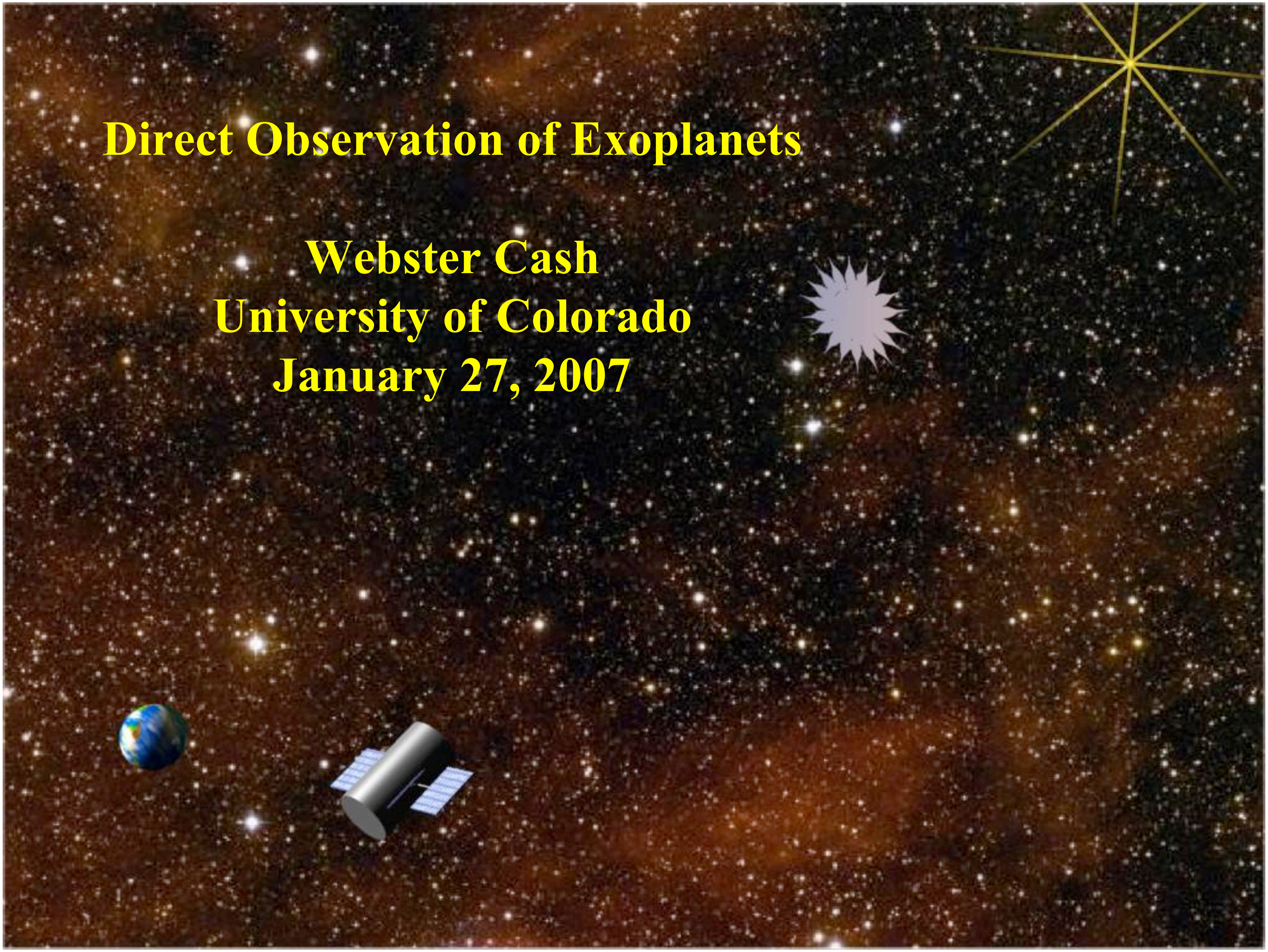
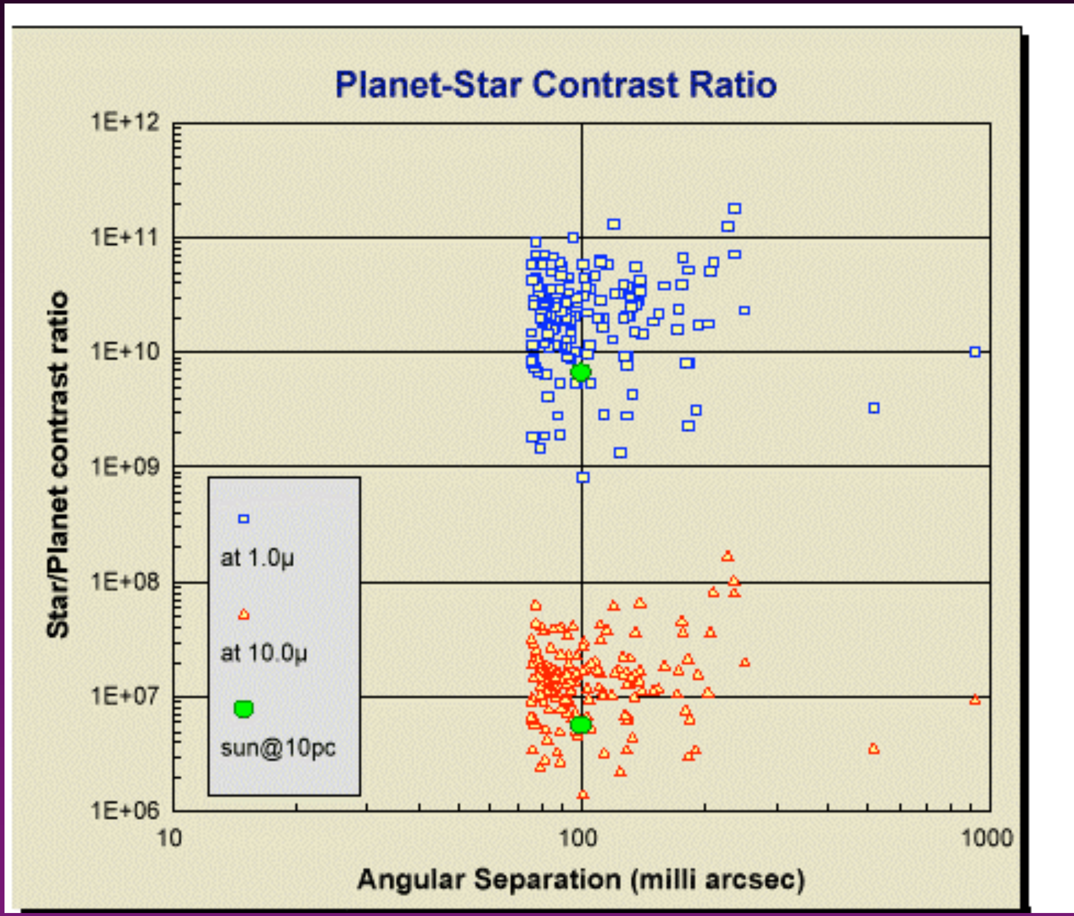

Direct Observation of Exoplanets
Webster Cash
University of Colorado
January 27, 2007

Planet Finding: Extinguish the Star

Contrast ratios better than 10 billion to one needed across a tenth of an arcsecond.

Wow. That's tough!

However will we get it done???



Courtesy of N-G

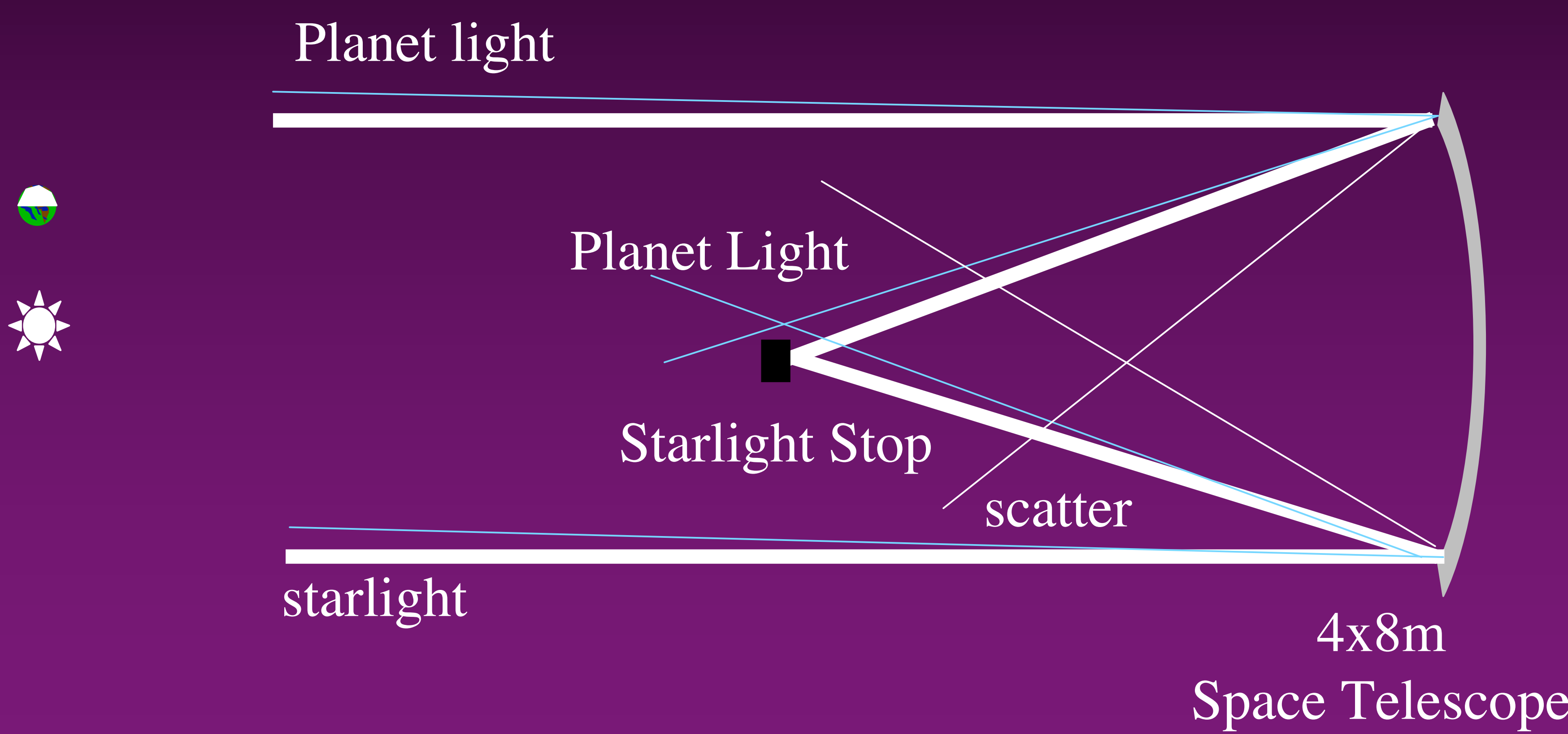
Terrestrial Planet Finder
JPL's Answer

TPF-C

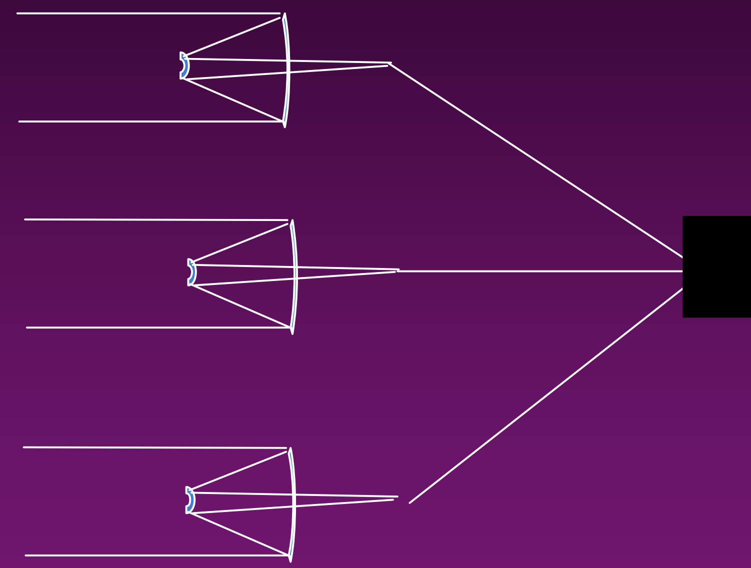
TPF-I

Must Be Done in Space Because of Atmospheric Twinkle

TPF-C
Visible Light Coronagraph

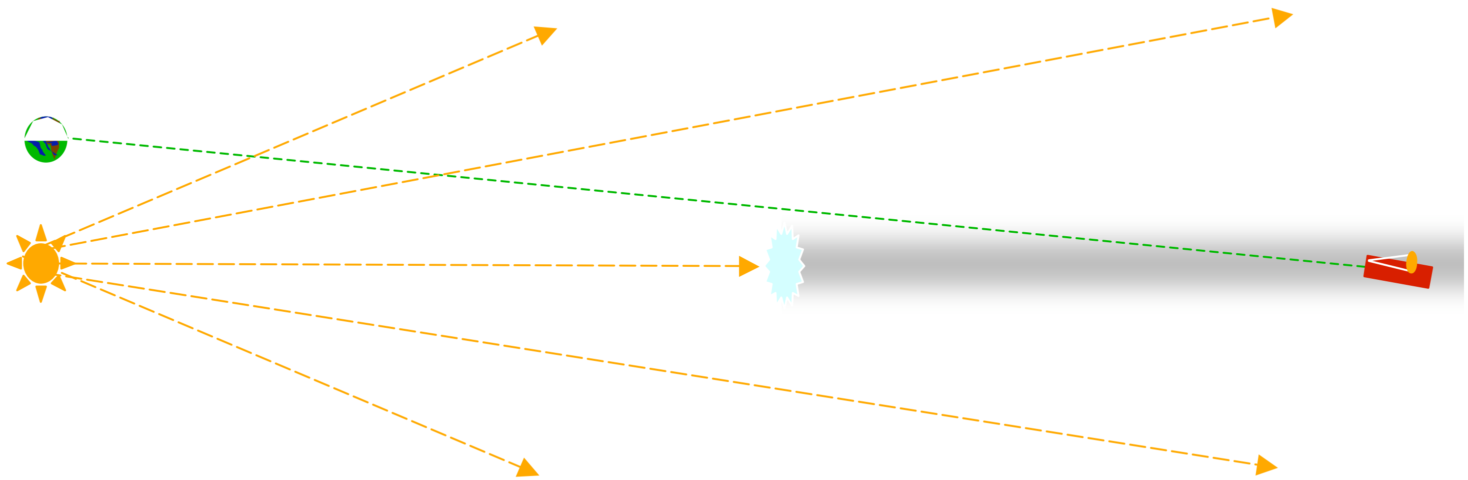


TPF-I & Darwin
Mid-Infrared Interferometer



Multiple Large Cooled-IR Telescopes Combine Beams
Null Out Star at One Angle
Constructive Interference at Nearby (Planet) Angle

