Developing a Star Tracker Algorithm for Small Satellites

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Outline

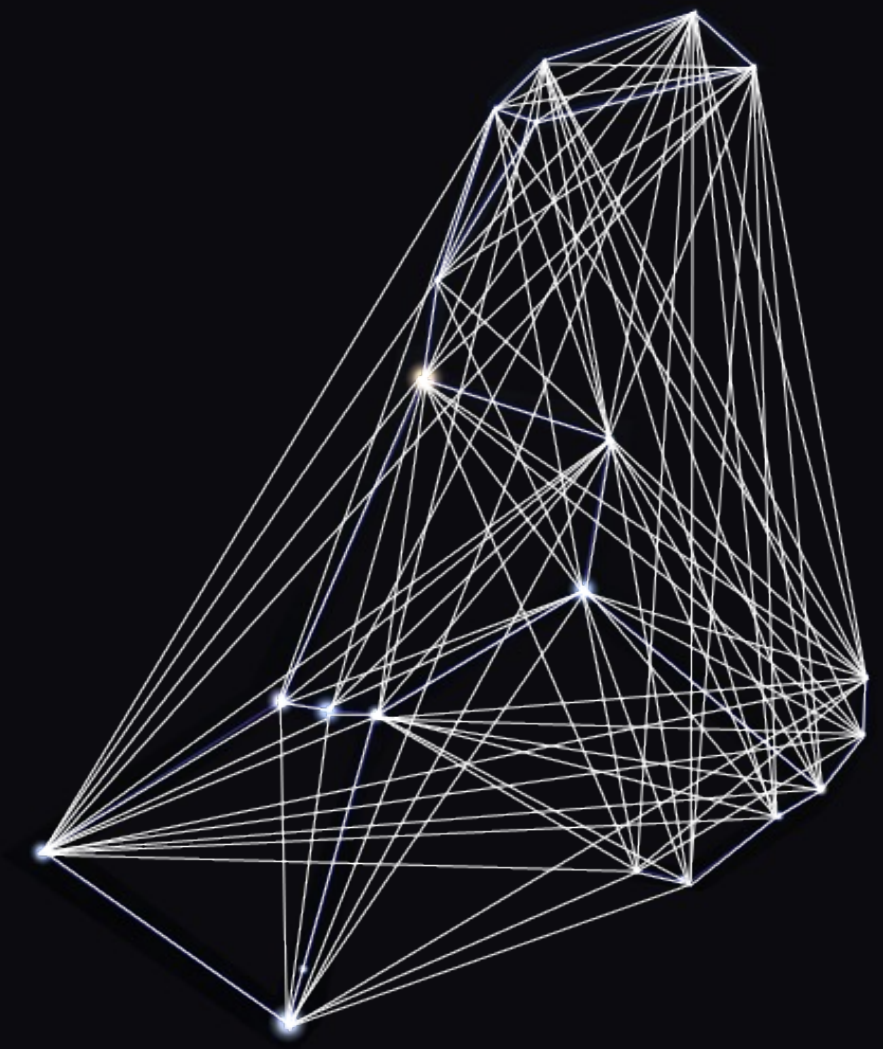
- Star tracker
- Star catalog
- Lost-in-Space mode
  - Robust to non-star objects
  - Robust to noise
- Tracking mode
  - Stray light elimination
- Night sky test
- Conclusions

Attitude sensors for SmallSats

- Earth sensor
- Sun sensor
- IMU
- Magnetometer
- Star tracker

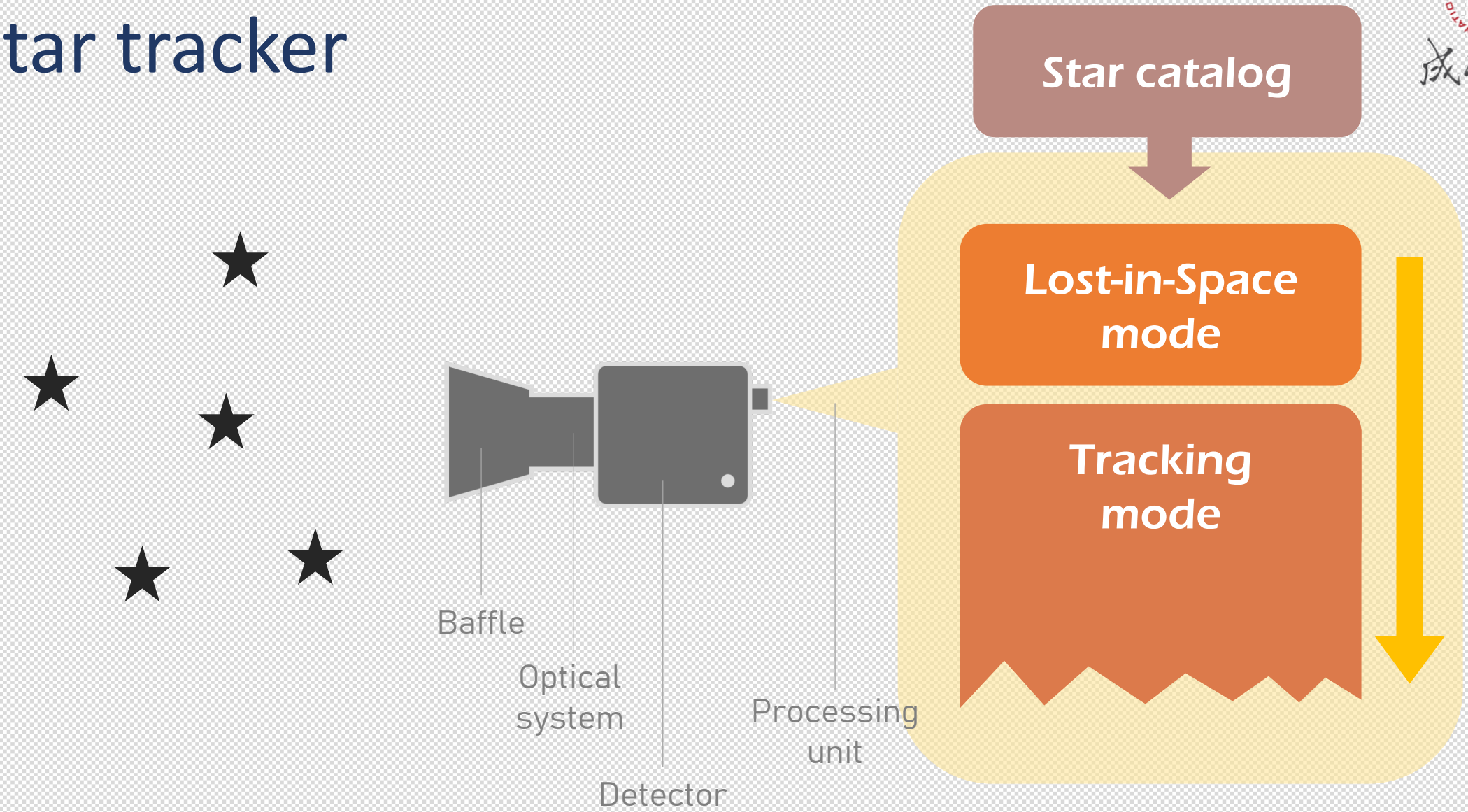
Star tracker

- Low mass, volume, power consumption
- Attitude determination with extremely high accuracy
- Autonomously without the aid of external navigation sensors
- Any orbit and wide angular range
- Long period without accumulating error



