Real-Time Identification of LEO Objects in the Tomo-e Gozen Camera Images with a Multi-GPU System

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Introduction

BACKGROUND

- LEO objects will appear as **streaks in images when tracking at sidereal rate**, with lengths depending on object elevation and camera exposure time.
- In the literature, there are many research works aimed to detect streaks, mainly focused in the **detection sensitivity**, where only a few of them focus on the **processing speed**:
  - (1) 4096 x 4096 (16.7 Mpixels) -> 3.19 sec **GPU**
  - (2) 1024 x 1024 (1.05 Mpixels) -> 3 sec CPU
  - (3) 2049 x 2047 (4.2 Mpixels) -> 2 – 7 min CPU
  - (4) 2048 x 2048 (4.2 Mpixels) -> 13 sec CPU
- **Reduction of processing speed** can be beneficial when:
  - There is a **massive amount of images** to process.
  - Orbital parameters of detected objects are **sent to follow-up observation stations** in next LEO object pass.

OUR SOLUTION

- We developed a **real-time processing system** to **detect and identify** objects as streaks, based in **heterogenous computing (mixed multi CPU-GPU),** in two variants (standard and high sensitivity):
  - STANDARD: 18 x 2000 x 1128 (40.6 Mpixels) -> 0.3 sec (detection); 3.3 sec(including identification)
  - HIGH: 18 x 2000 x 1128 (40.6 Mpixels) -> 3.7 sec (detection); 6.7 sec(including identification)
- We achieved **Real-Time performance** (file processed before next file arrives):
  18 frames of 2000 x 1128 pixels with 0.5 sec exposure time = 9 sec per file (without considering nudging time)

(1) Diprima, F et al., T. 2017, 7th European Conference on Space Debris, Darmstadt, Germany

(2) Hickson, P. 2018, Adv. Space Res., 62, 3078-3085

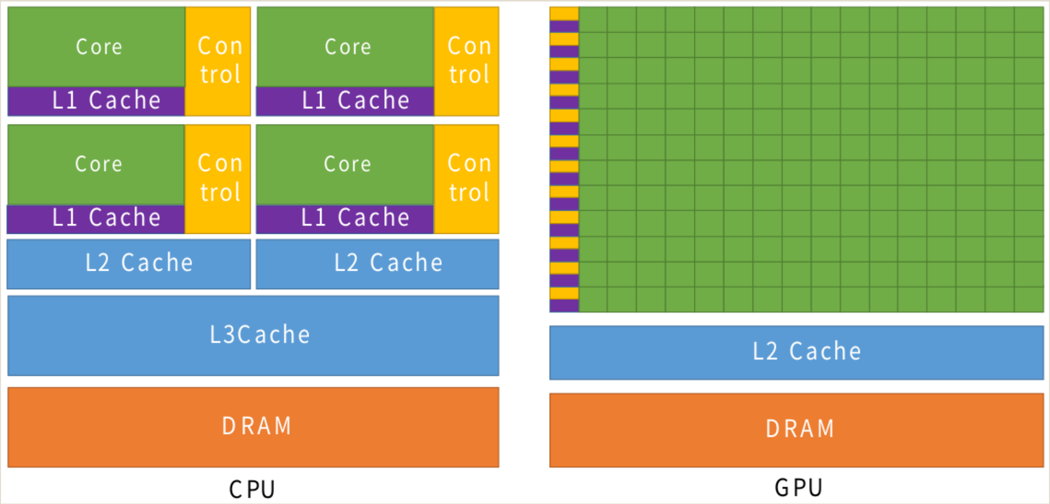
(3) Cvrcek V. et al. 2019, 14th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications, 5, 498-509, Prague

(4) Virtanen, J. et al. 2016, Adv. Space Res., 57, 1607-1623

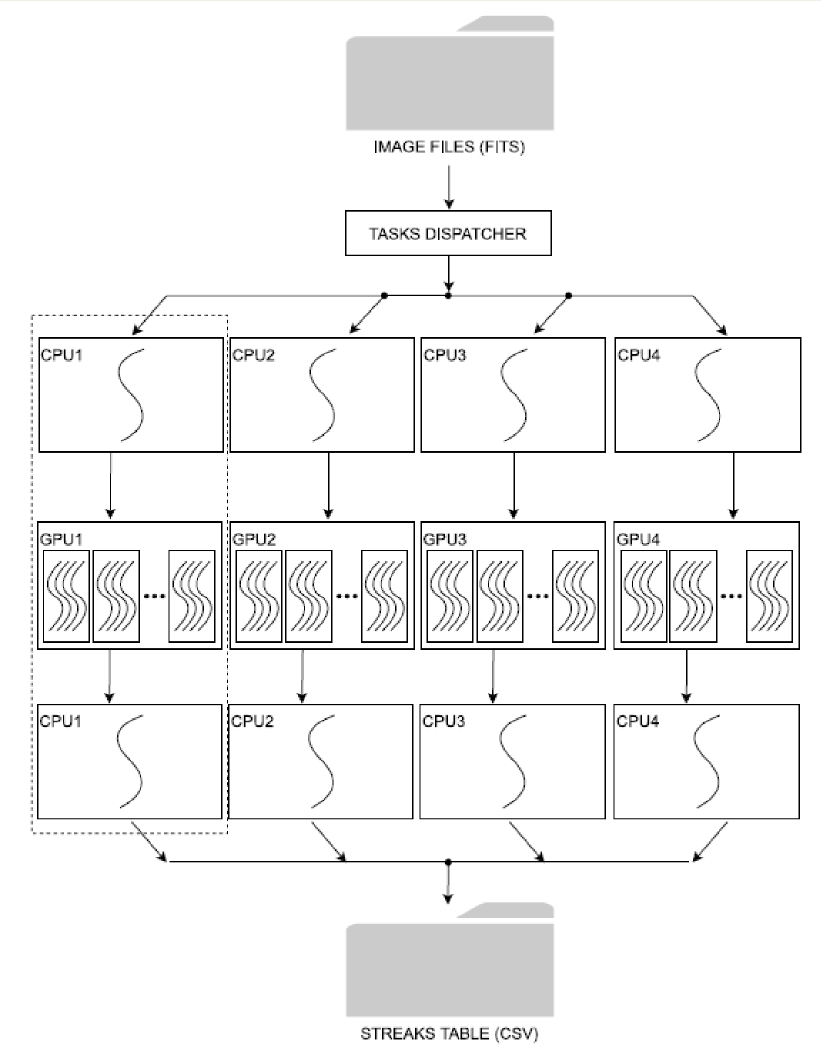
GPU Technology

IMPORTANT CONCEPTS

- **GPU technology is well suited for image processing** of massive number of pixels (memory) in parallel (same operations).
- **Heterogeneous computing**: systems that use several types of processors or cores. Current workstations and high performance computers include many CPU cores and a high number of GPU cores.
- Nowadays there exist **mature NVIDIA CUDA GPU libraries** for image processing and algebra to help in development: opencv, cublas, magma, etc.



