Synthetic Tracking on a Small Telescope

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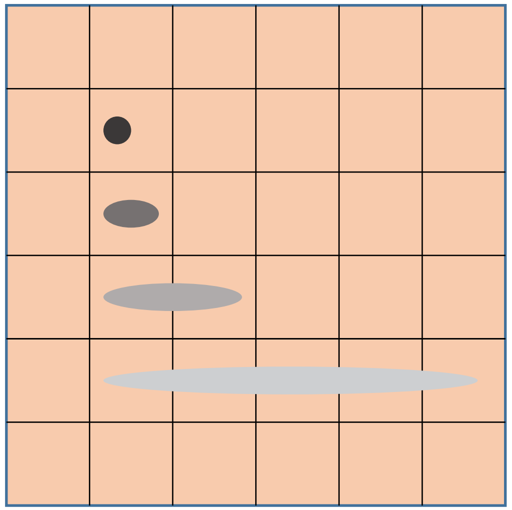
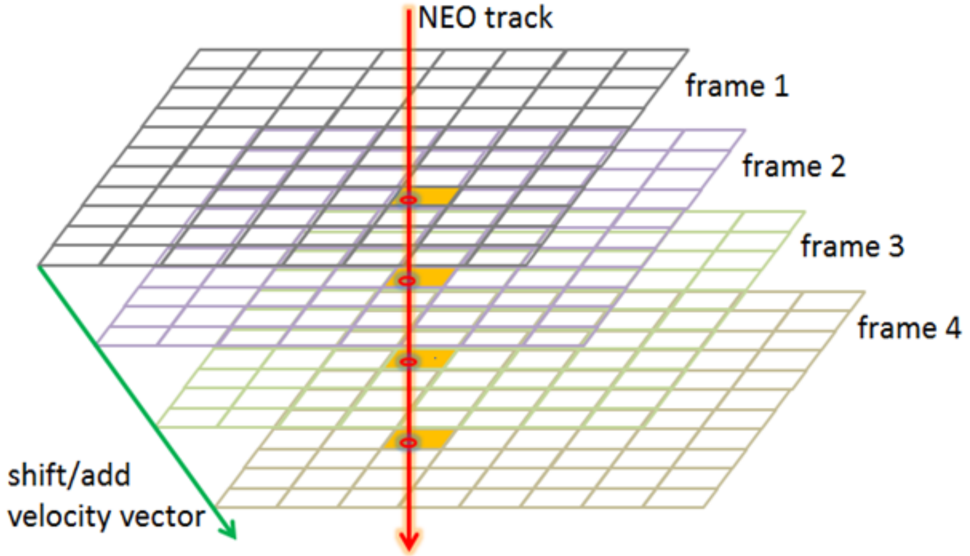
Outline

- What is synthetic tracking, what are its advantages and what hardware is needed to use it.
- Description of small (mostly) automated telescope hardware
- Overview of synthetic tracking processing steps
- Early demonstrations
  - Magnitude limit for NEO detection using very long integrations (fainter than 20mag 400sec)
  - Detection of multiple moving objects in 1 data cube with objects moving at different velocities.
  - Astrometric accuracy < 0.1 arcsec for short (4 sec) integrations
- Future tests and NEO search potential (of a cluster of 4~6) small telescopes.

Detection of Moving Objects

- When an object is moving across a focal plane the photons are deposited across a streak of pixels.
- The maximum SNR occurs for an integration time where the motion ~= PSF diameter.
  - Longer exposure times do no increase the peak flux, just the sky background noise.
- Synthetic tracking overcomes this by taking multiple short exposures and “stacking” them with a shift/add algorithm.
  - For this advantage to be realized, two technologies need to exist, that have become available in the last several years.