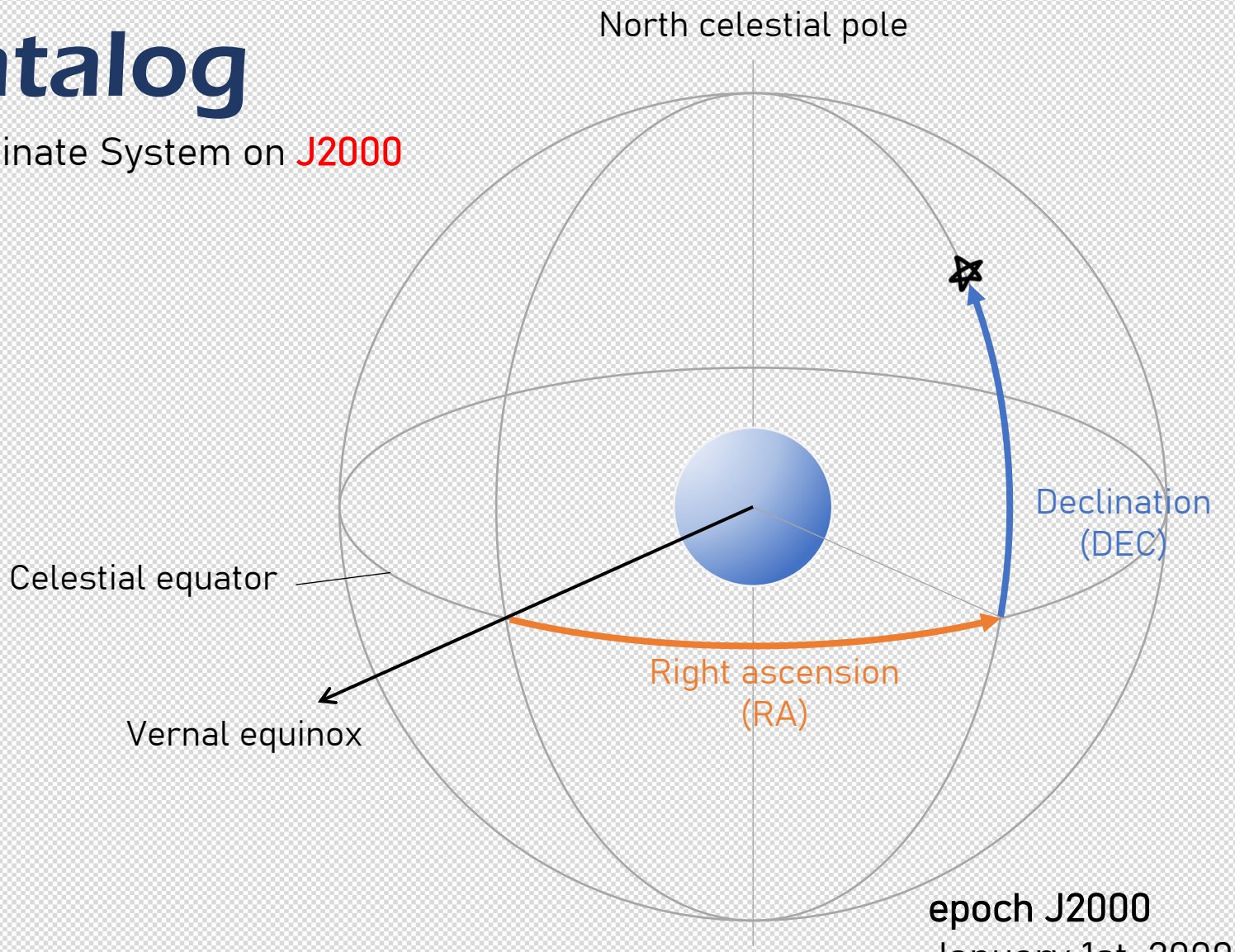
Interstar angles

Star tracker



Star catalog

Celestial Coordinate System on J2000



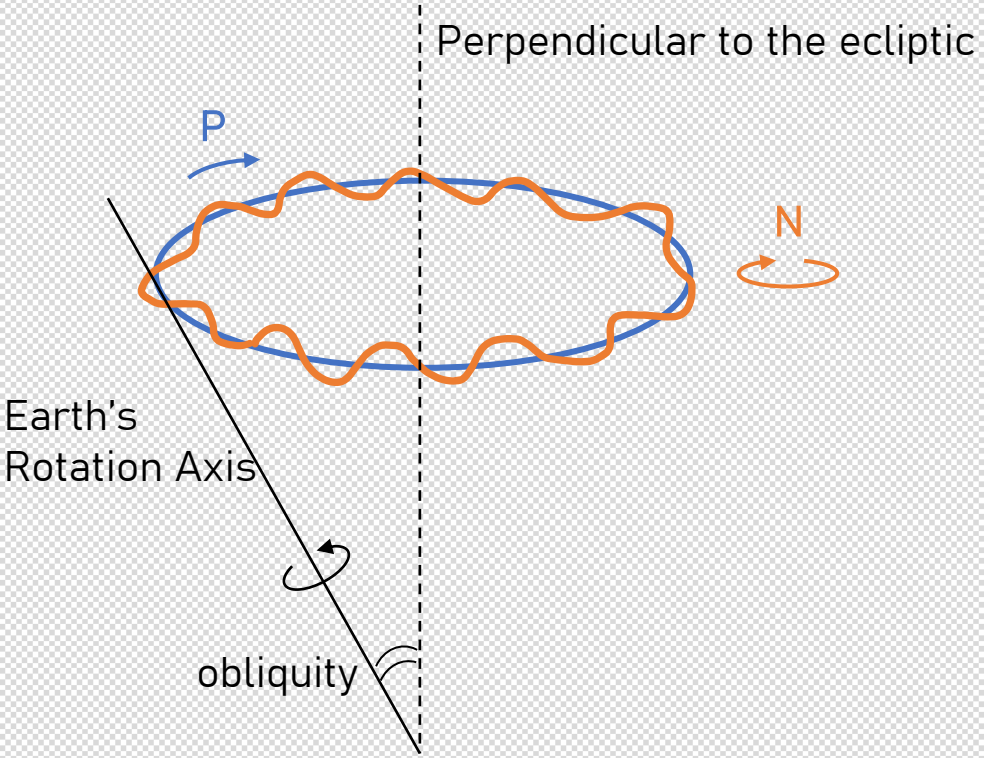
epoch J2000

January 1st, 2000, 12:00 Terrestrial Time

Star catalog

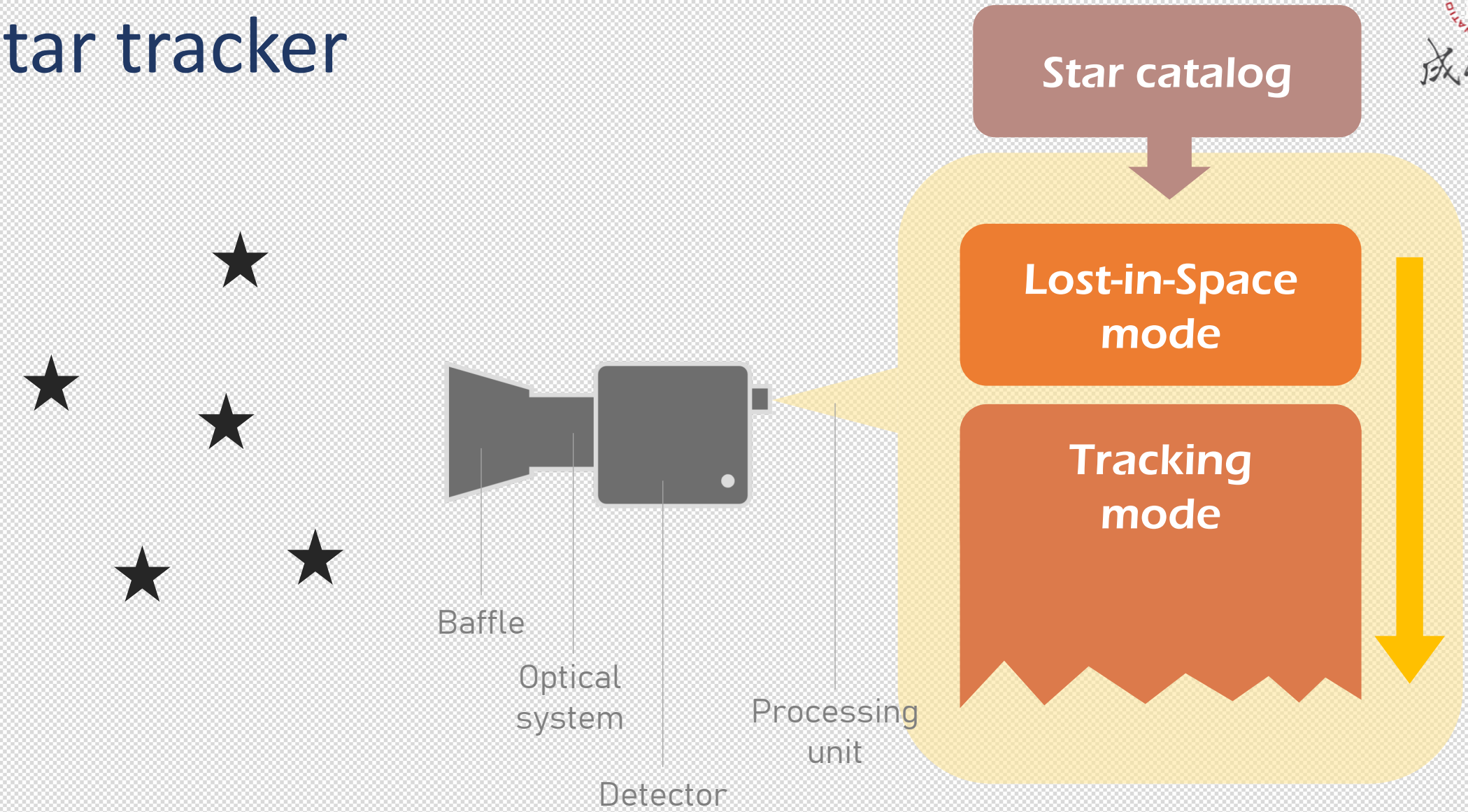
Celestial Coordinate System at a certain time

- Proper motion
- Precession
- Nutation
- Annual aberration



- SKY2000 Master Catalog
  (http://tdc-www.harvard.edu/catalogs/sky2k.html)
  - RA, DEC, and proper motion

Star tracker



Lost-in-Space mode

Centroid Extraction → Star Identification → Attitude Estimation

Lost-in-Space mode

Centroid Extraction

- *Global threshold*
- *Removing small regions*
- *Centroiding*

$$I'(u,v) = \begin{cases} I_0(u,v) - T, & I_0(u,v) \geq T \\ 0, & I_0(u,v) < T \end{cases}$$

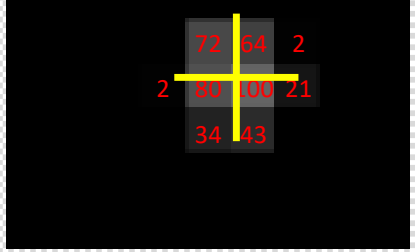
$$T = global\ threshold = \mu + 5\sigma$$

44	15	47	45	37	40	23	40	34
45	130	34	47	38	37	40	67	23
49	43	36	41	50	47	46	64	55
35	46	43	59	92	86	94	32	45
44	27	48	77	162	154	92	49	36
28	54	56	92	170	190	111	67	63
47	37	49	74	124	133	86	35	68
63	38	44	62	76	72	41	46	34
47	26	31	38	61	57	30	36	31

$$I(u,v) = \begin{cases} I'(u,v), & \sum\limits_{\substack{u'=u\pm w \\ v'=v\pm w}} 1\{I'(u',v') \neq 0\} \geq (w+1)^2 \\ 0, & \sum\limits_{\substack{u'=u\pm w \\ v'=v\pm w}} 1\{I'(u',v') \neq 0\} < (w+1)^2 \end{cases}$$

0	0	0	0	0	0	0	0	0
0	40	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	2	0	4	0	0
0	0	0	0	72	64	2	0	0
0	0	0	2	80	100	21	0	0
0	0	0	0	34	43	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0

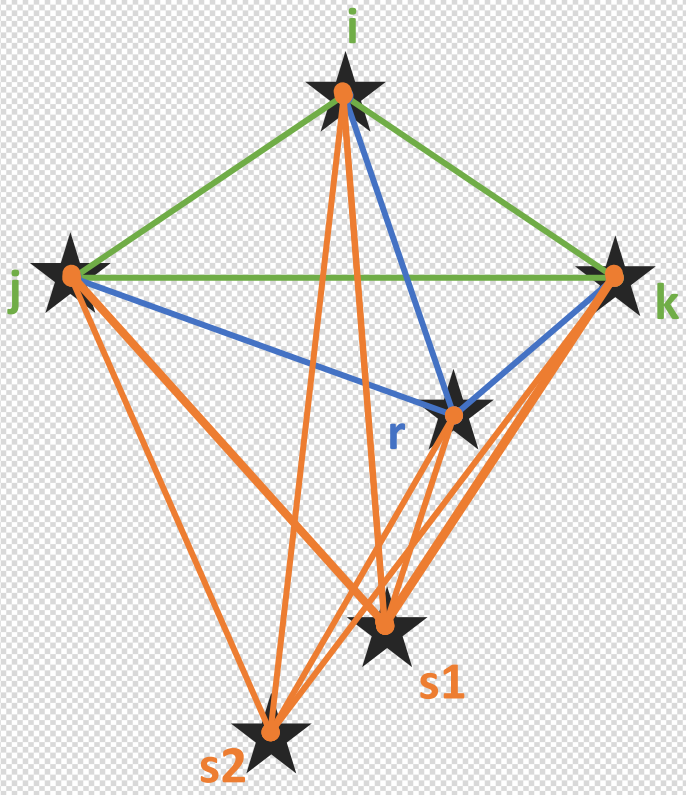
$$u_c = \frac{\sum_{u_{start}}^{u_{end}} \sum_{v_{start}}^{v_{end}} I(u,v)u}{\sum_{u_{start}}^{u_{end}} \sum_{v_{start}}^{v_{end}} I(u,v)}, v_c = \frac{\sum_{u_{start}}^{u_{end}} \sum_{v_{start}}^{v_{end}} I(u,v)v}{\sum_{u_{start}}^{u_{end}} \sum_{v_{start}}^{v_{end}} I(u,v)}$$