Hardware architecture CPU vs GPU
(source: NVIDIA CUDA C++ Programming Guide)



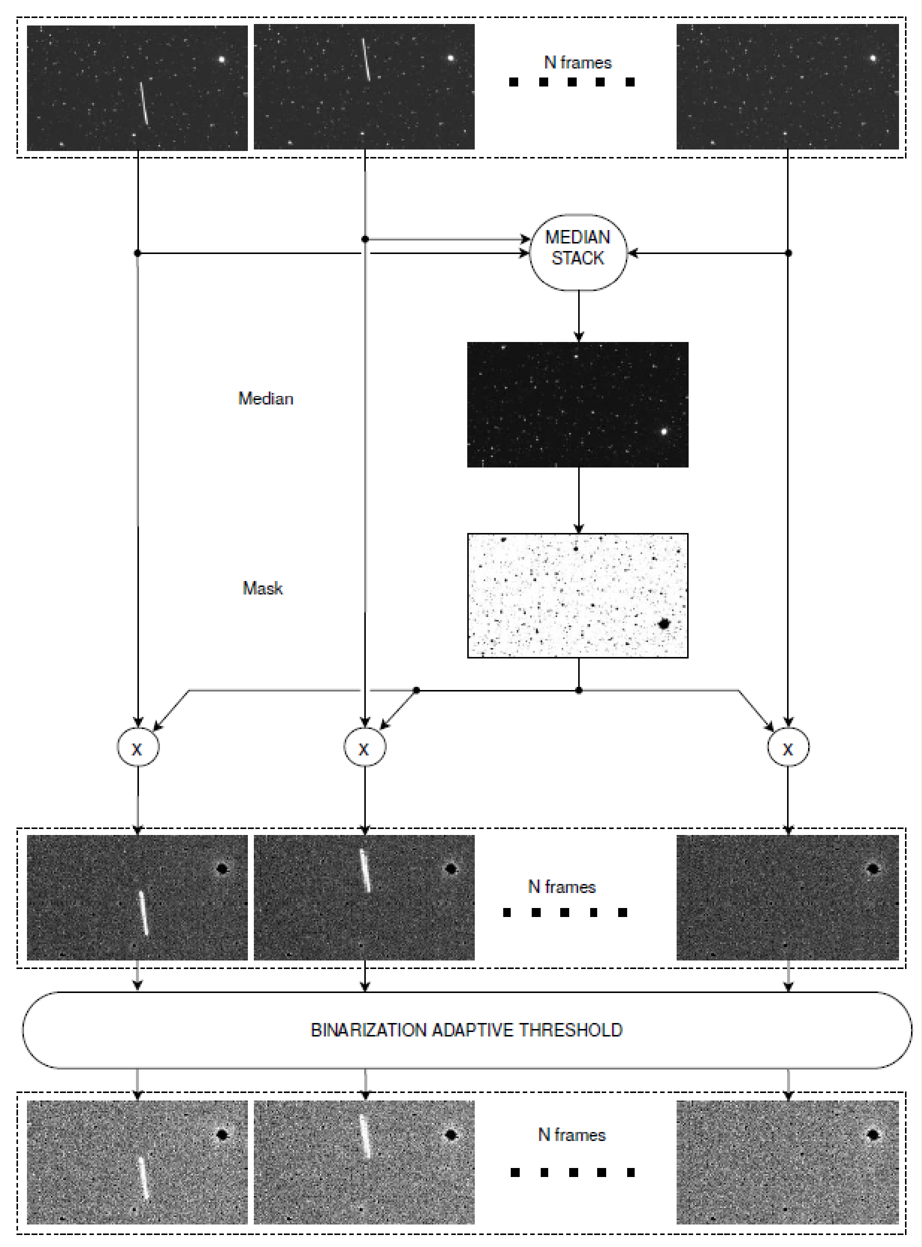
Our Top Level Parallel Processing heterogeneous CPU-GPU computing system

GPU001
4 x NVIDIA Quadro RTX8000
4608 CUDA CORES each

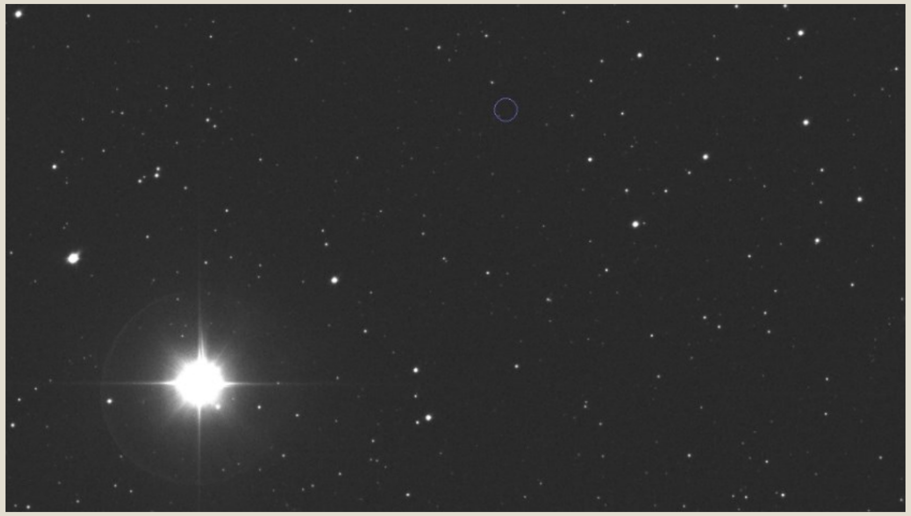
GPU002
2 x NVIDIA Ampere A6000
10752 CUDA CORES each

