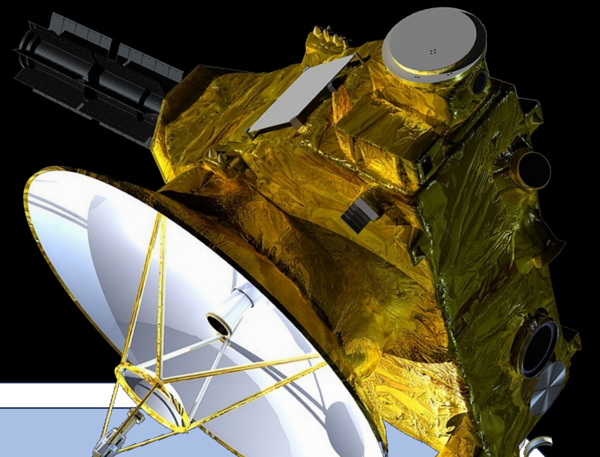
A DEEP ANALYSIS FOR NEW HORIZONS' TNO SEARCH IMAGES



Fumi Yoshida[1,2], Toshifumi Yanagisawa[3], Takashi Ito[2,4], Hirohisa Kurosaki[3] and Makoto Yoshikawa[3], [1]University of Occupational and Environmental Health, Japan, 1-1 Iseigaoka, Yahata, Kitakyusyu 807-8555, JAPAN, E-mail: fumi-yoshida@med.uoeh-u.ac.jp, [2]Chiba Institute of Technology, [3]Japan Aerospace Exploration Agency, [4]National Astronomical Observatory of Japan

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. NH mission has revealed the surface layers of outer Solar System bodies for the first time. Data analysis is ongoing and a number of excellent results are being published.

An extended mission to continue exploring the outer solar system after the Arrokoth flyby has been approved and Japanese scientists (including F.Y. and T.I of authors) 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-Camera (HSC) to discover (1) a second KBO flyby candidate and (2) KBO objects that can be observed from the spacecraft. The goal of (1) above is obvious. The purpose of (2) is to observe KBOs from the spacecraft in the Kuiper belt. From the ground, only KBOs with a solar phase angle close to 0 degrees can be observed, but if observations are made from the spacecraft when it is in the Kuiper belt, KBOs can be observed in configurations with large solar phase angles. The combination of ground-based observations at near-zero solar phase angles and observations from the Kuiper belt will provide surface reflections of KBOs at a wide range of solar phase angles, which can be used to infer information about the KBO surface (e.g. grain size, roughness, etc.). This observation can only be made while the spacecraft is in the Kuiper belt, making it a rare observation opportunity.

The TNO survey, which performed by the NH KBO search team, along the trajectory of the NH spacecraft, began in May 2020 with Subaru Telescope + HSC. Two fields of view of HSC were surveyed where the NH spacecraft can make a flyby. During half a night, one field of view of the HSC was continuously imaged with 90-second integrations. For half a night, one field of view of the HSC was continuously imaged with 90-second integrations. 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 sources is increased.

Unfortunately, the series of observations did not find any objects that were flyby candidates when the New Horizons spacecraft passed the Kuiper Cliffs, the outer edge of the Kuiper Belt (estimated to be at a heliocentric distance of about 50 au). Nevertheless, we were able to detect many KBOs, and this data set will allow us to study the orbital distribution of Kuiper belt objects in detail.

2. Data on public archive

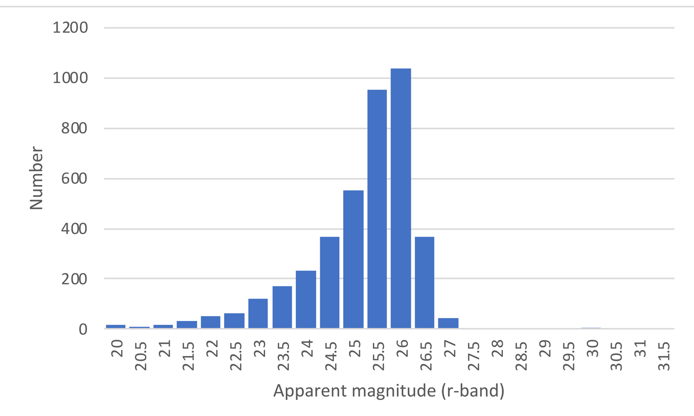
The data sets acquired as described above are perfectly suited to the Moving Object Detection System developed by JAXA to detect near-Earth objects. By superimposing images in the Moving Object Detection System, JAXA has been able to detect a number of faint near-Earth asteroids that were not visible in a single image. We, therefore, tried to see if we could find fainter TNOs using JAXA's Moving Object Detection System. Since the JAXA members of this research group are not NH Science team members, we used data already available in the public archive for this study.

