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B612 and Ball NEO Survey Studies

Presentation to the
National Academies Committee on Near Earth Object Observations in the Infrared and Visible Wavelengths

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Ball (retired) and B612 Foundation

February 25, 2019

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Outline

- Ball/B612 NEO Mission studies
- Lessons Learned from Sentinel and Synthetic Tracking studies
- Importance of the “Virtual Impactor” population for Planetary Defense
- Overview of Sentinel mission
  - Performance model predictions
- Overview of SmallSat synthetic tracking mission
  - Performance predictions
- On-orbit synthetic tracking demonstration

Early B612/Ball NEO Survey Activities

- 2002 Planetary Defense Conference presentation by Ball of a mission concept for a 60-cm visible telescope in a Venus-distance heliocentric orbit
- 2006 NASA NEO Workshop presentation of a visible wavelength survey telescope using Kepler 1-m optics and 96 megapixel detector
- 2009 Target NEO workshop presentation of a 0.5-m IR telescope
- 2009 Presentation of NEO-Survey mission concept to NRC Committee to Review Near-Earth Surveys and Hazard Mitigation Strategies
- 2010 B612 and Ball coordinated in developing the Sentinel mission concept
- 2012 Sentinel Program Implementation and Concept Review presented to a Standing Review Board
- 2012-2015 NASA Space Act Agreement for tech support and data sharing
- 2015 B612 funded studies at CalTech (Shao) to study Synthetic Tracking (st)
- 2017 B612 teamed with Planet Labs to collect ST data on known asteroids to study space-based application issues, CalTech analysis

Survey Design Lessons Learned

1. Large aperture and wide field of view (AΩ) are essential for surveys. Key technologies are widefield telescope optics and large-format detectors.
2. **Infrared and visible wavelengths each have advantages. Infrared surveys are more technically challenging but give better results for comparable cost.**
3. **Reliable orbit determination requires multiple observations of an object over an extended epoch. This topic needs thorough investigation but community consensus is that ~1 month span of observations will ensure targeted recovery during the next apparition. This time span is more difficult for fainter NEOs.**
4. **Adjacent observatories largely duplicate detections, making heliocentric orbit advantageous. Multiple heliocentric longitude stations are additive for small objects.**
5. **Small NEOs must be closer than larger NEOs for discovery, and close objects have higher apparent motion, causing them to cross pixel boundaries, preventing long integration times. Synthetic tracking is a method to address discovery of fast-moving objects. (The next significant impact will be by a small NEO.)**
6. Many objects have long synodic periods or highly elliptical orbits, requiring long survey durations to reach high completeness levels.
7. Design optimized for impactor detection also finds rendezvous/landing candidates.

Comparison Of Visible And IR Technical Issues

Visible

+ Mature detector technology
  - Large format
  - Low noise
  - Good photometric perf.
+ Modest detector thermal requirements
+ No thermal requirements on optics
- **Strong phase dependence for brightness**
- **Substantial background confusion**

Infrared

+ Low albedo objects are bright in IR
+ Gives reliable size estimate
- Detector technology not as mature as visible
- IR detectors require low T
- IR optics need cooling to eliminate thermal emission
+ **Less-demanding optical quality**

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Importance Of "Virtual Impactor" Population

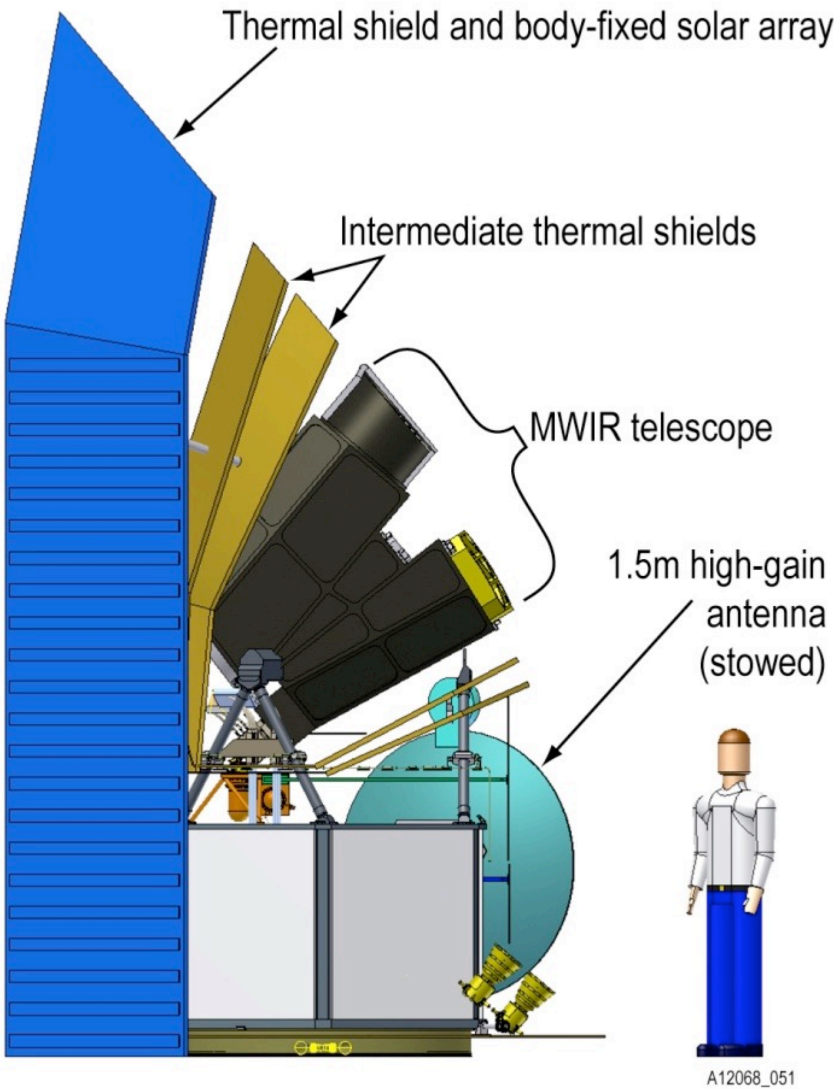
- "Virtual Impactors" (VI) are a modeled population of NEO orbits that will intersect with the Earth within 100 years.
- This is a subset of NEOs that is most important to Planetary Defense
- A search that is motivated by Planetary Defense interest can be optimized for this sub-population of NEOs
- VIs are a subset of NEOs with orbits that typically have lower eccentricity, lower inclination and semi-major axes lower than for the general NEO population, mostly in the range 1-2 AU
- Mission optimized for VI discovery finds ~2x as many small VIs than a NEO-optimized survey
- VI population is also of interest to missions that intend to rendezvous or soft-land on the NEO. The Delta-V required to visit these objects is often under ~2 km/sec. Such missions include human, science and resource utilization missions.

A science survey optimized for Virtual Impactors has additional practical applications.

