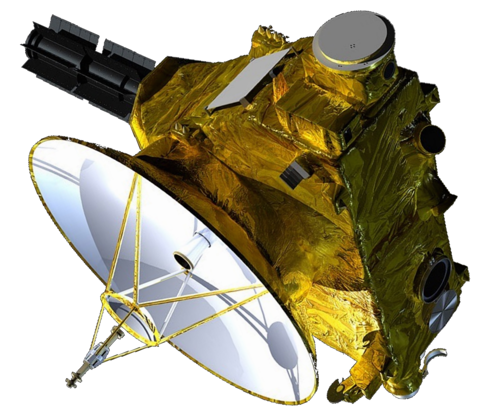
A DEEP ANALYSIS FOR NEW HORIZONS' TNO SEARCH IMAGES



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1. Introduction

NASA's New Horizons (NH) is a flyby mission to study the Pluto system and Trans Neptunian Objects (TNOs). Launched in 2006, the spacecraft reached the Pluto system in 2015, and made a flyby of (486958) Arrokoth, one of the Classical TNOs, in 2019. The NH mission has observed the surface layers of outer solar system bodies in detail for the first time. Data analysis is ongoing and a number of excellent results are being published.

An extended mission to continue exploration of the outer solar system after the Arrokoth flyby has been approved, and Japanese scientists (including the authors F.Y. and T.I.) have joined the science members of this extended mission from April 2020. The primary goal of the Japanese participation is to use the Subaru Telescope and its Hyper Suprime-Cam (HSC) to discover (1) a second KBO flyby target candidate and (2) KBO objects that can be observed from the spacecraft. The goal of (1) is obvious. The purpose of (2) is to observe KBOs from the spacecraft as it flies through the Kuiper belt. From the ground, we can only observe KBOs at a solar phase angle close to 0 deg, but if observations are made from the spacecraft while it is in the Kuiper belt, we can observe KBOs at a large solar phase angle. By observing a KBO at a wide range of solar phase angles, we can obtain information about the surface of the KBO (e.g. grain size, roughness, etc.) from the change in brightness of the KBO at different phase angles. This observation can only be made while the spacecraft is in the Kuiper belt, making it a rare observation opportunity.

The TNO survey, carried out by the NH KBO search team along the NH spacecraft's trajectory, started in May 2020 with Subaru Telescope + HSC. Two fields of view of the HSC were surveyed, where the NH spacecraft can make a flyby. For half a night, one field of view of the HSC was continuously imaged with an exposure time of 90 seconds. The next day, the other field was imaged in the same way. At intervals of about a month, the same observation was repeated to extend the observation arc. In this way, the accuracy of the orbital determination of the detected KBO is increased.

Unfortunately, this set of observations did not find any objects that the NH spacecraft could flyby before it passed the Kuiper Cliffs, the outer edge of the Kuiper belt, which appears to be about 50 AU from the Sun. However, the observations detected a large number of TNOs, so this data set could be used to study the orbital distribution of TNOs in more detail.

2. Dataset

The data used in this study are only a part of the datasets obtained from the above observations, all of which are beyond the proprietary limits of the original observers and are fully and publicly available from SMOKA (https://smoka.nao.ac.jp). Because except authors F.Y. and T.I., others are not members of the NH Science team, we had to use a limited dataset.

We have applied the 'Moving Object Detection System' developed by JAXA for the detection of near-Earth objects to the dataset acquired as described above. The 'JAXA's Moving Object Detection System' superimposes many images with shifting based on the assumed velocity of the moving object at any speed and in any direction. Using this 'Moving Object Detection System', JAXA has succeeded in detecting many faint near-Earth asteroids that were not visible in a single image. So we thought that we should be able to find fainter TNOs using this detection system.

