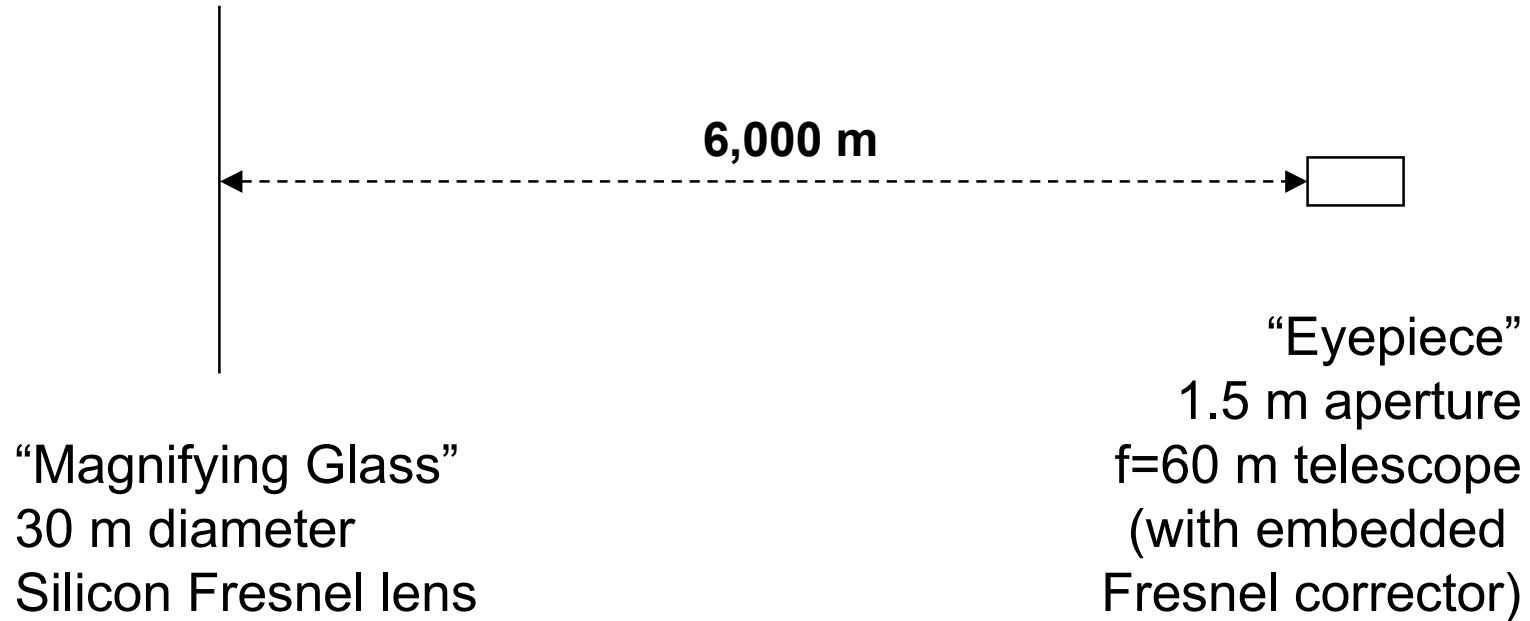


Space & Electronics Group

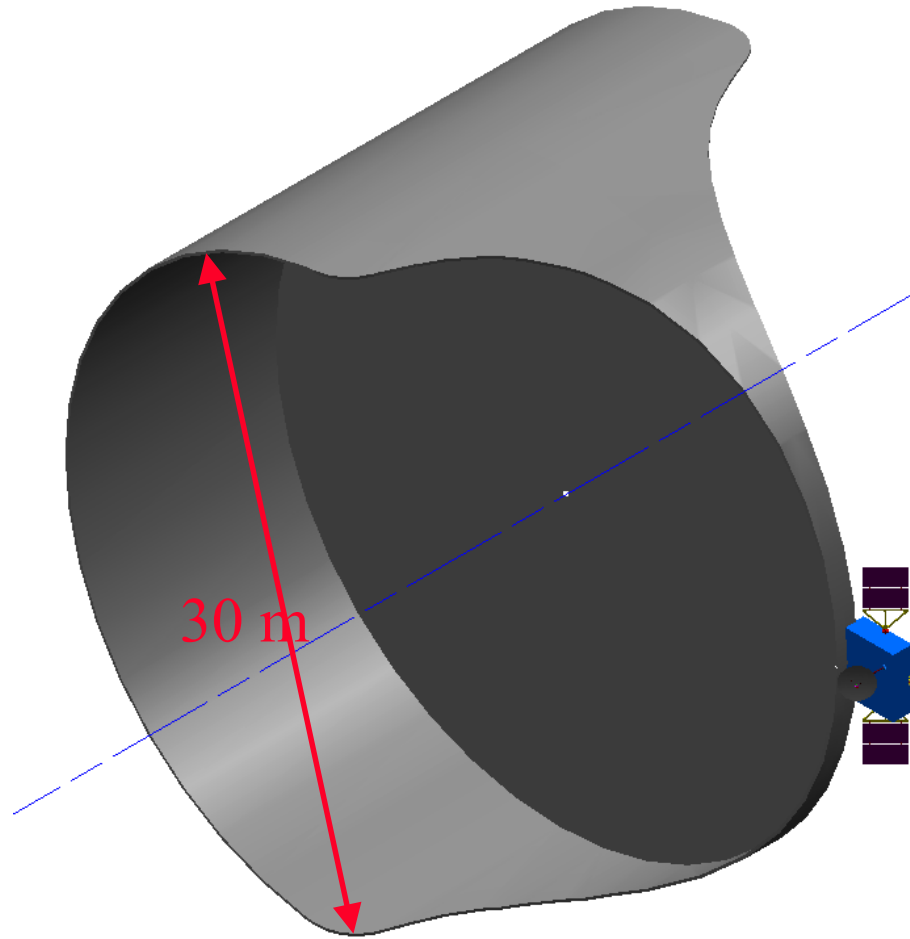
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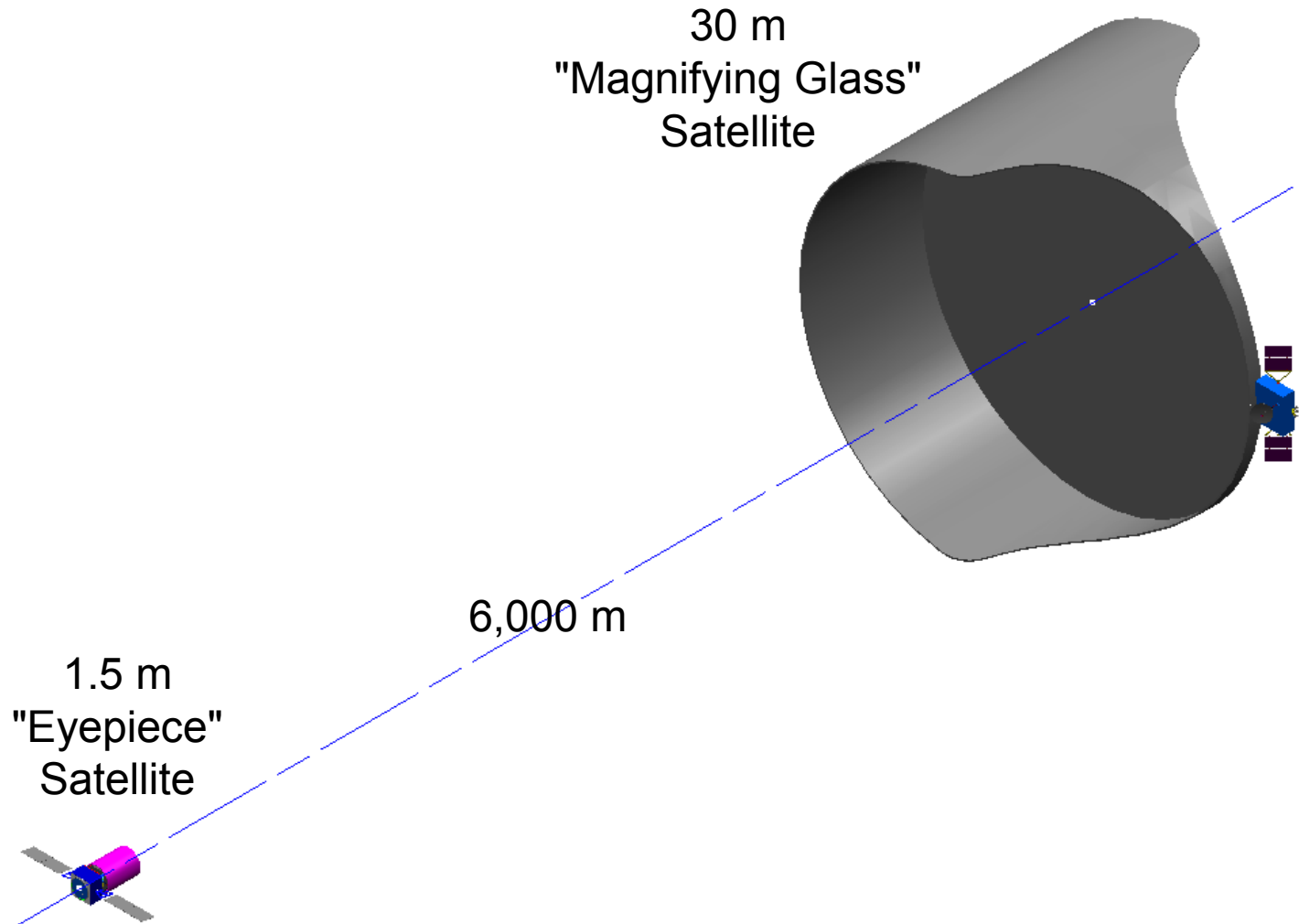
# **Fresnel Coronagraph for TPF**

