ParaSOL: data-parallel methods for fast and deep detection of asteroids on the Umbrella platform

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Who we are?

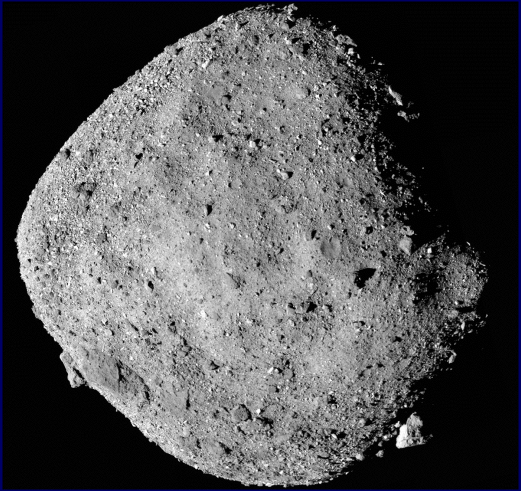
ParaSOL project (UEFISCDI funding) under EURONEAR

- Research network in NEA discovery
- Collaborators in many European countries (and Chile)
- Umbrella, a EURONEAR MOPS: Stănescu and Văduvescu 2021 [1]

- ParaSOL: UEFISCDI-funded project to complete the suite
- Started as a collaboration between professional and amateur astronomers
- STU (Synthetic Tracking on Umbrella)
- IPP (Image Processing Pipeline)
- Webrella

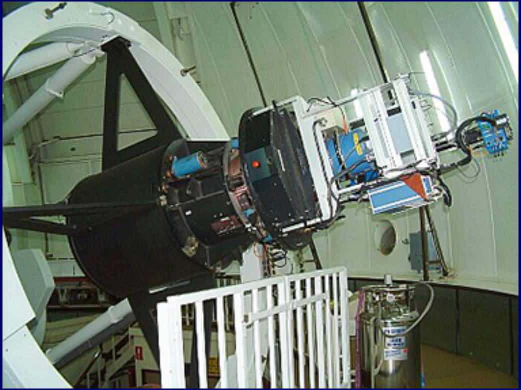
Asteroids

- Not just asteroids (name zoo, don't ask)
- What are they like?
- Why bother with them?
  - Primordial
  - Delta-V
  - Annoying impacts



Asteroid detection

- We do it optically
- Properties
  ~ 1 arcsec/min; $>$ mag. 21
- Example INT+WFC:
  2.5 m, 4xCCD EEV4280 2Kx4K
  0.27 sq. deg., 30 s – 120 s exp time



Detection methods

- Blink!
  Take a few exposures, alternate between them
- Automated blink is actually pairing.
- The Signal and the Noise
- What does maximum likelihood say?
- The atmosphere *glows*

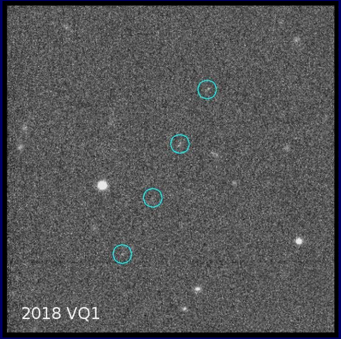


Figure: **2018 VQ1**, discovered using the blink method of NEARBY pipeline on INT

More faint than ever

- Mirror of the hill
  Pan-STARRS: $2 \times 1.8\,\mathrm{m}$, LSST: $8\,\mathrm{m}$
- Can we keep it small?
- Trails cover noise
- What of unknown asteroids?

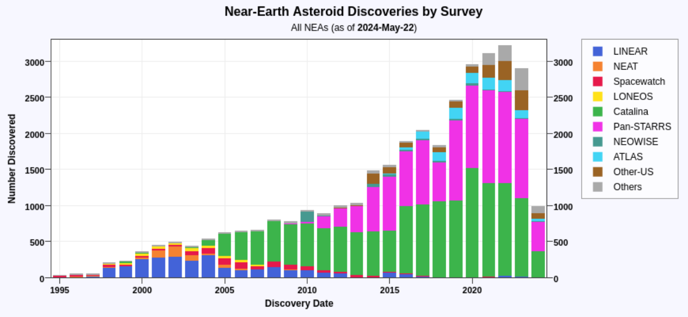


Figure: **Asteroids by detecting survey**. From NASA CNEOS.