Part of data set obtained for the above observing program and used for this study are all beyond the proprietary limits of the original observers and are fully and publicly available from SMOKA to anyone. More details can be found at https://smoka.nao.ac.jp/. Initial data analysis was performed by Jian Jiang (then at Kavli IPMU, now at NAOJ) with his kind permission.

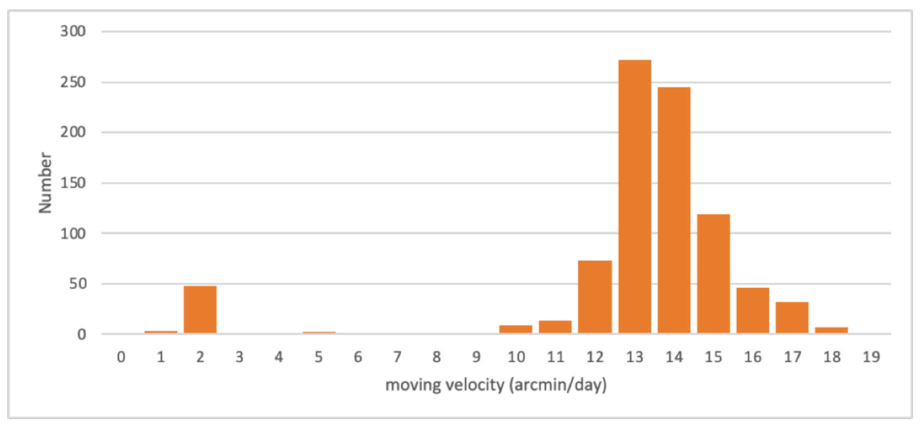
3. Data set

The JAXA Moving Object Detection System uses 32 images of the same field of view 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 6479, of which 4034 were judged to be real objects. Approximately 62% of the object candidates detected were real objects.

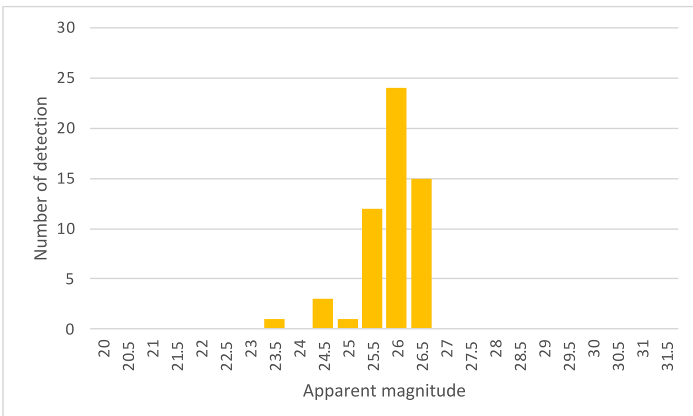
Date (HST)	Obs. field	real object /number of detections	Date (HST)	Obs. field	real object /number of detections
May 27	F2	276 / 435 (63%)	June 21	F2	283 / 457 (62%)
May 28	F1	677 / 1042 (64%)	June 23	F1	150 / 227 (66%)
May 29	F2	715 / 918 (78%)	June 24	F2	312 / 459 (68%)
May 30	F1	315 / 404 (78%)	Aug 11	F1	251 / 354 (71%)
June 19	F2	54 / 198 (27%)	Aug 12	F2	441 / 712 (62%)
June 20	F1	75 / 207 (36%)	Aug 13	F1	485 / 1066 (45%)



Apparent magnitude distribution of detected moving objects in the whole 2020 data.

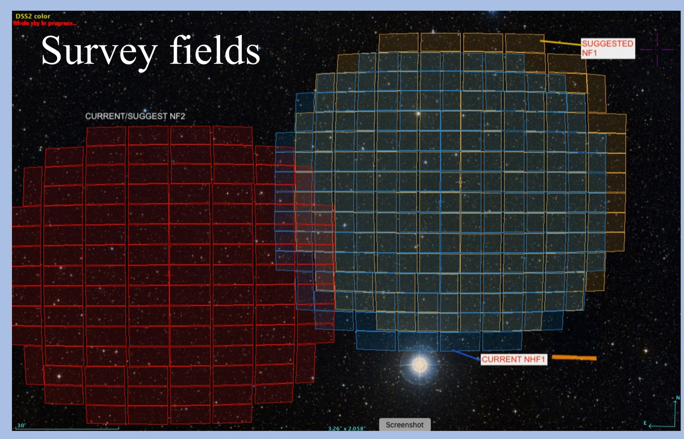


Apparent velocity distribution of the moving objects detected during the June 2020 observation, when the survey areas were close to the opposition.



Apparent magnitude distribution of detected TNO candidates in the 2020 June data.

4. JAXA Moving Object Detection System



A set of multiple images of a particular region of the sky taken with a constant time interval.