**Charles L. Bennett (LLNL)**

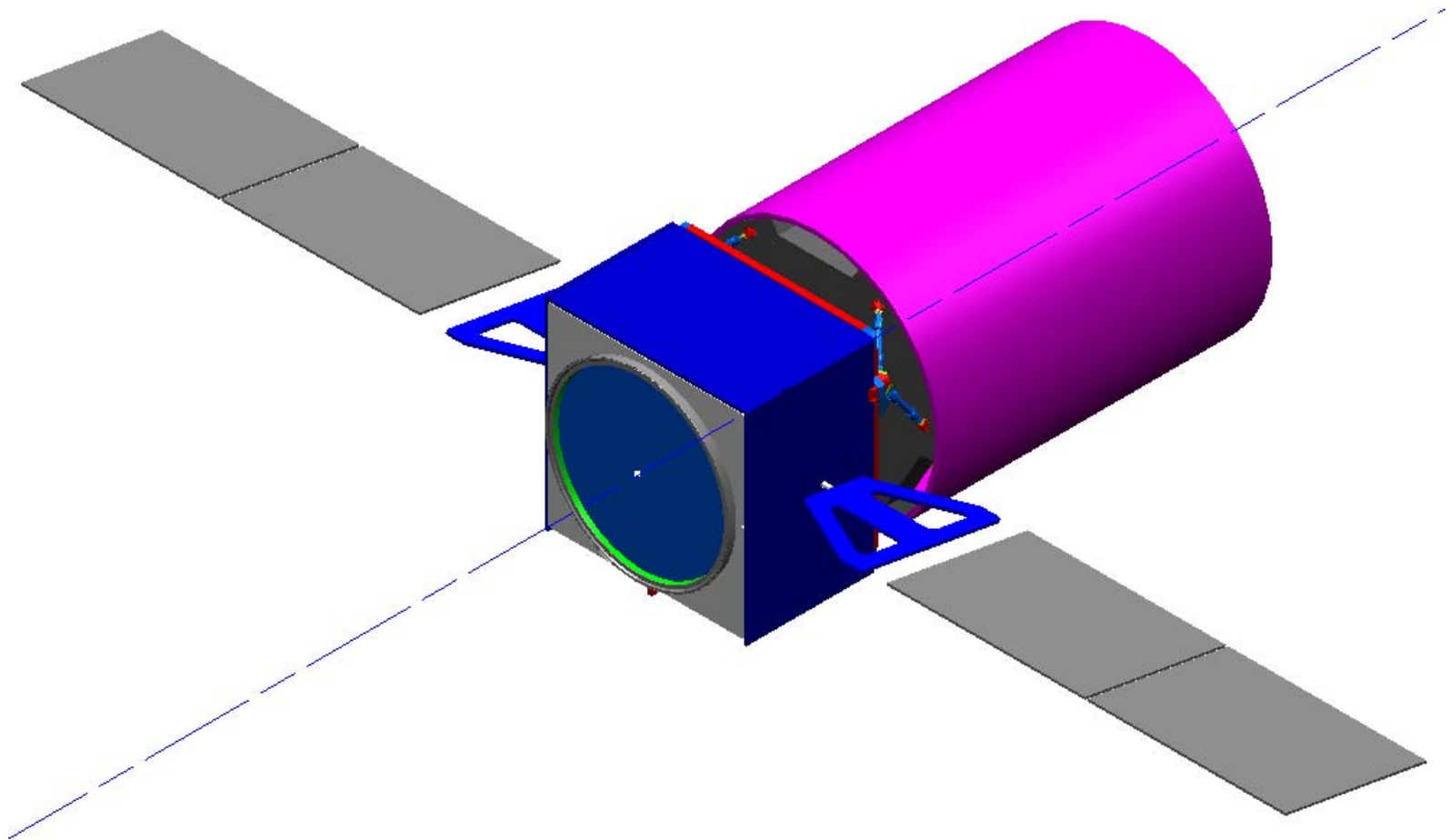


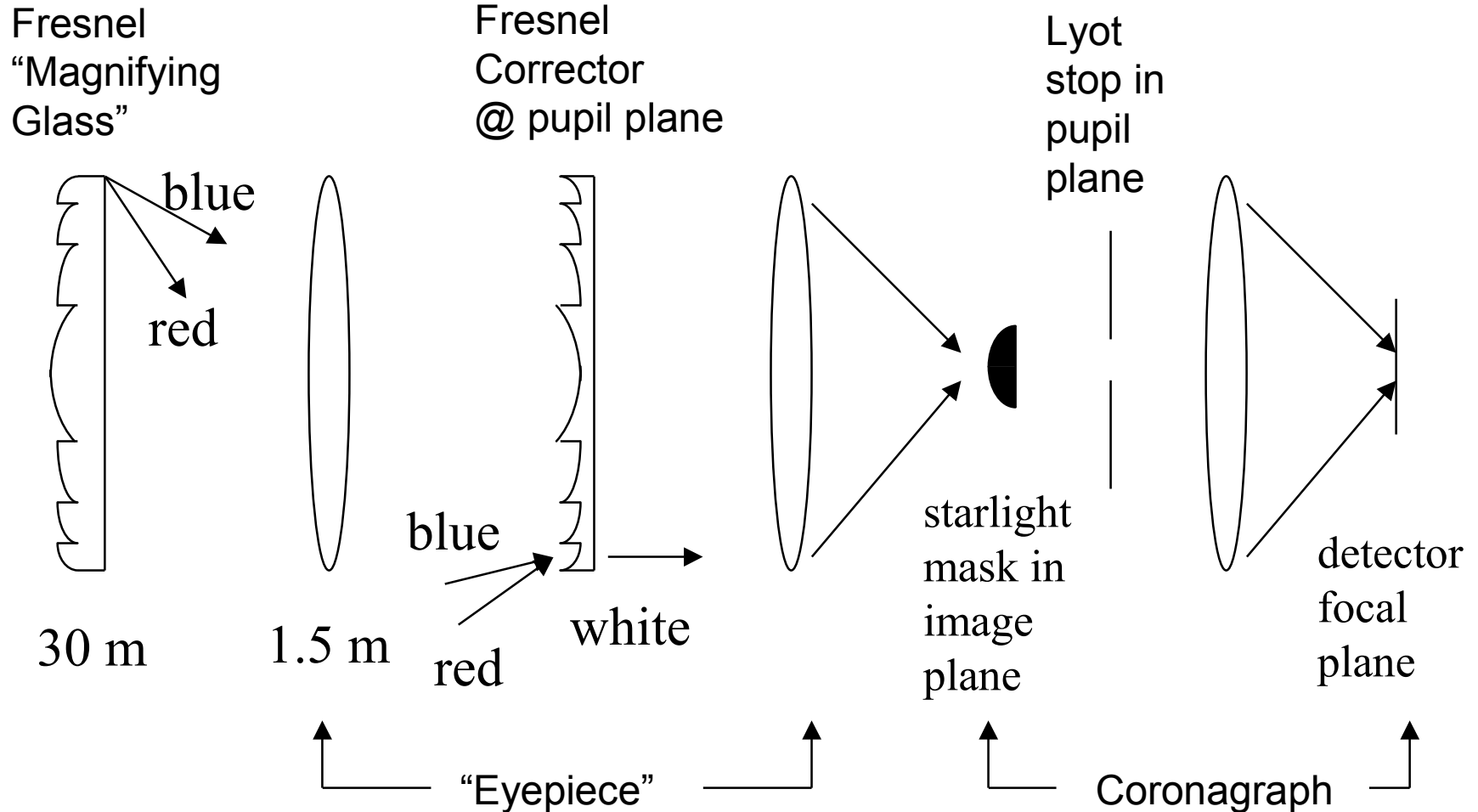
**Coronagraph “rear end” used for planet finding**  
**Wide field imaging available for general astronomy**





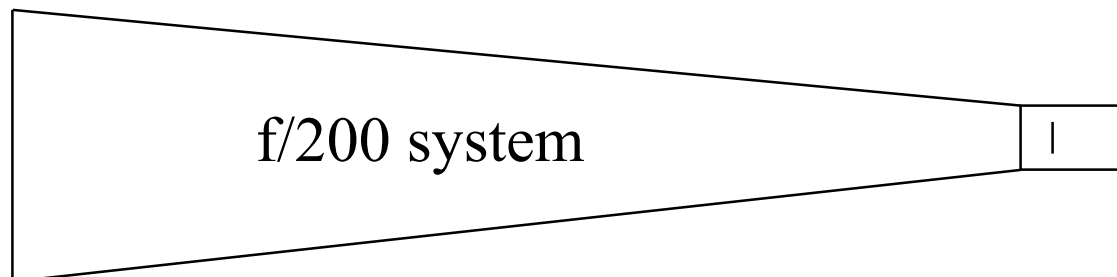
# "Eyepiece" Satellite



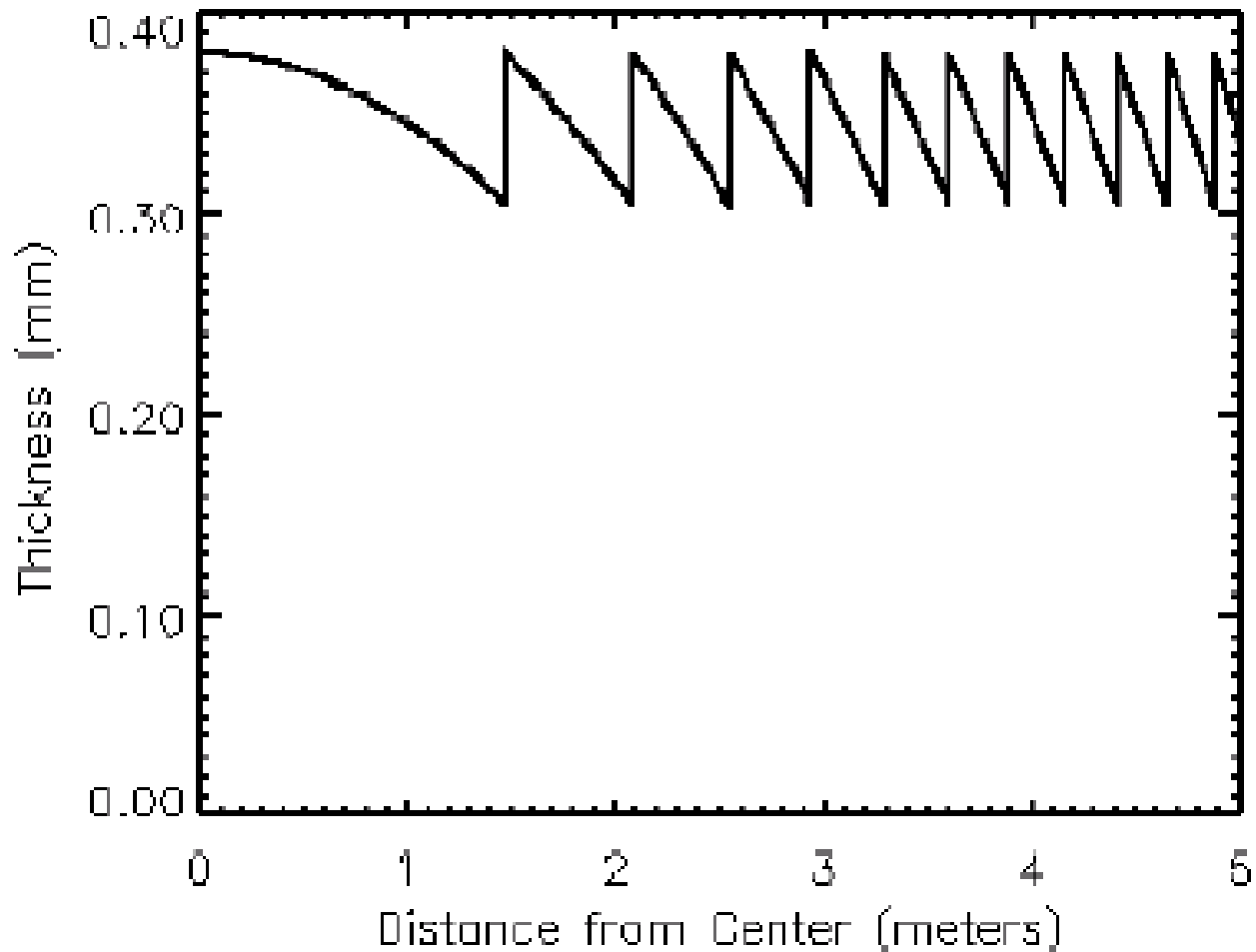


Chromatic aberration of Fresnel Magnifying Glass  
is removed with Fresnel Corrector

- Covers spectral range 1-25  $\mu\text{m}$  except  $9\pm0.2 \mu\text{m}$  and  $16.4\pm0.4 \mu\text{m}$
- Mass of primary lens: 750 kg
- Aperture: 30 m
- Number of zones: 104
- Focal length: 6,000 m
- Secondary aperture: 1.5 m
- Primary may be slowly spun to provide stabilizing tension
- Remainder of optical train is in separate free-flyer
- Both Fresnel primary “Magnifying Glass”, and Fresnel corrector are constructed of readily available 0.38 mm (0.015”) silicon wafers
  - silicon wafers up to 12” in diameter are common