Lost-in-Space mode

Centroid Extraction → Star Identification → Attitude Estimation

Lost-in-Space mode



Star Identification

Pyramid Method

Identify a basic triangle

Confirm the basic triangle with 3 legs from the point to the basic triangle

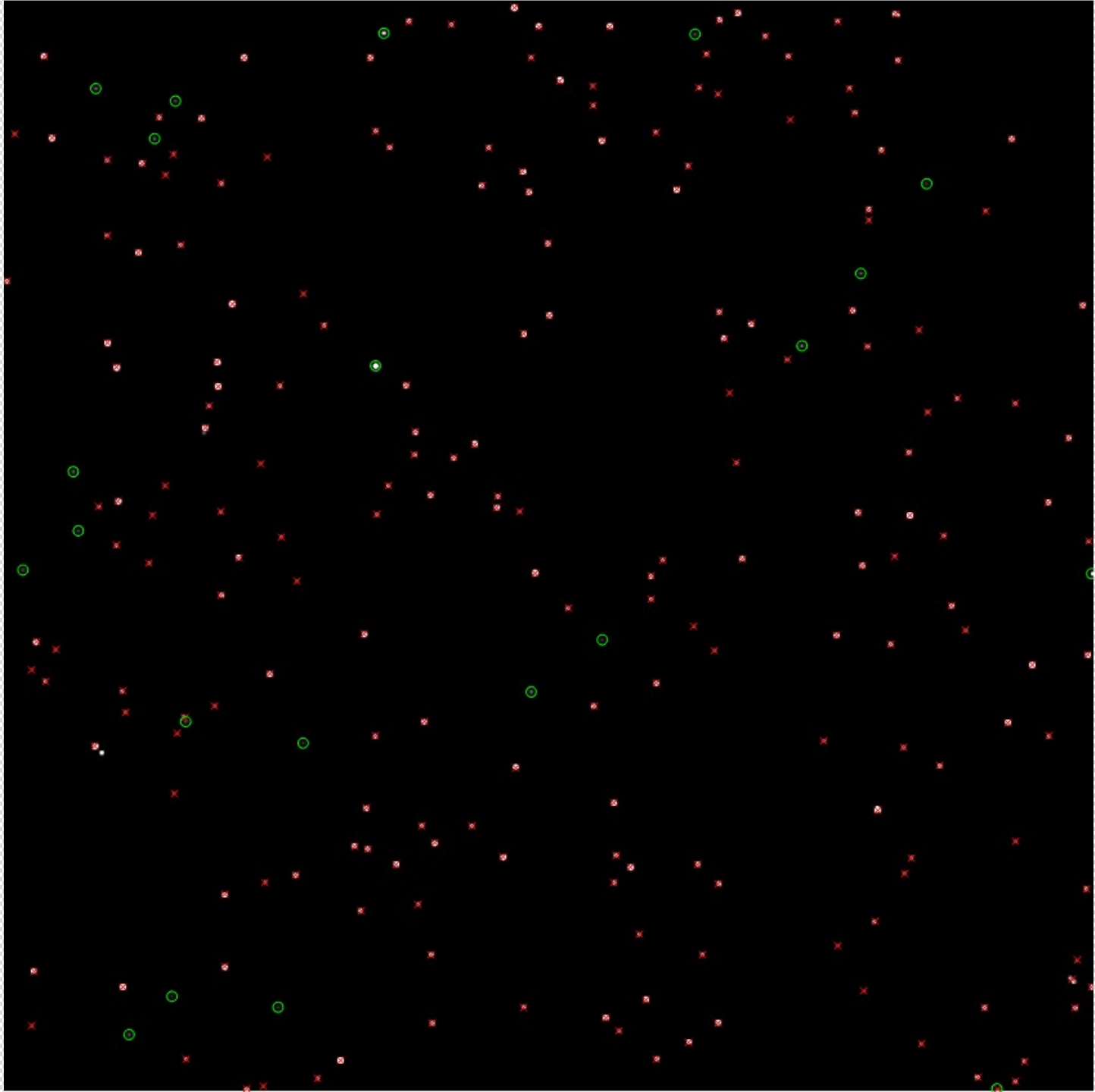
Identify remaining points with 4 legs from the point to the basic quadrilateral

High confidence with 6 interstar angles

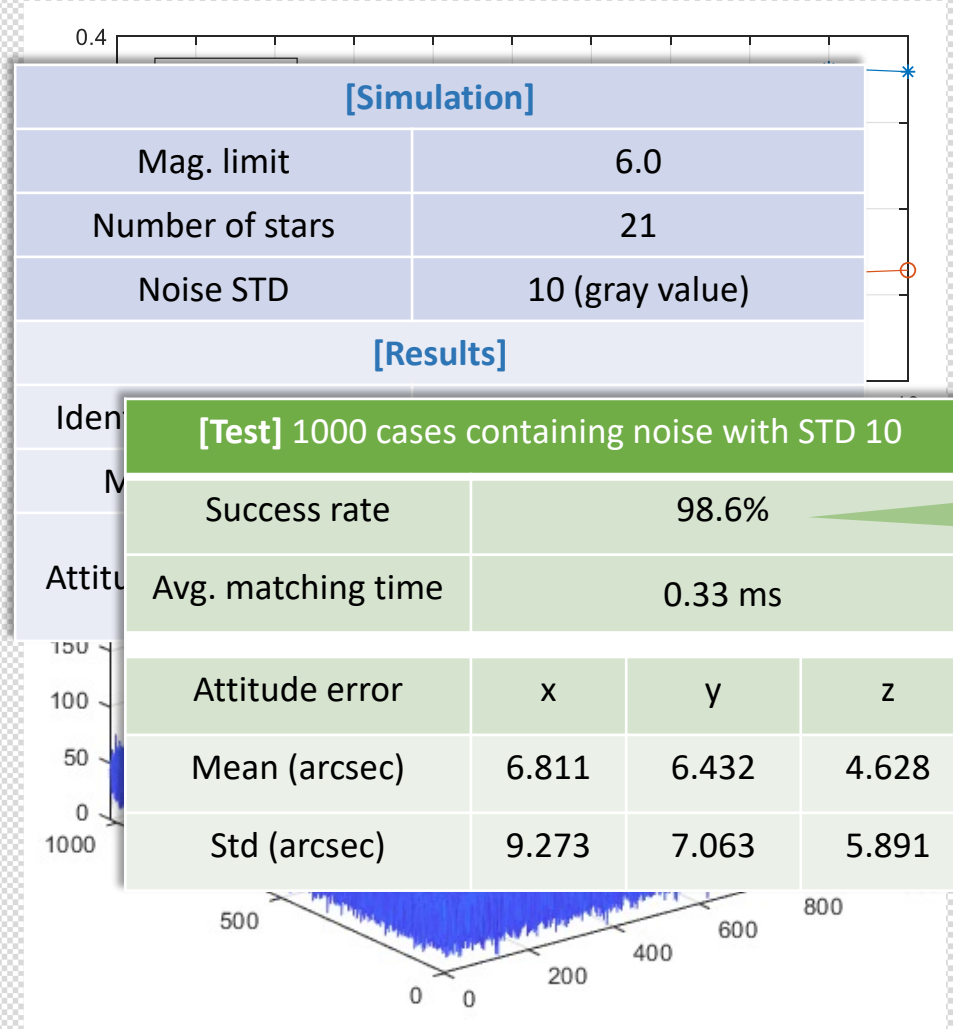
Lost-in-Space mode

[Simulation]	
Mag. limit	6.0
Number of stars / points	21 / 231
[Results]	

[Test] 1000 cases containing spikes which are 10 times as numerous as actual stars			
Success rate	100%		
Maximum matching time	1.97 sec (600 points)		
Attitude error	x	y	z
Mean (arcsec)	0.456	0.448	0.367
Std (arcsec)	1.277	0.875	0.823



Lost-in-Space mode

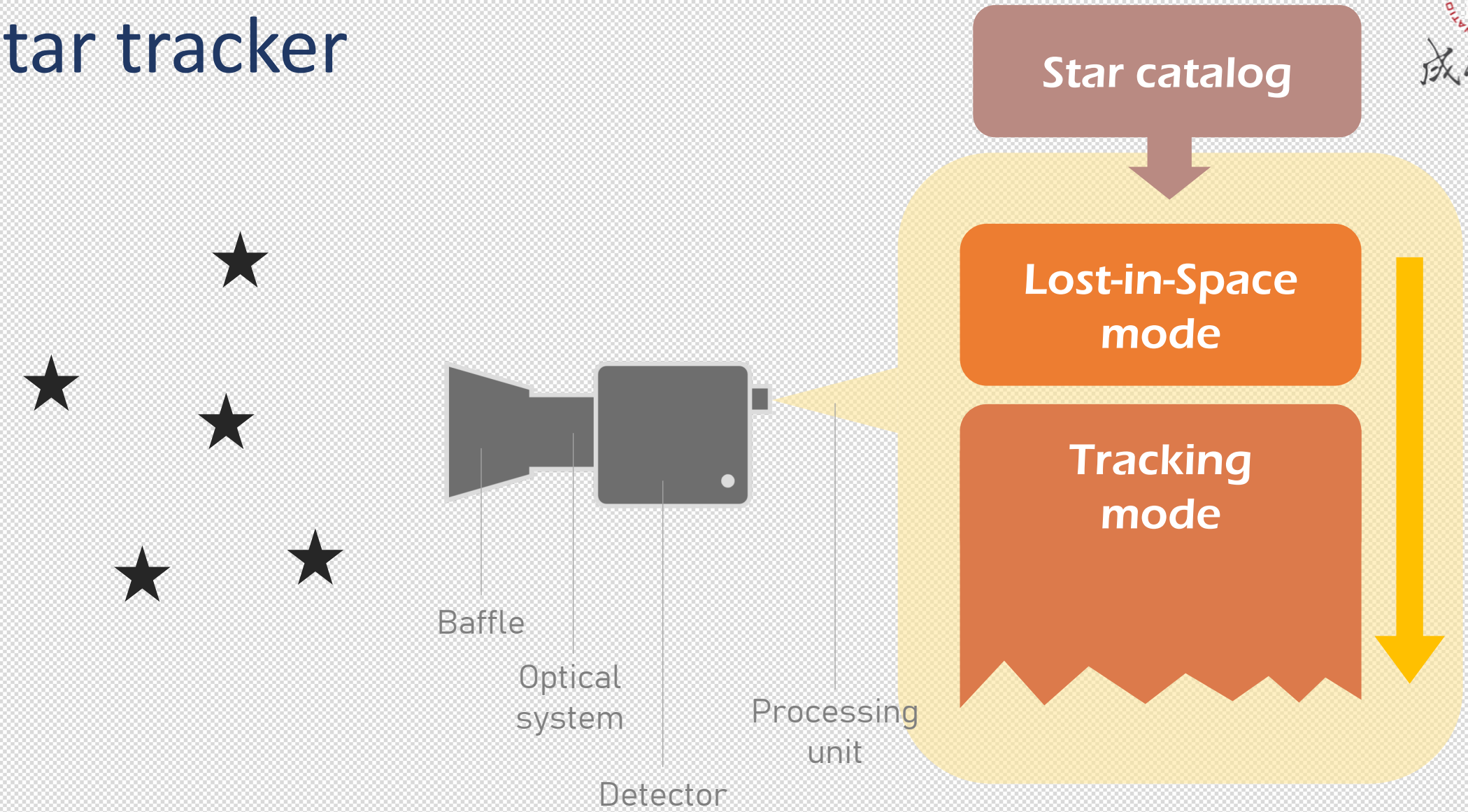


[Simulation]	
Mag. limit	6.0
Number of stars	21
Noise STD	10 (gray value)
[Results]	
Iden	
M	
Attitu	

[Test] 1000 cases containing noise with STD 10			
Success rate	98.6%		
Avg. matching time	0.33 ms		
Attitude error	x	y	z
Mean (arcsec)	6.811	6.432	4.628
Std (arcsec)	9.273	7.063	5.891

