Steps towards a space-based occultation survey of the outer solar system

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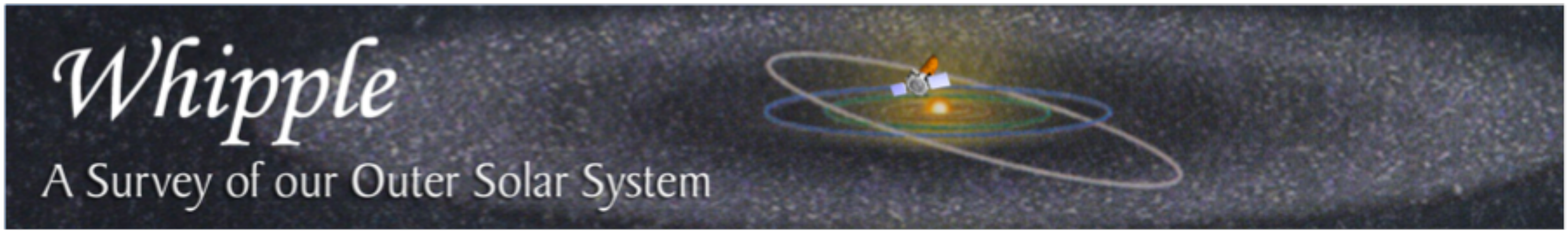
- First design (*Whipple I*) based closely on the *Kepler* spacecraft was submitted in the last NASA Discovery competition and was not selected
- New conceptual design study in progress (*Whipple II*)
- Alternative approach under development in Canada



Whipple-I Mission

Survey the reservoirs of small bodies in the outer solar system, (from the Kuiper Belt to the Oort Cloud), to reveal the physical and dynamical record of the origin of the solar system preserved in these vast clouds of remnant icy planetesimals.

Whipple deployed spacecraft

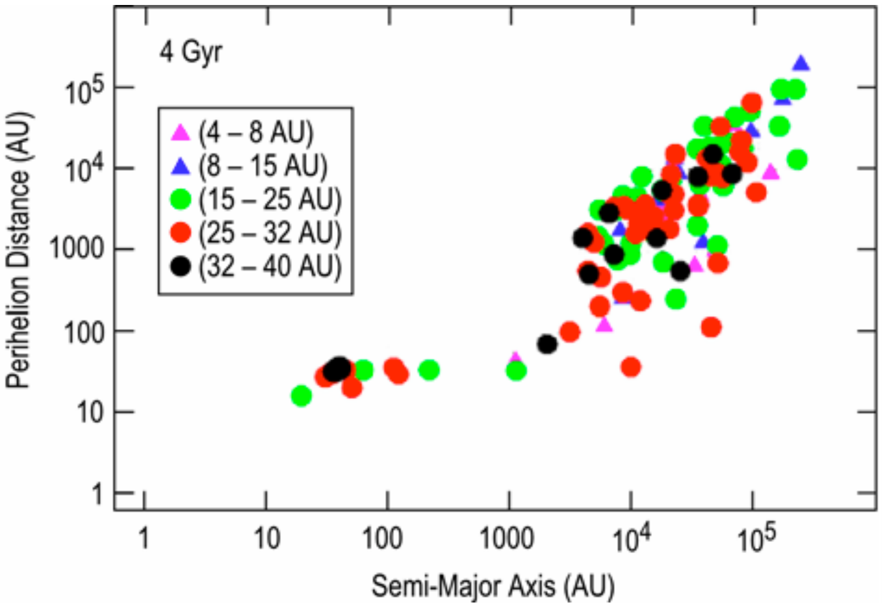
Proposal to Discovery Program January 2006

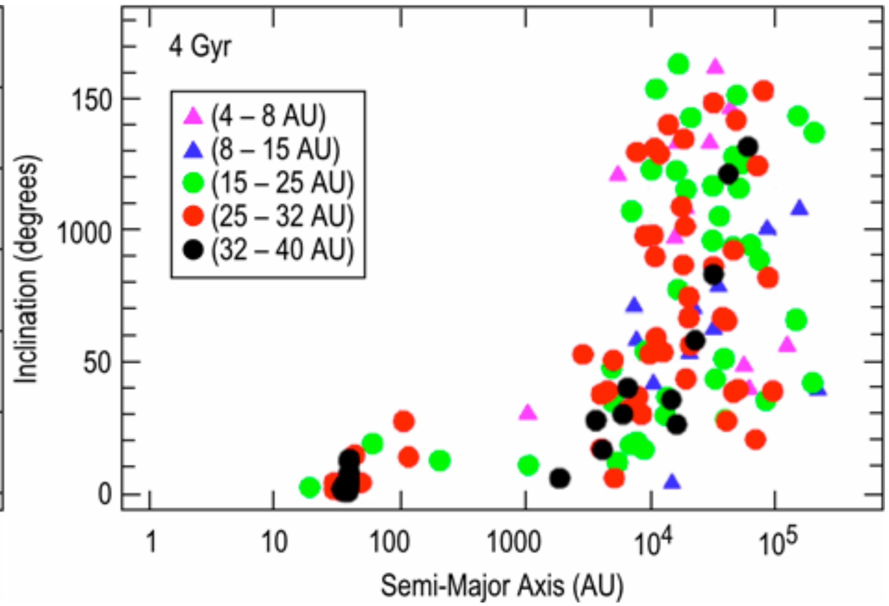
Science Overview

- Characterize the size and spatial distribution of small Kuiper Belt Objects
- Measure the number and size distribution of Oort Cloud Objects
- Probe the region between the Kuiper Belt and the Oort Cloud (Sedna-like population)

Oort Cloud Objects

- To date no object has been detected at Oort Cloud distances
- Only estimates of numbers, sizes, mass (0.1 to 30 Earth masses?)
- Long Period Comets only sample observed