Technology Requirements for Synthetic Tracking

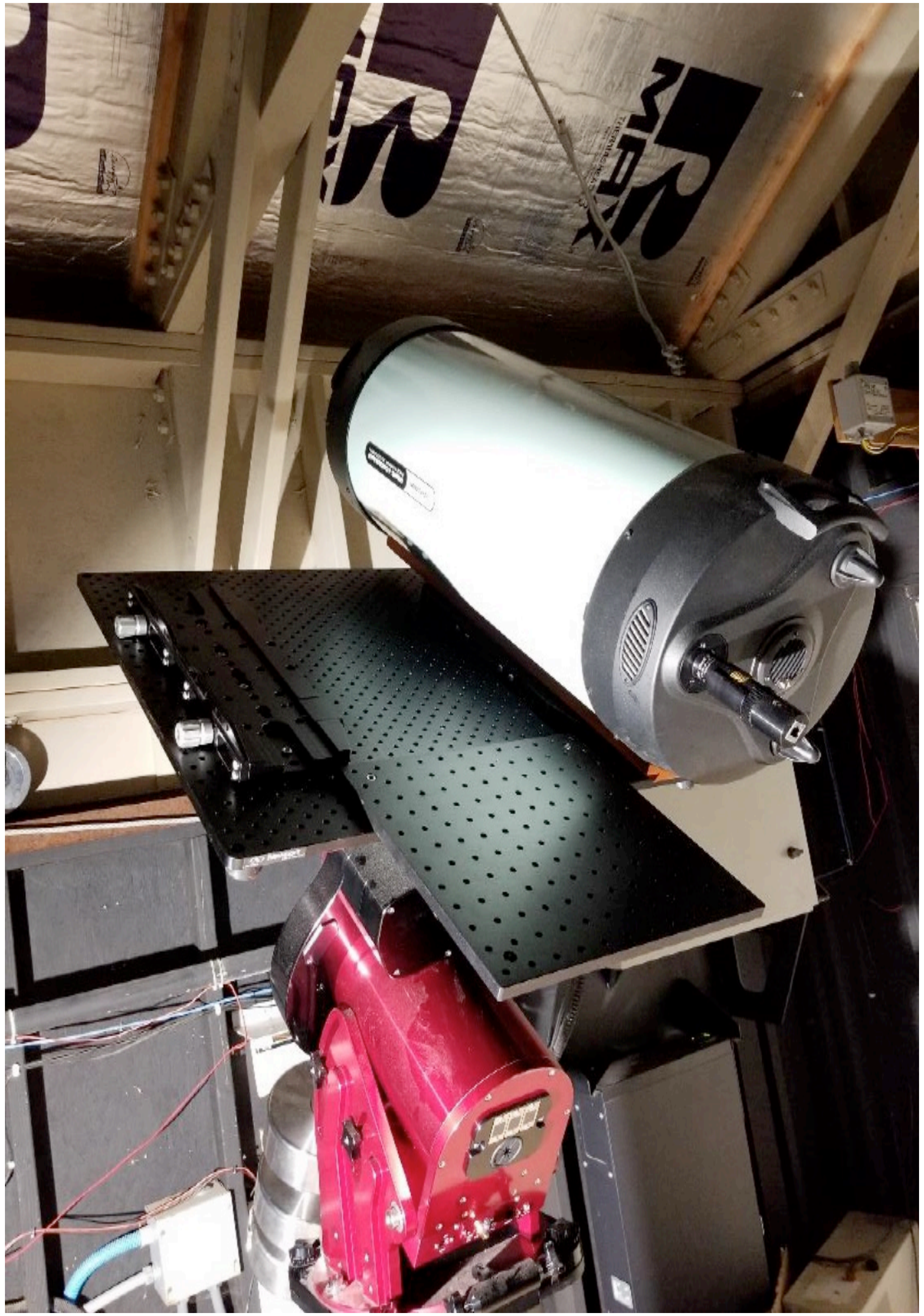
- The first is low noise, high frame rate focal planes
  - The read noise must be below the photon noise of the zodi-sky background.
    - The current generation of sCMOS detectors with ~1.5e read noise satisfies this requirement. 16Mpix devices are now available and 36Mpix and even >120Mpix devices will soon be available.
- When using shift/add algorithm, we don't know what velocity the object is moving until it's detected. As a result we have to "try" many velocities, as many as allowed by the target set we're trying to detect. Typically for NEOs we try ~10,000 velocities.
- This is computationally expensive and requires teraflop class processing. The data volume is large (we're taking video not single images) and in many instances its inconvenient to transport the data from the mountain to a super computer.
  - Modern GPUs and FPGAs are now available that can provide TFLOP processing at very low cost.