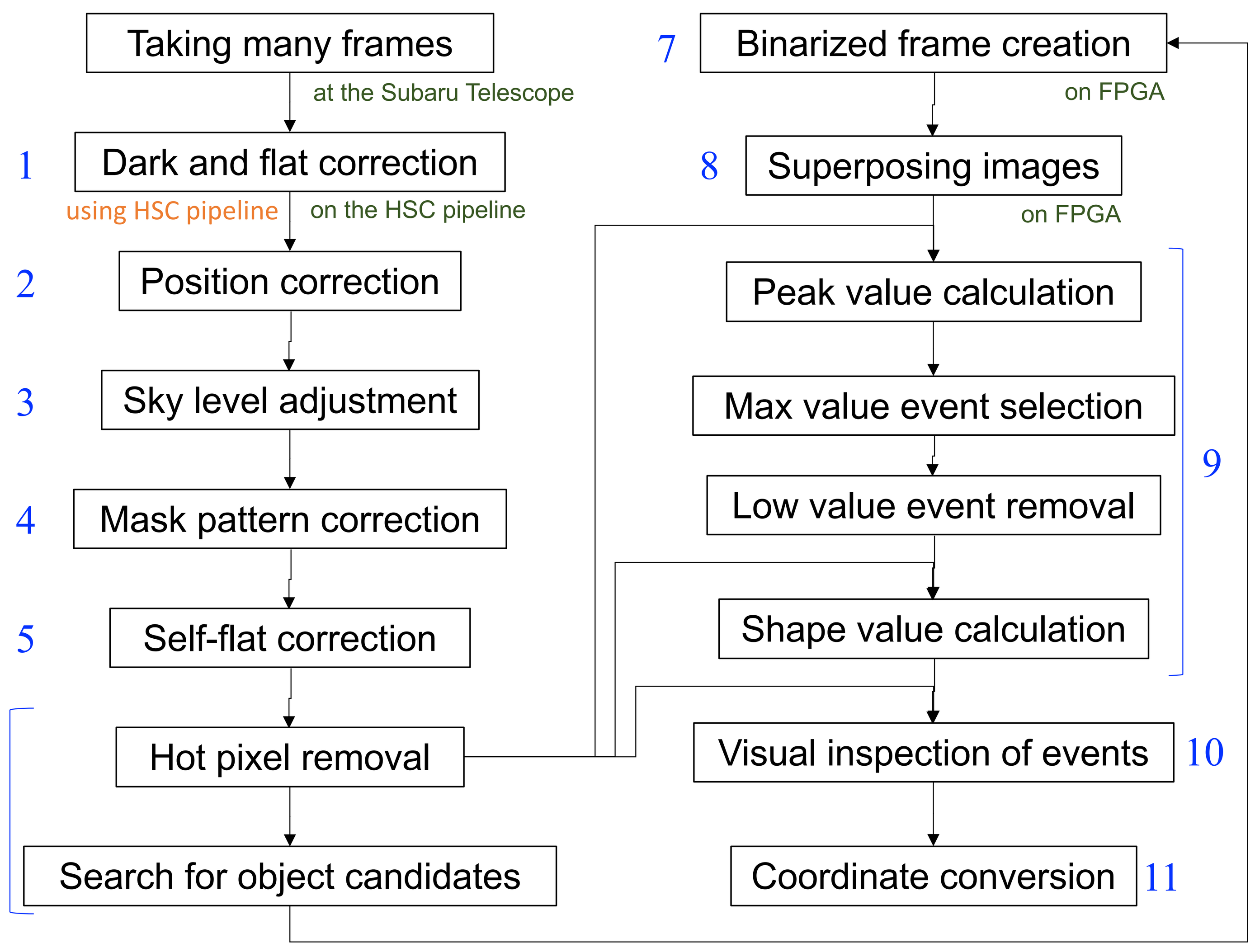
3. Detection of moving objects

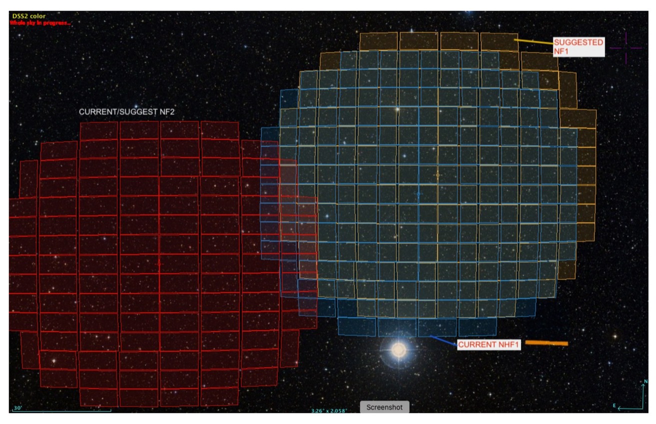
'JAXA's Moving Object Detection System' uses 32 images of the same field taken at equal time intervals, so only datasets with such image sets available were selected. The total number of moving object candidates detected by the JAXA system was 6980, of which 4339 were judged to be real moving objects. Approximately 59% of the detected moving object candidates are real.