Sentinel Mission

Sentinel Observatory

- Concept developed at Ball Aerospace beginning in 2007
- “Discovery-class”
- Spacecraft
  - 7.7 m (25.4 ft) tall x 3.2 m (10.5 ft) across
  - 1,500 kg (3,300 lbs)
  - 2.0 kW solar array, 24 Ahr battery
- Instrument
  - 50-cm telescope
  - Field of View: 11 deg^2
  - HgCdTe detector cooled to 40 K
  - 30 megapixels
  - 5-10.4 mm wavelength range
- Data Handling
  - Large data volume compression by on-board identification of moving objects
- Launch Vehicle – Space X Falcon 9

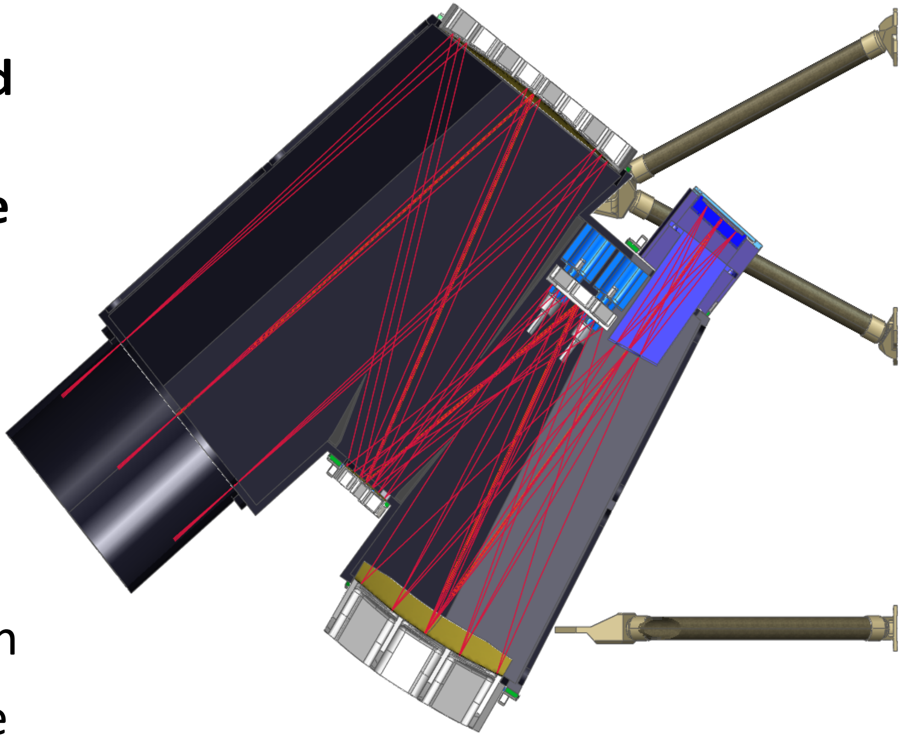


Sentinel Parameters

Item	Value	Notes
Telescope Aperture	50 cm unobstructed	Passively cooled to 65K
Pixel Scale	2.2 arcsec/pix	1.6x Diff @ 8.5 um wt'd mean λ
Read noise	110 e-/pixel	per readout
Dark current	600 e-/sec	Active closed-cycle cooling to 30K
Field of View	2◦ by 5.5◦	2x5 detector mosaic
Fill Factor	96%	small gaps between detectors
Wavelength	5 – 10.2 μm	5 um cut-on filter, 10.2 set by detector
Exposure	180 sec	six 30-sec images
Field of Regard	Solar Elongation > 80◦	set by sunshade
Observing Cycle	28 days	covers FOR four times
Cycle Cadence	0, 1h, 48h, 49h	two pairs
Semi-major axis	0.66 AU	Similar to Venus
Eccentricity	0.091	Not critical
Inclination	0.27◦	Not critical

Sentinel Wide-Field Telescope Design for IR

- 50-cm aperture, f/6 focal ratio
- **4-element system for unobstructed view over 5.5 x 2 degree field of view with diffraction-limited image quality**
- Includes a fold mirror to provide access to focal plane for alignment and cooling
- All aluminum for thermal stability
- Forms a pupil for straylight rejection
- Passively cooled to 65K to eliminate signal noise from thermal emission from optics



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Sentinel Mission Performance Modeling

- Two independent models of NEO detection were developed under B612 Foundation guidance.
- Both models included
  - NEO population models
  - NEO radiometric properties
  - Telescope and detector physical properties
  - Spacecraft orbit and operating efficiency
  - Observing parameters including cadence, exposure time and observing plan.
- The models keep track of each NEO and recorded detection SNR and astrometric accuracy.
- Models were used to investigate contemporaneous observations with ground-based observatories (LSST was the reference).
- Model figures-of-merit were the percent of the NEO population that were seen at least once ("discovered") with SNR > 5 and the percent of NEOs that were seen at least three times in a 1-month period ("cataloged").
  - Model by Dr. Roger Linfield (initially at Ball Aerospace)
    - Used for design tradeoffs during concept development of the Sentinel Mission
  - Model by Dr. Marc Buie (SwRI)
    - Used to evaluate orbit and observing cadence variations

Detailed performance models are essential to survey mission design.

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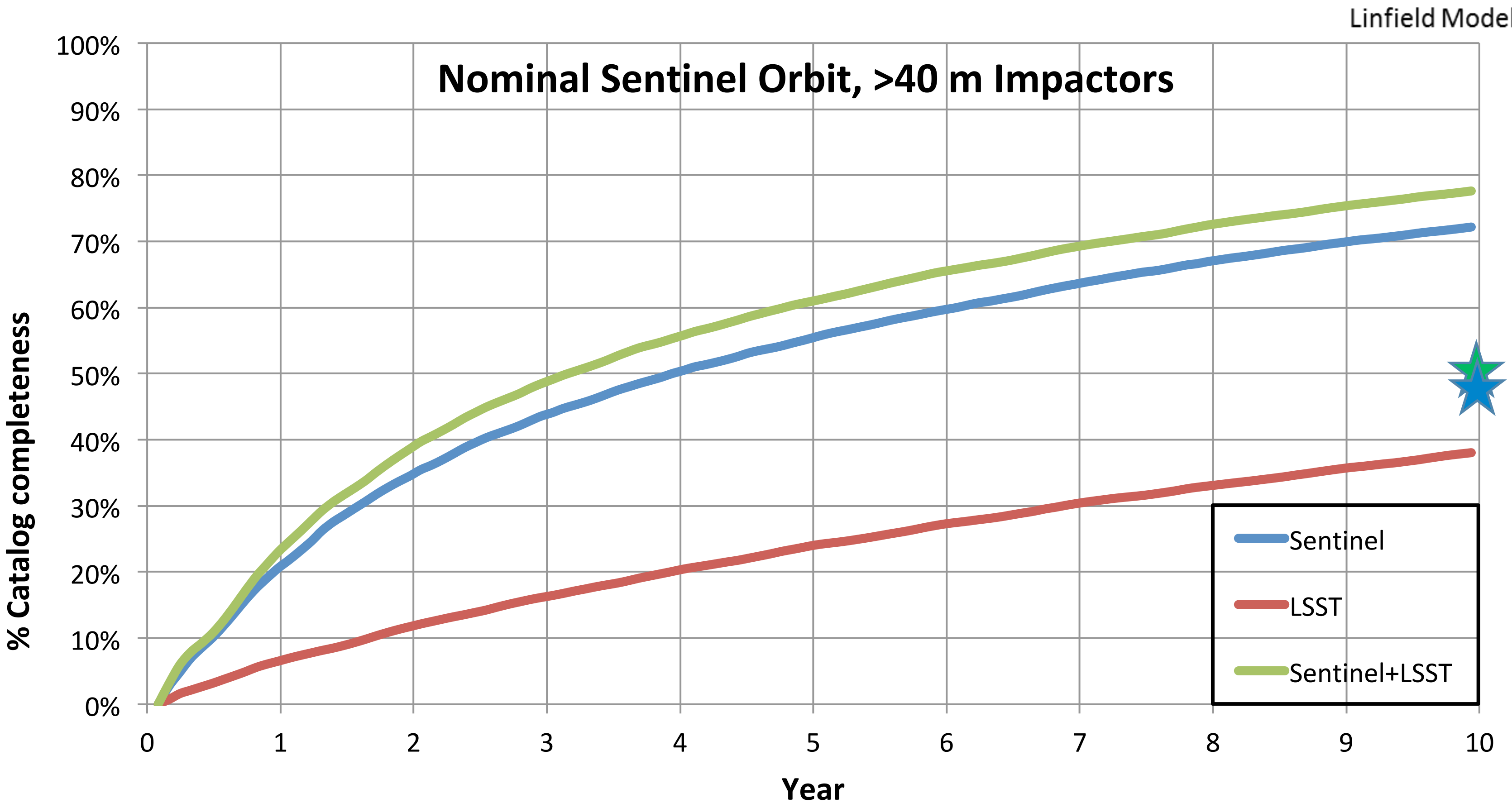
Sentinel Performance Model Results