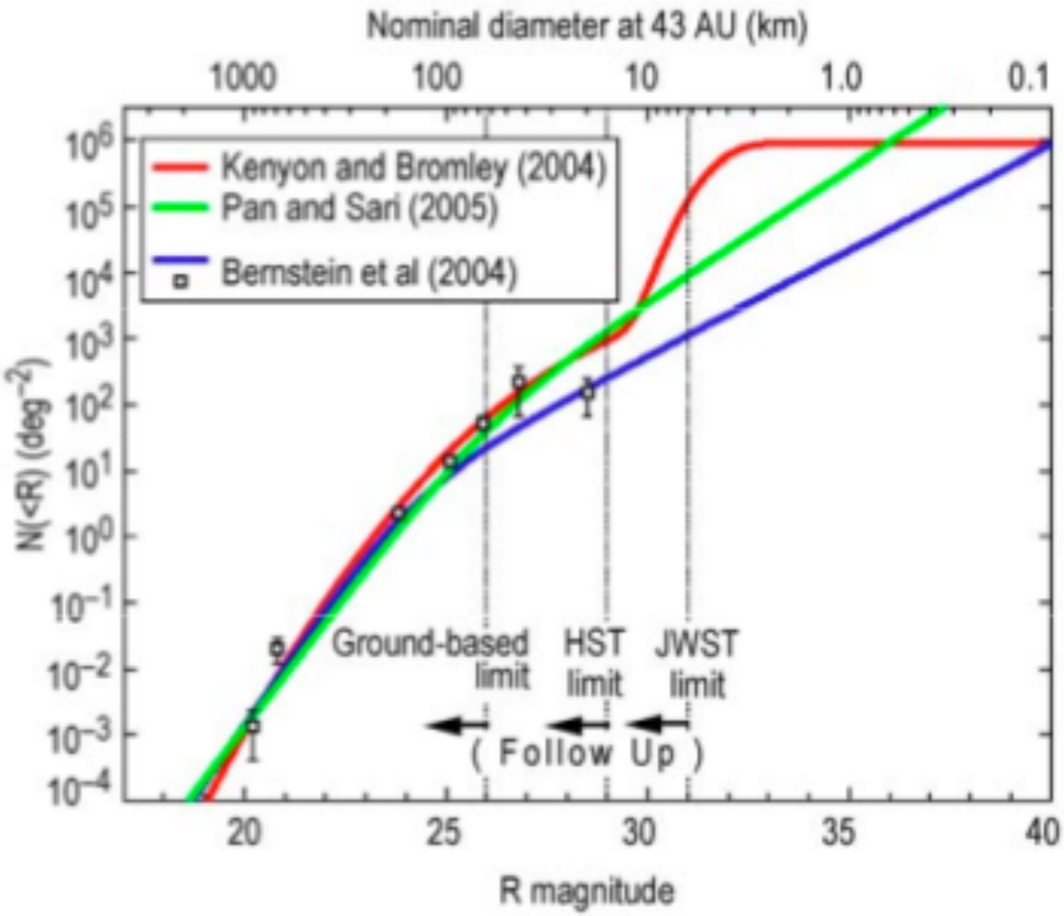


Perihelion versus semi-major axis at 4 billion years for the simulation of Dones et al. (2004). The different point types indicate where the objects formed.

Inclination versus semi-major axis at 4 billion years for the simulation of Dones et al (2004). The different point types indicate where the objects formed.

Kuiper Belt Objects

- Over 1000 observed KBOs with distances between 35 and 150 AU, and sizes of ~30 to ~1000 km
- Orbits have broad range of eccentricities and inclination, extending up to 30˚out of the ecliptic plane
- Sizes follow a power law that “breaks” at the faint end



Cumulative distribution of the observed brightnesses of Kuiper Belt objects. The observational data are binned as in Bernstein et al. (2004). The blue line is the two-power-law fit of Bernstein et al.; the green line is a model of Pan & Sari (2005); the red line is the model of Kenyon & Bromley (2004) that includes Neptune stirring.

Between the Kuiper Belt and the Oort Cloud

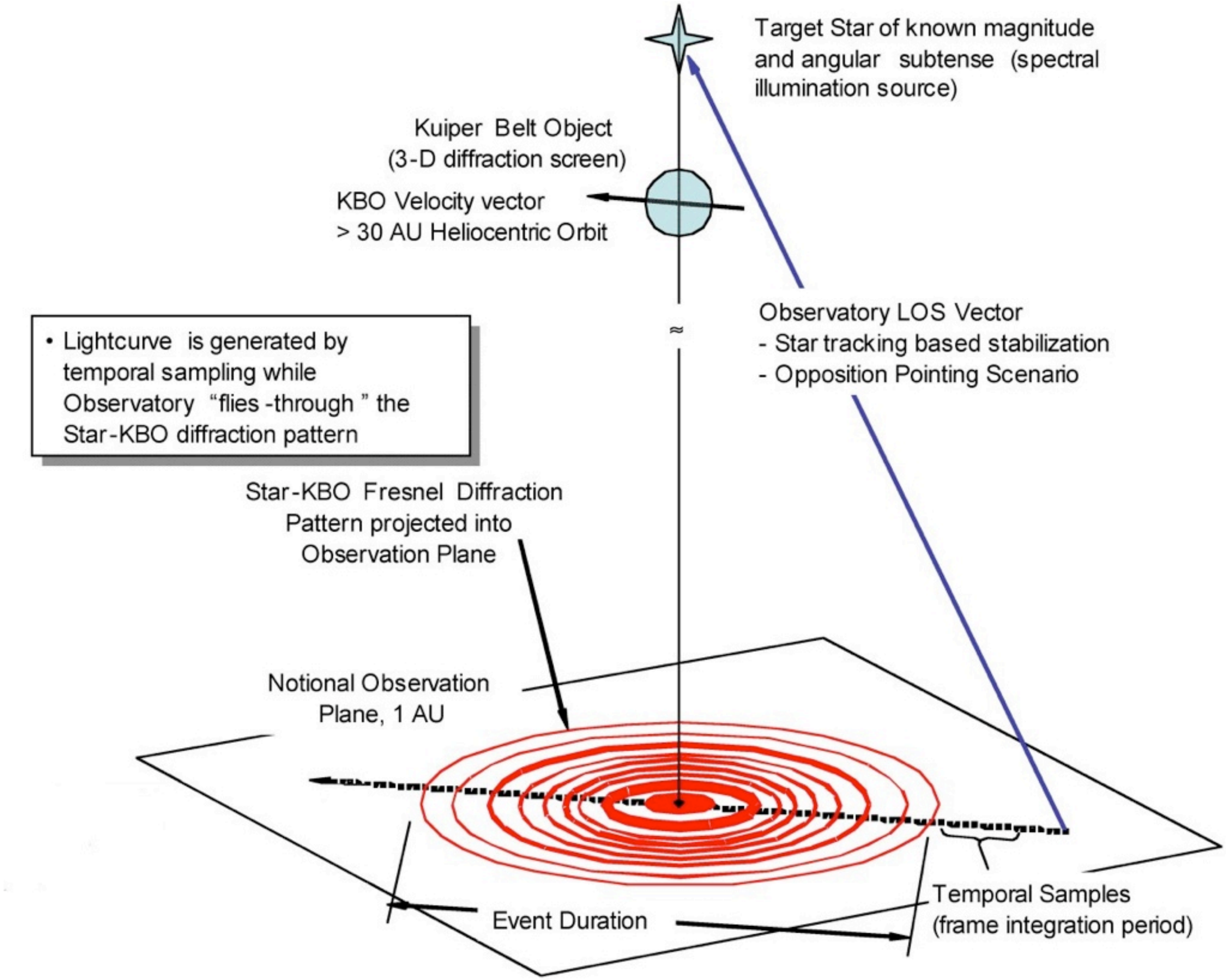
- Scattered disk population
- Sedna: perihelion 76 AU, and semi-major axis 492 AU
- Estimates suggest up to 5 Earth masses in this region, mostly in smaller bodies

