C13

東京大学木曽観測所広視野 CMOS モザイクカメラ Tomo-e Gozen による人工天体の観測

Observations of Artificial Objects with a wide-field CMOS mosaic camera: Tomo-e Gozen

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Ryou Ohsawa, Shigeyuki Sako, Yuto Kojima (Univ. Tokyo), Shin-ichiro Okumura, Seitaro Urakawa (Japan Spaceguard Association), Toshifumi Yanagisawa, Makoto Yoshikawa (JAXA) and Tomo-e Gozen Science Group

東京大学木曽観測所では 105-cm シュミット望遠鏡に搭載する広視野 CMOS モザイクカメラ Tomo-e Gozen の開発を進めている. Tomo-e Gozen は 4 つのモジュールから構成されるカメラである. 各モジュールに 21 枚, 合計 84 枚の CMOS イメージセンサを搭載する. 20 平方度の領域を 2 Hz でモニタリングする能力を持ち, 恒星に対する限界等級はおよそ 18.5 等である. また, 部分読み出しをすることで, より速いフレームレートでの観測も可能である. こうした性能から Tomo-e Gozen は微小なスペースデブリの発見やデブリの運動状態の決定に高いパフォーマンスを発揮すると考えられる. 2018 年 2 月には 1 つのモジュールを用いて機能試験観測を実施した. 現在では 21 枚のイメージセンサでサーベイ観測試験を進めている. また残りのモジュールの開発も進行中である. 発表では地球接近小惑星や人工衛星の観測結果を紹介するとともに, スペースデブリ監視への貢献可能性について議論する.

We are developing a new wide-field mosaic CMOS camera, Tomo-e Gozen, for the 105-cm Kiso Schmidt Telescope at Kiso Observatory, the University of Tokyo. Tomo-e Gozen is composed of four individual camera modules, each of which has 21 CMOS image sensors. Equipped with the 84 CMOS image sensors in total, Tomo-e Gozen is able to monitor a sky of about 20 sq-degree at up to 2 Hz. The limiting magnitude for stars is about 18.5 mag. Frame rates faster than 2 Hz are available by narrowing the field of view. Tomo-e Gozen is expected to show high performances in detecting tiny space debris and deriving the motion of space debris. The development of the first camera module Q1 was completed in February, 2018. In the experimental observations, the camera was successfully operated with the 21 CMOS image sensors. Currently, a high-cadence wide-area survey is in operation. We'll present some observations of near earth asteroids and artificial objects with Tomo-e Gozen, and discuss possible contributions of Tomo-e Gozen to the surveillance and tracking of space debris.

8th Space Debris Workshop in JAXA

Observations of Artificial Objects with a wide-field CMOS mosaic camera: Tomo-e Gozen

Ryou Ohsawa, Shigeyuki Sako, Yuto Kojima (U. Tokyo),
Shin-ichiro Okumura, Seitaro Urakawa (JSGA),
Toshifumi Yanagisawa, Makoto Yoshikawa (JAXA),
and Tomo-e Gozen Science Group

Tomo-e Gozen

The world largest video camera (84 CMOS sensors+ 1.0 m telescope)

Suitable specifications to characterize/detect debris

Wide field-of-view	—	20 deg² sky coverage with 1.2″/pixel
High sensitivity	—	stars of 18 mag detected in 2 Hz observation
High time-resolution	—	2 Hz observation, higher framerate available by partial readout
Accurate timestamp	—	synchronized with the GPS time, accurate to ~0.2 ms

Operating with a limited performance / Full operation is scheduled in 2019

Performance of Tomo-e Gozen in debris observations

Detection limits: ~30 cm board & ~3 mm mirror in GEO / ~ 5 cm namecard in LEO

Follow-up capability:
sub-second time-resolution lightcurve revals the shape and motion of debris

Daily moving object survey:
detect ~1,000 high-speed (>1″/s) objects and self follow-up in 2 hours

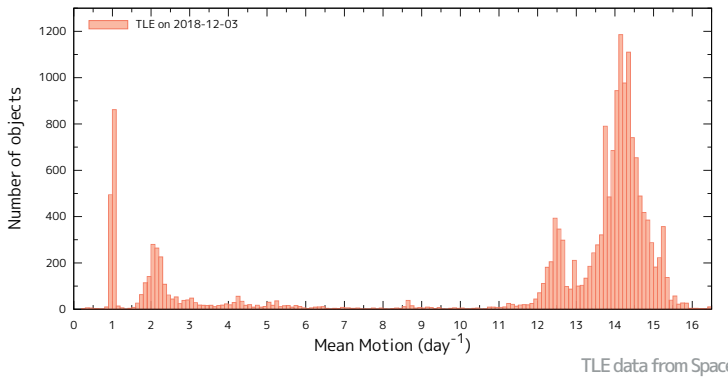
1. Ground-based observations of orbit debris
2. Tomo-e Gozen project
3. Examples from observations with Tomo-e Gozen

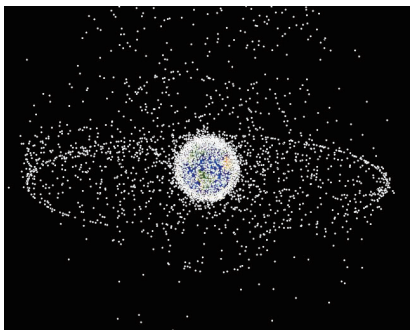
Backgrounds

More than 17,000 objects orbiting around the Earth are identified

Observable characteristics: the size, orbit, and motion of orbit debris

understanding the population of space debris
removal missions of orbital debris





TLE data from Space-Track.org, debris distribution from www.orbitaldebris.jsc.nasa.gov

Backgrounds

Ground-based optical observations:

- Only available in night time
- Brightness $\propto$ distance^{-2} (c.f. $\propto$ distance^{-4} in radar observation)
- Advantages in observations of distant small debris

Preferred specifications of telescopes and cameras

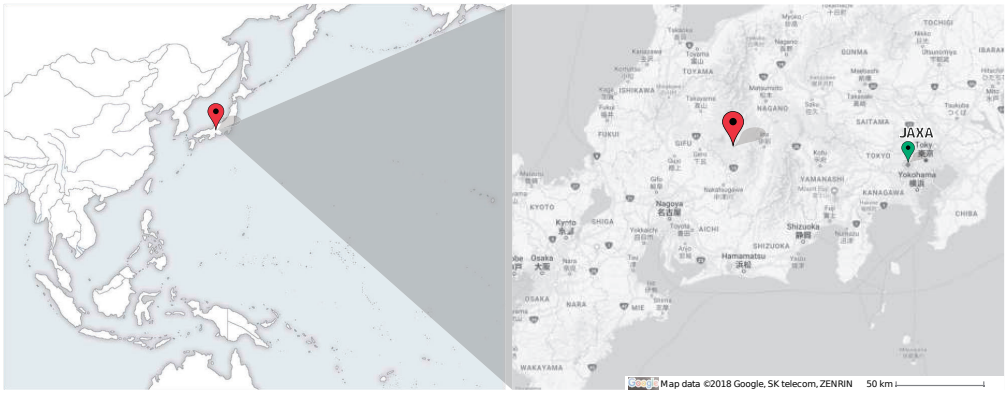
Erroneous ephemeris	—	wide field-of-view
Size ~ brightness	—	high sensitivity
Moving & rotating	—	high time-resolution
Fast movement	—	accurate timestamp

