Advanced Near-Earth Object (NEO) Tracking System (ANTS)

Astronomical Optics Team 2
Spring 2013

Outline

- Team
- Science
- Systems Engineering
- Optical and Mechanical Engineering
- Conclusions

Team

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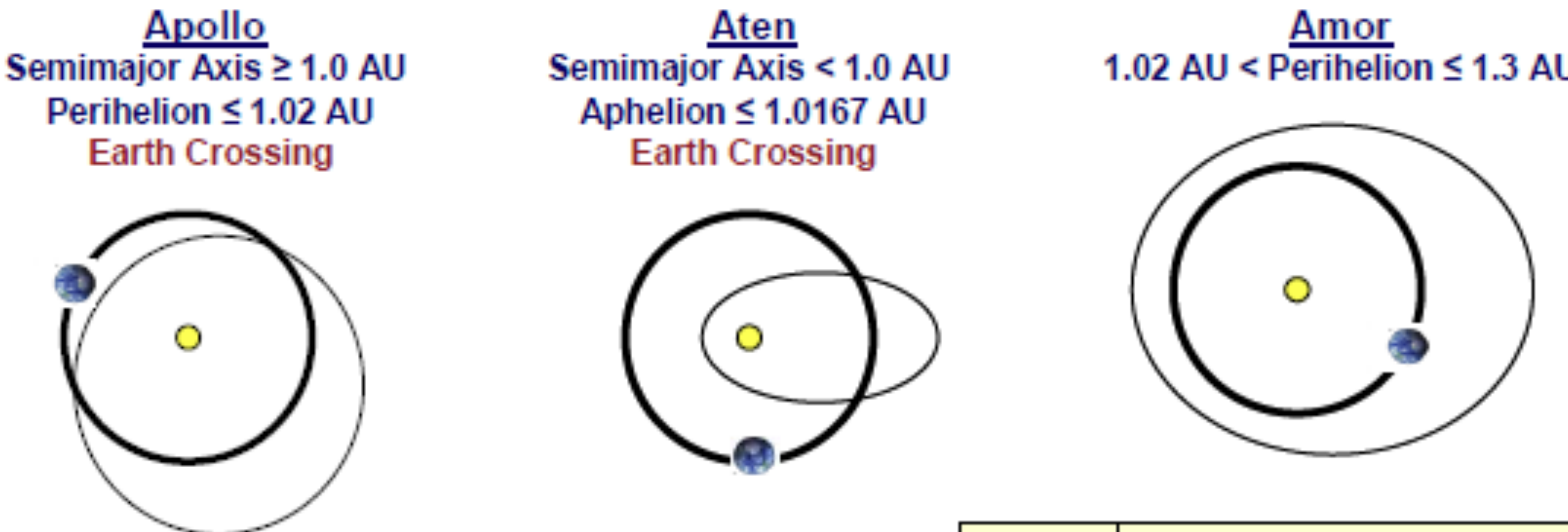
The Science

Near Earth Objects (NEOs)

- Asteroids and comets with perihelion distance less than 1.3 AU
- NECs: comets < 200 yr
- NEAs: majority
- ~ 10000 found
- PHAs (Potentially Hazardous Asteriods:
  < 7.5M km & > 150m)

There are ~1400 known PHAs

Types of NEOs



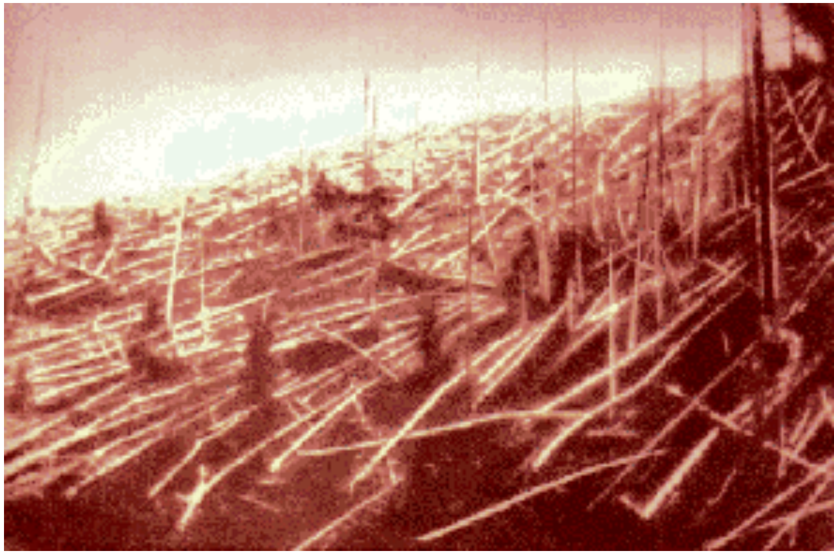
Type	Near-Earth Population
Apollo	62% of known asteroids
Aten	6% of known asteroids
Amor	32% of known asteroids
IEO	6 known asteroids