Process steps: Preprocessing

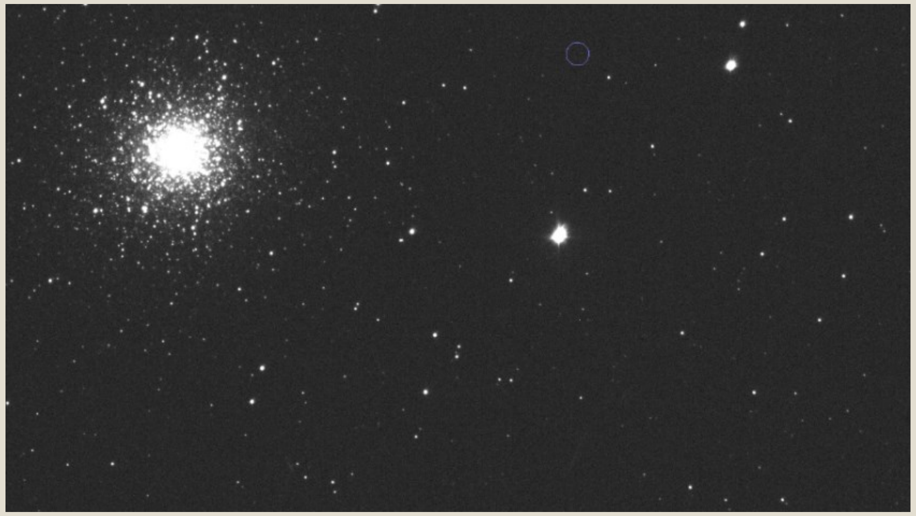
- Includes 2 substages:
  - **Removal of stars:** (variation of star removal method*) to avoid detection of false positives of streaks created by diffraction spikes of bright stars or other astronomical objects.
  - **Binarization**: global or local (adaptive thresholding).



Substages of preprocessing step



Diffraction spikes of bright star (Tomo-e camera)



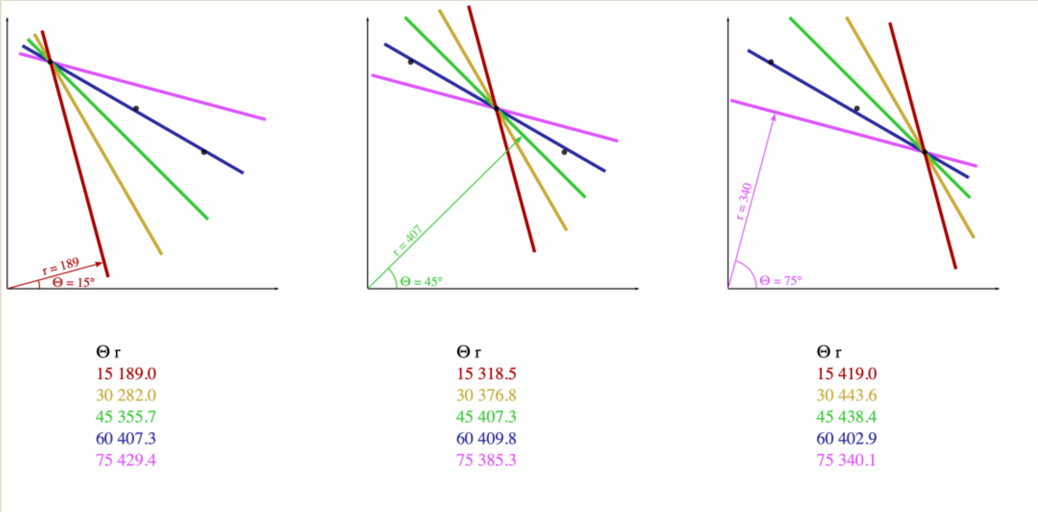
Globular cluster (Tomo-e camera)

(*) Yanagisawa, T. Et al. Automatic Detection Algorithm for Small Moving Objects, PASJ, Vol. 57, Issue 2, 2005, Pages 399–408

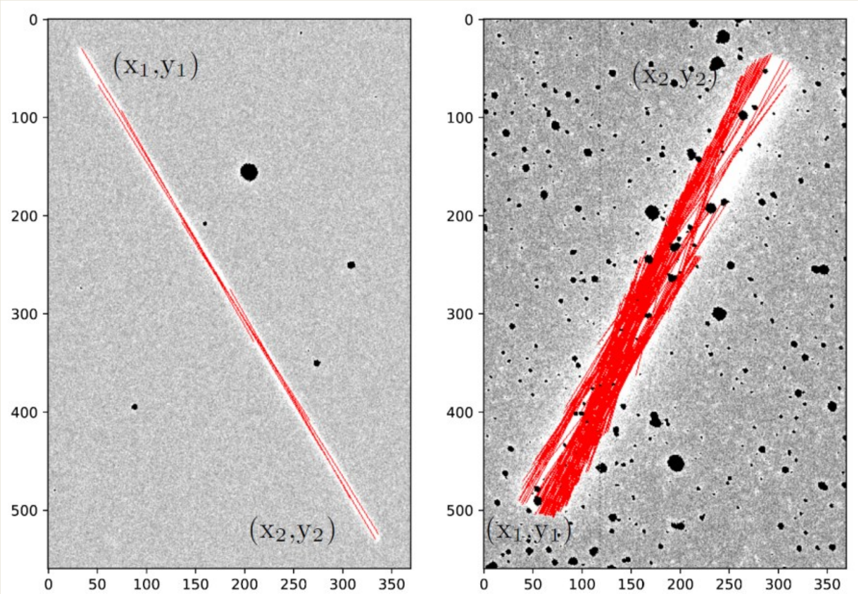
Process steps: Detection

STANDARD SENSITIVITY (HOUGH TRANSFORM*)

- **CUDA OpenCV implementation** of the PPHT (Progressive Probabilistic Hough Transform) -> **Fast**, **detection of segments** instead of lines
- **Longest of each group** of segments of len. > 200 pixels.



