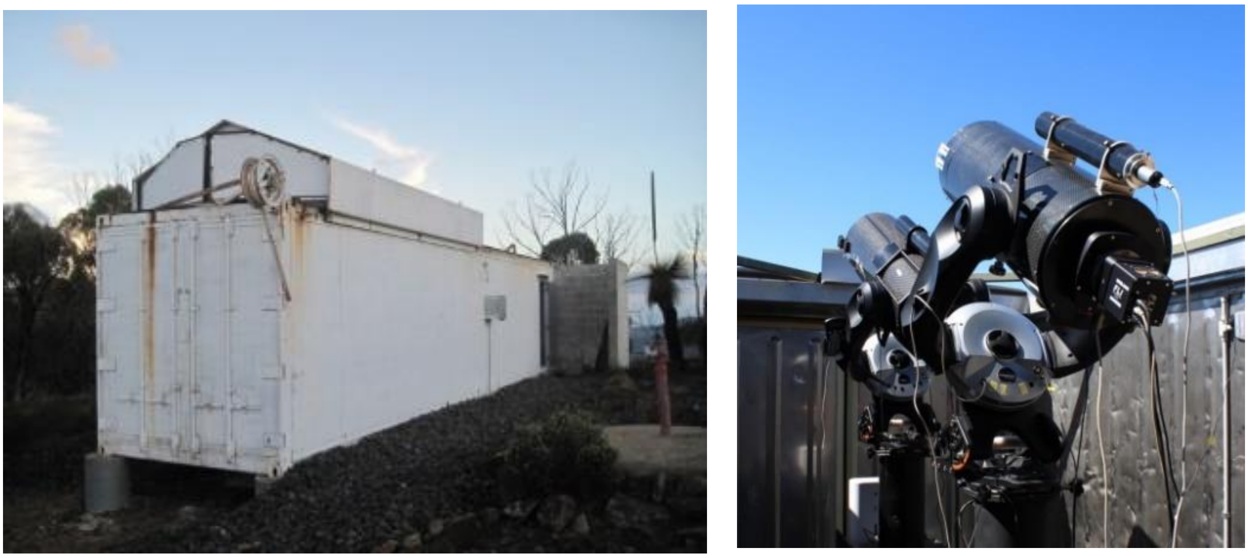

Figure 11. The remote observation site at the Siding Spring Observatory in Australia. 3 telescopes (two 25cm-telescopes and one 18cm-telescope) with the wide-field CCD cameras manufactured by FLI are installed.

where the NEO should exist. The centre 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.

5 NEW RESEARCH AT JAXA

After the discoveries of new NEOs, JAXA organized a new team called JAxa Neo Survey System (JANESS) and started new researches on the NEO problem. The principle of the research is to apply the new technology to more ground sites and satellites for the detection of many NEOs of 10m to a few hundred meters which existing survey groups cannot discover. For the first step, we need to demonstrate the effectiveness of the new technologies by discovering more NEOs. We established the remote observation site at the Siding Spring Observatory in Australia (Figure 11) where the weather condition is much better than that in Japan. As the powerful NEO survey groups are almost located in northern hemisphere, the observation from Australia will complement the entire survey area. In our site, 3 telescopes (two 25cm-telescopes and one 18cm-telescope) with the wide-field CCD cameras manufactured by FLI are installed. The field of views of each telescope are 2.5 times 2.5-degree, 2.25 times 2.25-degree and 3.5 times 3.5-degree , respectively. 10 days of the new moon season are devoted to NEO survey observation using the technology. 5 NEOs have been discovered since March of 2018 (2018 EZ2, 2018FH1, 2018 PM10, 2018 RR4, 2018 UG3).

Table 2. Expected detection number of 1 year using various size of space telescopes and various orbits (Sun-synchronous orbit(SSO), L1 point of sun-earth system(SEL1), and Artificial equilibrium point(AEP))

Telescope aperture(cm)	Weight of satellite(kg)	Cost(Euro)	Ground	SSO	SEL1	AEP
10	70	12 million	1760	1760	1760	2800
25	100	16 million	8840	8840	9320	12840
60	500	80 million	36040	36040	36840	45800

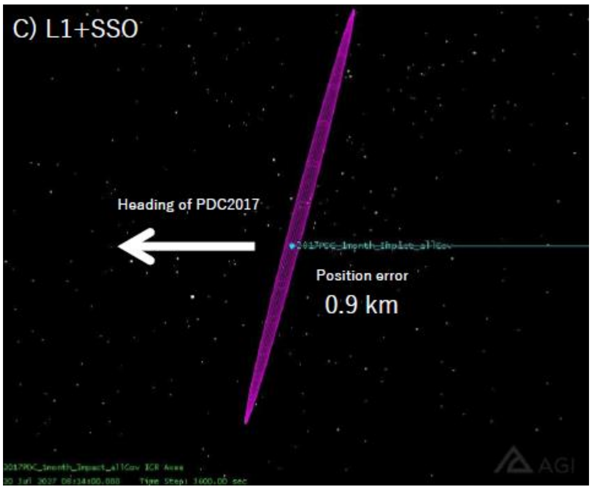

Figure 12. Covariances of fabricated NEO PDC2017 used for the NEO counter measure demonstration at the Planetary Defence Conference in Japan 2017.

