Near-Earth-Object Astrometry using Synthetic Tracking and Applications

Chengxing Zhai, Michael Shao, Navtej S. Saini, Russell Trahan, William Owen

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

and

Philip Choi, Kutay Nazli, Nez Evans

Pomona College, Claremont, CA

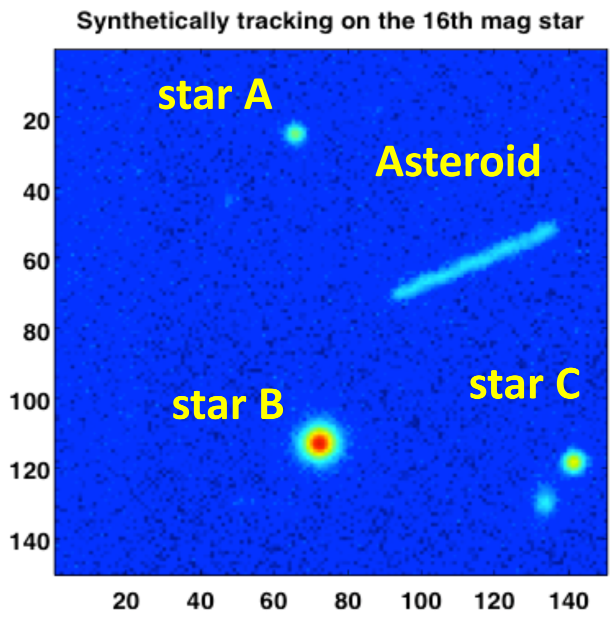
Outline

- Introduction to Synthetic Tracking
- Accurate near-Earth-Asteroid Astrometry using Synthetic Tracking
- Applications of NEO Accurate Astrometry
- Conclusions

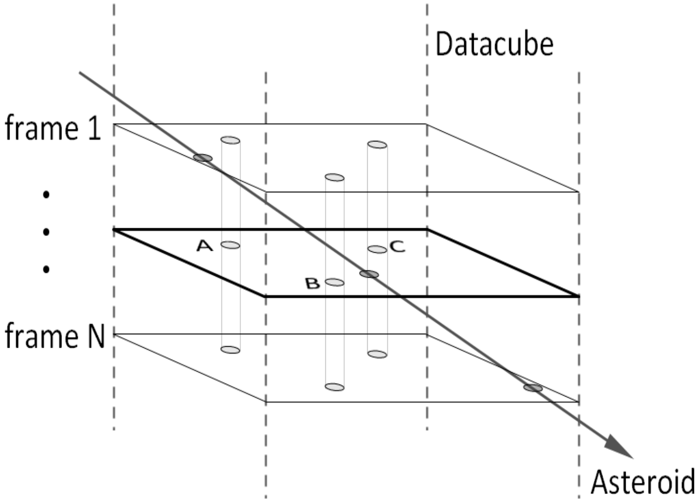
Synthetic tracking is for detecting **faint moving** objects

- Use exposure time **short** enough so that moving objects **do not streak**.
- Integrate frames in post-processing to **systematically search** for moving objects.
- Use **parallel computation** to achieve a quasi-real-time data processing for continuous operation.

Traditional approach: single image of exposure ~ 30 seconds



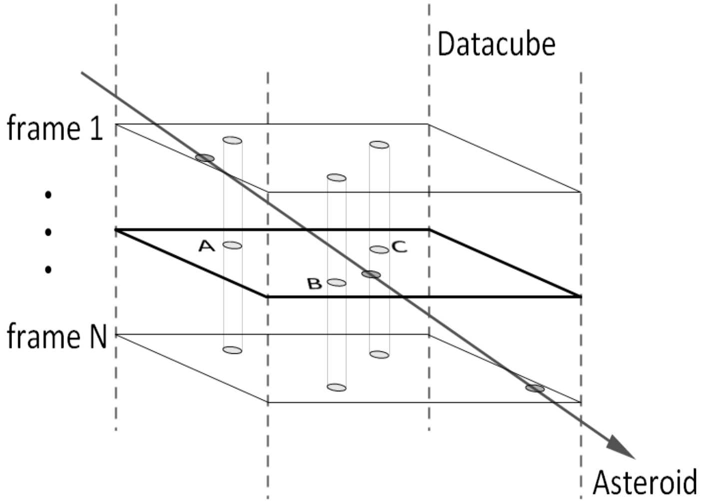
Synthetic tracking: a data cube with multiple frames



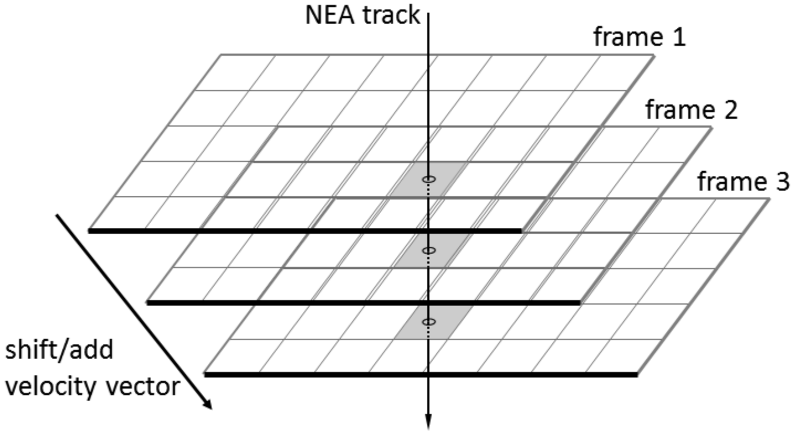
Synthetic Tracking can simulate telescope tracking at any velocity in post-processing

- Track stars and moving objects, avoid streaks, **trailing loss** from spreading signals over multiple pixels.
- Search for moving objects
  - Simulate tracking for a grid of velocities.
  - Currently, GPU-accelerated computation is used.

