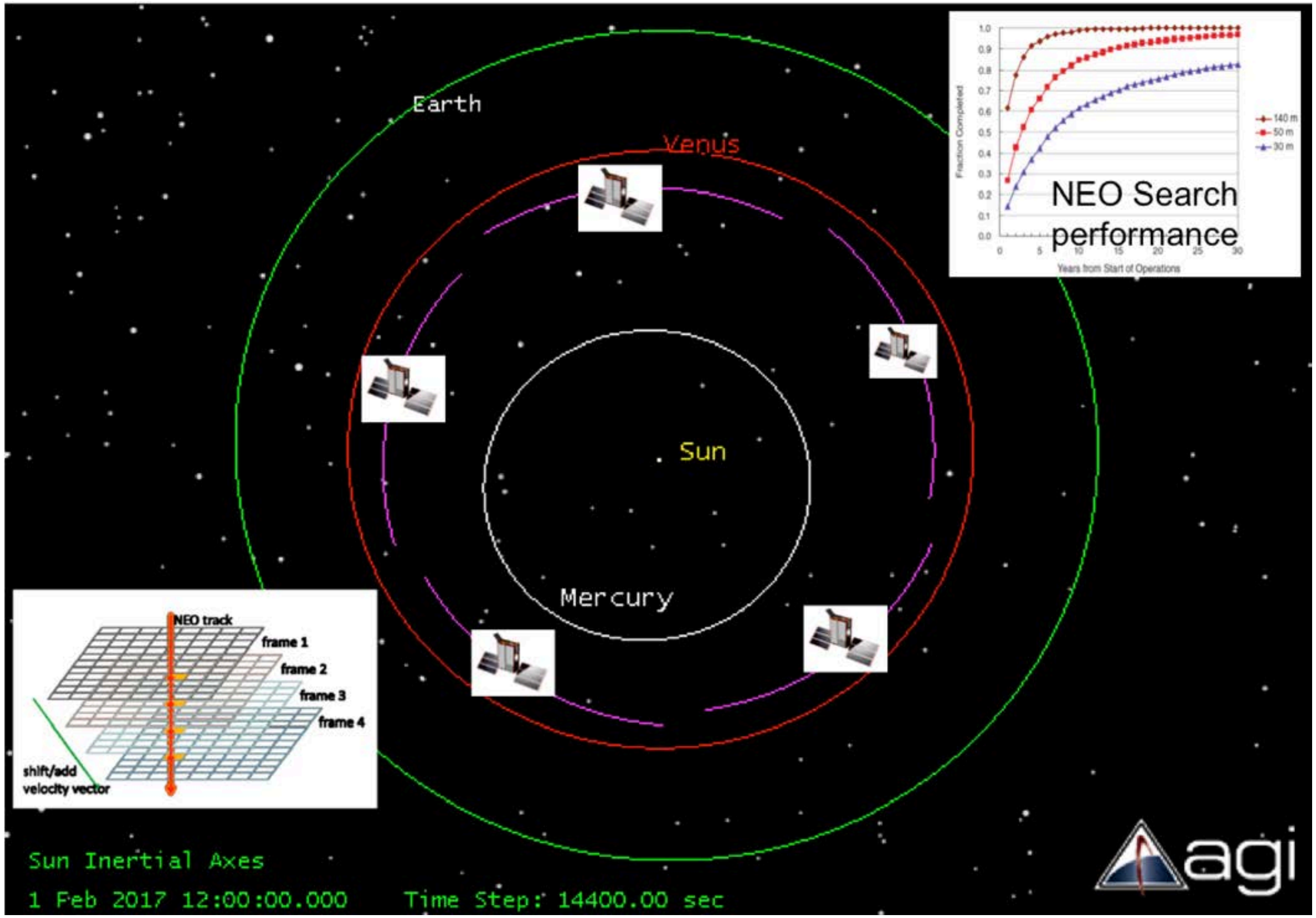
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Big Science in Small Packages: a Constellation of Cubesats to Search for Near Earth Asteroids

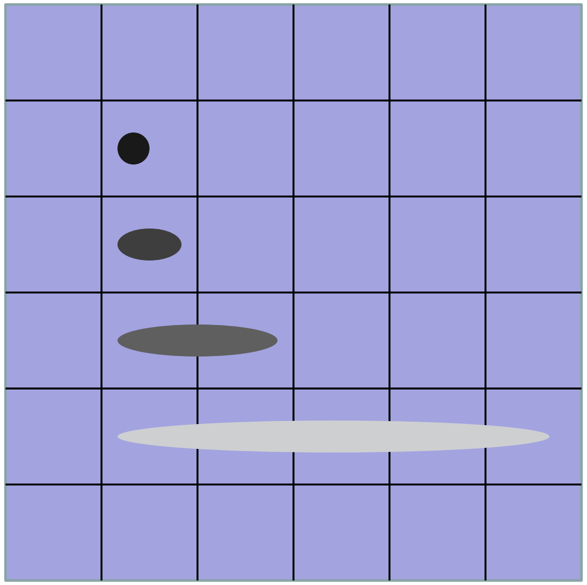


M. Shao, S. Turyshev, T. Werne, C. Zhai

Jet Prop Lab, Pasadena, California

Detecting Moving Objects

- **When an object moves on a focal plane array during an exposure, the image streaks**
- **The faster it moves, the fewer photons it leaves in each pixel**
- **Detection of an object is limited by the noise in the image**
  - Detector (Read Out) Noise
  - Photon Noise from Background
    - Space-zodiacal dust
- **Factor of 10X loss in SNR is possible**

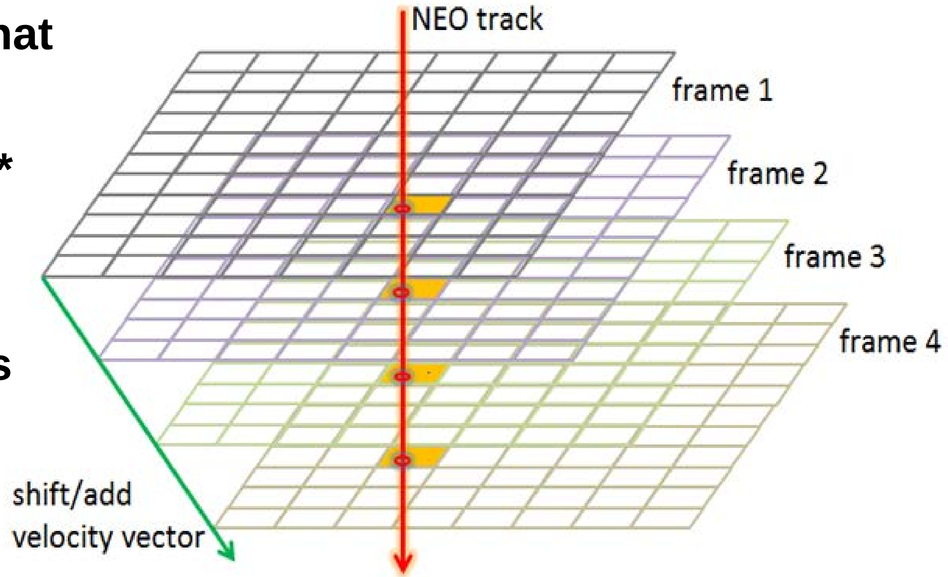


SNR increases with longer Exposure until the streak is Longer than 1 pixel.

