Initial Analysis Results of Subaru/HSC Observations of TNOs for New Horizons Navigation Support

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Using the Subaru Telescope and HSC,
- ☐ Find KBOs that are observable by the NH spacecraft at large solar phase angles that are impossible to observe from which are unable to perform from Earth.
- ☐ Discover KBOs that the NH spacecraft can flyby.

- ☐ To incorporate machine learning into our moving object detection method, we analyzed data acquired in 2024.
- ☐ For moving object candidates detected in the 2020 data from the survey's early phase, we performed orbital liking using various combinations.

- ☐ We detected many TNO candidates moving very slowly, with a detection limit of 26-27 mag.
- ☐ Two new TNOs were found in the 2020 data.

What is the New Horizons (NH) mission?

- To **study the unexplored regions of the solar system**, the dwarf planet Pluto and its moons, as well as other objects within the Kuiper Belt, a region where traces of the early stages of planetary formation remain.
  NASA launched the NH spacecraft in 2006, investigated the Pluto system in 2015 [1][2], Arrokoth (2014 MU69) in 2019.
- The extended mission was started in 2016.
  The main purpose : **(1)Flyby another KBO**
  (2)Observe as many KBOs as possible from the spacecraft.

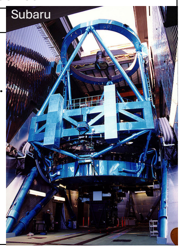
- In 2020, a series of survey observation for the extended mission began **using the Subaru Telescope + HSC and is still ongoing.**
  Analysis results from data acquired between 2020 and 2023 have already been reported [3][4].

Objectives of the 2024 Observations and Dataset

Table 1. The observational datasets

Obs. Date(UT)
2024.06.11
2024.06.12
2024.07.08
2024.07.09
2024.07.10
2024.07.31
2024.08.01
2024.08.02

- ☐ Objective1 : Followup observations for determining the orbits of ~240 KBOs discovered between 2020 and 2023.
  Objective2： Discover new KBOs
- ☐ Observation Nights：8 nights
  Exposure Time per Image：90 seconds
  Filter：r2
- ☐ Continuous imaging throughout the half night and shifting-stacking the images will enable the discovery of fainter objects.



How do we identify KBOs in HSC images?

1. The NH main team performed the primary image processing.
2. Chose 32 images taken at equal time intervals from images obtained during one night of observation and then input them into JAXA's moving object detection system.
3. JAXA's system superimposes 32 images in all directions at various assumed KBO velocities.
   If a light source is present at the center of the 32 superimposed images, that is considered a KBO candidate.(Fig. 1.)
4. Our team developed a machine learning program that classified objects as real or spurious and extracted genuine KBO candidates (Please refer to the poster by Shibukawa+, P. 10).
5. This procedure was performed for each night's data, and then the KBO candidate detections from all nights were combined and examined for continuous orbital solutions.
6. We will report objects with orbits connected over two or more nights to the Minor Planet Center.

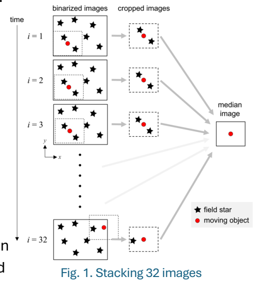


Fig. 1. Stacking 32 images by the JAXA detection method

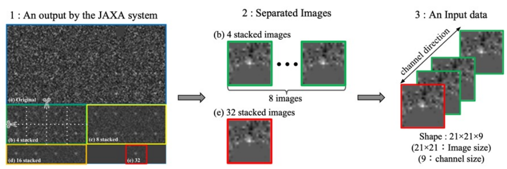


Fig. 2. Flow Chart about stacking 32 (Fig.2-1 displays the detection system's output for each object. The image's upper half shows cropped sections of individual light source images, while the lower half presents stacked images of 4, 9, 16, and 32 exposures.)

Results, Discussions, and Prospectives

Goal : Create training data for the project's new machine learning model.

Source Data : June 11, 2024 observations. **Candidate Extraction :** JAXA system identified 2,895 KBO candidate objects.

Training Set Creation : Human visual inspiration identified 1,535 true moving objects among 2,895 candidates, providing the "real vs. fake" classification used for machine learning training.