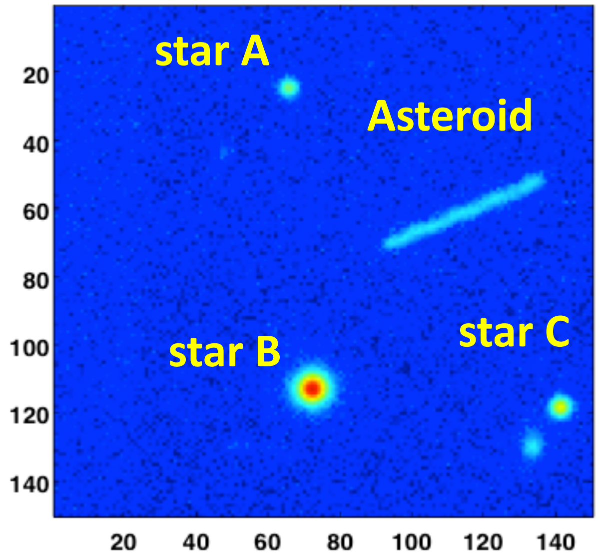
tracking sidereal



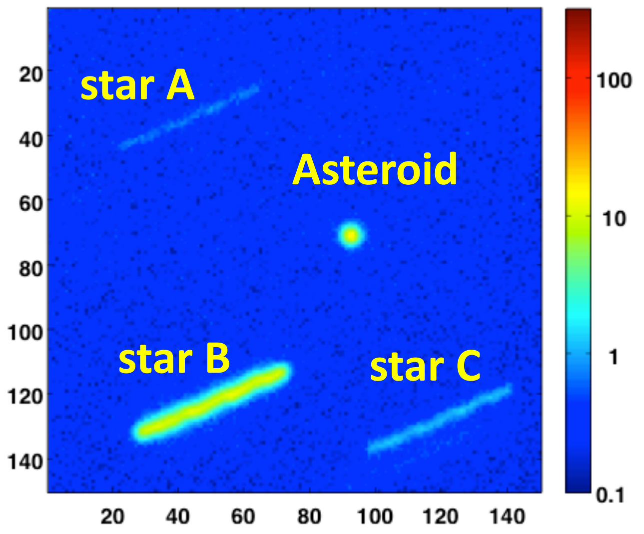
tracking asteroid



Synthetically tracking on the 16th mag star



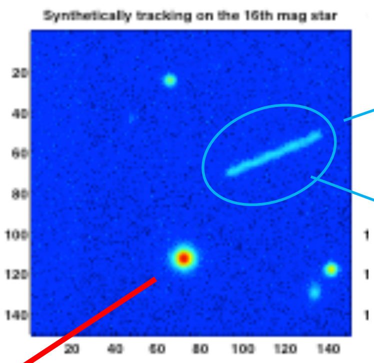
Synthetically tracking on asteroid 2009BL2, 19th mag

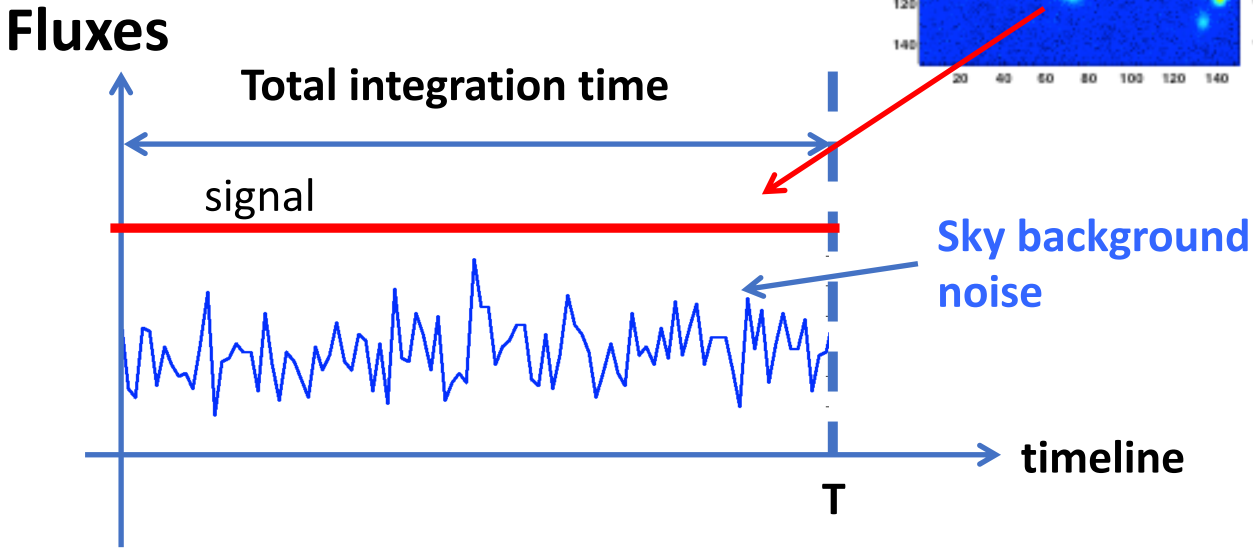


Improve detection signal-to-noise ratio (SNR) by *avoid trailing loss*

- SNR can be improved by integration over a longer time for a well tracked object

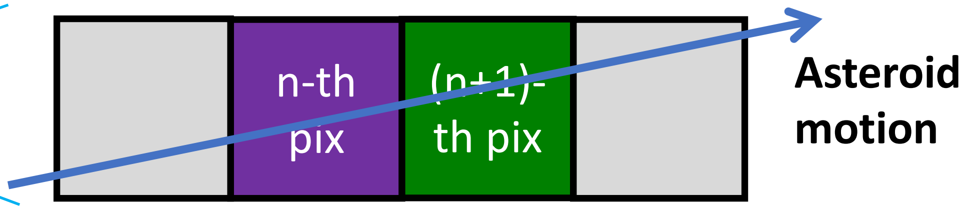
$$\text{Signal} \propto \text{T}, \text{Noise} \propto \sqrt{T}$$
$$SNR \propto T/\sqrt{T} = \sqrt{T}$$
$$\text{T} = \text{integration time}$$

