A deep analysis for New Horizons' TNO search images

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Abstract

JAXA has been developing the image-processing technologies to detect faint moving objects in the sky. The stacking method which uses a lot of consecutive frames can detect moving objects invisible on a single frame. To reduce analysis time, the FPGA board was developed. The method showed the usefulness by discovering 10m-class NEOs using 18cm telescopes.

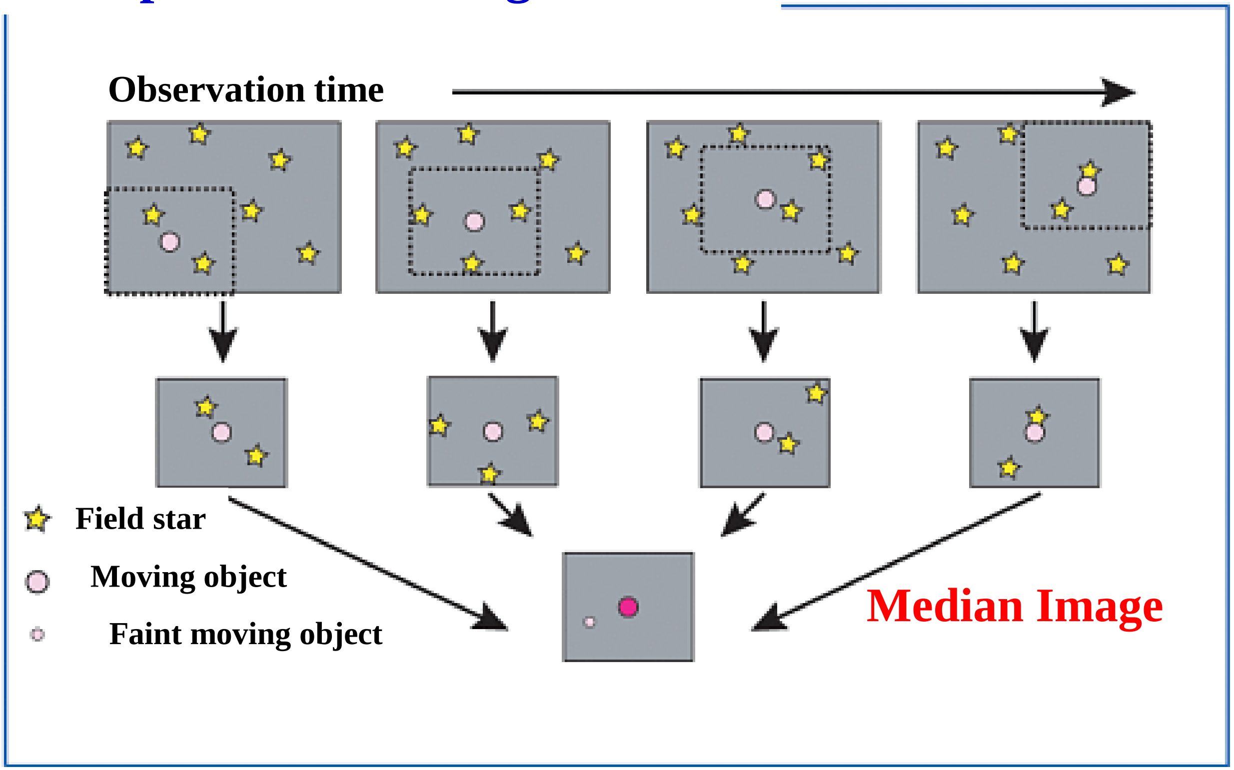
We applied the method to analyze NH data taken with Subaru telescope and succeeded in detecting lots of moving objects including TNOs. The detection limit is about 26 magnitude.

In this talk, I would like to explain how the stacking method detects faint moving objects, and to report the first result of TNO detection using the method.

Data analysis process：Stacking method

The stacking method uses multiple CCD frames to detect very faint objects that are undetectable on a single CCD frame.

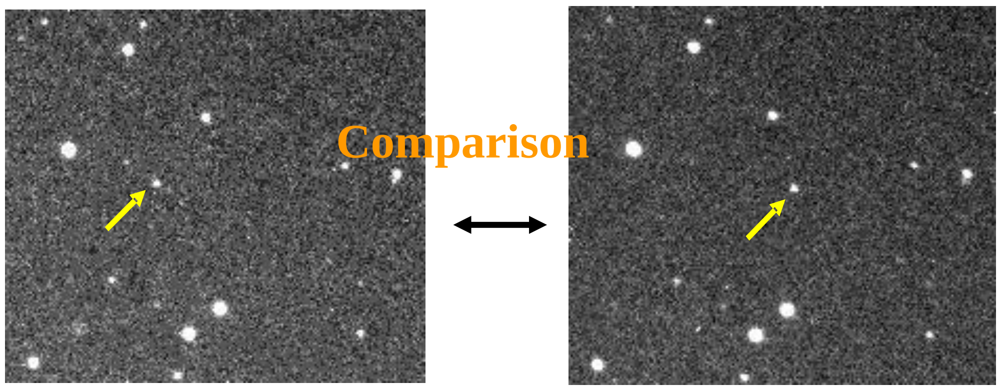
Concept of the stacking method



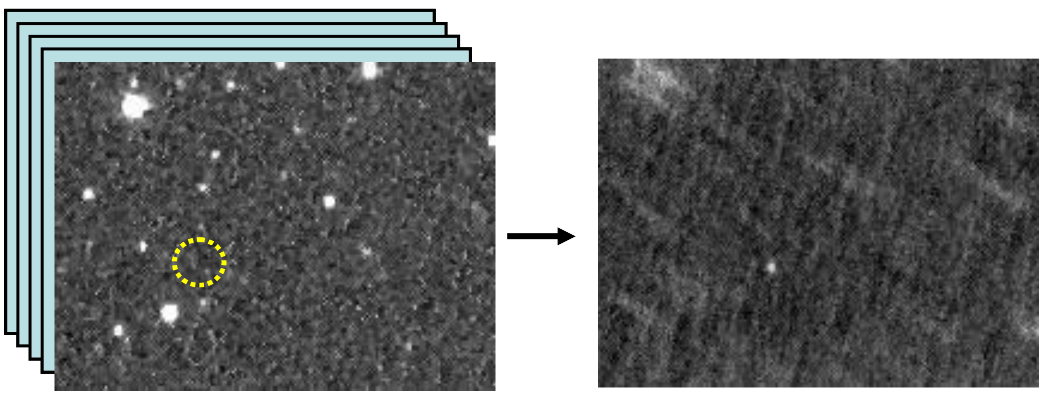
Sub-images are cropped from many CCD frames to follow the presumed movement of moving objects. Faint objects are detectable by making the median image of these sub-images.