Thereafter, the SNR actually decreases.

Synthetic Tracking Concept Overview

- **Synthetic Tracking (ST) is made possible by combining two new technologies**
  - 2nd gen sCMOS detectors (5 Mpix) with 100 fps and 1e- read noise (now 10Mpix)
  - GPU Technology: ~2500 processors in 1 Chip, ~3-4 Teraflop peak throughput
- **Developed to search for small near earth asteroids (NEAs); like the one that exploded over Russia, Feb 2013**
- **Employs a simple shift/add algorithm***
- **Since we don't know the velocity vector before "finding" the object, we have to "try" multiple Velocity vectors**
- **3-4 GFlops computing is needed to "try" many 100's of velocity vectors for Synthetic Tracking**

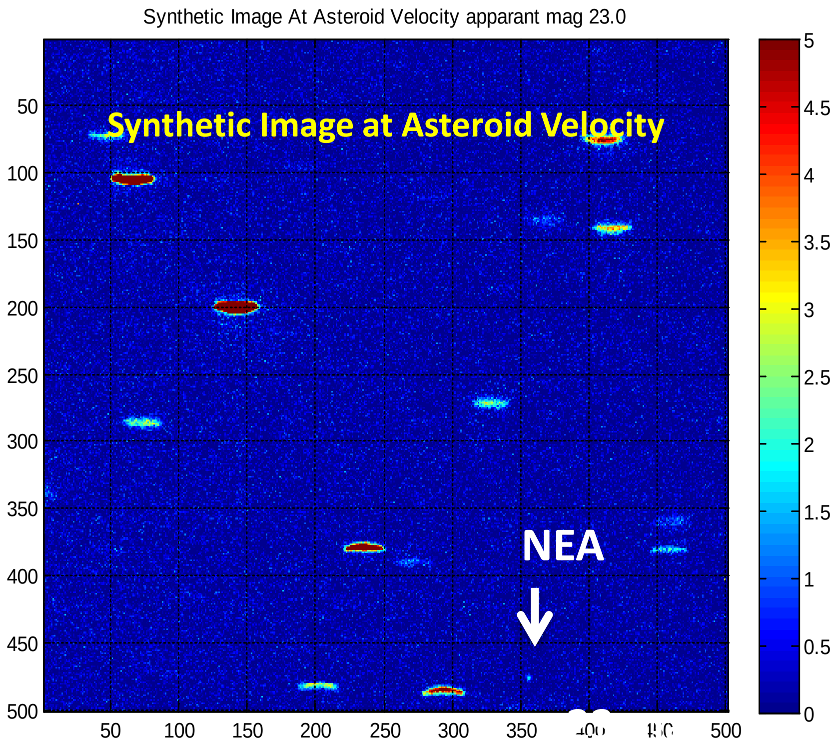


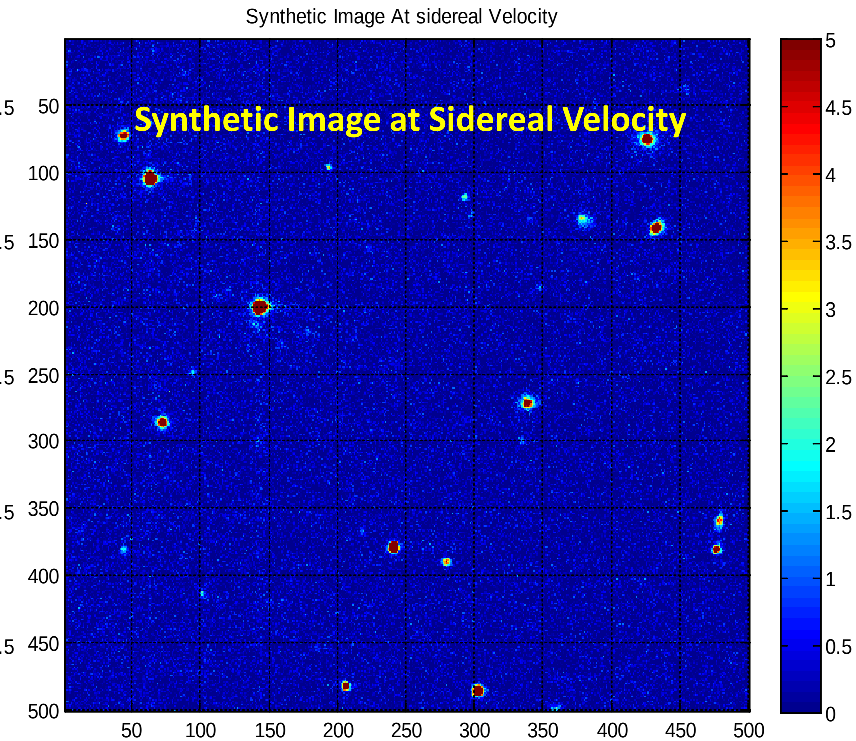
- **When the "correct" velocity vector is found**
  - All the photons from the target appear in 1 pixel (not smeared over the streak)
  - The "compact" image allows higher SNR, and more accurate astrometry

*generically called Multihypothesis Matched Filter (MHMF)

Detection of a Small Near Earth Asteroid

- Two images below were created from a datacube of ~450 images taken at 15 Hz using a ground-based telescope. The existence of the asteroid was not known when the images were taken. The 450 images were added with a constant velocity offset between adjacent images for ~10,000 different velocity vectors.
- The NEA, was detected twice, 1 hr apart with a SNR=15 each time. This NEA is 23mag, and if moving at 10km/s would be ~6 million km from Earth and ~4m in diameter.
- Without syn tracking, ~25mag and 30m dia telescope would be needed to get SNR=15



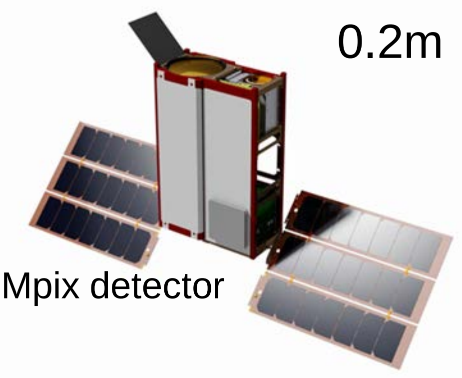


Increased Sensitivity (per telescope m^2)

- Typically a 15~30 sec CCD exposure is used for NEO search with ground based telescopes
  - LSST 24.7 mag (15sec)
  - Panstarrs ~22 mag (30sec)
  - 20cm telescope 22 mag (800 s) on nanosat