Advantages

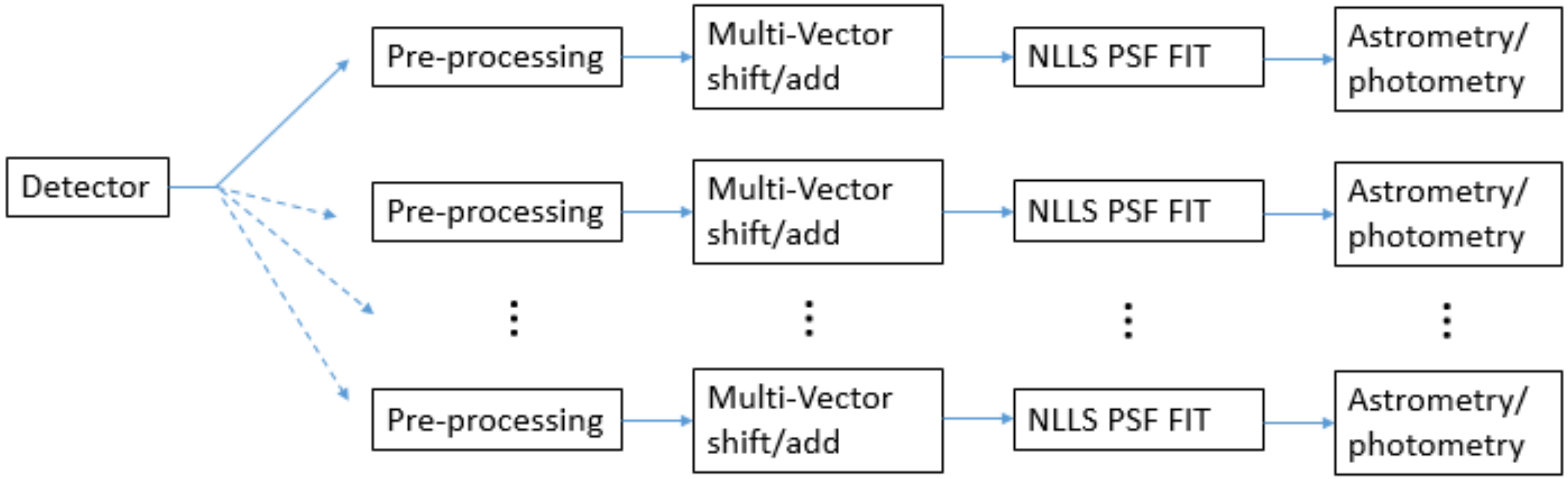
- Medium and large telescopes searching for NEOs use 30~45 sec CCD exposures. Similar sensitivity can be had with much smaller telescopes and multiple exposures and total integration times much longer than 30sec.
  - The longer integration time means less sky coverage (sqdeg/hr) but can be compensated by using multiple small telescopes.
  - The economic advantage can be very substantial. For ground based NEO searches a Cluster of (~6)) 28cm telescopes (< 10K/each) can equal a ~2m class telescope with > 1 Gpix focal plane.
- In space the economic advantage is even larger.
- For NEOs much smaller than 140m, on average they are much closer to the Earth by the time they become detectable, and a 30 sec exposure is too long, giving synthetic tracking an even greater advantage.

Small Telescope at Dark Site

- Telescope is a 28cm Celestron RASA with a prime focus f/2.22 CMOS camera.
  - Currently we have 2 telescopes on the same mount. (4 in another ~ month)
- Robotic (automated) telescope
  - In large shed with other users
  - Remote operator starts at beginning of night. (pointing and autofocus automated)
- Focal plane 1.26 arcsec pixels.
  - Low read-noise 1.6e, ~35%QE, max 10hz video (full frame)
- On site, PC for mount/camera control GPU for data processing