Data analysis process：Stacking method

Blink method



Stacking method

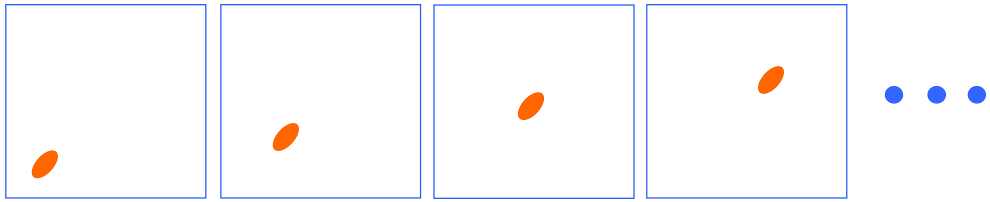


An asteroid detected by the stacking method. Before(left) and after(right).

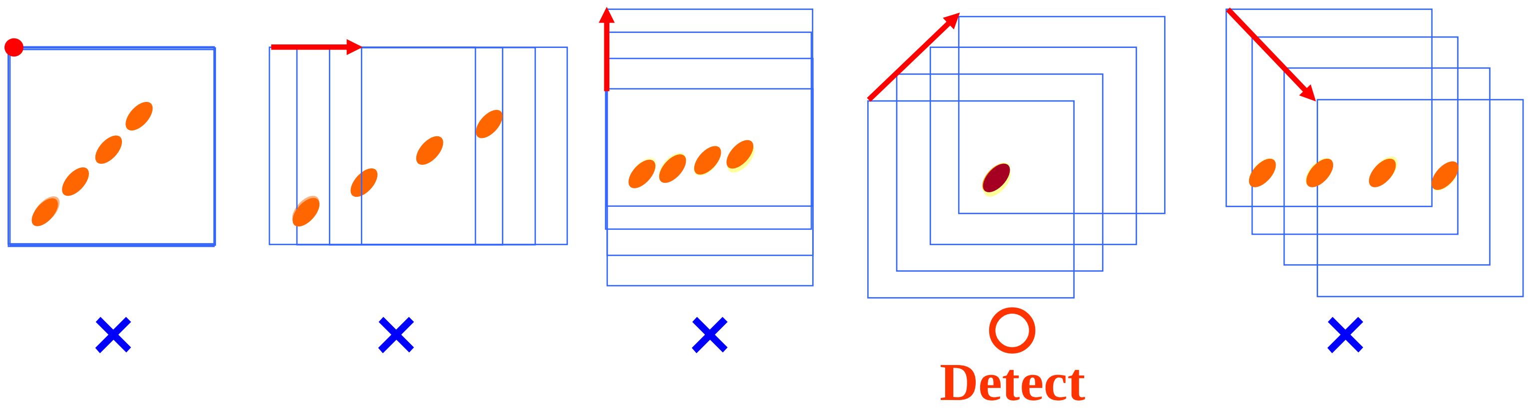
About 350 main-belt asteroids were discovered by this method.

Data analysis process：Stacking method

The only weak point of the method is taking time to analyze the data in case of detecting unseen object whose movement is not known, because various movements of the faint object have to be presumed.



Many CCD image are taken with telescope-fixed mode.

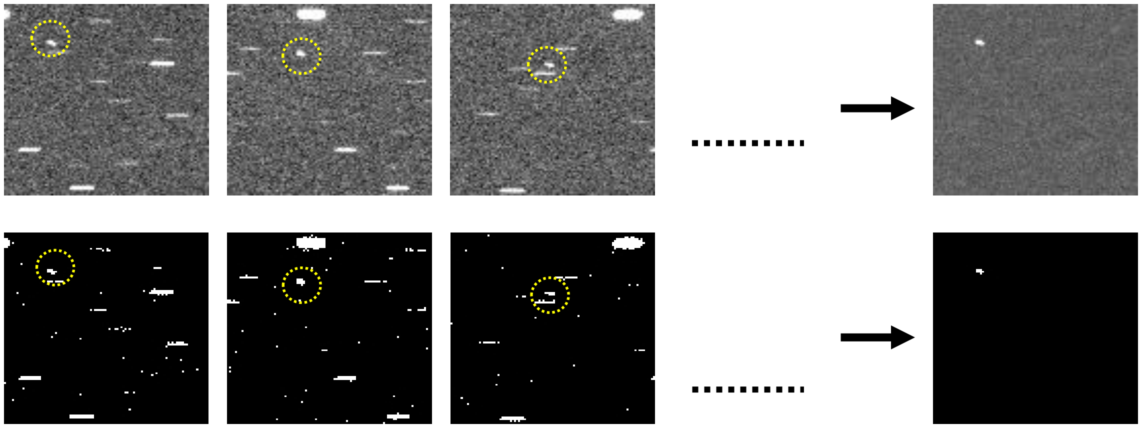


Images are stacked in many ways, as various shift values are presumed.
Typical analysis time using 1PC is about 280 hours!!

FPGA(field programmable gate array) system has been developed to reduce analysis time.

Data analysis process：Stacking method

A new algorithm and FPGA board for the stacking method has been developed to reduce analysis time.