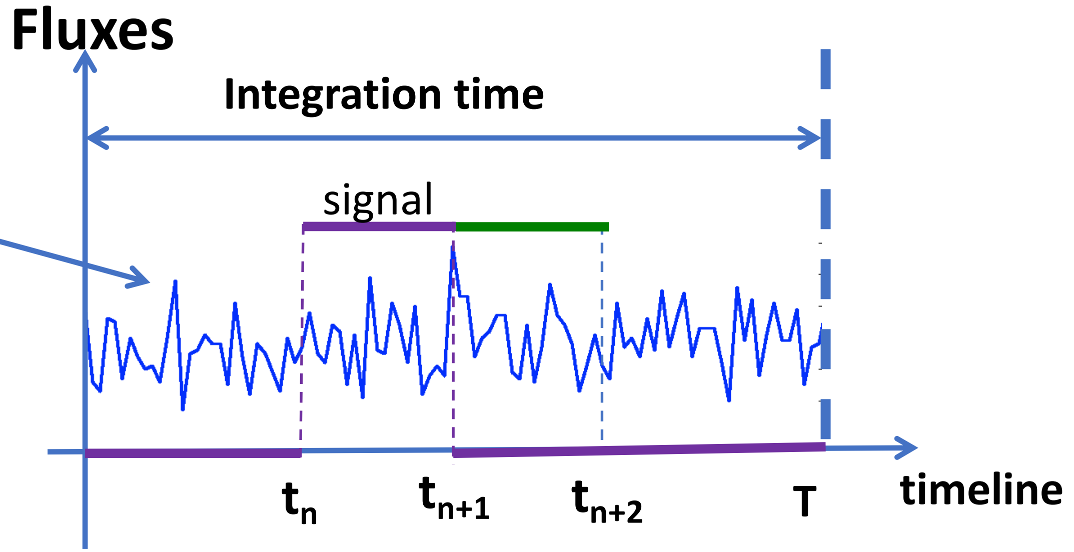




- A moving object (not tracked) suffers trailing loss,

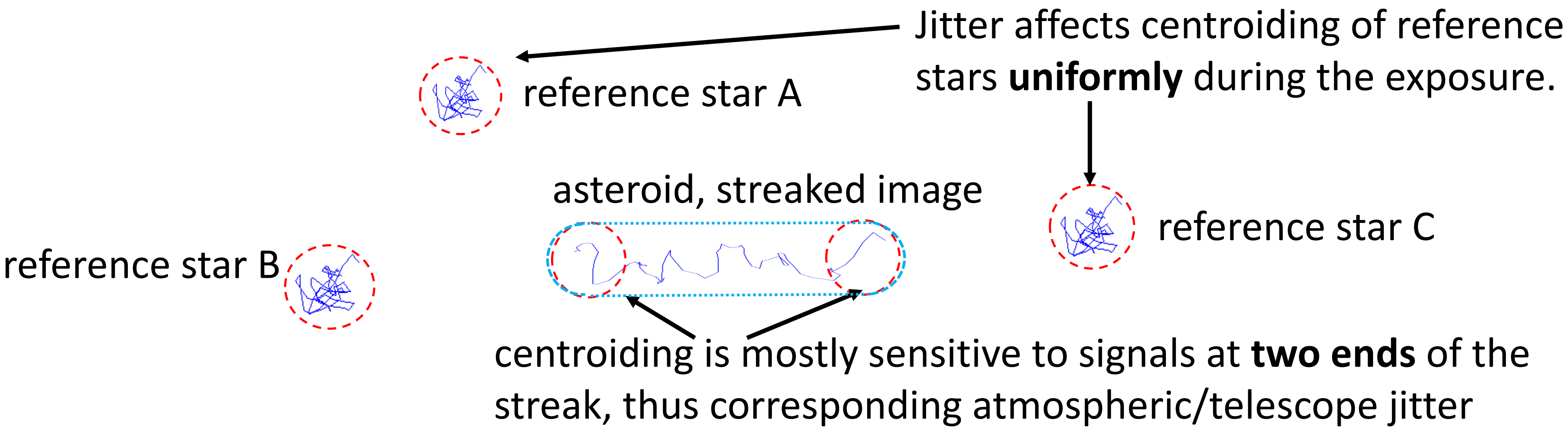
$$Loss = \frac{Pixel\_detection\_time}{Exposure\_time}$$





Produce Accurate Astrometry

- It **avoids streaked images**
  - **Improved SNR** for astrometry.
  - Use **compact PSF** for more accurate astrometry (seeing/optics limited, no streak)
  - Making **atmospheric/telescope pointing jitter effects common** between moving object and reference stars.



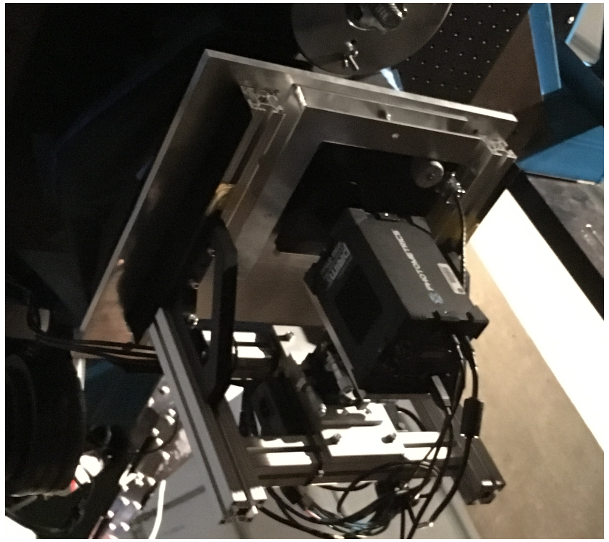
Summary of synthetic tracking

- Advantage
  - **Improving detection sensitivity** for faint moving object by avoiding trailing loss. [ref 1-3]
  - Producing **accurate astrometry** for moving objects, comparable to stellar objects. [ref 1-2,4]
- Requirements
  - **High performance computation (e.g. GPUs)** to process large amount of data (not needed if doing astrometry only)
  - **Fast camera (e.g. CMOS)** for low read noise/high frame rate for many applications.