1.8m 7sqdeg

0.2m 13sqdeg

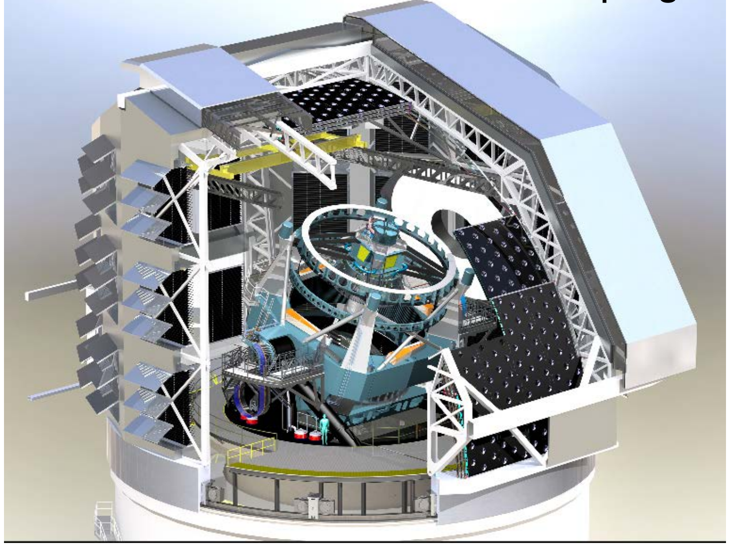


~60Mpix detector

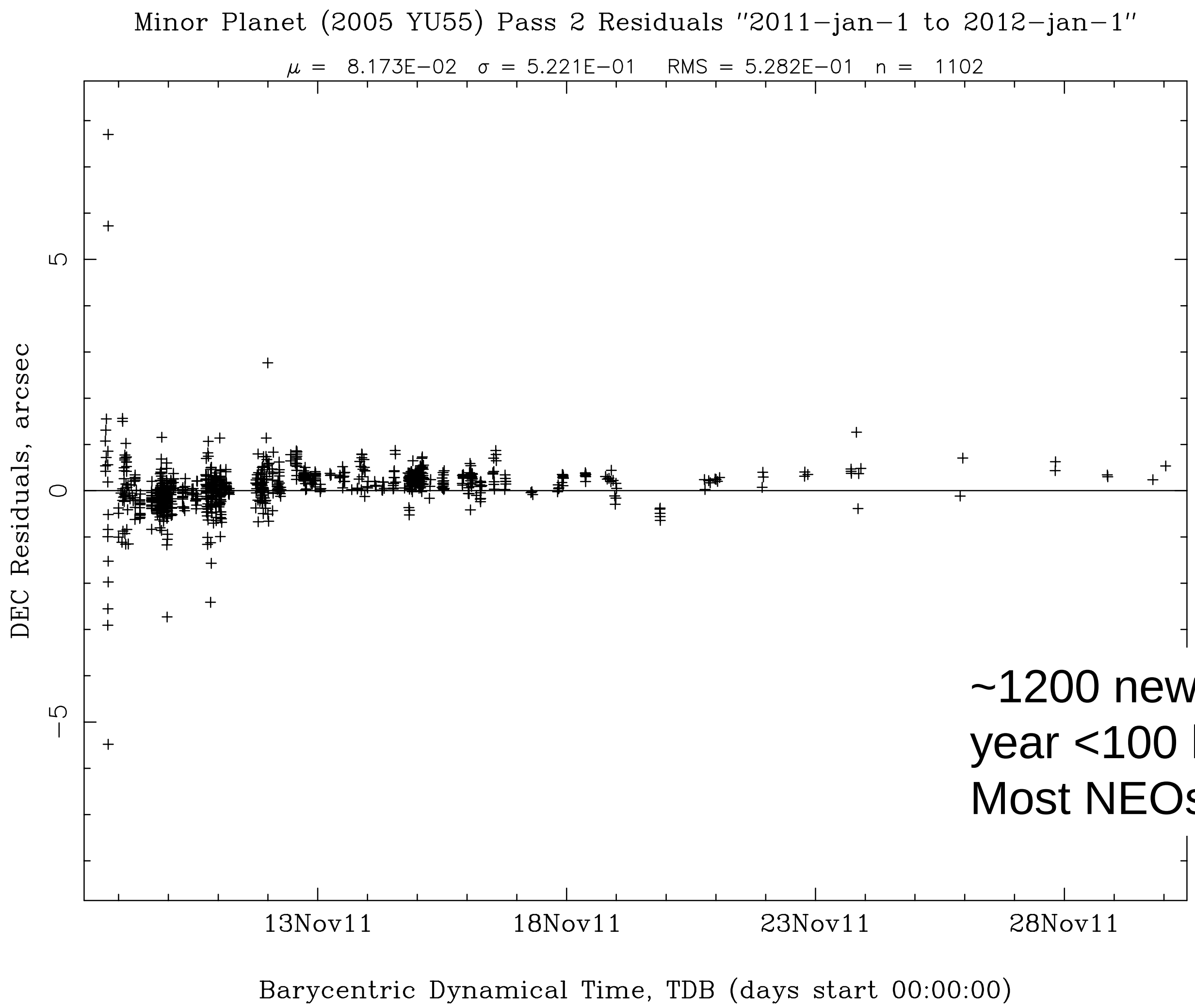
Lower sky
Background

No turbulence
Only zodi

8m 9 sqdeg



Astrometry on NEOs ~2013



Residuals of optical observations from orbit that used both optical and Radar data

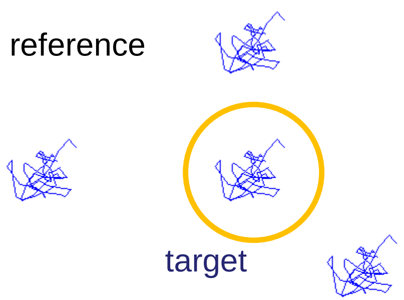
RMS 0.2~0.5arcsec

~1200 new NEOs are discovered each year <100 have radar observation. Most NEOs are found then lost.

Graph by J. Giorgini, 2013

Astrometry of Streaked Images

- **The dominent error source in NEO astrometry is due to the "streaked" image.**
- **Synthetic tracking removes the streak by a shift/add algorithm. But the image that shows the NEO as a point, has the stars streaked.**
- **In ccd astrometry one centroids the image using a least sq fit of a PSF and a 2D image. (solving for X,Y, Intensity)**
- **In synthetic.tracking we fit a "moving" PSF to a 3D datacube and we do the Lsfit to X,Y, Vx, Vy, Intensity.**



Stationary objects on sky

Image motion caused by telescope pointing and atmospheric turbulence is mostly **common mode**, and drop out, for "relative" astrometry