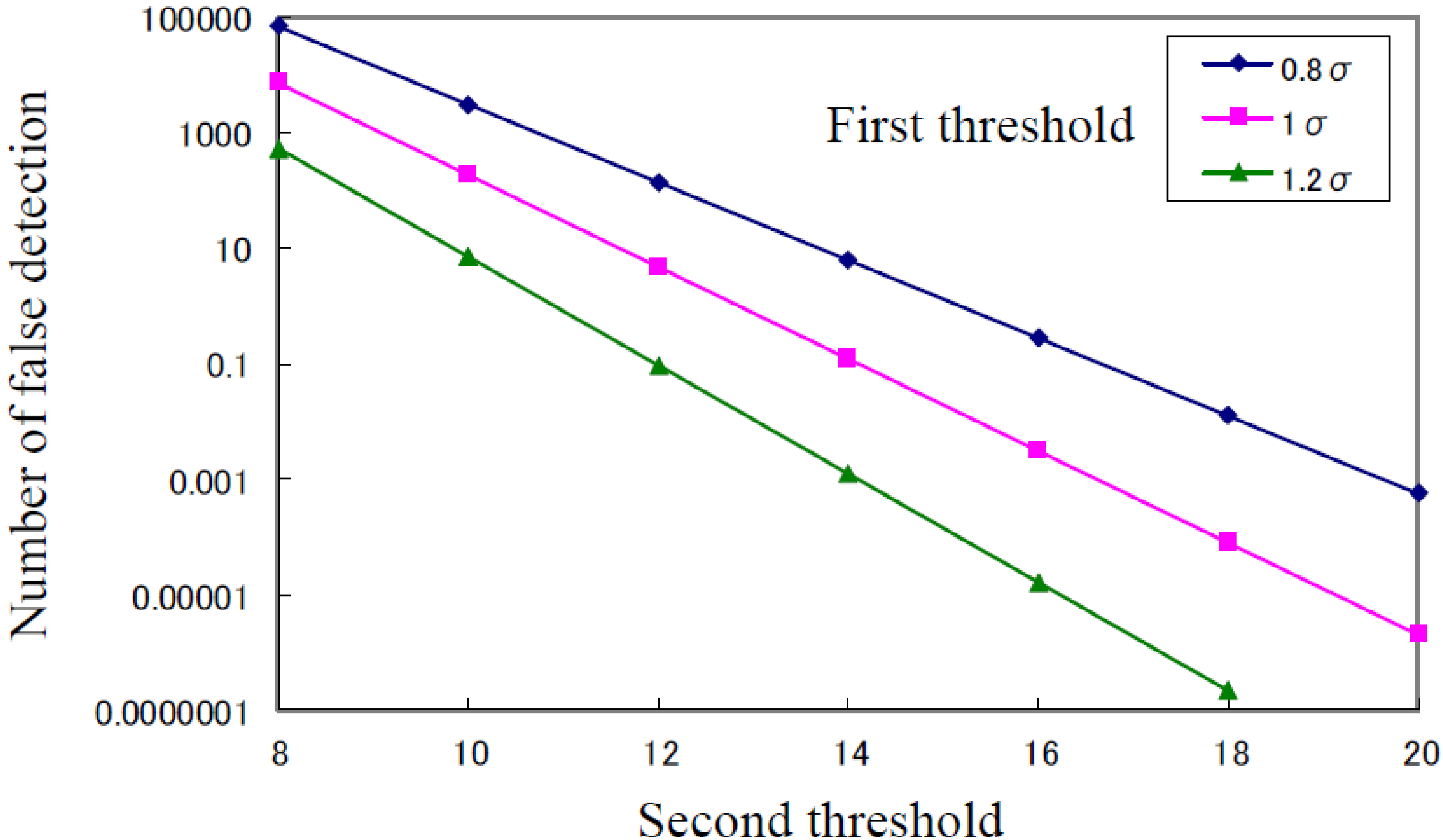


Deference between the original algorithm of the stacking method (upper) and the new algorithm using binarized images.

FPGA board Expresso 5A manufactured by Soliton systems

The FPGA board reduces analysis time by 1/1200

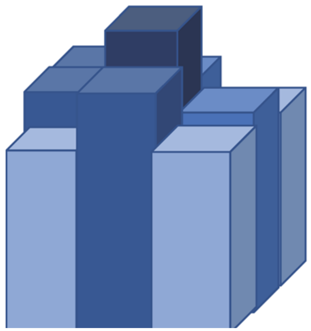
Data analysis process：Stacking method



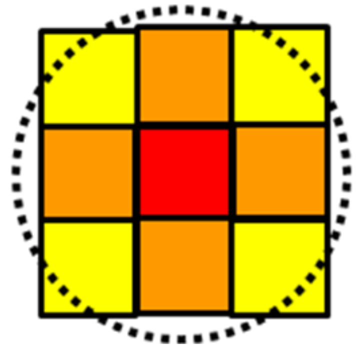
False detection under the various conditions

Data analysis process：Stacking method

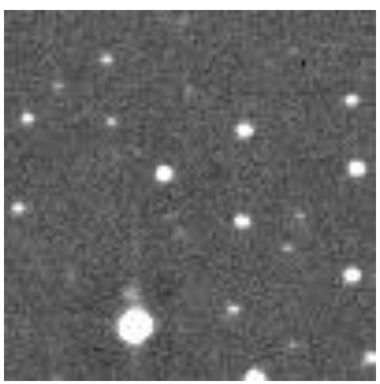
Object candidate search



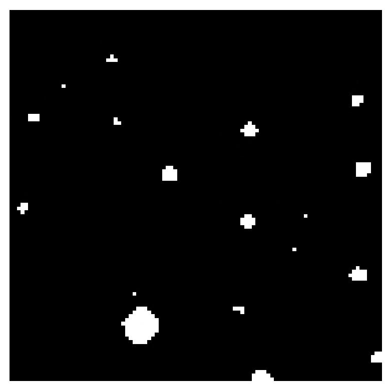
Central pixel has higher value than surrounding 8 pixels



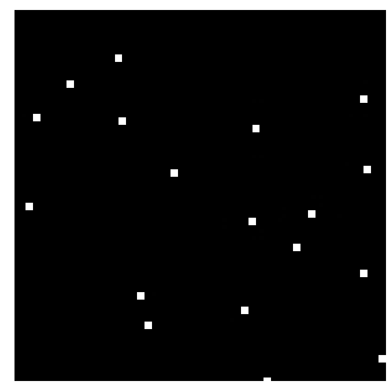
Shape parameter = total value of nine pixels / the value of central pixel