Accurate near-Earth-object astrometry using Synthetic Tracking

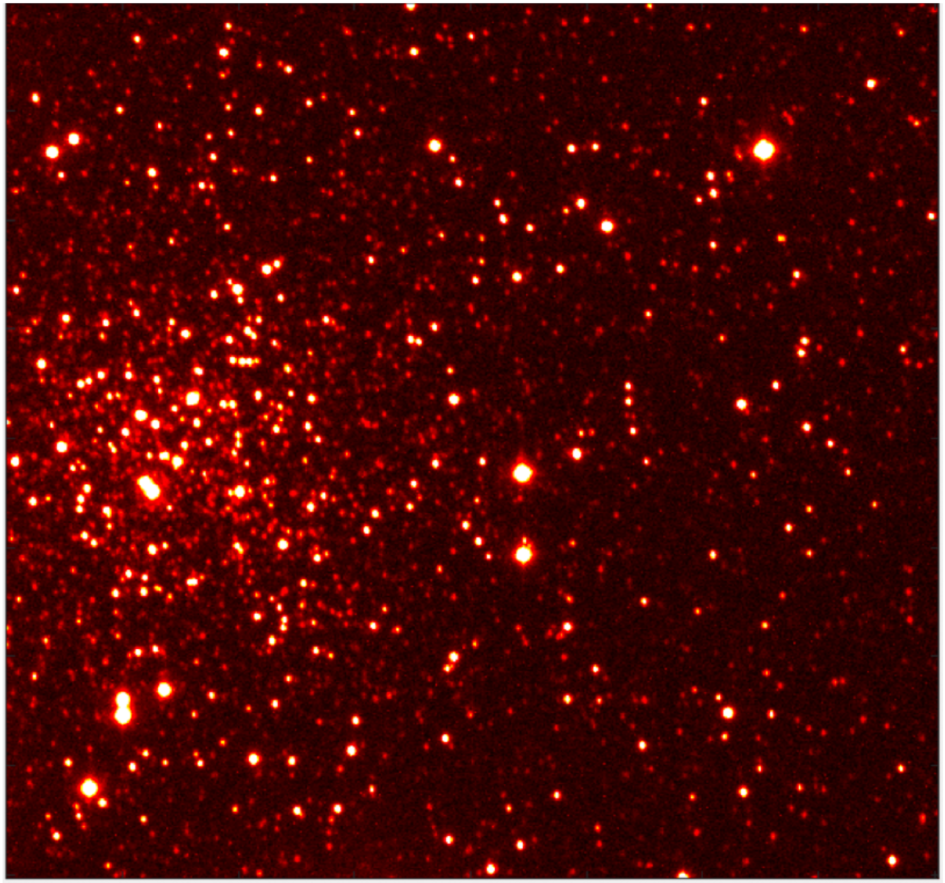
- Detector: Photometrics Prime 95B CMOS (1600x1600)
- Telescope: Pomona College’s 1 m telescope at the Table Mountain Facility (654)
- FOV: 6’x6’
- Limiting magnitude: ~ 21.5 (G) with 600 second integration