Whipple-I Questions

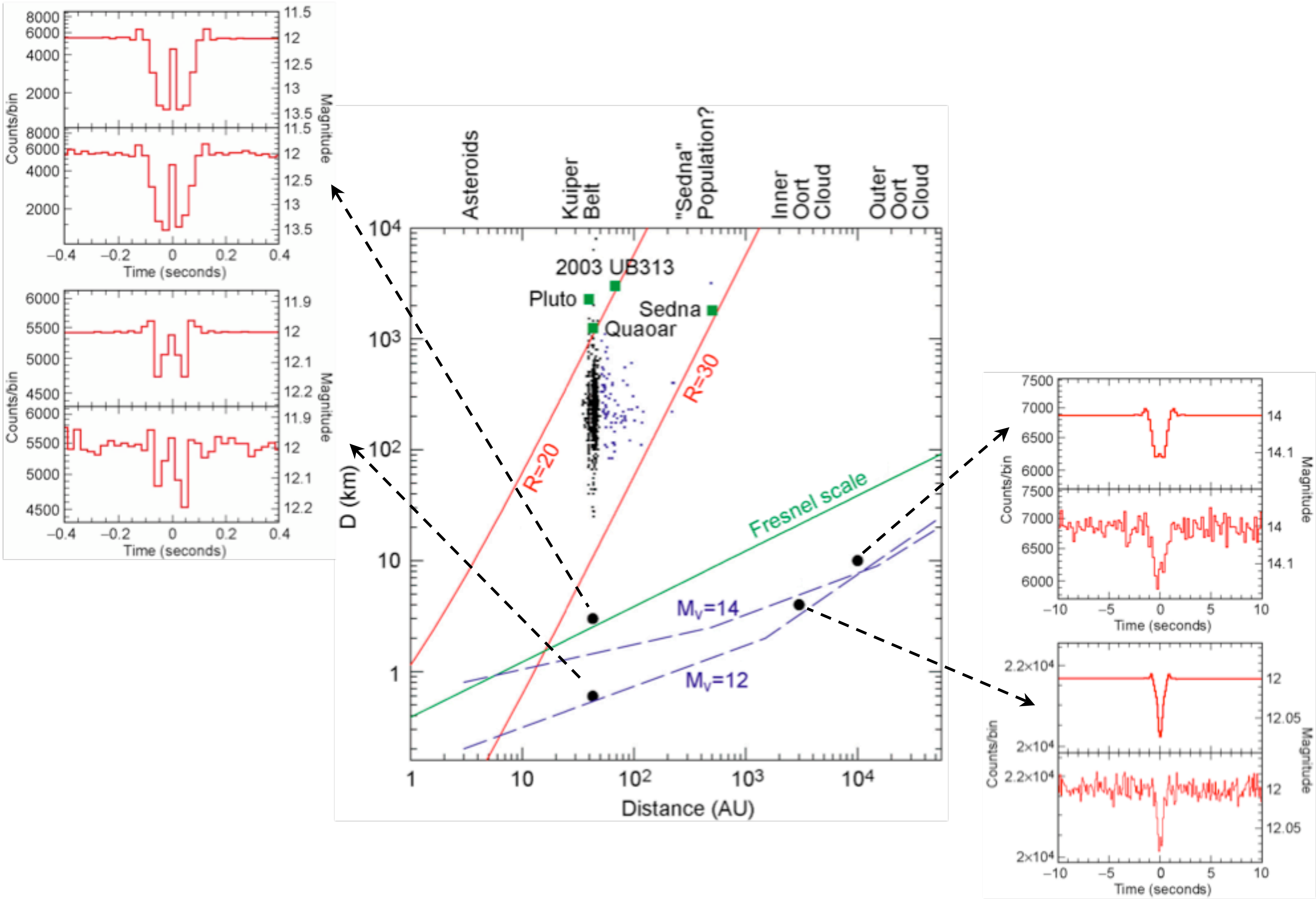
- Is there a large population of objects in Sedna-like orbits?
- Is the classical Oort Cloud as massive as the standard models suggest?
- Is there a cold disk of small objects in the ecliptic plane that extends beyond 50 AU?
- What is the size distribution of KBOs smaller than the HST limit?