Figure 1. Near Earth Asteroid Orbit Types

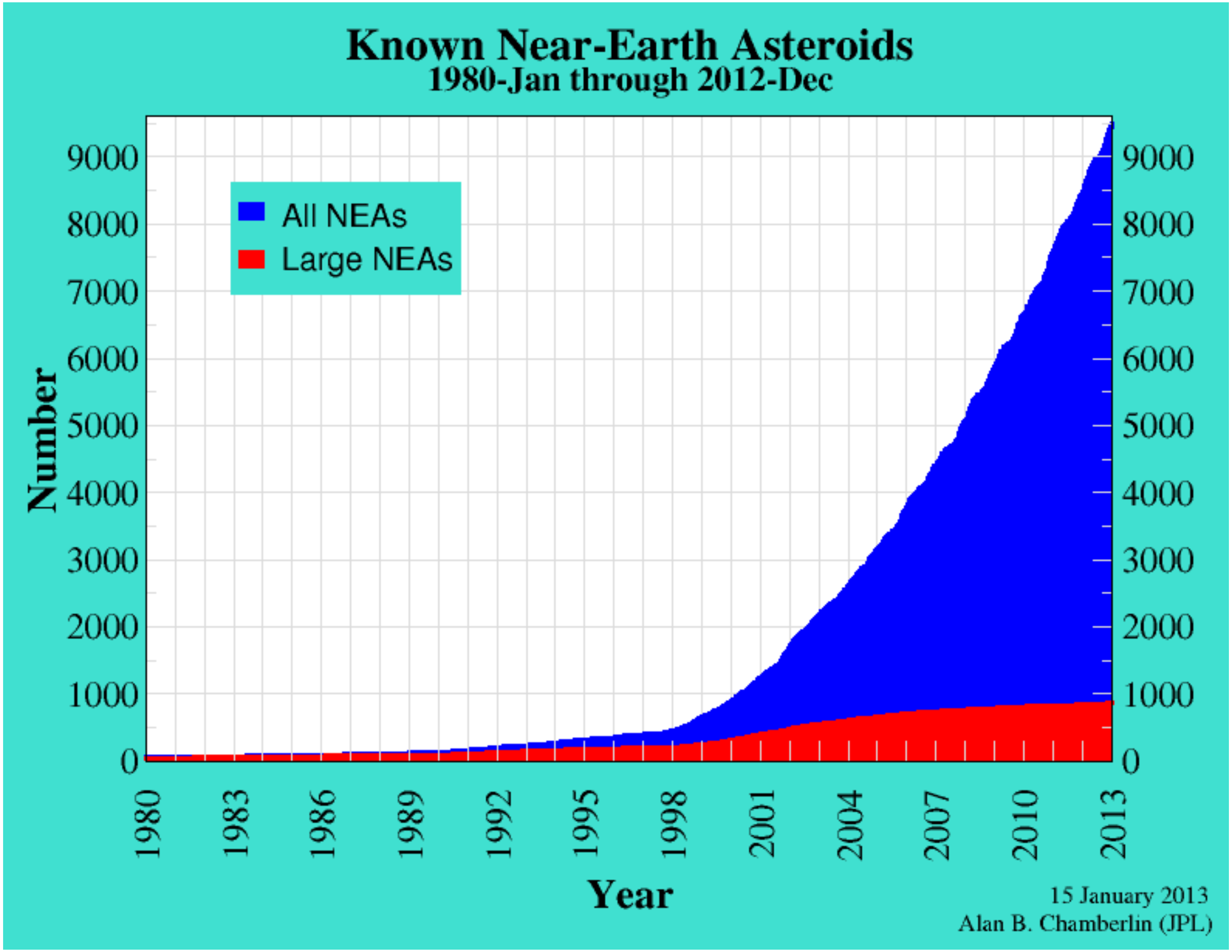

~ 65 Myr ~10 km: > 75% species gone

1908 ~50 m: 2000 km^2 forest gone

2013 ~15 m: 1500 injured

Type of Event	Diameter of Impact Object	Impact Energy(MT)	Average Impact Interval (years)
High altitude break-up	**< 50 m**	**<5**	**1 - 50**
Tunguska-like event	**> 50 m**	**>5**	**250 - 500**
Regional event	**> 140 m**	**~150**	**5,000**
Large sub-global event	**> 300 m**	**~2,000**	**25,000**
Low global effect	**> 600 m**	**~30,000**	**70,000**
Medium global effect	**> 1 km**	**>100K**	**1 million**
High global effect	**> 5 km**	**> 10M**	**6 million**
Extinction-class Event	**> 10 km**	**>100M**	**100 million**



Known Near-Earth Asteroids
1980-Jan through 2012-Dec
All NEAs
Large NEAs
Number
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
1980
1983
1986
1989
1992
1995
1998
2001
2004
2007
2010
2013
Year
15 January 2013
Alan B. Chamberlin (JPL)

Number of NEOs

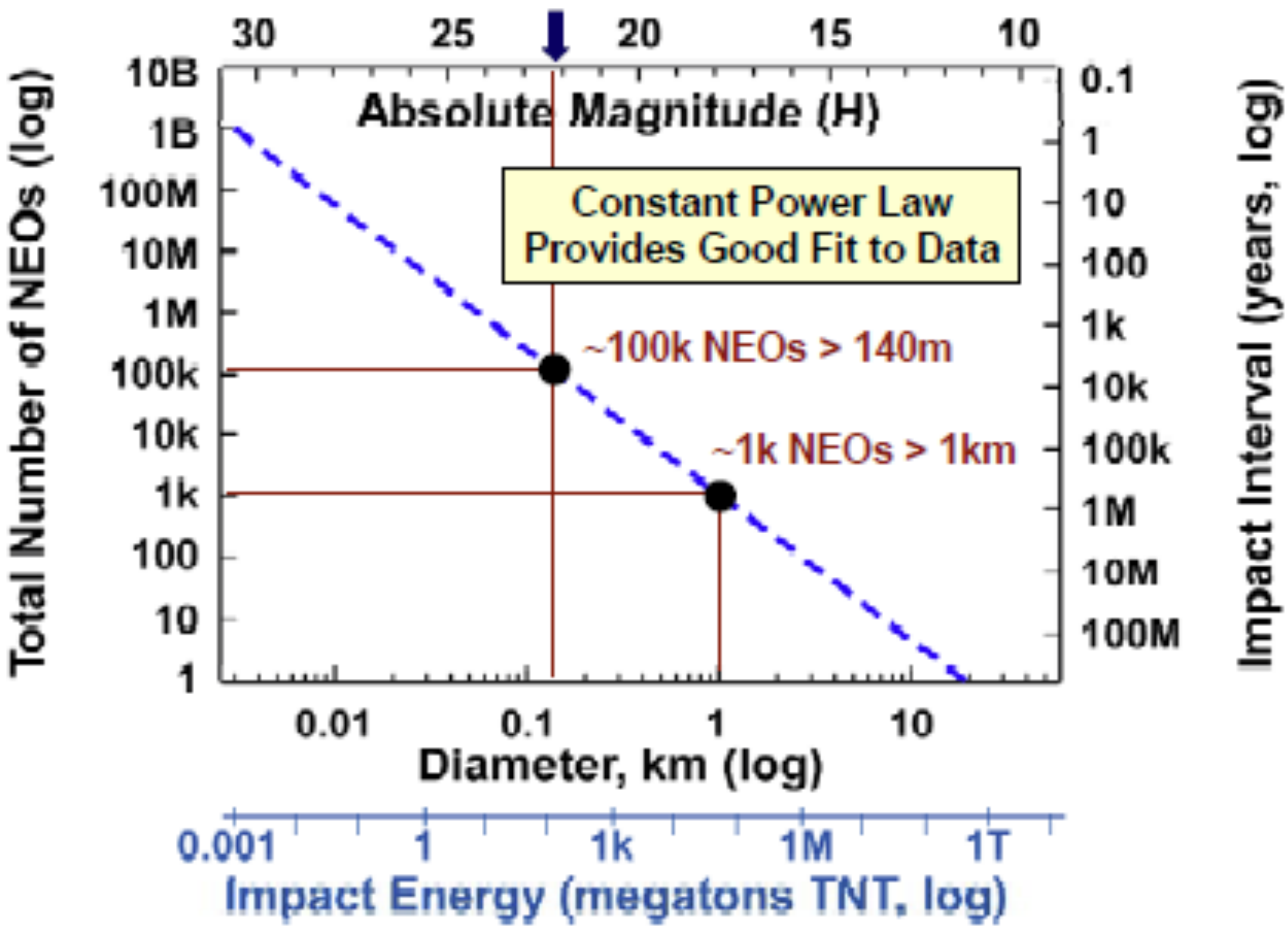
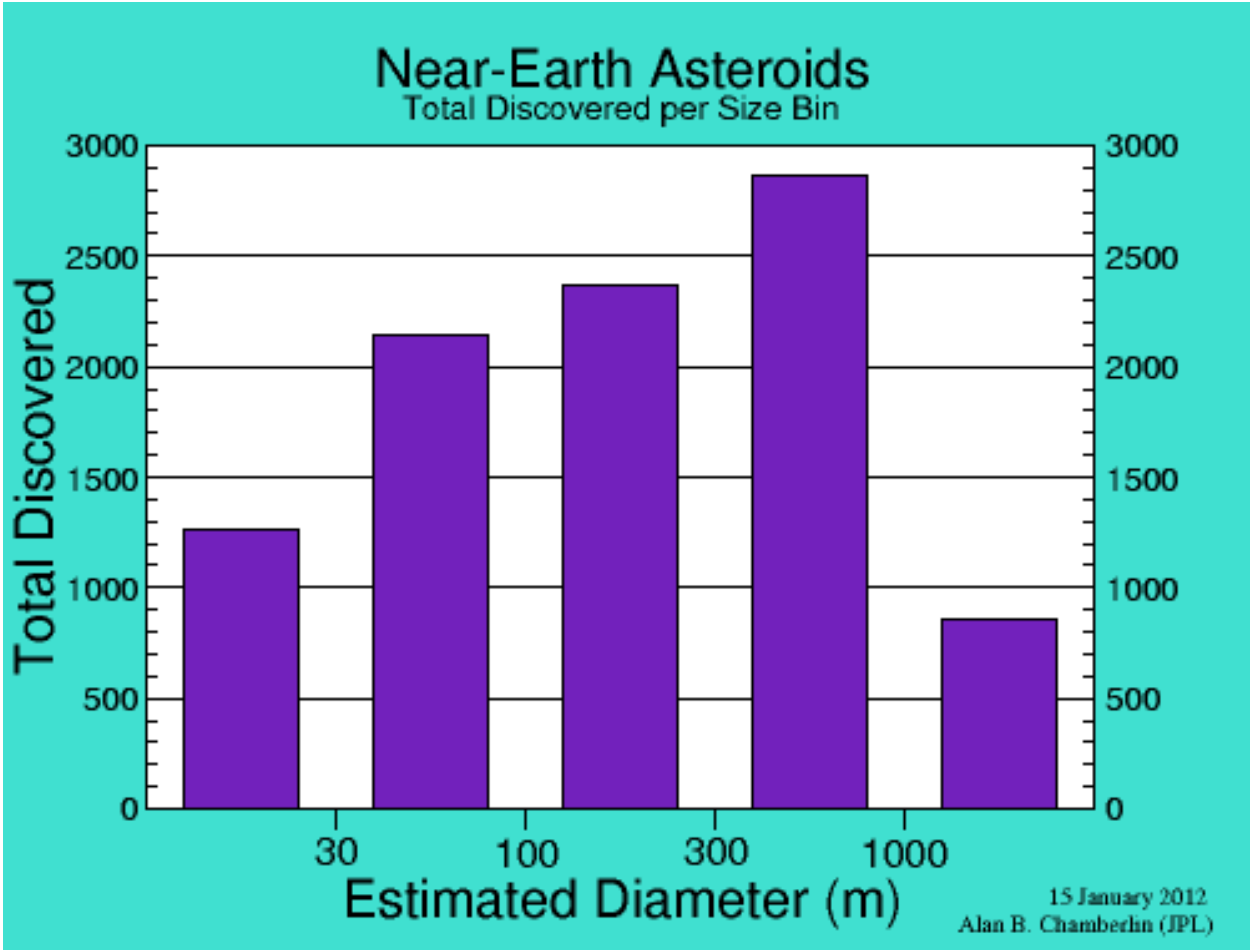


