Blink and you miss it: Real-time synthetic tracking for near-Earth object surveys

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Finding Solar System Objects

- Minor planet discovery still significant
- Smaller Near Earth Objects (NEOs) discovered only during close flybys
- Faint and fast asteroids (most NEAs) impossible to detect with blink even on the largest telescopes
- Recovery doable, through *track-and-stack* (T&S).
- Synthetic Tracking extends T&S to the detection of unknown Solar System Objects

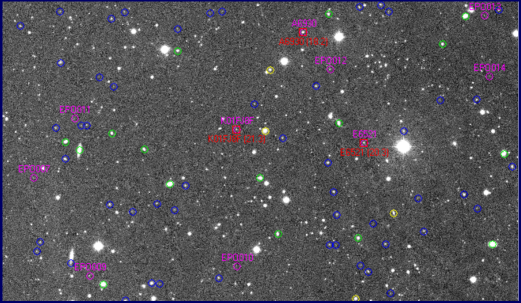


Figure: A 290 *arcmin*^{2} INT-WFC field from Feb 28, 2012, after applying blink method. Out of ten detected asteroids (pink highlight), only three were known at the time (red highlight).

Who are we?

- **Data-parallel detection of Solar System objects and space debris** – ParaSOL
- Part of EURONEAR network, origins in professional – amateur collaboration
- Umbrella software suite (Stănescu and Văduvescu 2021) – blink detection.
- Financed by Romanian National Authority for Scientific Research and Innovation, CNCS – UEFISCDI
- Aim is to "complete" the suite: **STU** (Synthetic Tracking on Umbrella), **IPP** (Image pre-Processing Pipeline), and **Webrella**, the web interface

Synthetic Tracking before us

- The synthetic Tracking Algorithm (e.g. Gladman et al. 1997) improves the signal to noise ratio by stacking across all possible apparent motion vectors
- Trades off smaller telescopes for longer integration times and computational power
- Used to be slow, but modern computers are faster, with major gains in "accelerator" hardware (GPUs)

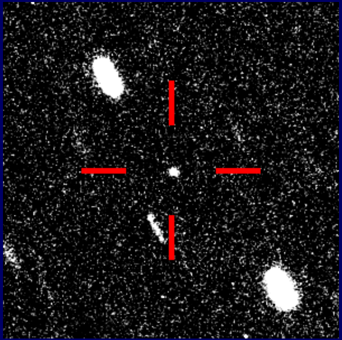
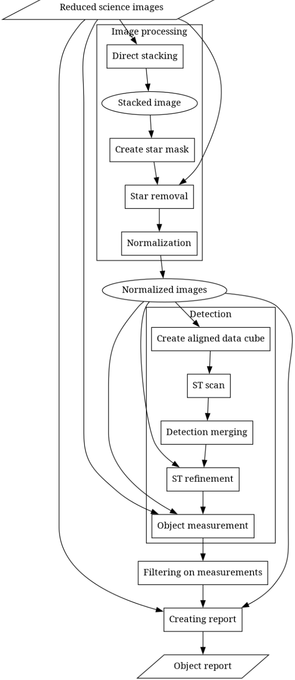


Figure: **1999 TH94**, observed with INT under bright time, integration time 12 × 30 s. At magnitude 21, it is at the blink limit. Detection obtained using our STU.

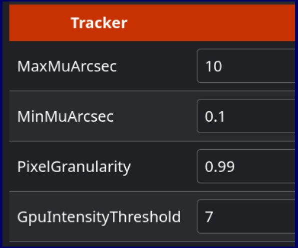
Synthetic Tracking with our STU

- Hypothesis rejection design (very cheap initial scan, increasingly powerful filters following)
  - Level inputs & remove fixed sources
  - Fast shift-and-(add & median)
  - Combine & refine motion vectors
  - Measure detections
- Efficient implementation on graphics processing unit (GPU)
- Written in .NET Framework + OpenCL → highly portable
- Tested on Linux and Windows with AMD and nVidia GPUs, as well as CPUs (but much slower)



Runtime in practice

- **Real-time** synthetic tracking even with **no binning**, at **full granularity**
- Much faster than data acquisition even on large cameras and modest PCs
- Our typical runs, with an AMD Radeon RX 6800 XT:
  - WFC on 2.54 m INT telescope: $4 \times 9\,\mathrm{Mpx}$, $0.33''\,\mathrm{px}^{-1}$, $12 \times 1\,\mathrm{min}$ cadence, $10''\,\mathrm{min}^{-1}$ search cone. **Runtime** $26\,\mathrm{s}$ **per CCD, with** $2\,\mathrm{s}$ **for actual ST scan,** $\ll 12\,\mathrm{min}$ **acquisition time**
  - 0.8 m T80S telescope: $1 \times 80\,\mathrm{Mpx}$, $0.55''\,\mathrm{px}^{-1}$, $20\times \sim 1.5\,\mathrm{min}$ cadence, $15''\,\mathrm{min}^{-1}$ search cone. **Runtime:** $5.5\,\mathrm{min}$ **per CCD, with** $23\,\mathrm{s}$ **for actual ST scan,** $\ll 30\,\mathrm{min}$ **acquisition time**



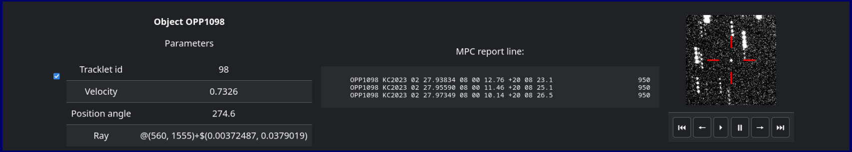
Tracker	
MaxMuArcsec	10
MinMuArcsec	0.1
PixelGranularity	0.99
GpuIntensityThreshold	7