Occulters



Telescope big enough to collect enough light from planet

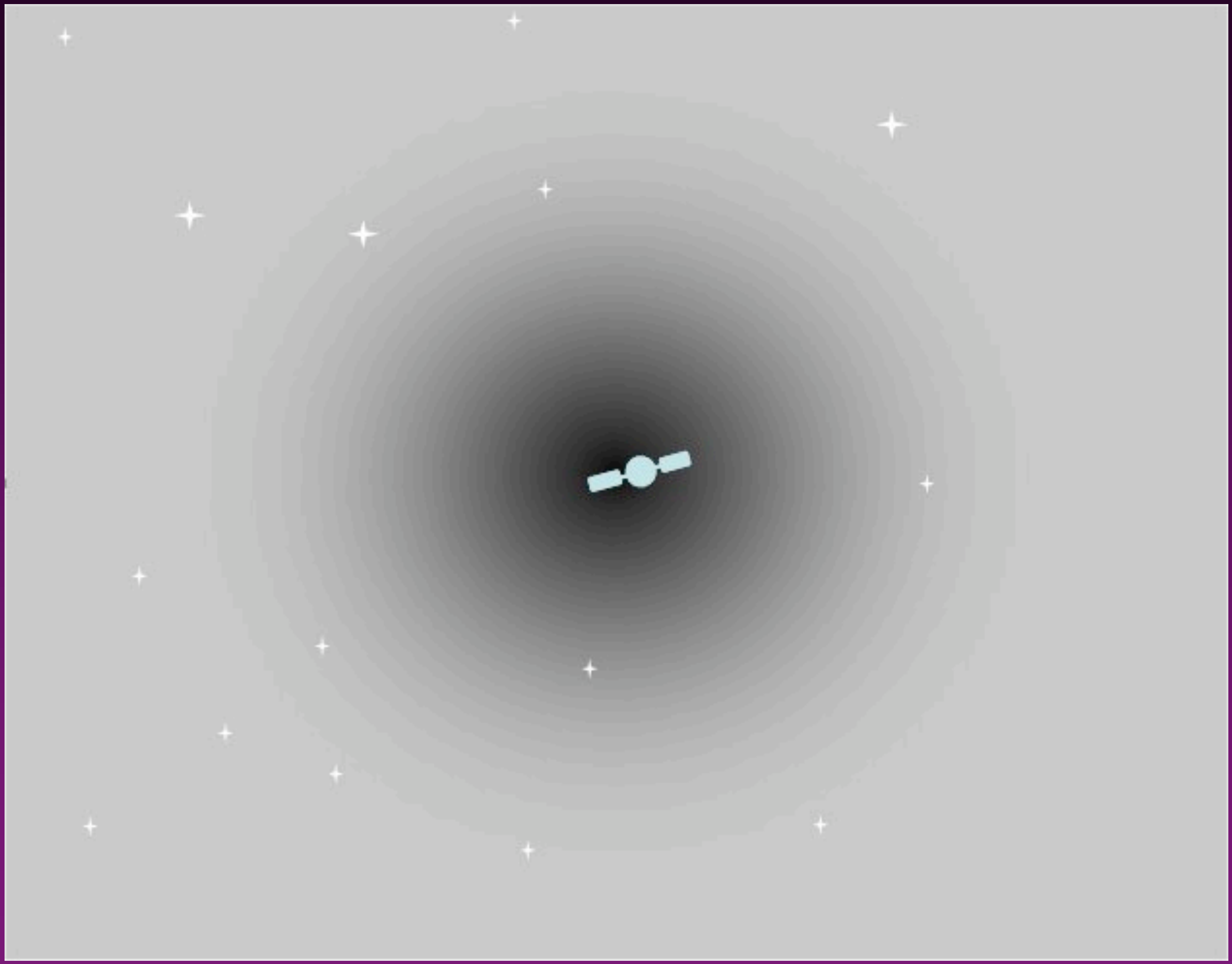
Occulter big enough to block star

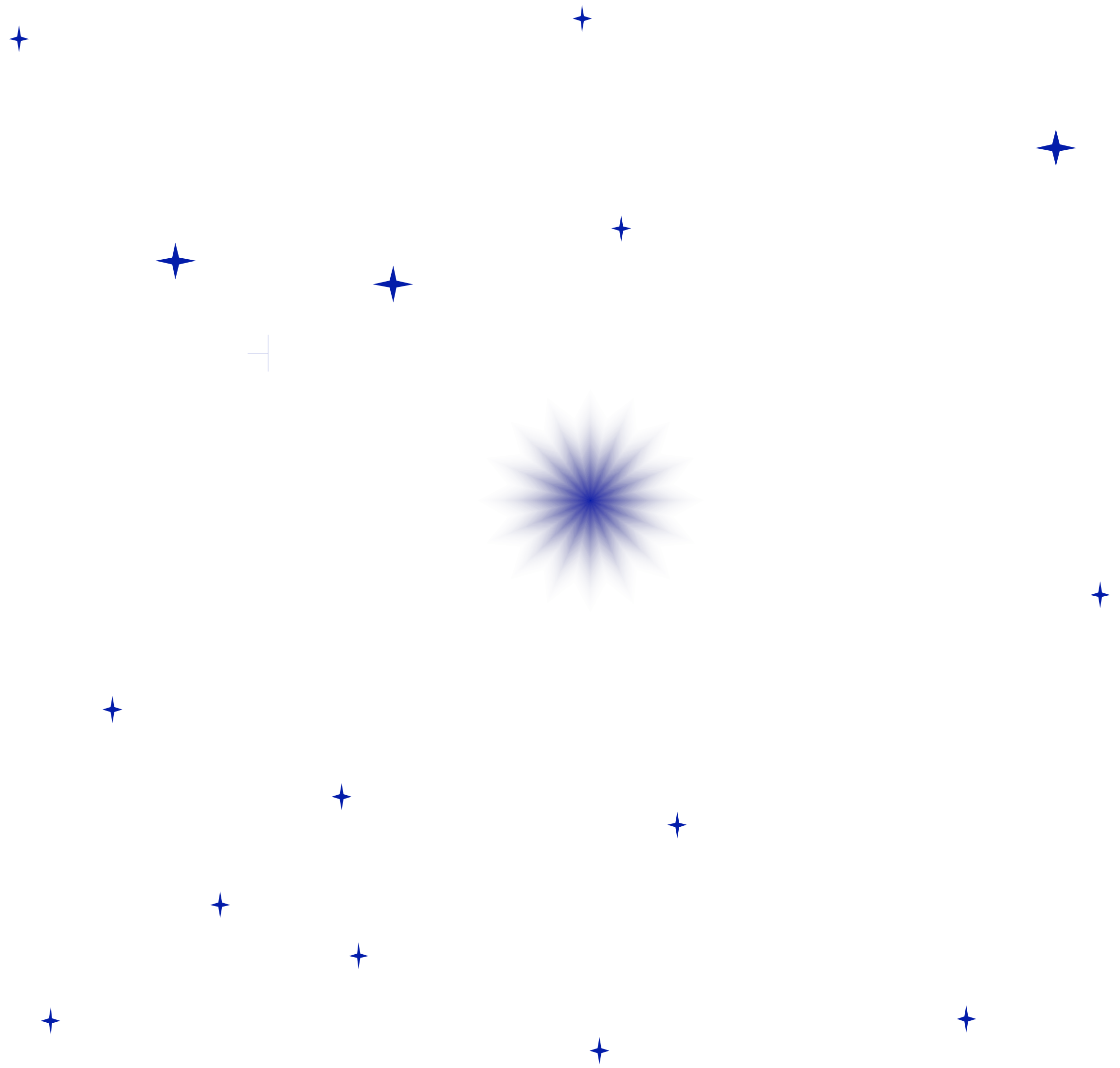
Want low transmission on axis and high transmission off axis

Telescope far enough back to have a properly small IWA

No outer working angle: View entire system at once

Fly the Telescope into the Shadow





Why Haven't Occulters Been Baselined All Along?

- ☞Because →
- ☞Everybody knows that diffraction around an occulter is too severe

Occulters

☞ **Several previous programs have looked at occulters**

– First look by Spitzer (1962)

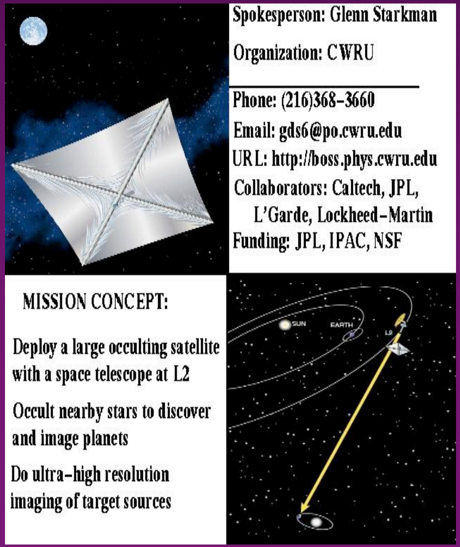
☞ **Used simple geometric shapes**

– Achieved only 10^{-2} suppression across a broad spectral band

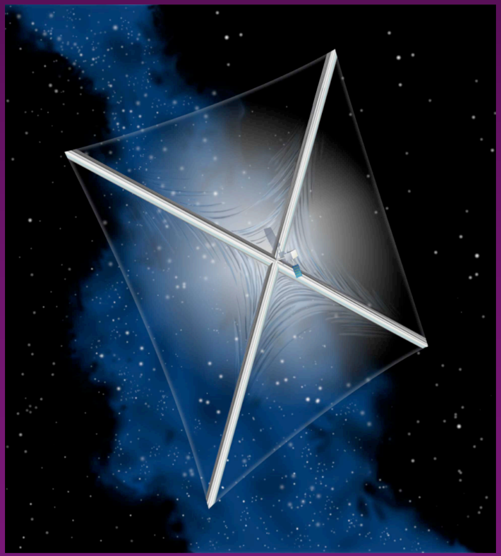
☞ **With transmissive shades**

– Achieved only 10^{-4} suppression despite scatter problem

http://umbras.org/



BOSS



Starkman (TRW ca 2000)

Extinguishing Poisson's Spot

☞ **Occulters Have Very Poor Diffraction Performance**
- The 1818 Prediction of Fresnel led to the famous episode of:
- Poisson's Spot (variously Arago's Spot)
- Occulters Often Concentrate Light!

☞ **Must satisfy Fresnel Equation, Not Just the Fraunhoffer Equation**

☞ **Must Create a Zone That Is:**
- Deep — Below 10^{-10} diffraction
- Wide — A couple meters minimum
- Broad — Suppress across at least one octave of spectrum

☞ **Must Be Practical**
- Binary — Non-transmitting to avoid scatter
- Size — Below 150m Diameter
- Tolerance — Insensitive to microscopic errors

The Apodization Function

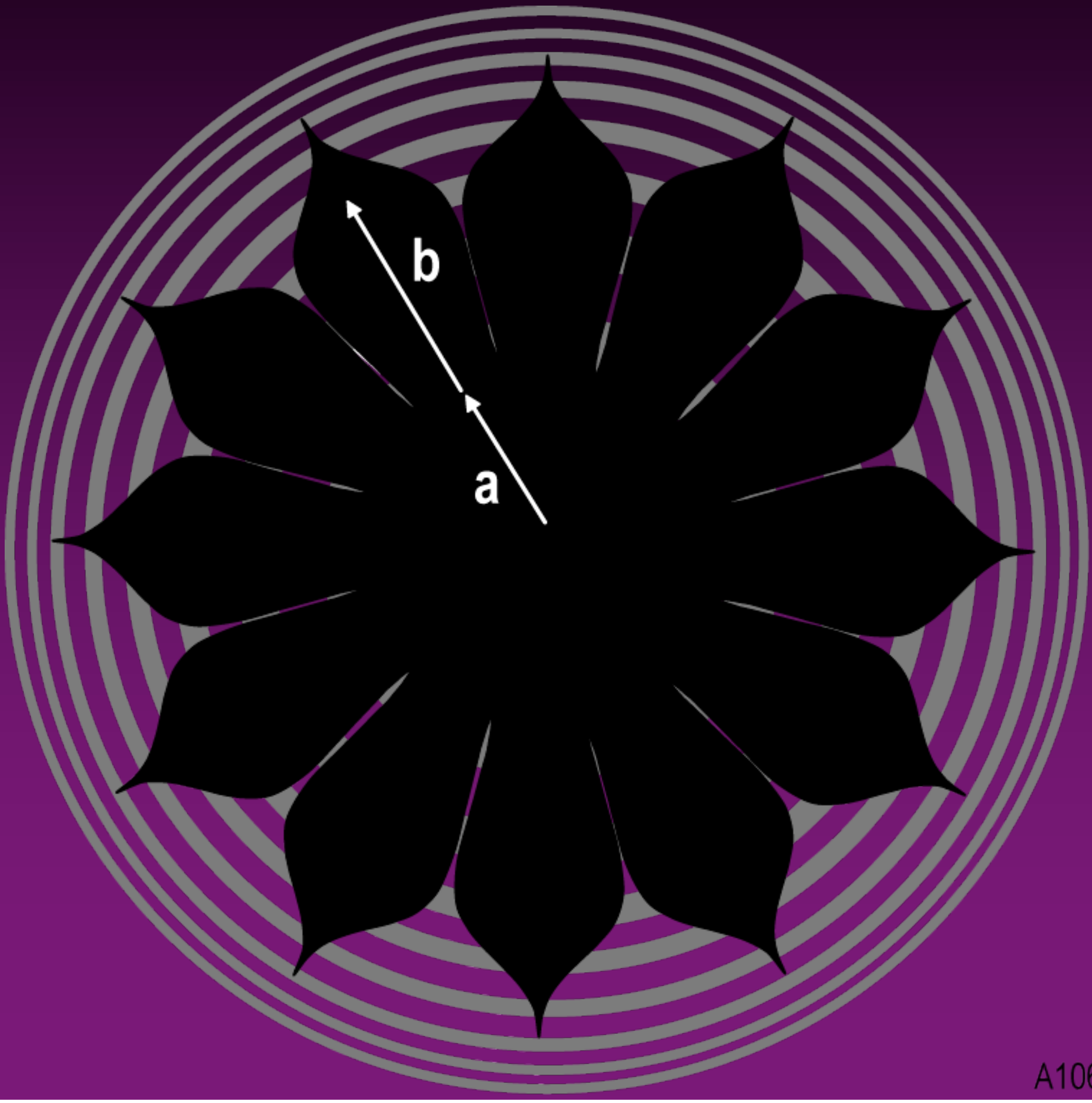
Found this in April. Extended in June.
This Function Extinguishes Poisson's Spot to High Precision

$$A(\rho) = 0 \quad \text{for} \quad \rho < a$$

and

$$A(\rho) = 1 - e^{-\left(\frac{\rho - a}{b}\right)^{n}} \quad \text{for} \quad \rho > a$$