Figure 2. Frequency of NEOs by Size, Impact Energy, and Magnitude


Near-Earth Asteroids
Total Discovered per Size Bin
Total Discovered
0
500
1000
1500
2000
2500
3000
30
100
300
1000
Estimated Diameter (m)
15 January 2012
Alan B. Chamberlin (JPL)

Where are We?

1. We found ~ 10000 NEOs
2. >90% of >1 km NEOs are detected!
3. No more extinctions
4. There are millions of small objects...
5. Congress: find >90% >140m NEOs ASAP

But a <100m NEO can destroy a city

We hope to detect > 30m NEOs

Strategy

Table 8. Ground-based Survey Performance

Survey Systems	Start	140 meter PHO Completion		
		by end of 2020	10 years	Year for 90%
Spaceguard	1998	14%	8%	>2030
PS4 (shared)	2010	72%	69%	>2030
PS4 (dedicated)	2013	72%	77%	>2030
PS8 (dedicated)	2014	74%	81%	>2030
PS16 (dedicated)	2014	77%	83%	2029
LSST (shared)	2014	75%	81%	>2030
LSST (dedicated)	2015	85%	90%	2024

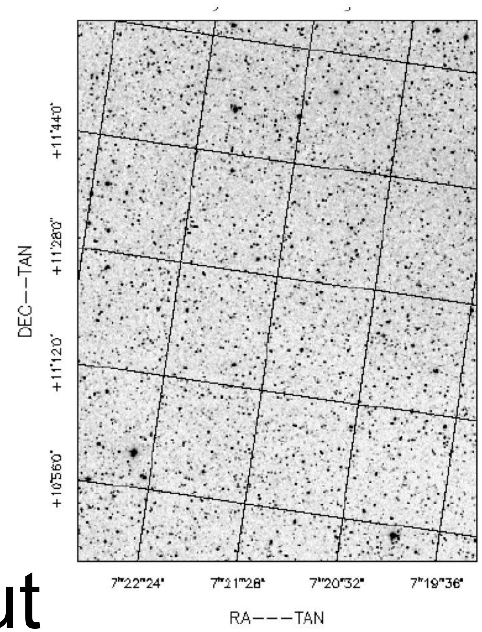
Table 9. Space-based Survey Performance

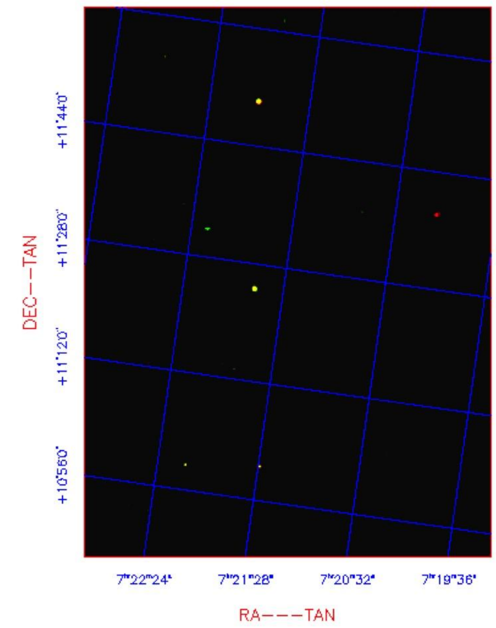
Survey Systems*	Start	140 meter PHO Completion		
		by end of 2020*	10 years	Year 90%
0.5m IR @ L1	2013	85%	88%	2024
1.0m IR @ L1	2014	86%	91%	2022
0.5m IR in Venus-like	2013	89%	93%	2021
1.0m IR in Venus-like	2014	92%	95%	2020
1.0m VIS in Venus-like	2014	82%	88%	2025
2.0m VIS in Venus-like	2016	87%	94%	2022

We propose a 1.5m IR space telescope in Venus-like orbit

- Why IR in space?

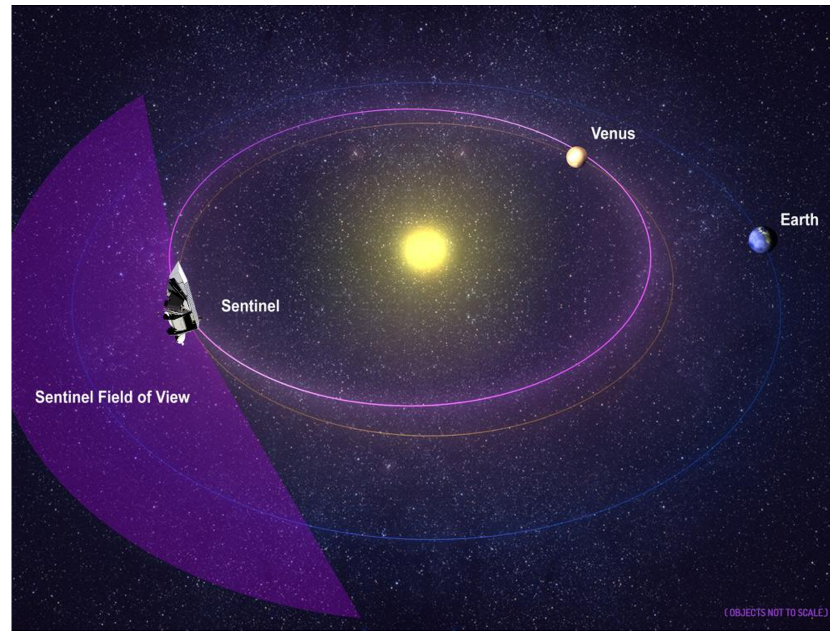
1. stars: ~ 1 um;
   NEOs: 5~15 um
2. less confusion
3. shorter exposure but
   higher SN ratio than visible
4. IR best observed in space
5. larger PSF; less trailing loss





- Why Venus-like orbit?