Tomo-e Gozen project

A mosaic CMOS camera at Kiso Observatory, the University of Tokyo

Tomo-e Gozen project

A mosaic CMOS camera at Kiso Observatory, the University of Tokyo



Blank map from www.wikimedia.org, detailed map from www.google.com/maps

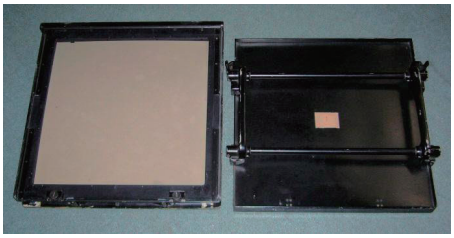
Tomo-e Gozen project

A mosaic CMOS camera at Kiso Observatory, the University of Tokyo

1.05 m Schmidt-type telescope (Kiso Schmidt)

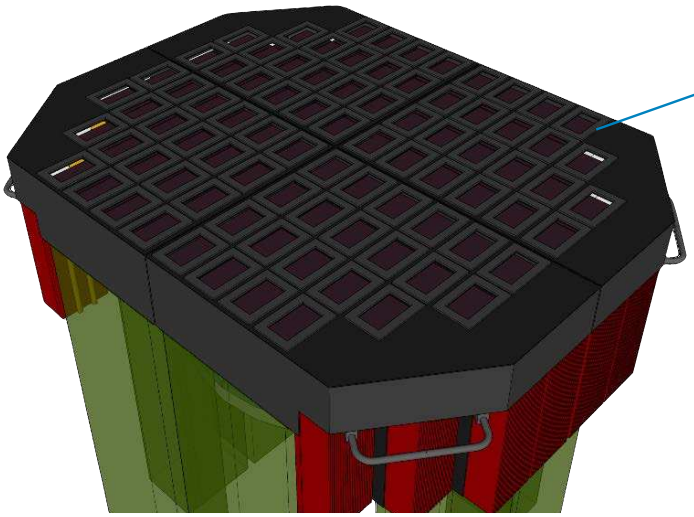
Designed for observations with photographic plate

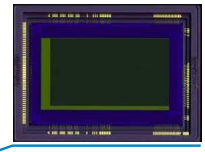
Extremely wide field-of-view (⌀ ~ 9°)



Tomo-e Gozen camera

A wide-field mosaic CMOS camera for Kiso Schmidt telescope



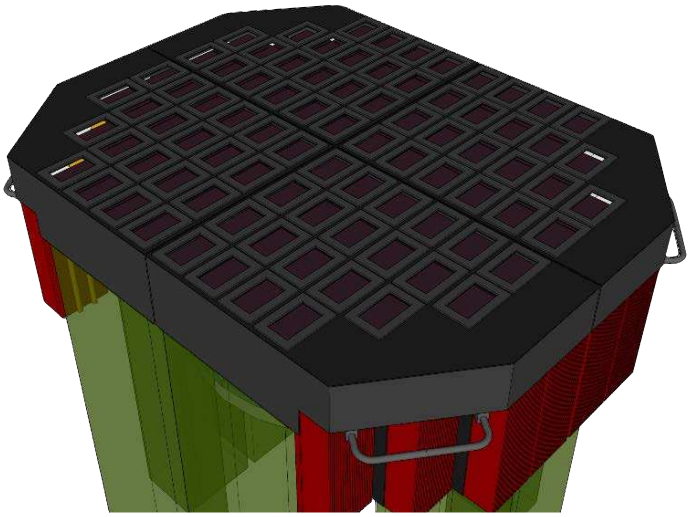


2K×1K CMOS image sensor by **Canon**

- 84 CMOS sensors covering ~20□°
- Composed of four camera modules
- Continous monitoring at 2 Hz
- High-speed observation by partial readout

Tomo-e Gozen camera

A wide-field mosaic CMOS camera for Kiso Schmidt telescope

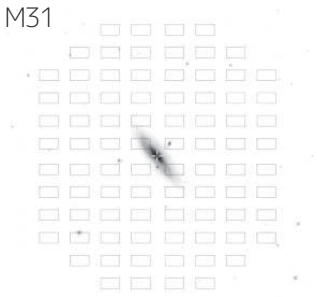


Specifications (Sako et al. Proc. SPIE, 2018)

Observatory	Kiso Observatory
Telescope	1.0-m f/3.1 Schmidt telescope
Sensor format	2160×1200 pix chip^{-1}
Field of view	**39′.7×22′.4 × 84 chips (~20 deg^2)**
Pixel scale	19 μm, 1″.189 pix^{-1}
Wavelength	350–700 nm (peak at 500 nm)
Filters	optical broadband (transparent)
Frame rate	**2 Hz (max, continuous, full frame)**
Read noise	~1.9 e$^-$ at 2 Hz
Dark current	~0.1 e$^-$ sec^{-1} pix^{-1} at 277 K
Well depth	~6,400 e$^-$
5σ lim. mag.	**~18.5 mag. in 0.5 sec exposure**

Tomo-e Gozen camera

Brief summary of the specifications of the Tomo-e Gozen



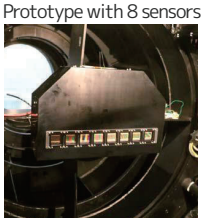
The world largest video camera (84 CMOS sensors+ 1.0 m telescope)

Located at 35° 47′ 50.0″ N, 137° 37′ 31.5″ E

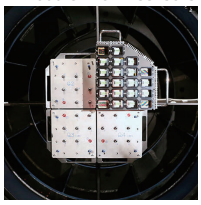
Distinctive specifications:

- 20 deg² sky coverage with 1.2″/pixel
- stars of 18 mag detected in 2 Hz observation
- 2 Hz observation, higher framerate available by partial readout
- synchronized with the GPS time, accurate to ~0.2 ms

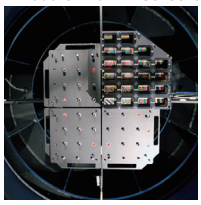
2015.07
Prototype with 8 sensors



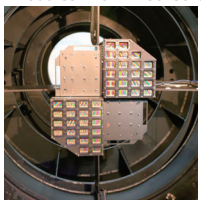
2017.09
1 module with 4 sensors



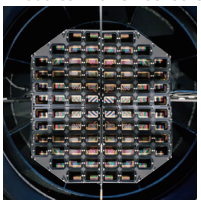
2018.02
1 module with 21 sensors



2018.11
2 modules with 42 sensors



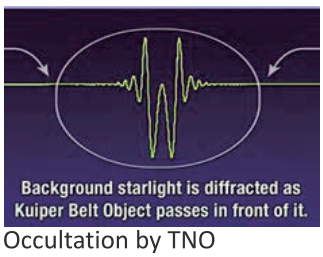
2019.04?
4 modules with 84 sensors



Science Cases of Tomo-e Gozen

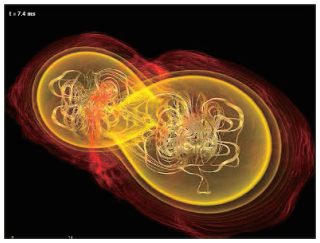
Rare & Fast Transient Phenomena

+ Shock Breakout of core-collapse SN
+ Optical follow up of Gravitational wave
+ Optcal counterpart of fast radio burst
+ Explosion of nova
+ Afterglow of gamma-ray burst
+ X-ray time variable objects
+ Transit of Exoplanet
+ Occultation by Trans-Neptunian object
+ Potentially Hazardous Asteroid
+ Faint meteor