Occultation Technique

- Blind Survey - monitor ~140,000 stars at up to 40 Hz cadence (M_v~15 limit)
- Mainly work near the Fresnel Scale
- Rare events in a massive amount of raw data



Target Star of known magnitude and angular subtense (spectral illumination source)
Kuiper Belt Object (3-D diffraction screen)
KBO Velocity vector
> 30 AU Heliocentric Orbit
Observatory LOS Vector
- Star tracking based stabilization
- Opposition Pointing Scenario
• Lightcurve is generated by temporal sampling while Observatory "flies-through" the Star-KBO diffraction pattern
Star-KBO Fresnel Diffraction Pattern projected into Observation Plane
Notional Observation Plane, 1 AU
Event Duration
Temporal Samples (frame integration period)



Asteroids
Kuiper Belt
"Sedna" Population?
Inner Oort Cloud
Outer Oort Cloud
2003 UB313
Pluto
Sedna
Quaoar
R=20
R=30
Fresnel scale
M_V=14
M_V=12
D (km)
Distance (AU)
Counts/bin
Magnitude
Time (seconds)

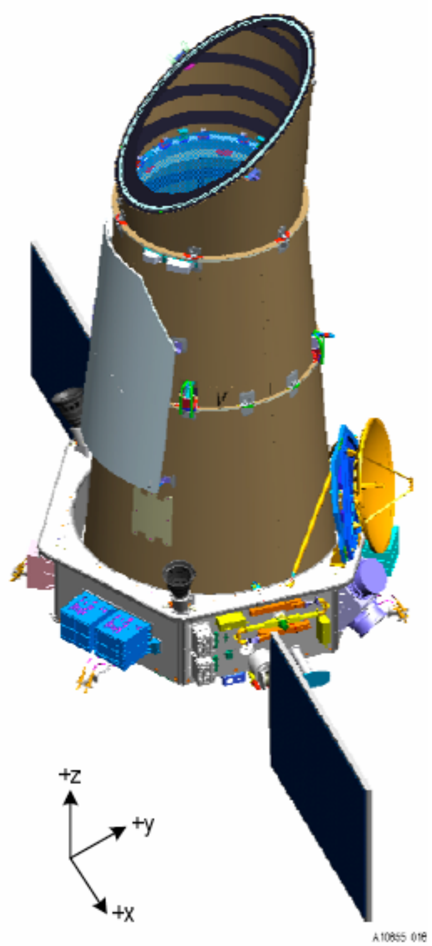
Whipple-I Science Objectives

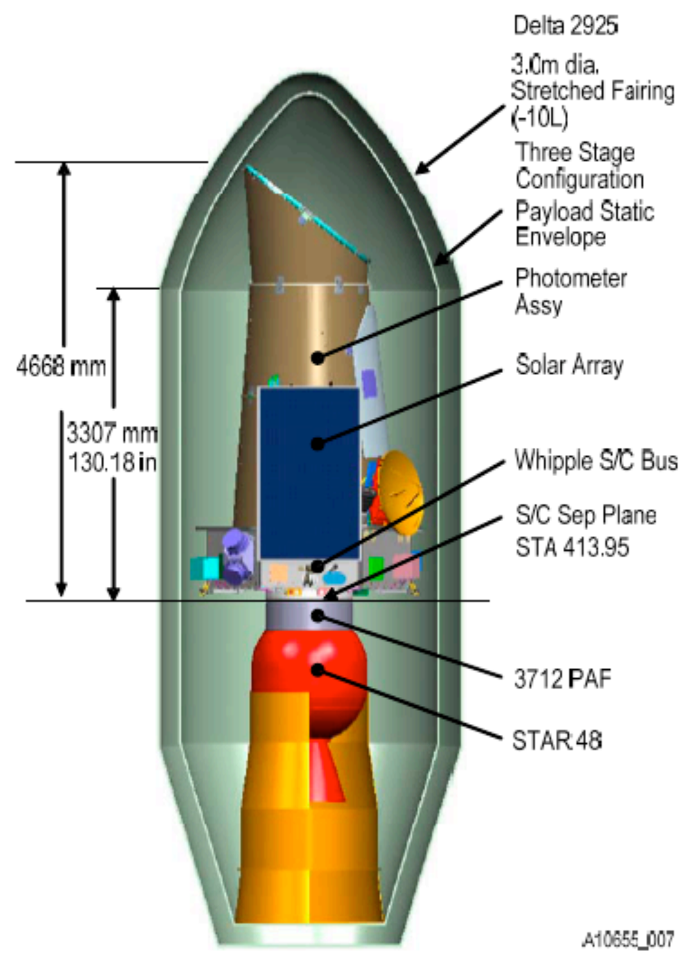
- Test theoretical predictions of the number and distribution of comets in the Oort Cloud
- Determine if the hypothetical population of Sedna-like objects exists
- Test predictions of the size spectrum of small Kuiper Belt objects
- Determine if there is an "edge" to the Kuiper Belt at ~50 AU
- Measure the albedos of large numbers of main belt asteroids
- Expand the horizon of solar system science from ~100 AU to ~20,000 AU.

Science Requirements

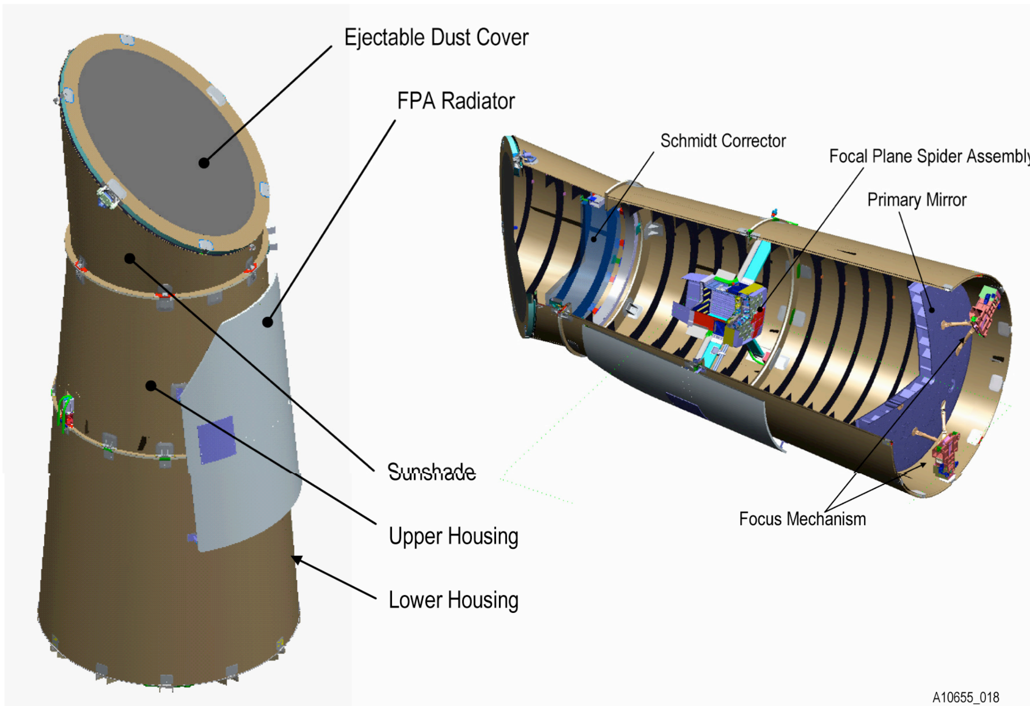
- Detect statistically significant number of outer solar system objects by stellar occultations
  - *Monitor 140,000 stars for 4 years*
- Determine size and distance estimates with a sensitivity to reach small KBOs
  - *Photometric sampling at up to 40 Hz*
- Obtain unbiased spatial distribution of KBOs and OCOs
  - *Point to the ecliptic ± 90°*
- Transmit to ground candidate events
  - *Rapid on-board event recognition*
- Normalize currently known size spectrum of KBOs with Whipple-I object size spectrum
  - *Rapid detection and notification of large object detection*