Original image

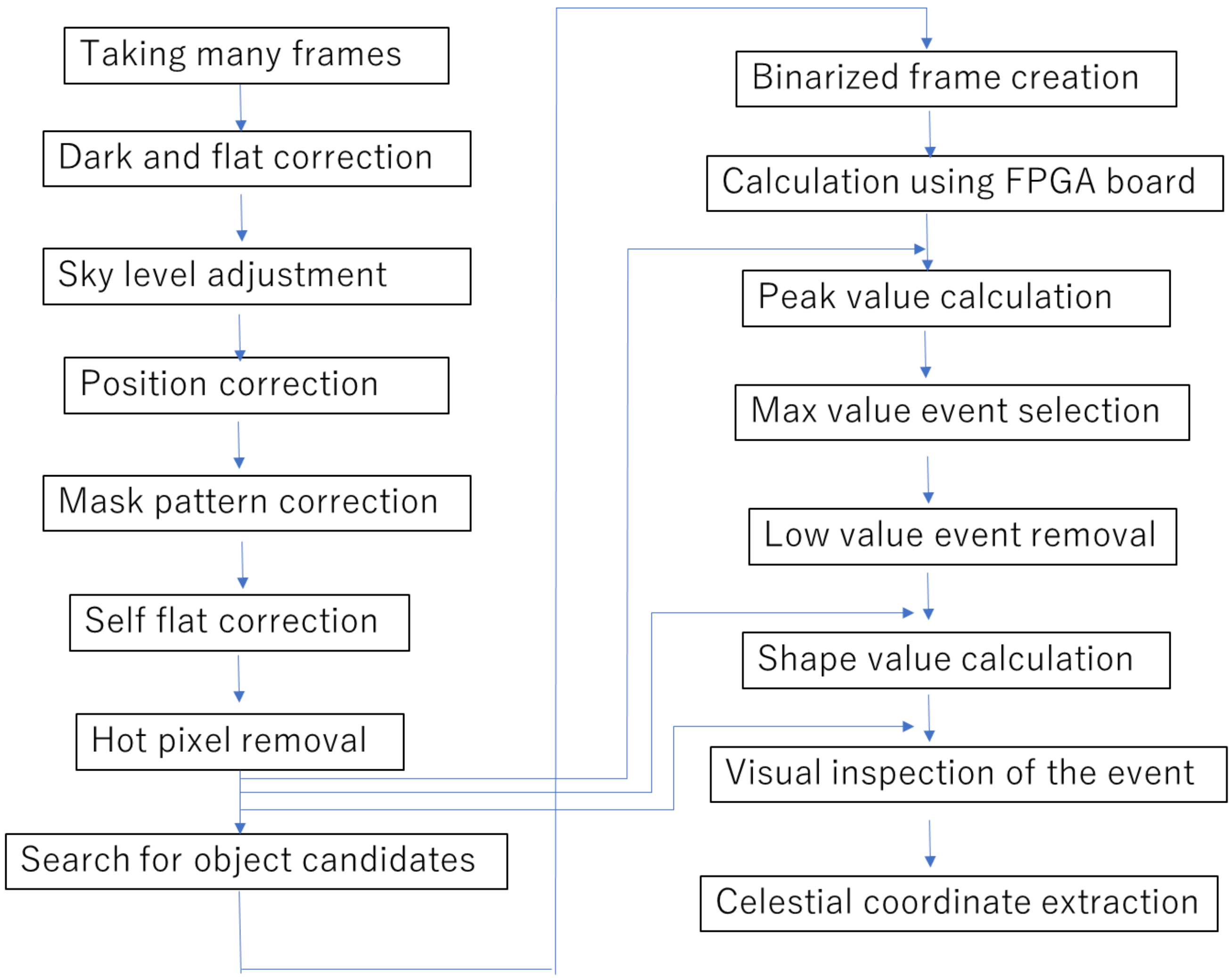


Binarized image



Object candidates

Data analysis process：Stacking method



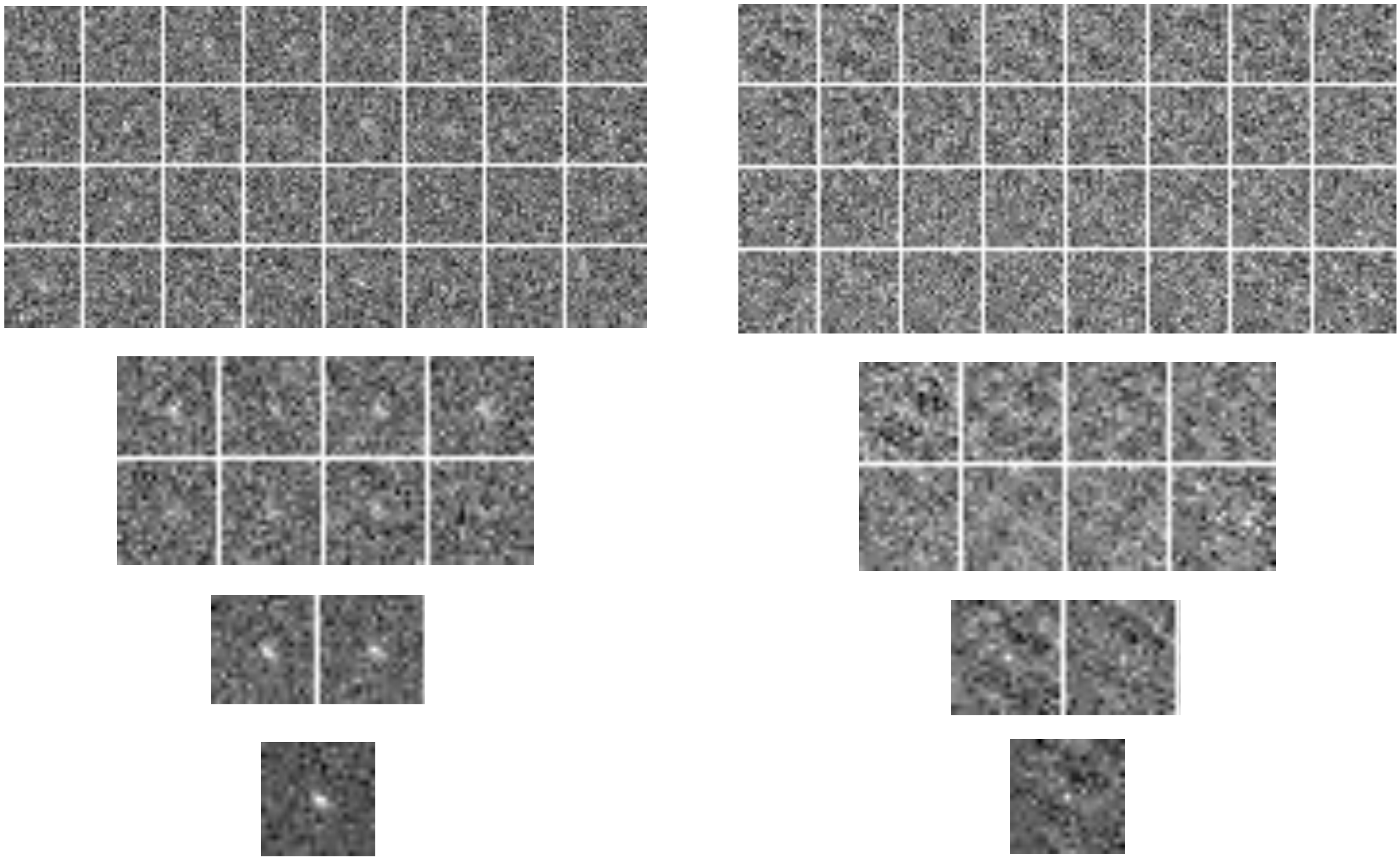
Analysis processes

Data analysis process：Stacking method

dx	dy	x	y	peak	shape
-88	13	971	1359	64.86	4.01
-49	-83	169	414	25.92	4.29
-188	-106	327	536	19.32	1.67
-103	11	1972	1851	17.27	1.82
-5	-30	1985	157	15.96	2.97
-47	101	1770	1579	15.78	3.32
-25	-35	1200	510	15.39	1.46
138	-74	212	891	15.01	1.92
…	…	…	…	…	…