Figure: **STU brute force parameters**: max & min proper motion ($\mathrm{px\,min}^{-1}$), granularity (in px), detection threshold in σ on median stack

Now with granularity

- We define granularity in pixels – how many we skip on the farthest image
- Same T80S dataset, still RX 6800 XT:
  - Near Earth Objects scan: $5\,''\,\mathrm{min}^{-1}$ search cone, 5 px granularity: 0.13 s
  - Main Belt Asteroids & slow NEOs: $1\,''\,\mathrm{min}^{-1}$ search cone, 2 px granularity: 52 ms
- Practically instant for slow-moving objects
- Now image processing needs to be moved to GPU and optimized

Modern validation methods: Webrella



Object OPP1098

Parameters

☑		
	Tracklet id	98
	Velocity	0.7326
	Position angle	274.6
	Ray	@(560, 1555)+$(0.00372487, 0.0379019)

MPC report line:

```
     OPP1098 KC2023 02 27.93834 08 00 12.76 +20 08 23.1                      950
     OPP1098 KC2023 02 27.95590 08 00 11.46 +20 08 25.1                      950
     OPP1098 KC2023 02 27.97349 08 00 10.14 +20 08 26.5                      950
```

Figure: **Webrella validator interface**: entry for 2023 DZ2.

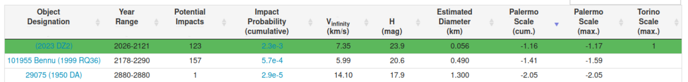
Web-based validation

- Expensive computation only on server
- Everyone can pitch in
- Link sharing

Not your everyday web page

- Hand-written, loads instantly
- Keyboard operation
- Information immediately available

Detection examples



Object Designation	Year Range	Potential Impacts	Impact Probability (cumulative)	$V_{infinity}$ (km/s)	H (mag)	Estimated Diameter (km)	Palermo Scale (cum.)	Palermo Scale (max.)	Torino Scale (max.)
(2023 DZ2)	2026-2121	123	2.3e-3	7.35	23.9	0.056	-1.16	-1.17	1
101955 Bennu (1999 RQ36)	2178-2290	157	5.7e-4	5.99	20.6	0.490	-1.41	-1.59	
29075 (1950 DA)	2880-2880	1	2.9e-5	14.10	17.9	1.300	-2.05	-2.05	

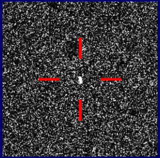


Figure: **2023 DW**, follow-up on 1st of March. Blind detection as reported by STU, from the observation archive. Detection stamp from trimmed mean of 4 images with stars masked, width 300px.

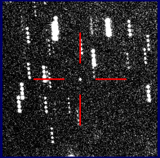


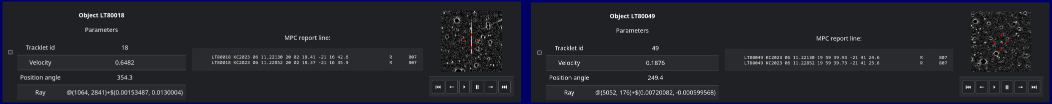
Figure: **2023 DZ2**, detected on 27th of February. Detection as reported by STU. Detection stamp from mean of 4 input images, width 500px.

- Discovery and physical characterization as the first response to a potential asteroid collision: The case of 2023 DZ_2 (Popescu et al. 2023 A&A, accepted)

Conclusions: Achievements

- Real-time synthetic tracking for the masses (cheap and fast)
- Tested using observations from various telescopes: 0.25 m T025-BD4SB, 0.6 m SARA, 0.80 m T80S, 1.5 m Telescopio Carlos Sánchez and the 1.6 m KASI (Korea Astronomy and Space Science Institute), and the 2.54 m Isaac Newton Telescope.
- More than 10^5 images processed
- Challenges from noise and image defects (insufficient pre-processing): the current successful rate varies from 50 to 100 percent depending on the instrument.
- End-to-end pipeline available (sadly every telescope software likes to be different)
- In survey conditions, limited mostly by transfer speed and human factors

Next steps



☐ **Object LT80018**

Parameters

Tracklet id	18
Velocity	0.6482
Position angle	354.3
Ray	@(1064, 2841)+$(0.00153487, 0.0130004)

MPC report line:

```
LT80018 KC2023 06 11.22130 20 02 18.41 -21 16 42.6                R      807
LT80018 KC2023 06 11.22852 20 02 18.37 -21 16 35.9                R      807
```

☐ **Object LT80049**

Parameters

Tracklet id	49
Velocity	0.1876
Position angle	249.4
Ray	@(5052, 176)+$(0.00720082, -0.000599568)

MPC report line:

```
LT80049 KC2023 06 11.22130 19 59 39.93 -21 41 24.6                R      807
LT80049 KC2023 06 11.22852 19 59 39.73 -21 41 25.8                R      807
```

Figure: Badpixel (left) vs valid detection (right). More tuning required to disambiguate the two.

Current activities

- Increasing automation (Webrella)
- Tuning STU parameters
- Improving runtime
- Usability improvements

Planned activities

- Improving many-chip handling
- Computer clusters work dispatch
- Integrating 3rd-party tools
- Tests on space debris datasets

NEO detection, where to?

What would our fast Synthetic Tracking mean for the future of NEO discovery?

Short term

- ST will "eat the world"
- Shallow deployments widely used, especially in existing surveys
- Knowhow disseminated, differences in behavior known widely
- First dedicated survey proposals

Long term

- Efficient deep synthetic tracking
- All large-scale surveys will be ST
- Niche approaches: ballon-borne and small space telescopes, etc.
- Fast computational techniques will spread to improve image processing
- ST will open up SSBs to industry (think NHATS)