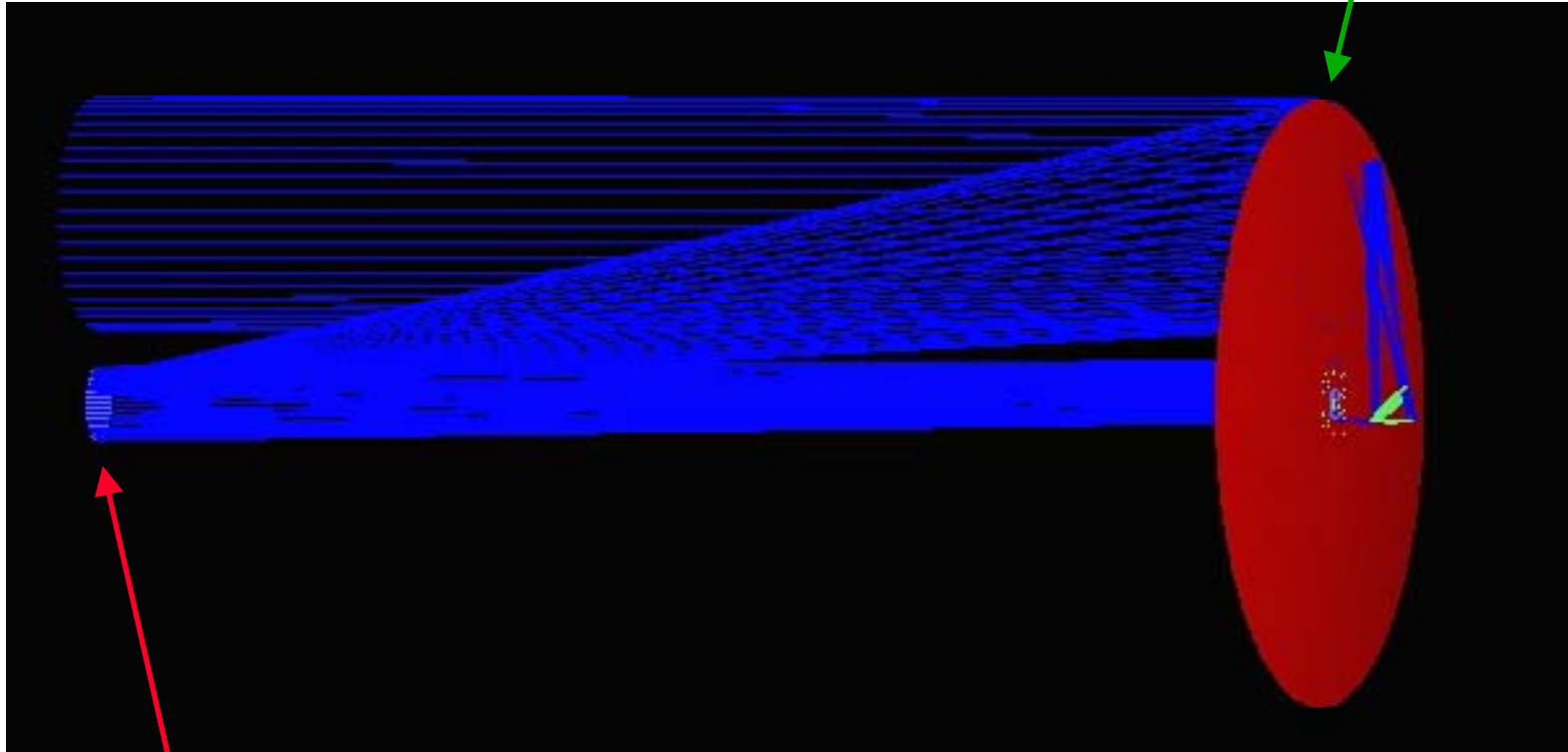
Profile of innermost 5 meters of “Magnifying Glass” lens





- Off axis four mirror design:
  - Forms a high quality image of the Magnifying Glass (MG) on the Fresnel Corrector (FC)
  - FC is on a spherically curved surface which is the 4th mirror in the Eyepiece telescope
  - Diffractive power of the FC is the complement of the diffractive power of the MG
  - After light passes FC, it no longer has the substantial chromatic aberration normally associated with Fresnel lenses
  - Prime focus is in the plane of the Eyepiece primary
    - Occulting spot for star suppression is located here
    - Optional wide field imager may be located here
  - Pupil plane with Lyot stop is formed behind the Eyepiece primary for coronagraphy

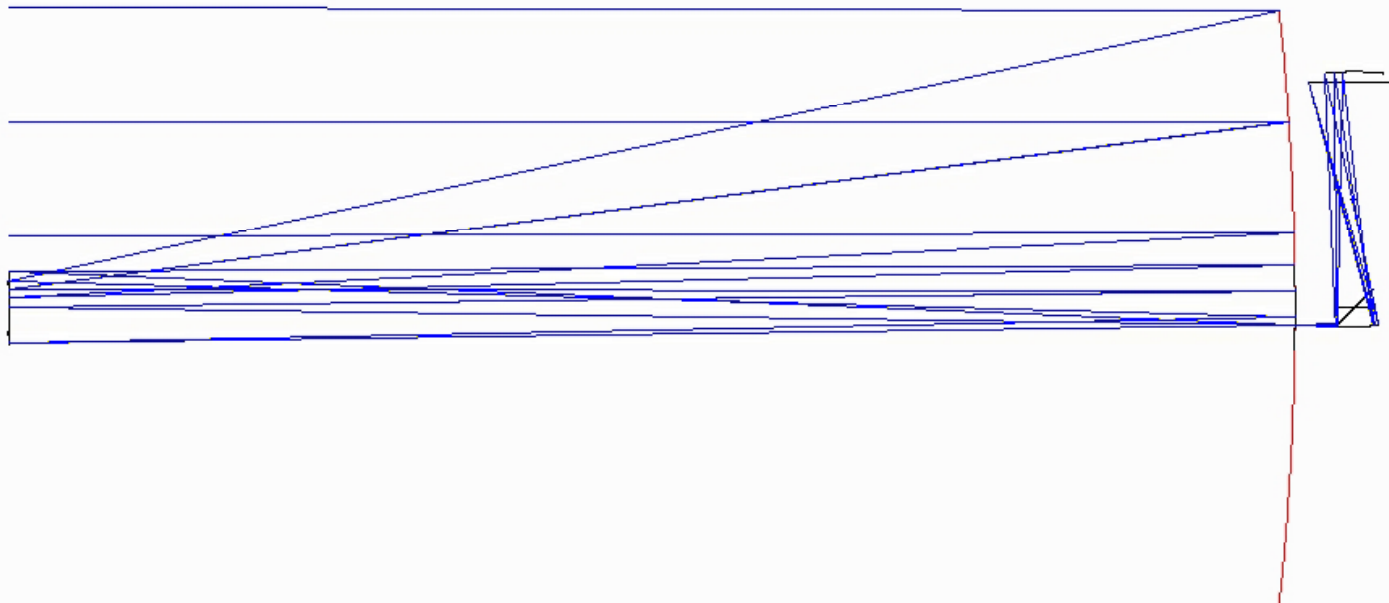
Eyepiece primary mirror is also the tertiary