Whipple-I Spacecraft

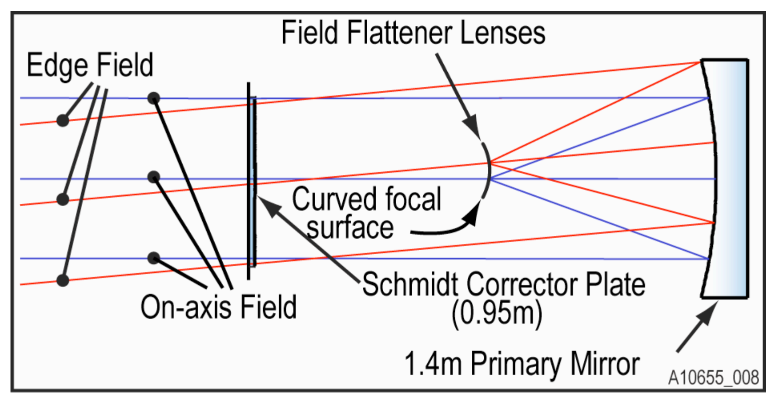




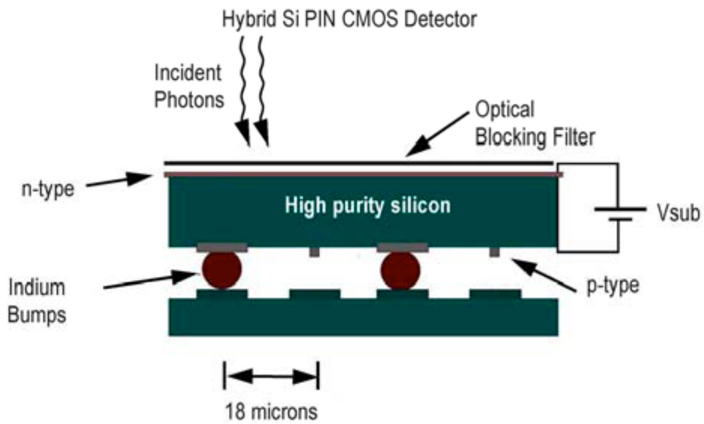
Photometer Telescope



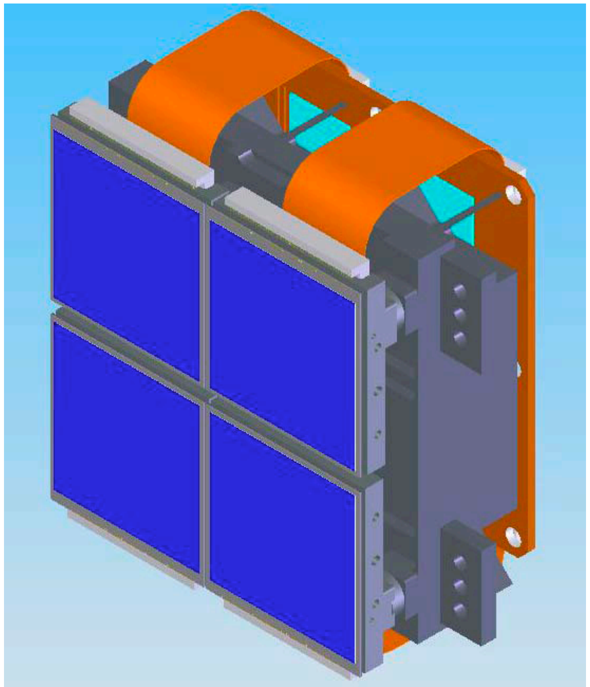
Photometer optics exact copy of Kepler mission