Simplified Data Processing Schematic



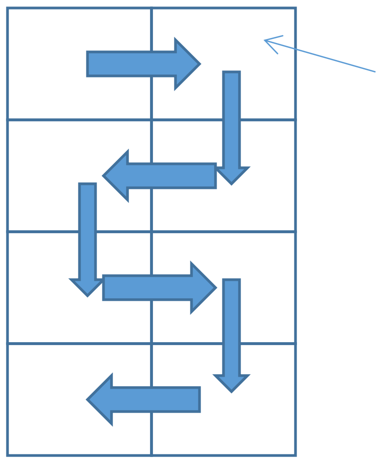
- Pre-processing (dark sub, flat normalize, Cosmic rays, sky gradient, star removal)
- MVSA (the computationally expensive part of Syn Track)
- Non-linear least squares fit of PSF to data cube. (candidates ID'd by MVSA)
- Astrometry/photometry Match ~100 stars to GAIA catalog. Photometric calibration against catalog, solve for optical field distortion. Output position, velocity and brightness of moving object(s).

Initial Demonstration Goals

- High sensitivity with long integration times
- Ability to detect multiple objects moving at different velocities (in the same data cube)
- Astrometric accuracy ~ 0.1 arcsec for short integration times

NEO Observations

- Typical exposure ~5 sec, total integration 400~500 sec
- Scans sky in a serpentine pattern
- Total eff QE (including central obs) ~30%
- Sky background 21 mag/arcsec^2 (New moon)
- PSF FWHM 2 arcsec (1.6 pix)
- FOV 2.0 sqdeg
- Magnitude limit in 500s (theoretical 21.0mag 500s)
  - Practical mag limt ~20.6 mag
  - No loss of sensitivity for fast moving NEOs
- Currently repeat after 1hr. But later will repeat only when we find a NEO. (real time analysis to trigger a confirmation observation.)