Fresnel pattern etched  
on Eyepiece 4th mirror

Coronagraph behind  
Eyepiece Primary

# Eyepiece Ray Trace Example



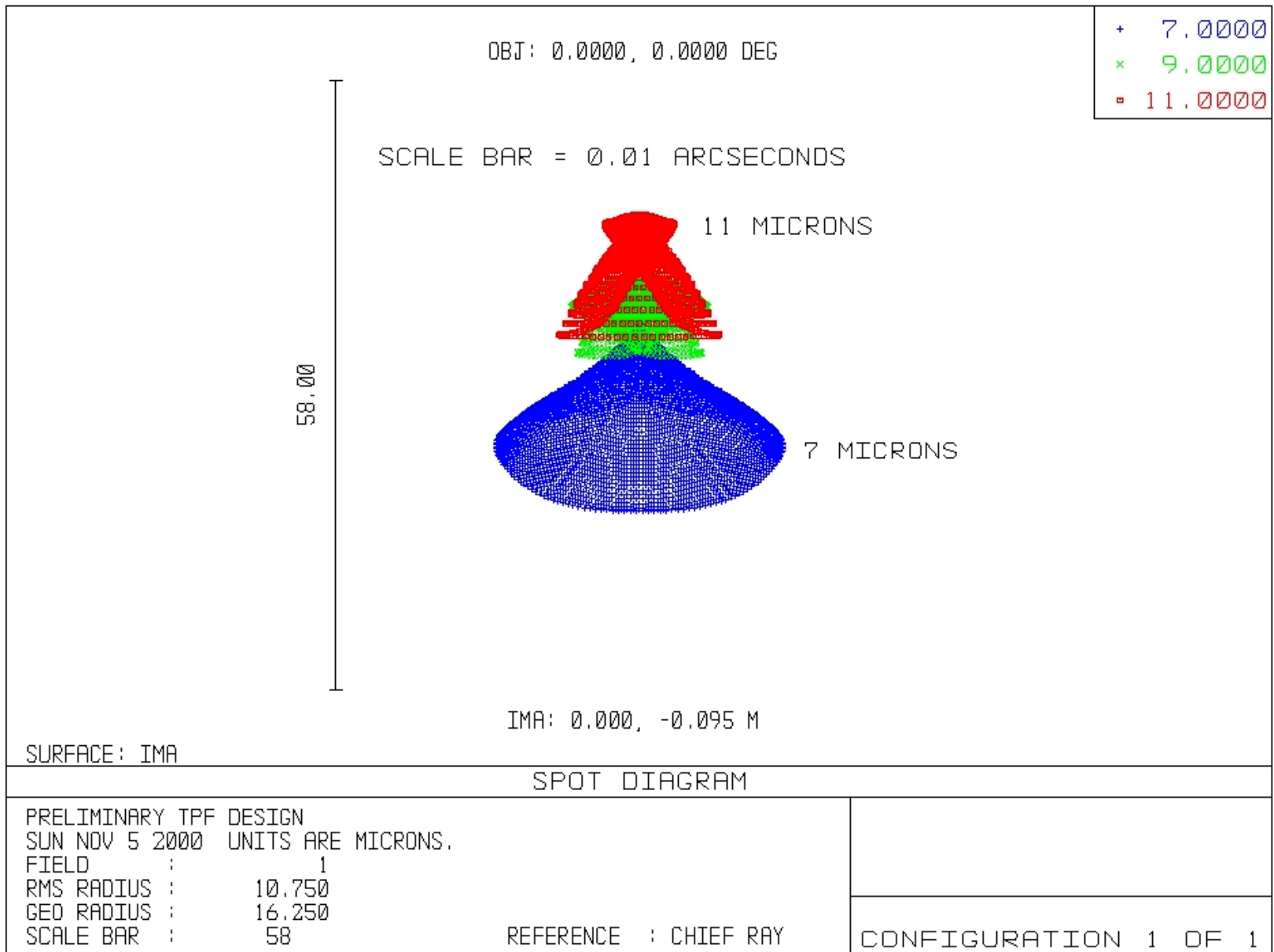
3D LAYOUT

PRELIMINARY TPF DESIGN  
FRI OCT 20 2000  
SCALE: 0.0400

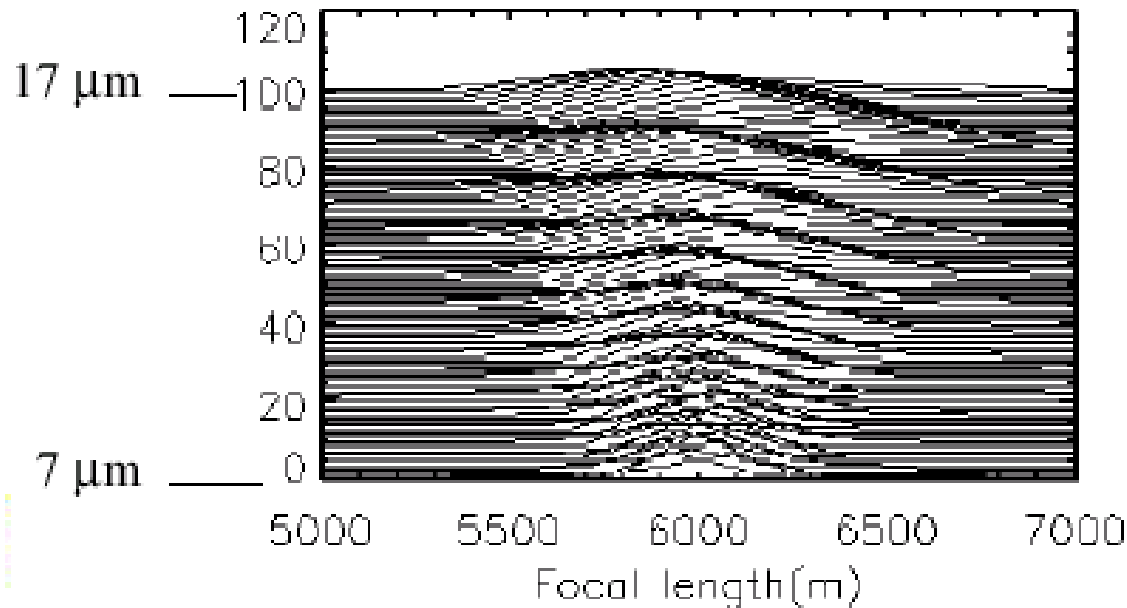
0.50 METERS

CONFIGURATION 1 OF 1

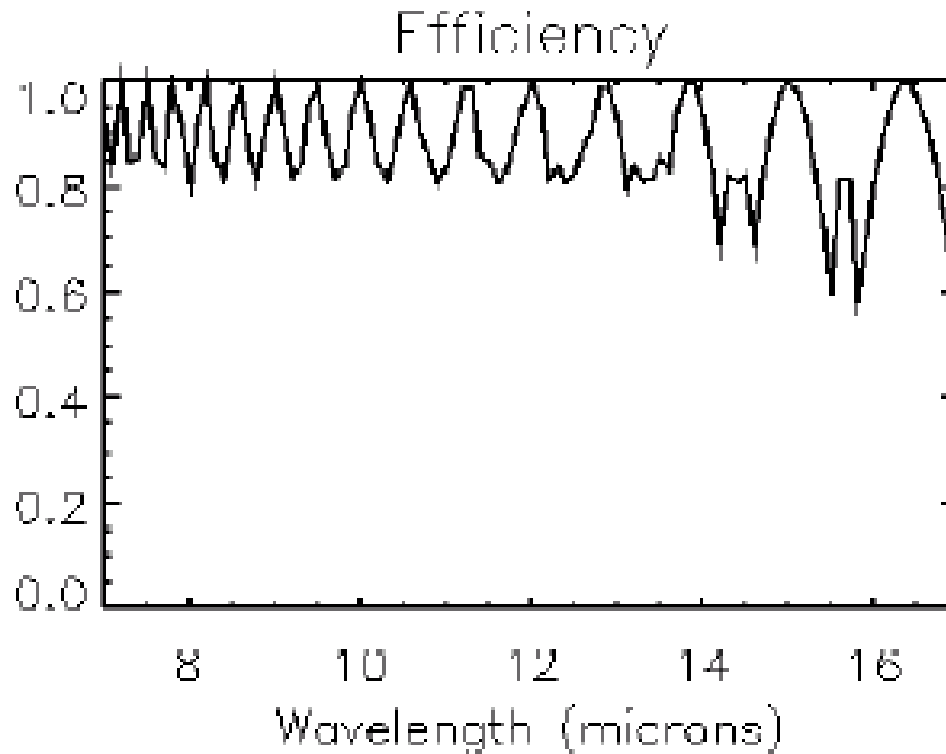
# Spot Diagram



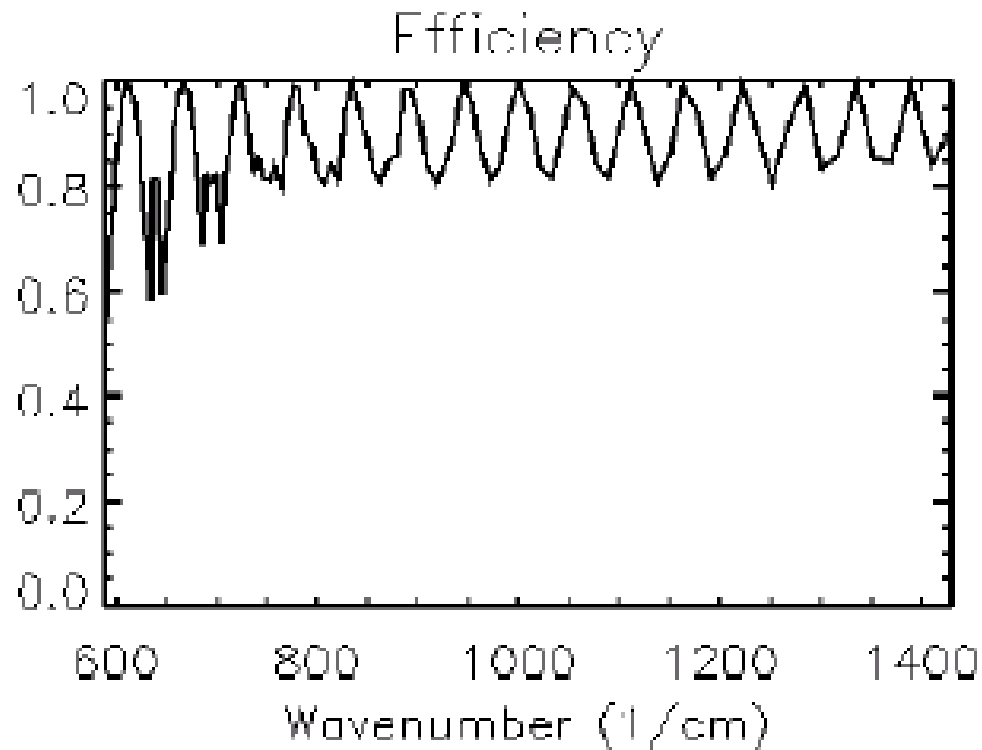
- Each wavelength has a different distribution of intensity vs. diffraction order, as indicated in the plot below
  - At steps of  $0.1 \mu\text{m}$  over the range 7 to 17, a series of profiles of the intensity vs. mode number are plotted
  - The focal length for each mode number is:  $f_n = f_1/n$
  - Total efficiency for a given wavelength is approximately the sum over all focal lengths within the range 5700-6300

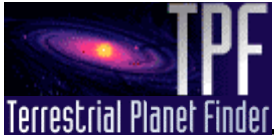


- The efficiency for collection of diffracted light vs. wavelength for the 30 m primary “Magnifying Glass” and 1.5 m aperture “Eyepiece” telescope is displayed below



- The same data as is on the previous chart, plotted as a function of inverse wavelength (i.e. wavenumber), displays a regular pattern of peaks





# Planet Detection Performance Model Assumptions

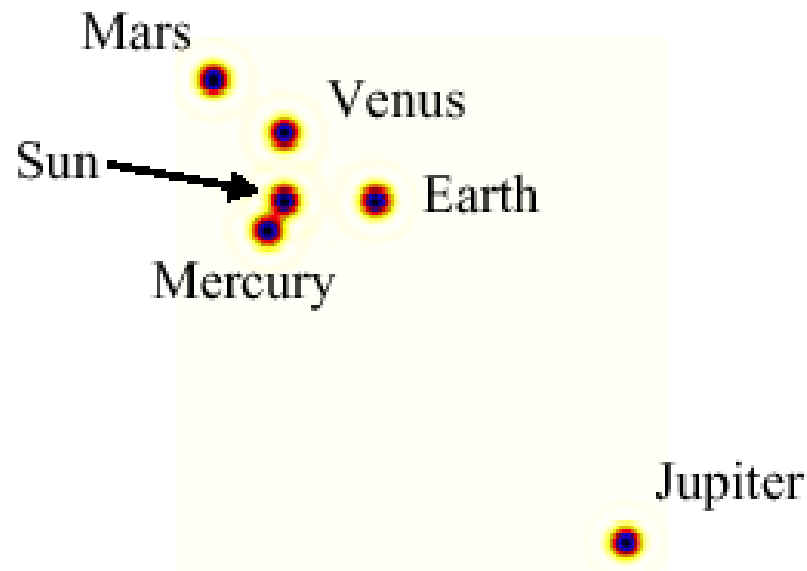
TRW

- Observe “Solar System” at 10 pc with 2 hour exposure at  $R=3$
- Diffraction limited performance of optimized coronagraph
- No central obscuration
- PSF widths are “achromatized”
- Occluding spot is “achromatized”



# Target “Solar System”

- Geometry: “Face on”
- Typical orbital phase angles displayed in diagram below
- Planet sizes, apparent temperatures, albedos, orbital radii are all equal to those of the solar system
- Exo-zodiacal background equals solar system distribution



- Wavelength=10 microns
- Aperture=28 m diameter
- Occluding spot=0.2" (1/e point with a Gaussian shape)
- Lyot-stop=17 m (Wood-Saxon shape)

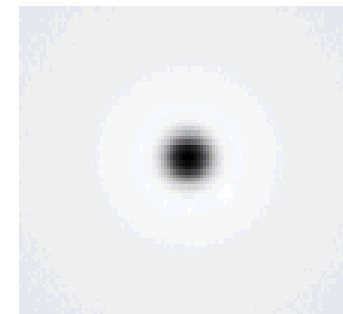
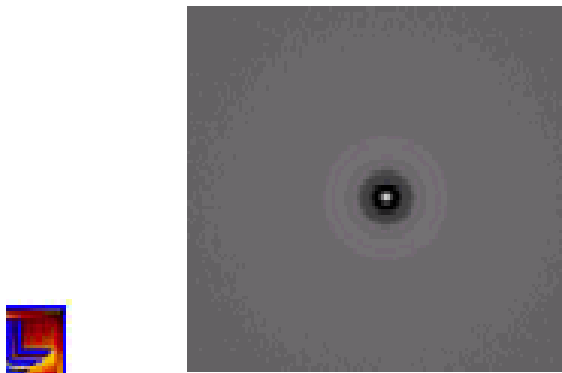
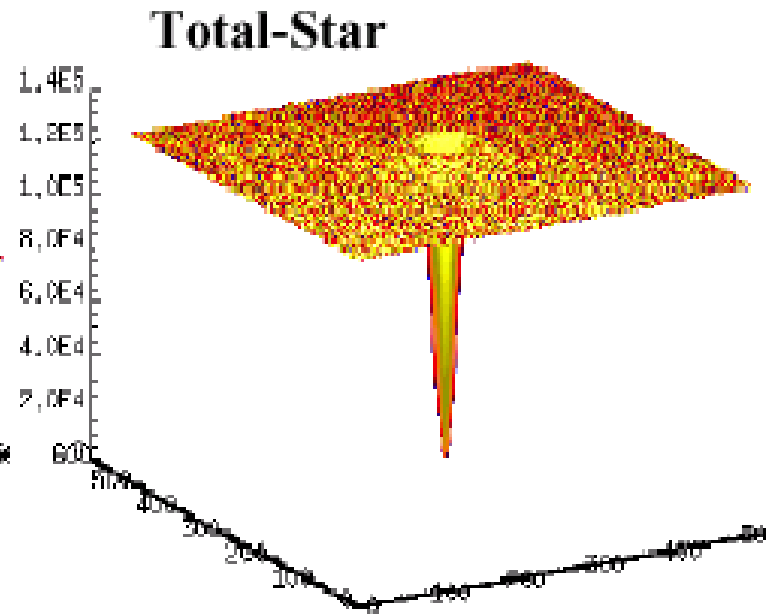
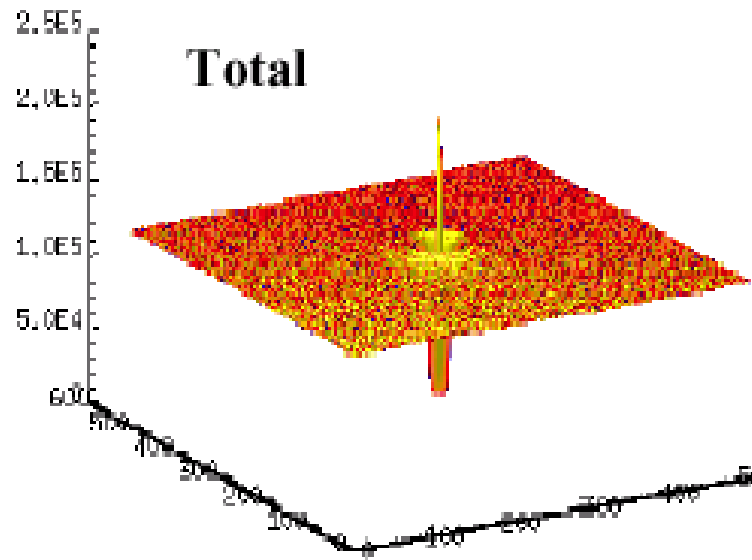
$$\frac{1}{1 + \exp((r - 17\text{m}) / 0.5\text{m})}$$