1. prevent seeing the back of NEOs
2. higher detection efficiency



- Where to search?

1. Ecliptic
2. close to earth: isotropically distributed
3. whole sky survey
4. away from the sun

How Fast & How Bright?

- Assume ~ 30 km/s & 1 AU distance:

  ~ 2.5" in 1 min or ~ 1 degree per day

  Revisit every 2 ~ 3 days

- Assume 10um, 200K, 1AU, 30m NEO, emissivity 1, 1.5m telescope, bandpass 5um, detector efficiency = 50%: 1.7 photon/sec
- Assume 30 sec & readout noise 30e:

  S/N = 1.7*30/sqrt(1.7*30+30) = 5.7

  Detectable!

Conclusion: a 1.5m IR telescope in Venus-like orbit can detect 30m NEOs!

Systems Engineering

Survey of Related Projects

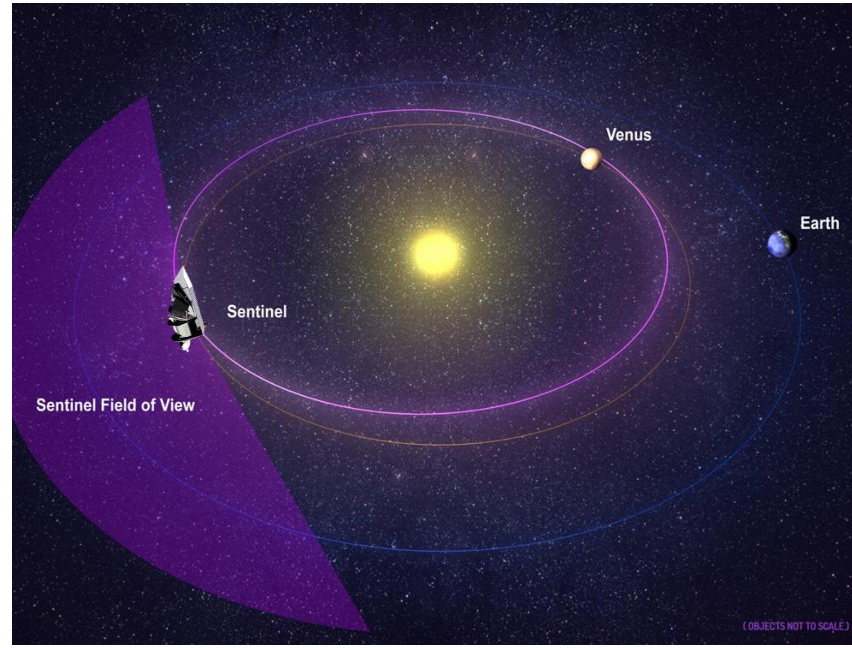
Projects intended to contribute to the NEO tracking problem were surveyed

- Some dedicated projects exist while others are multi mission
  - Dedicated projects solve the problem much faster than shared systems

Projects

- Multi-mission Ground Telescopes
  - PanStaars Telescope
  - LSST
- IR Heritage and/or Large Aperture Space Telescopes
  - Kepler
  - Spitzer
  - Hubble
  - Hershel
  - Joint Dark Energy Mission (JDEM)
  - Wide Field Infrared Explorer (1999) - Failed on Launch
  - Wide-field Infrared Survey Explorer (WISE)
  - Wide Field Infrared Survey Telescope WFIRST - NASA Proposed System
    - 1.5m IR Telescope 144 megapixel HgCdTe FPA (200 milliarcsec IFOV)
- Dedicated NEO Detection Projects
  - Space-based
    - B612 Foundation (Sentinel) - Private
    - Near Earth Object Surveillance Sat (NEOSSat) - Canada
  - Ground-based
    - Asteroid Terrestrial-impact Last Alert System Project (ATLAS)
- Asteroid Mining
  - Planetary Resources
  - Deep Space Industries (CubeSats)

B612 Sentinel Project



- B612 foundation intends to privately fund a $400M effort to field a NEOSat style mission
  - Space-based IR survey
  - 0.5 m aperture
  - launched 2017~2018
    - discovered ~ 500000 NEAs in 6.5 yrs
    - > 90% > 140m cataloged
    - many < 50m detected
  - Supplements LSST
    - Little use below 140m
- Venus-like orbit (0.7AU)
  - typical engagement range is <0.8 AU for NEOs
- 6.5 yr 165 degree^2 per hour
  - 11 degree^2 FOV = 4 second integration time per frame
- 24 million pixel HgCdTe sensor cooled to 40K using Sterling coolers
  - Provides long mission lifetime over helium
- Reverse engineering of Sentinel was performed by the ANTS team for comparison