❶ Bias subtraction/Flat correction/Sky subtraction. This process was carried out on the HSC pipe line.

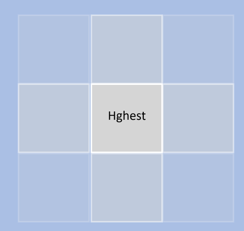
❷ Alignment (as the telescope pointing may be slightly off)

❸ Create a median image using all the images, and subtract the median image from each image.

❹ Mask each image with the mask patterns created from the median image.

❺ Search for moving object candidates from the remaining light sources on the masked image. **Introduce Shape parameter.**

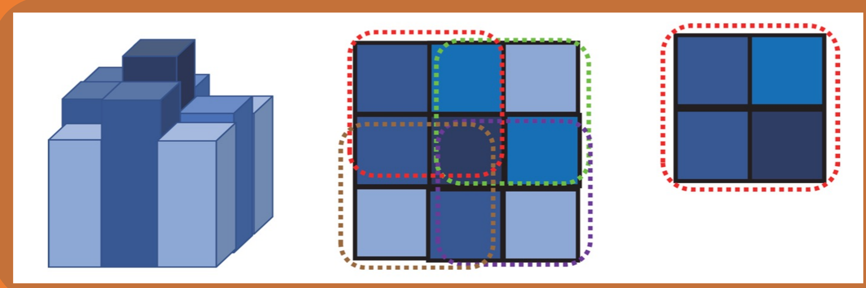
Shape parameter



The star's luminosity distribution has a central peak.

The value obtained by dividing the sum of the values of the nine pixels around a peak by the highest central pixel value is defined as the shape parameter. If the shape parameter is close to 1, it means that only the central pixel has a sudden high value (possibly a dead pixel, noise, or cosmic rays). If the shape parameter value is high, it is considered a candidate for an extended object image.

This process is carried out using FPGA. JAXA did the FPGA programming. Binarising the image in step ❻ and doing steps ❼ and ❽ on an FPGA made it 20 times faster than running the moving object detection program on a normal PC.



❻ Create a binarised image with four pixels around the object candidate set to 1 and the remaining pixels set to 0.

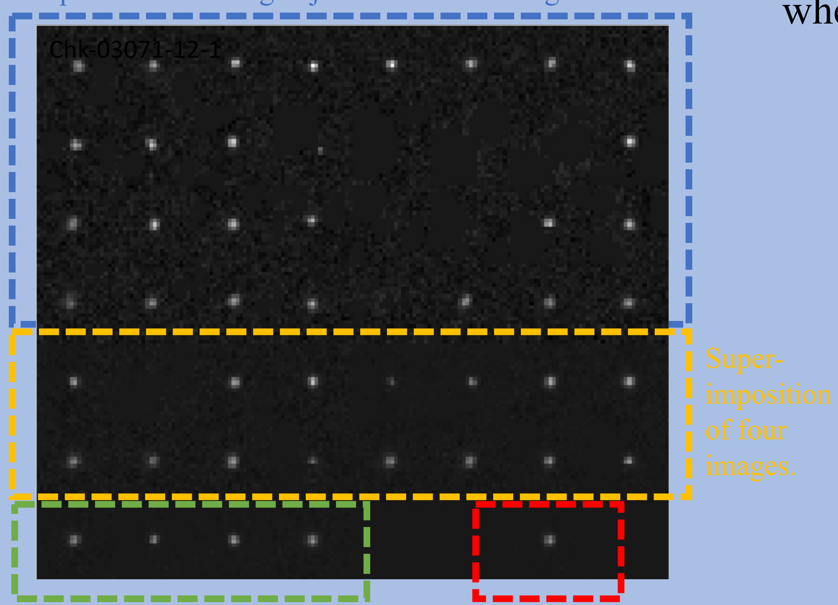
❼ Assuming the motion of the moving object we want to detect, the binarised images are superimposed while shifting in the range dx: -256 to 256, dy: -256 to 256.

❽ In a virtual 3D space with the position (x,y) of the object candidate and the image number as z, find the groups of object candidates that are linearly aligned. = moving objects

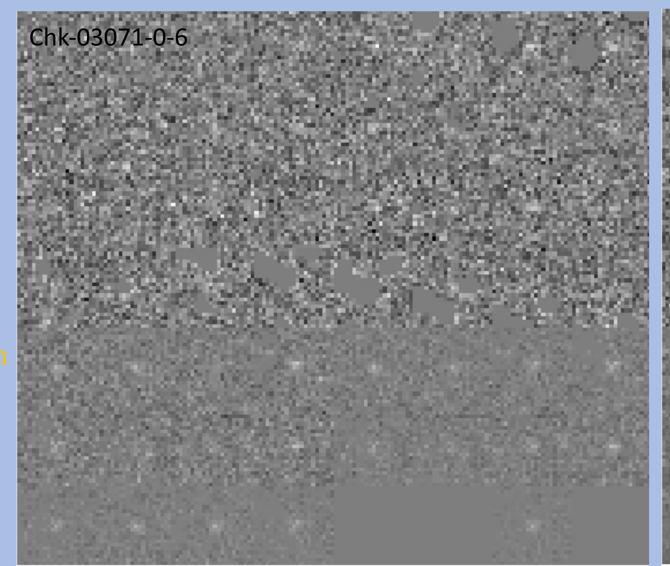
❾ The superimposed images are checked by the human eye to determine whether they are real objects or not.