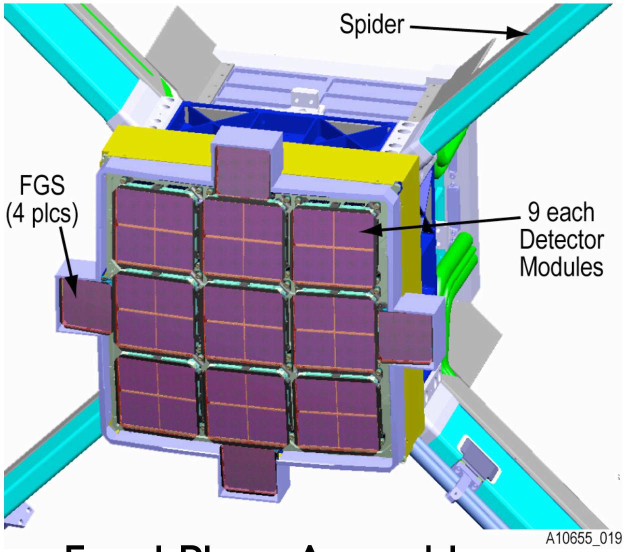
Focal Plane Assembly



H2RG-HiViSi 1024x1024x36 µm



Quad Module with SIDECAR ASICs

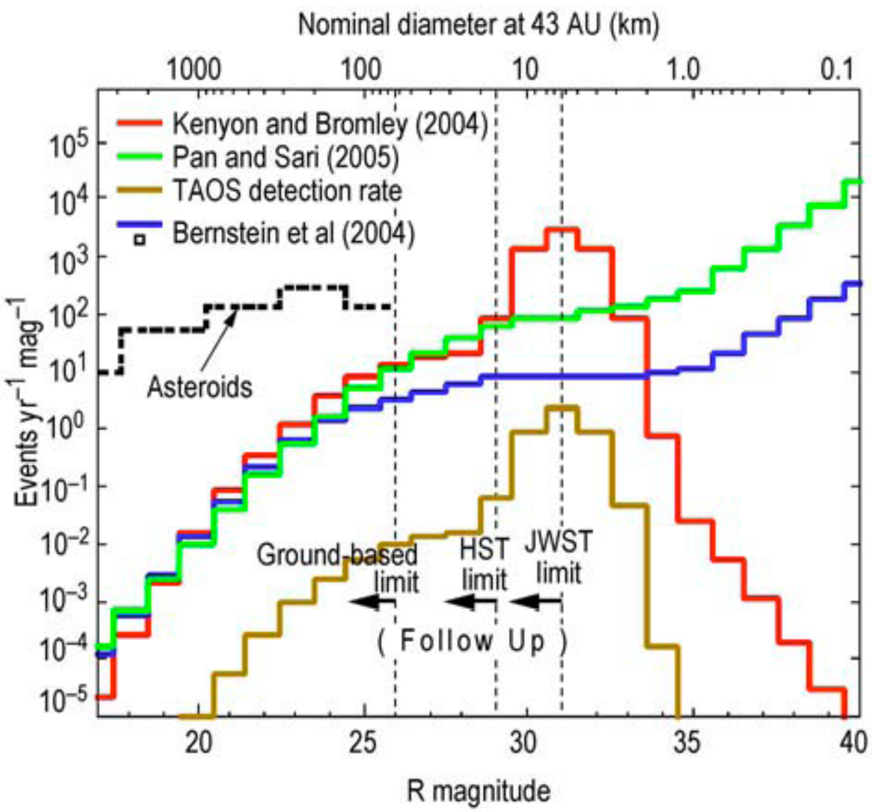


Focal Plane Assembly

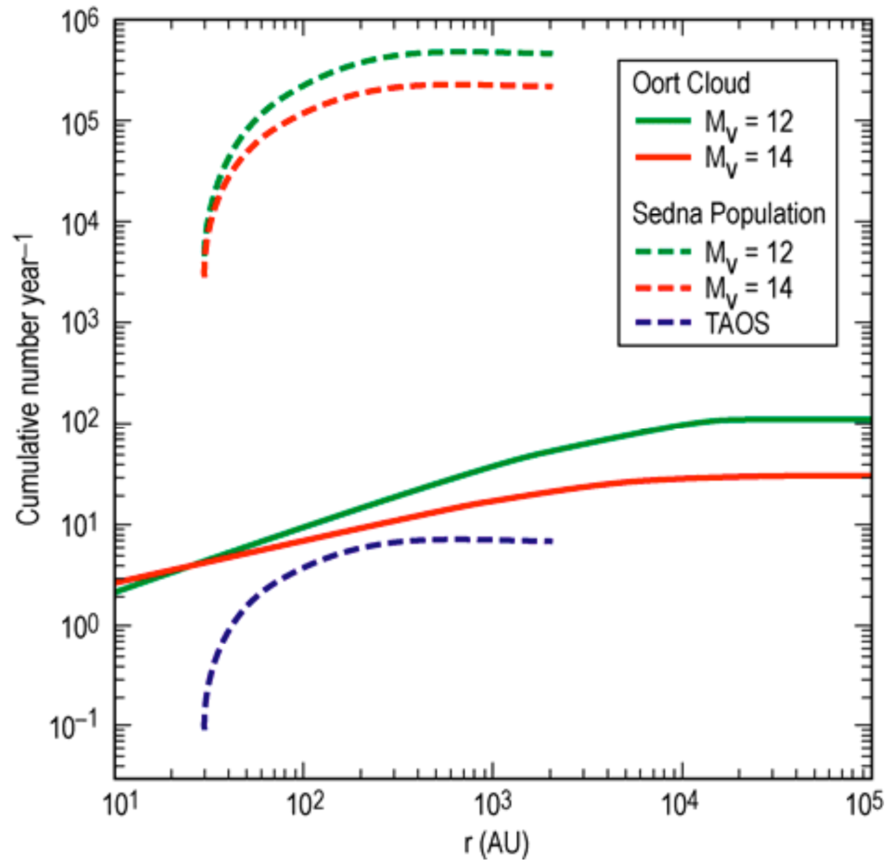
Mission Performance

Parameter	Performance
Target Stars	140,000, observed for 10-20 days over 4 years
Differential Precision	1% for M_v=10 star
Cadence	40 Hz (25 msec/frame)
Detectors	36 Hawaii 2RG Hybrid CMOS
Data Volume	5 Gb/day
Optics	1.4 m focal length, 0.95 aperture Schmidt
FOV	100 deg^2
Bandpass	420-915 nm
Power	408 watts
Mass	425 kg
Pointing Stability	1.5 arcsec (3σ) for 30 seconds
Orbit	Earth-trailing heliocentric 370 day period