Linfield Model

NEA population	LSST (6.5 yr)	LSST (10yr)	Sentinel (6.5 yr)	Sentinel (10 yr)
>140 m NEAs (GEB)	60%	71%	83%	91%
>40 m NEAs	12%	17%	30%	38%
>20 m NEAs	3%	4%	8%	12%
>140 m impactors	69%	77%	94%	97%
>40 m impactors	28%	37%	62%	72%
>20 m impactors	11%	15%	27%	34%

40m virtual impactors are detected at ~2 times the detection rate for NEAs

Performance Of Sentinel With LSST – 40m Impactors



★ Stars indicate performance for Sentinel in an Earth L2 orbit

Sentinel sees most of the objects that LSST does, but also many more.
Sentinel with unmodified Field of View at Earth L2 is redundant with LSST.

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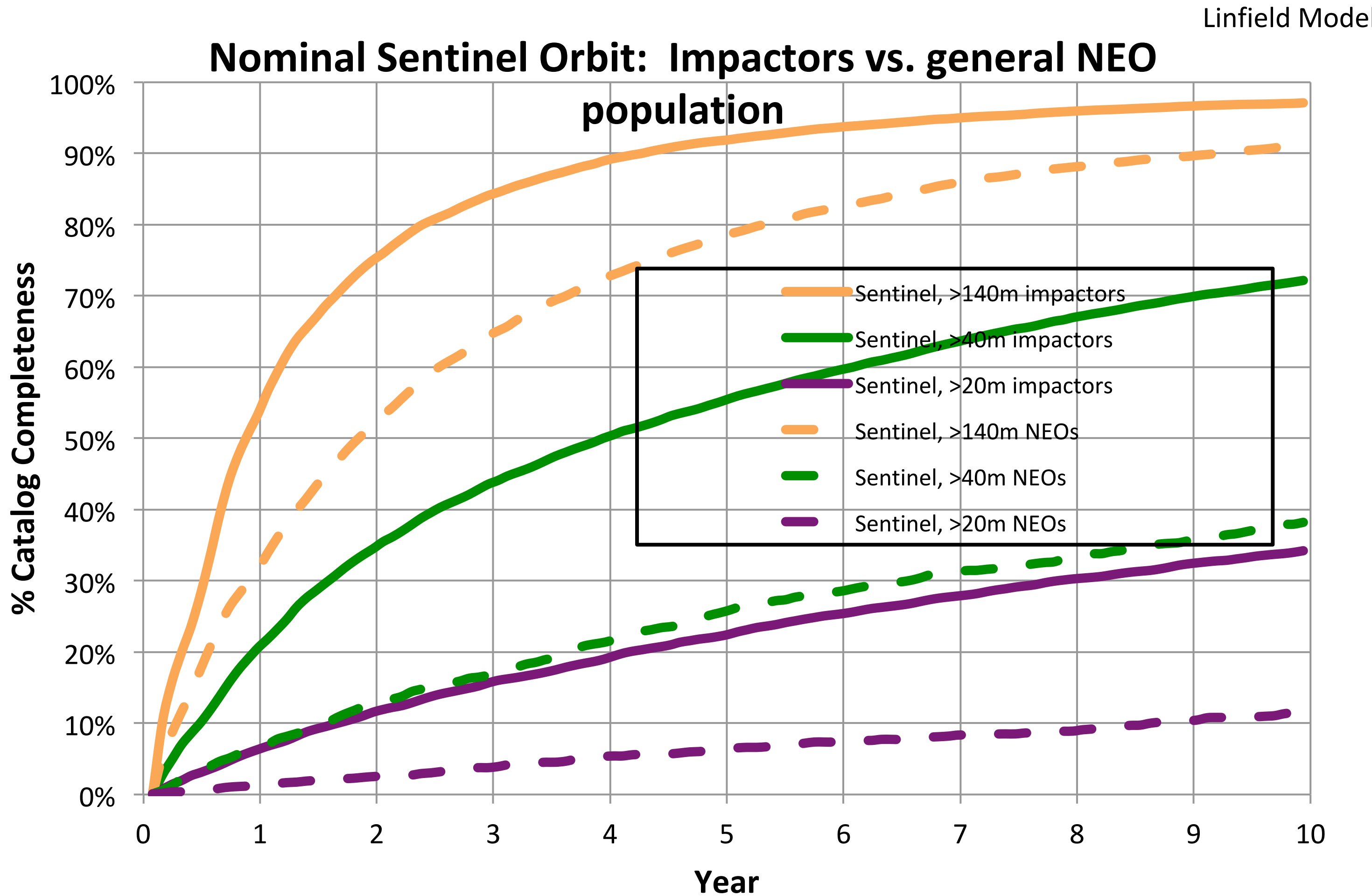
Comparison of NEO and Impactor Performance



40m virtual impactors are detected at 2x the detection rate for 40m NEOs

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Survey Completion For Impactors, With LSST

Buie Model

Population	Sentinel (6.5 yr.)	LSST (10 yr.)	S+L	f_S	f_L	f_{S+L}
NEA (D > 140 m)	82%	69%	91%	4%	10%	66%
NEA (D > 40 m)	27%	15%	34%	56%	21%	23%
NEA (D > 20 m)	8%	4%	10%	60%	20%	20%
VIMP (D > 140 m)	93%	83%	97%	14%	4%	82%
VIMP (D > 40 m)	57%	35%	67%	48%	15%	37%
VIMP (D > 20 m)	23%	13%	30%	57%	23%	20%