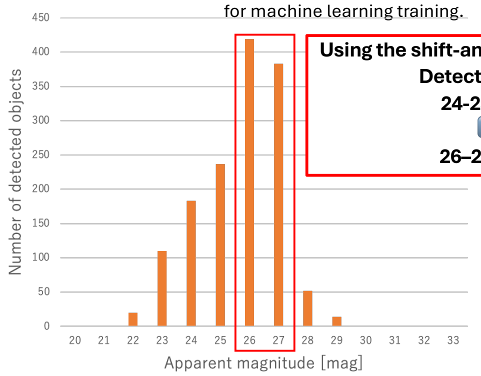


Fig. 3. Distribution of Apparent Magnitudes for the 1,535 Objects

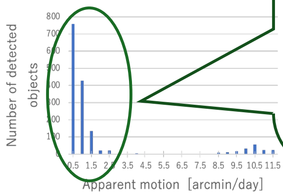


Fig. 4. Distribution of Velocities for the 1,535 Objects

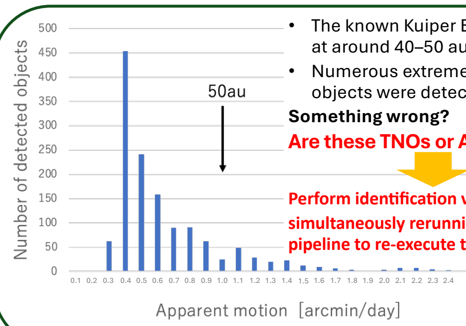


Fig. 5. Velocity Distribution of Slower-Moving Objects Among the 1,535

- The known Kuiper Belt is located at around 40–50 au.
- Numerous extremely slow-moving objects were detected.

Something wrong?
Are these TNOs or Artifacts?

Perform identification via orbital links while simultaneously rerunning the image reduction pipeline to re-execute the detection.

To avoid contamination from main-belt asteroids, we extracted objects moving slower than 11 arcmin/day.

Most observations of the outer solar system have been limited to apparent magnitudes of around 24. ➡ **Stacking images of the same region enables the discovery of fainter outer solar system objects.** ➡ **Finding smaller, undiscovered TNOs.**

As a result of our continuous search, we discovered two new TNOs.

For orbit fitting

- ☐ Utilize Stella Hunter and Find_Orb
- ☐ Identify orbit links among the TNO candidates from the entire dataset to find real TNOs.
- ☐ With the establishment of machine learning techniques and improved analysis speed (see P.10)
- ☐ Analyze all data acquired since 2020 to discover new TNOs.

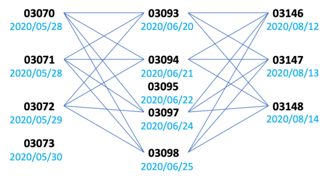


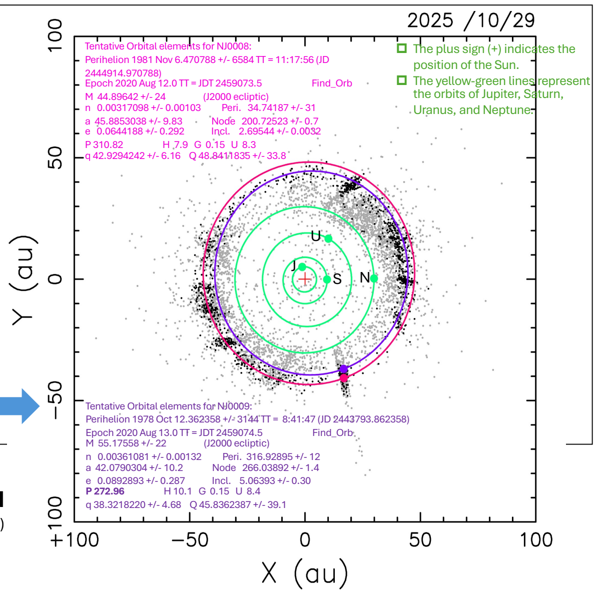
Fig. 6. Diagram of the Linked Orbital Data

+2 new TNOs

- With our previous search, two TNOs have been assigned provisional designations (2020 KJ60 and 2020 KK60).[3]

- ☐ **In addition to the previous two TNOs, we found two more new objects** by linking 3-night observations in 2020 (Fig. 8). They are probably classical TNOs.
- ☐ These objects were reported to Minor Planet Center on 2025 October 17, and will be assigned provisional designations soon.

Fig. 7.
Orbits of the two new TNOs detected in the 2020 observational dataset.
Their observation arc is ~2.5 months.



- ☐ The numbers on both the vertical and horizontal axes denote the distance from the Sun.
- ☐ Black dots represent Classical KBOs
- ☐ Gray dots represent TNOs with semi-major axes greater than 30 au.

(Summary) Importance of the Kuiper Belt study

Current observations suggest the classical Kuiper Belt is sharply truncated around
(If 50 au is the outer edge of the protoplanetary disk, it is smaller compared to other protoplanetary disks around G-type stars.)

Observing the region beyond the current Kuiper Belt is crucial for understanding the structure of the outer solar system!

References (1)Stern+ (2015), Science, 350, add1815, (2) Buie+ (2024), PSJ, 5, 196, (3) Yoshida+ (2024), PSJ, 724, 729, (4) Fraser+ (2024), PSJ, 5, 227, (5) Miyazaki+ (2018),PASJ, 70, S1, (6) Yanagisawa+ (2005), PASJ, 399, 408, (7) Shibukawa+ (2025), (under review)