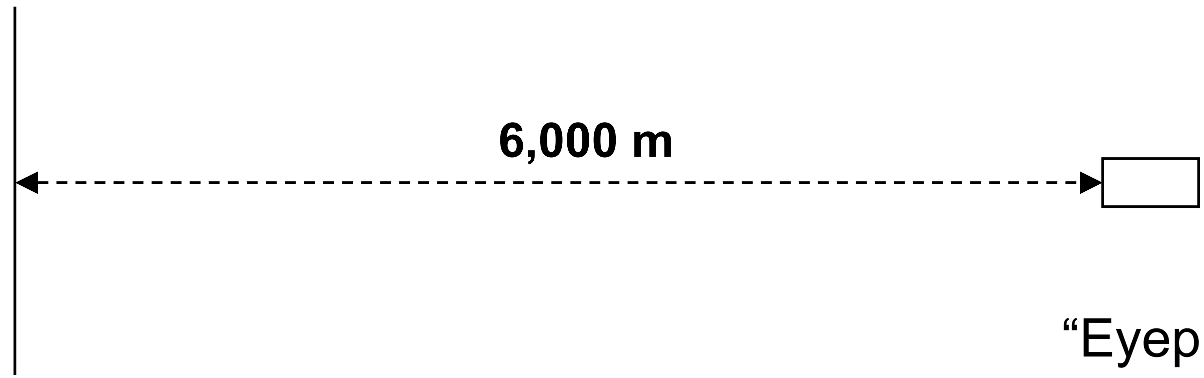
Space & Electronics Group

Fresnel Coronagraph for TPF

Charles L. Bennett (LLNL)

Fresnel Lens Design

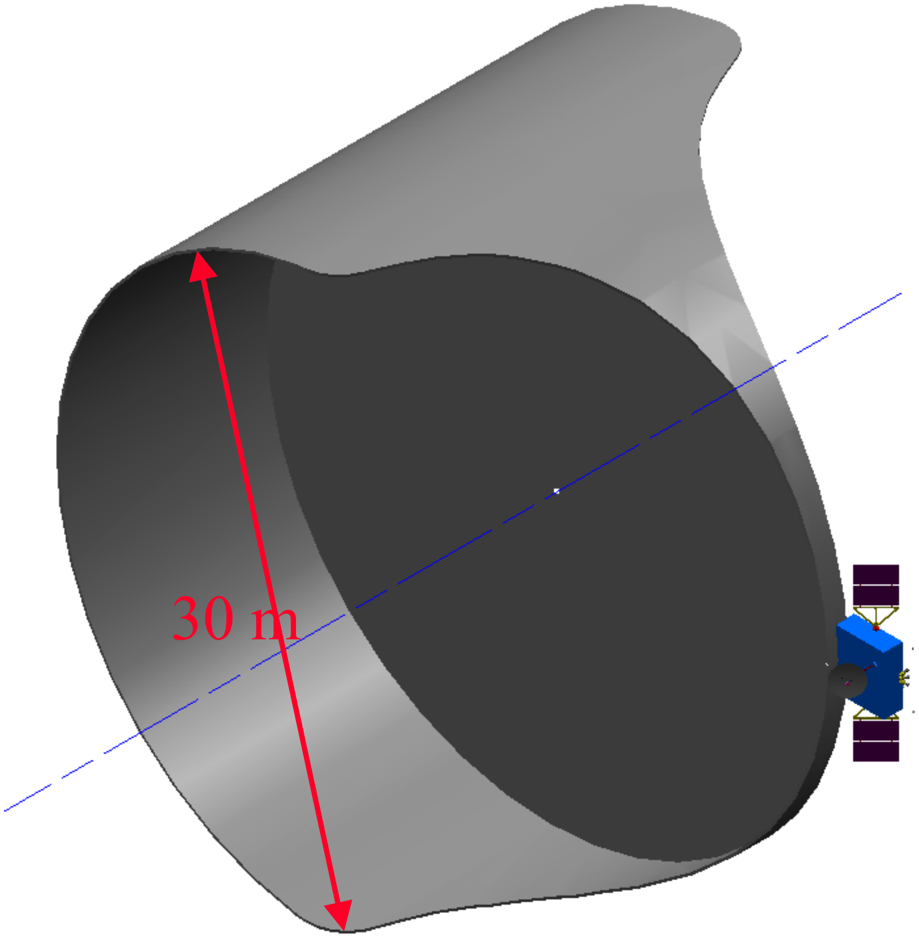


"Magnifying Glass"
30 m diameter
Silicon Fresnel lens

"Eyepiece"
1.5 m aperture
f=60 m telescope
(with embedded
Fresnel corrector)