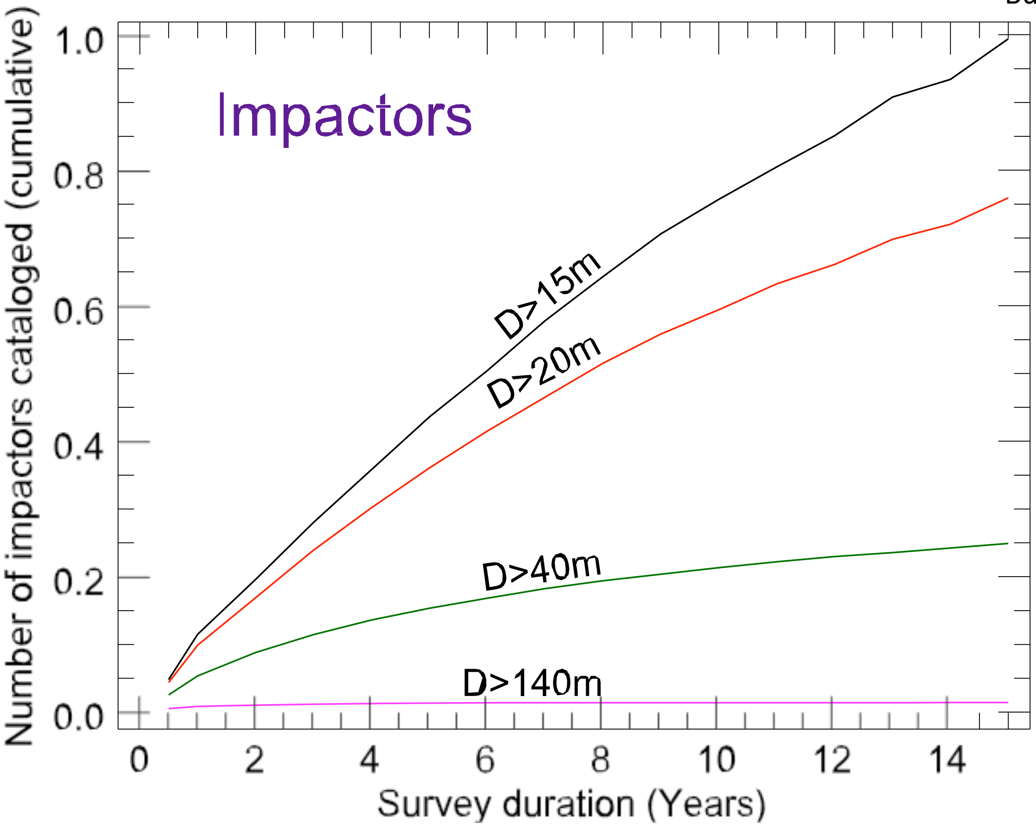
There is about 50% overlap in catalog efficiency between Sentinel and LSST

f_S is fraction seen only by Sentinel
f_L is fraction seen only by LSST
f_{S+L} is fraction seen by both

Impactor Catalog Completeness With Time

- When only a small fraction of objects have been cataloged completeness rate is nearly linear with time.
- Long duration surveys will be required for small objects – the survey only finds them when they come close.

Buie Model



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Observing Arc Affects Recovery

Baseline Cadence Linkage Summary

Buie Model

N_{obs}	N_{cycles}	arc	predict	σ_ξ (arcsec)	σ_η (arcsec)
2	0.5	1 hr	2 day	229	251
4	1	2 day	26 day	8640	11520
8	2	28 day	28 day	30	69
12	3	56 day	28 day	2.0	3.7
12	3	56 day	10 year	37	12

Note – This table shows the sky-plane uncertainty at the time each linkage is made. In extending the arc from discovery into being cataloged, N_{obs} is the cumulative number of observations over N cycles (where one cycle is 28 days) that are used to support each linkage. "Arc" gives the length of the constraining arc and "predict" gives the extrapolation time from last linked observation to the new data being linked. Astrometric uncertainty was assumed to be 1.3 arcsec per observation.

- 2 observations separated by 1 hour give a prediction on the location 2 days later that has an error of >200 arcsec
- A set of 12 observations spread out over 56 days gives a very good prediction for at least 10 years.

Observing cadence is important to determining orbits for detected NEOs

Discovery Locations – Venus and Earth - NEOS

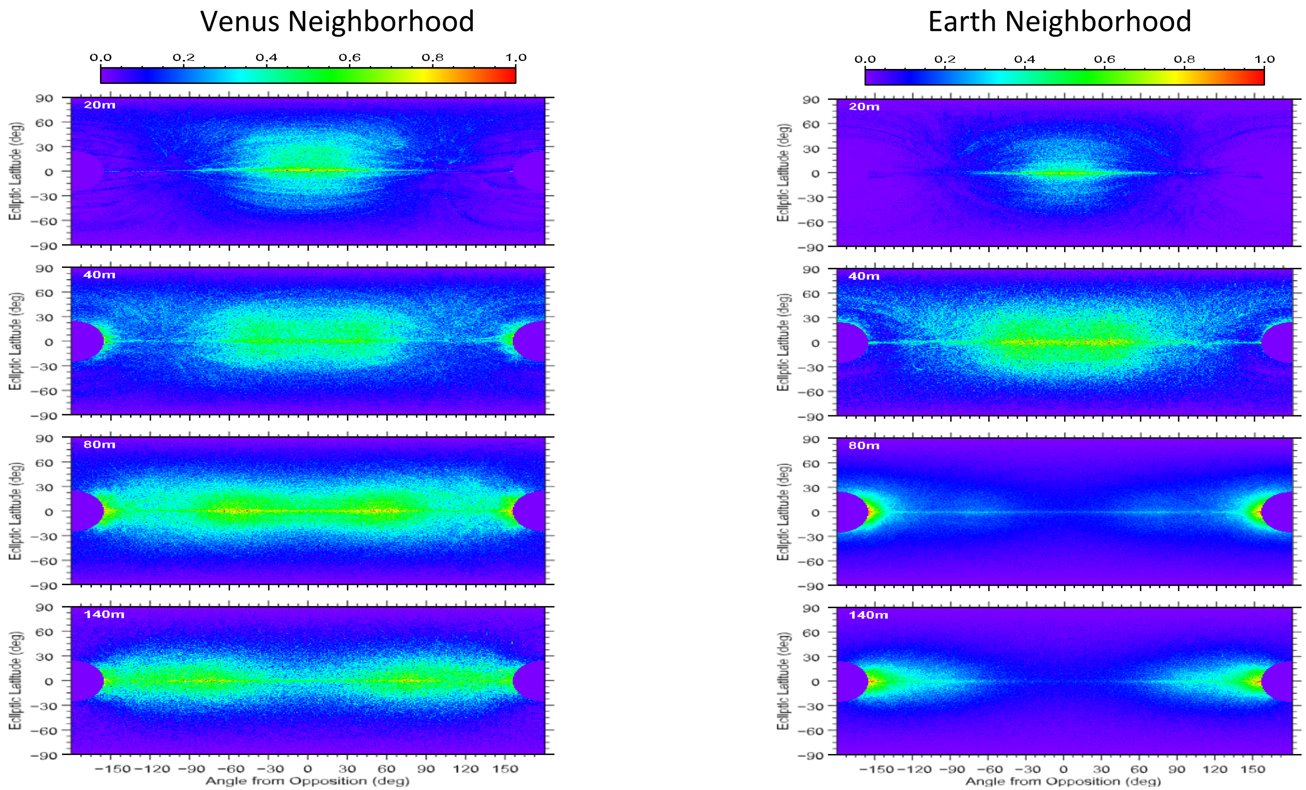
Buie Model

20m

40m

80m

140m



- Coordinates x,y are ecliptic latitude and longitude with the anti-sun point in the center
- Locations of individual detections are shown. Orbit determination requires detections over an span of time, rewarding detectability over a range of viewing angles