Synthetic Tracking

- Synthetic Tracking [2][3][4][5]: co-add all possible motion vectors
- Trade 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)

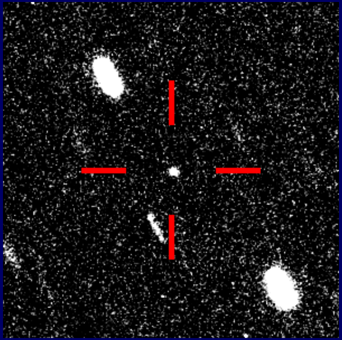


Figure: **1999 TH94**, observed with INT under bright time, integration time $12 \times 30\,\mathrm{s}$. At magnitude 21, it is at the blink limit.

Why is Synthetic Tracking hard?

- Trillions of hypotheses to check ($> 10\,\mathrm{kpx}^{-1}$)
- Have to co-add images
  - Memory ($\sim 10^{14}$ pixel reads from memory)
  - Outliers need median
- Sorting is expensive
- Detection and filtering are expensive too

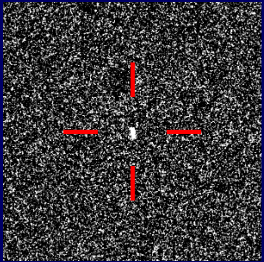


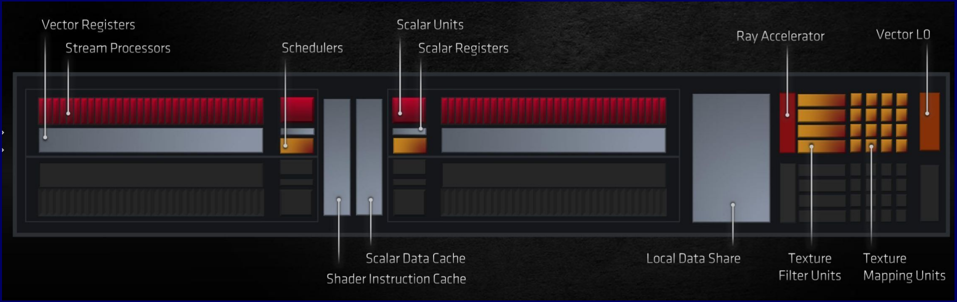
Figure: **2023 DW**, follow-up on March 1st 2023. Blind detection as reported by STU, from the observation archive. Detection stamp from trimmed mean of 4 images with stars masked, width 300px.

Can we make it fast?

- Yes!
- Hypothesis rejection design
  very cheap initial scan, increasingly powerful filters following
- Massively parallel brute force scan
  Use accelerators (such as GPUs)
- Median without sorting
- Use hardware efficiently

Why is an 'accelerator' fast?

- Massively parallel design
  No single-thread acceleration silicon
  Trade off speed for many dense ALU
- More resources:
  Silicon, power, bandwidth
- Parallel programming model



How do we program these accelerators?

- 'Software Development Kit': OpenCL
- One thread per lane
- Use the caches
  Regardless of CPU, GPU, C/C++, Python, or Bash!
- Branchless code
- Overall, takes time to set up, but easy to process data if you know C

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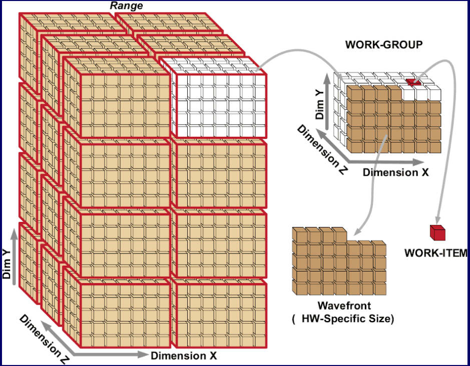
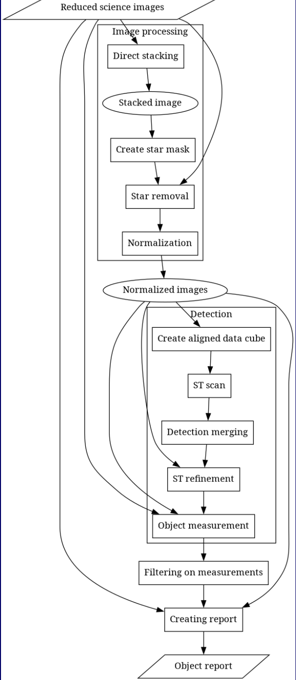