Theoretical principle of Hough Transform
source:https://commons.wikimedia.org/w/index.php?curid=74745305

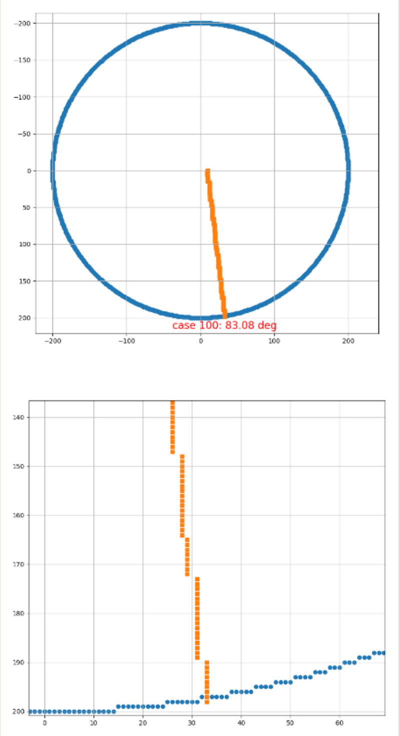


Segments detected for a narrow (left) and a wide (right) streak

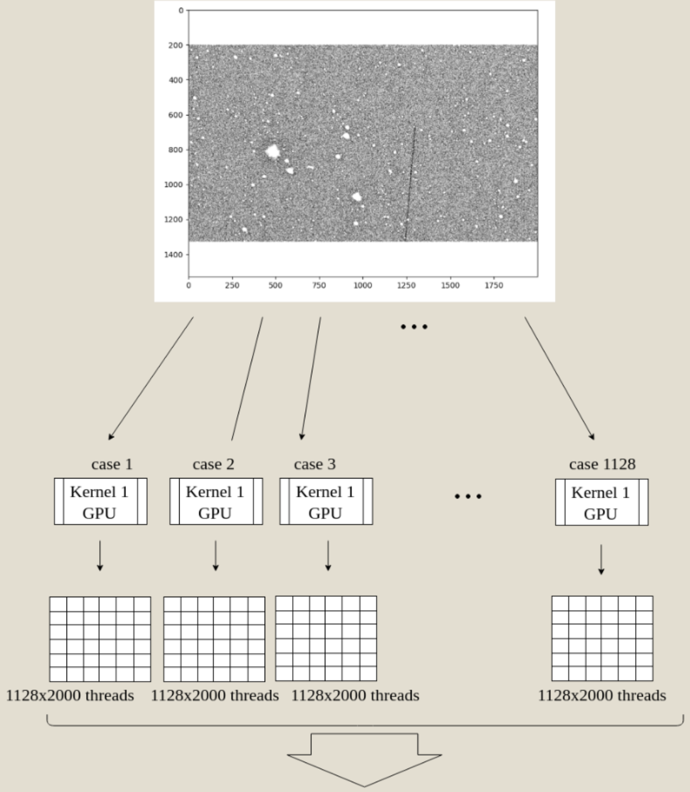
* Hough, P.V.C. 1962, U.S. Patent 3069654

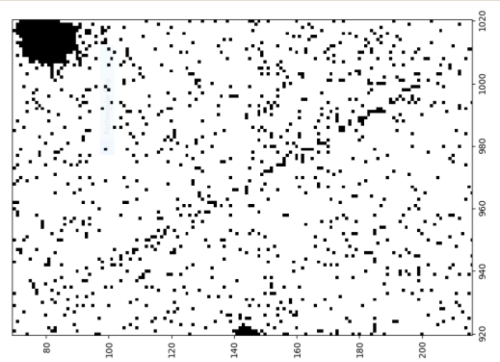
HIGH SENSITIVITY (STACKING METHOD**)

- Pixel binary values (0/1) are **accumulated** over segments of length 200 pixels.
- Casefile includes **1128 possible directions**.
- Cases over **threshold (~130/200)** are candidates.



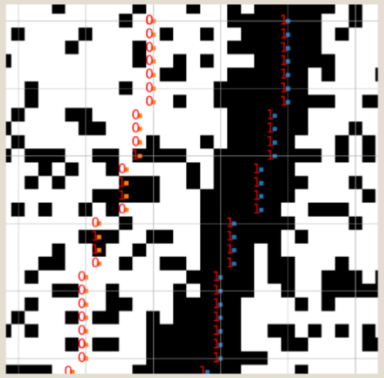
Generation of casefile





Faint streak after binarization

Case	Pixel	It
42	162000	130
42	162001	131
42	162002	130
42	162003	138
42	162004	140
42	162005	141

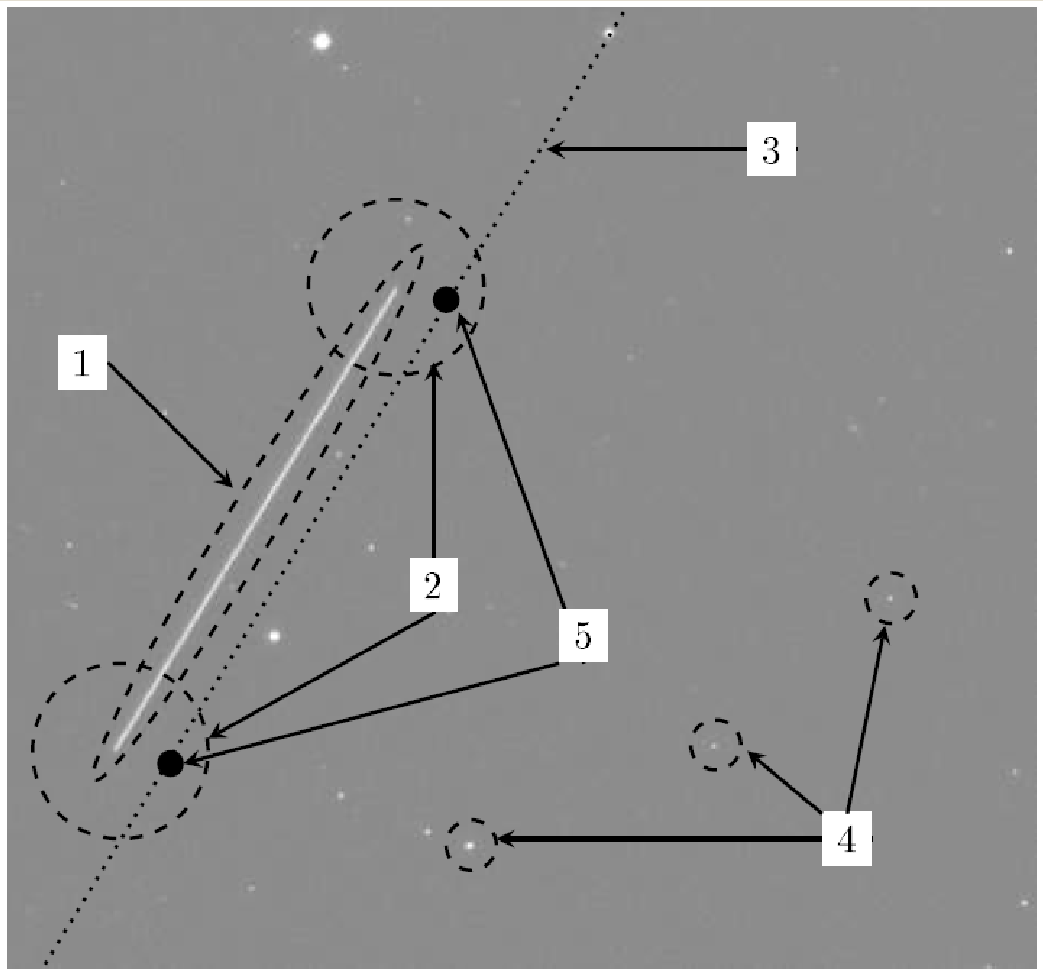


raw output: case, pixel and value over threshold

** Detection of Small GEO Debris by Use of the Stacking Method", Yanagisawa T. et al, T. Japan Soc. Aero. Space Sci., V.44, No. 146, pag. 190-199, 2005