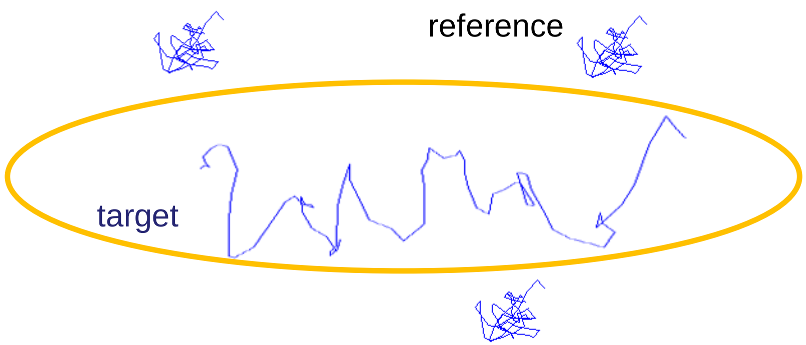
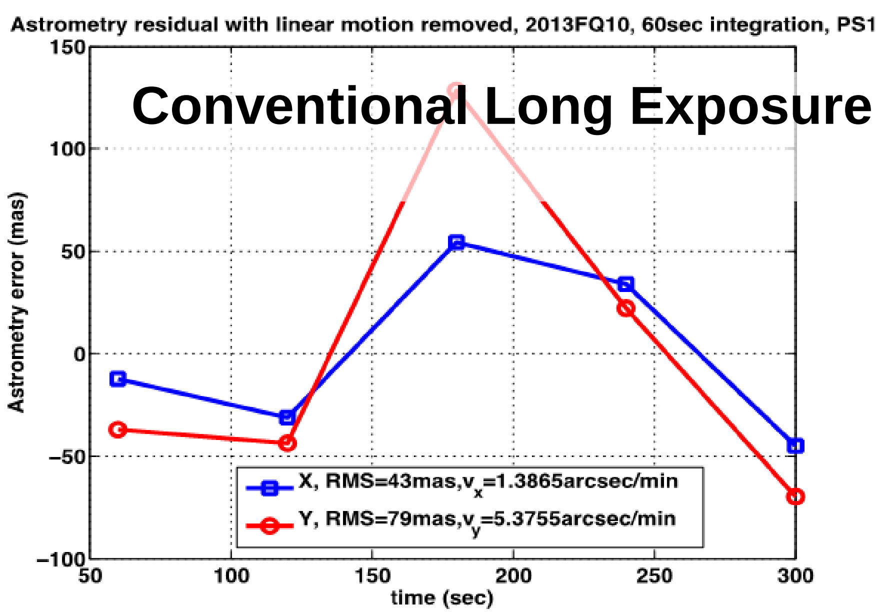
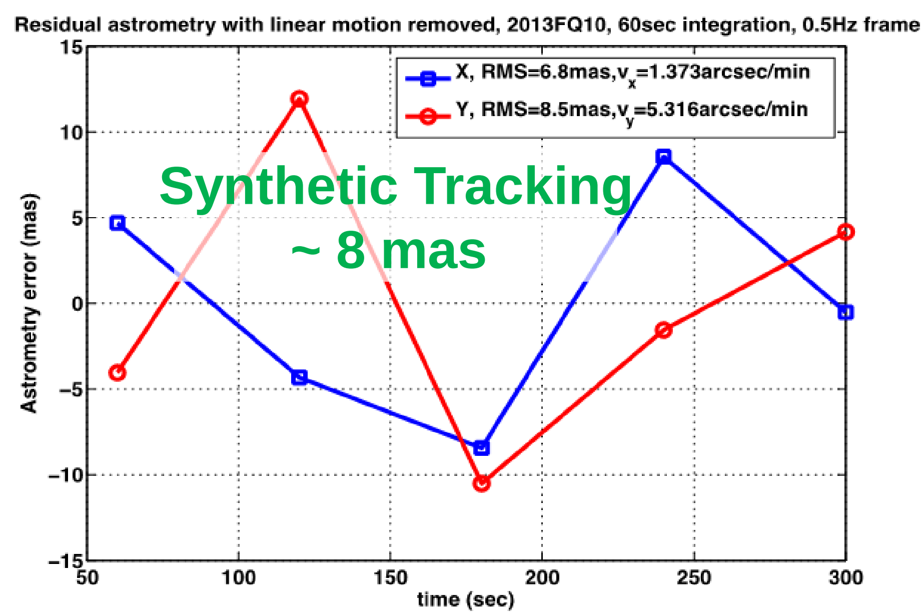


Image position of a streaked image with telescope or atmospheric jitter: astrometric errors are *no longer common mode*

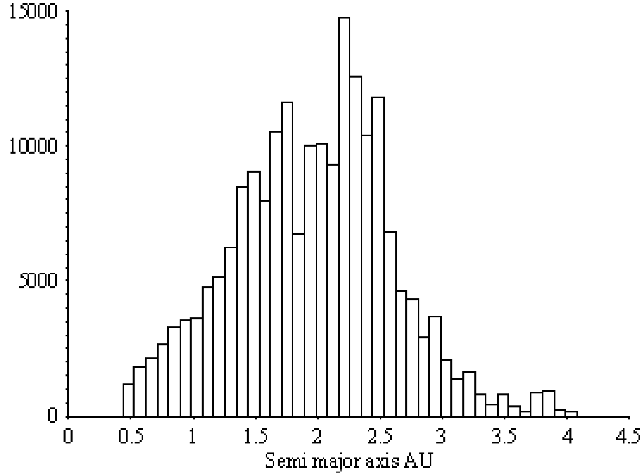
Synthetic Tracking Benefits

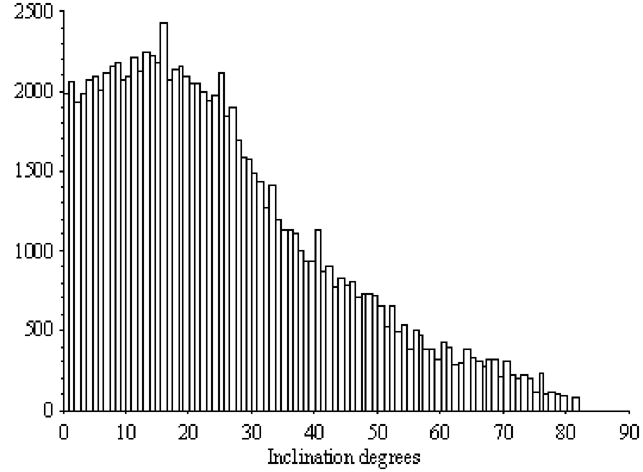
- **Ground-based tracking of asteroids limited in accuracy to ~ 0.2 arcseconds (1 μrad) mostly due to image streaking (minor contribution from atmospheric turbulence)**
  - Synthetic tracking mitigates image streaking
  - Demonstrated **~ 0.008 arcsecond** astrometry
  - Vastly improved astrometry with Synthetic Tracking can provide precise orbits



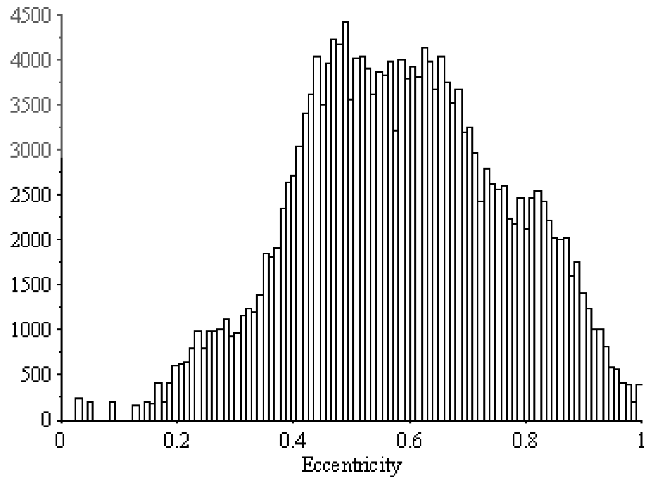


Near Earth Asteroid Population





Parent population
Of 200K NEOs



1) Start with parent population
2) Calculate MOID and identify “Impactors” here defined MOID<0.002AU
3) Searched for “impactors” using N cubesats

Fig. 6.— Orbital distribution of the synthetic parent population of the ~200,000 NEOs.