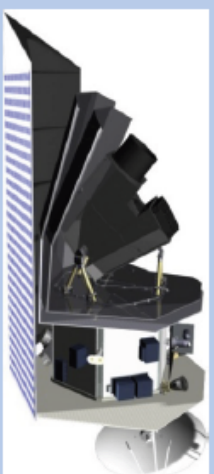
"*NEOStar*" Concept

Spitzer

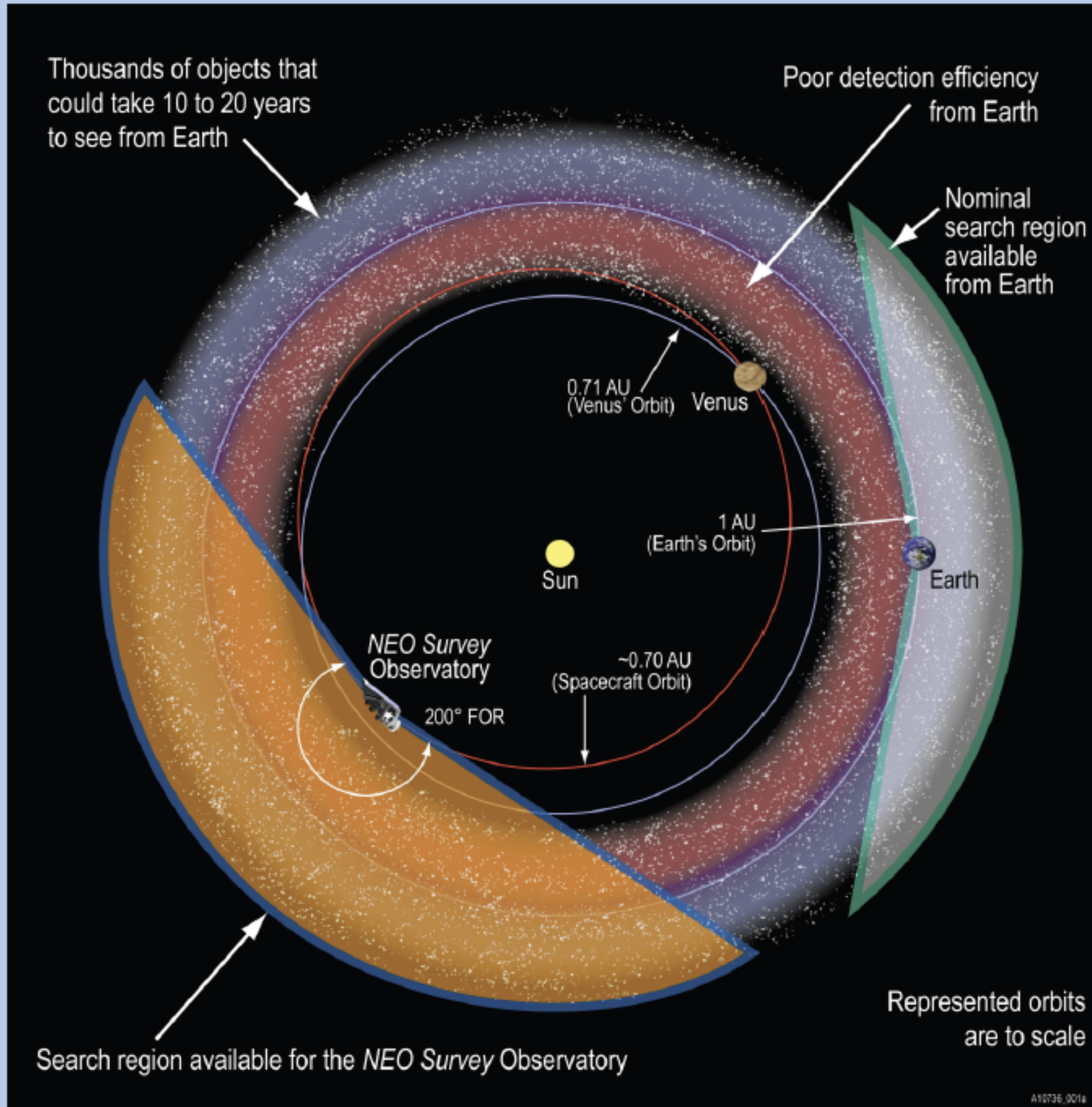
Kepler

x

≈



"NEOStar"



Systems Engineering

Objective

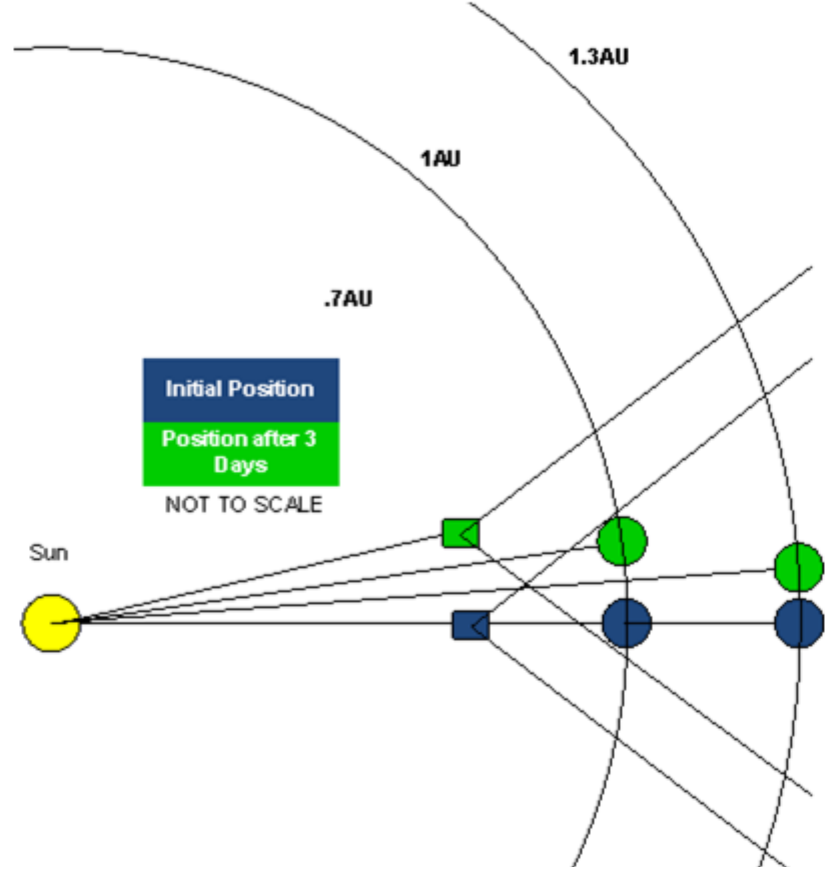
- Increase sensitivity while completing the survey in a reasonable amount of time
- We set an initial goal of an order of magnitude smaller than the congressional mandate
    - Congress: 90% PH NEOs >140 m
    - ANTS: 90% of PH NEOs > 14 m
        - This is nearly impossible to meet with a 1.5 m aperture
- Design for reasonable survey time and higher sensitivity than existing concepts
    - Larger aperture and FOV than Sentinel

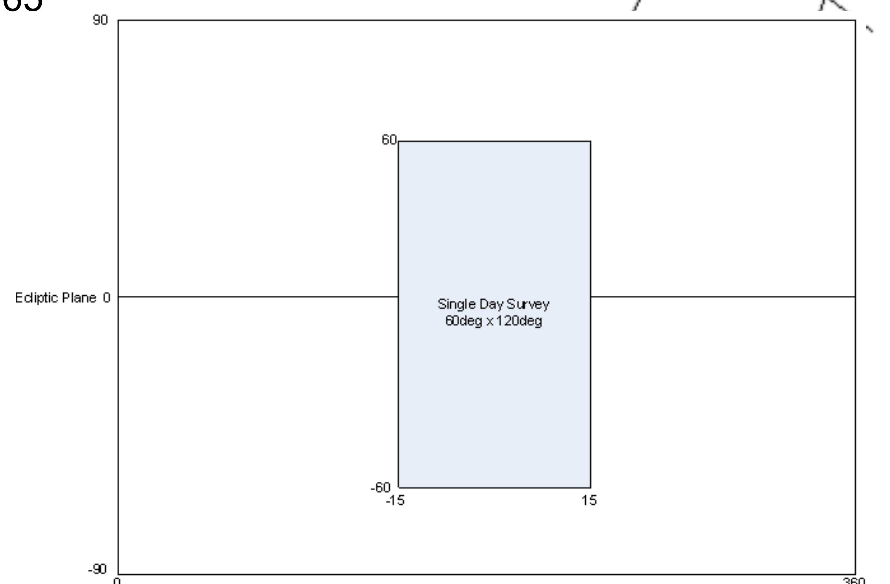
Approach

- Develop a large-aperture space-based Wide FOV observatory optimized for detection of potentially hazardous NEOs
- Surveys of heritage sensors show that a >11 deg^2 FOV is difficult to scale for a few reasons
    - WFOV becomes harder at larger apertures due to increasing focal length and thereby increasing detector size requirements
    - At 1.5 m an 18cmx18cm focal plane is already at the limit of current technology for both detectors and cooling
- We chose the 1.5m as an upper limit of current technology for WFOV IR space systems
    - Designed around this upper-limit aperture
    - Wide FOV: > 11 deg^2 as an initial requirement
        - Limited by detector array sizes

Survey Strategy and Orbit Determination

- Orbit determination requires "long" tracks
  - NASA reports that several (2 to 5) tracks over 3 days will be sufficient for 100 year orbit determinations
  - 3 days equates to nearly 1% of Earth's orbit
- Correlation of tracks is vital
  - It is not useful to see (and revisit) objects if those objects are not identifiable as the same object
  - Multiple tracks of the same object aid in correlation
- Our survey will look at ~7200 deg^2 per day
  - Just under twice the coverage of Sentinel (165 deg^2/hour = 3960 deg^2/day)
  - Provides more revisits than Sentinel
    - This allows better chance of object correlation
  - Requires a 6x6 degree FOV telescope
    - Limit of what is possible using current technology and a 1.5 m aperture
  - Provides 220s of integration time per deg^2 per day
  - Allows for a simple "blinking" + thresholding algorithm