By assuming the speed of a moving object, then shifting and superimposing the images with in any direction, the object can be seen in the superimposed image.

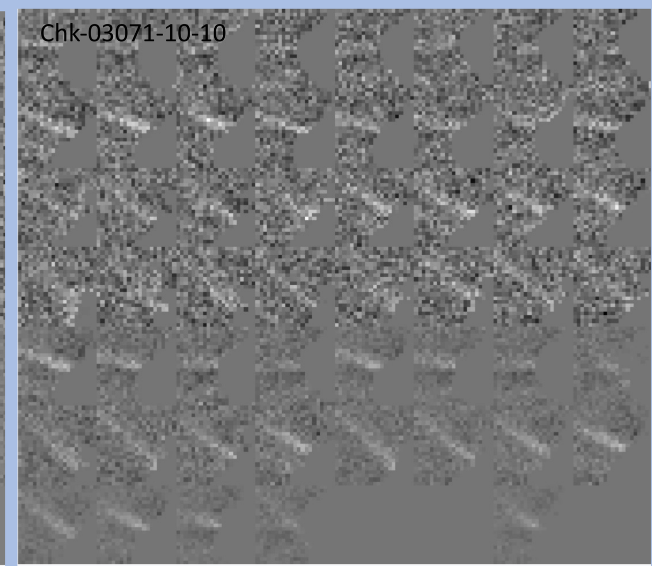
Crops around moving objects from each image.



Superimposition of eight images. Superimposition of 32 images.



A faint object (real)



A stray light (not real object)

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, corresponding to an integration time of 2880 seconds (90 seconds x 32 images). The total number of moving objects detected in this way is 4034. The detection limit seems to be around 26 mag. 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. Assuming that the apparent moving velocity of TNOs is < 8"/hr, we have detected 56 TNO candidates.

5. Orbit link

Identification of the objects detected during the May, June and August observations is underway; the June observation was closest to the opposition, so the observation arc will be extended backwards and forwards based on June.

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. The orbital elements of the unknown objects are shown below.

F1

Detect ID	Epoch	M	n	Peri	a	Node	e	Incl.	P	H
03071-096-02 03094-092-01 03146-093-03	2020 May 31.0	11.28143	0.00220614	15.68541	58.4404403	242.23978	0.3964207	4.23433		8.53
03071-080-02 03097-074-01	2020 May 31.0	359.95345	0.00191703	90.65816	64.1775983	195.03697	0.3379206	2.68321		7.71
03071-090-05 03097-085-01	2020 May 31.0	179.82848	0.00706483	352.26576	26.8989165	113.28983	0.6167589	21.27055	139.51	9.61
03071-094-11 03097-089-01	2020 May 31.0	359.94102	0.00242844	124.95387	54.8173809	160.32114	0.2339671	3.52256		9.51

F2

Detect ID	Epoch	M	n	Peri	a	Node	e	Incl.	P	H
03070-066-06 03072-050-07 03147-020-06	2020 May 31.0	359.77854	0.00298581	132.00232	47.7633370	154.91643	0.0822065	2.56450		9.39
03098-014-04 03147-014-06	2020 May 31.0	359.71567	0.00383246	20.64859	40.4406149	266.42684	0.0025594	5.15591		10.19
03447-027-01 03455-027-02	2021 July 5.0	0.03091	0.00174529	147.31747	68.3215293	139.02814	0.3493611	1.83469		8.96

6. Summary and future expective

The TNO search image set acquired by the Subaru Telescope + HSC for the NH extended mission was run through JAXA's Moving Object Detection System. 56 TNO candidates were found. Compared to the TNO candidates detected in the 28 May (HST) dataset by the NH Science team, the number of detections is 43 by NH team, meanwhile 49 by JAXA system, suggesting that the JAXA system has an advantage in its detection method, as JAXA system has a slightly higher number of detections. Currently, the system uses a set of 32 images, but the number of superimpositions could be increased to 64 by improving the system. With 64 superimpositions, it should be possible to detect even fainter objects.

References for the NEO Detection System by JAXA (Japan Aerospace Exploration Agency) (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