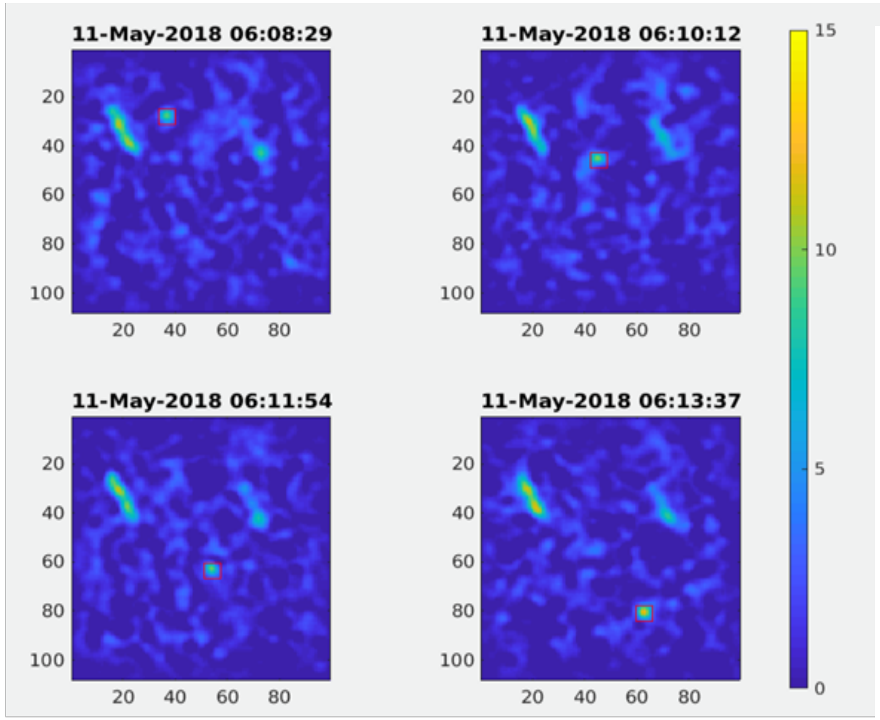
2 sqdeg
Per telescope

Revisit field after ~ 1hr
Velocity range

Vel Range	Arcsec/sec	Deg/day
Min Vel	0.01 arcsec/s	0.24
Max Vel	0.5 arcsec/s	12

Vel range for full sensitivity

Example Data from a Ground based 28cm Syn Track Telescope

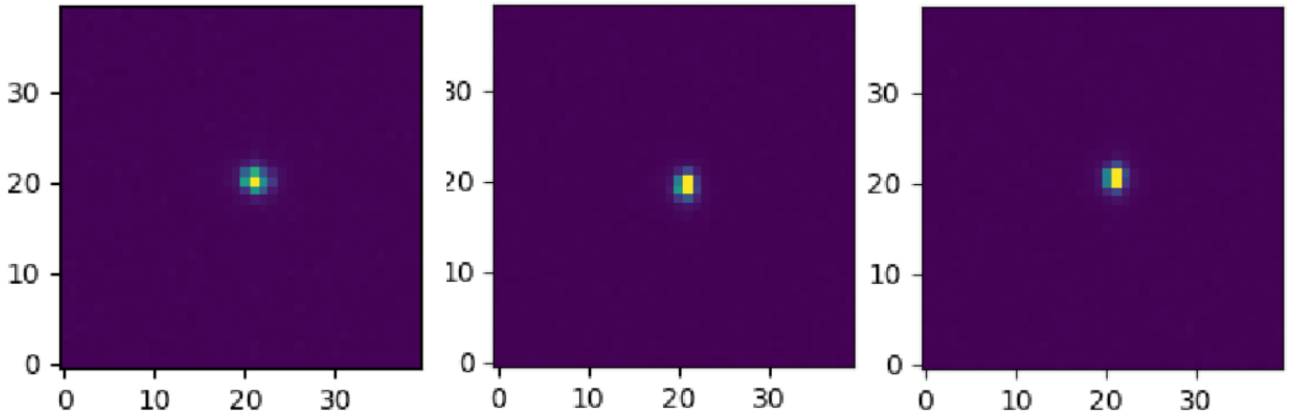