Process steps: Identification

- Includes 3 substages:
  - **Astrometry**: Obtention of astronomical coordinates (RA, Dec) of each streak end.
  - **Identification**: coordinates ends are compared with those of known objects of a space-track.org database of 29,082 entries, based in the SGP4 orbital propagation or their initial TLE coordinates.
  - **Differential Photometry:** Only to characterize system sensitivity, not intrinsic to the object, and not included in the main loop process.



1 **Elliptical area** surrounding the detected streak to compute the total brightness.

2 Circular areas surrounding both ends of the detected streak, that defines the **error with the TLE database** of objects comparison.

3 **Trajectory of real object** in the database obtained through the propagation of its TLE data with SGP4 algorithm.

4 **photometric stars** for differential photometry.

5 **(RA,Dec) coordinates** of object from database corresponding to the timestamps of start and end of camera integration time. if these points are encompassed by the circular areas (2), the streak is associated with the candidate object.

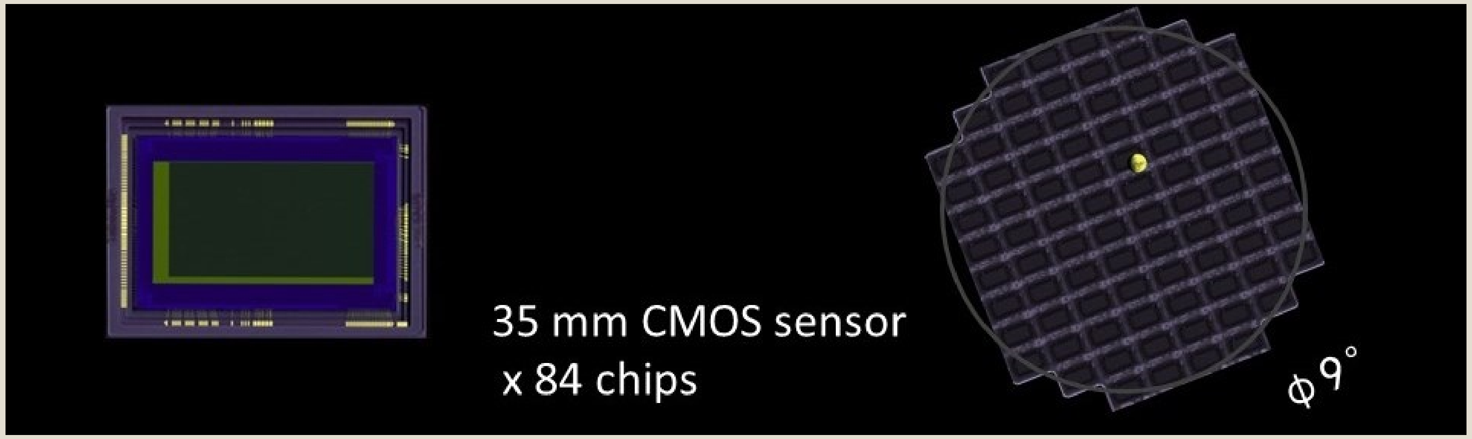
Results: Experimental Set-up

TOMO-E CAMERA AT 1M SCHMIDT TELESCOPE AT KISO OBSERVATORY

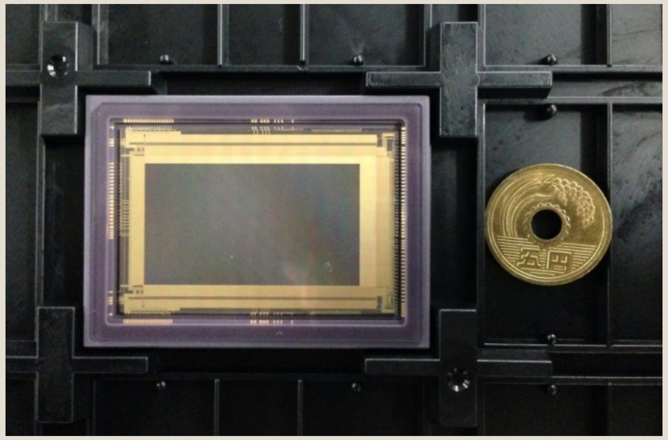
FITS files:	18 consecutive frames of 0.5 s exposure time
	2000 x 1128 x 18 ~ 40.61 Mpixels ~ 162.4 Mbytes
Data rate:	~ 1.7 Tbytes / hour
Sensor model:	Canon 35MMFHDXM
Sensor type:	CMOS Front illuminated
Pixel size:	19 μm/pixel
Pixel scale:	1.198 arcsec/pixel
No. sensors:	84

OBSERVATION SET

STANDARD SENSITIVITY:	21,084 FITS files (2 hours)	~3.4 TB
HIGH SENSITIVITY:	2.373 FITS files	~386 GB