14 failed cases:
detected stars<7, identified stars<4

Star tracker



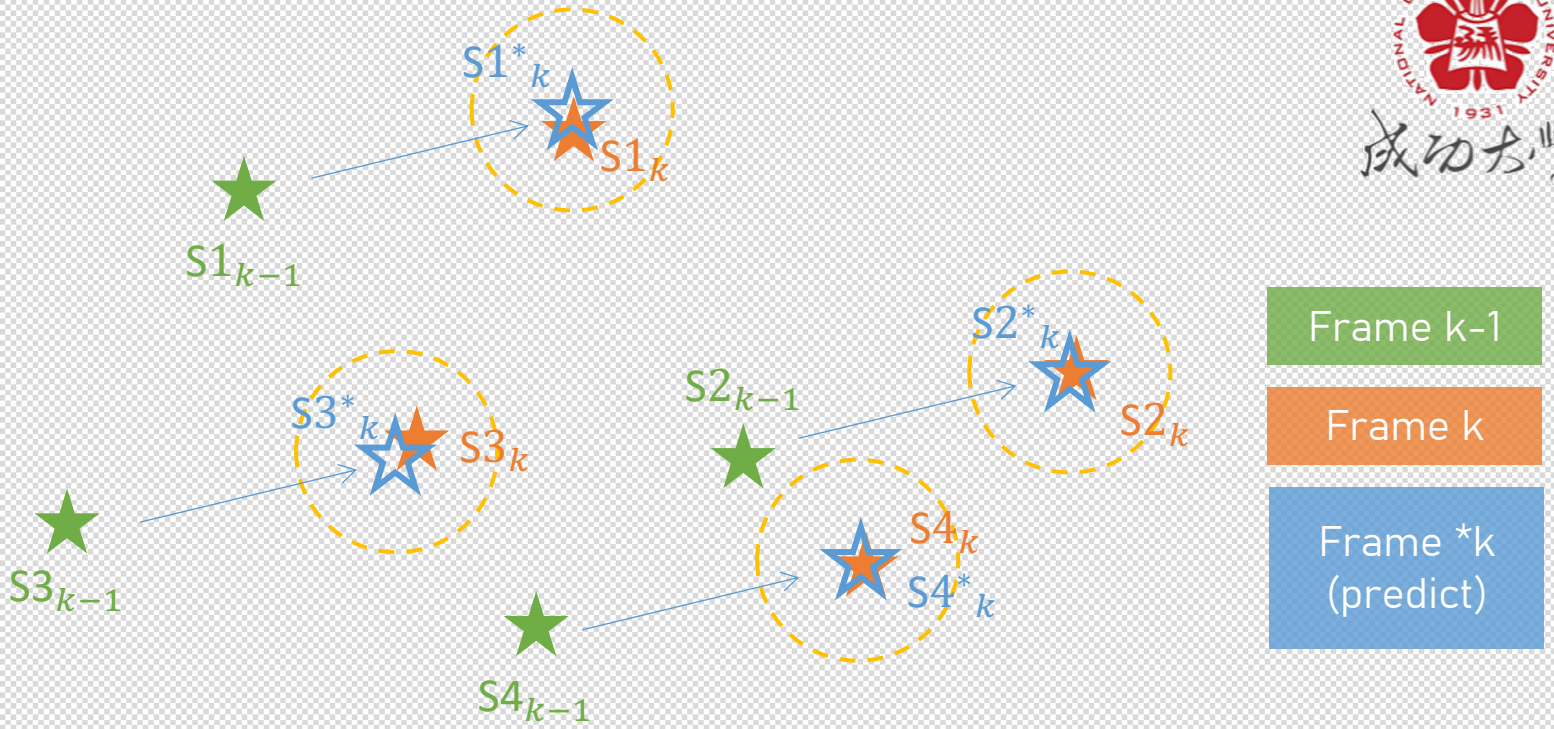
Tracking mode

Updating reference stars

Extended Kalman Filter

Local dynamic background template

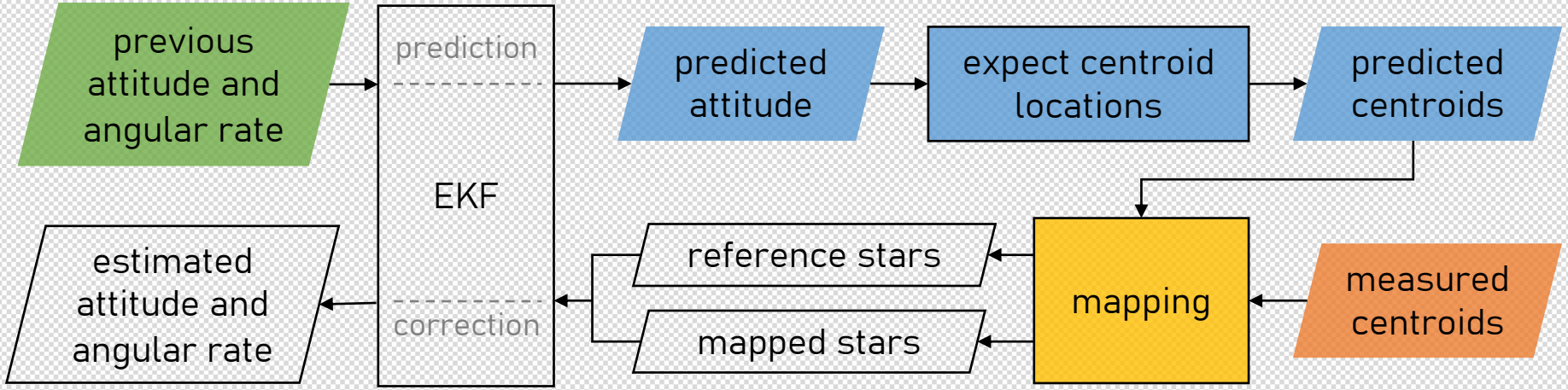
Tracking mode



Extended Kalman Filter

$$\boldsymbol{q}^*_k = \boldsymbol{Q}_{tran}\boldsymbol{q}_{k-1}$$
$$\boldsymbol{P}^*_k = \Phi_{k-1}\boldsymbol{P}_{k-1}\Phi_{k-1}{}^T + \boldsymbol{Q}_{k-1}$$

$$\boldsymbol{K}_k = \boldsymbol{P}^*_k\boldsymbol{H}_k{}^T(\boldsymbol{H}_k\boldsymbol{P}^*_k\boldsymbol{H}_k{}^T + \boldsymbol{R}_k)^{-1}$$
$$\boldsymbol{q}_k = \boldsymbol{q}^*_k + \boldsymbol{K}_k(\boldsymbol{z}_k - h(\boldsymbol{q}^*_k))$$
$$\boldsymbol{P}_k = (\boldsymbol{I} - \boldsymbol{K}_k\boldsymbol{H}_k)\boldsymbol{P}^*_k$$