Binary Shape



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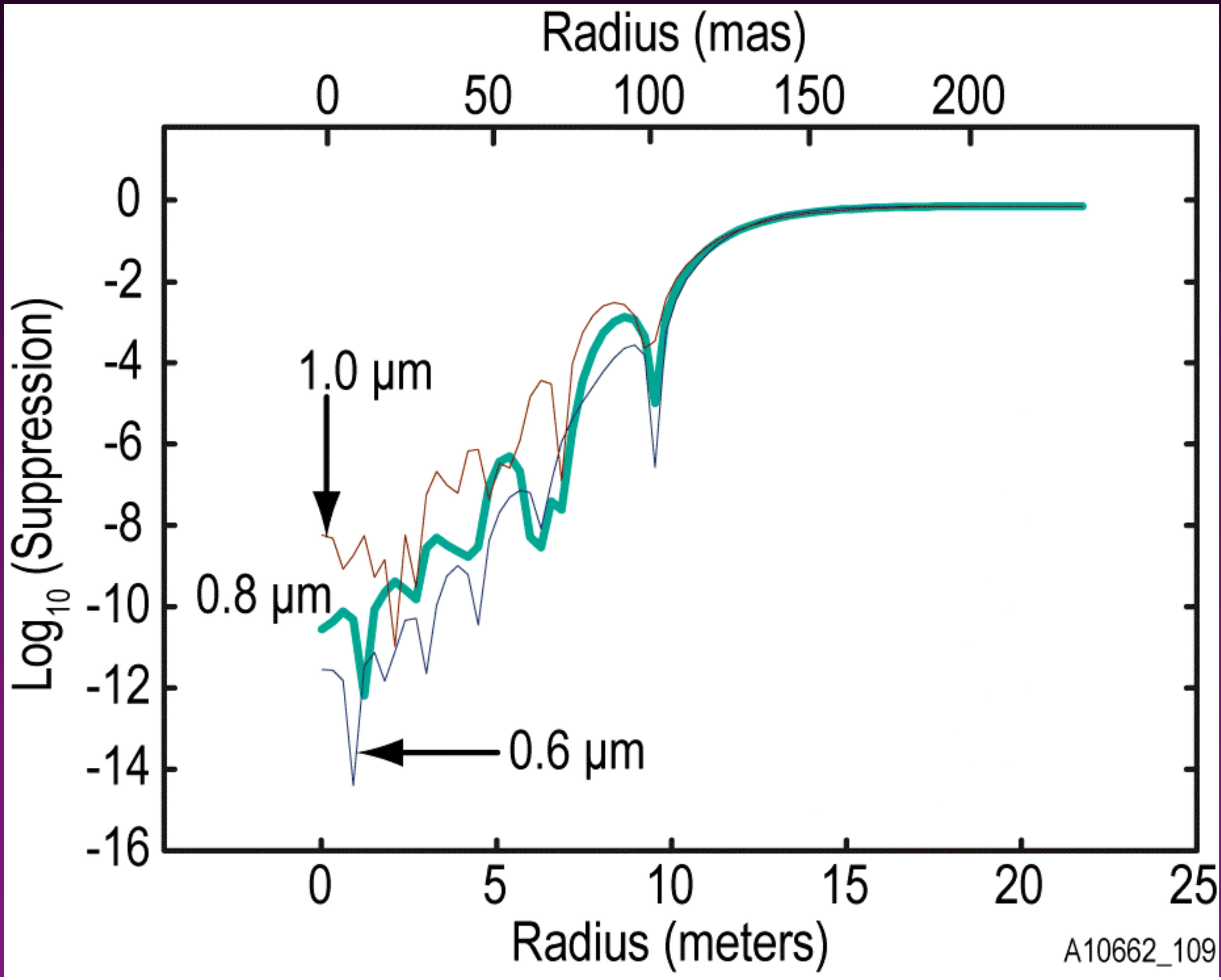
Shadow Depth



Doing the Math (Cash, Nature 2006)

- ☞The Residual Intensity in the Shadow is $I_s = E_s^2$
- ☞By Babinet's Principle $E_s = 1 - E_A$ where E_A is field over Aperture
- ☞So We Must Show

$$\frac{k}{2\pi F}\left[\int_0^{2\pi}\int_0^{a} e^{\frac{ik\rho^2}{2F}} e^{-\frac{ik\rho s\cos\theta}{F}} \rho \, d\rho \, d\theta + \int_0^{2\pi}\int_a^{\infty} e^{\frac{ik\rho^2}{2F}} e^{-\frac{ik\rho s\cos\theta}{F}} e^{-\left(\frac{\rho-a}{b}\right)^n} \rho \, d\rho \, d\theta\right] = i$$

- ☞ *F* is distance to starshade, *s* is radius of hole, *k* is $2\pi/\lambda$
- ☞To one part in $\sqrt{C} \approx 10^{-5}$

Contrast Ratio

☞ **Preceding integral shows the contrast ratio is**

–

$$R = \left[\frac{n!}{a^n b^n} \left(\frac{F\lambda}{2\pi} \right)^n \right]^2$$

– n is an integer parameter, typically n=6

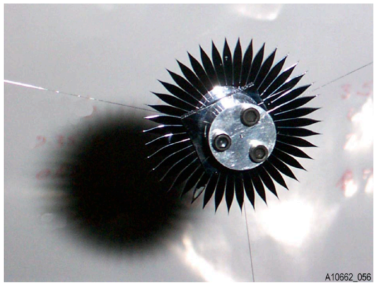
☞ **To keep R small a~b**

– this is the reason the occulter has that symmetric look

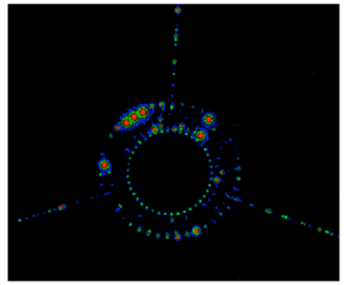
Starshade Tolerances

- ☞ **Position**
  - ➢ Lateral — Several Meters
  - ➢ Distance — Many Kilometers
- ☞ **Angle**
  - ➢ Rotational — None
  - ➢ Pitch/Yaw — Many Degrees
- ☞ **Shape**
  - ➢ Truncation — 1mm
  - ➢ Scale — 10%
  - ➢ Blob — $3cm^2$ or greater
- ☞ **Holes**
  - ➢ Single Hole — $3cm^2$
  - ➢ Pinholes — $3cm^2$ total

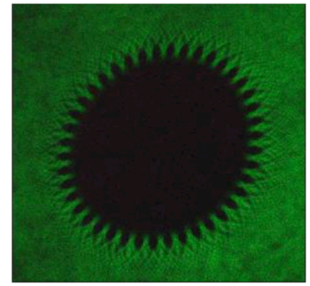
Lab Studies



a)

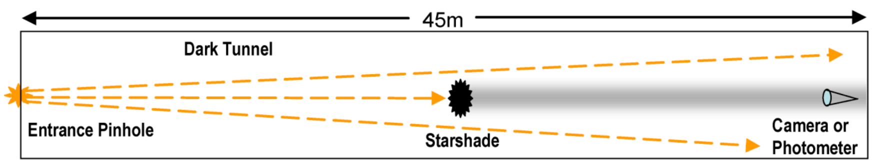


b)



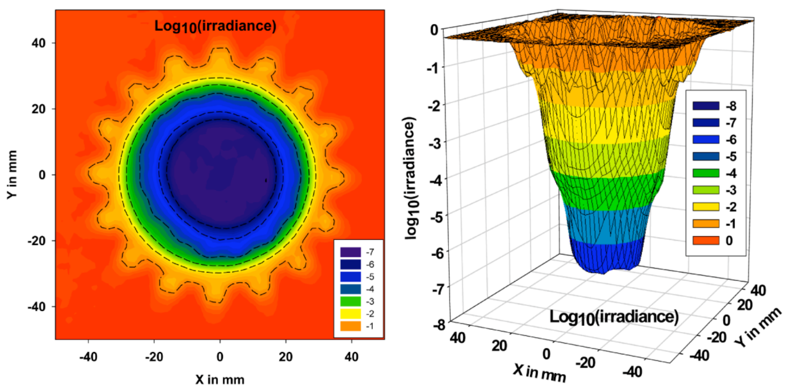
c)

Figure D-12 a): A test starshade, 35mm tip to tip made from silicon by lithographic techniques and suspended by three thin wires with a = b = 8mm, n = 6, and 42 petals; b) image of starshade back-illuminated by diverging beam of sunlight with approximately the same Fresnel number as expected in flight; clearly visible are scattering off support wires, two rings of bright points that correlate with tips of petals and gaps at bases of petals; c) when illuminated with coherent light (a green HeNe laser), one can see that diffraction by the starshade is primarily in the azimuthal direction.

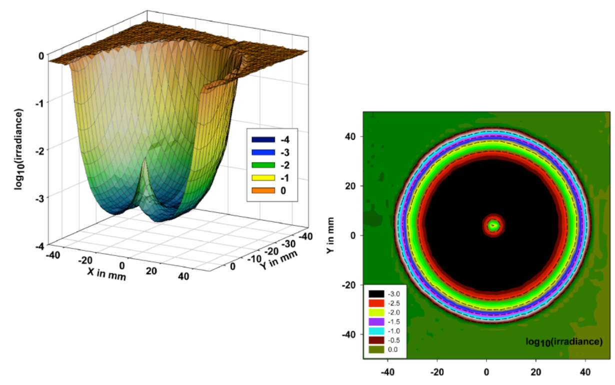


d) Schematic of test beamline; a heliostat feeds sunlight into the dark tunnel; a photon counting photometer scans the shadow to measure its depth; a camera can image the diffraction and scatter by defects around the starshade.

e) Students near one end of dark tunnel at University of Colorado



f) Photometer mapping of shadow from 16 petal silicon starshade in white light shows suppression of several orders of magnitude of irradiance within a few millimeters, with an ultimate suppression level of < 1 x 10^{-7}.



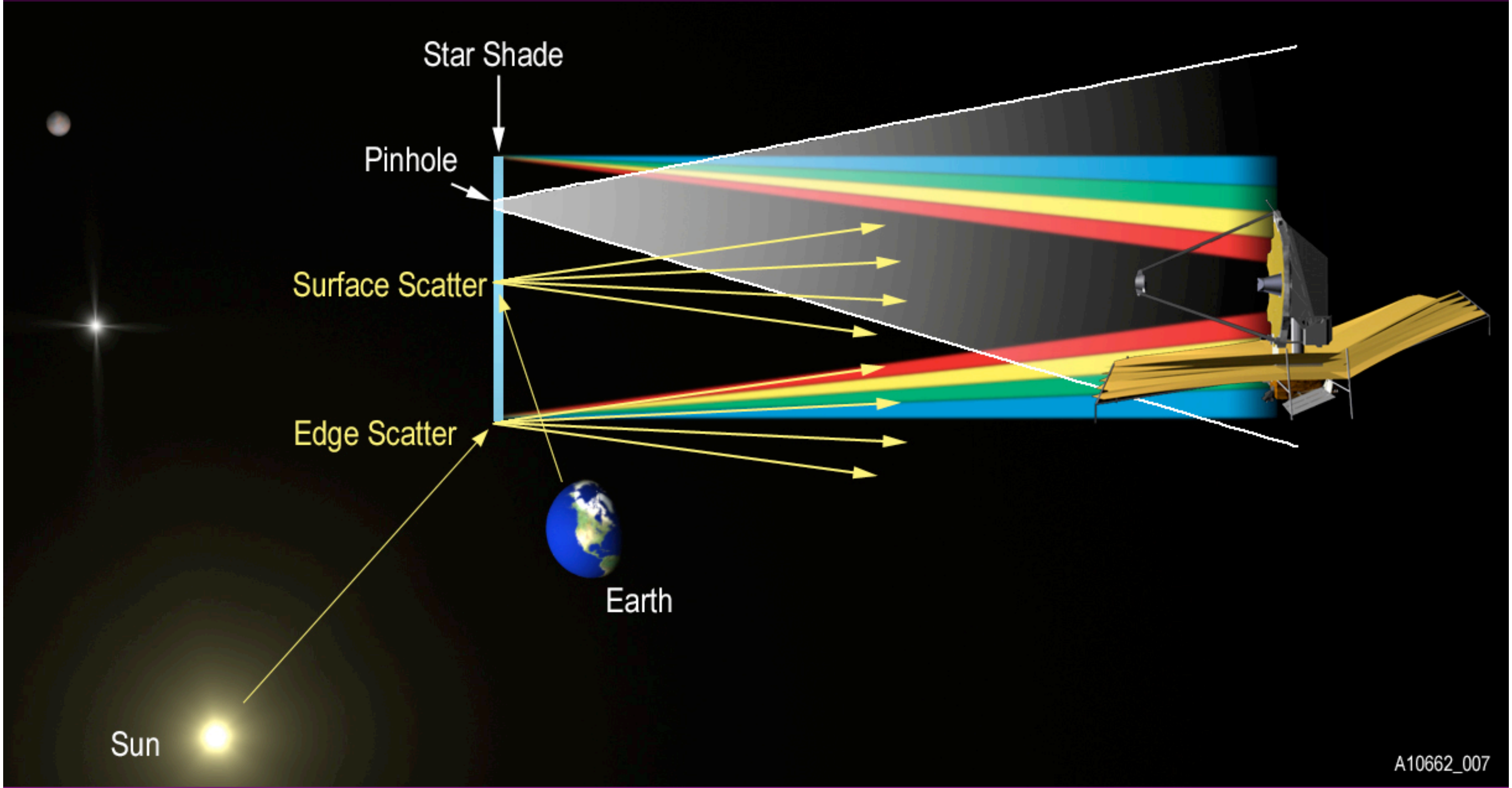
g) Map of shadow from a precision circular disc in white light showing amplitude of Poisson's spot at a predicted irradiance level 1% of incident level, verifying the photometric accuracy of measurement facility.