Observations from inner solar system orbit can see objects over a much orbital arc

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Discovery Regions for Virtual Impactors

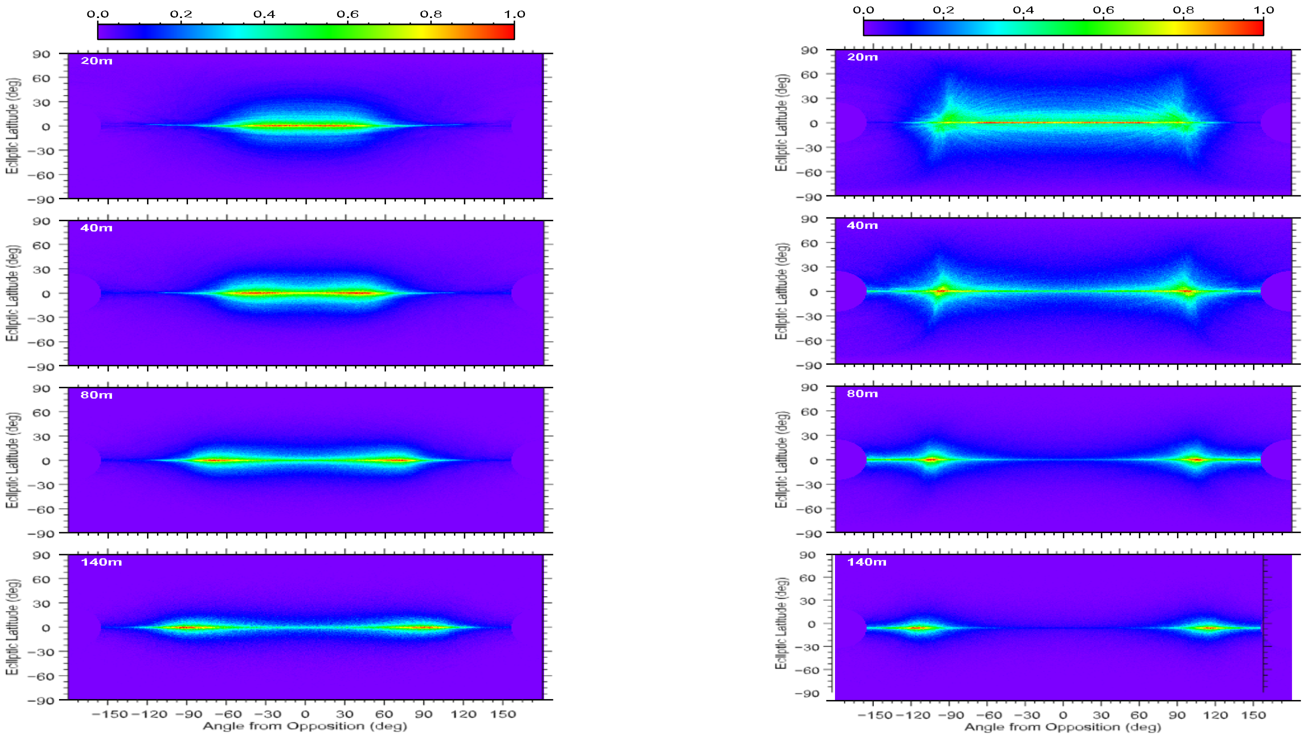
Venus Neighborhood | Earth Neighborhood | Buie Model

20m

40m

80m

140m



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B612/CalTech Synthetic Tracking Investigation

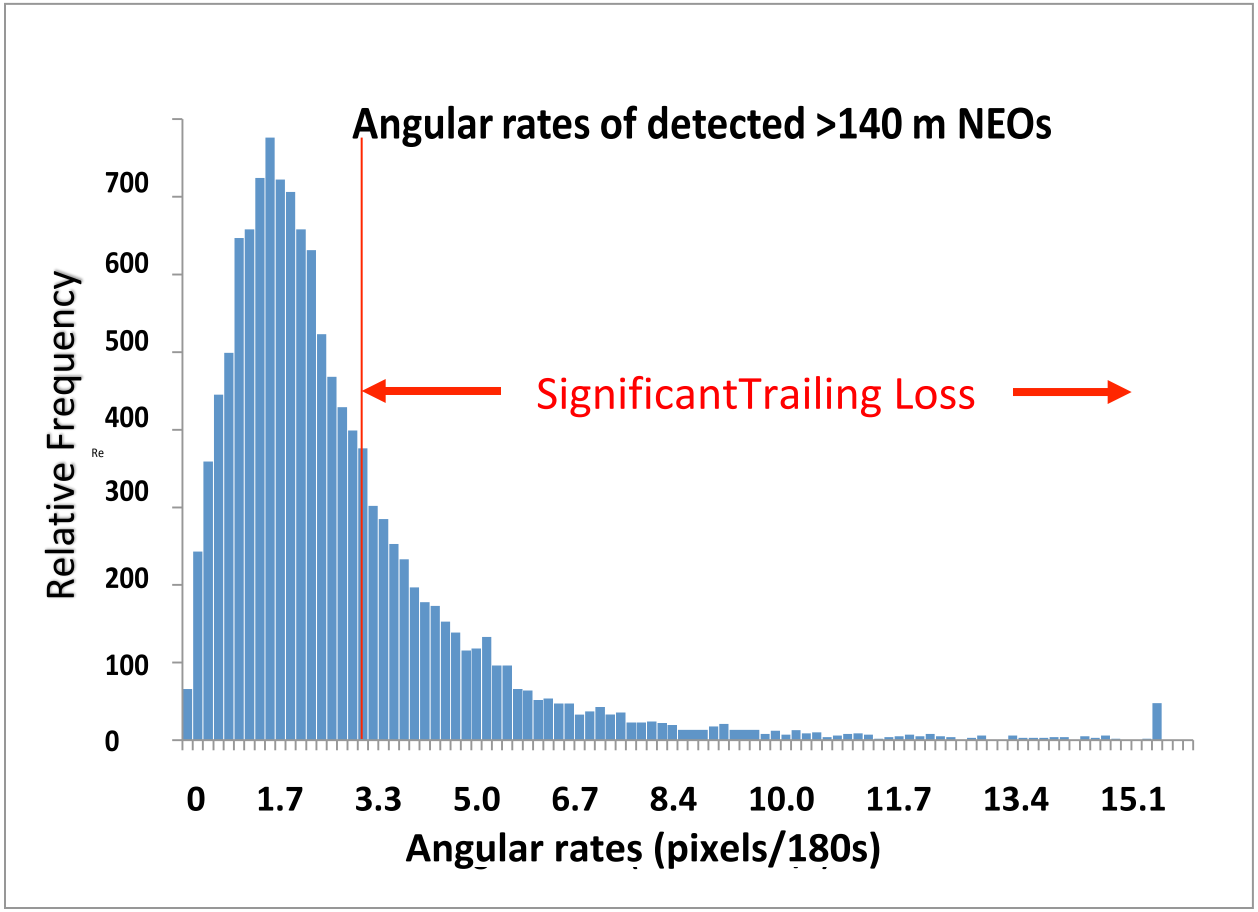
Synthetic Tracking Studies by B612/CalTech