Background and Sensor Considerations

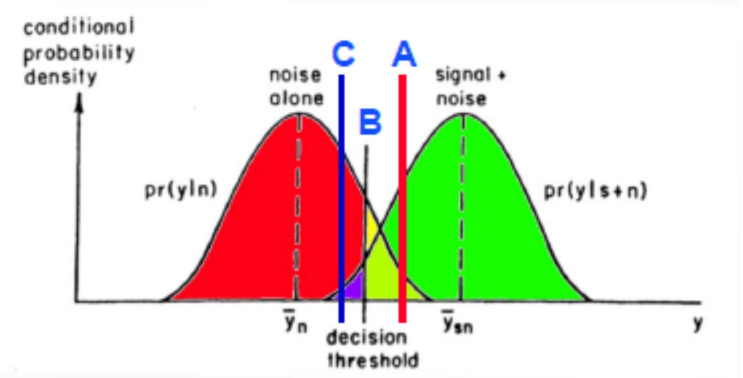
- We have chosen a HgCdTe sensor
  - Bandpass may be tuned from NIR to beyond 16 microns though changing the mix
    - Flown on dozens of IR telescope missions
    - Well understood noise characteristics
  - Readout and nonuniformity noises are the largest contributors from the sensor
  - We have selected a Teledyne ROIC with a custom 5-10 micron FPA
    - Potential to extend band to 5-12 or even out to 16 microns with the same ROIC
    - Nonuniformity increases as wavelength increases!
    - Further study required to determine optimal band
      - Must trade NUC noise with increasing signal
    - Heritage equipment is "buttable" - many arrays can be used in a variety of configurations to increase effective sensor size
      - Available in up to 4k by 4k 10-15 micron pitch
      - 144MP possible using existing technology!
- Background noise sources
  - Space: ~4K
  - Sensor,Optics, and Dewar: Stirling Cooler: 40K
  - Optics: cooled 40K
  - Zodiacal Background: IR is the largest single noise contribution
  - Stars
    - Low emission in the 5-10 micron band
- We modeled a short integration time and sensor noise limited system

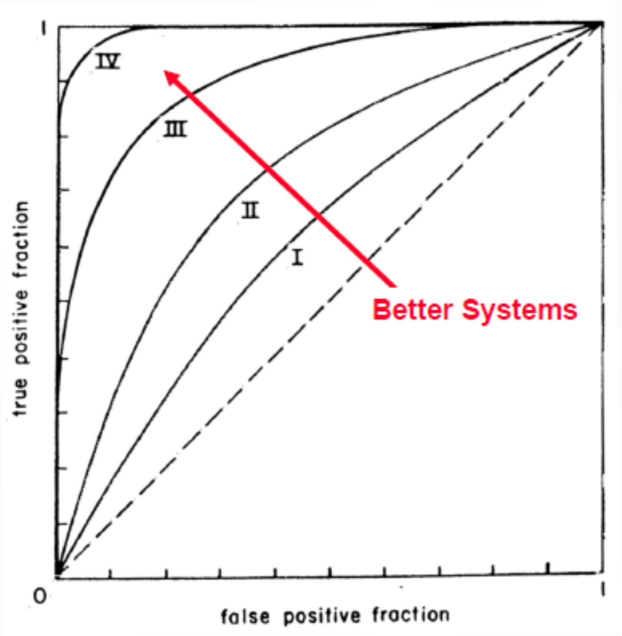
First-order Zodiacal Background

- Caused by dust particles between 10 microns and 0.3 mm
- Causes 60% of the total light on moonless nights
  - Brian May (Lead Guitarist of Queen) wrote his Ph.D. Thesis on Radial Velocities in the Zodiacal Dust Cloud
- MagV of the zodiacal light at Earth is ~23.3 mag/arcsec^2 and is brighter near the ecliptic
  - Flux of about 6.3 photons/s/arcsec^2/m^2/micron
- IR (Leinert, 1998) is ~10^-7 W/m^2/sr/micron at earth
  - 5 micron bandpass provides ~5*10^-7 W/m^2/sr
- Steady state object temperature at 1AU is 280K and at 0.7 AU is 330K
  - At 0.7AU this represents a 2.7X increase in the IR Zodiacal Light level
  - 5-10 micron passband at 0.7 AU is then ~1.4x10^-6 W/m^2/sr
- This represents the largest contribution to the background

Probability of Detection (and False Alarm Rate)

- To completely solve the problem, a detector must be characterized based on a probability of detection PD analysis
  - The PD must be maximized while the probability of false alarm PFA is kept at a specified level
  - System comparisons are performed using Reciever Operating Characteristics (ROC) curves
  - Time did not permit such an analysis but this trade should be performed prior to PDR
- The result of a PD/PFA study is a required SNR for a specific detection probability
  - Typical detection is specified between an SNR of 5 and 9
  - Reverse engineering of Sentinel with our model gives an SNR of 11 for a 140 m object
  - This represents a high PD, which makes sense for a high chance of multiple detections
- Our threshold SNR is ~11





SNR Calculations

- Simple SNR model using

$$SNR = \frac{Signal}{\sqrt{Signal + \langle Background \rangle + \langle Detector\ Noise \rangle}}$$

- Assuming that detector noise dominates for short integration times
  - Detection noise
    - Our Teledyne system has ~15e- of read noise
    - Assuming ~15e- of nonuniformity, we can make SNR estimates using a ~30e- detector noise
    - Long integration times will see optics and other backgrounds dominate
  - This can be improved through incorporation of actual dark current, ROIC readout noise, real nonuniformity, etc.
    - Not sufficient time to compare sensors and make a final selection
    - Detailed detector modeling must be performed as a study prior to PDR
  - These assumptions provide SNR of 11 for the Sentinel 0.5m 140m object detection mission
    - Good agreement with Sentinel reverse engineering - reasonable probability of detection
    - Similar integration times for Sentinel mean that our noise assumptions are OK
      - Moving forward using these assumptions is reasonable

SNR Calculations - Continued

- Taking a 1.5 m telescope
  - 4 mirror design for WFOV (FOV = 6 deg = 36deg^2)
  - 98% reflective (dirty space optics!)
  - WFOV obscuration is high - ~30% of area assumed
  - QE for detector ~80%
  - Overall a reasonable assumption is ~50% of photons are captured
- The table below shows the SNR for .5, 1, and 1.5 m apertures for 30, 80, and 140 m objects with a temperature of 200 K
  - For our purposes "detection" means catalogable detection (high PD)
  - To get to our original goal of 14 m, an SNR of 11 is achieved for a ~5 m aperture
    - The reasonably detectable NEO size for a 1.5 m telescope is 50 m diameter

Aperture	SNR 140 m	SNR 80 m	SNR 50 m	SNR 30 m
0.5	11	5.4	2.7	1.1
1	23	13	7.3	3.6
1.5	36	20	12	6.4