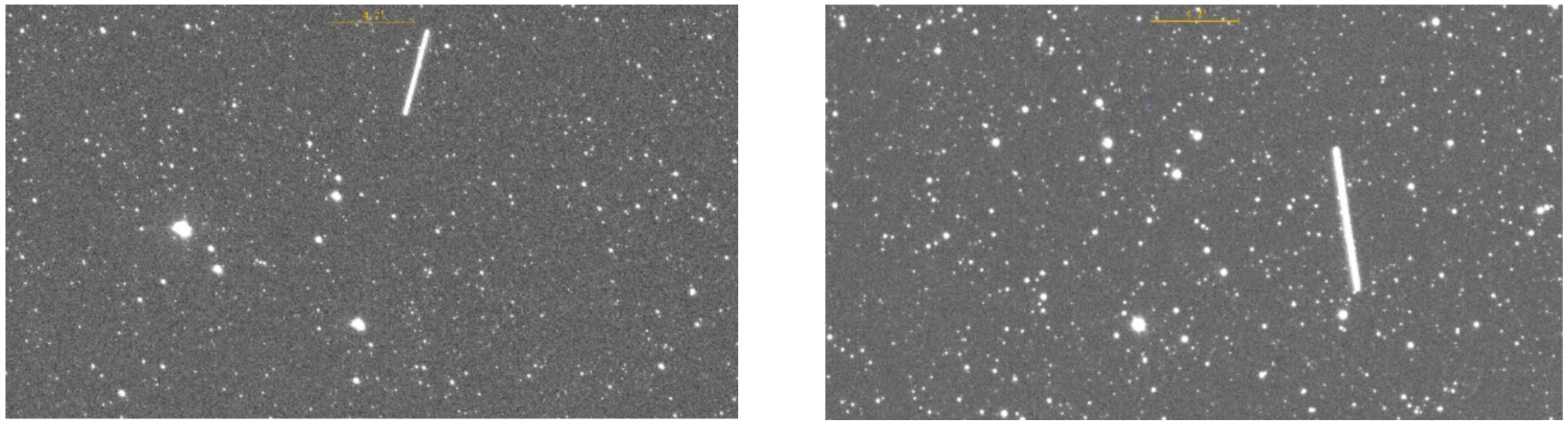


Layout of CMOS sensors in Tomo-e Gozen camera. 1.198 arcsec/pix
source: www.ioa.s.u-tokyo.ac.jp/tomoe