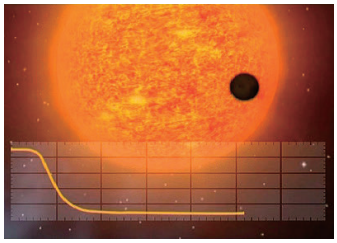


Occultation by TNO

Gamma ray burst



Neutron star marger → GW



Planet transit

From the presentation by S. Sako in the Kiso Schmidt symposium 2016

Science Cases of Tomo-e Gozen

Rare & Fast Transient Phenomena

+ Shock Breakout of core-collapse SN
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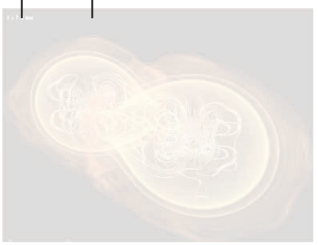
+ Potentially Hazardous Asteroid
+ Faint meteor

Skipped

Occultation by TNO

Gamma ray burst



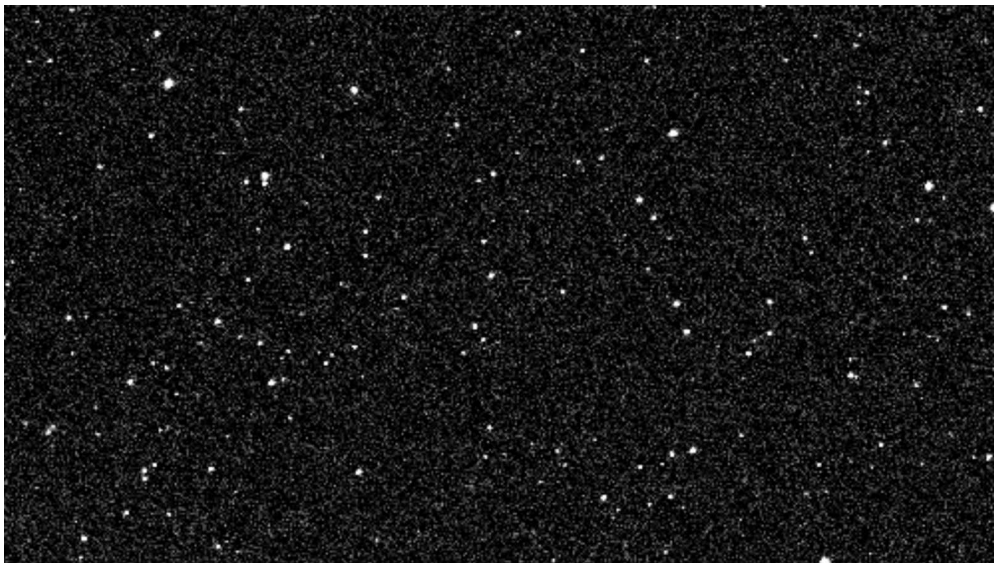
Neutron star marger → GW

Planet transit

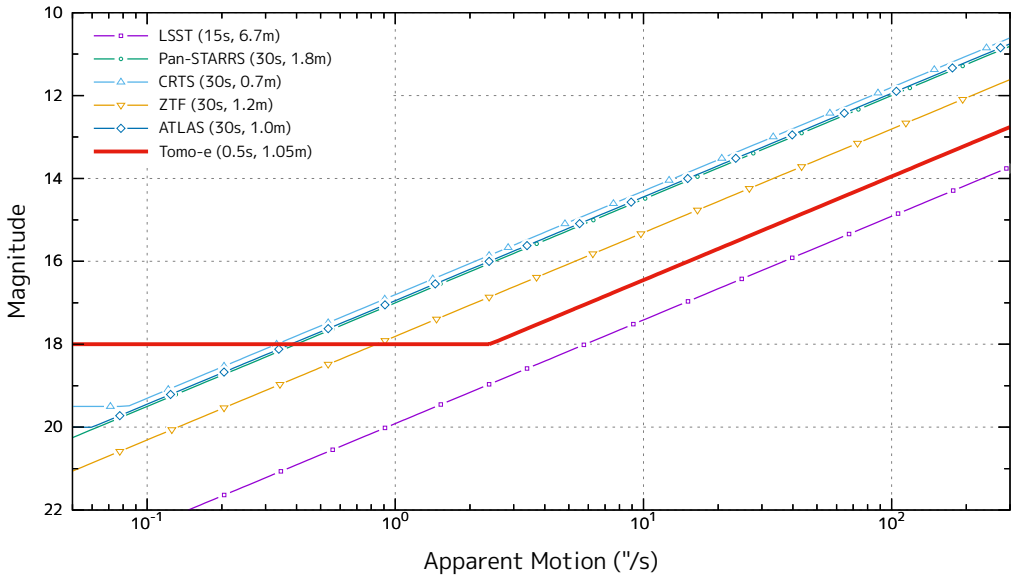
From the presentation by S. Sako in the Kiso Schmidt symposium 2016