- Seminal paper by Shao et. al. 2015* showed the value of a constellation of five 10-cm telescopes in heliocentric orbit using synthetic tracking
- Studies funded at CalTech by B612 Foundation 2015-2017 added detail and insight to the concept
- Synthetic tracking increases system sensitivity for fast-moving objects
- Small NEOs are observed best when they are close to the telescope, a time when their apparent motion in the sky causes them to be recorded as streaks rather than points of light.
- Synthetic tracking performs in electronics what astronomers do at the telescope to track known moving objects with known motions to "freeze" the object in one location on the detector and allow the signal to integrate over the duration of a long exposure.
- The power of synthetic tracking is that it provides the same long integration time for objects whose motion is not known.
- Challenge of synthetic tracking is on-board image stacking

*A constellation of CubeSats with synthetic tracking cameras to search for 90% of potentially hazardous near-Earth objects," by Michael Shao, Slava G. Turyshev, Sara Spangelo, and Thomas Werne. http://arxiv.org/abs/1503.07944v1

Angular Rates For Sentinel Detection

Linfield Model



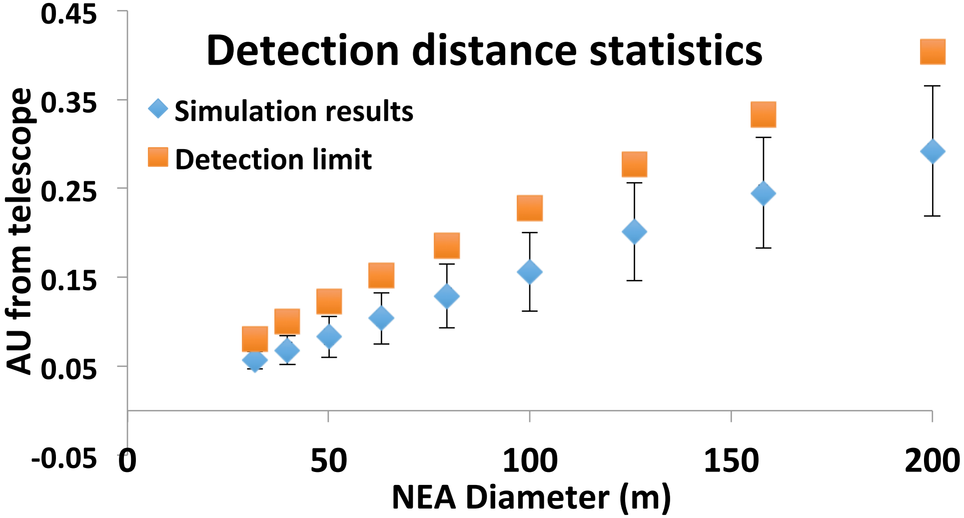
For Sentinel's detection range and 0.7 AU orbit, trailing losses are acceptable for 140-m NEOs

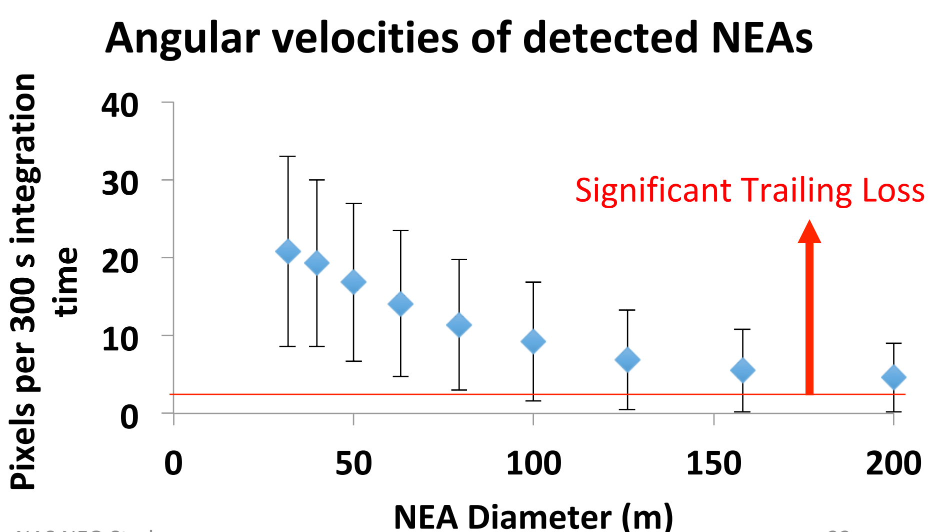
Synthetic Tracking Advantage

- B612/Linfield model
  - 300-sec exposure
  - 15-cm telescope
  - 1 AU orbit
  - 3 arcsec pixels
- Plots show that larger NEOs are detected at larger distances, giving them lower angular velocities
- Without Synthetic Tracking, trailing losses occur above red line in lower plot
- Synthetic tracking allows the small NEOs to integrate for the full 300 seconds
- Angular velocities are higher than for surveys with larger apertures because the small 15-cm aperture has a closer detection region

Even larger NEOs have trailing losses with a small telescope because of limited detection range.