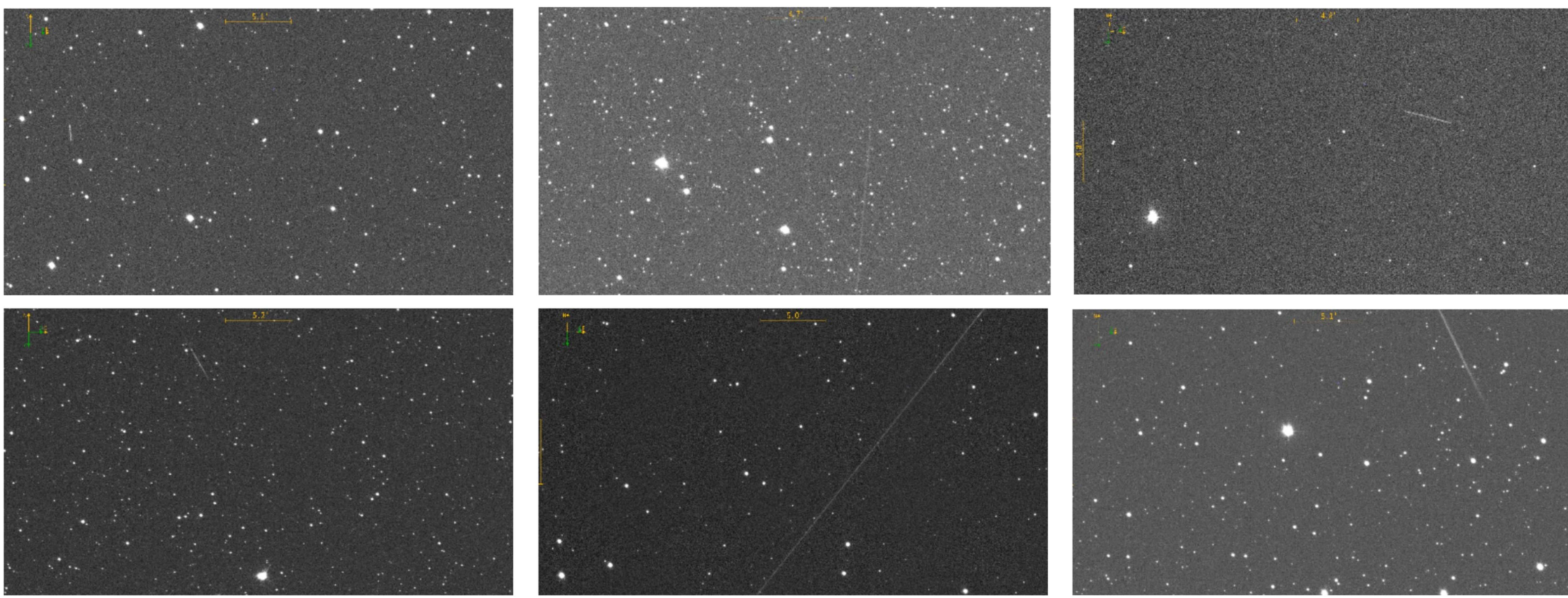


35 mm Full HD 2000 x 1128 pixels
source: www.ioa.s.u-tokyo.ac.jp/tomoe

Results: Sample Images



Detected by Standard and High Sensitivity Methods

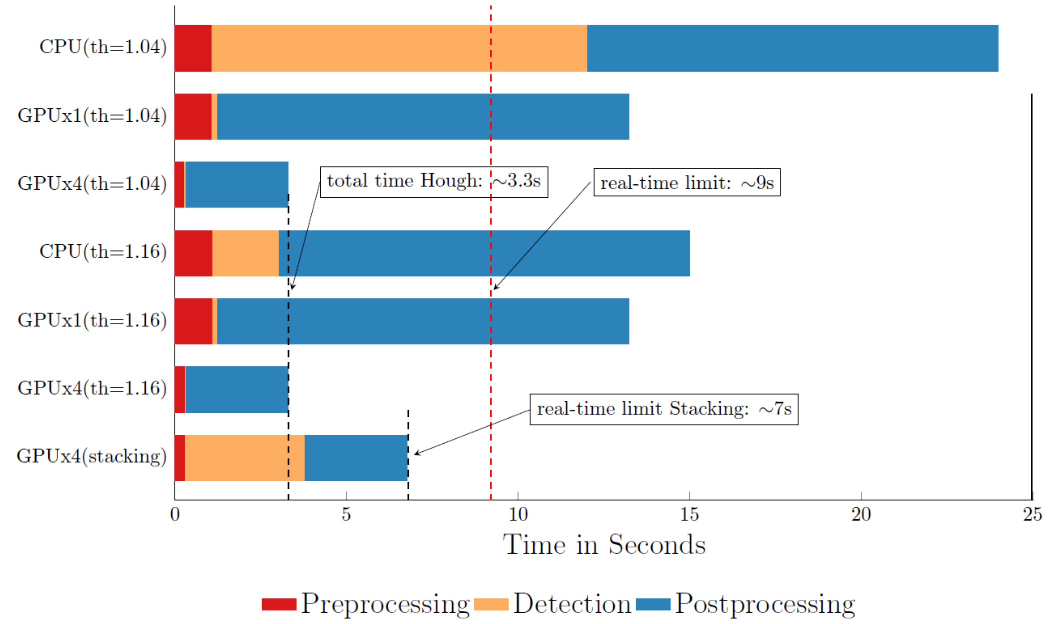


Detected **ONLY** by High Sensitivity Method

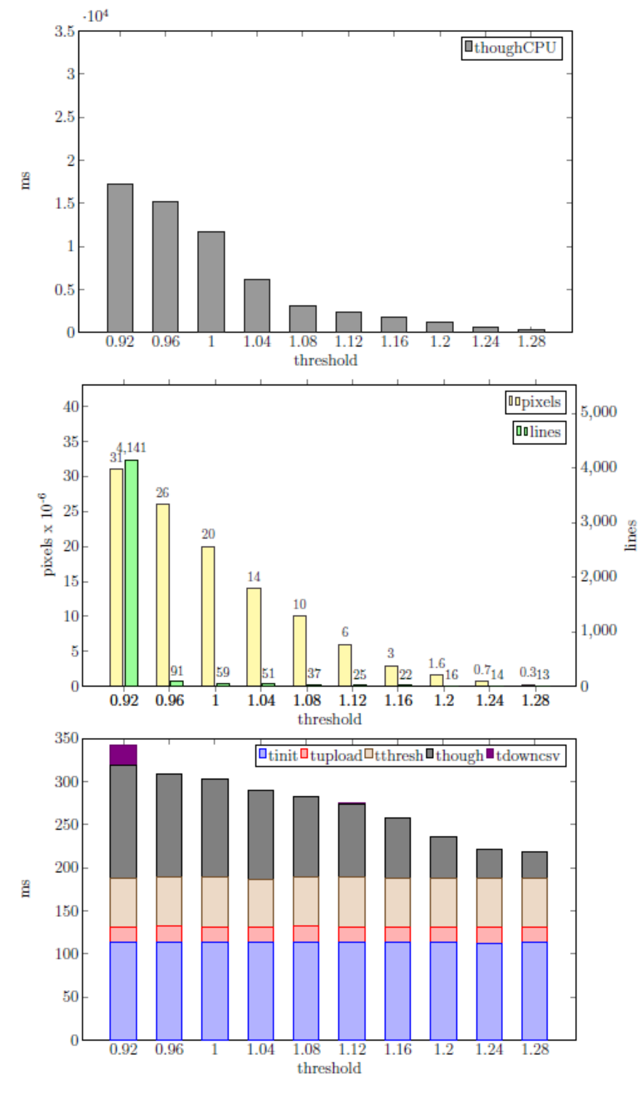
Results: Performance

STANDARD SENSITIVITY (HOUGH METHOD)
detection time: ~**100 ms per FITS file (18 frames)**
12-130 times faster than CPU
REAL-TIME (4xGPU): **3.3 s < 9 s**
Detection rate: **~ 0.5%**
Identification rate: **83%**
Min. apparent magnitude: +11.3

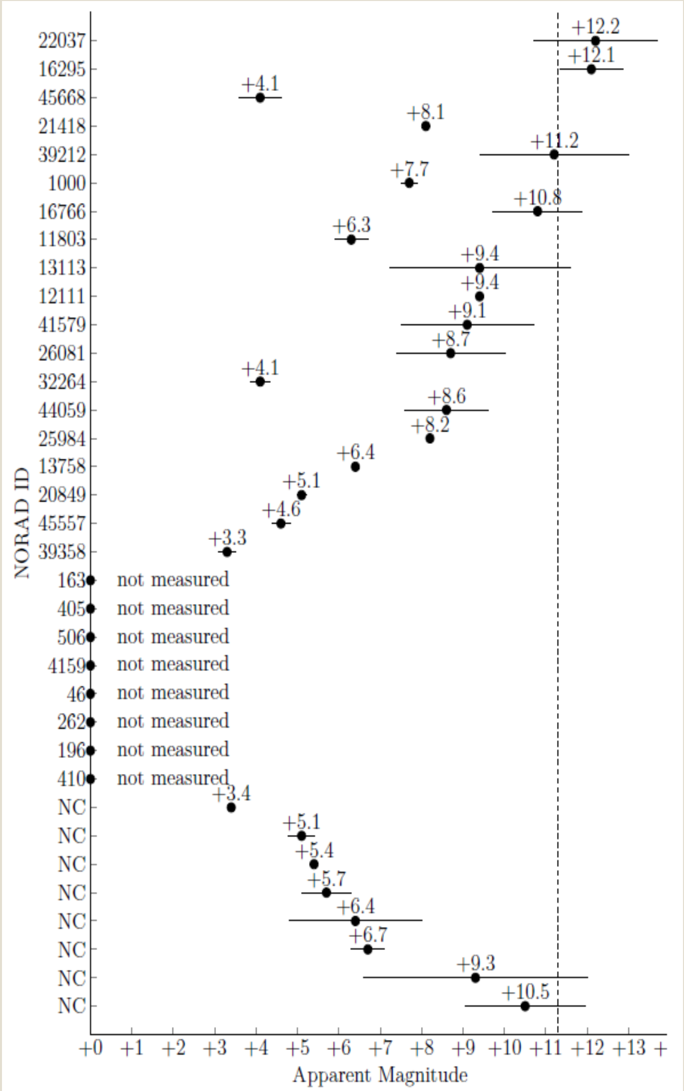
HIGH SENSITIVITY (STACKING METHOD)
detection time: **~14 s per FITS file (18 frames)**
60 times faster than CPU
REAL-TIME (4XGPU): **7 s < 9 s**
Detection rate: **~ 5%**
Identification rate: **~66%.**
Min. apparent magnitude: >+11.3



Comparative speed performance at CPU vs. GPU vs. 4xGPU of Hough and Stacking Detection algorithms



Comparison of CPU vs. GPU processing time in the detection stage for a range of thresholds (Hough Method)



Photometry of 35 objects detected. NC are Non-Catalogued Objects. 8 objects where not measured as one of their ends was out of bounds of the image sensor (Hough Method)