Sample of the result file

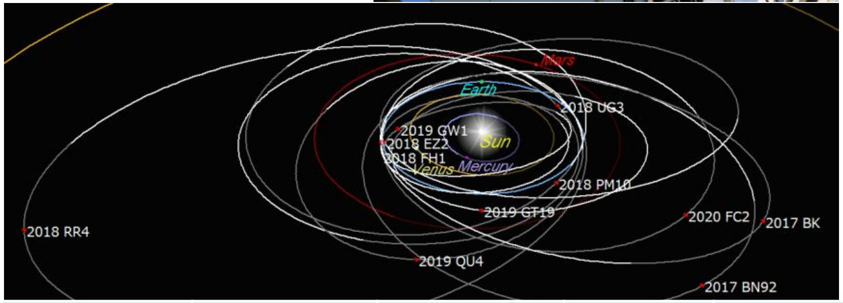
Data analysis process：Stacking method



Visual inspection of detected objects

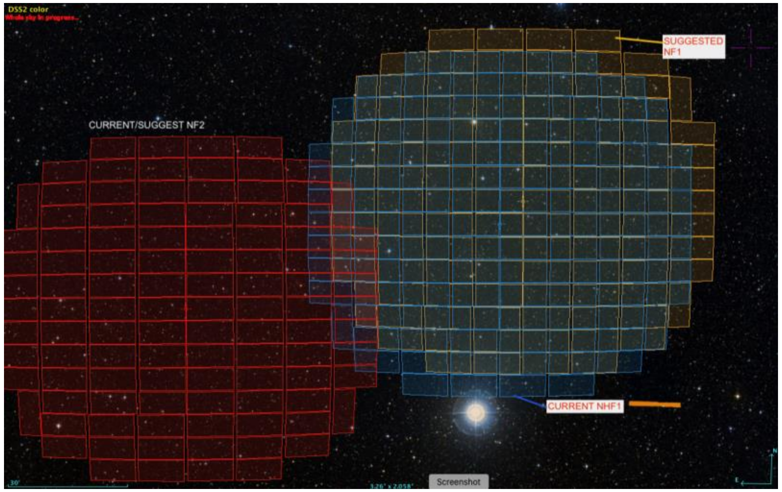
NEO discoveries

NEO survey was carried out using four 18cm-telescopes at Siding Spring Observatory in Australia. The data was analyzed with the stacking method. NEOs of 10m class, which are very difficult to discover even using 1m telescope, are detectable with the method.



ID	Discovered date	V mag	family	e	a(AU)	i	RAAN	abs mag	size(m)
2017 BK	2017.1.17	17.5	Apollo	0.489	1.909	6.6359	110.89	24.0	67
2017 BN92	2017.1.31	17.1	Apollo	0.483	1.921	1.0734	324.06	25.6	32
2018 EZ2	2018.3.12	18.2	Apollo	0.510	1.951	4.9718	173.92	26.6	20
2018 FH1	2018.3.18	18.7	Aten	0.177	0.938	3.5468	181.41	26.6	20
2018 PM10	2018.8.9	18.3	Amor	0.427	1.780	9.2065	317.51	27.0	17
2018 RR4	2018.9.11	18.0	Apollo	0.621	2.637	3.1793	351.37	27.1	16
2018 UG3	2018.10.31	19.4	Apollo	0.423	1.662	6.1673	47.27	24.5	53
2019 GW1	2019.4.4	17.5	Aten	0.114	0.934	13.2945	194.67	26.1	25
2019 GT19	2019.4.12	18.2	Apollo	0.370	1.273	7.7488	202.69	27.5	13
2019 QU4	2019.8.28	18.1	Apollo	0.332	1.426	10.1313	333.97	24.8	46
2020 FC2	2020.3.17	18.5	Apollo	0.398	1.644	6.8153	357.15	28.0	11

Analysis of Subaru data

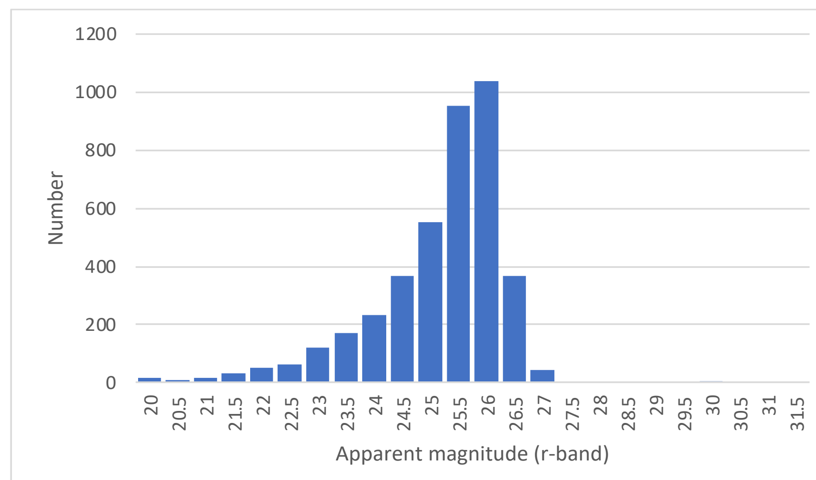


Observed area, F1 and F2

We carried out the analysis of NH project's data taken with Subaru telescope by using the stacking method. We detected lots of moving objects, not only TNO but also main-belt asteroids. Currently, we are using 32 consecutive frames. Analysis time for one field is about 24 hours.