- Lyot-stop "diffuseness"=0.5 m
- 0.01" per pixel
- 2 hour exposure time at spectral resolution R=3

- Signal to Noise Results for Individual Planets

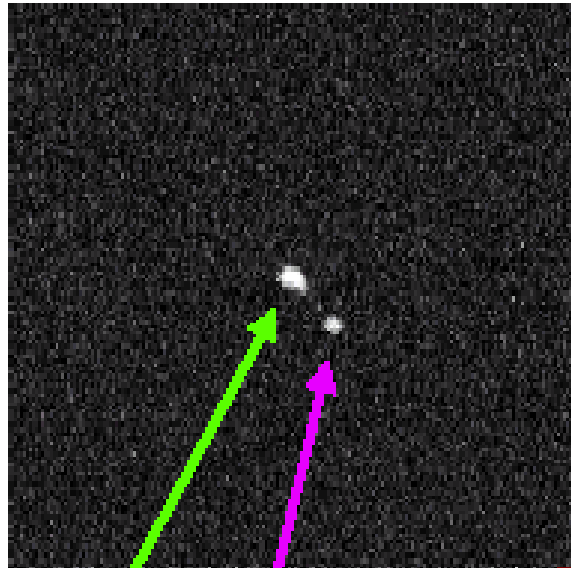
	Venus	Earth	Mars	Jupiter
	59	11	7	31

- (Other planets not detected)



TDC/CI D 10

**Total - Star - Zodi**  
**Relative to noise, clipped to [0,2]**



**“Venus”**

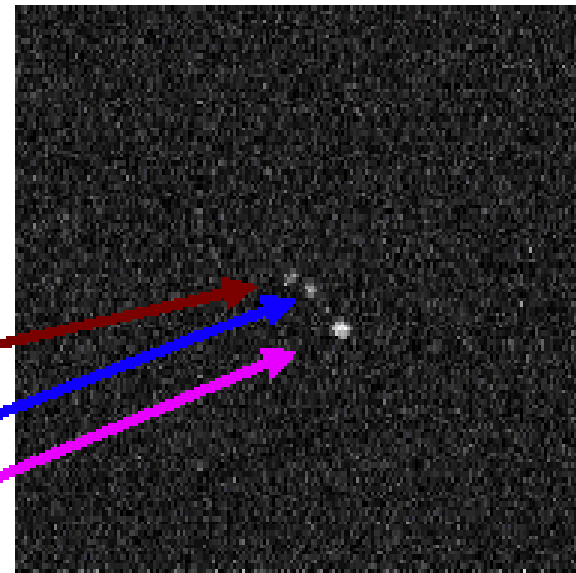


**“Mars”**

**“Earth”**

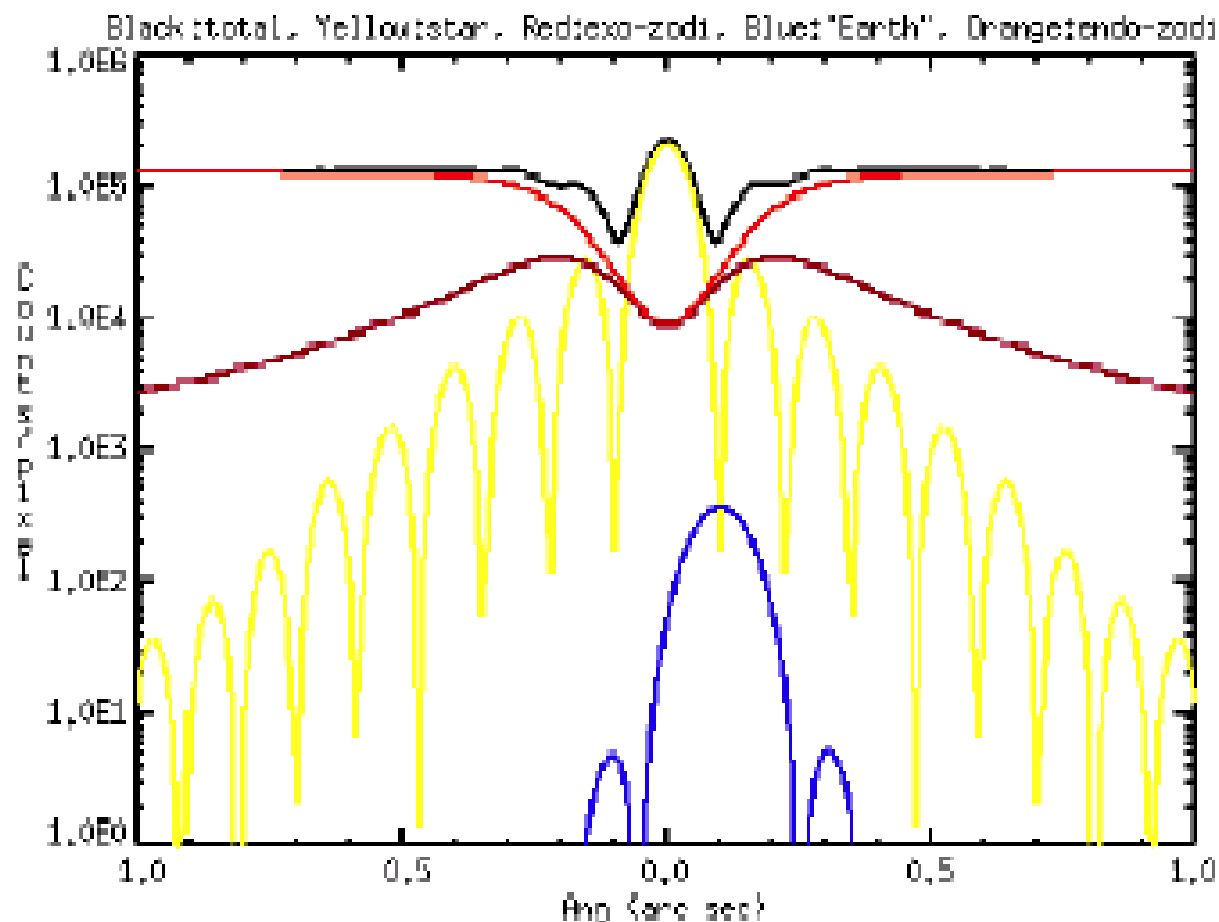
**“Jupiter”**

**Total - Star - Zodi - Venus**  
**Relative to noise, clipped to [0,2]**

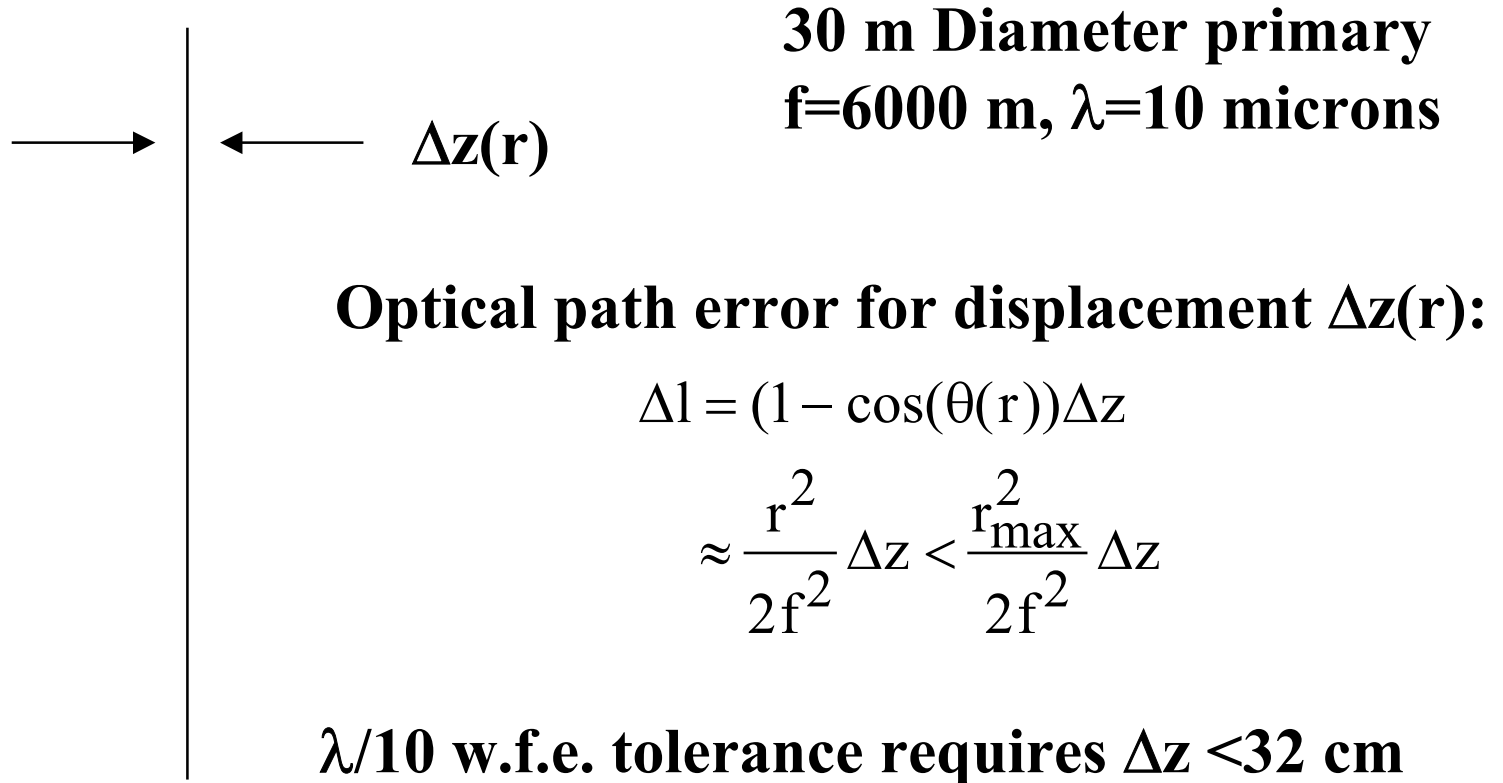


TPF-CLB 20

# Line Across System Through "Earth"



- In the following slides a variety of types of aberrations are considered, and an estimate of the impact on performance of each type is given
- Each aberration is considered in isolation, i.e. cross-talk between aberrations is ignored