https://tmf.jpl.nasa.gov

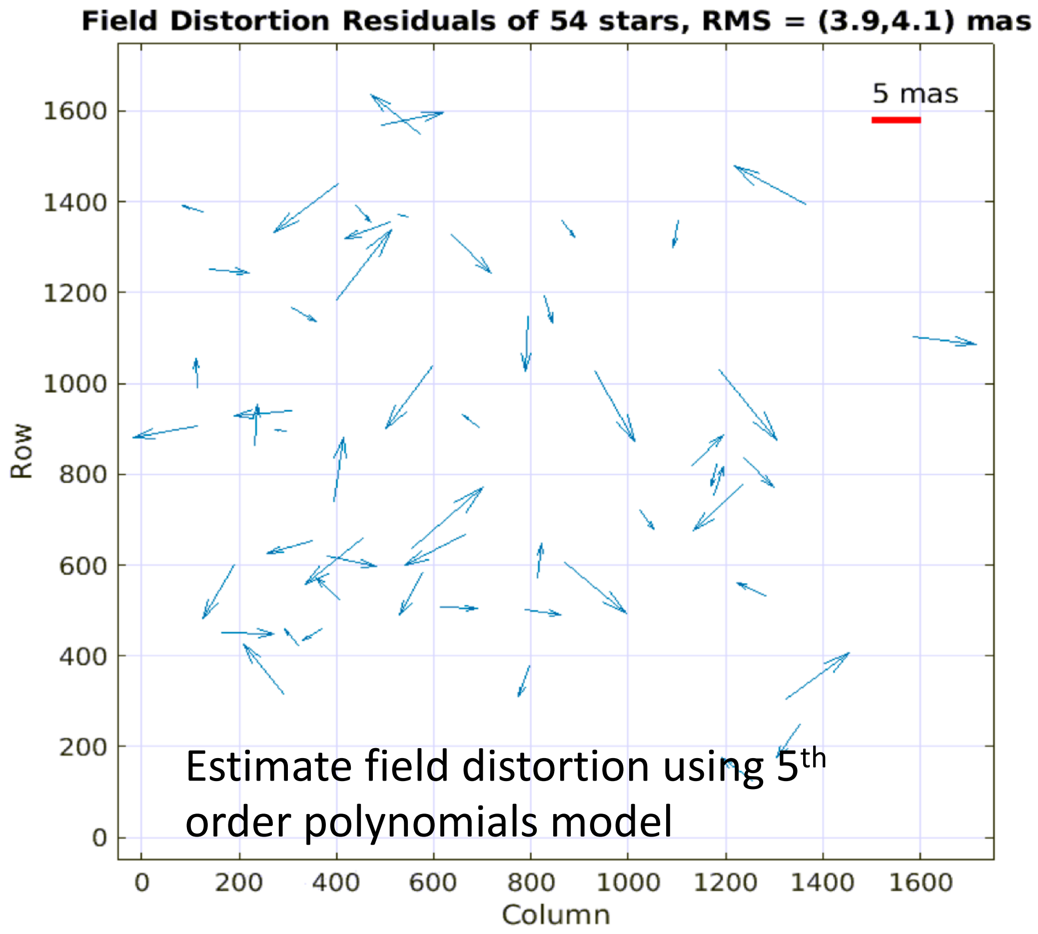


Astrometric solution residuals ~ 10 mas with best < 5 mas

M71

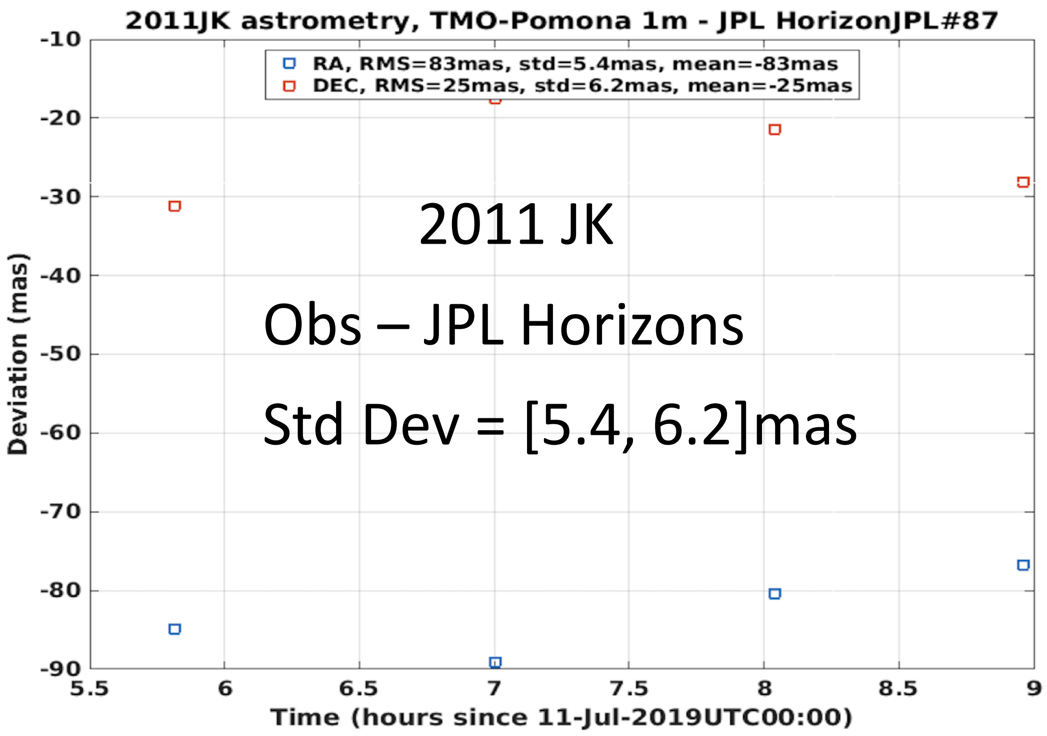


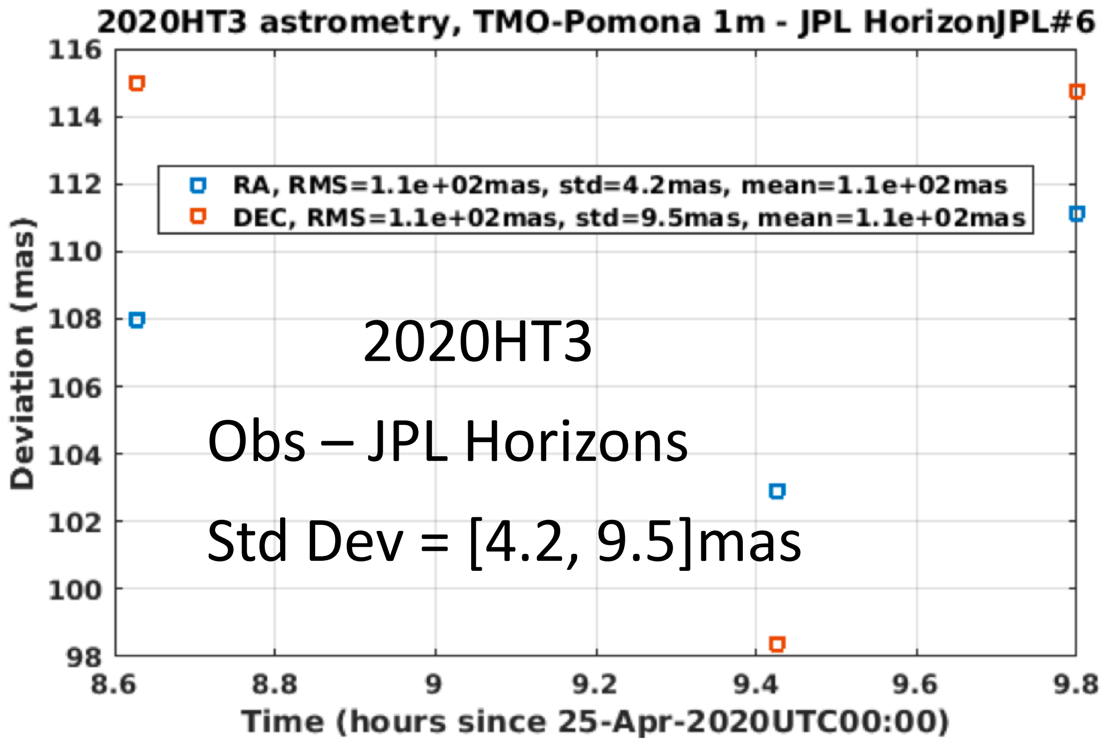
Gaia DR2 Catalog used



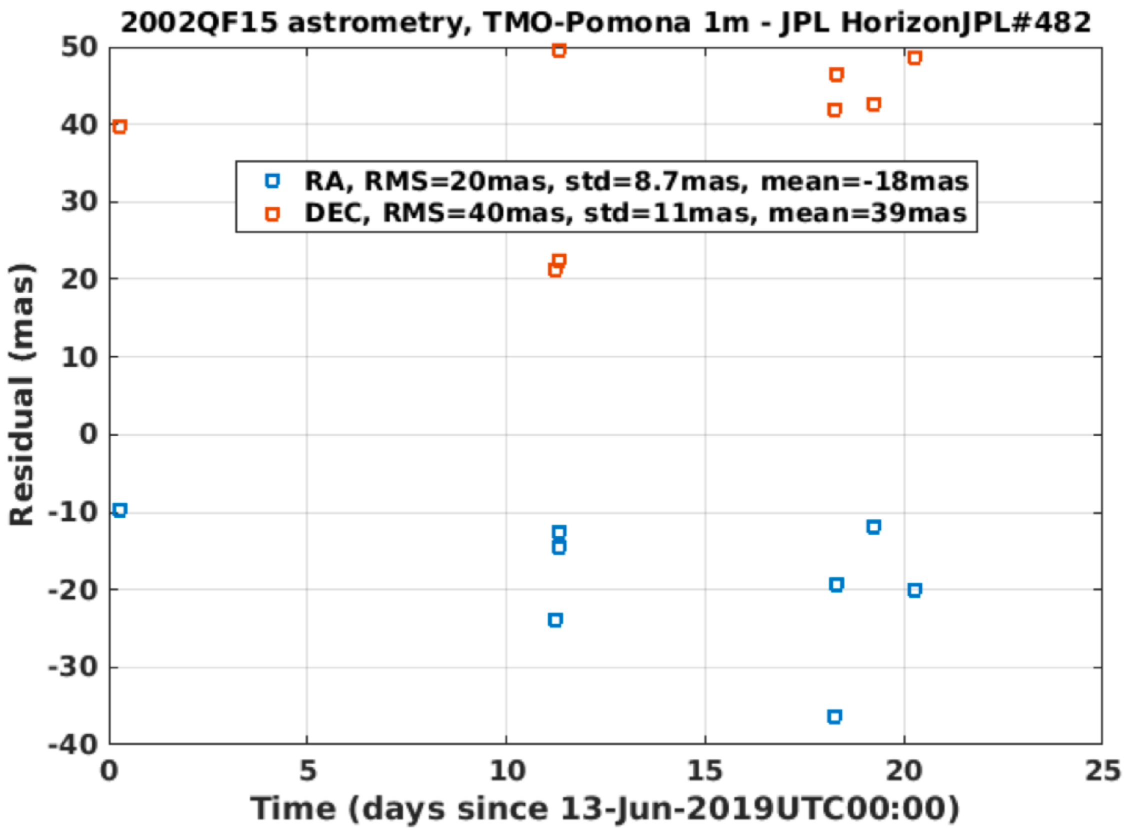
Examples of astrometric residuals over one night

- The residuals (after subtracting JPL Horizons ephemeris) have Std Dev less than 10 mas.