Table 1. Observation date, reduction ID, field, the number of real objects N_{real} and the number of detections N_{detec}

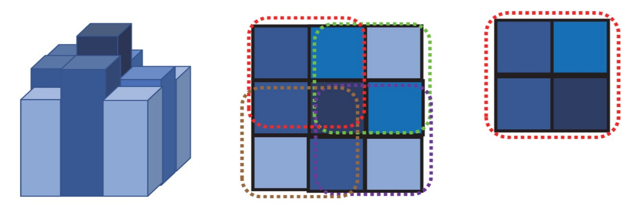
Obs data (UT)	Red.ID	Field	N_{real}	N_{detect}
2020 May 28	03070	F2	279	435
2020 May 29	03071	F1	689	1042
2020 May 30	03072	F2	727	918
2020 May 31	03073	F1	316	404
2020 June 20	03093	F2	54	198
2020 June 21	03094	F1	77	207
2020 June 22	03095	F2	286	457
2020 June 24	03097	F1	151	227
2020 June 25	03098	F2	316	459
2020 Aug 12	03146	F1	251	354
2020 Aug 13	03147	F2	448	712
2020 Aug 14	03148	F1	495	1066
2021 June 09	03447	F2	41	91
2021 June 17	03455	F2	209	410

4. JAXA Moving Object Detection System

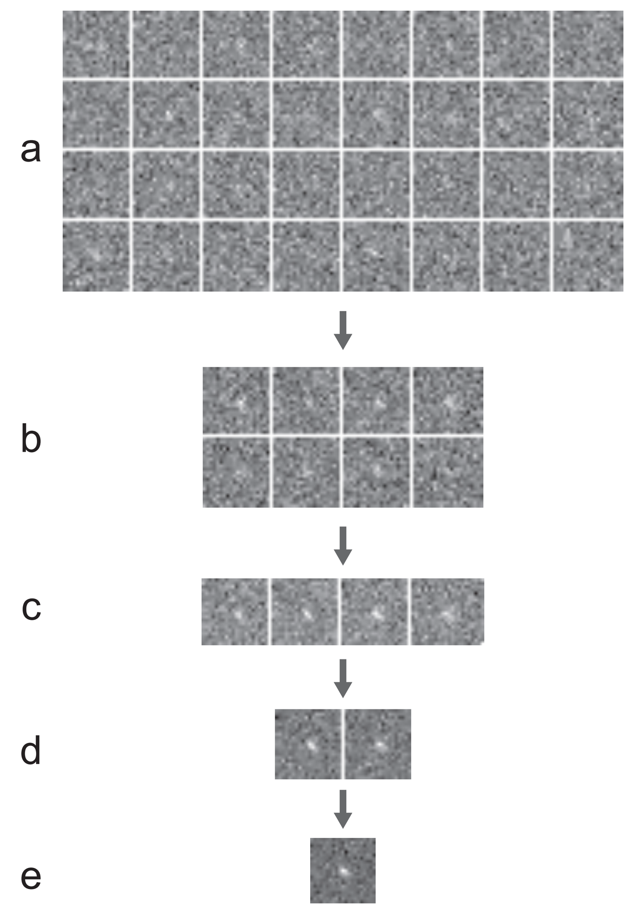




Survey fields



Schematic illustration of the 4-pixel selection process in procedure 7. The left panel shows the pixel values around the pixel of the object candidate. The middle panel shows the top view of the left panel. The sum value of each 2 × 2 set (shown in the dotted lines) is calculated. The four pixels with the maximum total value (the right panel) are set to 1.



A sample set of visual inspection images of a real moving object with low noise (the images are from the actual observation dataset). 32 images (panel **a**) represent the individual images after shifting the cropped small region containing an almost invisible object (at the center of all these images). Panels **b**, **c**, **d**, **e** show the combined images of the 4, 8, 16 and 32 images with the median filter.

There are 11 steps. Procedure 1 was done with the HSC pipeline. Procedure 7 and 8 were done in FPGA. In the procedure 7, we created a binarized image with four pixels with the maximum total value set to 1 around the object candidate, while the values of the remaining pixels are set to 0. In the procedure 8, we assume the motion of the moving object we want to detect, the binarized images are superimposed while shifting over the range dx : −256 to 256, dy : −256 to 256 pixels. In procedure 9, we search for the groups of object candidates on each image that are linearly aligned in a virtual 3D space with the position (x,y) of the object candidate on the each image and the image number as z.