Synthetic Tracking with STU

- Hypothesis rejection design
  - Level inputs & remove fixed sources
  - Detection scoring method associative mean and *median*
  - Combine & refine motion vectors
  - Measure detections
- Efficient GPU implementations Benefits from modern AI instructions
- Portable: .NET Framework (Linux, Windows and other OSes) + OpenCL (AMD, nVidia, Intel)



Runtime in practice

- **Real-time** synthetic tracking even at full granularity
- Faster than data acquisition even on large cameras and modest PCs
- Our typical runs on, with an AMD Radeon RX 6800 XT:
  - WFC on INT: $4 \times 9\,\mathrm{Mpx}$, $0.33\,''\,\mathrm{px}^{-1}$, $12 \times 1\,\mathrm{min}$ cadence $10\,''\,\mathrm{min}^{-1}$ search cone
  - Acquisition time: $12\,\mathrm{min}$
  - Runtime at full granularity: $26\,\mathrm{s}$ per CCD, with $2\,\mathrm{s}$ for actual ST scan
  - T80S: $1 \times 80\,\mathrm{Mpx}$, $0.55\,''\,\mathrm{px}^{-1}$, $20\times \sim 1.5\,\mathrm{min}$ cadence, $15\,''\,\mathrm{min}^{-1}$ search cone
  - Acquistion time: $30\,\mathrm{min}$
  - Runtime: $7\,\mathrm{min}$ per CCD, with $2.5\,\mathrm{min}$ for actual ST scan

Now with granularity and thirding

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

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	

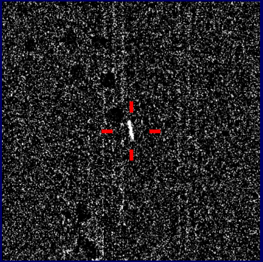


Figure: **2024 CW2**, detection by STU as shown in Webrella, on February 11th 2024. This, at $9.5''\,\mathrm{min}^{-1}$, along with three other fast moving asteroids were reported to MPC within 24 h.

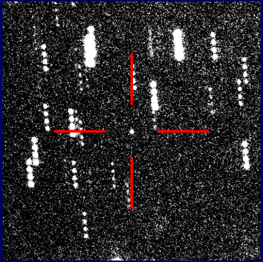
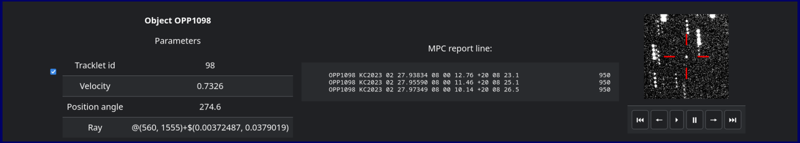


Figure: **2023 DZ2**, as detected on February 27th 2023. Detection as reported by STU, with reporting stage re-ran for press release. Detection stamp from mean of 4 input images, width 500px.

Modern validation methods



Web-based validation

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

Not your everyday web page

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

Achievements

- Real-time synthetic tracking for the masses (cheap and fast)
- Telescopes tested: TCS, INT, T025, SARA, KASI, T80S; $> 10^5$ images in total
- Challenge from noise and image defects; no object was missed on T025_good
- End-to-end pipeline available (sadly every capture software likes to be different)
- In survey conditions, limited mostly by transfer speed and human factors

Limitations

Synthetic Tracking as a method

- Data dredging pitfalls
- Diurnal circle
- Image cube size
- Sensor cost

STU

- Detection hijacking
  - Pixel hijacking
  - Cluster hijacking
  - Catastrophic percolation
- Primitive barycenter measurements
- Need more post-detection filtering

Next steps

Current activities

- Increasing automation
- Improving STU and IPP runtime
- Improving many-chip handling
- Publishing results

Planned activities

- Publishing even more results
- Integrating 3rd-party tools
- Usability improvements

NEO detection, where to?

What does 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)

Q&A

Question time

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