- The biases are consistent with JPL Horizons ephemeris uncertainties.





Consistency over multiple days



Applications of Accurate NEO Astrometry

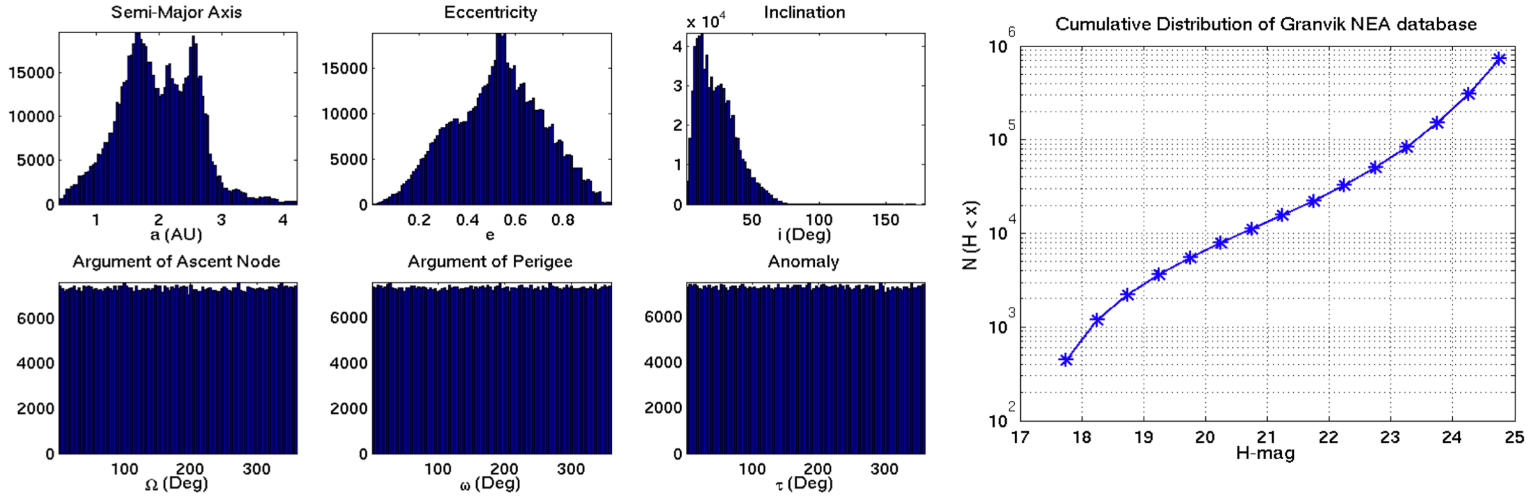
- Perform efficient NEO follow-up observations to catalog newly discovered NEOs.
- Optical Navigation
- Measure non-gravitational acceleration to study physical properties of NEOs