Currently, the number of images to be superimposed is limited to 32 due to the limitations of the algorithm embedded in the FPGA. With 32 superimposed images, this corresponds to an integration time of 2880 seconds (90 seconds x 32 images). The total number of moving objects detected in this way is 4339. The detection limit appears to be around 26 mag (Fig.1). Since the detection limit for a single HSC 90 second integration image is typically 24-25 mag, this system clearly detects fainter objects. The detected moving objects are classified into main belt asteroids, Jupiter Trojan group asteroids, Centaurs, TNOs, etc. based on the apparent moving velocity (Fig.2). Assuming that the apparent moving velocity of TNOs is < 8"/hr, we have detected 84 TNO candidates (Fig.3).

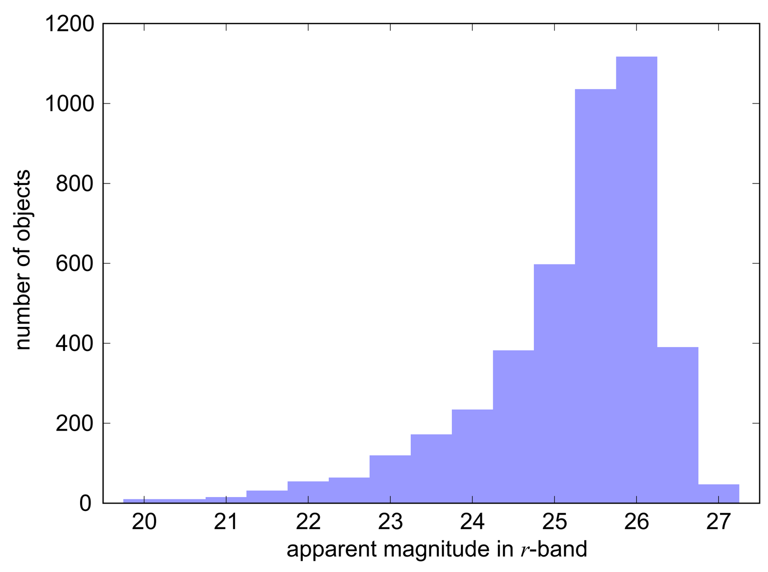


Fig. 1. Apparent magnitude distribution of the moving objects detected in this study. Note that there are five objects in the bin between 19.0 and 19.5 mag that do not appear in the area of this plot.

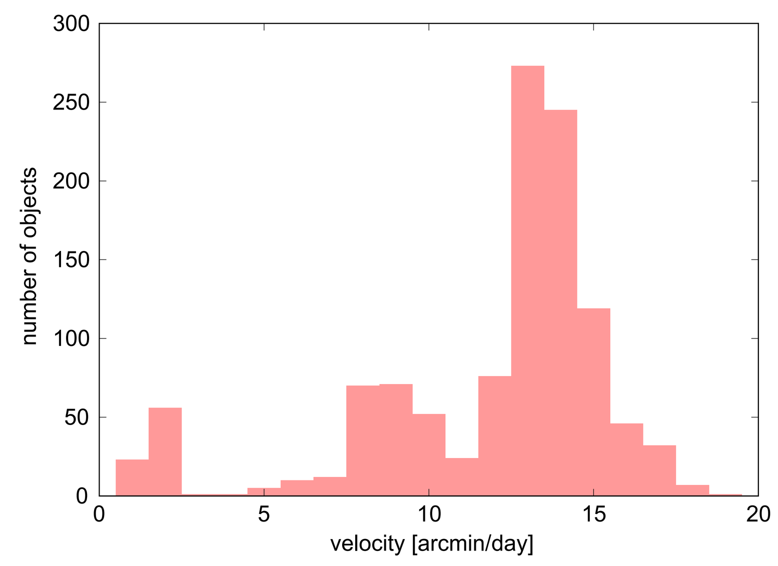


Fig. 2. Apparent velocity distribution of the moving objects detected in the June 2020 and the June 2021 observations when the survey fields were close to the oppositions. The group with a peak around 13'/day can be the main belt objects. The group with a peak around 8'/day is thought to be a Jupiter Trojan objects. The observation fields were close to the L5 point in June 2021. The group on the left with a peak at 2'/day is a TNO candidates.