Example: Catalina C/2013 US10

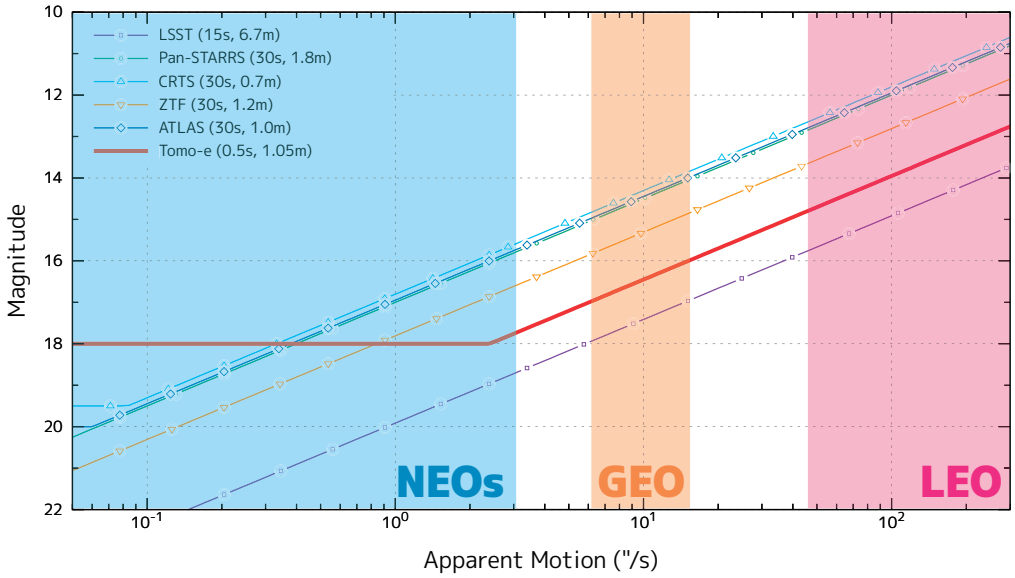
Example: Meteor trail



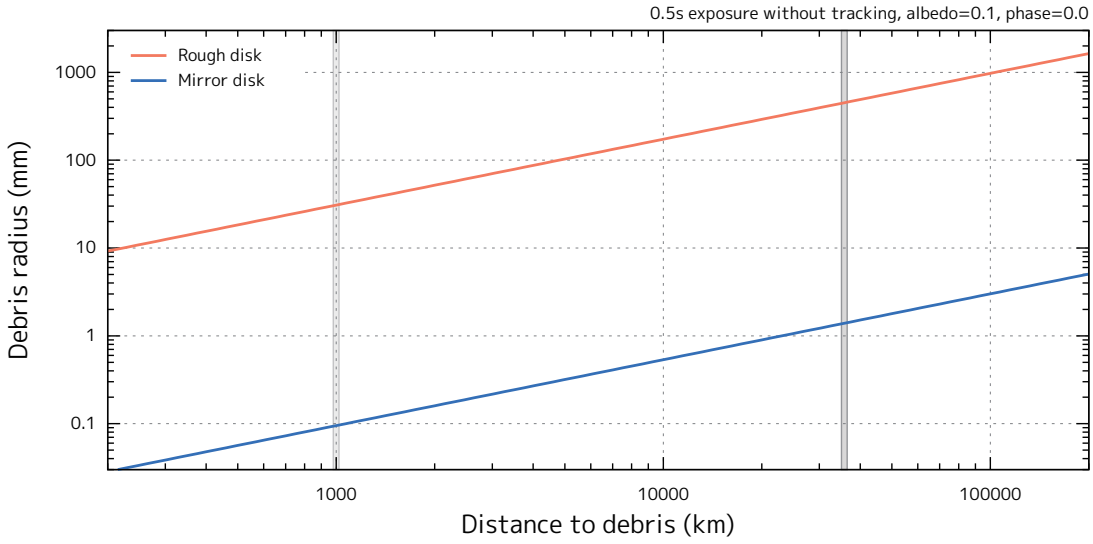
Comparing with other facilities



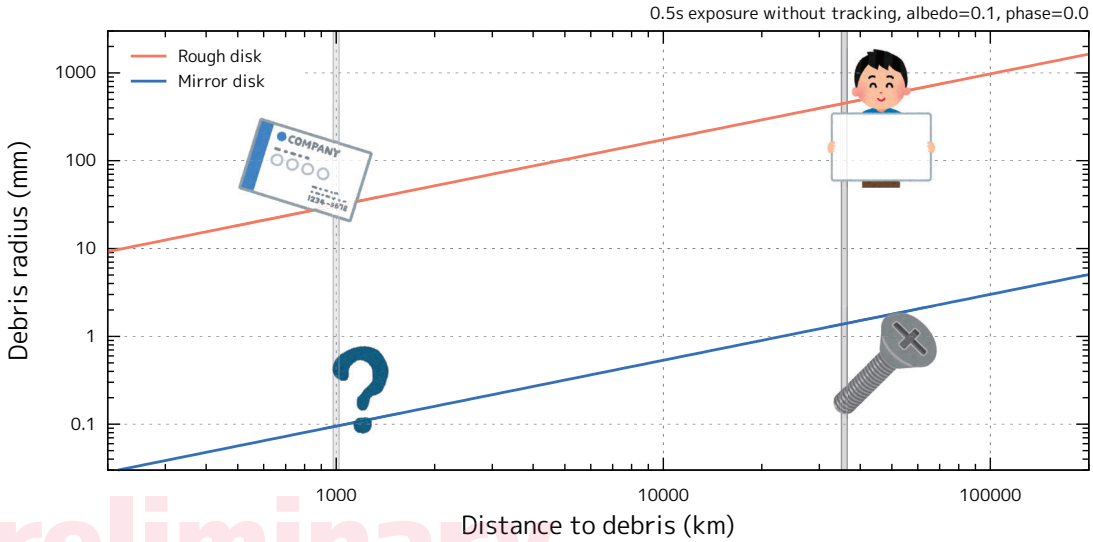
Comparing with other facilities



Detection Limits in 2 Hz



Detection Limits in 2 Hz

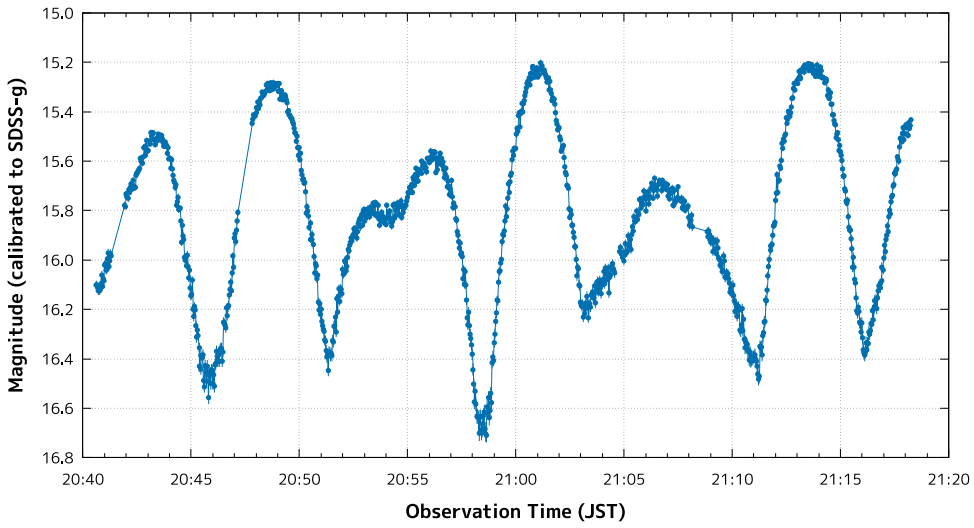


Flash detected by Tomo-e Gozen

1. Follow-up/monitoring observations

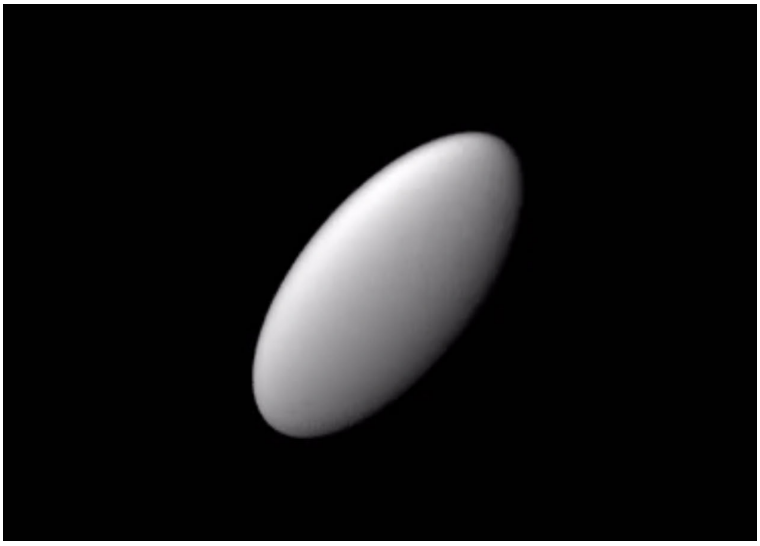