Tracking mode

○: stars inside the FOV
△: mapped stars

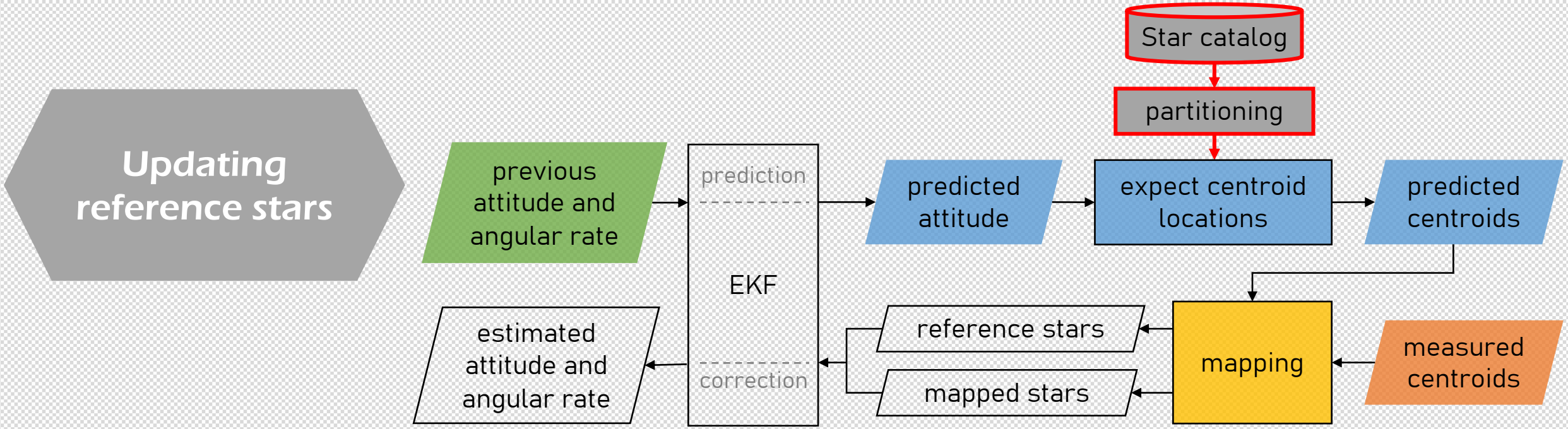
Tracking mode

Updating reference stars

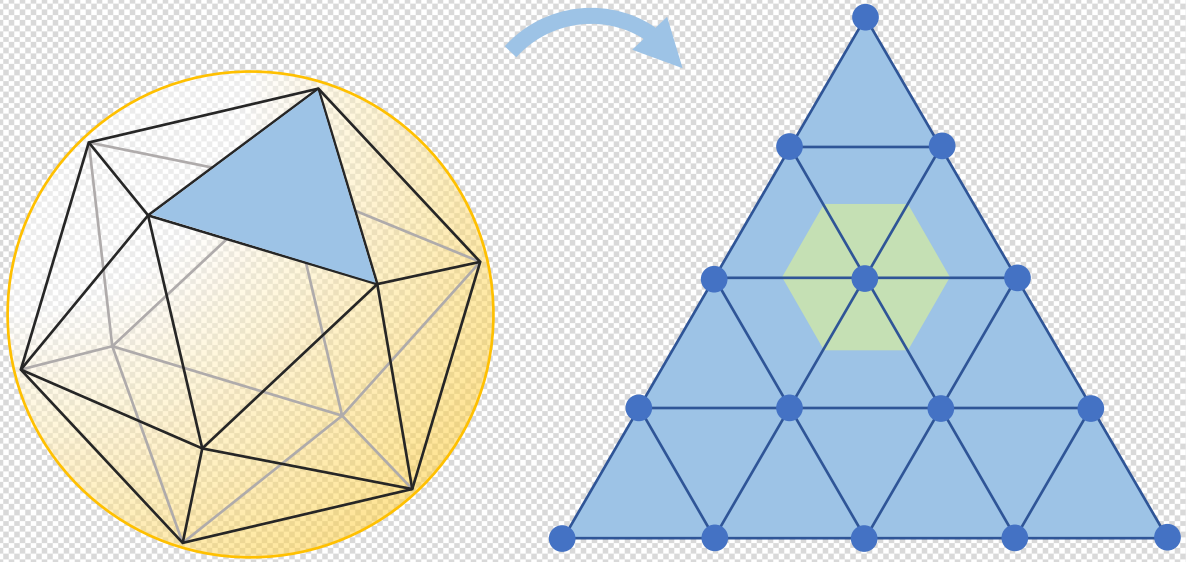
Extended Kalman Filter

Local dynamic background template

Tracking mode

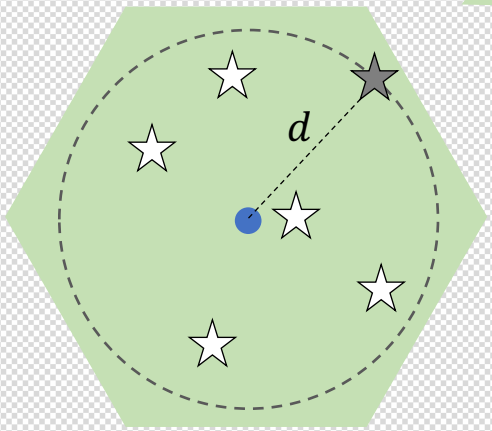


Tracking mode



Updating reference stars

Partitioning

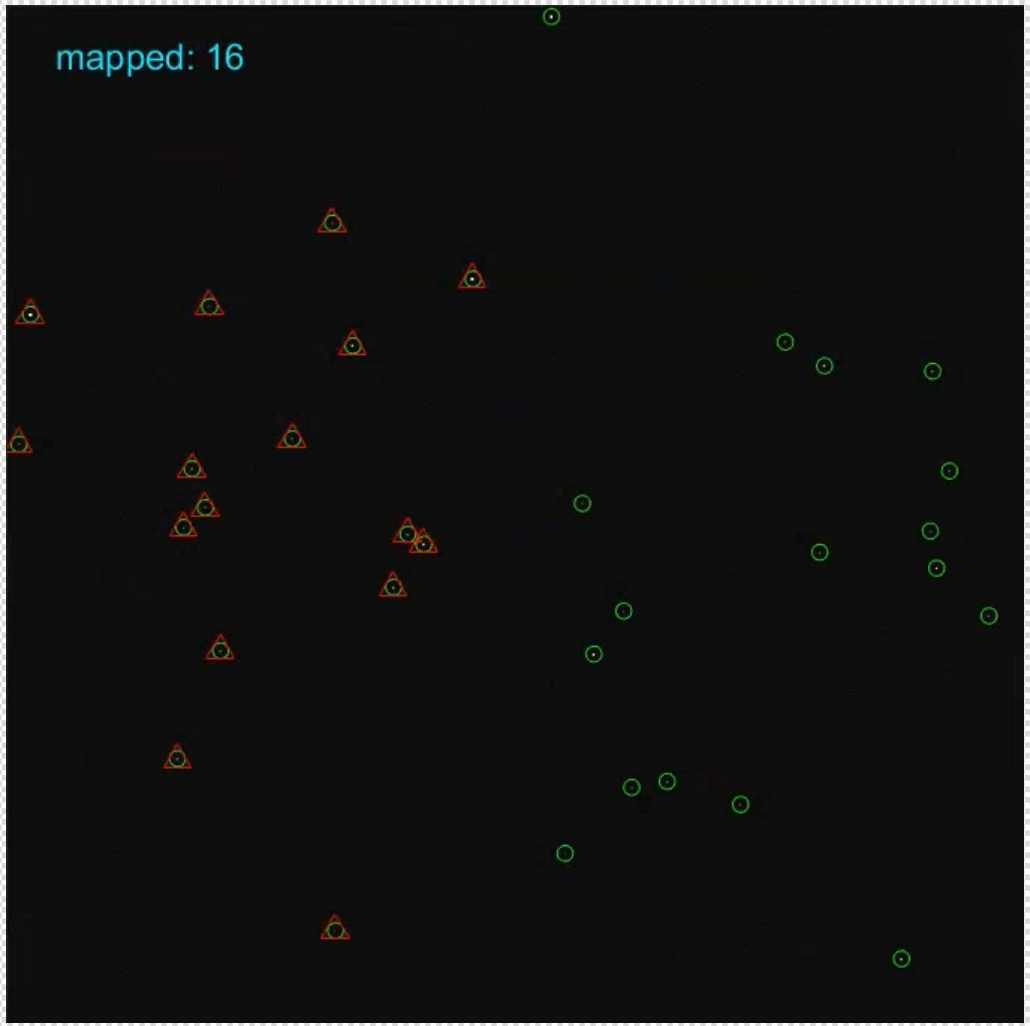


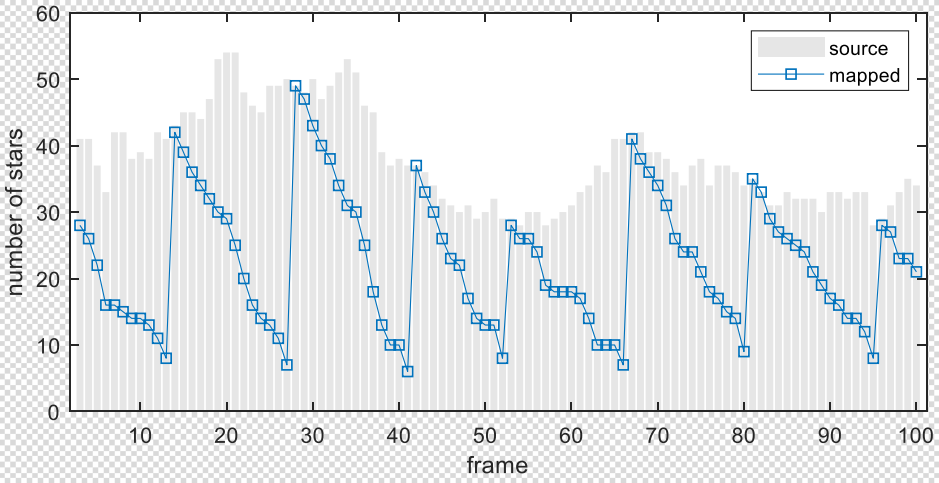
subcatalog

Partition Table:

each subcatalog
Center vector
Number of members
Member's indices
Max distance to center