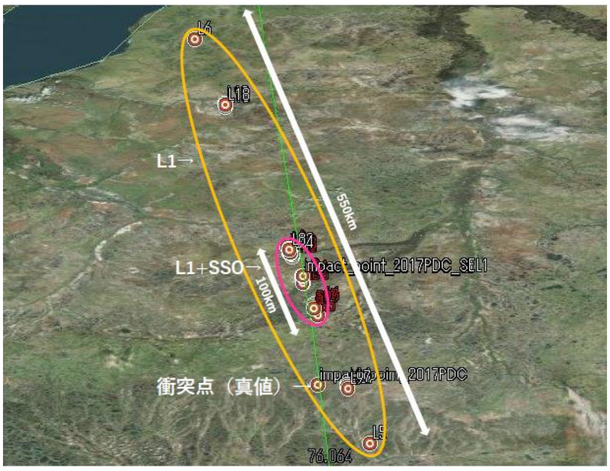

Figure 13. Falling prediction map of the NEO, PDC2017.

We are working on an international collaboration with ATLAS team [9]. Applying our technology to the ATLAS data taken by 50cm telescope enables us to detect new small NEOs which have not been detected by present system.

We started the consideration of the satellite. All the data will be downloaded to the ground and analysed with the technology. We will carefully select the orbit with the consideration of the expected detection number, the cost and so on. We have to show the advantage of the space observation. Table 2 shows the expected detection number of 1 year using various size of space telescopes and various orbits (Sun-synchronous orbit(SSO), L1 point of sun-earth system(SEL1), and Artificial equilibrium point(AEP)). Granvik model was used to generate a synthetic population of 800 thousand virtual NEOs. In the case of ground observation, lighting conditions and weather conditions were considered. The costs of the satellite were roughly estimated from the costs of past satellites. As shown in the table, larger telescope and more distant orbit will detect more NEOs. These parameters contribute to the cost directly.

Orbital determination and falling prediction were evaluated in some cases. Figure 12 shows the covariances of fabricated NEO PDC2017 used for the NEO counter measure demonstration at the Planetary Defence Conference in Japan 2017. Data from two space crafts located in L1 and SSO were used for the orbital determination. Figure 13 shows the falling prediction map of the NEO. Observation from multiple satellites can determine the falling position precisely.

University of Tokyo is developing large CMOS camera, Tomo-e Gozen, which is for 105cm Schmidt telescope at the Kiso observatory, the University of Tokyo [10]. The Tomo-e Gozen camera is the world's first wide-field CMOS camera. The entire focal plane area of the Kiso Schmidt telescope, 9 degrees in diameter, is covered by 84 chips of 35 mm full HD CMOS image sensors (figure 14). Total sky coverage of one shot is about 20 square degrees. And the maximum frame rate is 2 frames per second. Optical wide-field and high-cadence surveys will begin from 2019 with the Tomo-e Gozen camera. First detection of rare and fast time-variable phenomena is expected in these surveys. We got a new fund from the Ministry of Education, Culture, Sports, Science and Technology of Japan to apply our technology to the Tomo-e Gozen camera from 2018. Constructing analysis pile line for 84 CMOS sensors must be hard work. When it is completed, we will detect enormous number of NEOs with the Tomo-e Gozen camera.

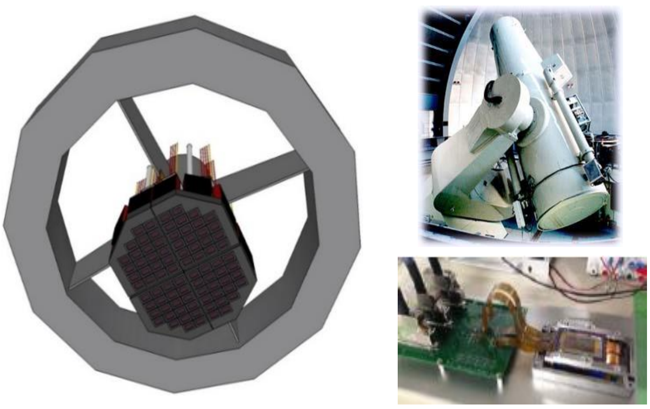

Figure 14. Tomo-e Gozen Camera (left). 84 chips of 35 mm full HD CMOS image sensors are installed at the focal plane of 105cm Schmidt telescope at the Kiso observatory (upper right). The lower right shows the readout electronics of the Tomo-e Gozen Camera.

By proceeding these activities, we would like to create the world-wide observation network including space asses and contribute the NEO problem.

6 SUMMARY

JAXA has developed a new observation technology for NEOs. The technology employs a very different process from existing NEO search programs like Pan-Starrs, CSS, and so on. It could possibly innovate the current NEO survey concept. We propose a new observation system using a new analysis process. The system 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. JAXA started various activities in 2018. The remote observation site at Siding Spring Observatory in Australia discovered 5 NEOs so far. We also started the consideration of space-based observation. Collaborative activities are in scope. By proceeding these activities, we would like to create the world-wide observation network including space assets and contribute to the small NEO survey.

7 ACKNOWLEDGEMENT

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