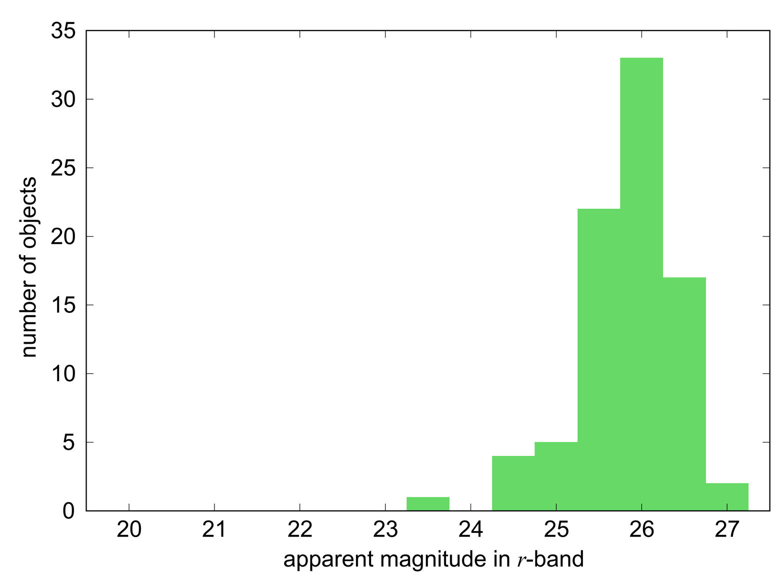


Fig. 3. Apparent magnitude distribution of detected TNO candidates in the June 2020 and the June 2021 observations.

5. Orbit link

The identification of the detected TNO candidates was done by a software code (called "Stella-Hunter Professional") developed by JAXA for the detection of moving objects.

The objects detected by the NH science team have already been reported to the MPC and given preliminary designations. We detected seven unknown objects that were not reported by the NH science team. Two of these have been given provisional designations by the MPC; 2020 KJ60 and 2020 KK60.

Table 2. Properties of 2020KJ 60 and 2020 KK60.

	2020 KJ60	2020 KK60
epoch	2023-09-13.0	2023-09-13.0
epoch JD	2460200.5	2460200.5
perihelion date	1984–01–18.13386	2006–03–16.60277
perihelion JD	2445717.634	2453811.103
argument of perihelion (deg)	69.3508	15.16474
ascending node (deg)	156.60392	242.43004
inclination (deg)	2.49898	4.24758
eccentricity	0.3752396	0.3888881
perihelion distance (au)	37.2882832	35.261981
semimajor axis (au)	59.6841373	57.7013481
mean anomaly (deg)	30.95781	14.36763
absolute magnitude	9.67	8.77
phase slope	0.15	0.15
uncertainty	9	9
observations used	6	6
oppositions	1	1
arc length (days)	77	75
residual rms (arcsec)	0.08	0.16
first observation date used	2020-05-28.0	2020-05-29.0
last observation date used	2020-08-13.0	2020-08-12.0
first detection (t_{detect}, UTC)	2020–05–28 11:18	2020–05–29 10:44
Earth Distance at t_{detect}	42.542 au	35.667 au
Sun Distance at t_{detect}	43.328 au	36.474 au

6. Summary and future expective

The set of observations originally designed for the New Horizons target search was performed using the Subaru Telescope and HSC. The image set obtained from the observations has been analyzed by 'JAXA's Moving Object Detection System'. So far, we have found 84 TNO candidates.

Currently, the system uses a set of 32 images for this study. This number can be increased from 32 to 64 by improving the system in the near future, and the TNO detection capability will extend to a much fainter (deeper) level.

With the current system, procedures 7 to 8 in the FPGA take 140 minutes per dataset. We have a plan to run our detection method on a GPU cluster, which we expect will reduce the turnaround time of the data analysis to ~ 1/5 or less.

In this study, we have only analyzed the data set from the New Horizons team's observations up to June 2021. The series of observations will continue. We will continue to search TNOs new data set in the archive and try to detect more moving objects in the outer Solar System.

References for the NEO Detection System by JAXA (a) New NEO Detection Techniques using the FPGA. Yanagisawa, Toshifumi ; Kamiya, Kohki ; Kurosaki, Hirohisa, Publ. Astron. Soc. Japan, 7, 519–529, 2021, (b) Automatic Detection Algorithm for Small Moving Objects. Yanagisawa, Toshifumi ; Nakajima, Atsushi ; Kadota, Ken-Ichi ; Kurosaki, Hirohisa ; Nakamura, Tsuko ; Yoshida, Fumi ; Dermawan, Budi ; Sato, Yusuke, Publ. Astron. Soc. Japan, 57, 399–408, 2005