~19 mag NEO Each image is sum of 20 5 sec exposures . Limiting mag ~20.4 (400 sec)

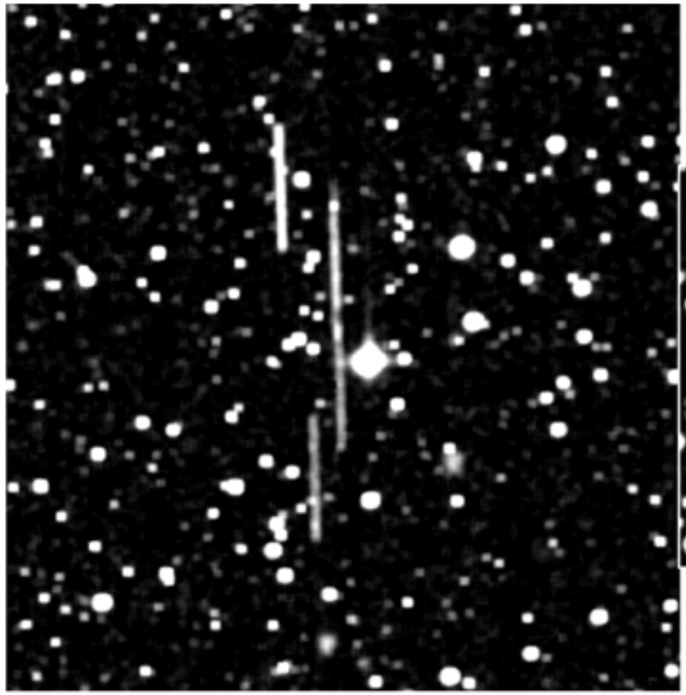
Detection of a 19 mag NEO with SNR ~24 in 400 sec (80 5 sec exposures) (may 2018)
Limiting mag @ SNR=7 was ~20.4 mag

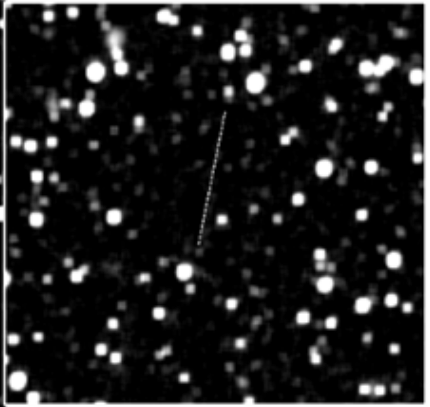
Since then we've improved our autofocus to get Images with FWHM (2 arcsec versus ~2.8 arcsec)