Results: Output table

subframe	file_name	positives	max_x	max_y	min_x	min_y	max_RA	max_Dec	min_RA	min_Dec	UTC_begin	UTC_end	TLE_candidate	NORAD ID
7	rTMQ1202010180038009611_7.fits	386984	1675	1055	1702	988	17:48:08.792	-07:10:54.57	17:48:10.992	-07:09:35.11	2020-10-18 09:22:34.165882	2020-10-18 09:22:34.665786	SATCOM K2 R/B(PAM-D2)	16295
8	rTMQ1202010180038009611_8.fits	694382	1720	983	1768	740	17:48:12.434	-07:09:29.32	17:48:16.424	-07:04:40.70	2020-10-18 09:22:34.665786	2020-10-18 09:22:35.165690	SATCOM K2 R/B(PAM-D2)	16295
9	rTMQ1202010180038009611_9.fits	1109989	1759	780	1823	508	17:48:15.680	-07:05:28.20	17:48:20.963	-07:00:05.25	2020-10-18 09:22:35.165690	2020-10-18 09:22:35.665594	SATCOM K2 R/B(PAM-D2)	16295
10	rTMQ1202010180038009611_10.fits	888185	1817	545	1884	286	17:48:20.461	-07:00:49.21	17:48:25.970	-06:55:41.79	2020-10-18 09:22:35.665594	2020-10-18 09:22:36.165498	SATCOM K2 R/B(PAM-D2)	16295
11	rTMQ1202010180038009611_11.fits	1914	1878	406	1889	200	17:48:25.418	-06:58:04.44	17:48:26.421	-06:53:59.56	2020-10-18 09:22:36.165498	2020-10-18 09:22:36.665402	SATCOM K2 R/B(PAM-D2)	16295
13	rTMQ1202010180038009611_13.fits	7985	1520	874	1524	433	17:47:56.527	-07:07:17.89	17:47:57.127	-06:58:33.38	2020-10-18 09:22:37.165306	2020-10-18 09:22:37.665210	SATCOM K2 R/B(PAM-D2)	16295
14	rTMQ1202010180038009611_14.fits	1	1567	399	1567	399	17:48:00.582	-06:57:53.33	17:48:00.582	-06:57:53.33	2020-10-18 09:22:37.665210	2020-10-18 09:22:38.165114	SATCOM K2 R/B(PAM-D2)	16295
13	rTMQ1202010180038009612_13.fits	10	1668	1127	1688	1004	17:48:09.131	-06:24:09.55	17:48:10.763	-06:21:43.31	2020-10-18 09:22:37.165306	2020-10-18 09:22:37.665210	SL-24 R/B	27610
8	rTMQ1202010180038009913_8.fits	7	9	505	1860	250	18:13:37.240	-12:24:43.90	18:16:07.676	-12:19:56.09	2020-10-18 09:23:46.185148	2020-10-18 09:23:46.685052	no match	no match
2	rTMQ1202010180038009914_2.fits	543	595	620	372	243	18:14:26.391	-11:39:02.85	18:14:08.548	-11:31:32.63	2020-10-18 09:23:43.185724	2020-10-18 09:23:43.685628	no match	no match
3	rTMQ1202010180038009914_3.fits	193	838	1024	614	622	18:14:45.858	-11:47:05.34	18:14:27.928	-11:39:05.36	2020-10-18 09:23:43.685628	2020-10-18 09:23:44.185532	no match	no match
13	rTMQ1202010180038010044_13.fits	332788	1597	407	1464	200	18:02:32.141	-11:56:49.87	18:02:21.646	-11:52:41.15	2020-10-18 09:24:09.086756	2020-10-18 09:24:09.586660	no match	no match
14	rTMQ1202010180038010044_14.fits	1676705	1940	953	1740	635	18:02:59.216	-12:07:46.06	18:02:43.423	-12:01:23.83	2020-10-18 09:24:09.586660	2020-10-18 09:24:10.086564	no match	no match
15	rTMQ1202010180038010044_15.fits	99026	18	1121	1897	855	18:00:23.118	-12:10:27.45	18:02:55.858	-12:05:48.60	2020-10-18 09:24:10.086564	2020-10-18 09:24:10.586468	no match	no match
8	rTMQ1202010180038010215_8.fits	22816	1781	1016	1990	985	18:25:08.817	-03:33:27.09	18:25:25.428	-03:32:51.57	2020-10-18 09:24:55.598711	2020-10-18 09:24:56.098615	no match	no match
8	rTMQ1202010180038010825_8.fits	235	540	245	747	200	18:07:40.656	+03:43:30.63	18:07:57.109	+03:44:24.10	2020-10-18 09:27:07.480134	2020-10-18 09:27:07.980038	no match	no match
4	rTMQ1202010180038011014_4.fits	11	375	1061	324	1018	18:23:12.382	+10:29:09.58	18:23:08.275	+10:30:00.77	2020-10-18 09:27:54.495094	2020-10-18 09:27:54.994998	no match	no match

Fragment of output table with the High Sensitivity method

File ID	rTMQ1202010180038024725.fits	
Subframe	0	1
length(arcsec)	316.8	316
slope	-39.2	-39
RA_1	49:53.9	50:17.2
Dec_1	+48:35:40.63	+48:39:10.14
RA_2	50:18.0	50:41.4
Dec_2	+48:39:05.58	+48:42:33.49
UTC begin	22:54.9	22:55.4
UTC end	22:55.4	22:55.9
TLE candidate	ORBCOMM FM 36	ORBCOMM FM 36
NORAD ID	25984	25984
RA rate (arcsec/s)	-491.2	-491.2
Dec rate (arcsec/s)	400.1	397.7
Streak counts	2190944.0	2196086.2
Instr Mag	-15.9	-15.9
Object Mag	8	8
Mag residuals	0.021	0.021

Details for one FITS file

Conclusions

- We developed a **real-time processing system** to **detect and identify** objects as streaks, based in **heterogenous computing (mixed multi CPU-GPU)**, in two variants (standard and high sensitivity), with **Real-Time** performance.
- CPU-GPU heterogeneous computing is a convenient solution for the **need of big data processing** in SSA and Astronomy.

- Plan to **shorten Postprocessing stage** time through GPU implementation.
- Next stage: **Integration and installation in existing SSA observatories under consideration**.

ACKNOWLEDGEMENTS

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--- どうもありがとうございました ---