Potential Impactor Population

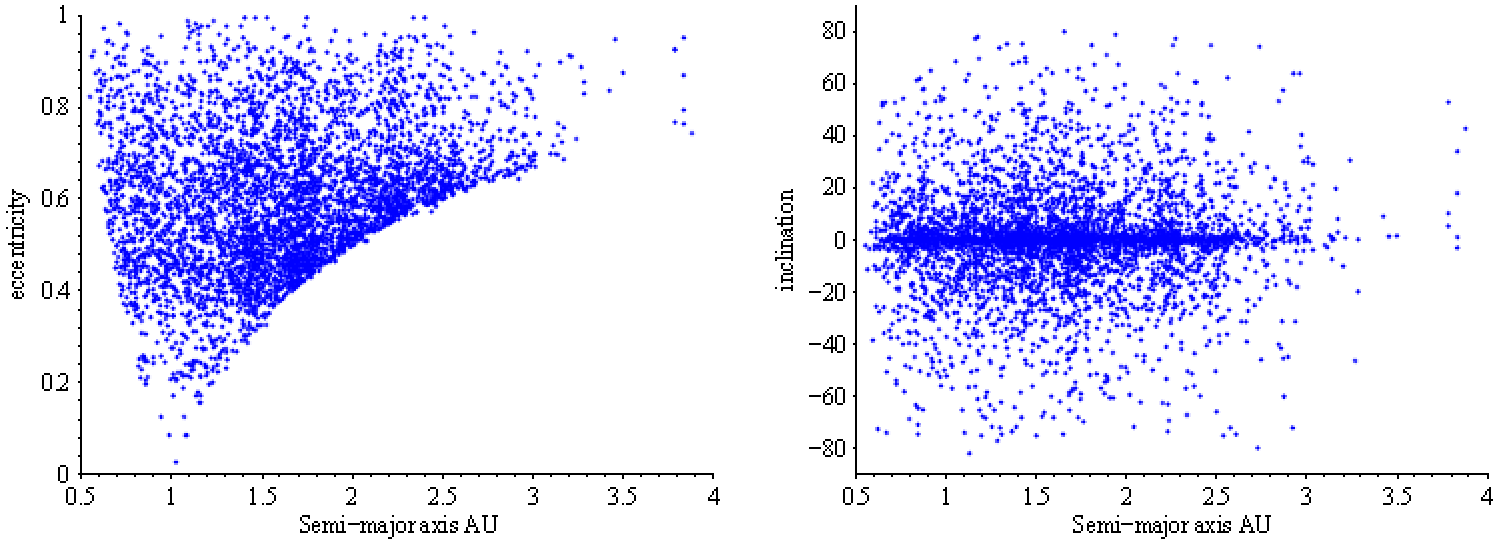


Fig. 7.— Orbital distribution of ∼5,000 "impactors" found within the parent distribution shown in Figure 6.

Starting with 200,000 NEOs ~5000 have a MOID, orbits that come within 0.002 AU ~300,000km to Earth's orbit. Very roughly ~100 would have orbits that come within an Earth Diameter.

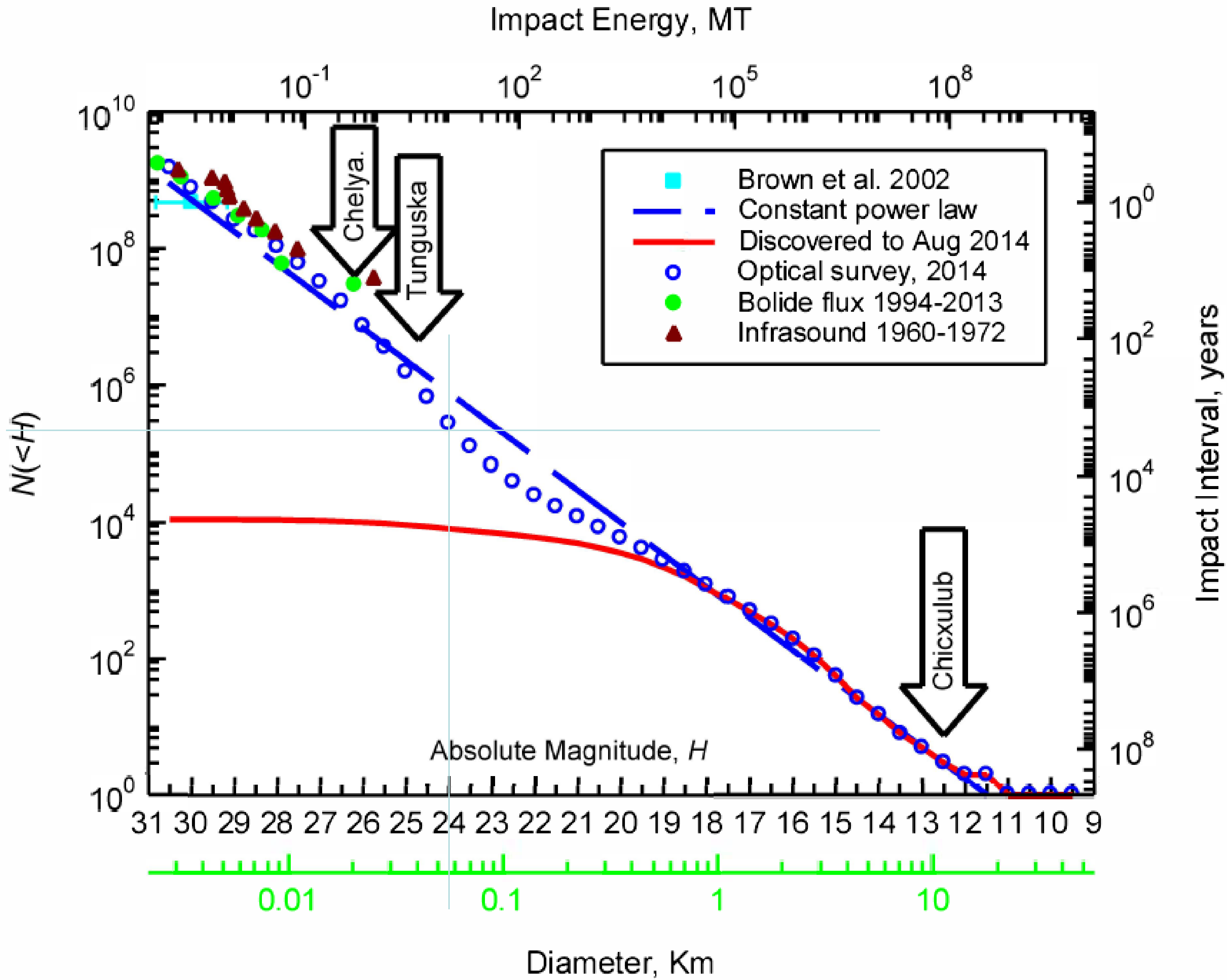
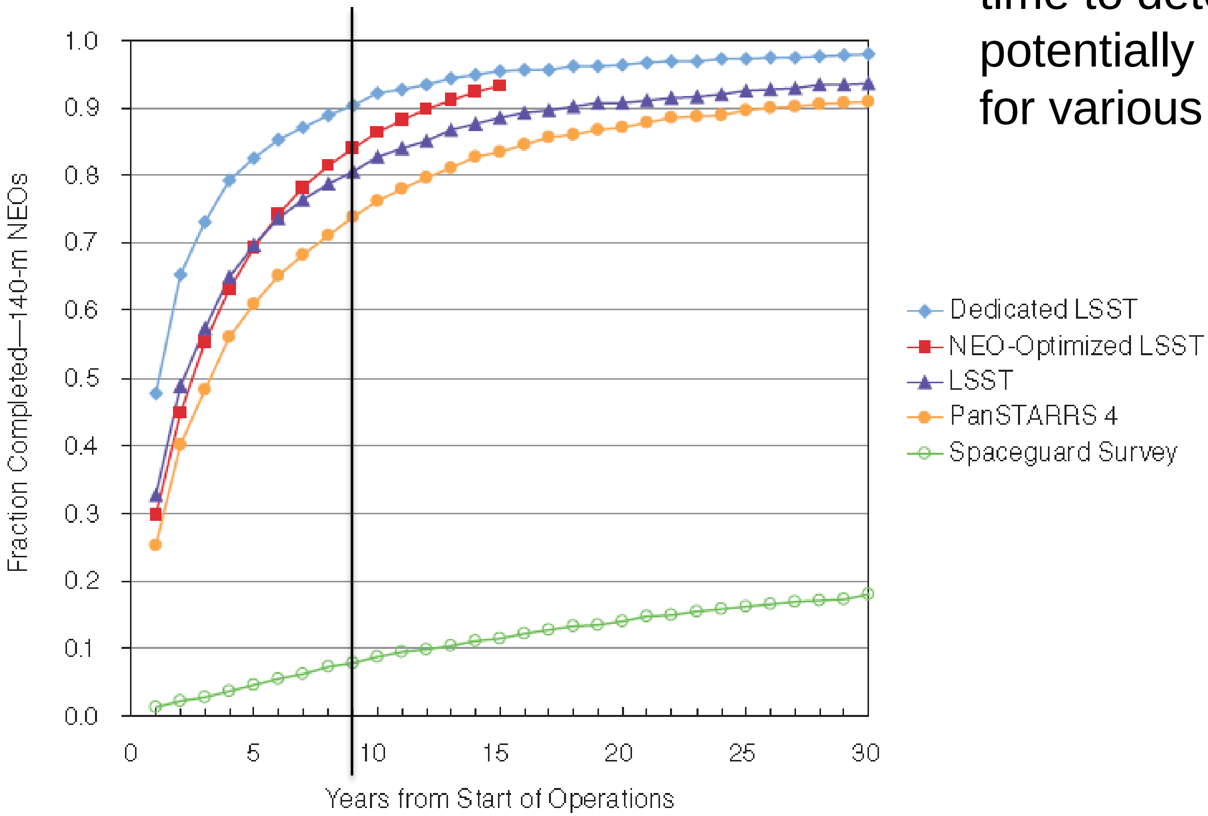