Observation of NEO: 2012 TC4

Observation of 2012 TC4

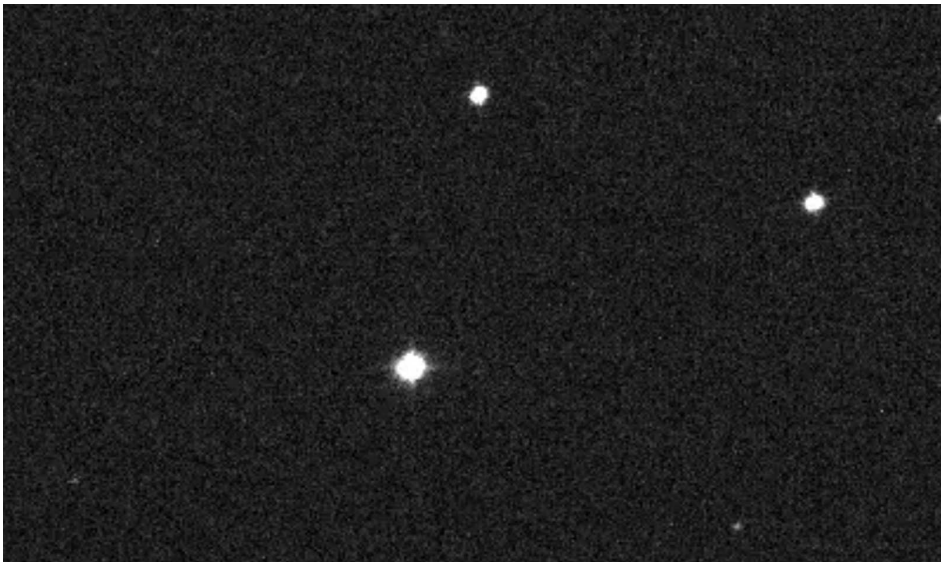


Data from Urakawa et al., submitted

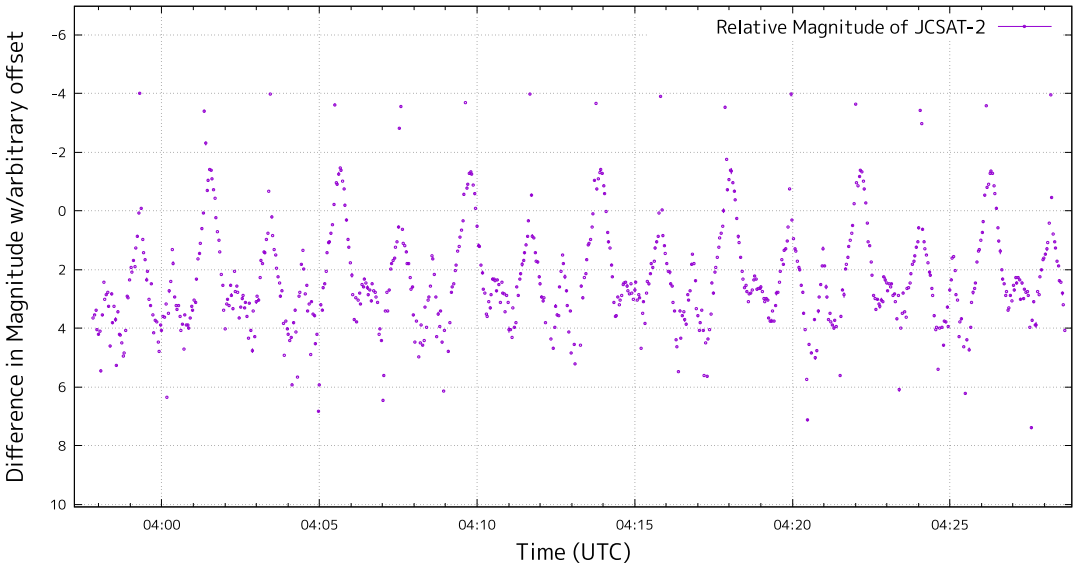
Observation of 2012 TC4



Observation of JCSAT-2



Observation of JCSAT-2



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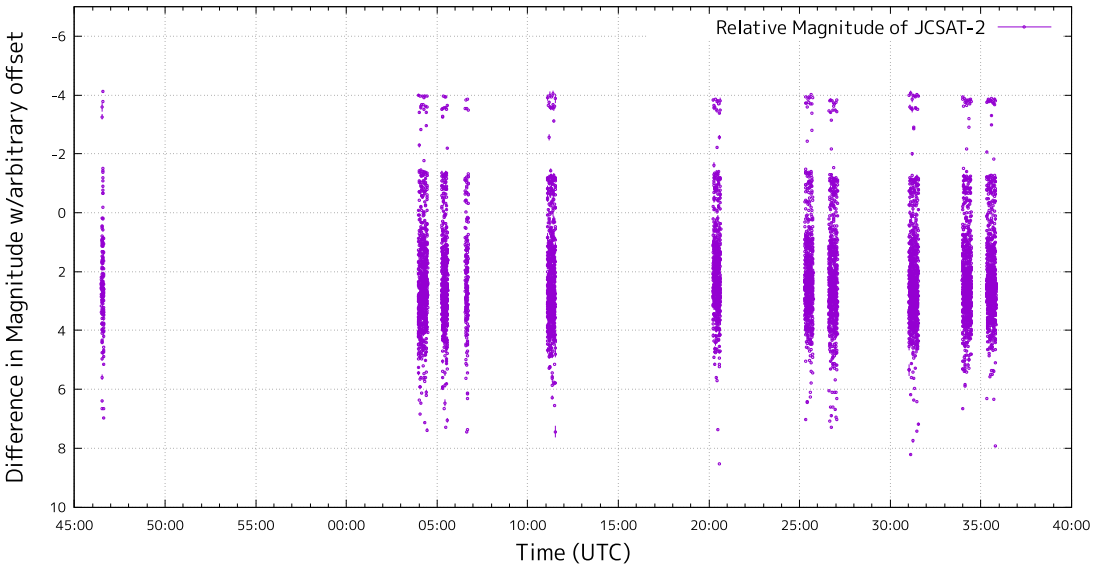
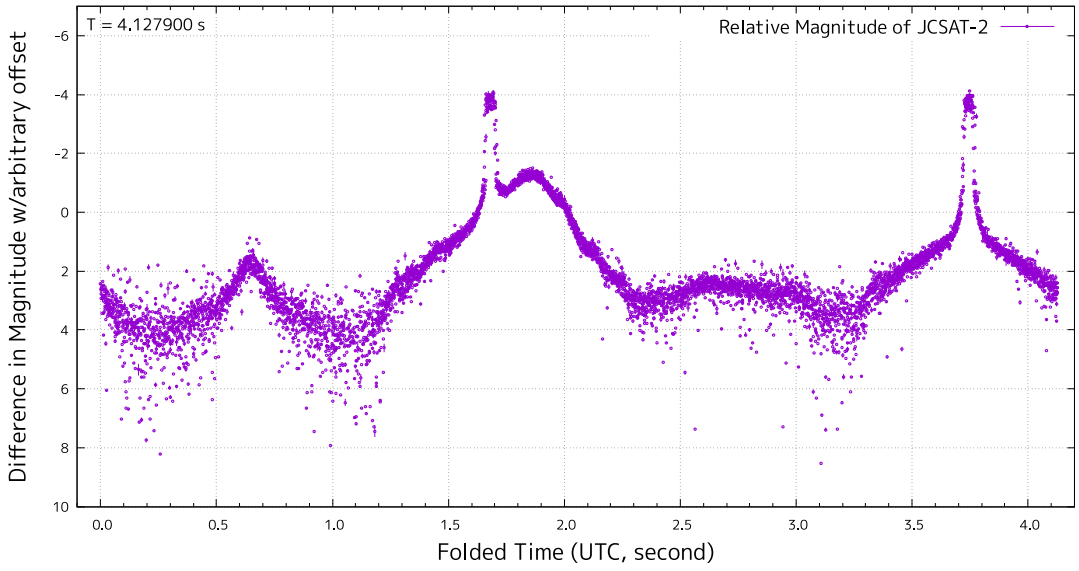
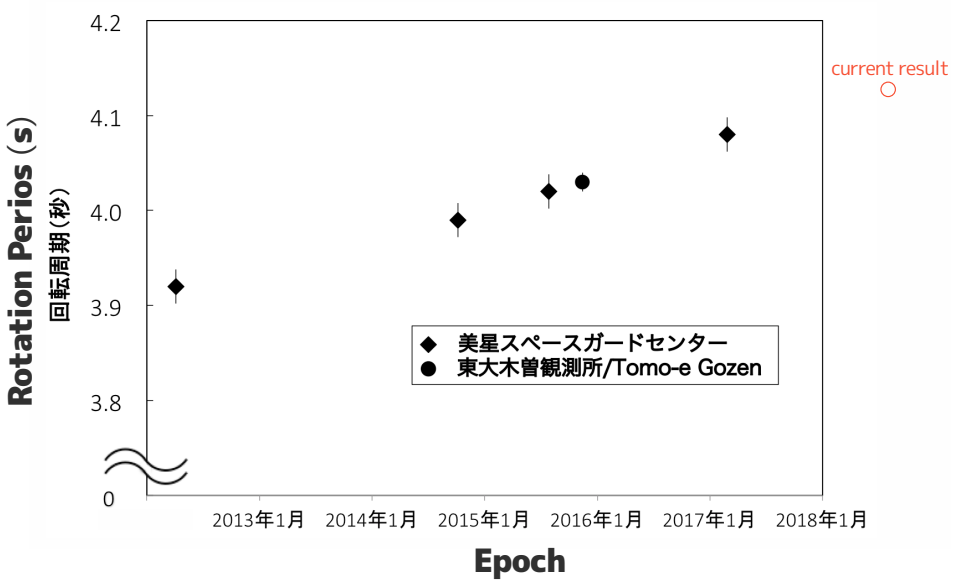