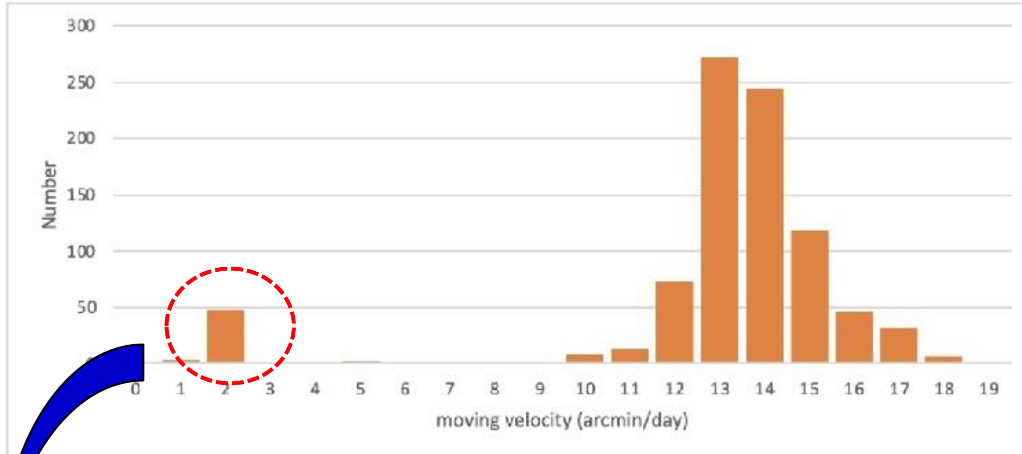
Date (HST)	Obs. field	real object /number of detections	Date (HST)	Obs. field	real object /number of detections
May 27	F2	276 / 435 (63%)	June 21	F2	283 / 457 (62%)
May 28	F1	677 / 1042 (64%)	June 23	F1	150 / 227 (66%)
May 29	F2	715 / 918 (78%)	June 24	F2	312 / 459 (68%)
May 30	F1	315 / 404 (78%)	Aug 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%)

Analyzed data set

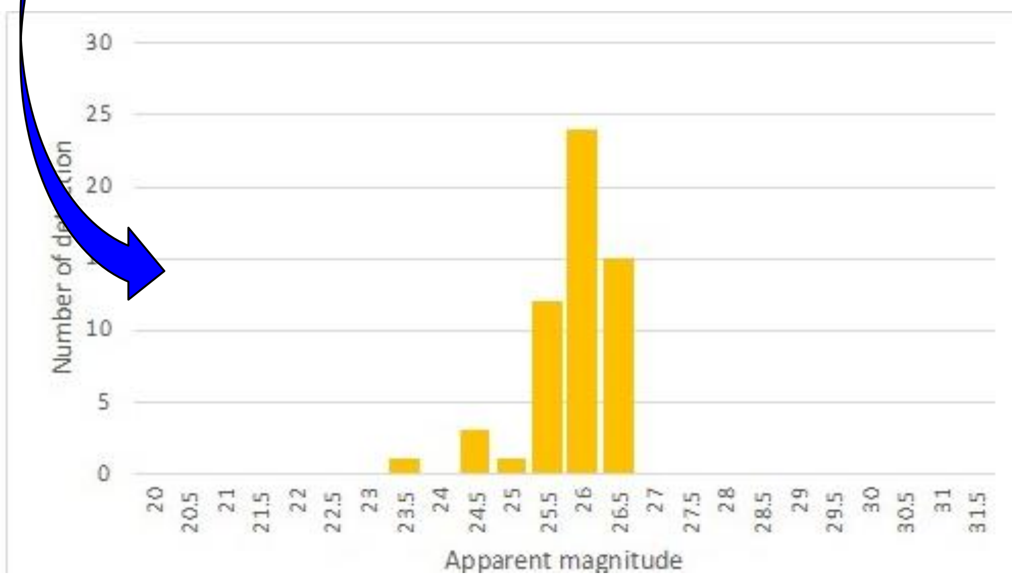


Brightness distribution of detected objects

Analysis of Subaru data



Velocity distribution of detected objects



Brightness distribution of TNO objects

Analysis of Subaru data

We discovered 7 TNOs which were not detected by NH team, and two of them got the ID as below. However, total number of TNO detection of NH team is much higher than Japanese team

2020KJ60

epoch	2023-09-13.0
epoch JD	2460200.5
perihelion date	1984-01-18.13386
perihelion JD	2445717.634
argument of perihelion (°)	69.3508
ascending node (°)	156.60392
inclination (°)	2.49898
eccentricity	0.3752396
perihelion distance (AU)	37.2882832
Tisserand w.r.t. Jupiter	6.4
ΔV w.r.t. Earth (km/sec)	11.2

semimajor axis (AU)	59.6841373
mean anomaly (°)	30.95781
mean daily motion (° /day)	0.0021375
aphelion distance (AU)	82.08
period (years)	461
P-vector [x]	-0.6948733
P-vector [y]	-0.67495763
P-vector [z]	-0.2481598
Q-vector [x]	0.71892373
Q-vector [y]	-0.6436918
Q-vector [z]	-0.26231572
absolute magnitude	9.67
phase slope	0.15

uncertainty	9
reference	E2023-N68
observations used	6
oppositions	1
arc length (days)	77
first opposition used	2020
last opposition used	2020
residual rms (arc-secs)	0.08
perturbers coarse indicator	M-v
perturbers precise indicator	003E
first observation date used	2020-05-28.0
last observation date used	2020-08-13.0
computer name	Alexander