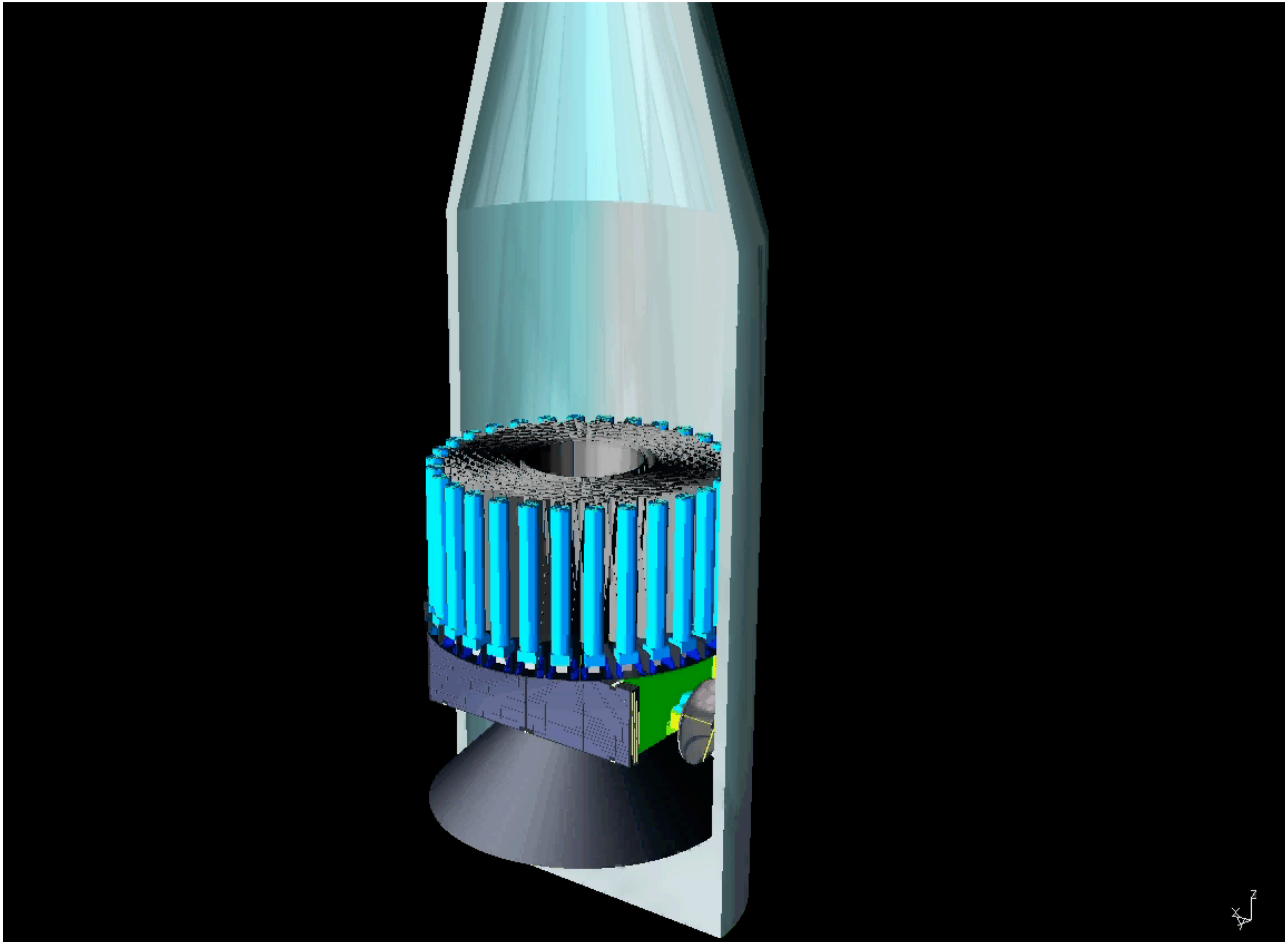
Tall Poles

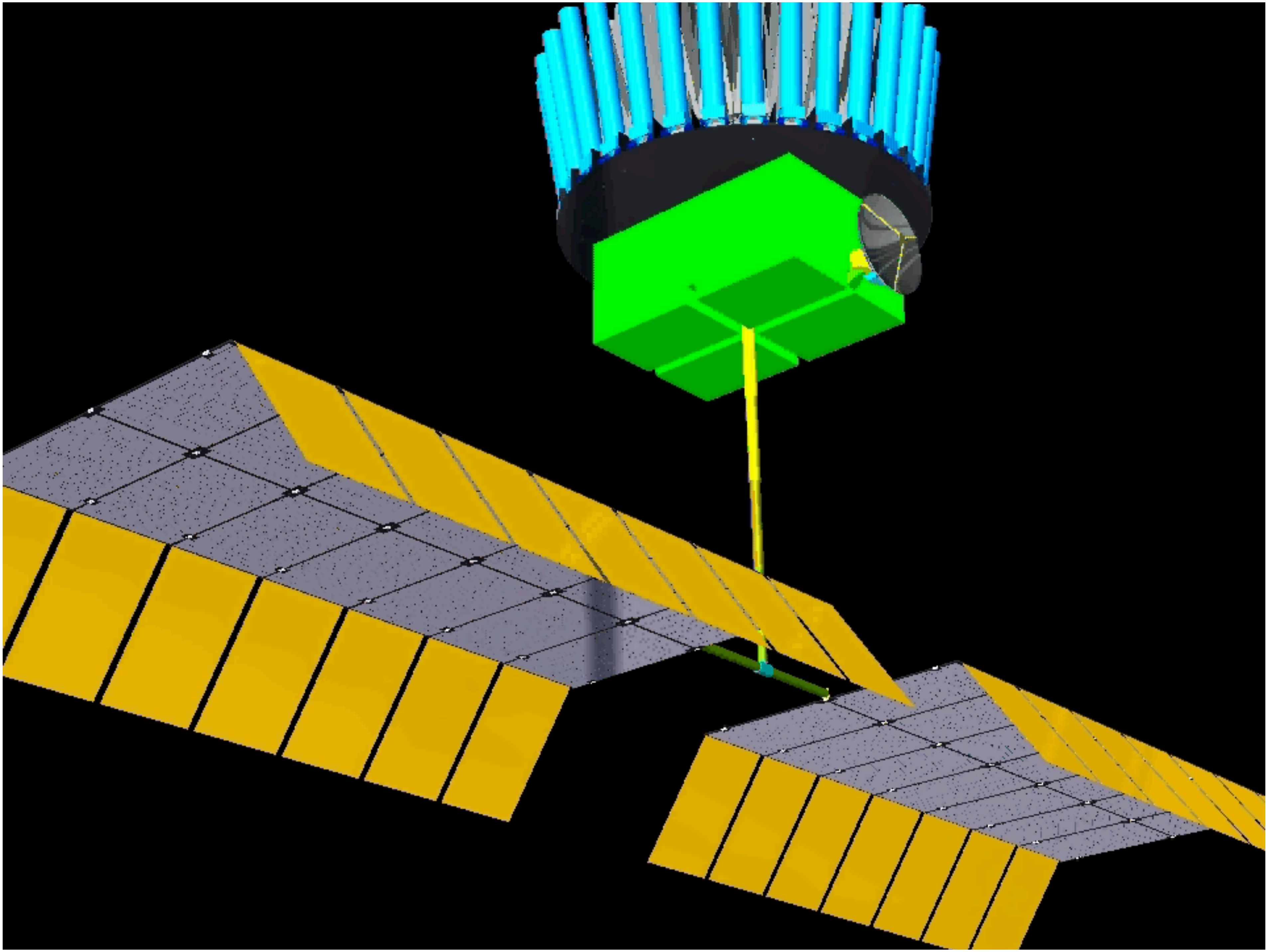
- ☞ Deployment of 35m shade to mm class tolerance
- ☞ Acquiring and holding line of sight
- ☞ Fuel usage, orbits and number of targets
- ☞ Stray Light – particularly solar

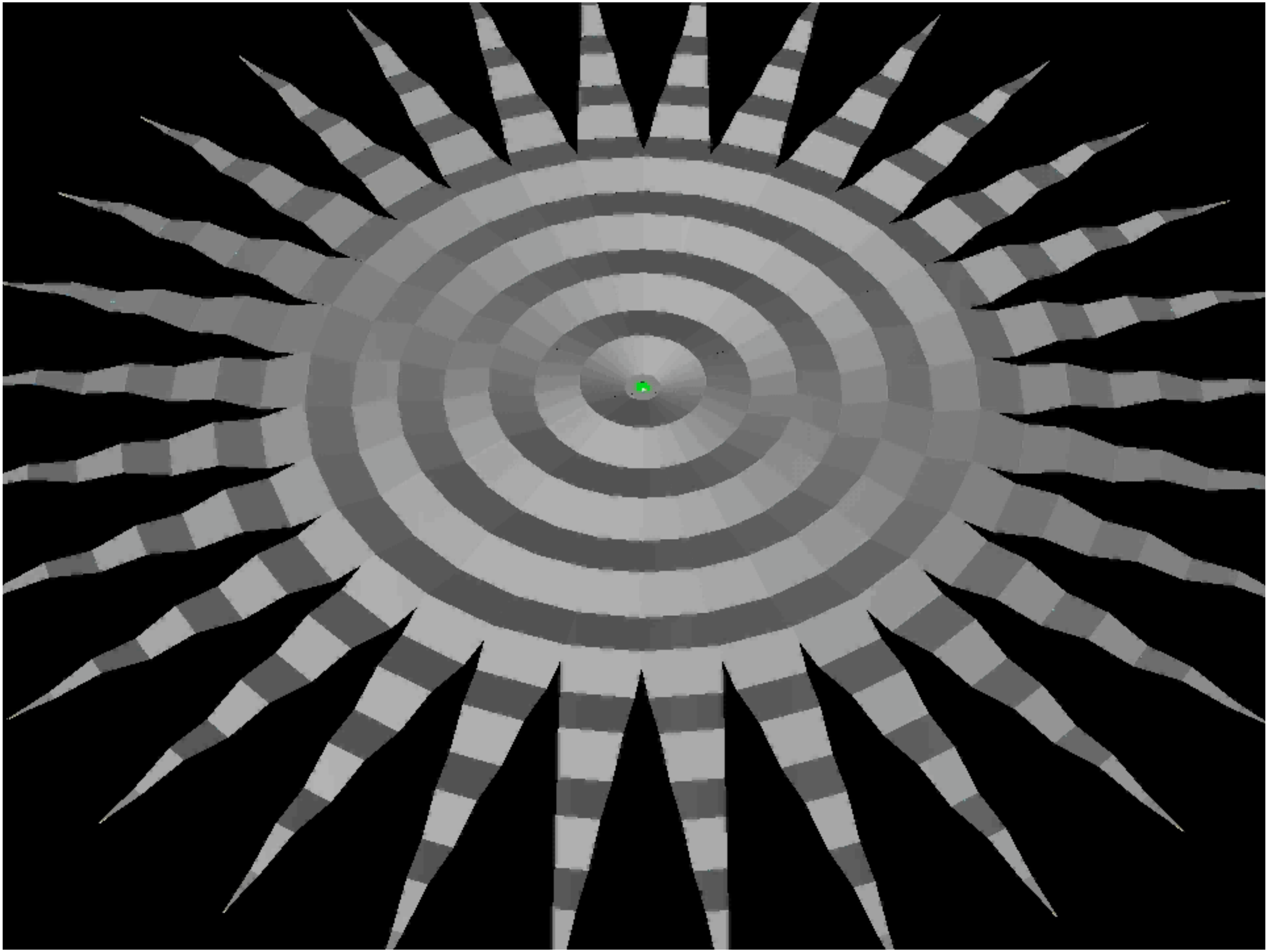
Scatter Control

View Nightside



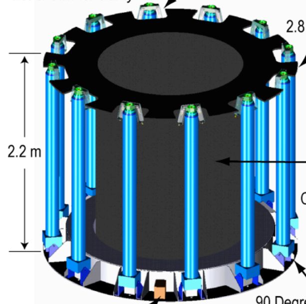




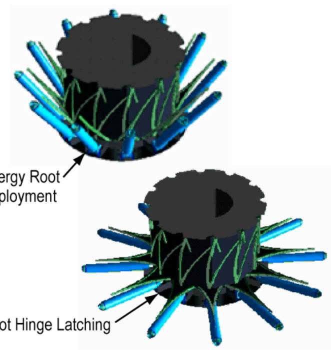


Deployment

Starshade Deployment Sequence

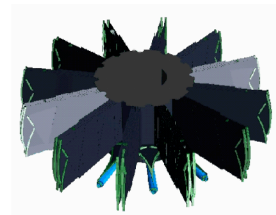


Stowed configuration, inside spacecraft envelope.

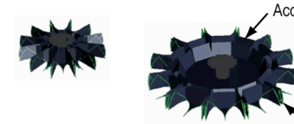


The booms fold down, each boom supports one petal, and there are twelve booms.

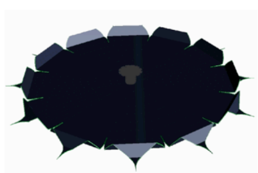
The folds of the occulter are swirled around a central holding cap, similar to the folding method of a collapsible umbrella.



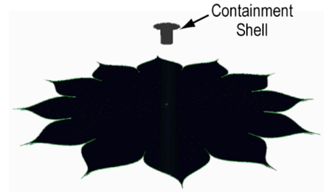
The swirled folds are straightened and ready for the booms to extend



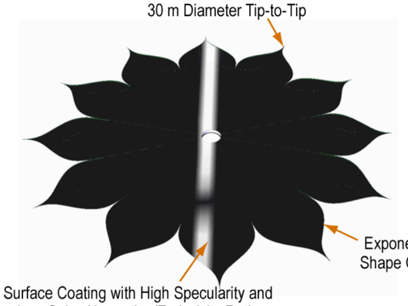
The stem drives extend the booms segment by segment. The occulter edge is fixed to the boom segment. Each segment locks into place when it becomes fully deployed.



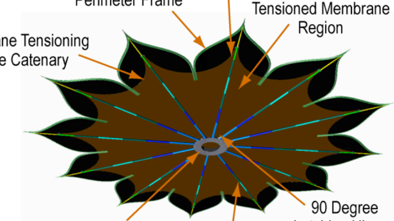
There are seven segments to the boom for this 25 meter occulter. The central object is a holder for the occulter while it is inside the spacecraft.



After full deployment, the holder is jettisoned.



The tips of the petals are composed of a solid rod of the appropriate shape, which folds out and locks onto the last boom segment.



A view of the underside of the occulter, each segment of the boom is represented by a different color. Cables run along the perimeter to hold the petal edges in proper tension.

Table Top Demonstrator

This paper model shows that all the planned folds can be accomplished with no interference or binding. The paper model is a standard step in the development of a viable deployable. All of the salient folds are included in this subscale demonstrator.