Not Detected
Threshold Detection
Detection

Quick Requirements List

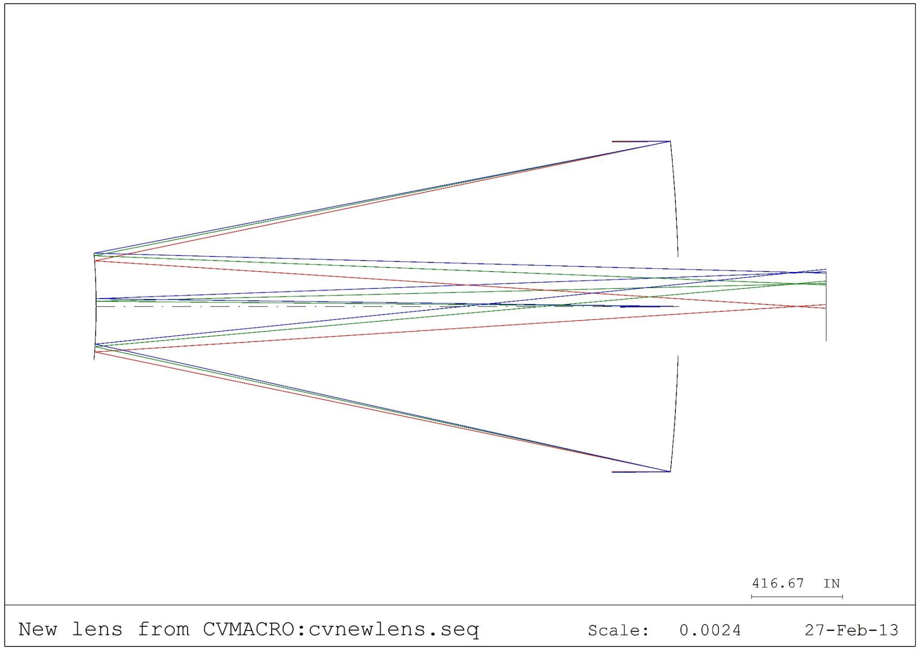
- Telescope and Sensor
    - Aperture diameter: 1.5 m
        - Optics cooled to 40 K
    - FOV: 6 degrees
        - 3 or 4 mirror design could permit this FOV
    - Detector: 144 MP, HgCdTe, Stirling Cooled to 40K, 15 micron pixels
    -
- Satellite Bus
    - Processing for "blink" detection of 144MP array
        - FPGA solution could perfrom simple blinking and thresholding
    - Downlink capable of sending all detections to Earth for processing
        - Rate of detections has not yet been calculated
    - Power for cooling and data processing are the drivers
- Launch Vehicle
    - Launch to 0.7 AU Heliocentric Orbit
- Co-boresighted Optical for Star Tracking

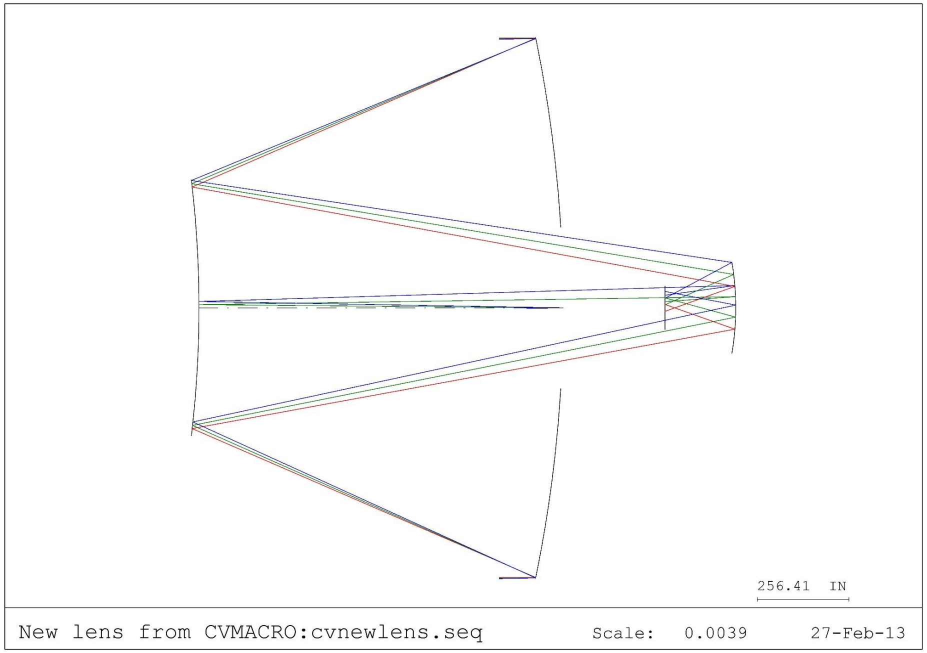
Optical and Mechanical Engineering

Optical Design

- Trade Study on two designs
  - Re-imaged Cassegrain
    - Narrower FOV
    - Compact in length
    - Optimized for chromatic aberration
  - Three Mirror Anastigmat
    - Wider FOV
    - Lightweight construction
    - Optimized for chromatic aberration, coma, and astigmatism

Possible Designs





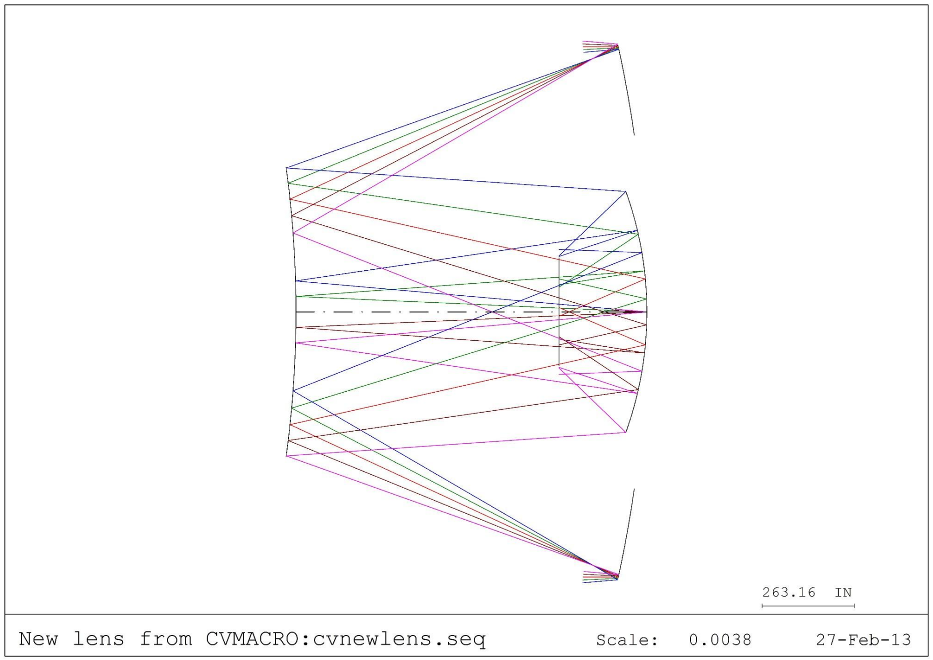
Two Mirror Cassegrain

- 1.5m Aperture
- +/- 1.0 deg FOV
- Parabolic Mirrors
- F/8

Three Mirror Anastigmat

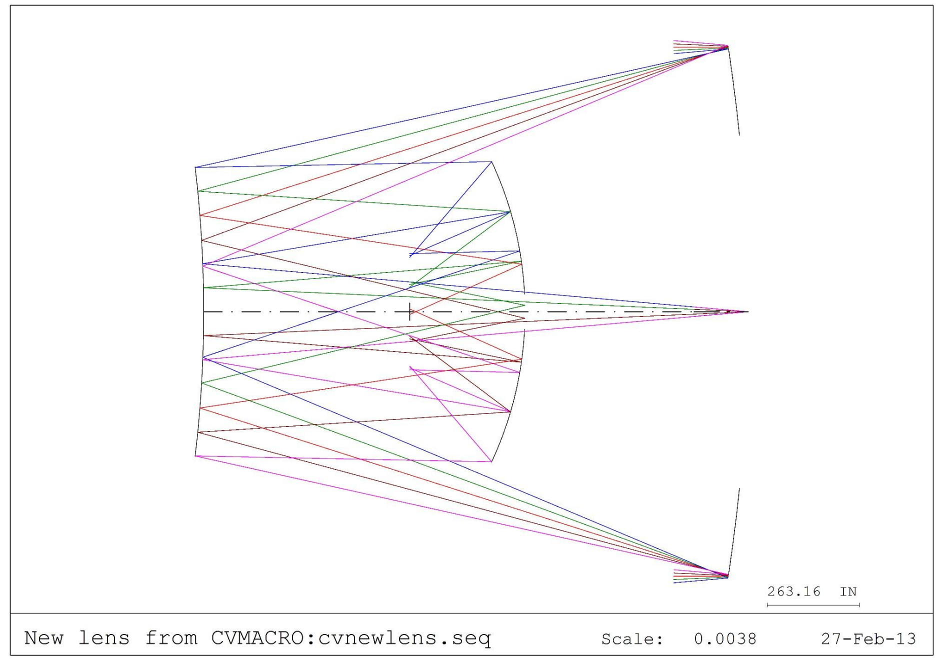
- 1.5m Aperture
- +/- 2.0 deg FOV
- Parabolic Mirrors
- F/1.3