## CONCLUDE:

Extremely loose tolerances for out of plane errors



$\Delta y(r)$

**Optical path error for displacement  $\Delta y(r)$ :**

$$\Delta l = \frac{(y + \Delta y)^2 - y^2}{2f} = \frac{y\Delta y}{f}$$

$$< \frac{r_{\max}}{f} \Delta y$$

**$\lambda/10$  w.f.e. tolerance requires  $\Delta y < 4$  mm at edge  
(much looser near center of primary)**

**CONCLUDE:**

Quite loose tolerances for in plane errors



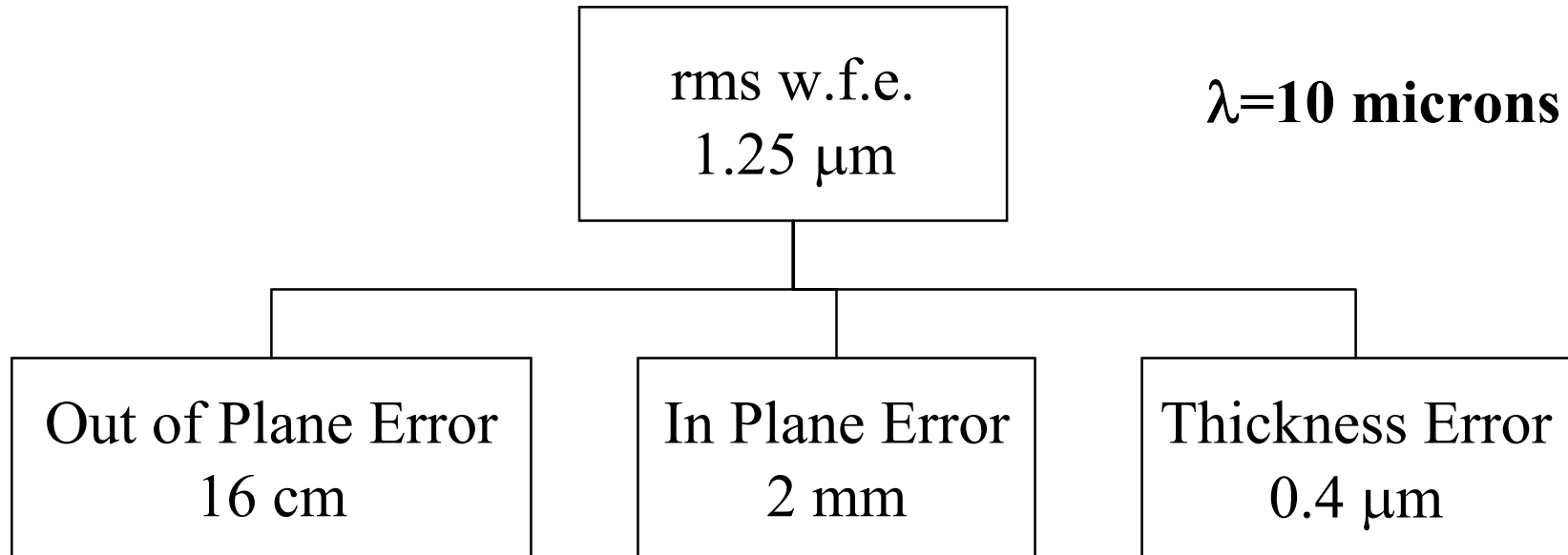
**Optical path error for thickness error  $\Delta t$ :**

$$\Delta l = (n - 1)\Delta t$$

**$\lambda/10$  w.f.e. tolerance requires  $\Delta t < 0.4 \mu\text{m}$**

## **CONCLUDE:**

Tightest tolerances for the Fresnel primary are on the thickness of the surface profile, but once manufactured to the appropriate specification, the thickness is very unlikely to change



\*Low to mid-range spatial frequencies are controlled by deformable mirror at the image of the Magnifying Glass

- Fresnel lens discontinuities introduce extraneous diffracted light
- The effects are approximately the same as series of obscurations of width  $w$ , where  

$$w = \text{step} \cdot \tan(\theta)$$

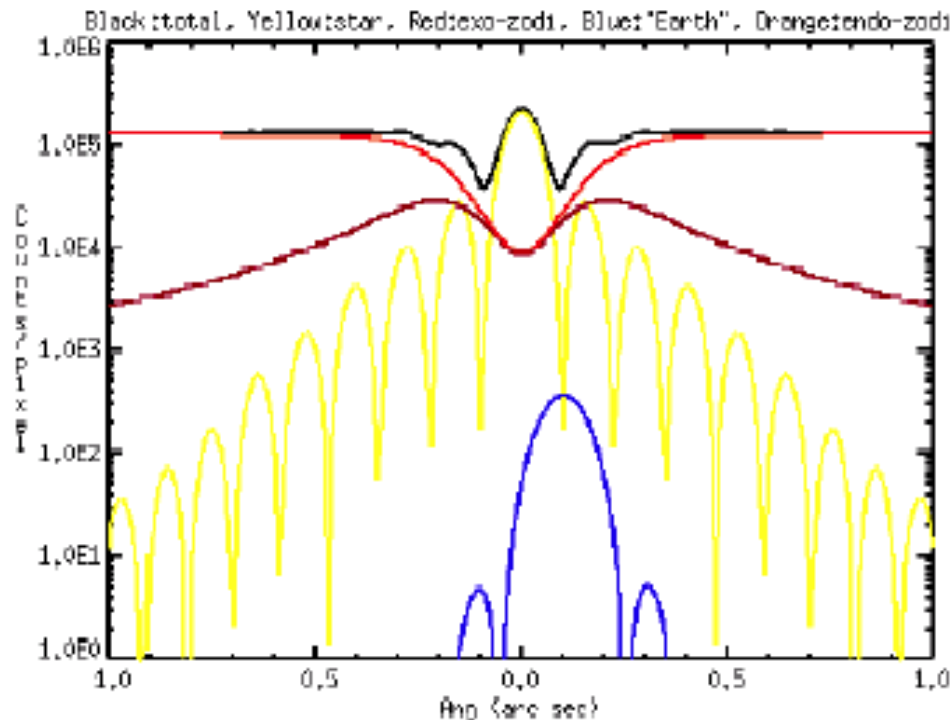
**Incoming waves**



The diagram illustrates the scattering of incoming waves by a Fresnel lens. On the left, four vertical black lines represent the incoming wavefronts, labeled "Incoming waves" with a right-pointing arrow. These waves encounter a series of three green, triangular-shaped segments representing the lens elements. The segments are arranged in a stepped fashion, with each subsequent segment shifted further to the right. To the right of the lens elements, the wavefronts are shown as diagonal lines, labeled "Outgoing waves" with an arrow pointing towards the bottom right. The green segments are filled with vertical lines, and the area between the segments and the outgoing waves is filled with diagonal lines, representing the diffracted light.

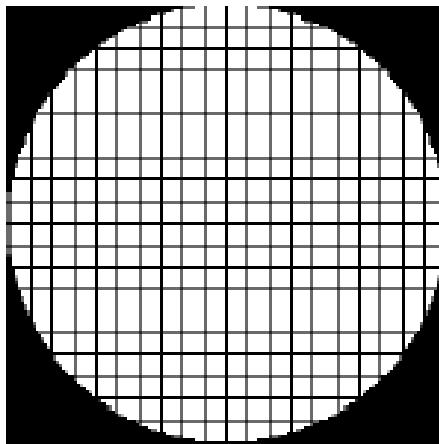
**Outgoing waves**

- For the current design, the “Magnifying Glass” produces almost no scattering, while the “Fresnel Corrector” scattering produces a contribution to the Strehl ratio of 0.9875 (Need to modify this for the new higher order design)
- The plot below displays the intensity of the psf from normal diffraction compared to the intensity of scattered light from the zone discontinuities in the current design

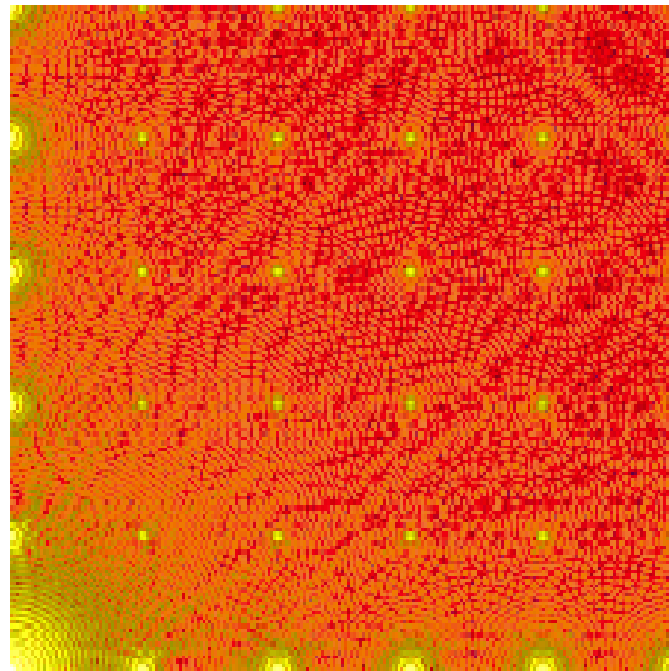


- Full aperture is constructed of identical segments
  - As an example, the effect of square segments on the diffraction limited psf is illustrated
  - Little impact on the “core” of the psf is seen