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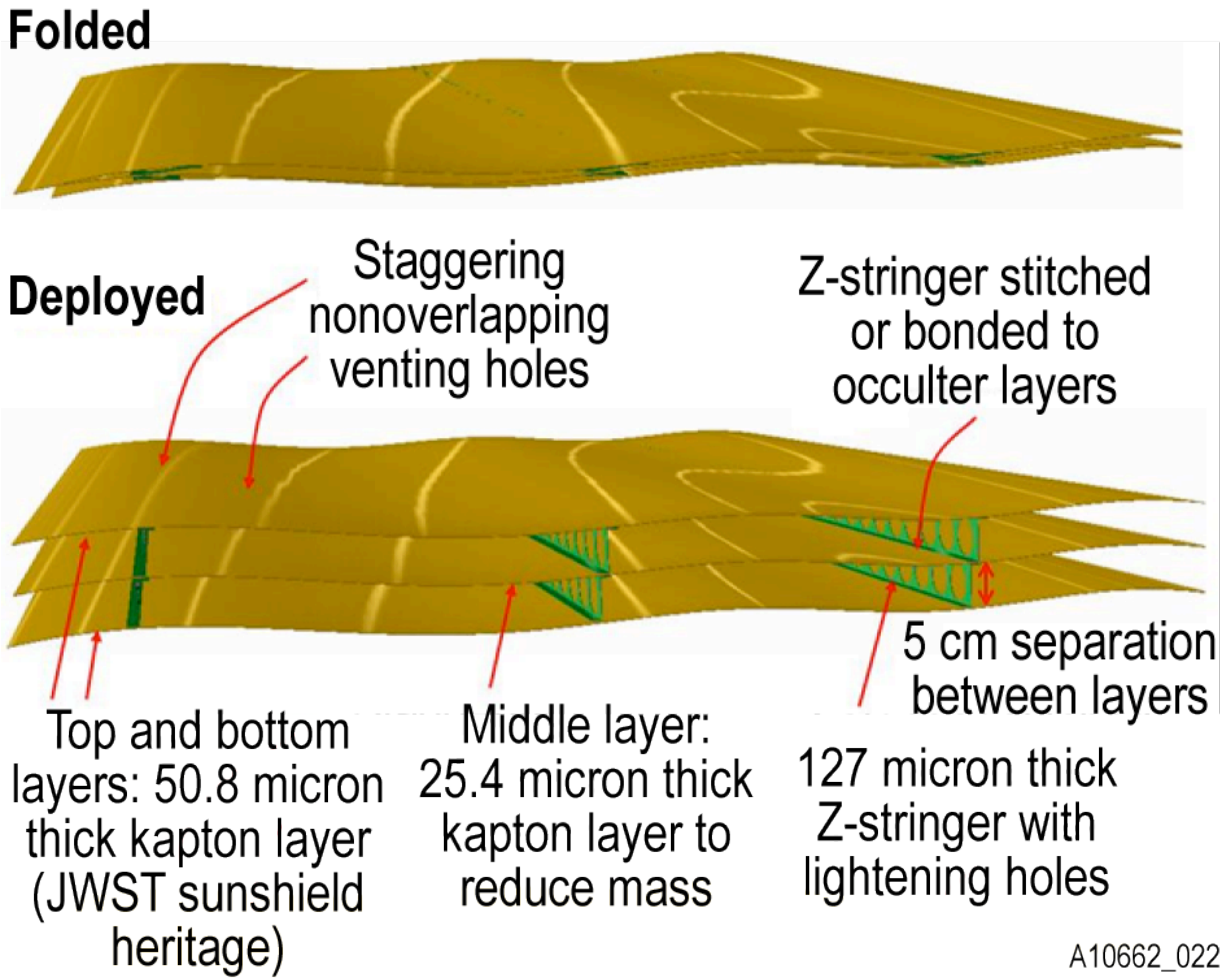
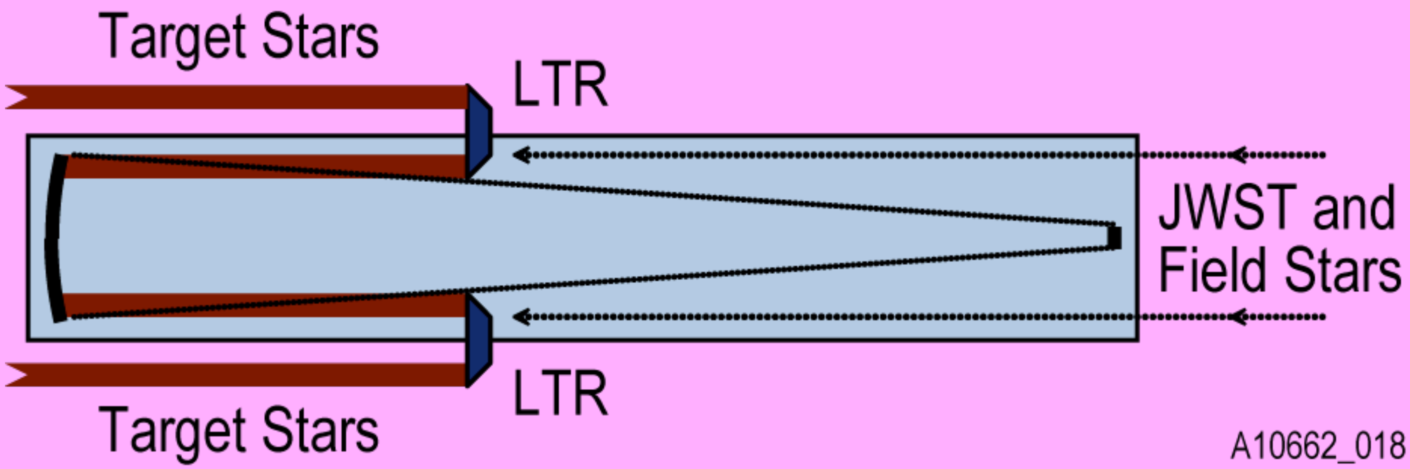
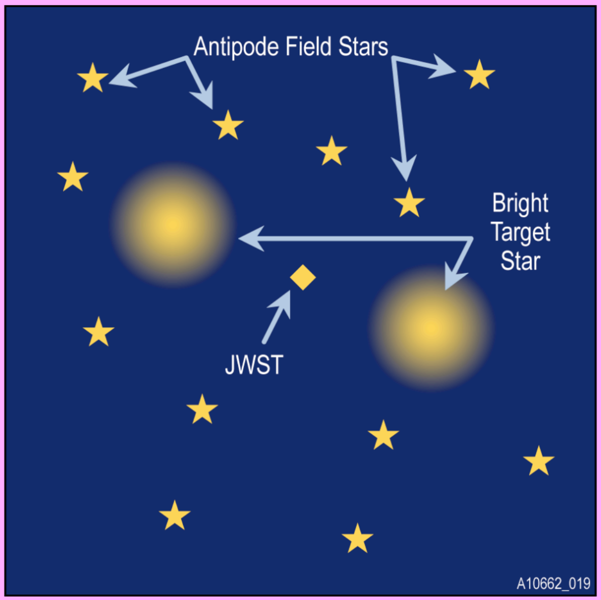
Triple Layered
Micro-meteor Protection