Tracking mode





○: stars inside the FOV
△: mapped stars

Tracking mode

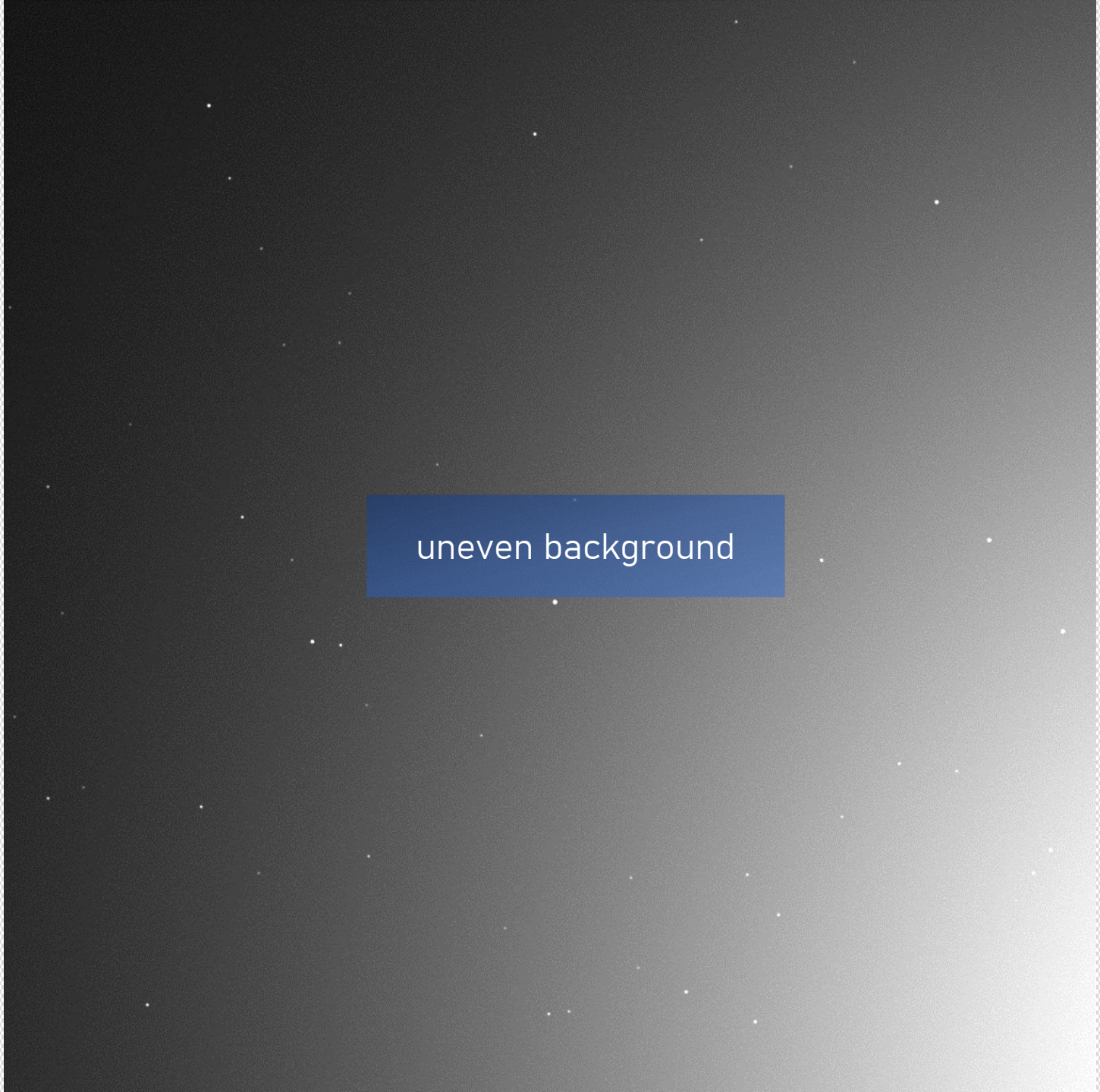
Updating reference stars

Extended Kalman Filter

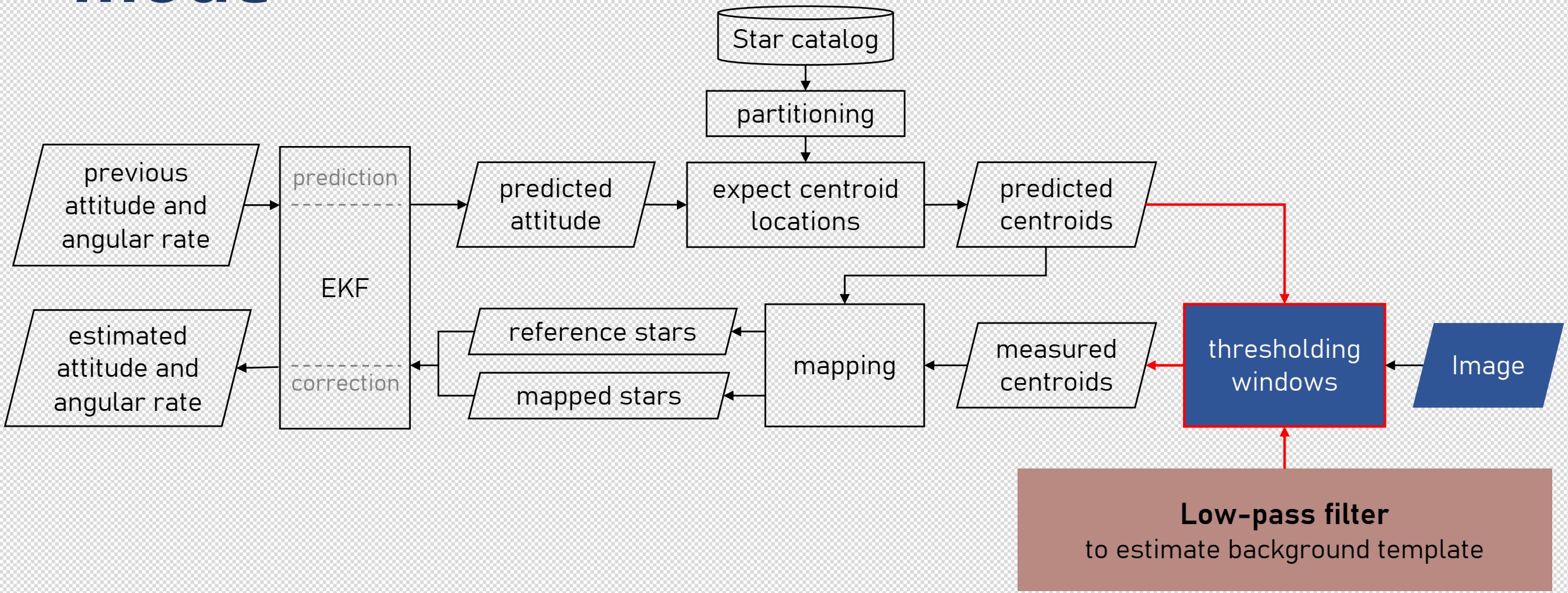
Local dynamic background template

Tracking mode

Local dynamic background template



Tracking mode



Tracking mode

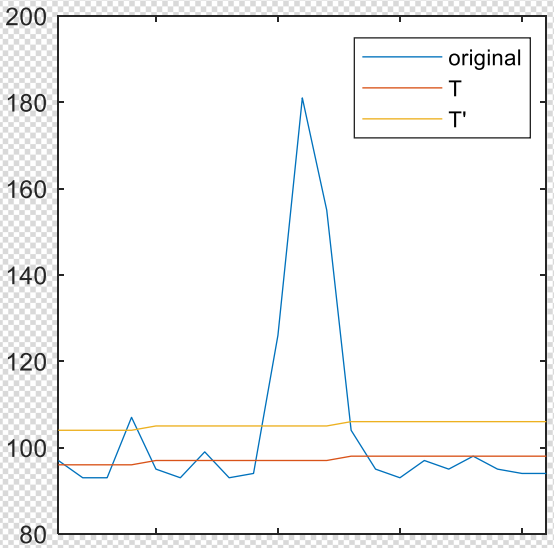
First filter

Background template by a low-pass filter

$$I'(u,v) = \begin{cases} I_0(u,v) - T, & I_0(u,v) \geq T' \\ 0, & I_0(u,v) < T' \end{cases}$$