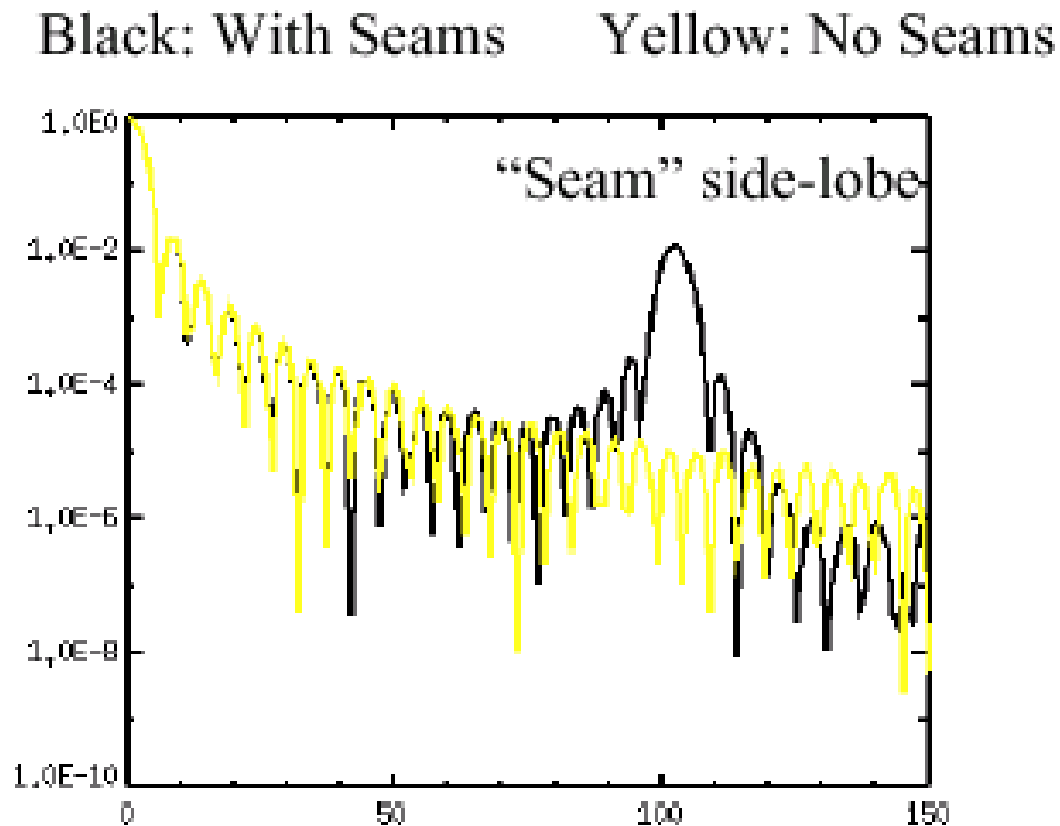
Aperture



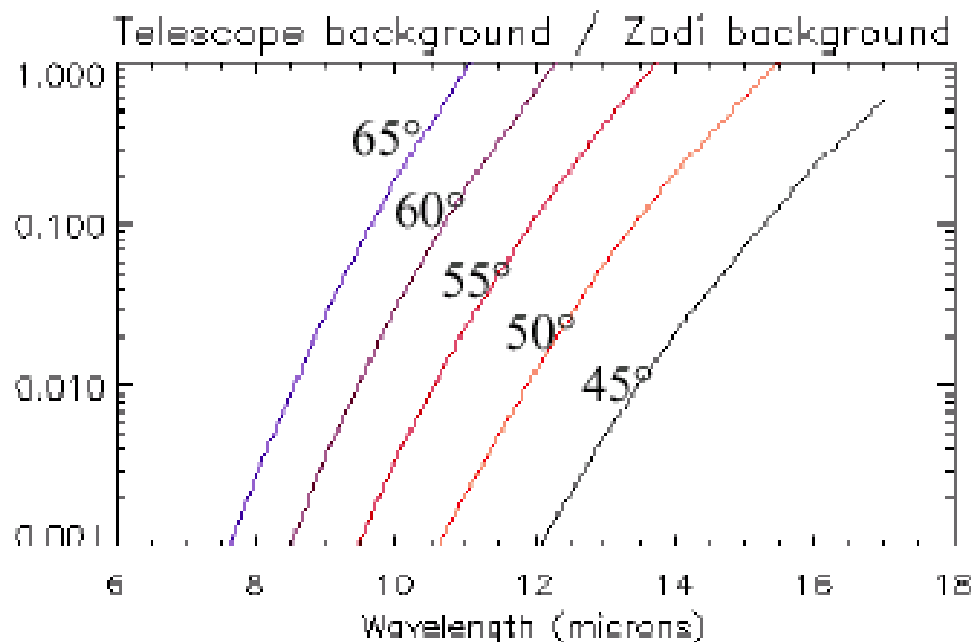
Log(psf)-Single Quadrant



- Along the “x” direction, having the worst side-lobe structure, the change in psf near the core is displayed in the plot below



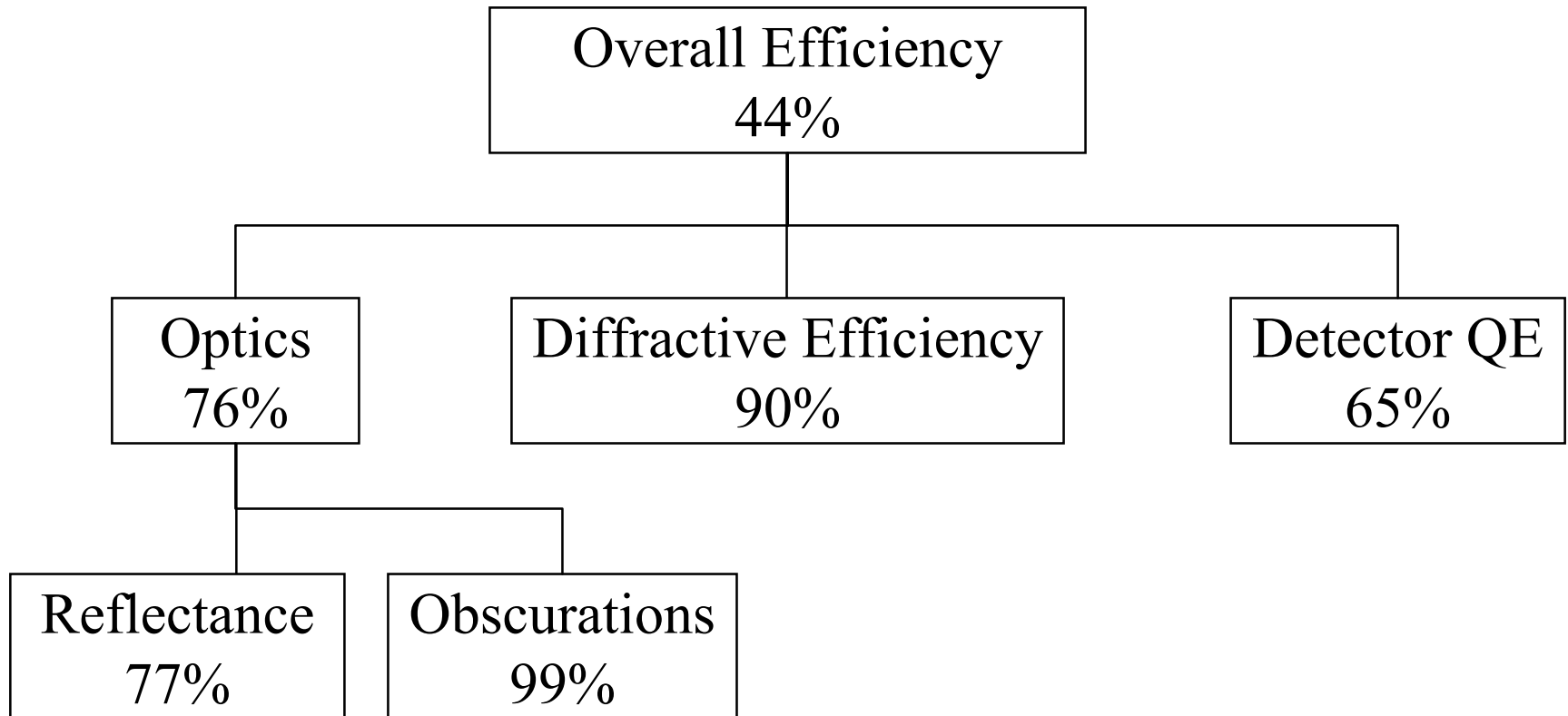
- Need to keep thermal emission from telescope elements below that of the endo-zodiacal emission
- The plot below displays the telescope thermal emission relative to the endo-zodiacal background emission for various telescope temperatures assuming a net emissivity of 30%
- The requirement to achieve Zodi background limited sensitivity at 17 microns dictates the temperature requirement  $T < 45^\circ\text{K}$



- Magnifying Glass: 2 ( + 1 bulk Silicon)
- Eyepiece: 6 ( + 2 bulk Silicon)
  - Fresnel corrector (FC) lens material is backed by reflective surface, thus beam transits the FC twice
- Coronagraph: 4
  - Once beyond the occluding spot, imaging performance is not as critical
- Contingency fold: 1

**Approximately 13 surfaces in total**

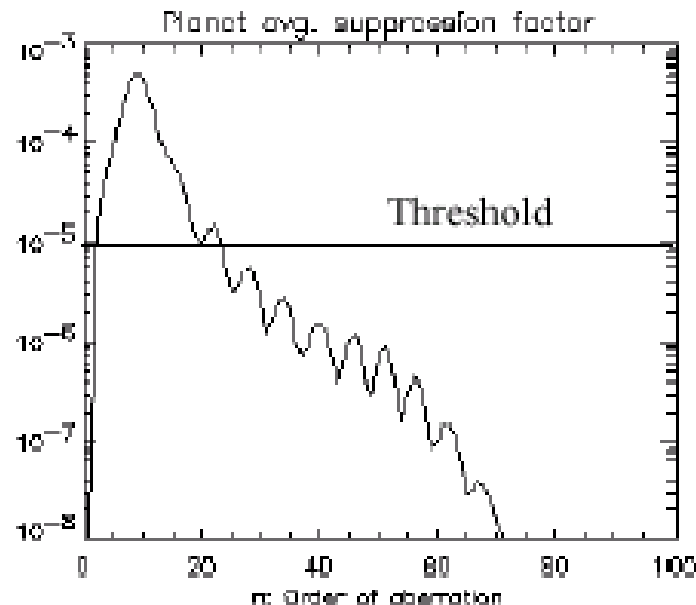


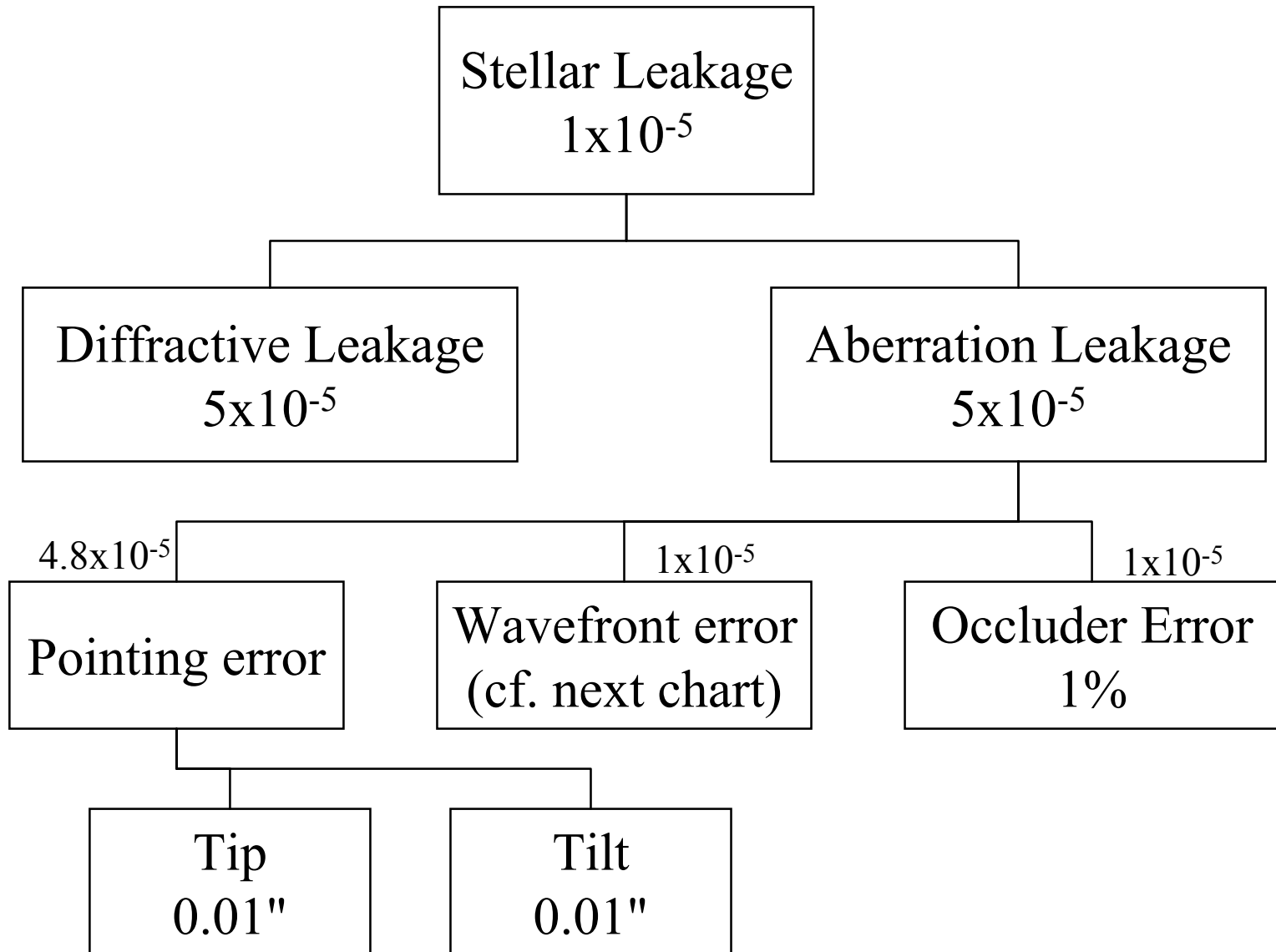


13 surfaces  
@ 98%

\*Excluding position dependent transmission of Coronagraph

- Symmetrical case: aberration of form  $\Phi = \lambda \cdot \rho^n$
- Plot displays the stellar light leakage averaged over the footprint of the planet for 1 wave of each order of aberration
- Aberrations in the mid-range are worst and must be well corrected by deformable mirror
- Aberrations at high spatial frequency cause some loss of efficiency, but are not so critical for coronagraphic rejection performance