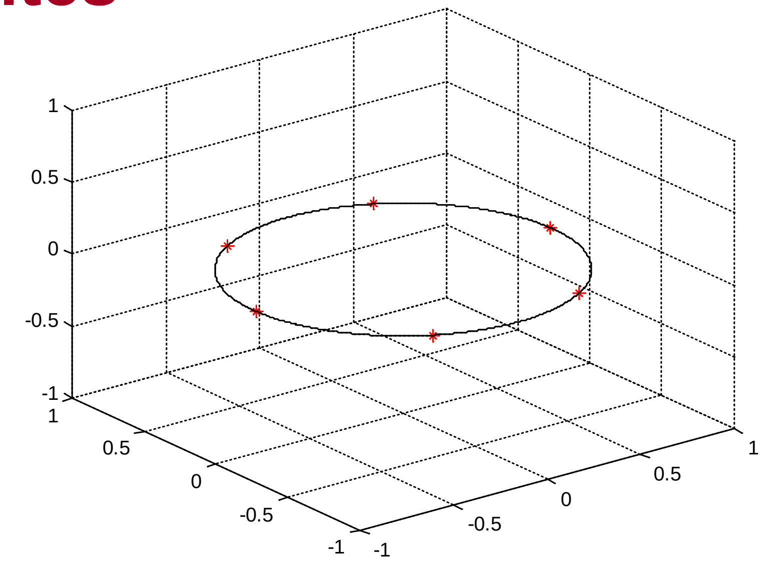
Figure 5 – Estimated cumulative population of NEAs.

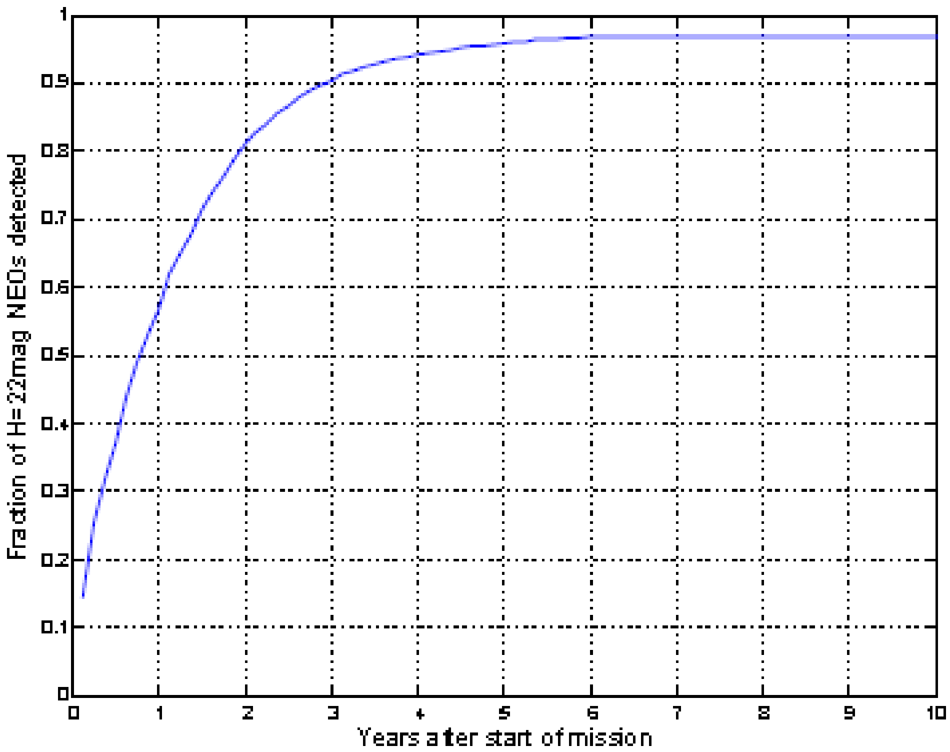
From 2010 NRC report time to detect XX % of potentially hazardous NEOS for various facilities



Hypothetical Constellation of nano/micro satellites

With small telescopes (10~20cm) and small satellites, one can consider a constellation of cubesates around the solar system.