$$T' = T + 4\sigma$$

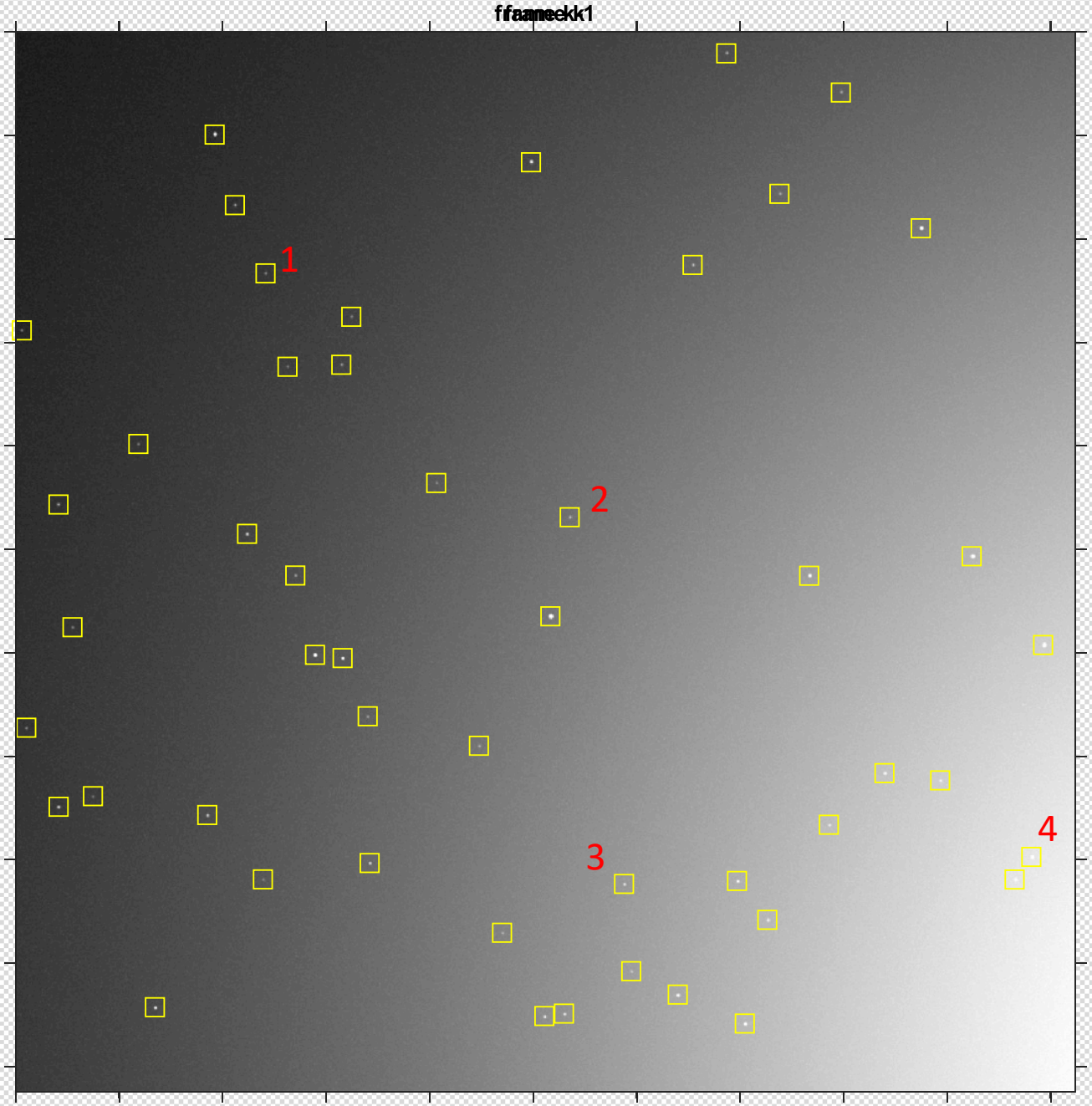
Threshold

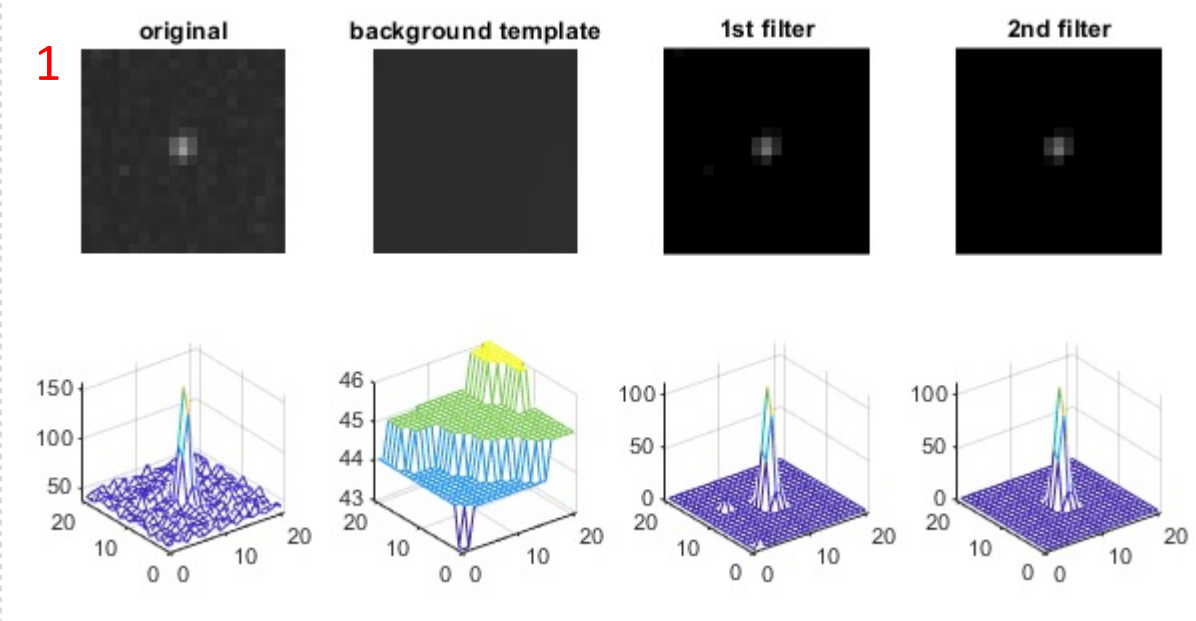


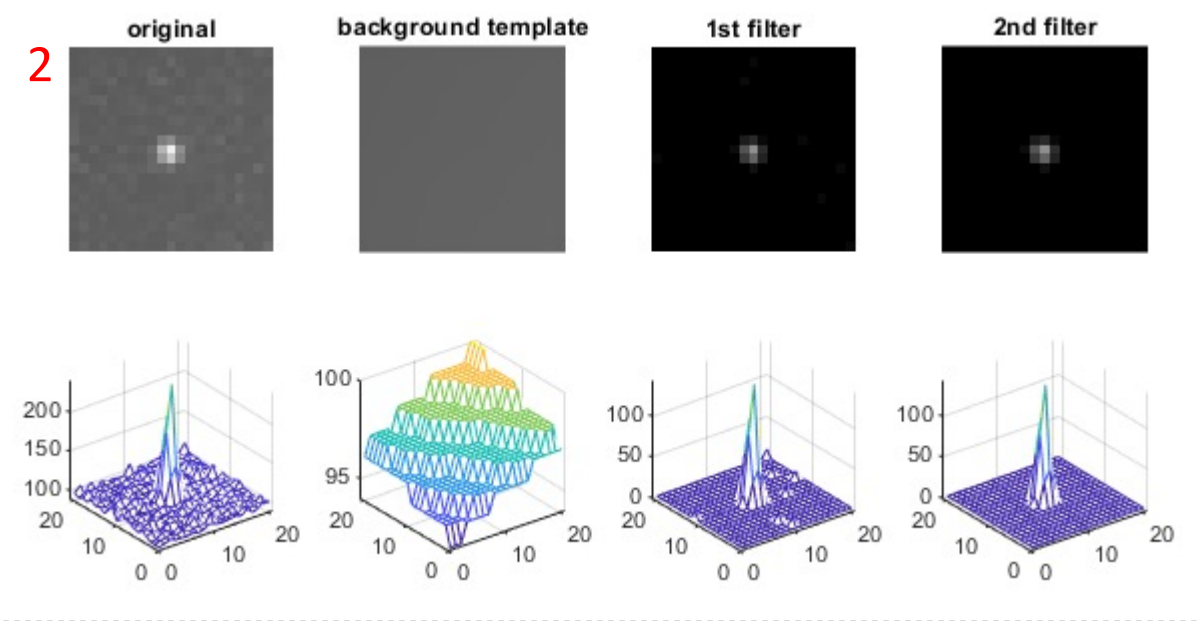
Second filter

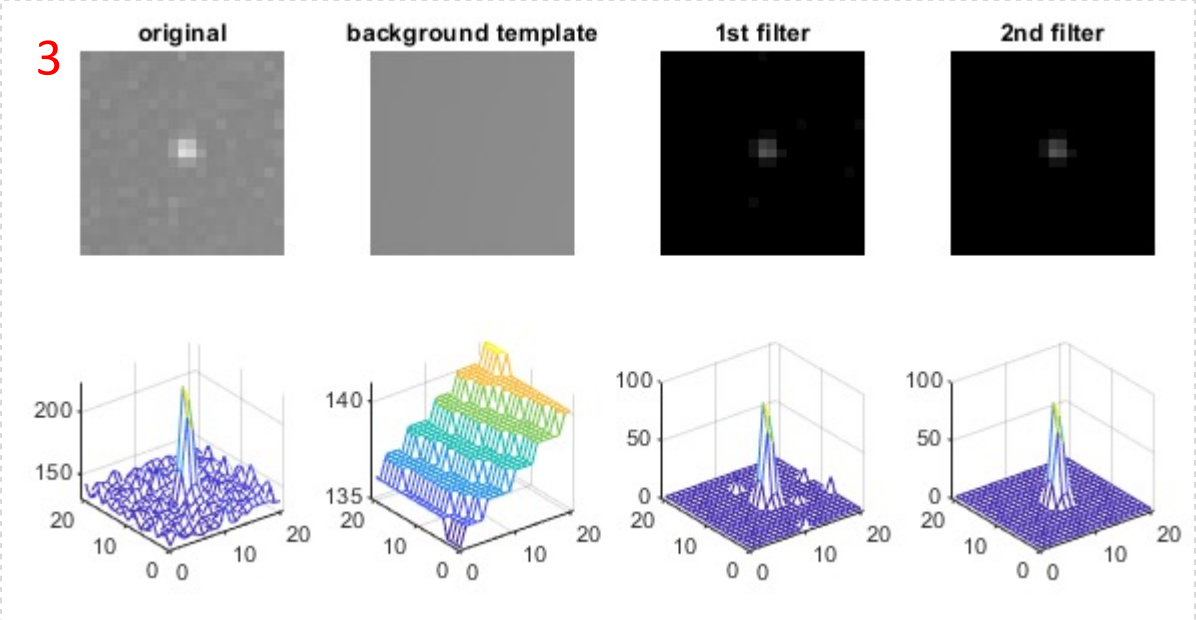
$$I(u,v) = \begin{cases} I'(u,v), & \sum_{\substack{u'=u\pm a \\ v'=v\pm a}} 1\{I'(u',v') \neq 0\} \geq (a+1)^2 \\ 0, & \sum_{\substack{u'=u\pm a \\ v'=v\pm a}} 1\{I'(u',v') \neq 0\} < (a+1)^2 \end{cases}$$