- Currently demonstrated (cost to date ~2.5M\$ over 4 years):
  - Color correction over 0.48-0.72 microns
  - Single aperture: 50 cm diameter
  - Spot diameter as expected
  - 6 segments with 6 seams to make a 75 cm aperture have been co-aligned with diffraction limited performance
- Near future (next 2 years)
  - LLNL LDRD SI project (1M\$ funded this year, next year anticipated funding ~ 1 M\$ ):
  - Expect to complete 5 m lens fabrication (segmented and foldable)
  - Cost scaling estimate  $\sim (\text{diameter})^{1.5}$
  - so 30 m cost est. 50 M\$

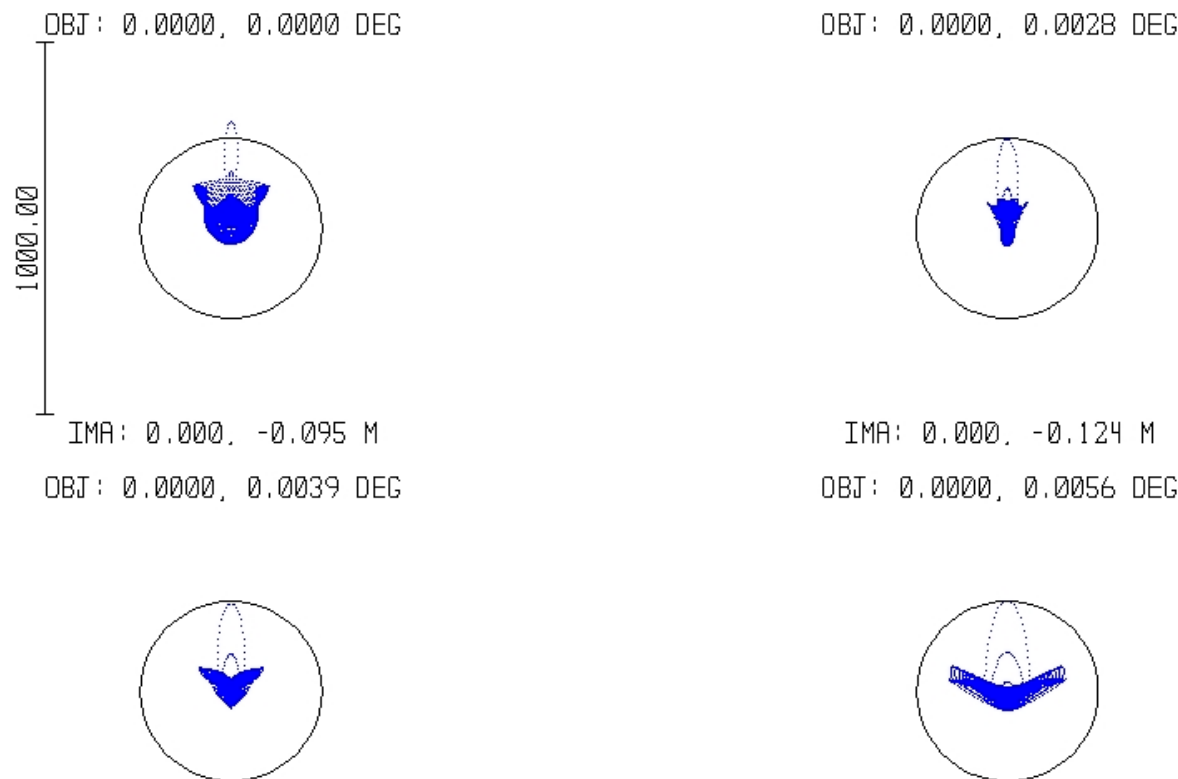
- Expect Real Stuff From Kodak
- Reflective optics in the Eyepiece telescope are relatively low risk and low cost
  - Not particularly large (1.5 m diameter)
  - Nor particularly challenging surfaces (all conic sections)
  - Nor particularly fine wavefront quality (most of the mid-range spatial frequency aberrations will be accommodated by the built in deformable mirror, while the high spatial frequency tolerances are loose  $\sim 1$  wave or more)

- Wide field imaging (up to 1' field of view)
  - Rather than optimize for the very narrow FOV associated with the planet detection problem ( a fraction of 1"), an extended FOV is available by adjusting the deformable mirror
  - Spot diagrams are displayed on the next viewgraph
  - Point source sensitivity is very good

At 12 microns,  $R=3$ , in 2 hour exposure:

Fresnel Lens	NASA requirement
0.006 $\mu\text{Jy}$	0.3 $\mu\text{Jy}$

# Spot Diagram for Imaging



SURFACE: IMA IMA: 0.000, -0.136 M

IMA: 0.000, -0.153 M

## SPOT DIAGRAM

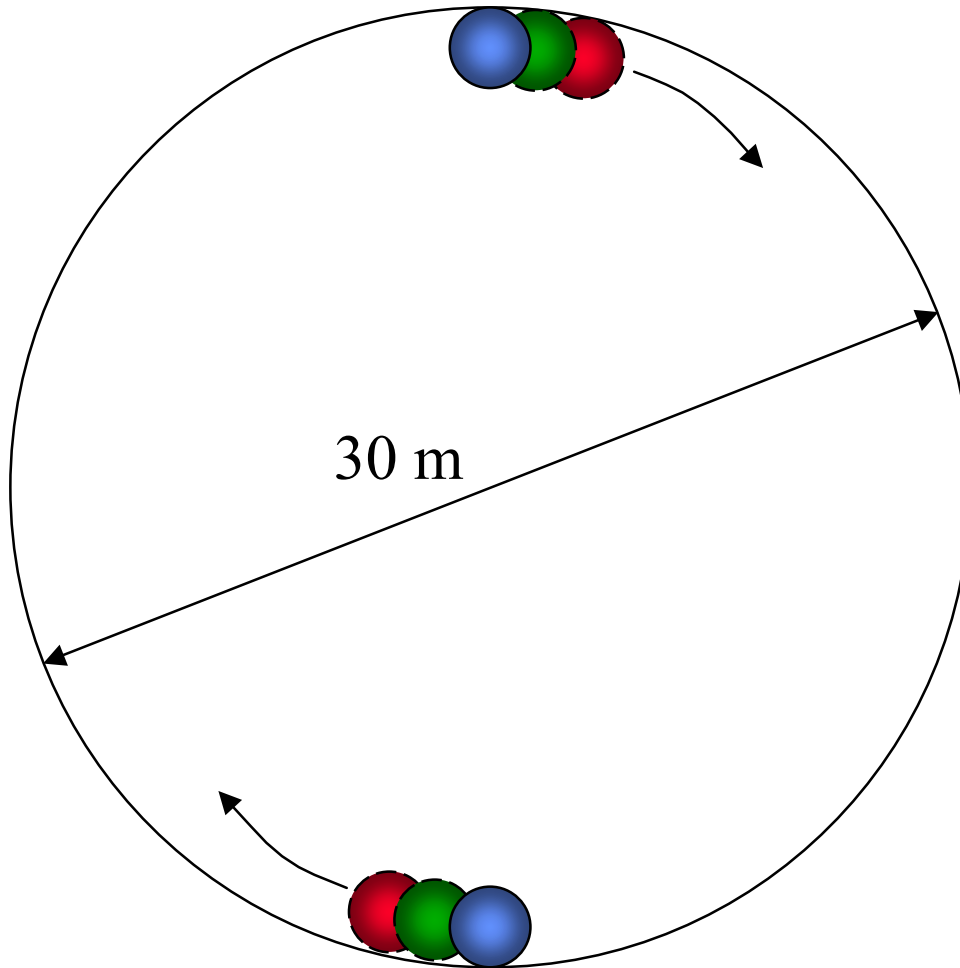
PRELIMINARY TPF DESIGN

WED NOV 22 2000 UNITS ARE MICRONS.

FIELD	1	2	3	4
RMS RADIUS	76.951	43.783	42.079	69.916
GEO RADIUS	285.878	240.958	236.063	242.819
AIRY DIAM	487.5			

REFERENCE : CHIEF RAY

CONFIGURATION 1

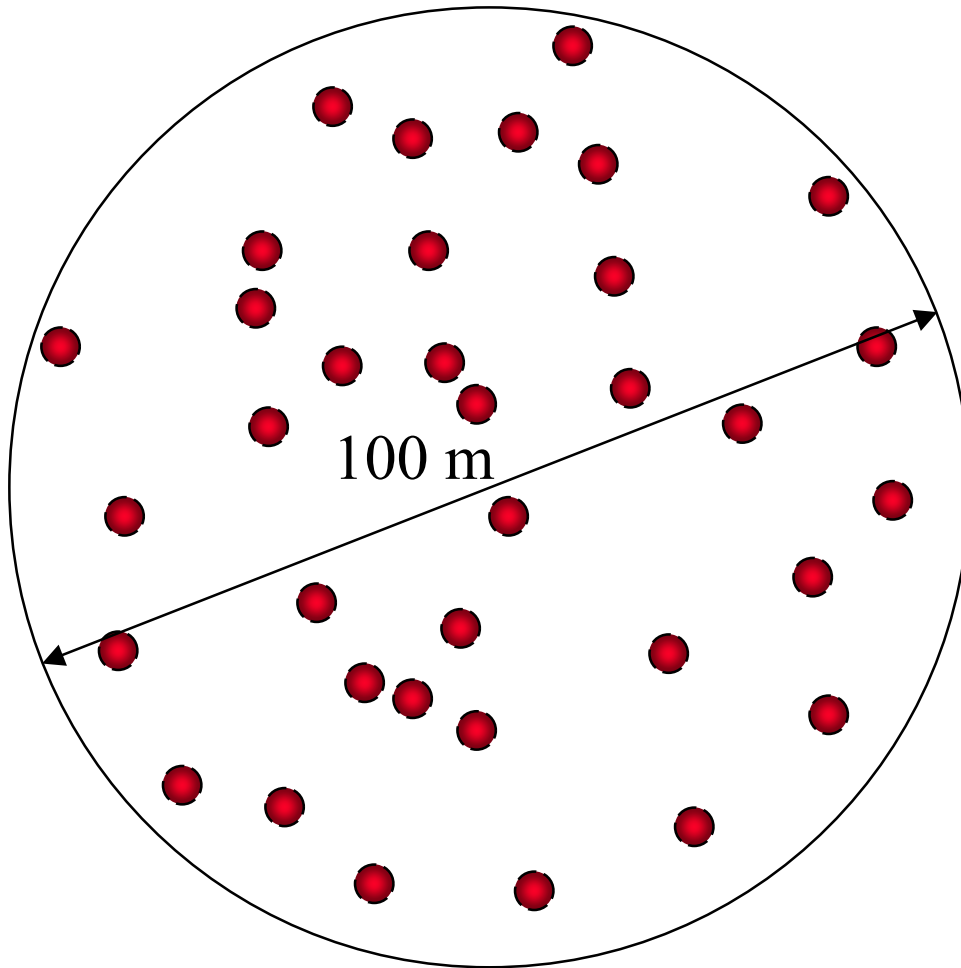


- For equivalent imaging performance, a complete set of positionings (covering the entrance pupil of the filled aperture with weighting proportional to the filled aperture MTF) is required
- By the Fienup theorem the speed of interferometric imaging relative to filled aperture imaging, in the statistical noise dominated limit, is approximately:

$$(\text{Relative area})^2$$

- The 30 m Fresnel Coronagraph is thus intrinsically faster than the 2.5 m OASES design by ~10,000





- By the Fienup theorem the speed of sparse aperture imaging relative to filled aperture imaging, in the statistical noise dominated limit, is approximately:

$$(\text{Relative area})^3$$

- A 100 m Fresnel Lens is intrinsically faster than the 100 m "Bed of Nails" design, having 120 apertures, each of 4 m diameter by the factor  $\sim 140 \times$