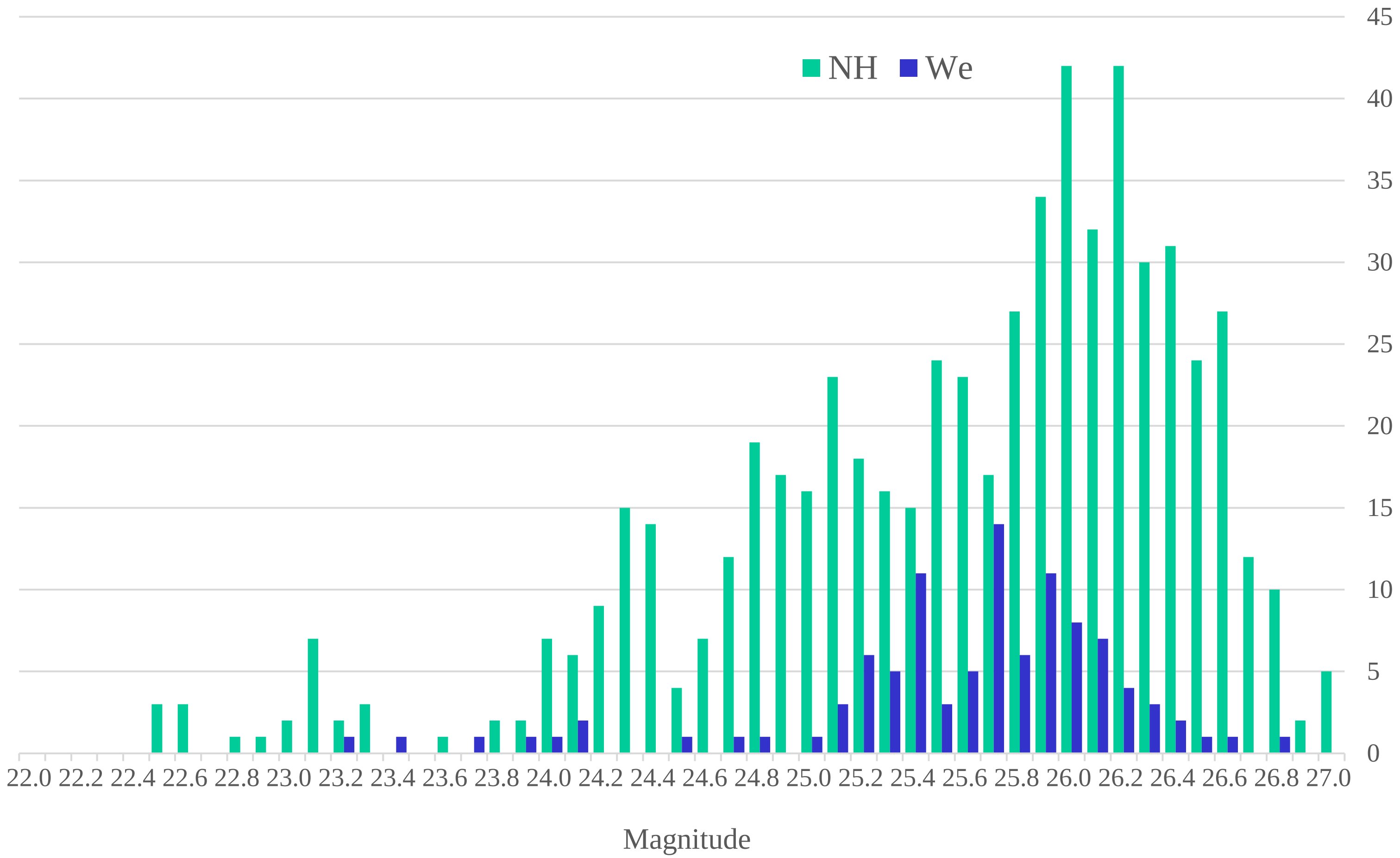
2020KK60

epoch	2023-09-13.0
epoch JD	2460200.5
perihelion date	2006-03-16.60277
perihelion JD	2453811.103
argument of perihelion (°)	15.16474
ascending node (°)	242.43004
inclination (°)	4.24758
eccentricity	0.3888881
perihelion distance (AU)	35.261981
Tisserand w.r.t. Jupiter	6.2
ΔV w.r.t. Earth (km/sec)	11.3

semimajor axis (AU)	57.7013481
mean anomaly (°)	14.36763
mean daily motion (° /day)	0.0022487
aphelion distance (AU)	80.141
period (years)	438
P-vector [x]	-0.21546136
P-vector [y]	-0.90346329
P-vector [z]	-0.37058127
Q-vector [x]	0.97430268
Q-vector [y]	-0.22440778
Q-vector [z]	-0.01937601
absolute magnitude	8.77
phase slope	0.15

uncertainty	9
reference	E2023-N68
observations used	6
oppositions	1
arc length (days)	75
first opposition used	2020
last opposition used	2020
residual rms (arc-secs)	0.16
perturbers coarse indicator	M-v
perturbers precise indicator	003E
first observation date used	2020-05-29.0
last observation date used	2020-08-12.0
computer name	Alexander

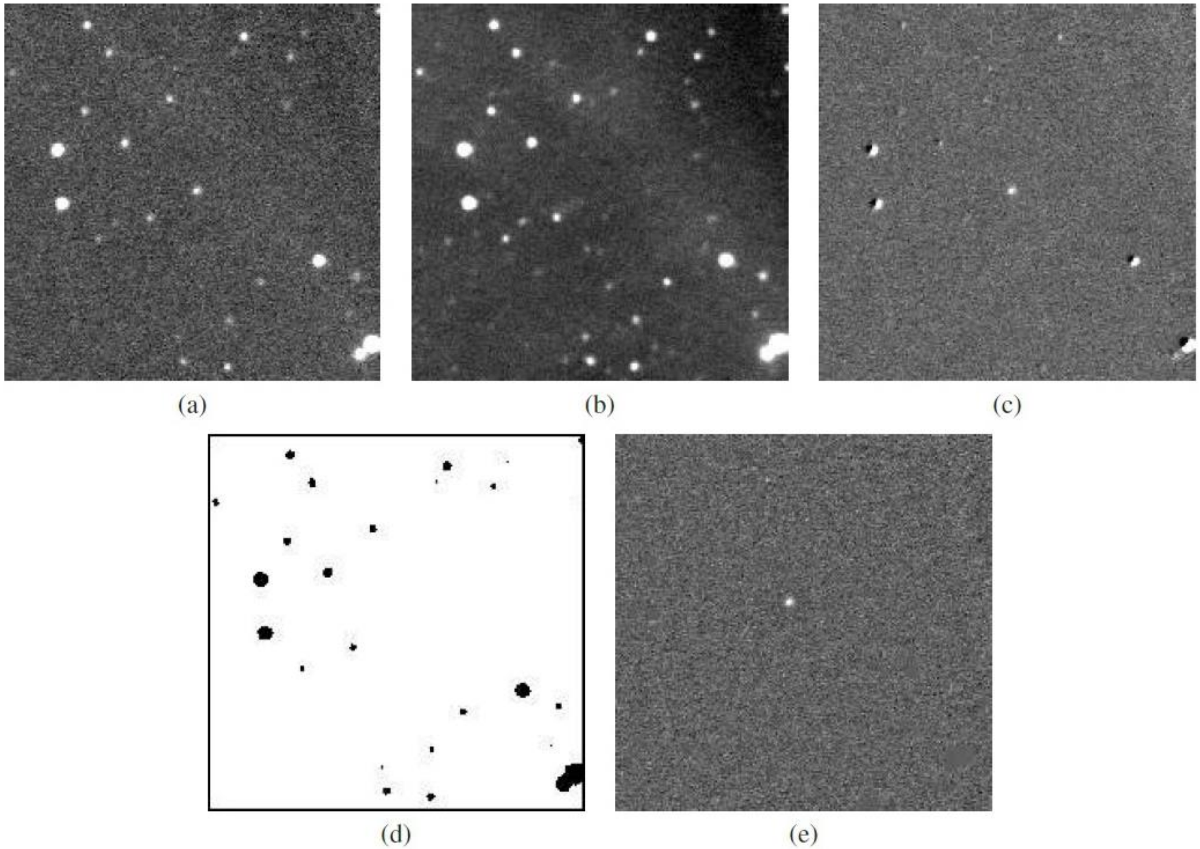
Analysis of Subaru data



Comparison of brightness distribution of TNO between NH team and Japanese team

We are investigating the reason of the discrepancy.