Improve NEO Orbit Determination

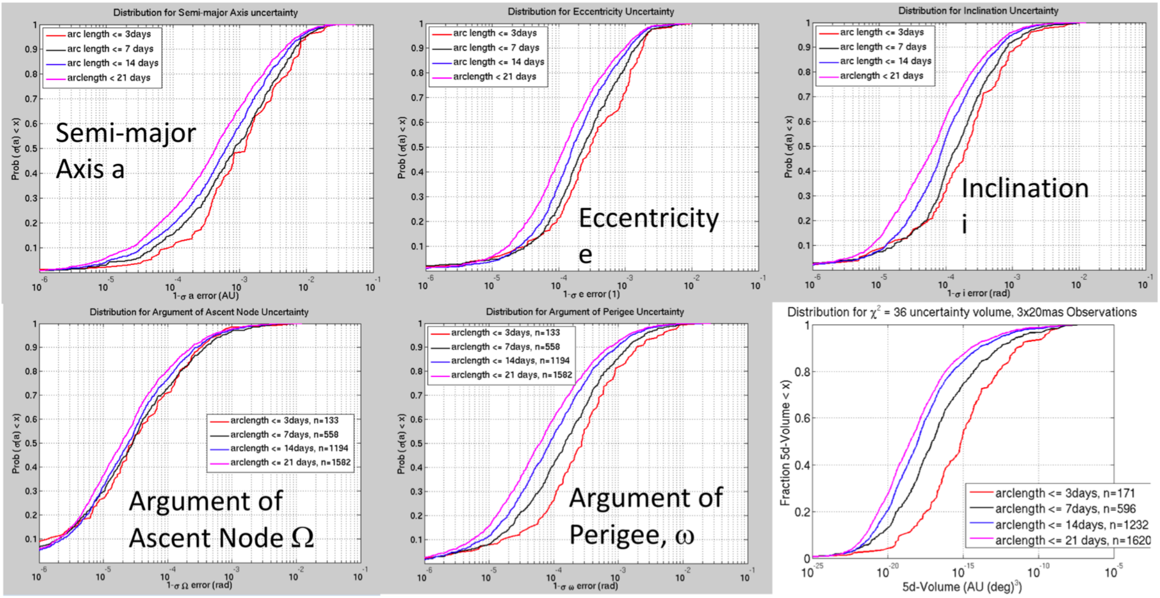
- Potentially hazardous asteroid (PHAs) gets very close to the Earth and posts threats. The traditional approach suffers inaccuracy from centroiding streaked targets or reference stars. Synthetic tracking would yield very accurate astrometry independent of the rate, so it would be very valuable for improving PHA orbits and thus better determine the chance for a PHA to impact the Earth.
- For newly discovered NEOs, it is very crucial to determine their initial orbits accurate enough so that there is no confusion at their next apparitions. This is particularly important for small NEOs with an observation window of about a few days. More accurate astrometry enables us to determine orbit with a shorter arc of observations.

Using Monte Carlo simulation, we estimated uncertainties of orbital parameters derived from three astrometric measurements of accuracy of 20 mas. Charts at the bottom right display the distributions of uncertainties of orbital parameters over about 2000 observation scenarios.

We found among the five orbit parameters (a, e, i, Ω, ω), the uncertainties are highly correlated; the volume of uncertainty in the corresponding 5-d space is very small, extremely unlikely to have confusion with another asteroid, assuming a NEO density ~ 16/(AU deg^3) in the 5-d space.



Distribution of 6 orbit parameters and H-mag of 731683 NEOs from Granvik's NEO orbit database, used for simulation.