Observation of JCSAT-2

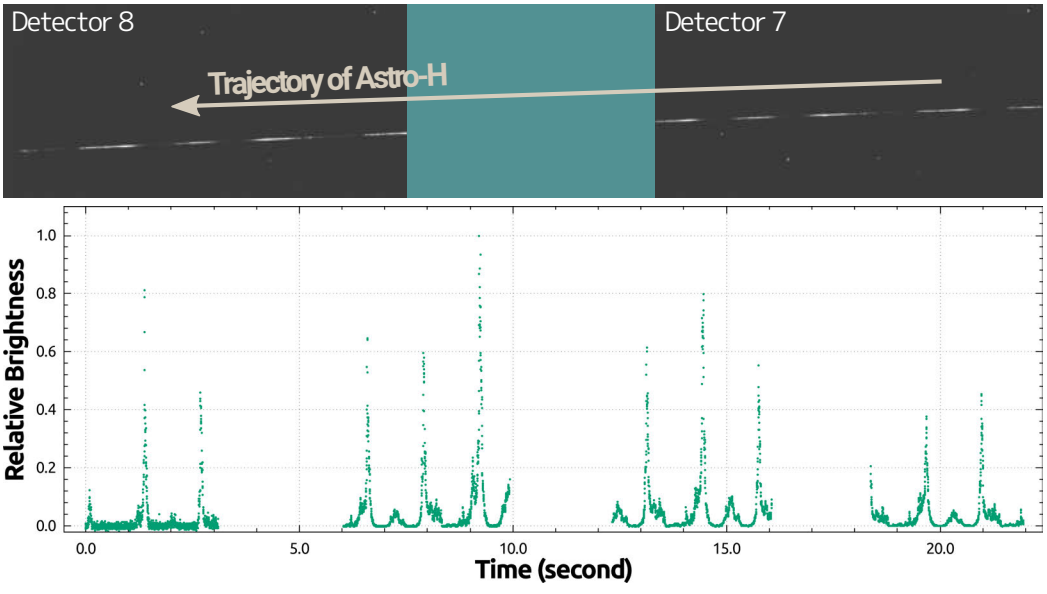


Observation of JCSAT-2



Observation of Astro-H

Observation of Astro-H



1. Follow-up/monitoring observations
2. **Blind survey of moving objects** by Yuto Kojima (Univ. Tokyo)

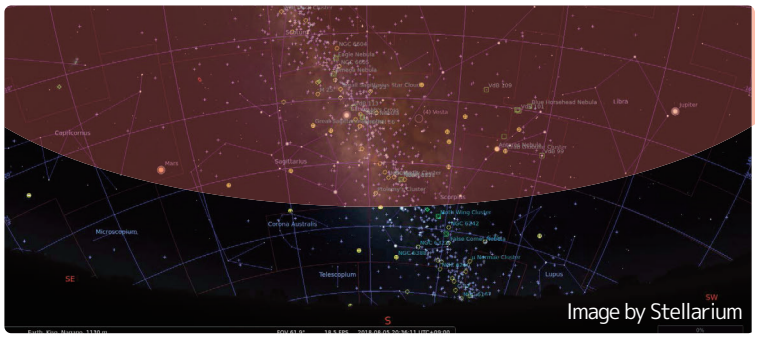
Tomo-e Gozen Supernova Survey

Tomo-e Gozen is originally developed to detect explosions in the Universe.

Take a 6-second video, move the telescope, take a 6-second video, and ....