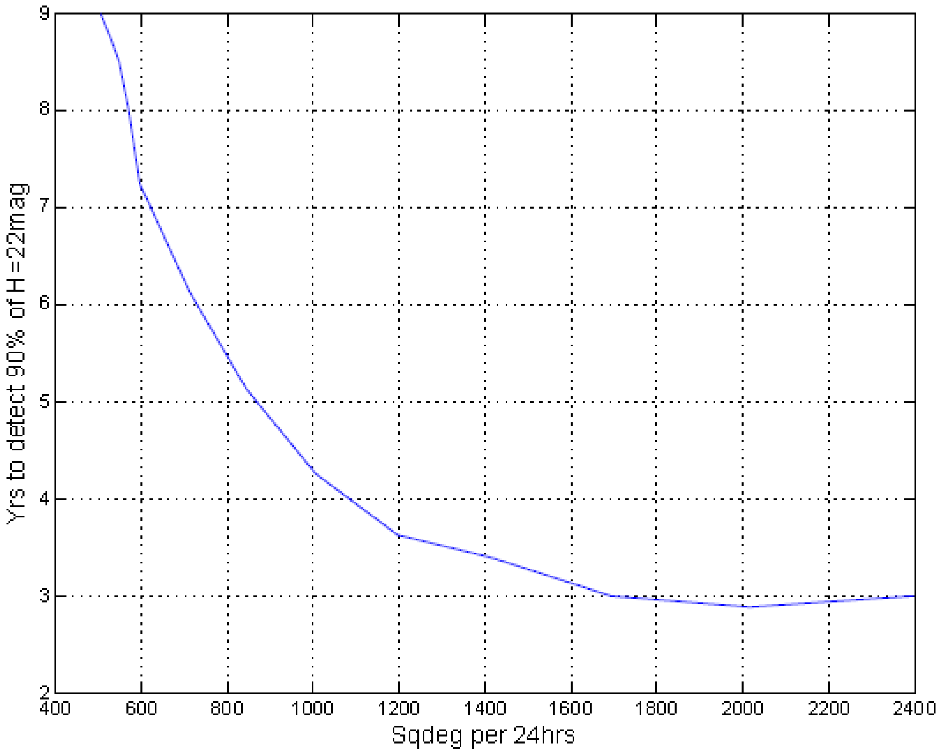


Constellation of 6 **10cm** telescopes ~3 yrs to detect ~90% of H=22mag (~140m) potentially hazardous NEOs.

14sqdeg fov, 800s/field, 60deg sun exclusion angle. 0.8AU orbit **4K^2** detector.

Parametric Studies

Why is it that a few small telescope distributed around the solar system can do such a good job of finding NEOs, compared to much more expensive facilities? What's the role of collecting area, FOV, # of satellites, the ability to look close to the Sun, the lower sky background in space?



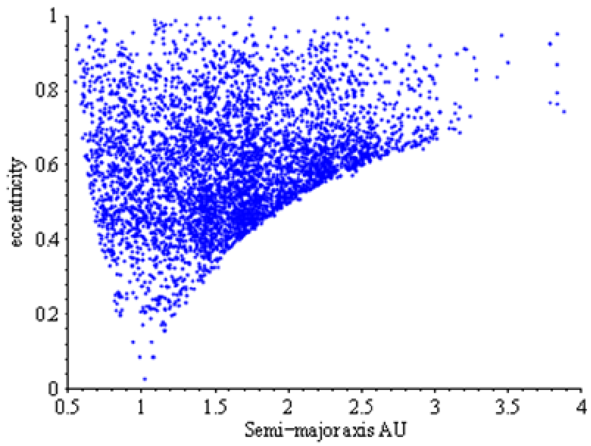
14 sqdeg/810 sec ~ 1500sqdeg/24hr

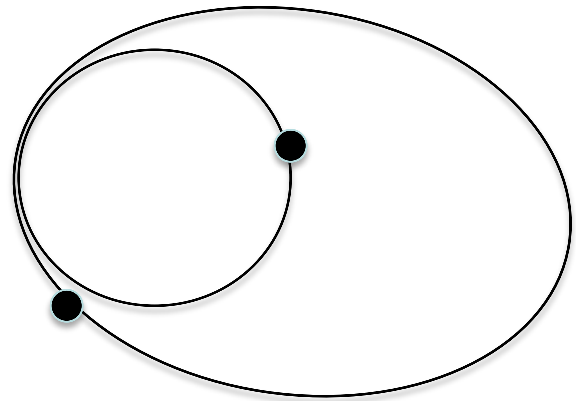
7sqdeg/45 s ~ 13,000 sqdeg/24hr
4,500 sqdeg/8hr

9sqdeg/25 s ~ 31,000 sqdeg/24hr

If one needs to scan the sky on a time scale faster than NEO sky changes. (NEO moves into detection range)

The Last 20~30% take the longest to find





A NEO with a semi-major axis of 2.5 AU has an eccentric 4 year orbit.

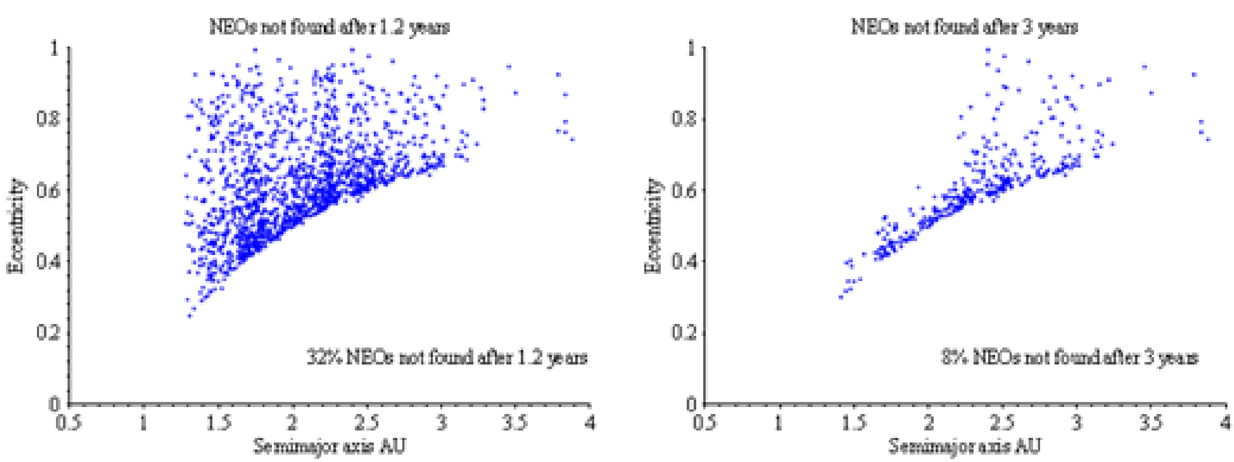
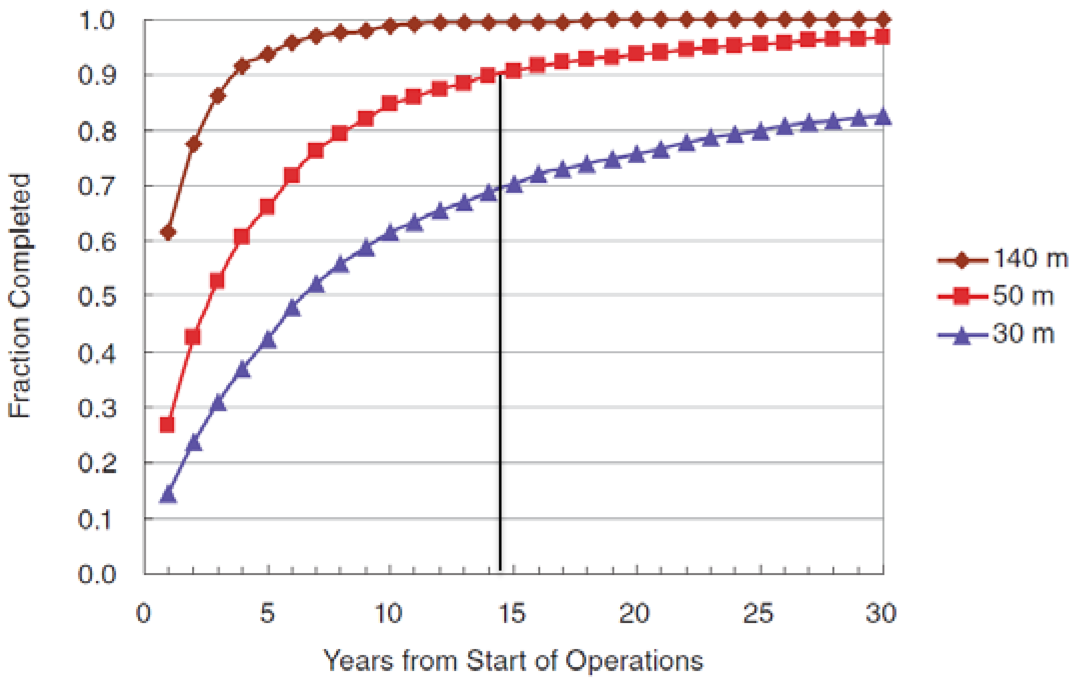


Fig. 12.— Orbital properties of NEOs that were not found after 1.2 years (left) and 3.0 years (right) with a representative CubeSat constellations in Figure 6.