Event Rates



Model predictions for Kuiper Belt event rate



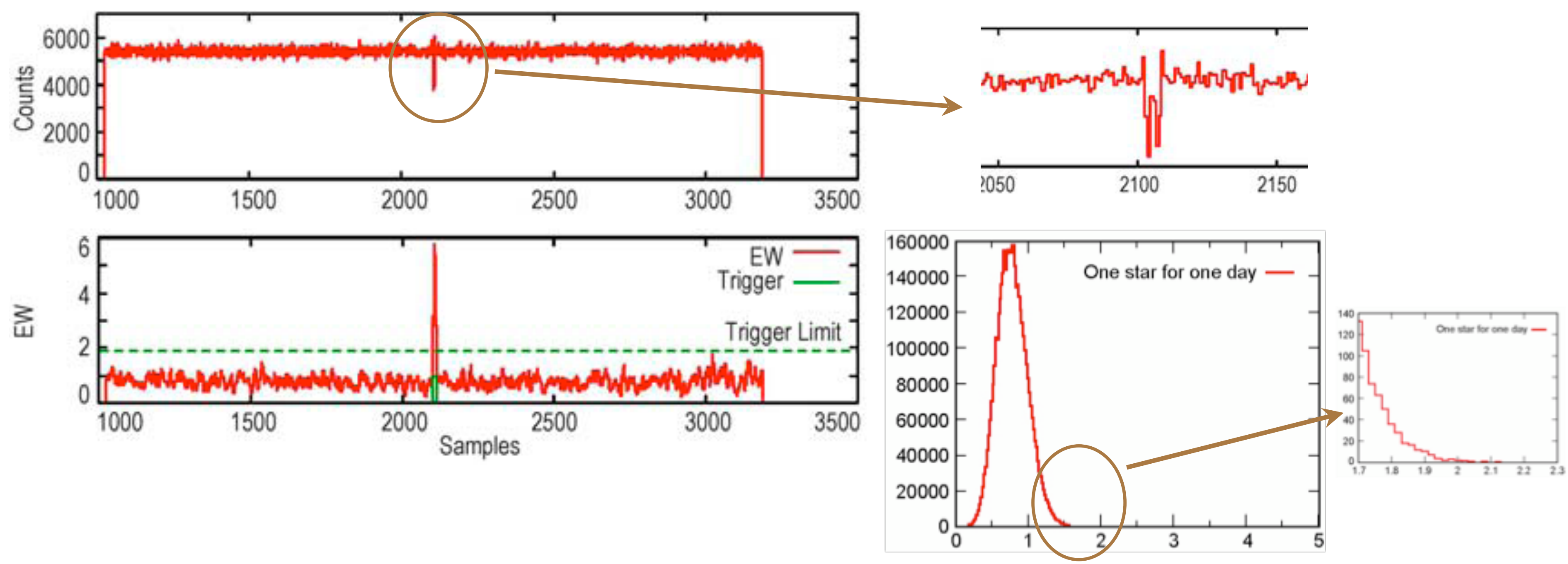
Model predictions for Oort Cloud and Sedna-like population

Event Recognition

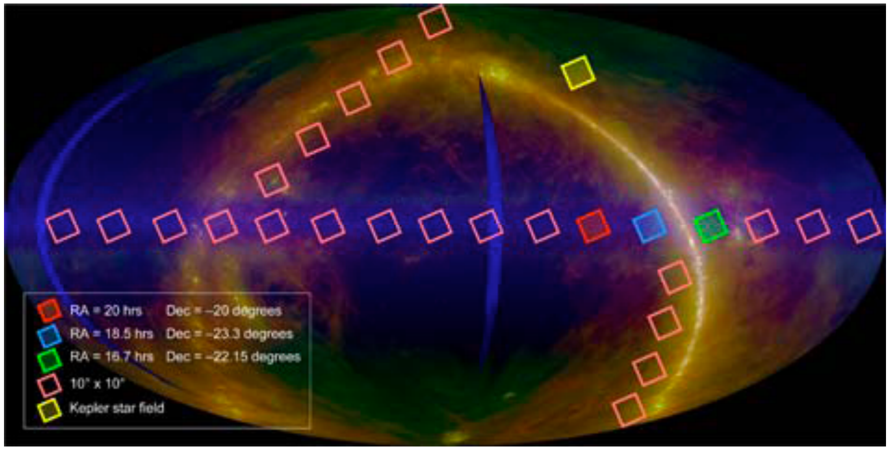
Equivalent Width Algorithm

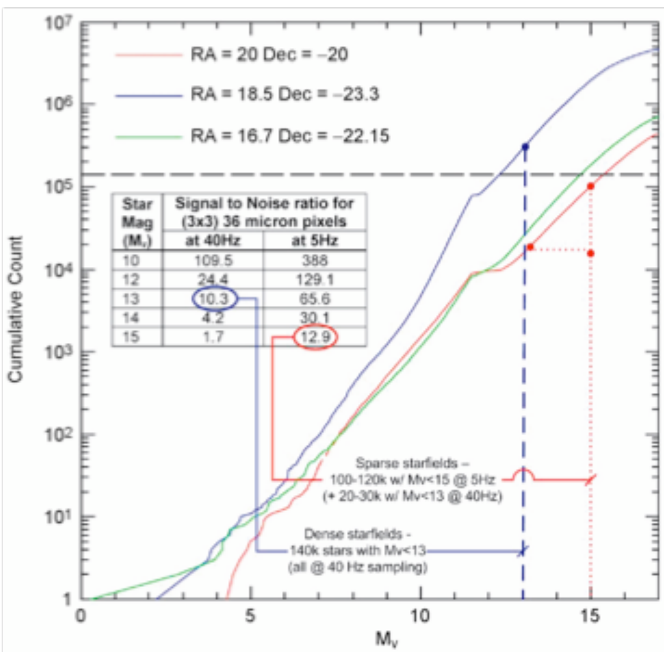
$$EW_i = \sum_{j=i-n_{sw}/2}^{j=i+n_{sw}/2} abs\left(1-\frac{F_j}{\langle F\rangle}\right)$$

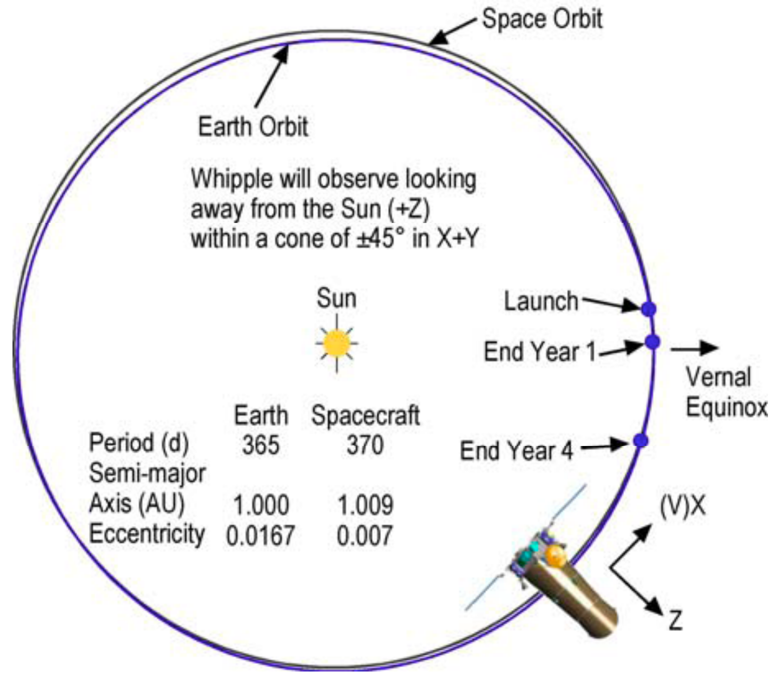
F_j = flux measurement at sample j;
$\langle F \rangle$ = average over 'long' window
n_{sw} = number of points in 'short' window centered on sample i