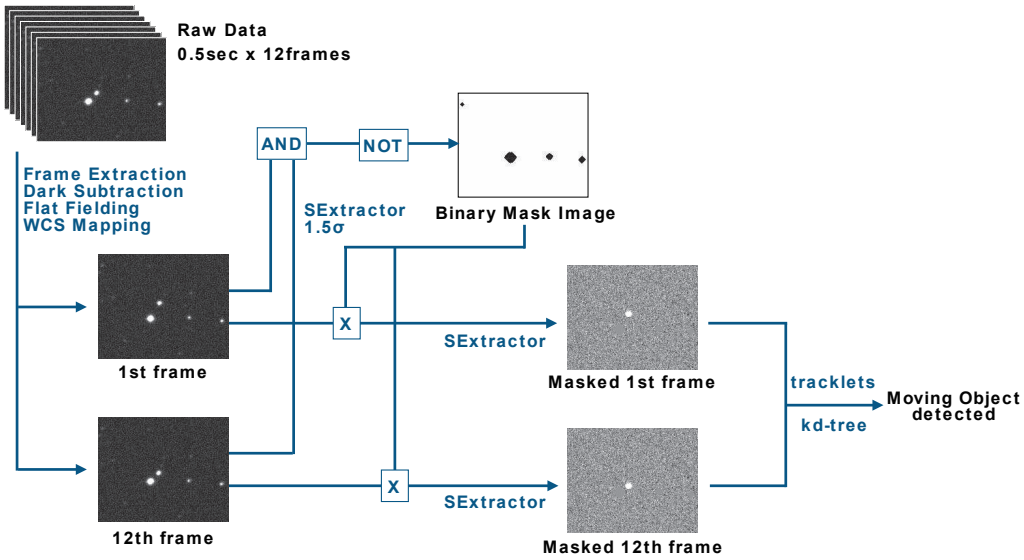
Patrol the entire visible sky at least twice in a night.

⇉ this data are useful for a blind survey of moving objects



For the details of NEO detection system, refer to the master thesis by Yuto Kojima

Near-Earth Object Tomo-e Gozen ~~Supernova~~ Survey



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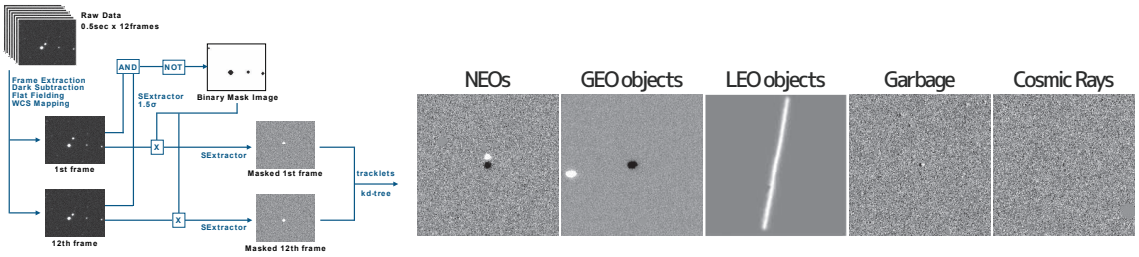

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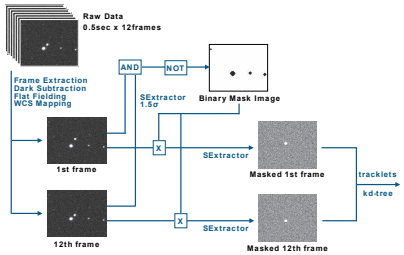

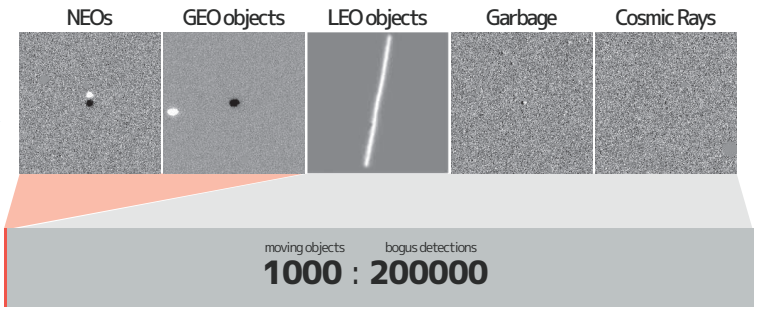

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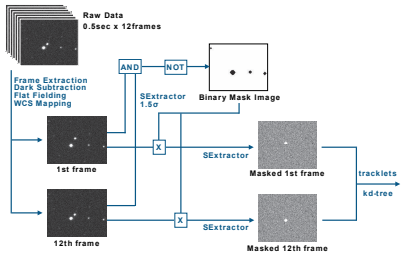

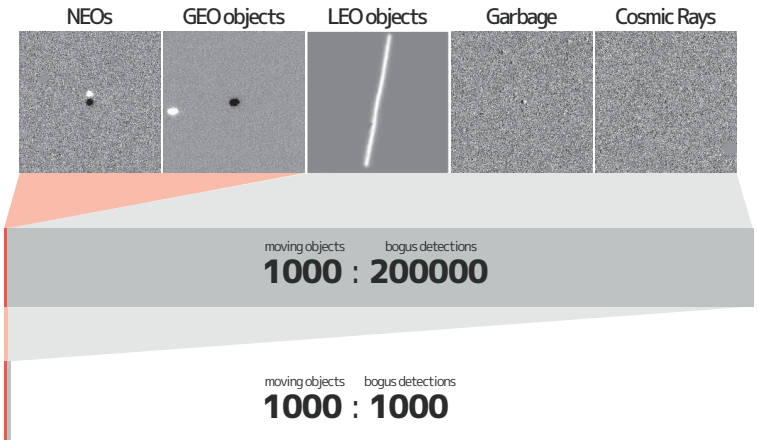

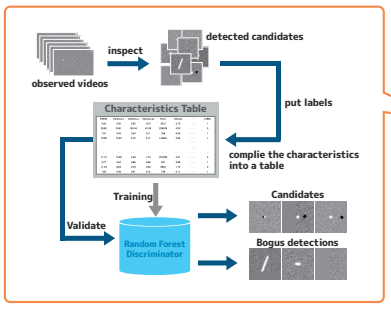

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Near-Earth Object
Tomo-e Gozen ~~Supernova~~ Survey

Tomo-e Gozen NEO Viewer

NEO candidates

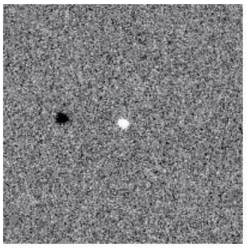
detections: 1545

No.	DATE(UTC)	Obj ID.	image	file	score	RA, DEC	Vx [pix/frame]	Vy [pix/fra
1070	2018-12-01 16:55:01.353510	42157_126_6		rTMQ1201812010004215726.fits	1.0	05h24m00.3529s +11d44m32.772s	4.61	0.37
1261	2018-12-01 17:56:06.295714	42360_126_1		rTMQ1201812010004236026.fits	0.999	07h33m47.7041s +26d45m53.3968s	4.26	0.32
646	2018-12-01 14:37:09.120533	41677_123_3		rTMQ1201812010004167723.fits	0.998	04h51m08.392s +09d25m32.7805s	6.27	0.82
1112	2018-12-01 17:04:18.968920	42189_115_3		rTMQ1201812010004218915.fits	0.998	03h10m31.5474s +03d40m01.6718s	6.09	1.0
774	2018-12-01	41798_112_3						