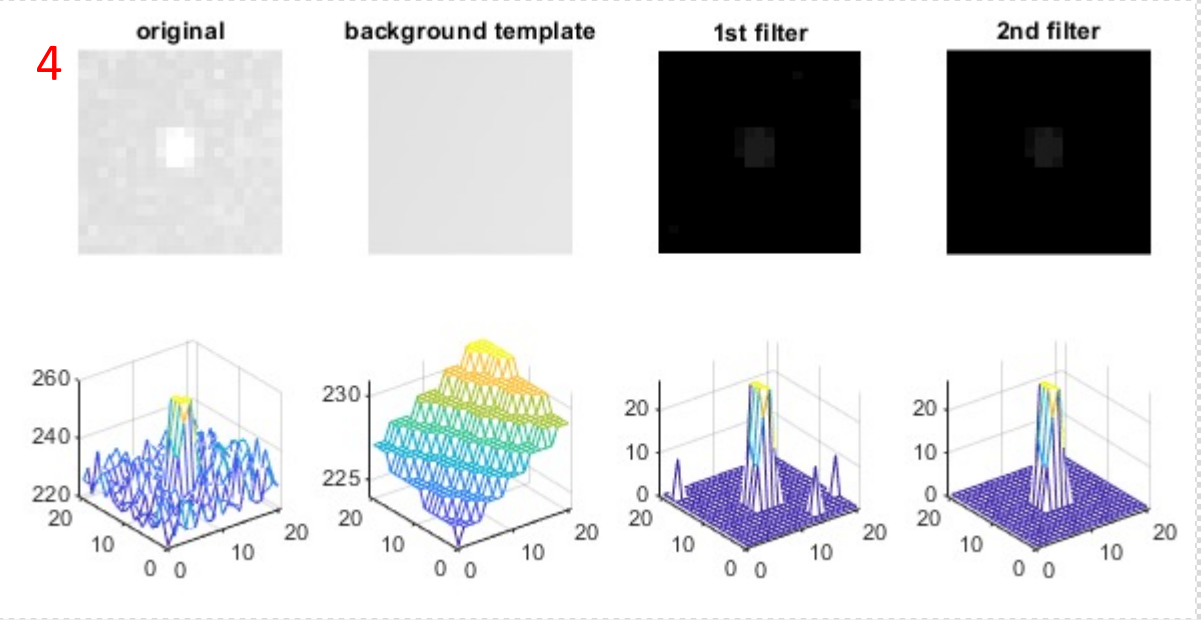
Tracking mode



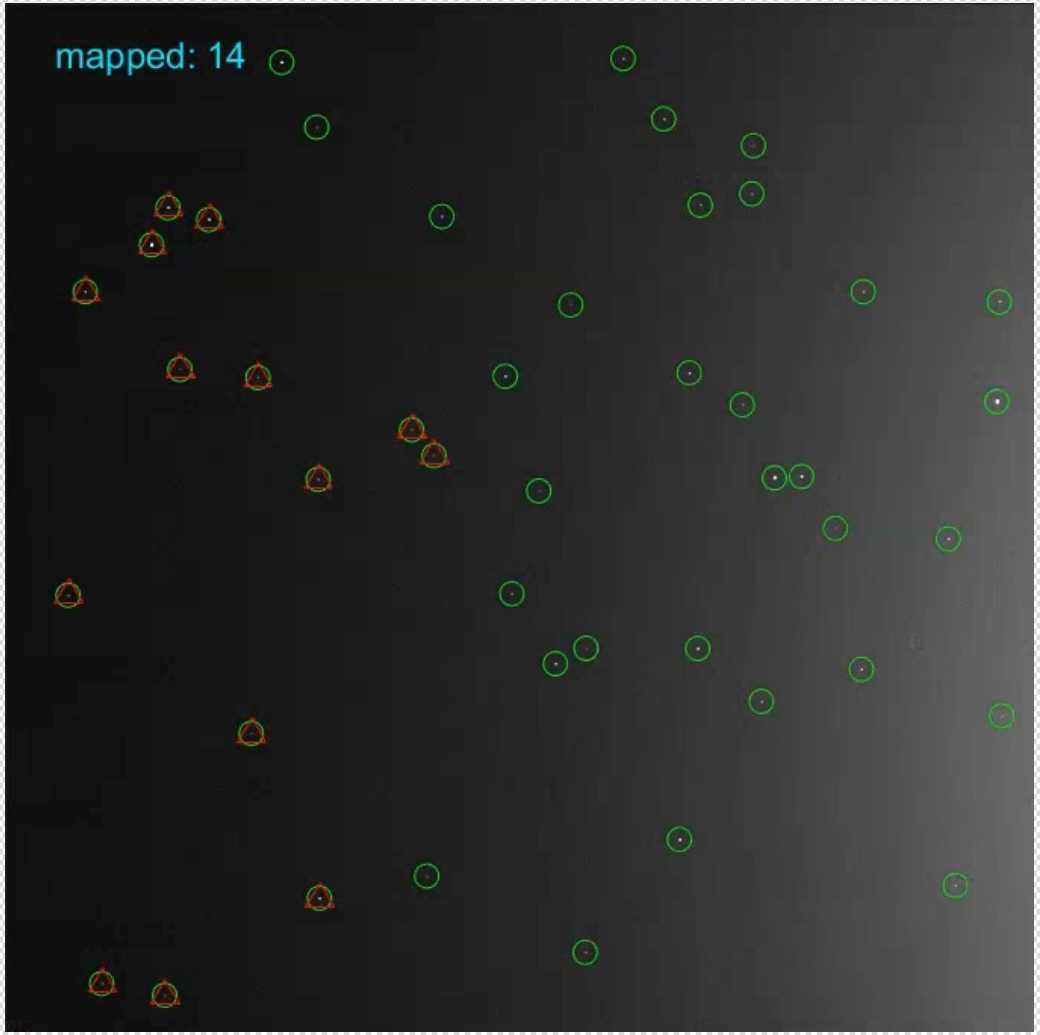

1
original
background template
1st filter
2nd filter


2
original
background template
1st filter
2nd filter

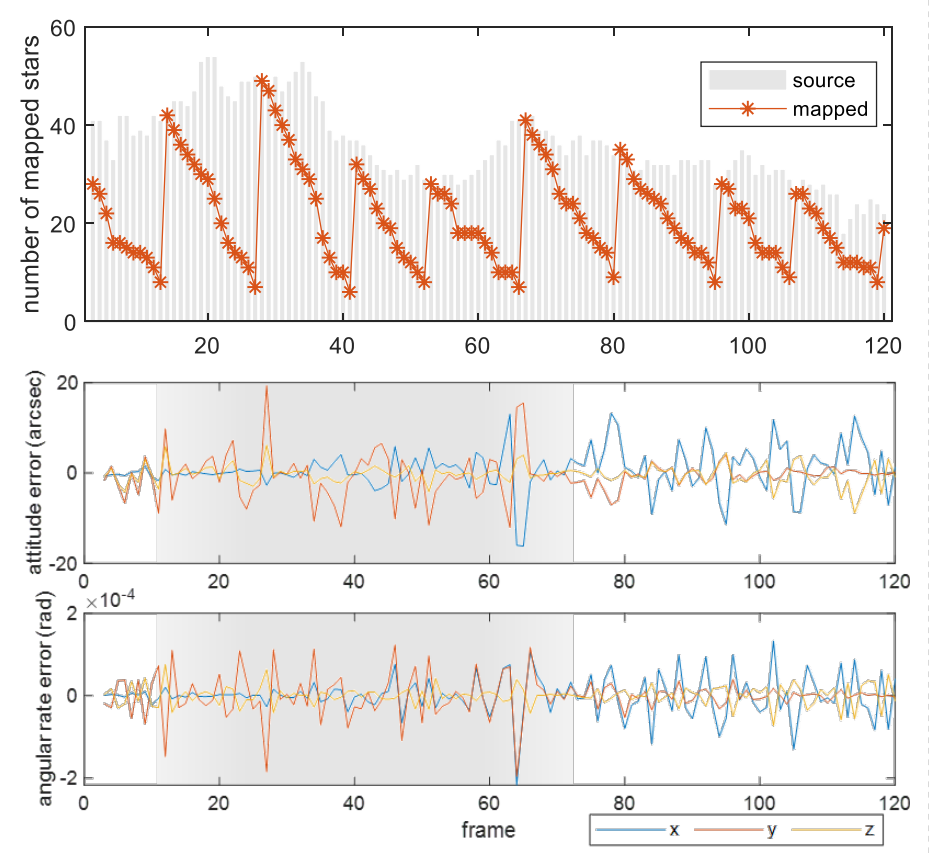

3
original
background template
1st filter
2nd filter


4
original
background template
1st filter
2nd filter

Tracking mode



○: stars inside the FOV
△: mapped stars



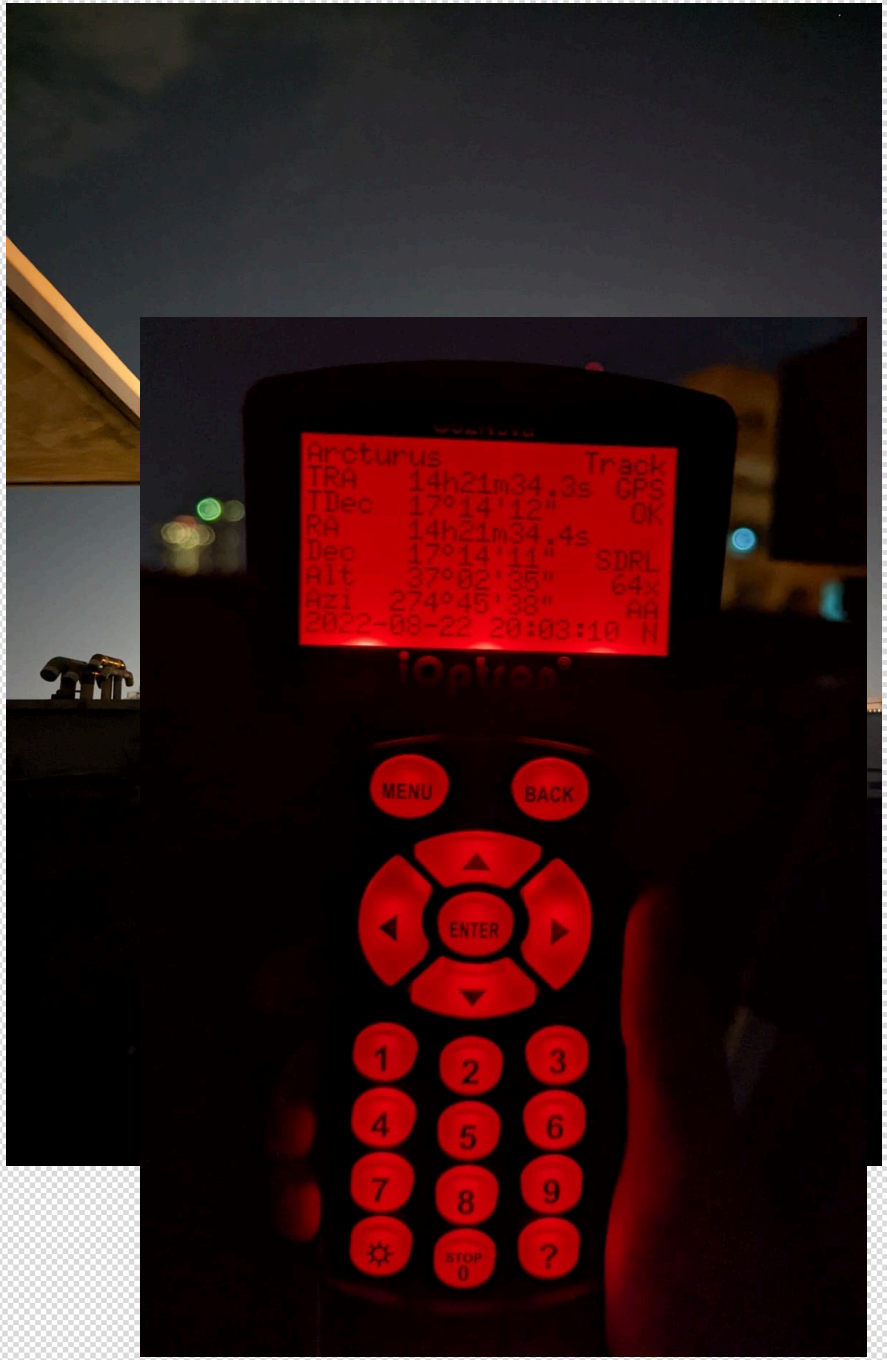
[Simulation]			
Noise STD	5 (gray value)		
Diagonal FOV (deg)	24.5		
Angular rate (rad/s)	[0.04, −0.03, −0.025]		
[Results]			
Attitude error	**x**	**y**	**z**
Mean (arcse)	3.18	3.01	1.54
Std (arcsec)	3.63	3.61	1.55

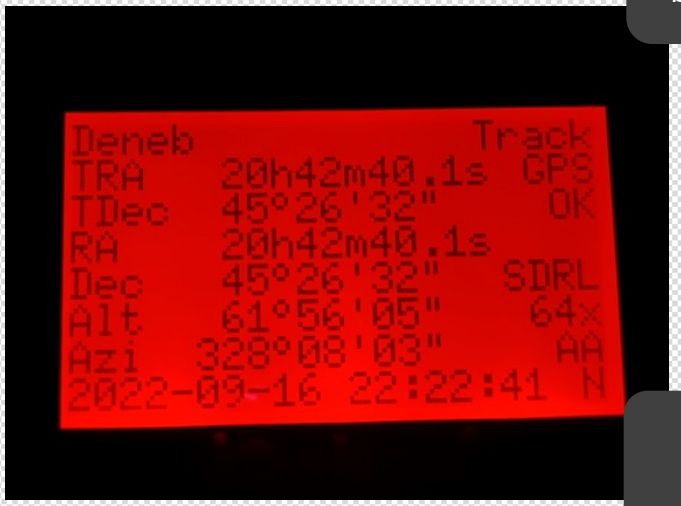
Night sky test

- Location: rooftop of NCKU DAA (urban area)
- Camera and Lens: Opto Engineering

Camera: COE-013-M-USB-030-IR-C		Lens: EN2MP1614	
Resolution (px)	1280 x 1024	Focal length (mm)	16.3363
Pixel size (μm)	4.8	Aperture	f/1.4 - f/22
Dimensions (mm)	29 x 29 x 30	Dimensions (mm)	37.9(L) x 34(ϕ)
FOV (deg)	21.3 x 17.1		
Mass (g)	56+76=132		

- Verification
  alt-azimuth mount: iOptron AZ Mount Pro

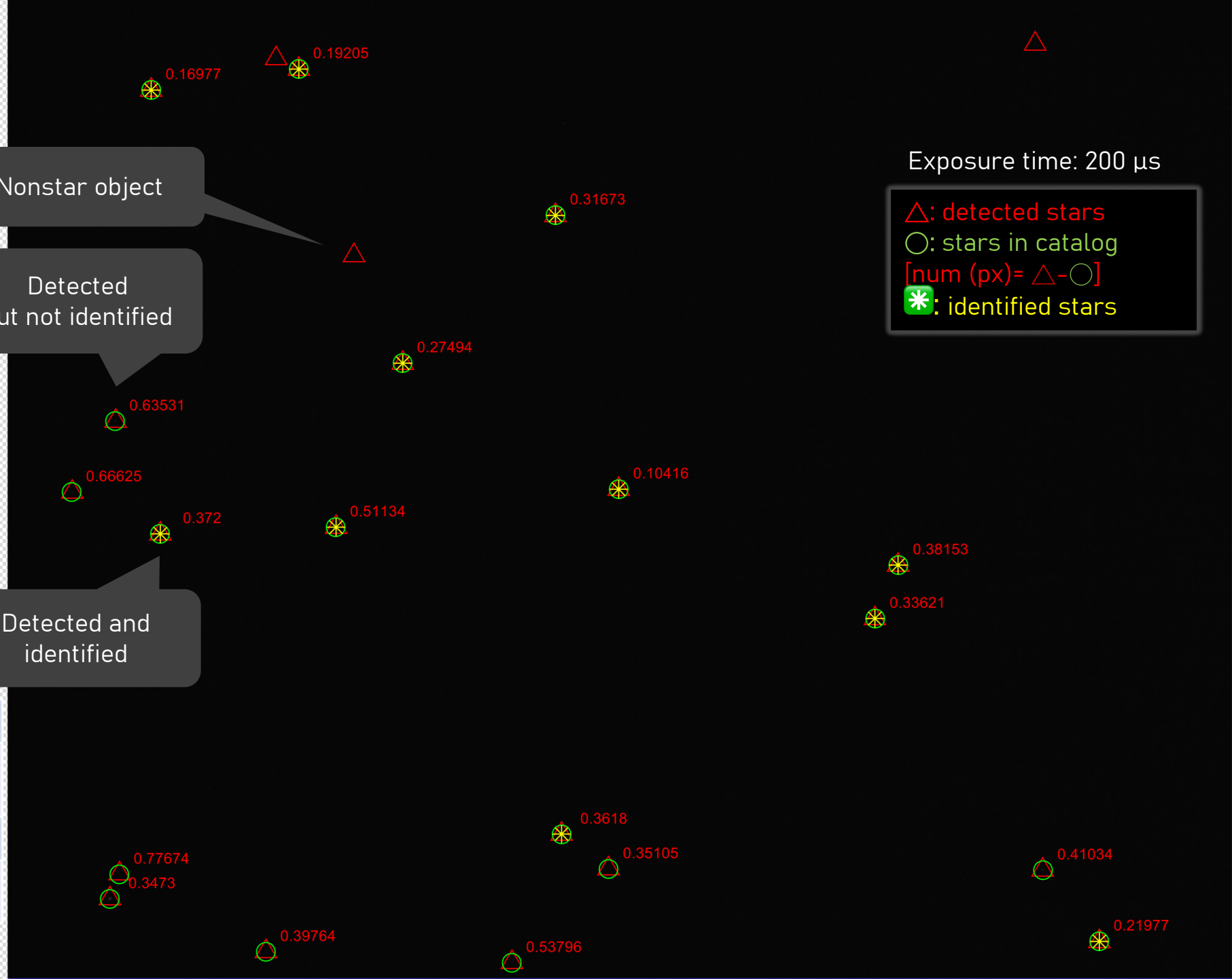




Nonstar object

Detected
but not identified

Detected and
identified



Exposure time: 200 μs

△: detected stars
○: stars in catalog
[num (px)= △-○]
✱: identified stars

[Results]			
Identified / Detected	11 / 22		
Attitude error (arcminute)	x	y	z
	8.50	4.43	4.68

Probable sources of error

- Camera calibration precision
- Camera mounting precision
- Alt-azimuth mount tracking precision
- Light pollution, cloud cover

Conclusions

- The software algorithm of a star tracker with high robustness to non-star objects, noise and stray light, was developed.
- It achieved attitude estimation at arcsecond-level accuracy in the test with simulated star-field images.
- It reached arcminute-level accuracy with real night-sky photos.
- The precise camera calibration and the hardware designing are the works in the next stage to improve the accuracy and the capability.

Reference

- [1] J. Meeus, "Astronomical algorithms," *Richmond,* 1991.
- [2] J. R. Myers, C. B. Sande, A. C. Miller, W. H. Warren, Jr., and D. A. Tracewell, "VizieR Online Data Catalog: SKY2000 Catalog, Version 4 (Myers+ 2002)," *VizieR Online Data Catalog,* p. V/109, September 01, 2001.
- [3] D. Mortari, M. A. Samaan, C. Bruccoleri, and J. L. Junkins, "The pyramid star identification technique," *Navigation,* vol. 51, no. 3, pp. 171-183, 2004.
- [4] R. C. Gonzalez, *Digital image processing*. Pearson education india, 2009.
- [5] C. R. McBryde and E. G. Lightsey, "A star tracker design for CubeSats," in *2012 IEEE Aerospace Conference*, 2012: IEEE, pp. 1-14.
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- [7] J. Li, X. Wei, and G. Zhang, "An extended Kalman filter-based attitude tracking algorithm for star sensors," *Sensors,* vol. 17, no. 8, p. 1921, 2017.
- [8] Y. He, H. Wang, L. Feng, and S. You, "A novel method of eliminating stray light interference for star sensor," *IEEE Sensors Journal,* vol. 20, no. 15, pp. 8586-8596, 2020.

Thank you for listening.