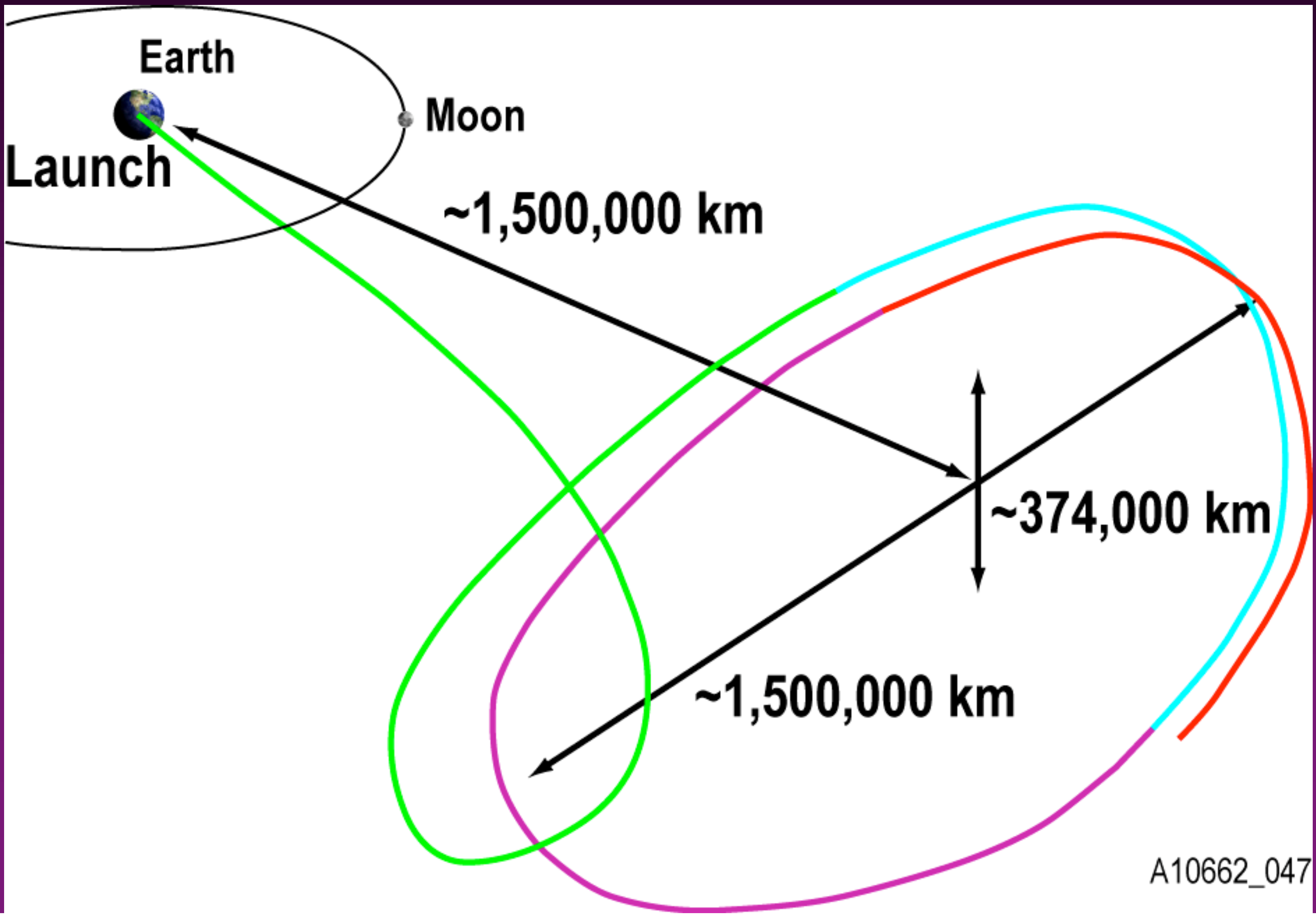


Alignment acquisition & hold

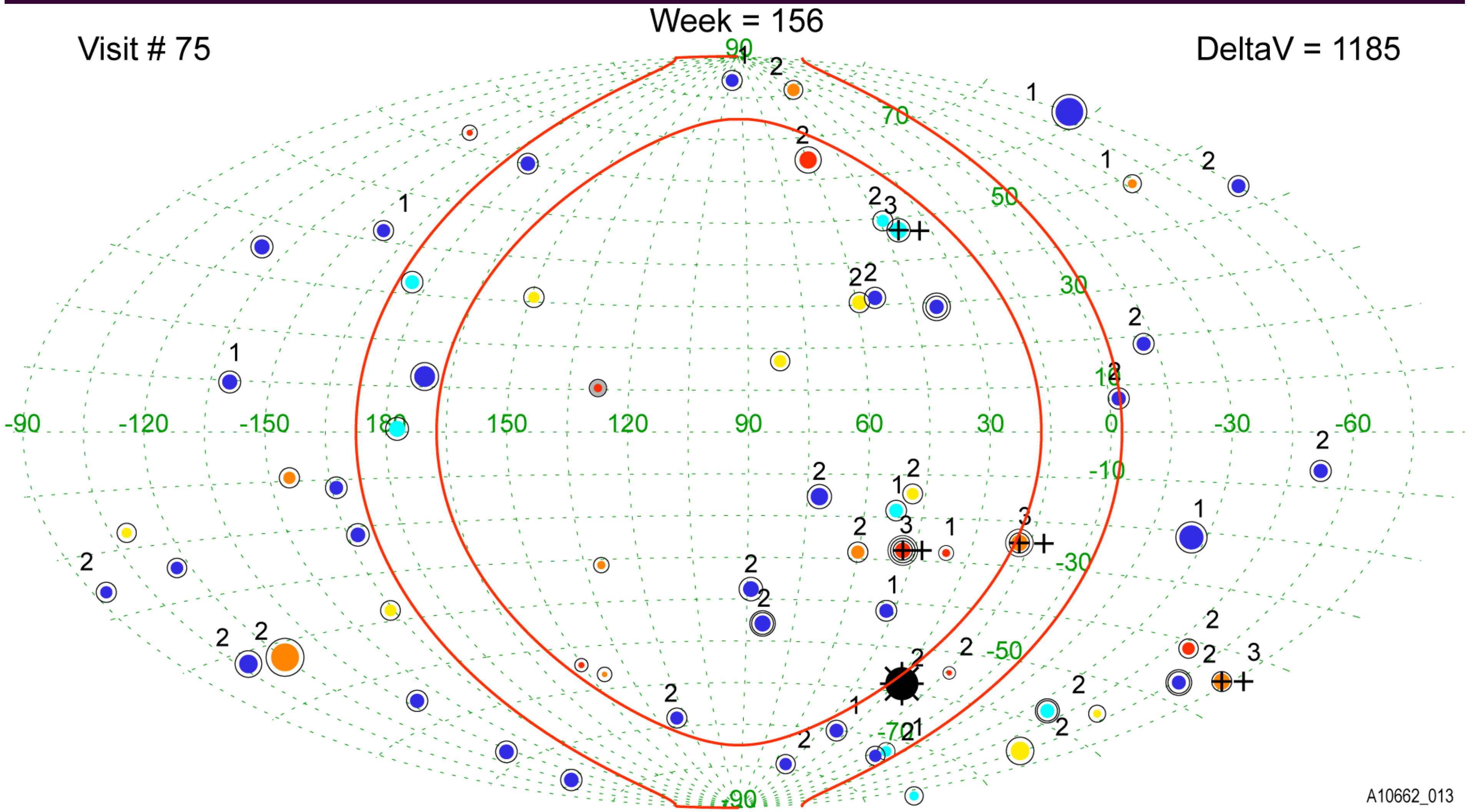




L2 Orbit Favorable



Planning the Mission

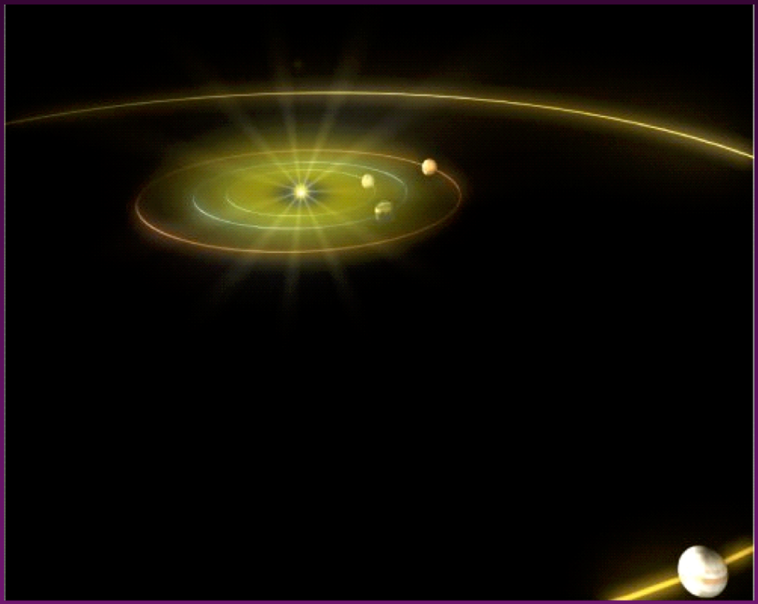


New Worlds Discoverer

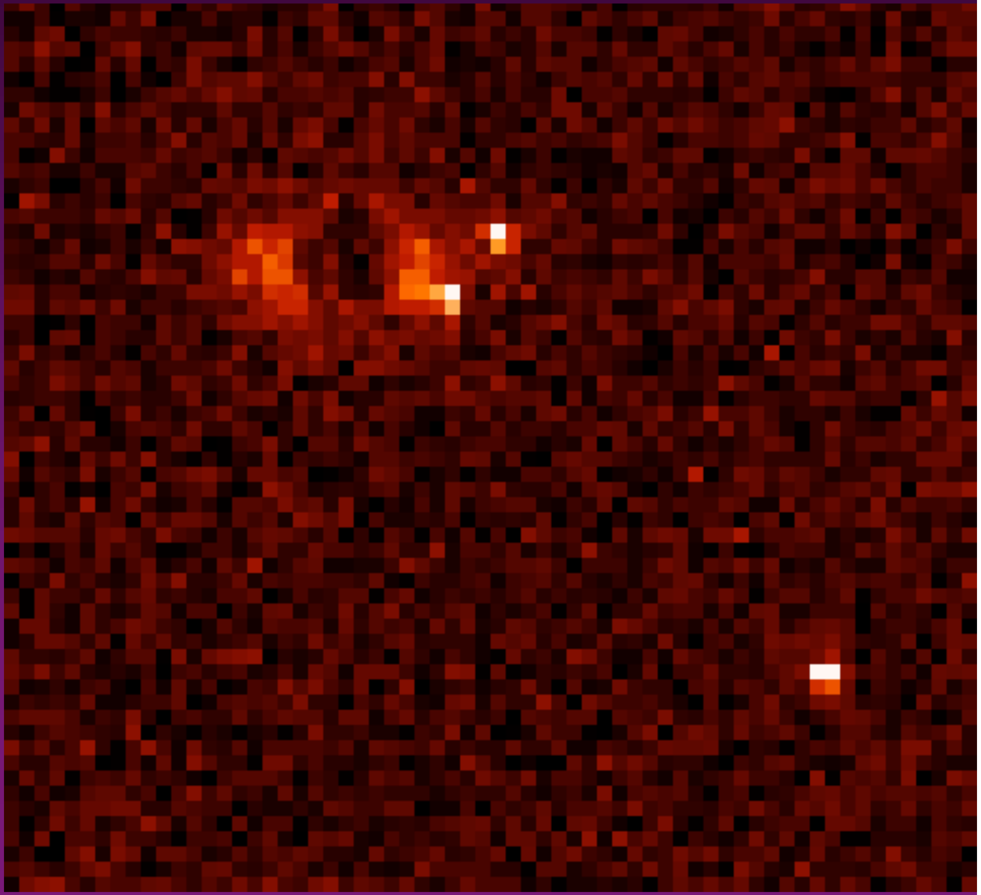
- ☞ **Could launch with JWST in 2013**
- ☞ **All formation flying requirements on starshade**
  - – JWST passive, just points
- ☞ **Meets cost cap and technology readiness requirements**
- ☞ **Three year mission – over 100 lines of sight**
- ☞ **Capable of detecting Earth to 10pc**
- ☞ **Spectroscopy of Jovian planets**
- ☞ **Earth spectroscopy marginal**