Mission Profile







Example of Whipple fields spanning the ecliptic and the Milky Way. The red, blue, and green highlighted fields are those shown in the plot. The Kepler field is highlighted in yellow.

Whipple-II Mission

Explore the structure of the solar system beyond 100 AU

- ***Start fresh!***
  - Science driven requirements
  - No *Kepler* dependency
  - Lower resource requirements e.g., cost, mass, power, telemetry, etc.

Science Goals

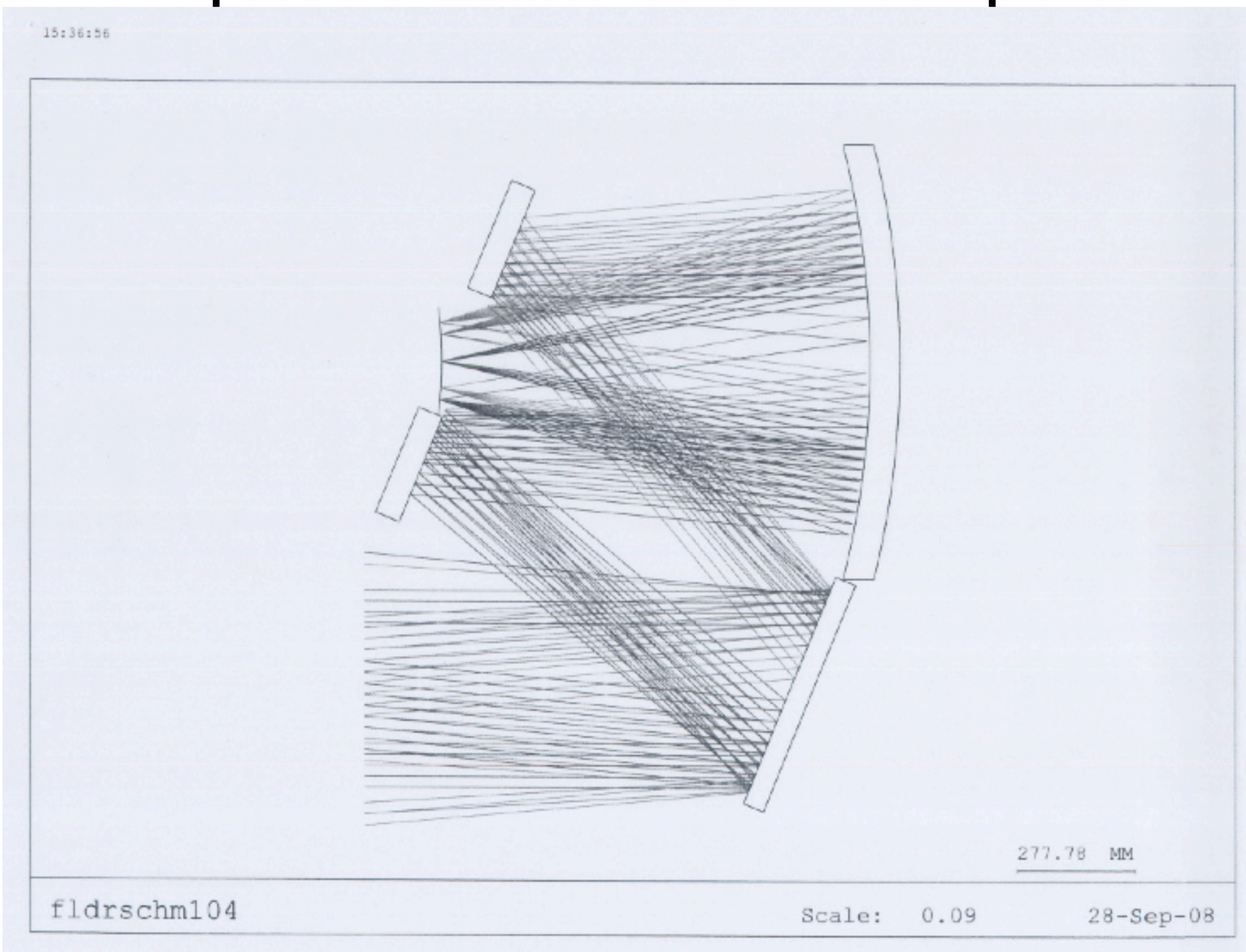
- Characterize the population of the “Sedna-Region” (100 - 1000 AU): *longitude and latitude distributions with some distance and size estimation*
- Characterize the transition from a flattened structure to more isotropic structure at ~5,000 AU
- Determine the size distribution of the various populations of small objects in the outer solar system - classical Kuiper Belt, scattered Kuiper Belt, Sedna-like and Oort Cloud (& asteroids)

Principal Changes from Whipple I

- Improvements in ground-based observations of KBOs reduce the requirement on the number of stars to monitor from 140,000 to ~40,000 (can recover objects fainter than R~27)
- Optical design for photometer not constrained to *Kepler*, off-axis and unobscured options are promising
- New focal plane technology - monolithic CMOS with low read noise improves signal-to-noise significantly
- Long period Earth orbit (more like *Chandra* than *Spitzer*)

Three Mirror Anastigmatic:

Compact, 40 cm unobscured aperture



Summary

- A dedicated space-based occultation survey can probe the outer solar system far beyond the reach of direct observation
- The design requirements can be achieved within the scope of a NASA *Discovery* class mission
- We plan to respond to the next NASA *Discovery* Announcement of Opportunity (no sooner than one year from now)
- Preliminary design studies are in progress.