For Earth based or Earth orbiting observatories, if the NEO swings near Earth's orbit when the Earth is on the other side of the Sun you have to wait another 4 yrs.

What About Smaller NEOs



From 2010 NRC report

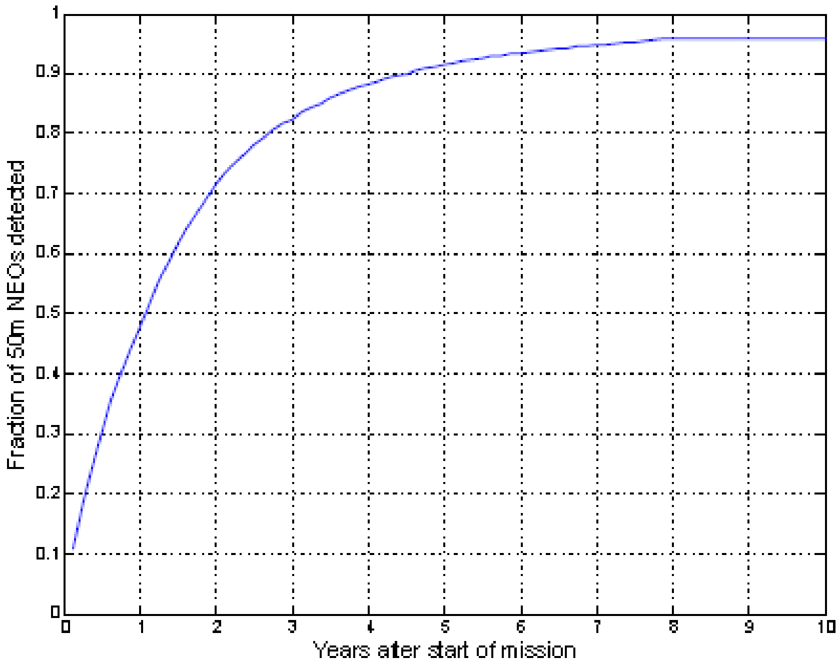
NRC report looked at a number of types of observatories to search for NEOs.

The most capable ground observatory was LSST 8m wide fov telescope

A space IR telescope in an Earth and Venus orbit were also considered.

This plot is for a combined LSST and ~0.7AU orbit space telescope. (0.7AU orbit so it's not searching the same volume of space as Earth telescopes.)

Advanced Cubesat Constellation Concept



Parameters	Value	Units
Telescope Diameter	20	cm
Image	2X	diff limit
Pixel size	1.6	arcsec
Effective background	2.8	arcsec
Magnitude limit	22.15	mag
Integration time	800	s
Number of satellites	8	
NEO size	50	m
H magnitude	24.24	mag

% of 50m NEOs detected vs time
For 8 cubesat constellation of 20cm
Telescopes.

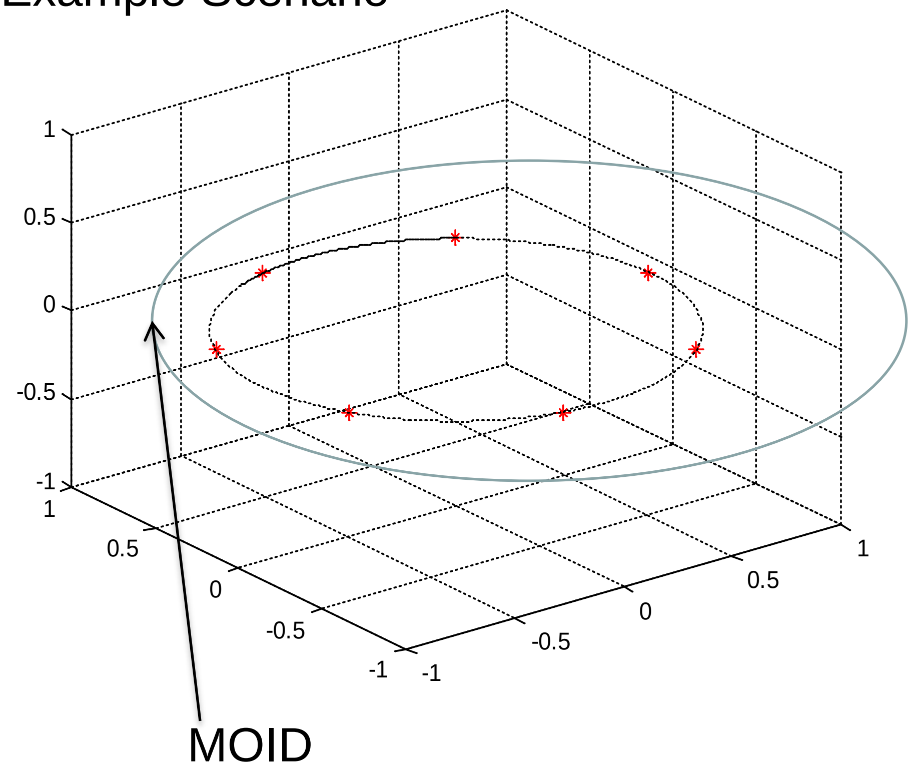
Detection, Cataloged, Orbit

- Detection means the NEO was detected at least once.
  - The problem is that a single detection almost always means the NEO is subsequently lost.
- A cataloged/linked observation is a **series** of observations that enable a “crude” orbit to be calculated. The idea is that two “cataloged” observations can be linked even if the two data sets are taken decades apart.
  - Typically this requires 3~4 observations taken over 22~28 days.
- An accurate orbit means 4 or more observations that covers a long orbital arc (120deg of the 360deg orbit). An accurate orbit is one where the MOID uncertainty is < ~ 1 earth diameter.

Minimum Orbit Intersection Distance

- If the MOID of the NEO orbit and Earth's orbit is < ~2 Earth radius the NEO will eventually impact the Earth.
- One advantage of a constellation of small satellites is that it can get a good orbit in a single pass of the NEO.
- 4 observations over 120deg orbital arc (0.4 arcsec ast accuracy) => MOID err ~2Re

Example Scenario



For ~50m Asteroids impact interval 500~1000 years.

A cataloged observation, if it predicted a 0 MOID would have only 1e-4 chance of collision.

Summary

- Several technologies have recently become available that together enable a major advance in the detection of Near Earth Asteroids.
  - Low noise, high speed detectors
  - High speed computing in space
  - Cubesat type technology that significantly lowers the cost of putting a constellation into space.
- The biggest impact of this technology would be when we start looking for 40~50 m sized NEOs and we want an accurate orbit for those objects, so we know which 200~500 out of a 500K~1M of them will eventually hit the Earth.