- ☞ **Constitutes a low cost TPF**
- ☞ **Not Selected on this round**

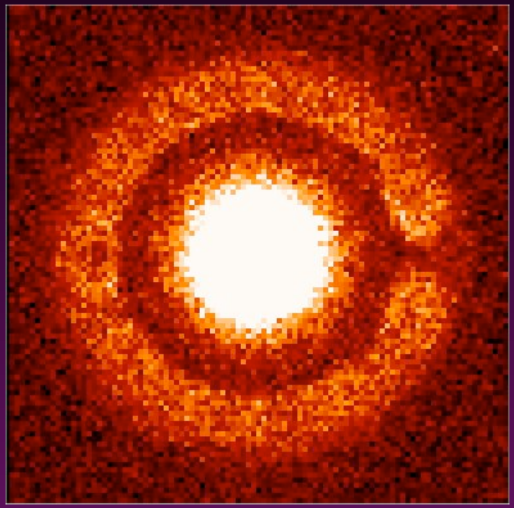
Simulated Solar System

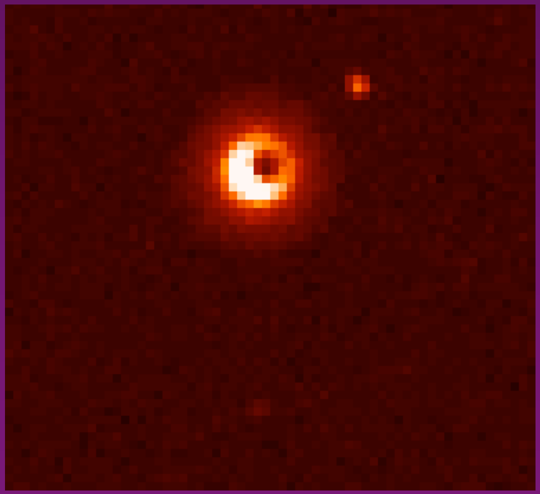


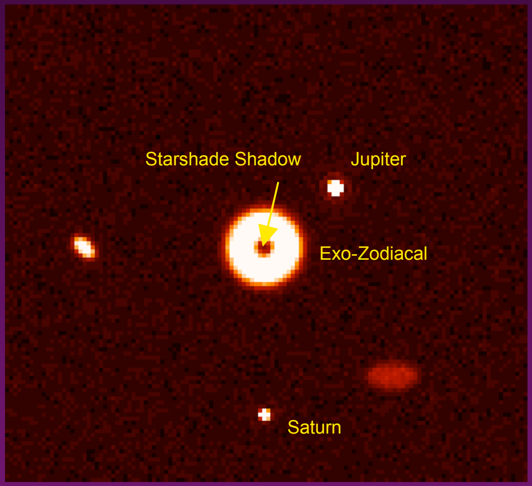
A10662_038

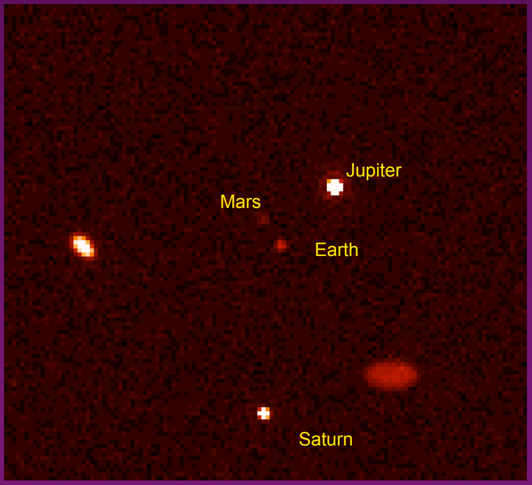


Discoverer Science Simulations



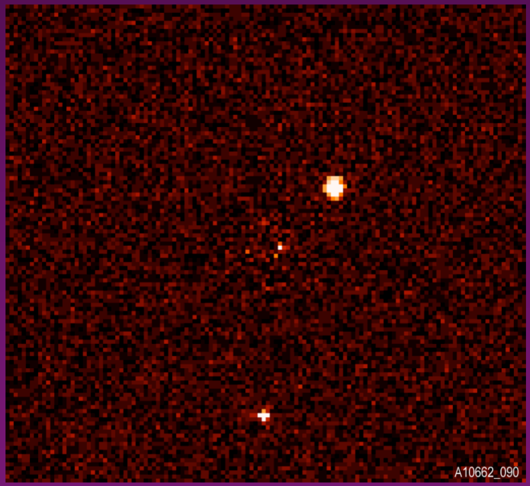




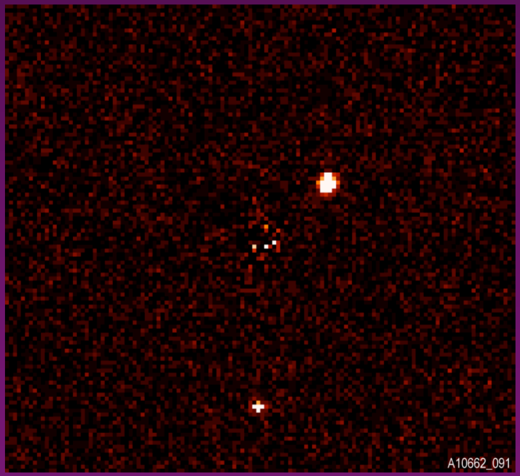


Additional Contrast from Telescope

10^{-8}

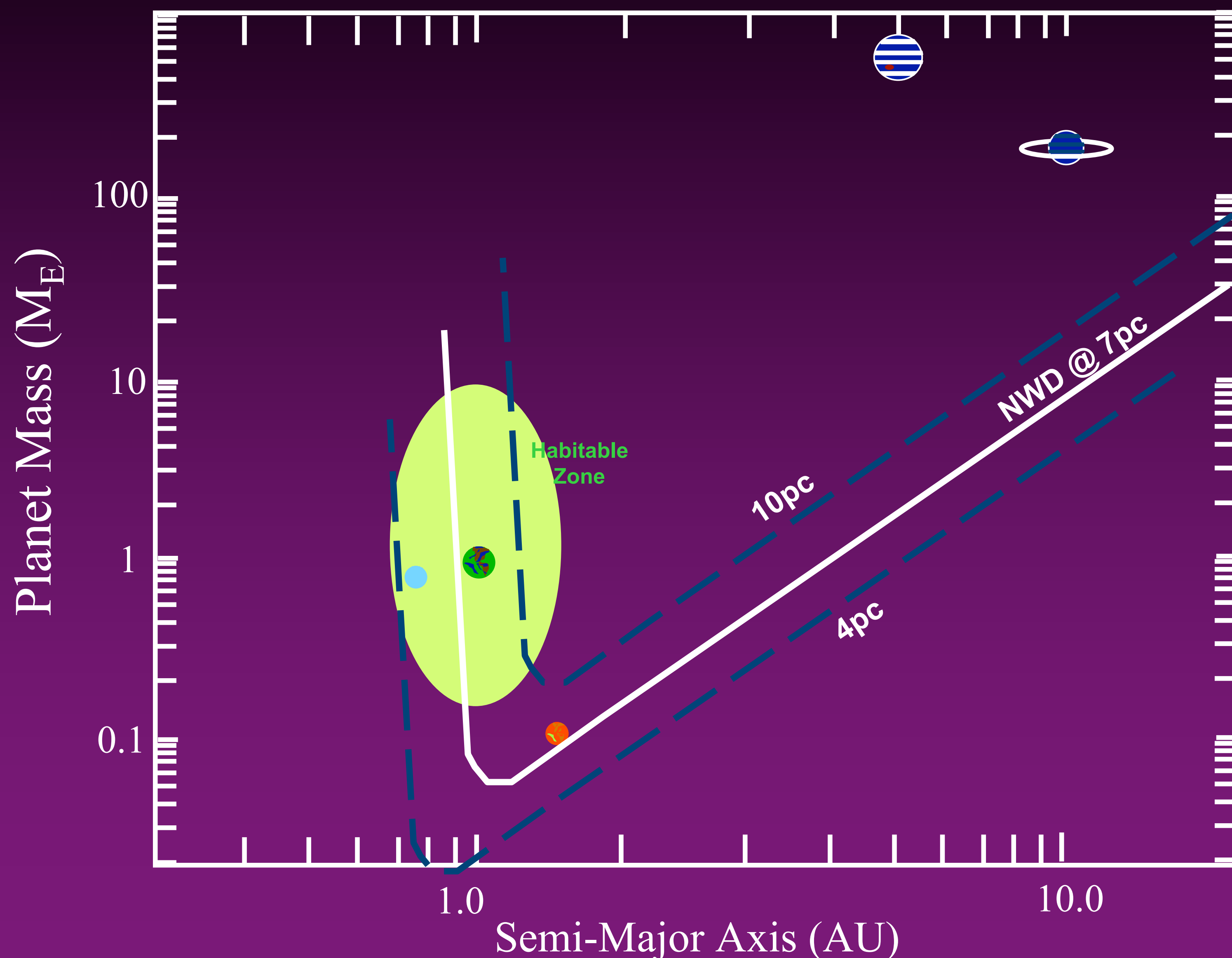


10^{-7}



10^{-6}

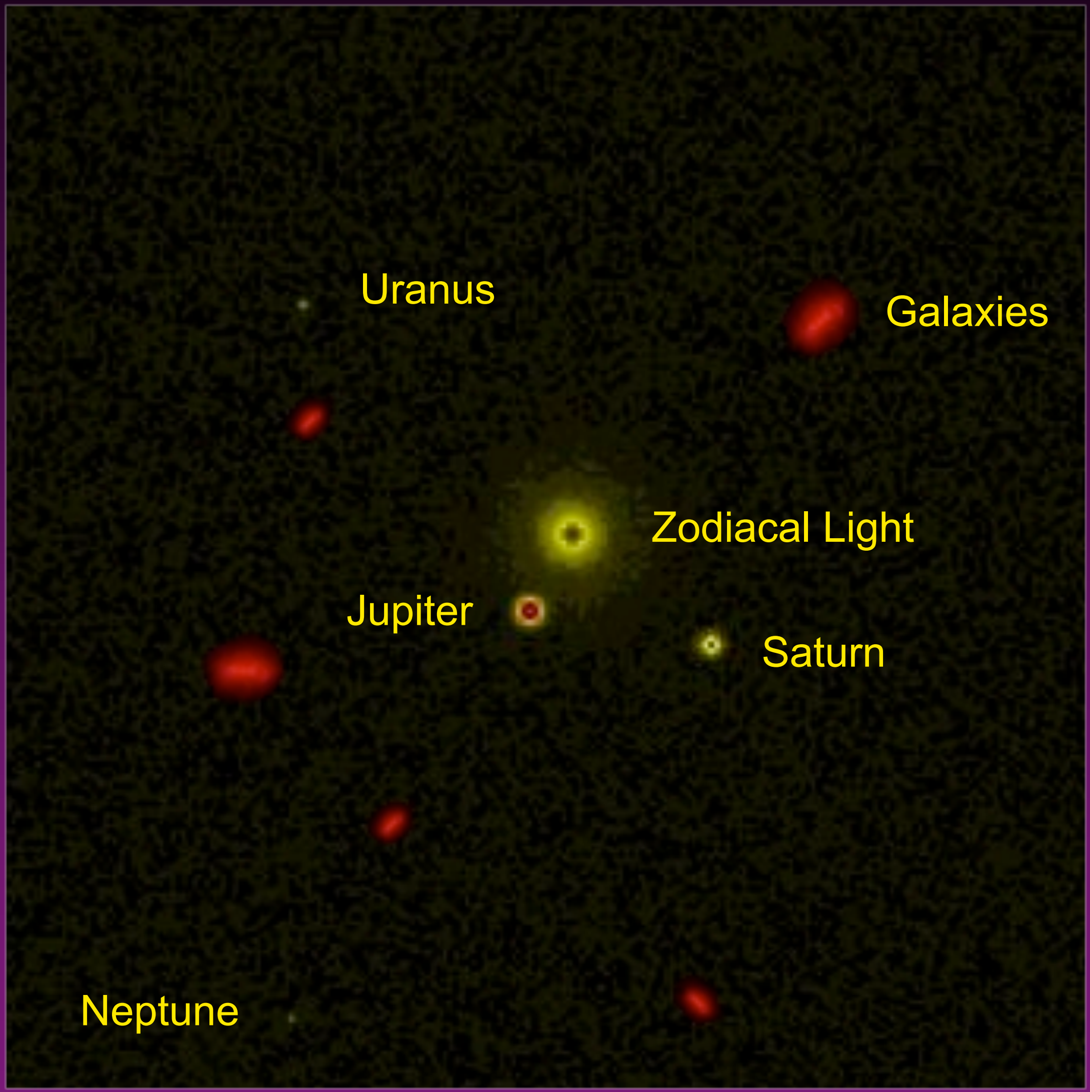
NWD Sensitivity



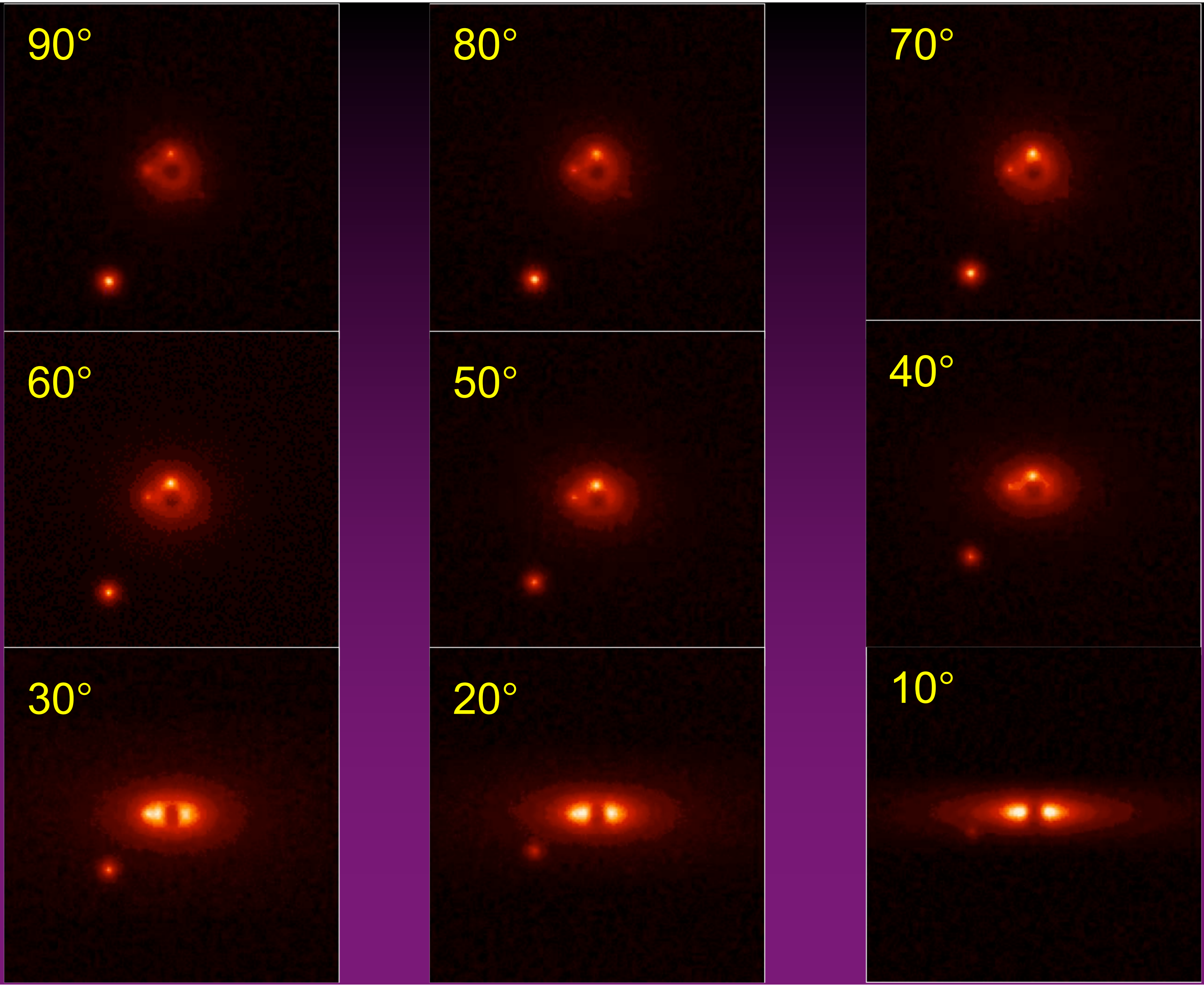
New World Observer Architecture

- ☞ After NWD Proposal Submitted NGST looked at full-up system
- ☞ 4m Telescope Diameter Breakpoint
- ☞ Two Starshades – one small and fast
- ☞ Very Powerful Scientifically
- ☞ Cost comparable to other missions on table

The First Image of Solar System

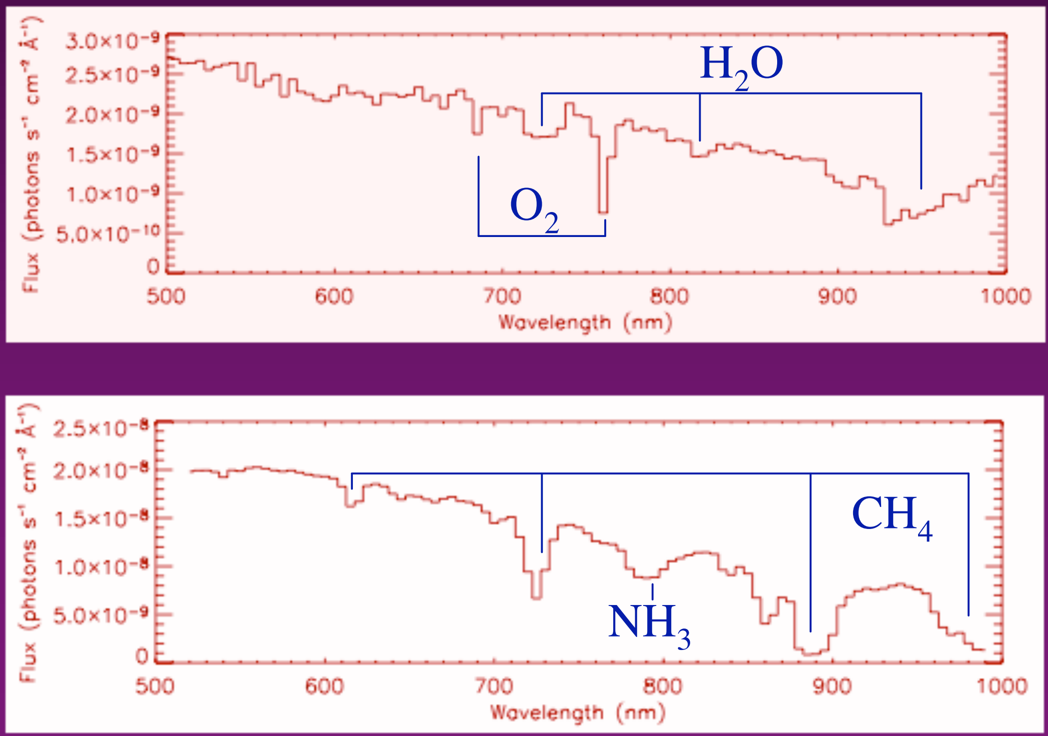


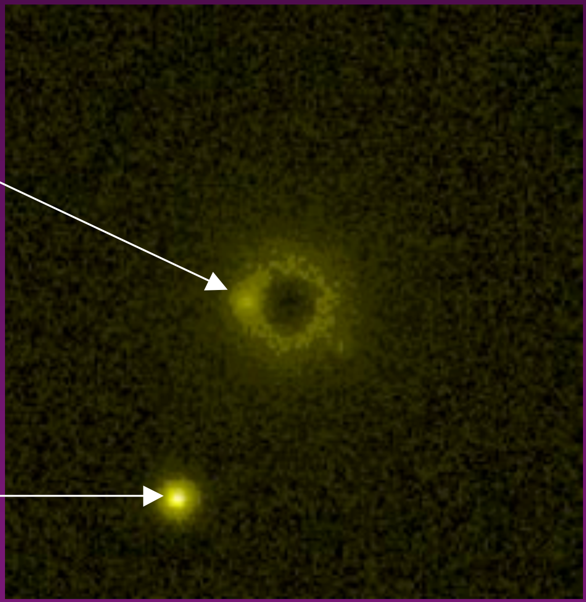
10 arcseconds


90°
80°
70°
60°
50°
40°
30°
20°
10°

Spectroscopy

☞R > 100 spectroscopy will distinguish terrestrial atmospheres from Jovian with modeling



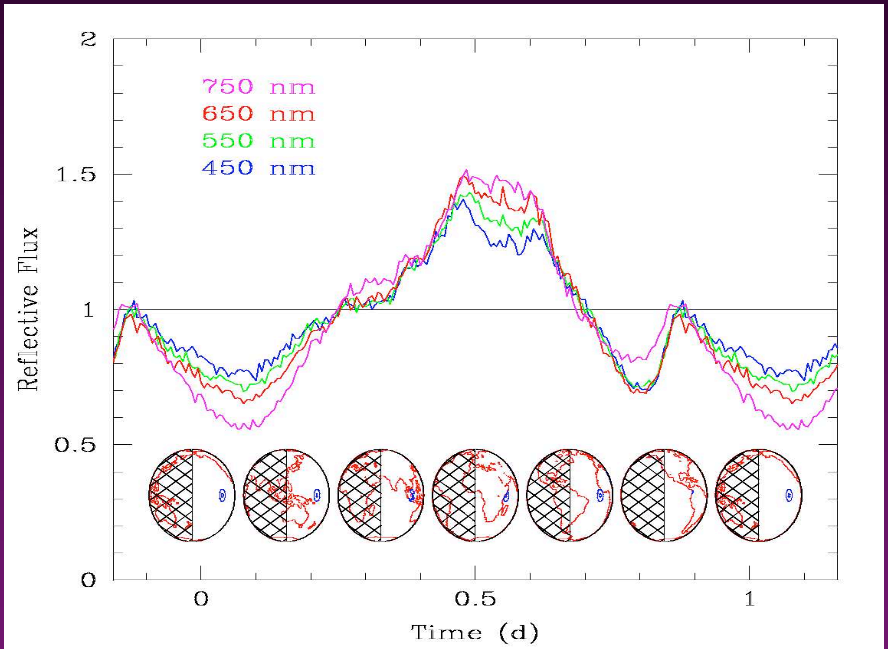


S. Seager

Spectroscopic Biomarkers

Water	Necessary for habitability
Oxygen	Free oxygen results only from active plant life
Ozone	Results from free oxygen
Nitrous Oxide	Another gas produced by living organisms
Methane	Life indicator if oxygen also present
Vegetation	Red edge of vegetation at 750nm

Photometry

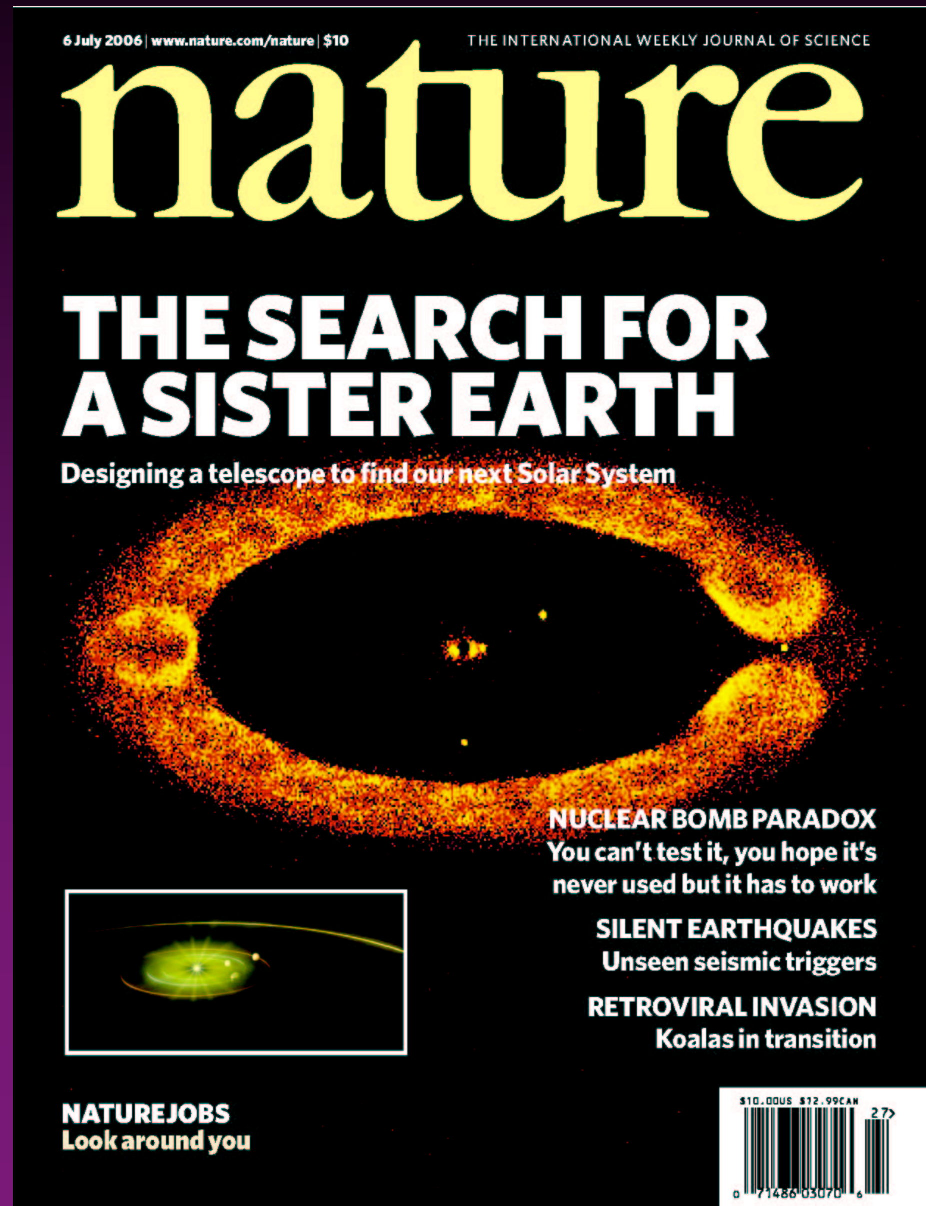


Calculated Photometry of Cloudless Earth as it Rotates

It Should Be Possible to Detect Oceans and Continents!