Near-Earth Object
Tomo-e Gozen ~~Supernova~~ Survey

Tomo-e Gozen NEO Viewer

Information of a NEO candidate 42157_126_6



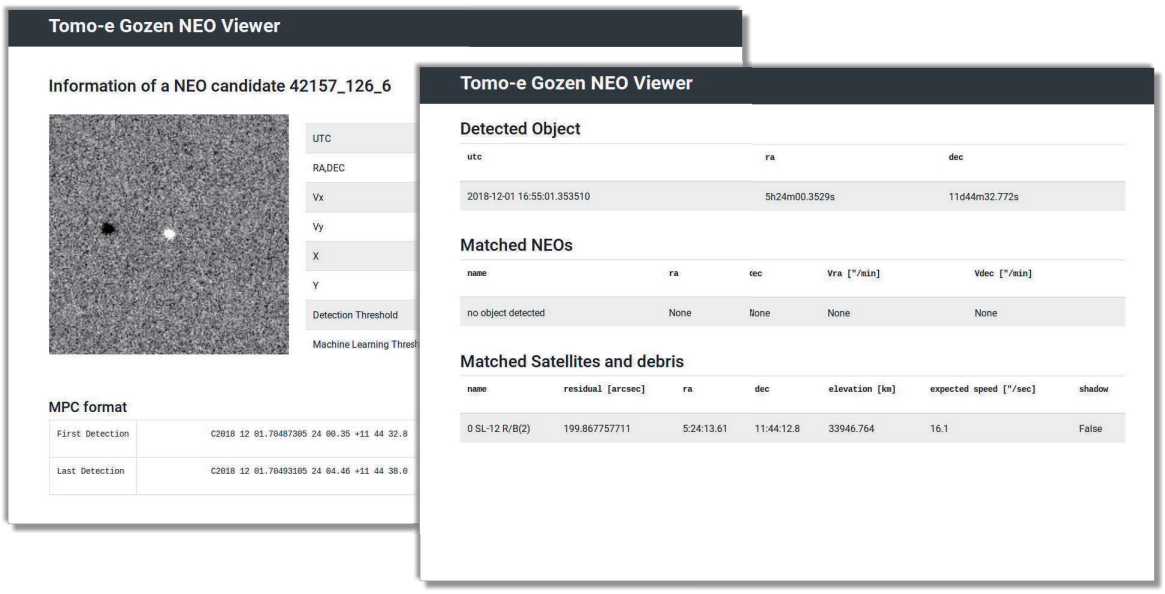
UTC	2018-12-01 16:55:01.353510
RA,DEC	05h24m00.3529s +11d44m32.772s
Vx	4.61 [pix/frame], 11.064 ['/sec]
Vy	0.37 [pix/frame], 0.887 ['/sec]
X	167.1186 [pix]
Y	646.0013 [pix]
Detection Threshold	1.7
Machine Learning Threshold	0.5

MPC format

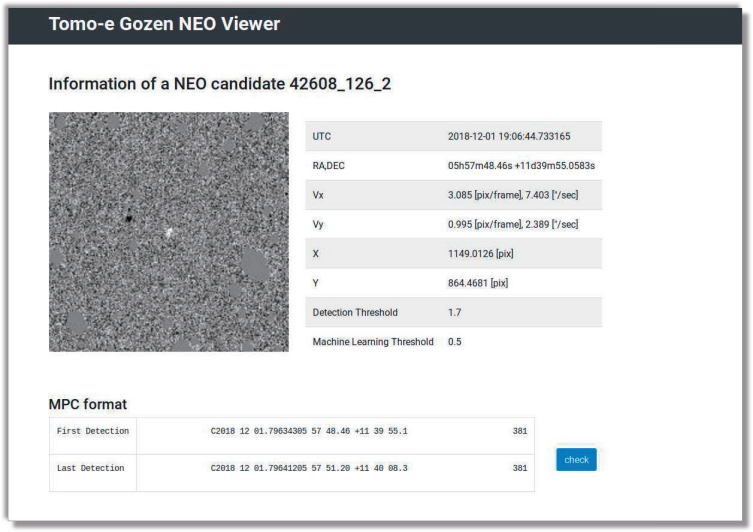
First Detection	C2018 12 01.70487305 24 00.35 +11 44 32.8	381
Last Detection	C2018 12 01.70493105 24 04.46 +11 44 38.0	381

check

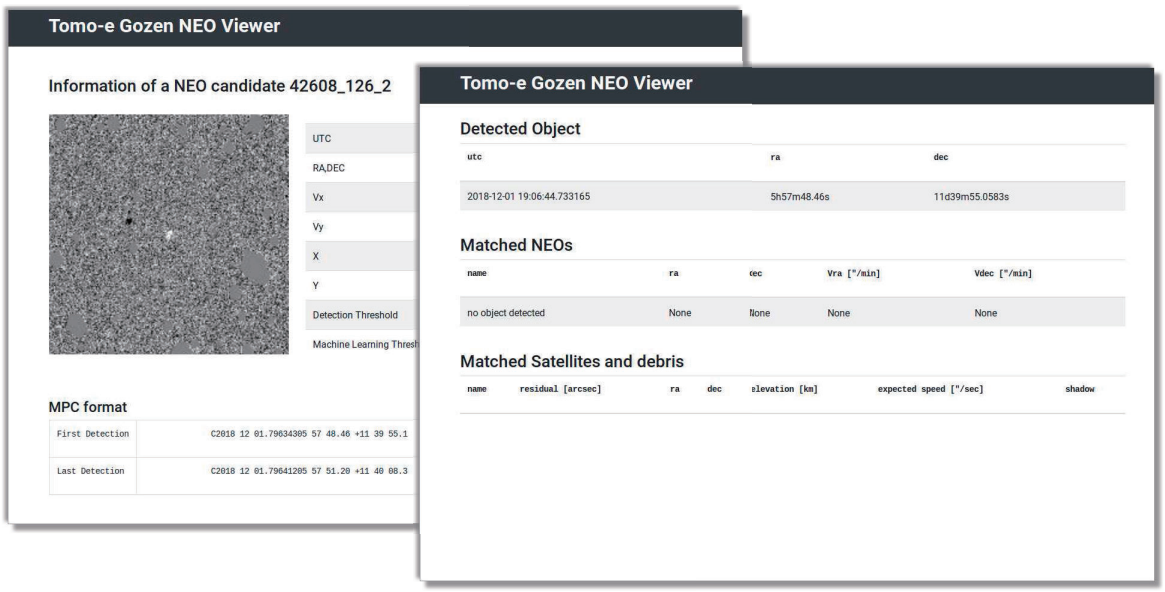
Near-Earth Object
Tomo-e Gozen ~~Supernova~~ Survey



Near-Earth Object
Tomo-e Gozen ~~Supernova~~ Survey



Tomo-e Gozen ~~Supernova~~ Near-Earth Object Survey



Summary

Tomo-e Gozen = The world largest video camerat (84 CMOS sensors+ 1.0 m telescope)

Suitable specifications to characterize/detect debris

- Wide field-of-view — **20 deg² sky coverage** with 1.2″/pixel
- High sensitivity — stars of **18 mag detected in 2 Hz** observation
- High time-resolution — **2 Hz observation**, higher framerate available by partial readout
- Accurate timestamp — **synchronized with the GPS time**, accurate to ~0.2 ms

Operating with a limited performance / Full operation is scheduled in 2019

Performance of Tomo-e Gozen in debris observations

Detection limits: **~30 cm board & ~3 mm mirror in GEO / ~5 cm namecard in LEO**

Follow-up capability:

sub-second time-resolution lightcurve revals the shape and motion of debris

Daily moving object survey:

detect **~1,000 high-speed (>1″/s) objects** and **self follow-up in 2 hours**