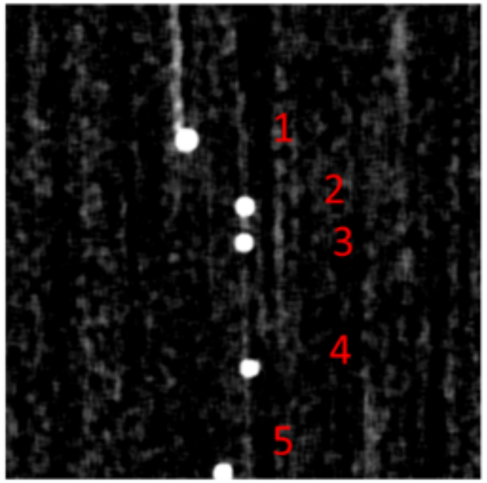
We've also improving our sky subtraction algorithm so that we're closer to the theoretical limiting mag.

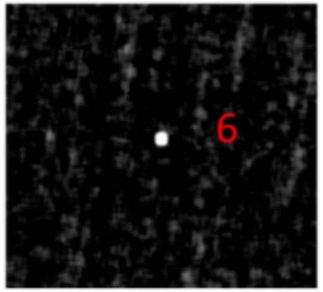


Detect Multiple Objects at Different velocities



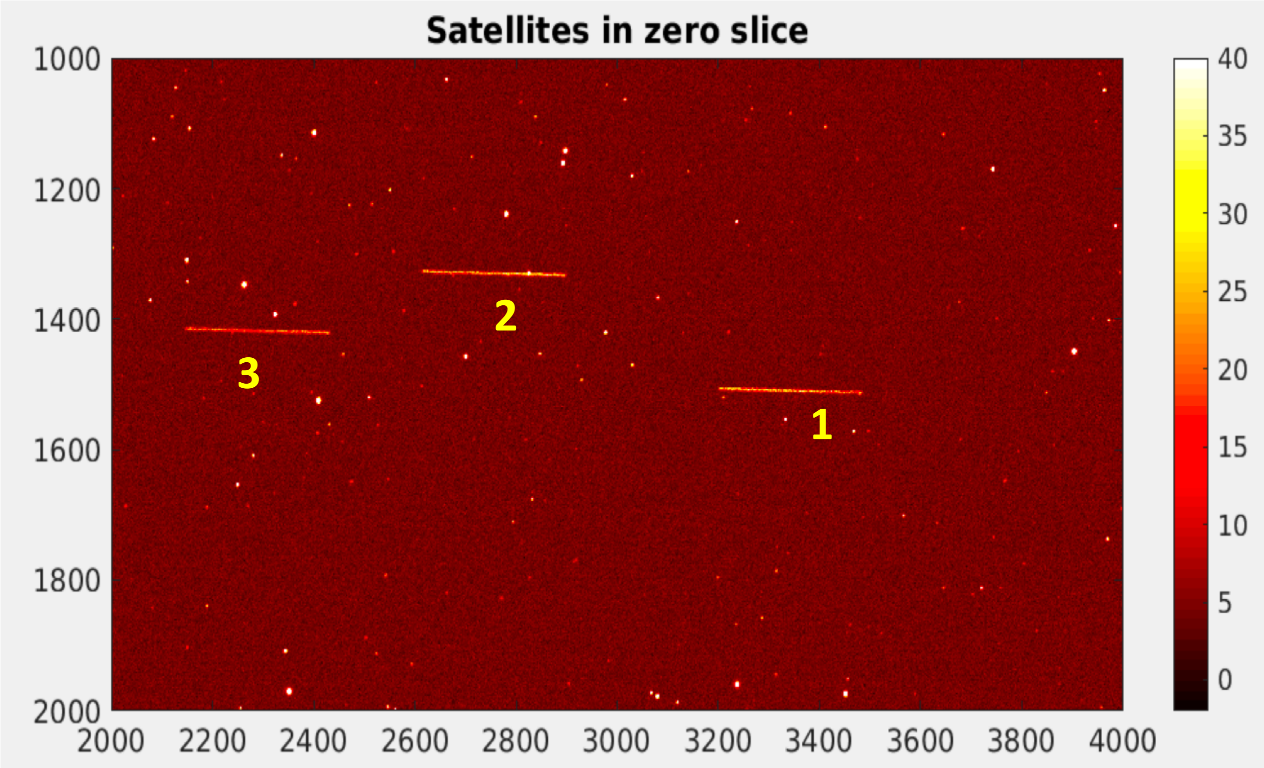




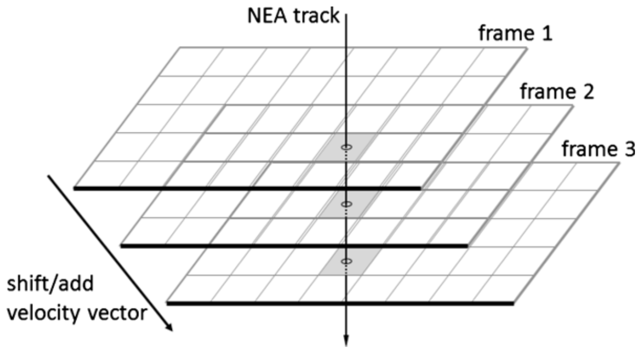


In this example the three streaks represent 5 objects
Moving at the same velocity. RA direction is up/down A 6th object (2nd image) Is not detectable in the sidereal image, the dotted line shows where the streak would be if it were bright enough to be seen.
The far right image is at the object's velocity. (inclined orbit)
The average flux for object 6 was 1.1 photons/frame. (240 frames coadded)

Astrometry (short integration times)