NWO Science

- ☞ **Result of Nature interviews**
  - ➢Many discussions with press and other interested parties
- ☞ **It is Life Seeking that EVERYBODY wants**
  - ➢ Just finding water planets enough, but its not what motivates the public
- ☞ **Can there be a bigger or more important question for astronomers?**
- ☞ **New Worlds Observer can do it**
  - ➢ $2-3 Billion and 10 years



The New Worlds Imager

Earth at 200km resolution. Oceans, continents and clouds are visible.

A simulated exo-planet at 500 km resolution.

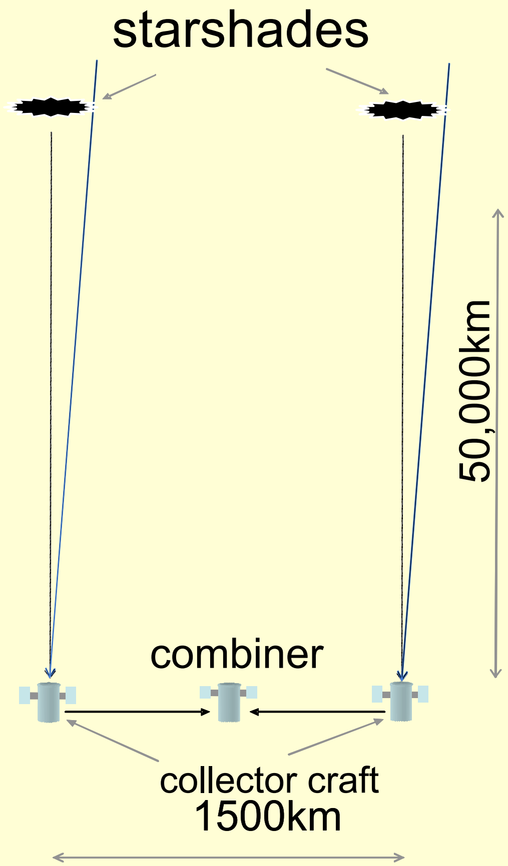
TRUE PLANET IMAGING

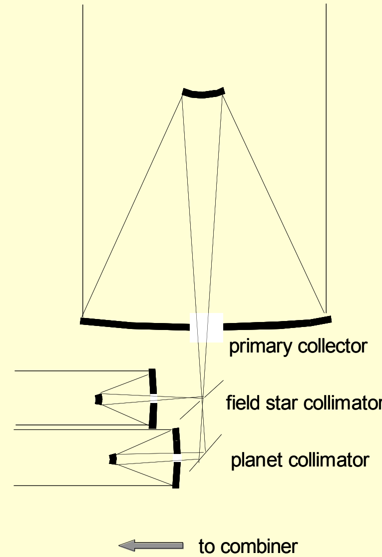
3000 km | 1000 km | 300 km | 100 km

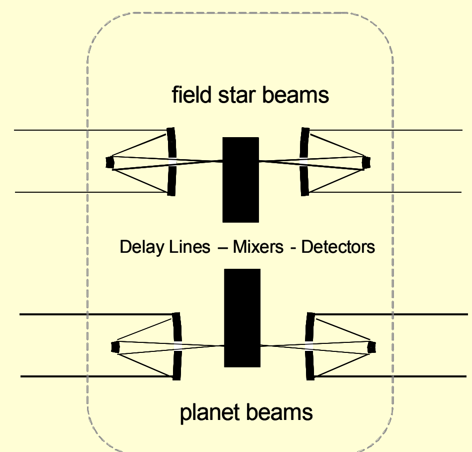
Earth Viewed at Improving Resolution

Solar System Survey at 300km Resolution

NWI Concept

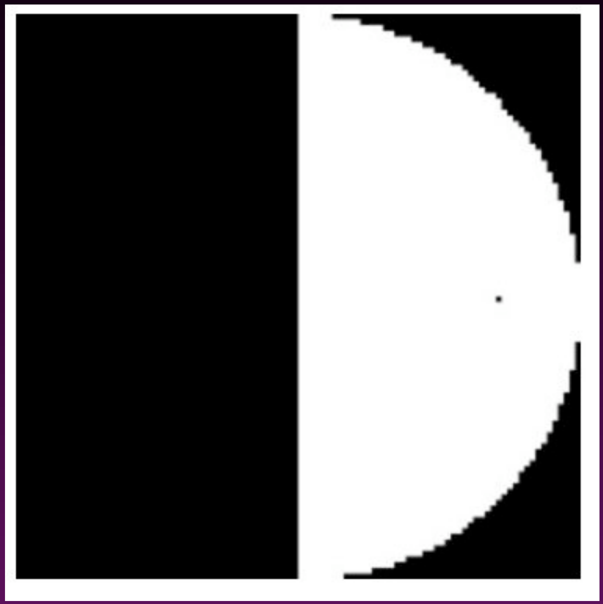

starshades
50,000km
combiner
collector craft
1500km


primary collector
field star collimator
planet collimator
to combiner


field star beams
Delay Lines – Mixers - Detectors
planet beams

Hypertelescope Problem

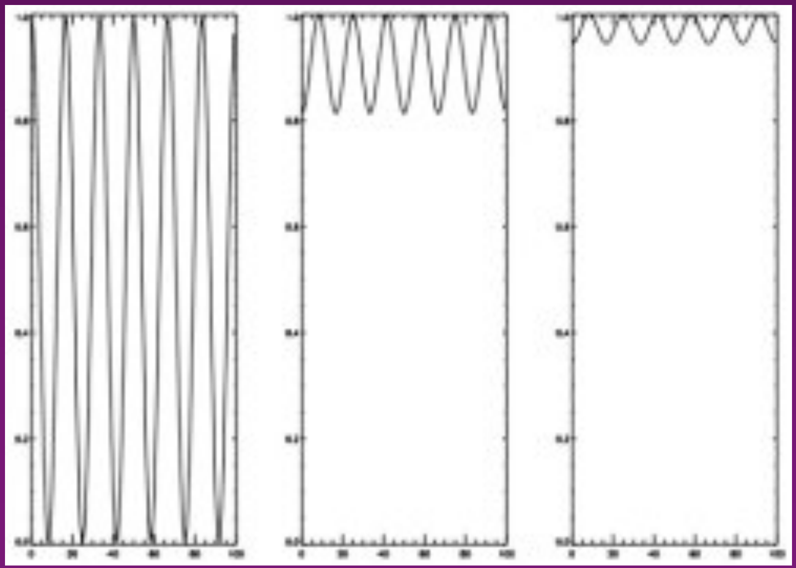
- ☞ **How Many Apertures Needed?**
  - ➢ One per pixel (no!)
- ☞ **Cost control of multiple craft**
- ☞ **Formation Flying to Tolerance**
- ☞ **Labeyrie has worked on this**
  - ➢ Amazing telescope even without starshades

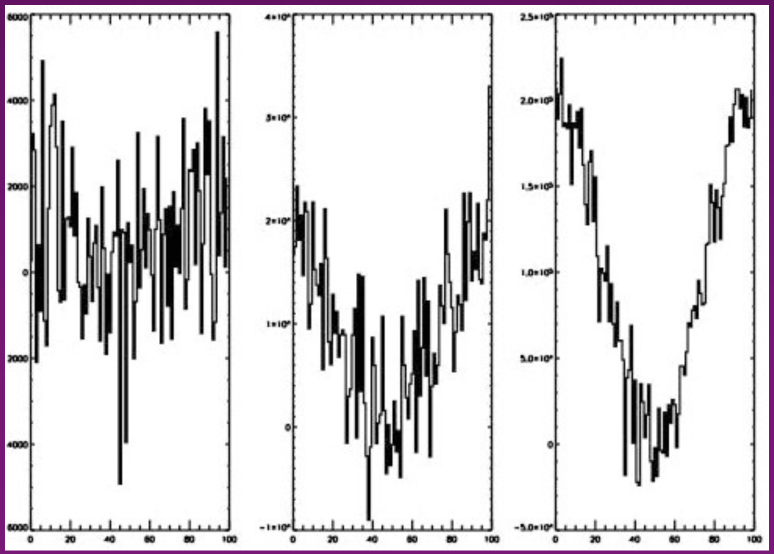


Sims

Established that information is present in the fringes and detectable.

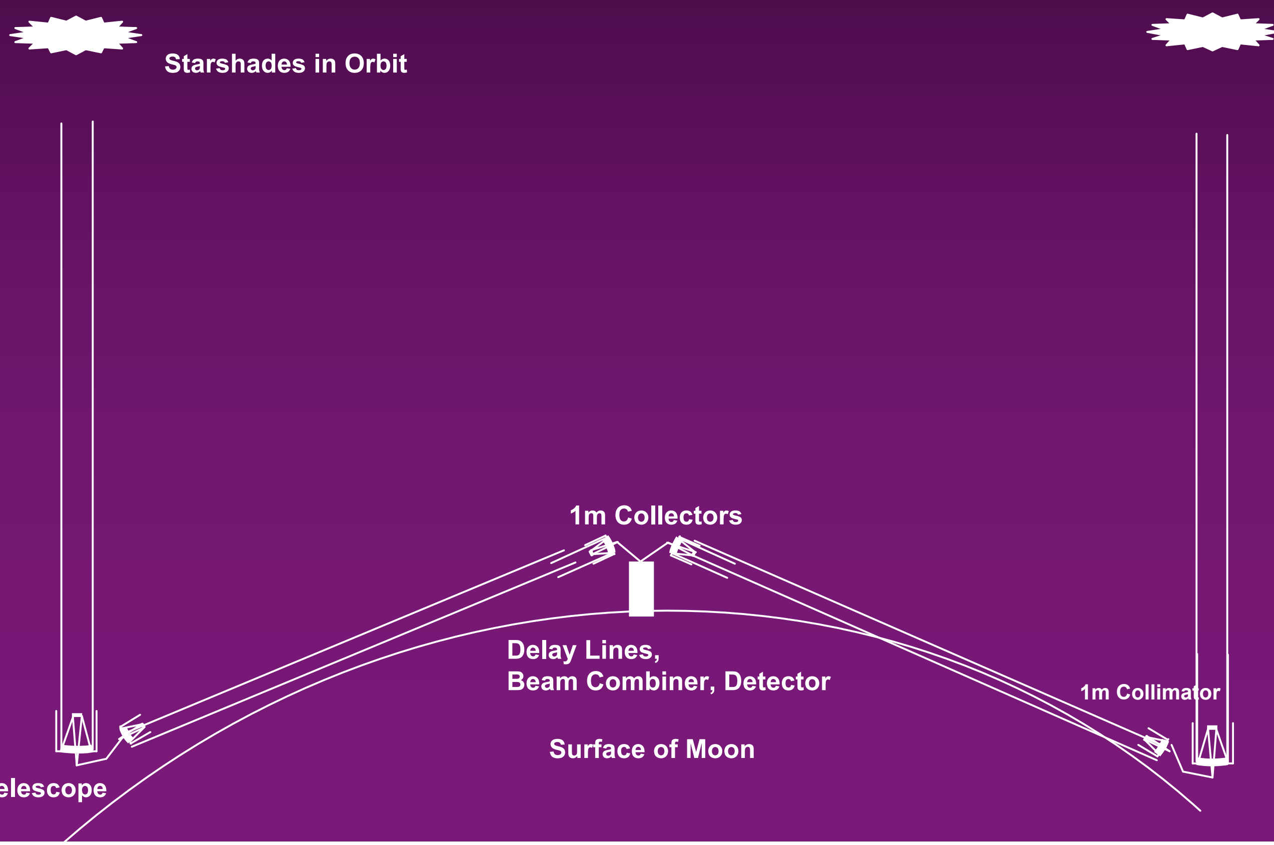
How do we invert into images?
Is this enough?





Lunar Option

- ☞ Planet Imaging is exciting enough to justify the expense level
- ☞ Appropriate Level of Challenge for 20+ years from now

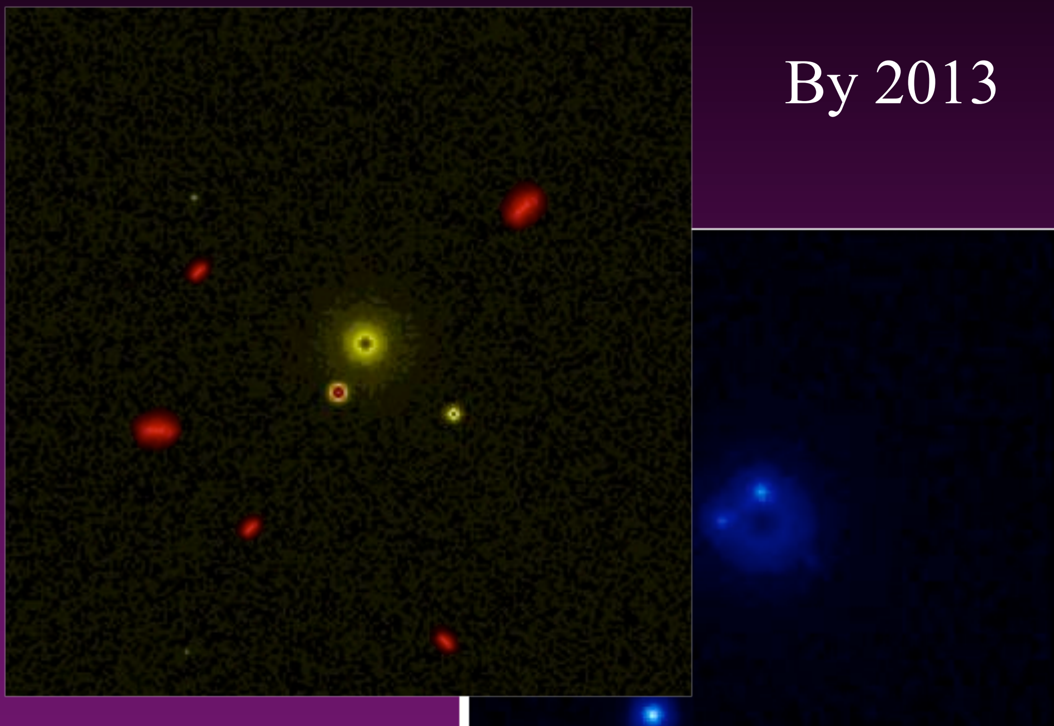


Tradeoff

Pro	Con
Infrastructure	Moon Rotates
Moon Stable Bench	100km class delay lines
Refuel Starshades	

Conclusion

By 2013



By 2025