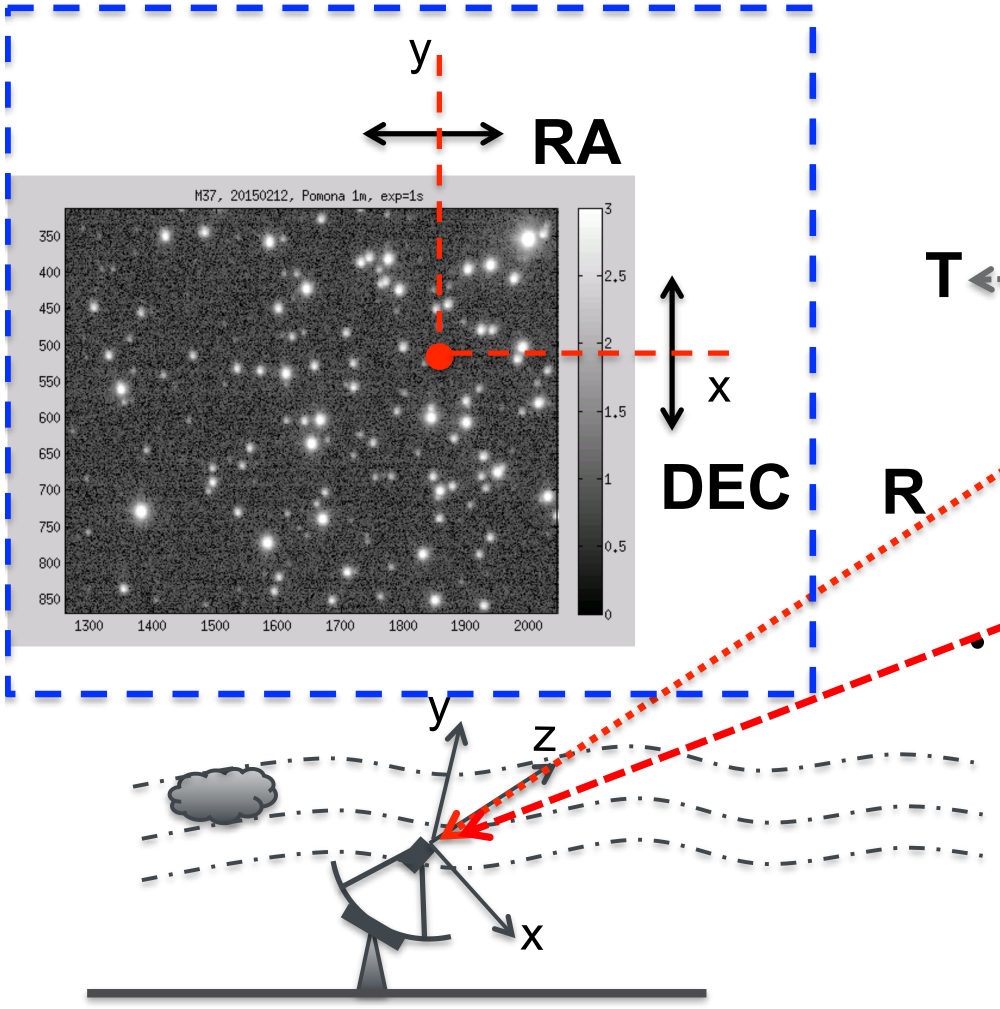


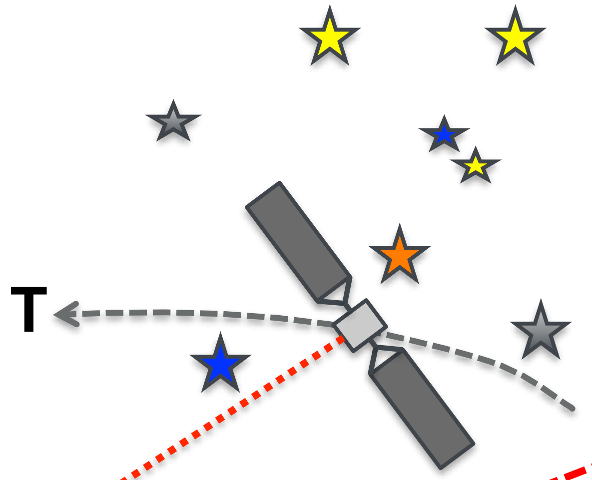
Distribution of uncertainties of 5 orbit parameters and volume in 5-d space of 6-σ uncertainty (χ^2 = 36).

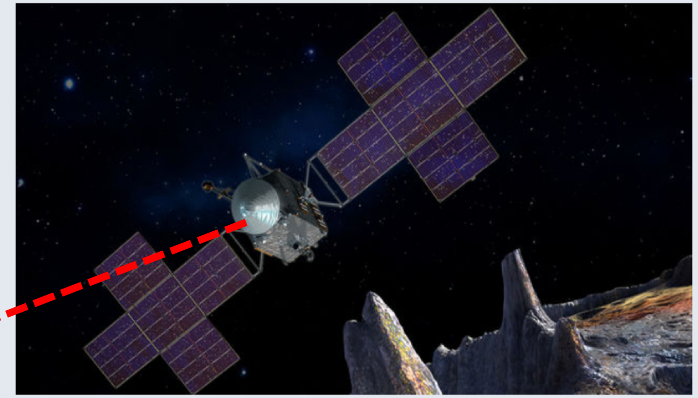
Application to Optical Navigation

- Future spacecraft will carry optical communication lasers for high data rate. JPL is developing Deep Space Optical Communications technology with the first prototype being part of the planned payload of the Psyche mission to be launched in 2022.
- Taking measurements of spacecraft astrometry and ranging data while it is communicating with ground via optical link for its navigation [5] has the following advantages:
  - Operationally more convenient than the current delta Differential One-way Ranging (delta-DOR) astrometry using two Deep Space Network antennas, which can be only done ~ once per day.
  - Reducing mass by removing radio frequency devices for navigation.
  - Navigating a large population of deep space cubesats.
- Ground-base optical astrometry using asteroid as proxy of spacecraft servers as a technology development and demonstration for the feasibility of optical navigation. The required accuracy is at 1-2 nrad (0.2-0.4 mas), this is comparable with the best delta-DOR measurements and sufficient for the most stringent requirement for navigation such as orbit insertion.

Optical Astrometry for Navigation







Deep Space Communications via Faraway Photons https://www.jpl.nasa.gov/missions/psyche/

- **Spacecraft position components relative to telescope can be measured optically:**
  - **LOS Range (R) and Doppler (D)**
  - **POS Astrometry (RA, DEC))**

Psyche spacecraft will be equipped with DSOC laser, that can be used for optical astrometry and ranging, thus optical navigation.

(x, y) define plane-of-sky (POS)
z defines line-of-sight (LOS)

Study physical properties by measuring non-gravitational acceleration

- Determine outgassing activity
- Measure Yarkovsky effect
- Measure mass/area ratio via solar radiation effect
  - With ranging and size data, it is possible to estimate density. Very crucial for the Asteroid Redirect Mission

Acceleration due to solar radiation pressure:

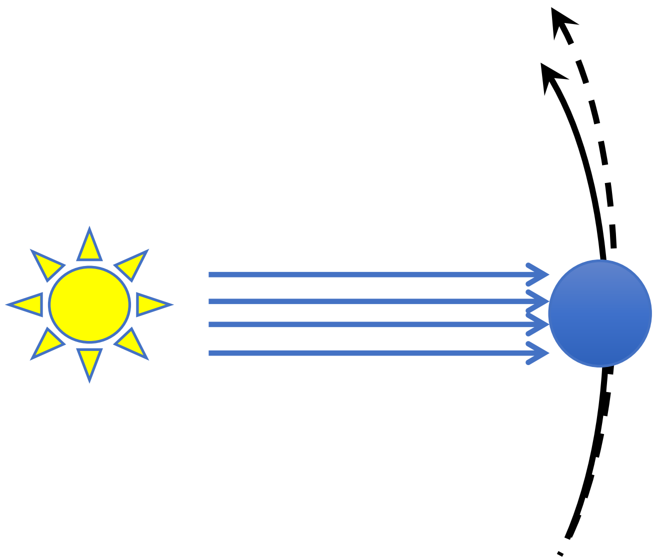
$$a_{\text{solar radiation}} = \frac{(S/c)A}{m} = (S/c)(A/m)$$

S ---- solar constant

c ---- speed of light

A ---- area of asteroid (projection view)

m ---- mass of asteroid



Conclusions

- Synthetic tracking technique yields accurate astrometry comparable to stellar objects for moving objects (NEOs).
- We are able to achieve 10 mas NEO astrometry with 10 minute integration on a 1 m telescope.
- Accurate NEO astrometry is useful for
  - Cataloging NEOs
  - Optical Navigation
  - Characterizing NEO physical parameters by measuring non-gravitational accelerations.

References

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5. T. J. Martin-Mur, C. Zhai, C. Jacobs, et al, *Using Optical Communications Links for Deep-Space Navigation, 2017 IEEE International Conference on Space Optical Systems and Applications*, Naha, Okinawa, Japan, (2017).