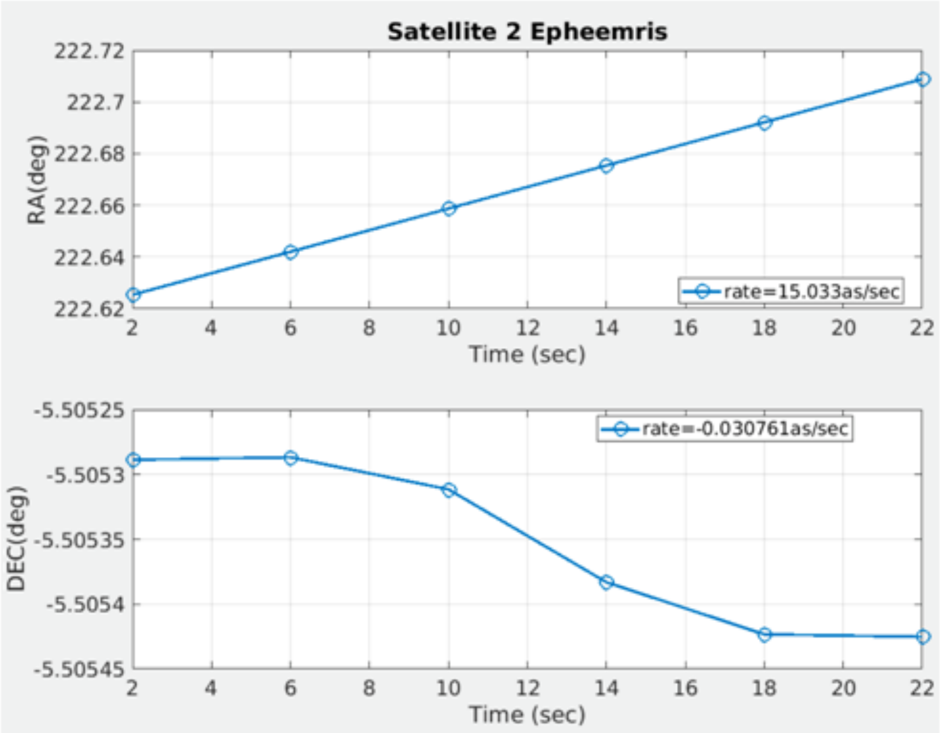


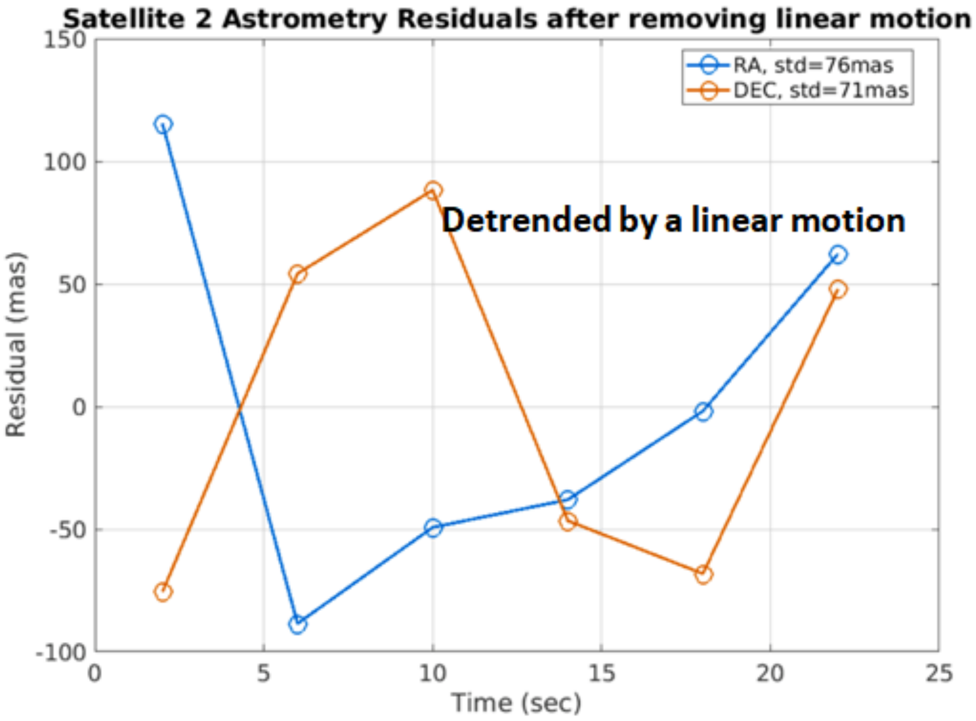
- Sidereal image of 3 moving objects.
- Observed for 24 sec. Broke data set into 6 4 sec datasets. 6 Position/vel measurements.



- Astrometry is performed in “post analysis”
- We use a stellar PSF as the “model”
- The model PSF is moved linearly in time through the data cube.
- The position/velocity and intensity are varied in the NLLS fit until we have a minimum variance between the model and data.
- Similar to conventional PSF fitting astrometry except extend into 3D and fit velocity as well.

Astrometry (4 sec integration)





- Look at internal consistency of 6 4 sec measurements.
- RA, Dec vs time (left graphs)
- Residuals after straightline motion removed. (RMS error ~ 0.07~0.08 arcsec)
  - ~0.36 urad in 4 sec close to the atmospheric turbulence limit

Future Tests and Operations/Summary

- Syn tracking using N images should have false positive rates similar to the 4 image tracklet in NEO processing.
  - In practice ST has some issues that are being addressed. (stars at the edge of the FOV that pop in/out because of telescope tracking error, etc.)
- One early test is to measure (and if necessary reduce) false positive to 1~2 % level.
- Another is real time data processing. (we've conducted trials and keeping up with real time is not an issue.)
- The combination of the above two, will lead to a change in our NEO observing program, where we will "trigger" a follow up observation ~ 1 hr later. Potentially increase the search speed by ~2X. (might extend to additional follow up observations to "catalog NEOs")
- Complete installation of 3 additional telescopes. (8 sqdeg total FOV) slight improvement in sensitivity to 20.8 mag (500s)
- We've conducted a simulation of cluster of **6** 28cm telescopes using Granvik NEO population model. => ~2000 new NEOs detected/year (8hr, 2wk/month, 75% weather)

Acknowledgements

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