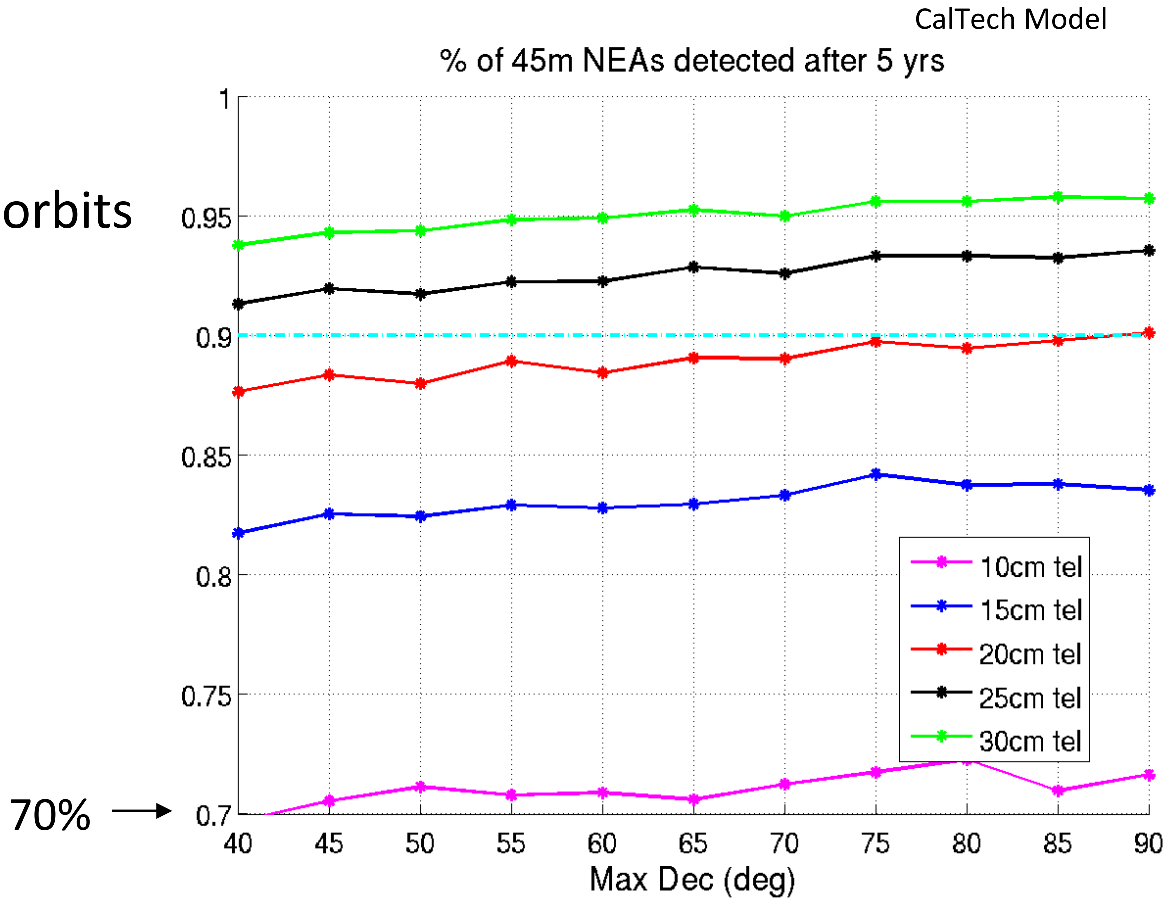
Linfield Model





Synthetic Tracking Constellation Performance

- 7 cubesats
- 0.9 AU semimajor axis orbits
- 8kx8k detector
- 1.4 arcsec/pixel
- 800s int
- 75 deg Sun avoidance

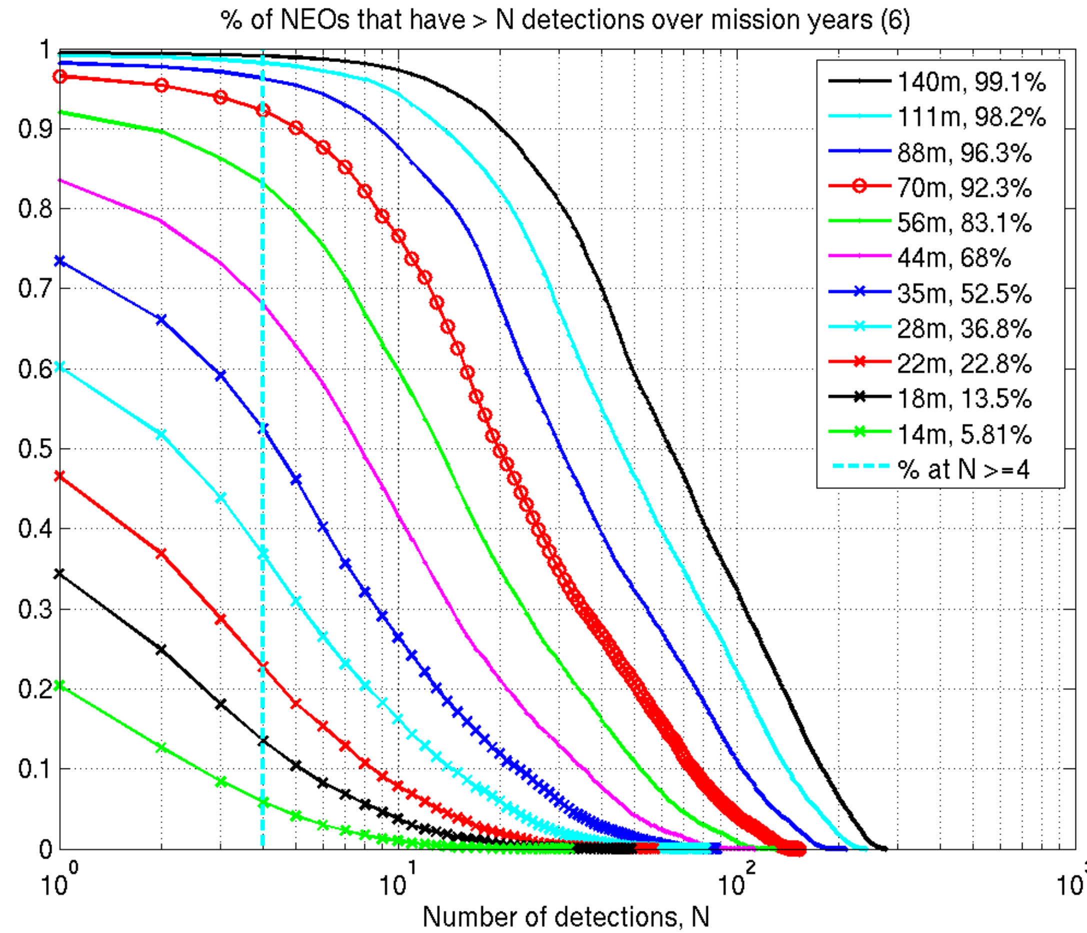


A constellation of seven 15 cm telescopes in heliocentric orbit will see ~86% of 45m NEAs in 5 years

Synthetic Tracking Constellation Performance

- Investigation of number of times an object is seen in 6 years.
- Four detections is minimum for acceptable orbit determination.
- 99% of 140-m NEOs seen 4 times
- 68% of 44-m NEOs seen four or more times.
- 48% of 44-m NEOs have 4 pairs of detections.*

CalTech Model



If cadence supports linkage, synthetic tracking constellation will derive good orbits for 68% of 44-m NEOs.