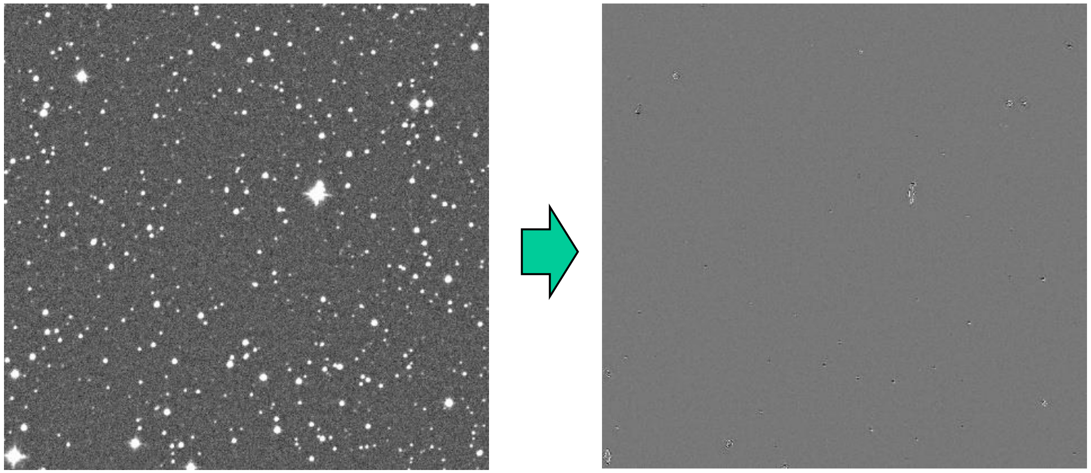
Analysis of Subaru data



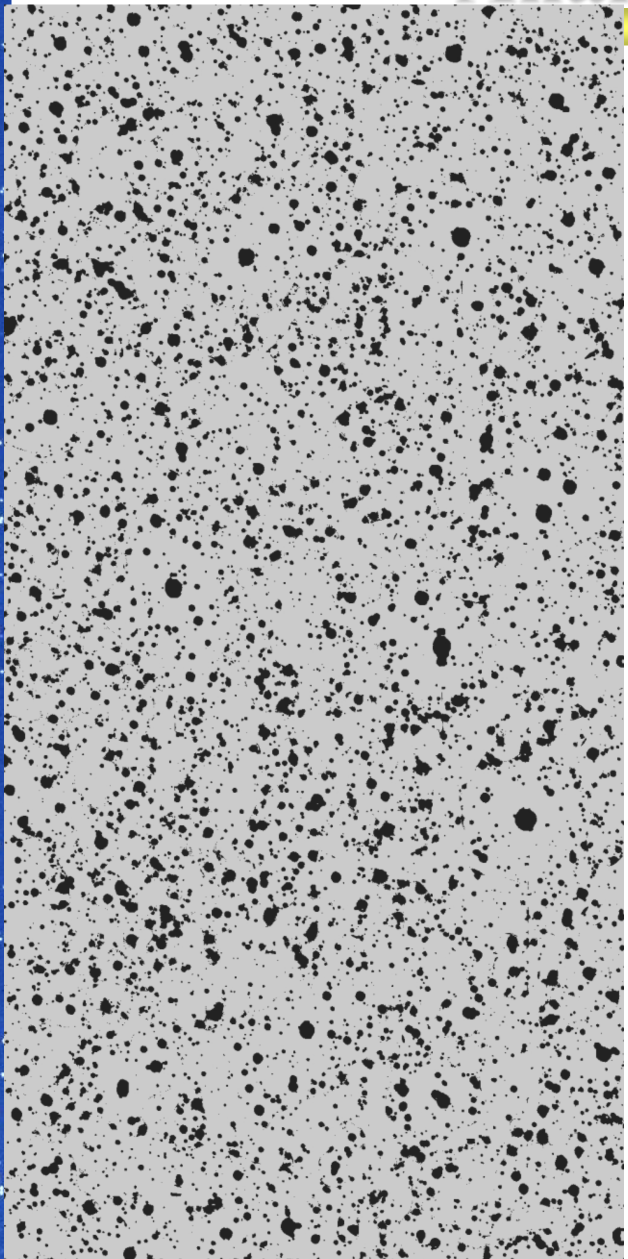
We are using the mask pattern to remove the effects of field stars.

Analysis of Subaru data

Observed regions were crowed with field stars which may effect the detections of TNOs. Image subtraction will be applied to prevent the effect.



Effect of image subtraction



Mask pattern of NH data

Future Plan

- Solve the problem which may be caused by the mask pattern.
- Apply the method to whole the data.
- Get scientific results from other objects (MBA, Centaurus, and so on)
- Install the algorithm of the method to GPU machine for further speed-up.
- Use the machine learning instead of the visual inspection.

FPGA board Expresso 5A manufactured by Soliton systems

GDEP DLEARNING BOX II

- 4 x NVIDIA QUADRO RTX8000 GPU
- 4 x 4608 CUDA cores
- 48 GB GPU Memory
- NVLink

- Intel i9-10940X CPU 3.30 GHz
- 28 CPU cores
- 128 GB RAM Memory

Summary

JAXA has been developing the image-processing technologies to detect faint moving objects in the sky. The stacking method which uses a lot of consecutive frames can detect moving objects invisible on a single frame. To reduce analysis time, the FPGA board was developed. The method showed the usefulness by discovering 10m-class NEOs using 18cm telescopes.
We applied the method to analyze NH data taken with Subaru telescope and succeeded in detecting lots of moving objects including TNOs. The detection limit is about 26 magnitude.
We found the number of detected TNOs were much less than that of NH team. We will solve the problem and apply GPU machine to reduce analysis time in the near future.