Other (Unconventional) Designs



Four Mirror Configuration

- 1.5m Aperture
- +/- 5 deg FOV
- Parabolic Mirrors
- F/1.16

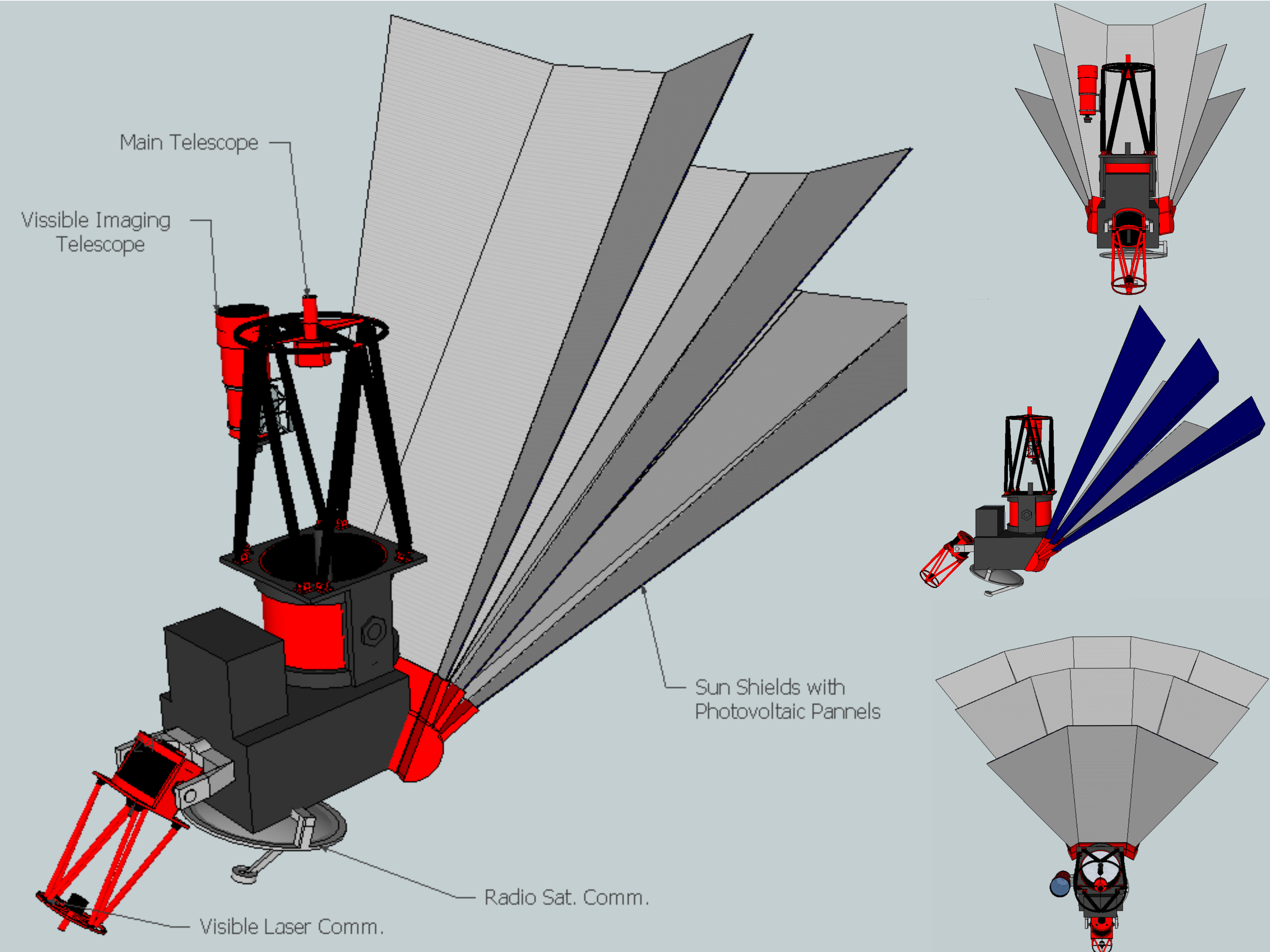


Two Focal Planes (On/Off Axis)

- 1.5m Aperture
- +/- 10 deg FOV
- Parabolic Mirrors
- F/1.16

We chose Three Mirror Anastigmat

- Meets our requirements:
  - Wide FOV (+/- 10 deg)
  - Wide spectral range (5um to 15um)
- Nondeterministic Requirements:
  - Four x 100Mpixel Detectors
  - 2 arcsec IFOV
  - 25 micrometer pixel size
- Derived Requirements:
  - 4kWhrs of electrical supply
  - +/- 30deg Field of Regard
  - F/5 or better


Main Telescope
Vissible Imaging Telescope
Sun Shields with Photovoltaic Pannels
Radio Sat. Comm.
Visible Laser Comm.

Substrate Material Trady Study

Material:	Mass Density: [g/cm^3]	Young's Modulus: [Gpa]	Thermal Expansion Coeff: [deg.K^-1]	Thermal Conductivity: [W/(m*deg.K)]
Pyrex	2.23	65.5	32.5 E-7	1.13
Fused Silica	2.2	73	5.5 E-7	1.38
Silicon Glass	2.5	73	86 E-7	0.75
Astrositall	2.46	90.2	0.6 E-7	1.18
Zerodur	2.53	90.2	0.2 E-7	1.63
BK-7 Glass	2.51	81.5	71 E-7	1.13
Beryllium	1.85	287	11.3 E-6	200
Silicon Carbide	3.21	450	2.77e-6	3.7

Source: http://www.fpi-protostar.com/bgreer/properties.htm

Design Review

- Heat Shield/Solar Panel Array
- 1.5m Primary Mirror
    - Beryllium Substrate for Primary and Secondary
        - Lightweight
        - Holds shape at Cryo temperatures
        - Extremely Young's Modulus - minimal material required for rigid structure
        - High thermal conductivity - thermal stability of support structures is easier to achieve
    - Passively cooled to 80 K
- Sensor
    - 144 MP HgCdTe Array from Teledyne or Sofradir
    - Stirling Cycle Cooler (40 deg Kelvin) - Ball Aerospace
- Body-Pointed Design
    - Inertial Reaction Wheel Pointing
    - Gyroscopes/IMU
    - Star trackers (3) and Sun tracker (1) provide orientation information
- Data Processing
    - SIDECAR ASIC from Teledyne (Low power digitizer - 11mW)
    - Single-board computers - 144MP x 16bit = ~275MB per image
        - 2 x SpaceMicro IPC5000 (900 MFLOPS - sufficient for "blink" processing and thresholding)
        - 1 x SpaceMicro Proton 200k
- Downlink
    - 2m RF Communication Antenna
    - High data-rate optical link