*Not shown on this graph

On-orbit Synthetic Tracking Demonstration

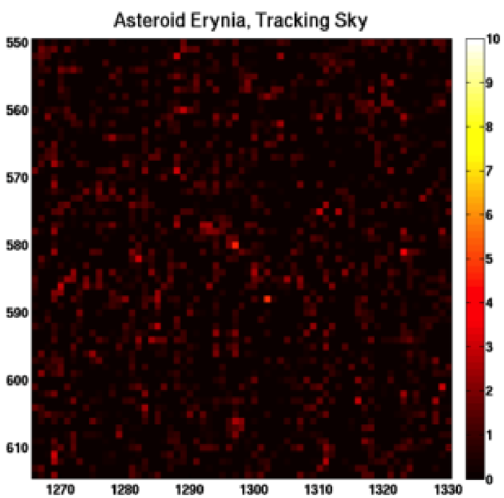
On-Orbit Synthetic Tracking Demonstration

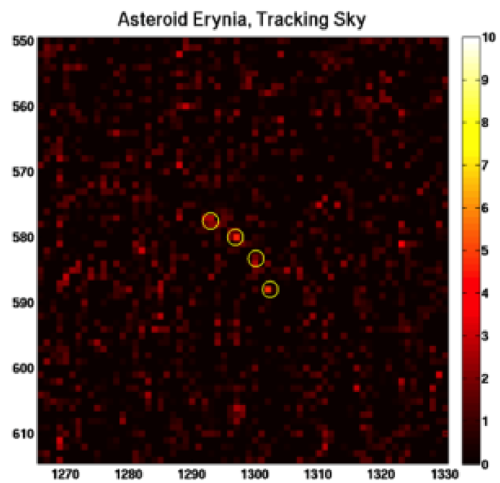
- Planet Labs contributed six nighttime orbits of data in 2017 using their on-orbit SkySat Earth-observing satellite
- 35-cm telescope, ~5 arcmin field of view, 50 msec exposures with 3 cameras: sub-optimal for synthetic tracking
- 50 seconds of data, taken in 3.3 second chunks spread over ~23 minutes: sub-optimal for synthetic tracking
- Data collected on two known asteroids
  - Main belt asteroid 889 Erynia ~14th magnitude
  - NEO 1998 YP11 at 16.1 magnitude – not visible in single frames
- Data processing by Shao group at CalTech

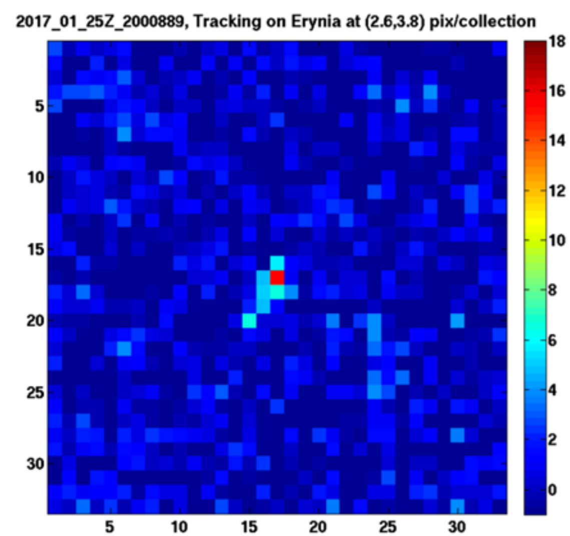
This set of observations gives hands-on experience with the detection issues experienced in space.

Performance of a Synthetic Tracking Constellation

- 889 Erynia detectable in 1.6 seconds of data
- 4 data sets over 14 minutes show parallax due to orbital motion
- Lesson learned: put survey fields at quadrature points to reduce parallax

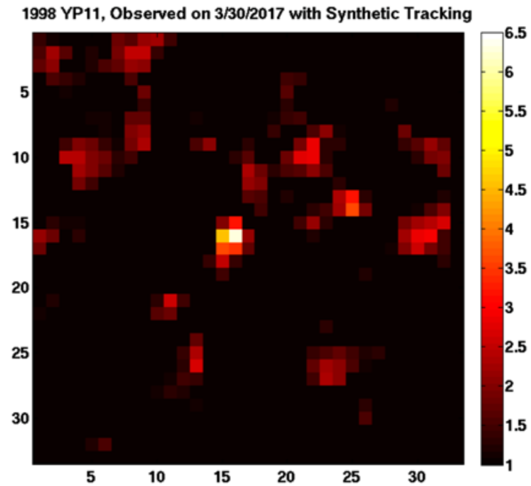




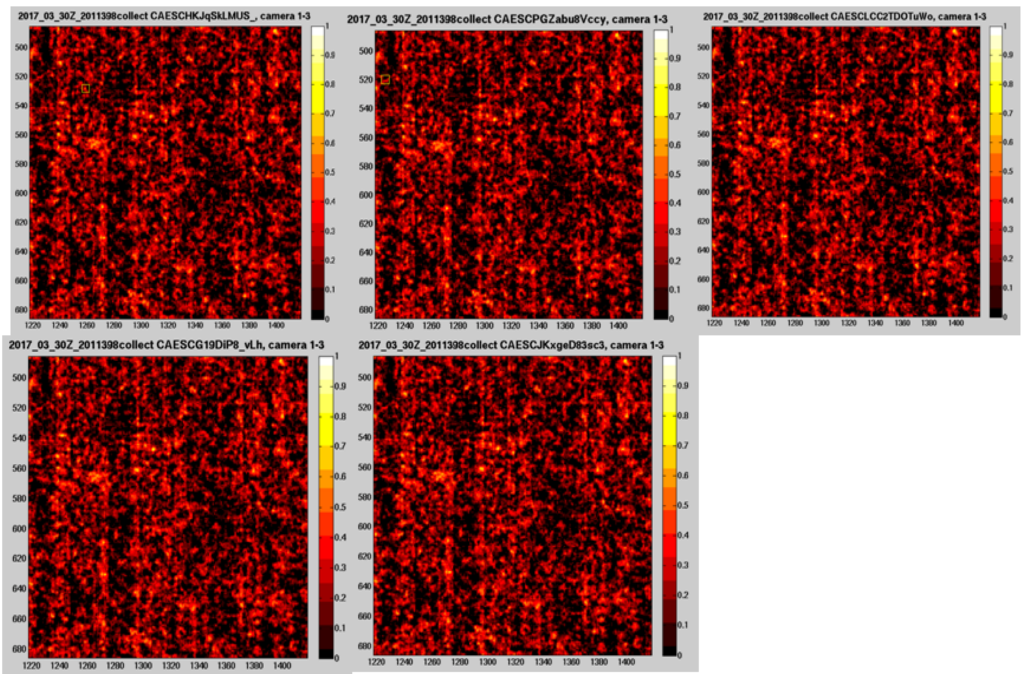


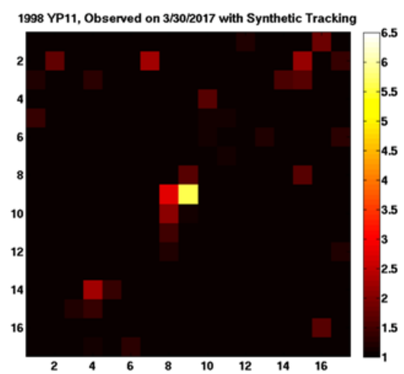
Performance of a Synthetic Tracking Constellation

- NEO 1998YP$_{11}$
- Five 10-second integrations
- Object not recognizable in each frame
- Top right is synthetic tracking image
- Lower right is convolution with PSF



SNR ~ 6.3, Estimated mag ~ 16.5





No low pass filter, SNR ~ 5.6