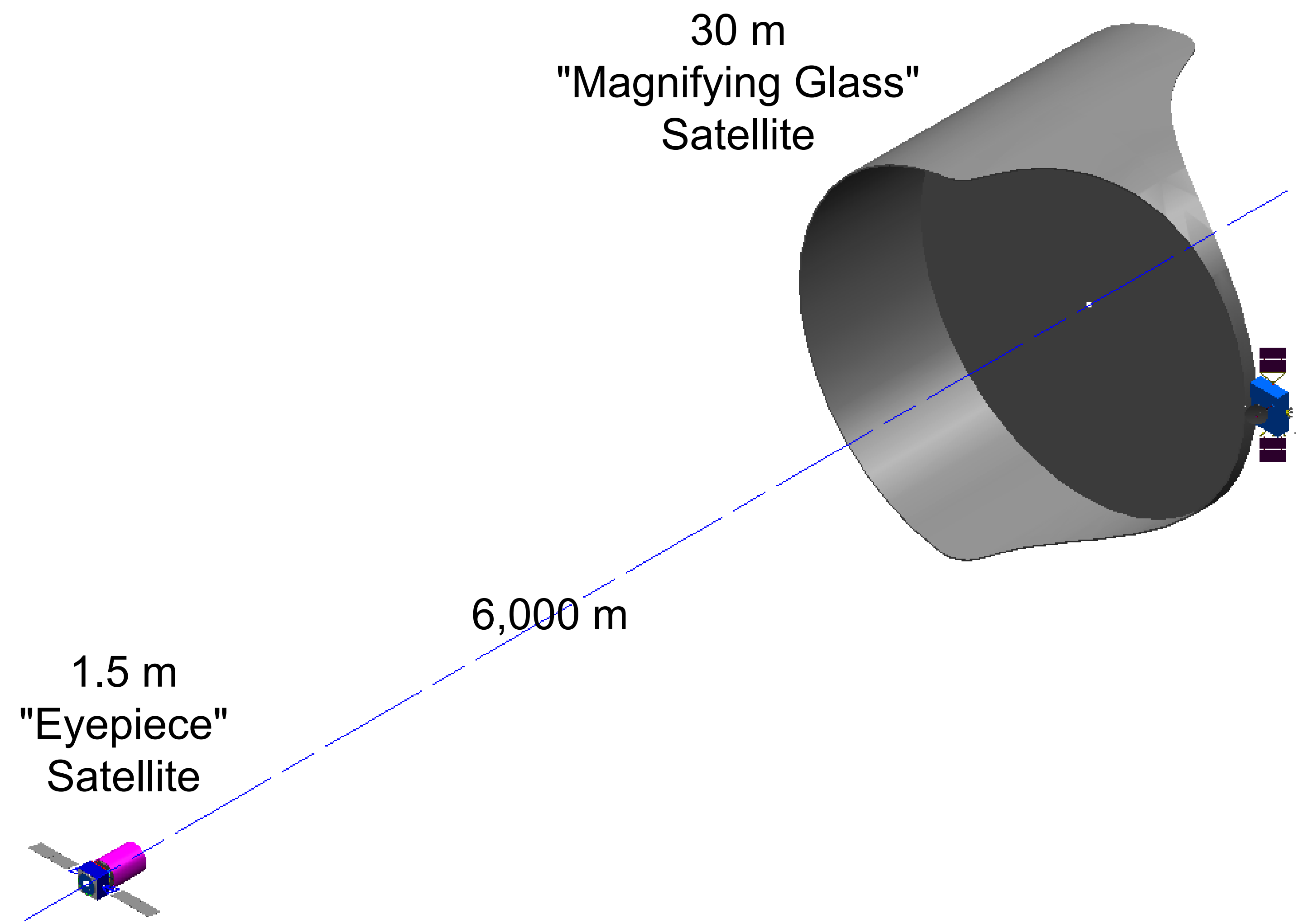
Coronagraph "rear end" used for planet finding
Wide field imaging available for general astronomy

"Magnifying Glass" Satellite

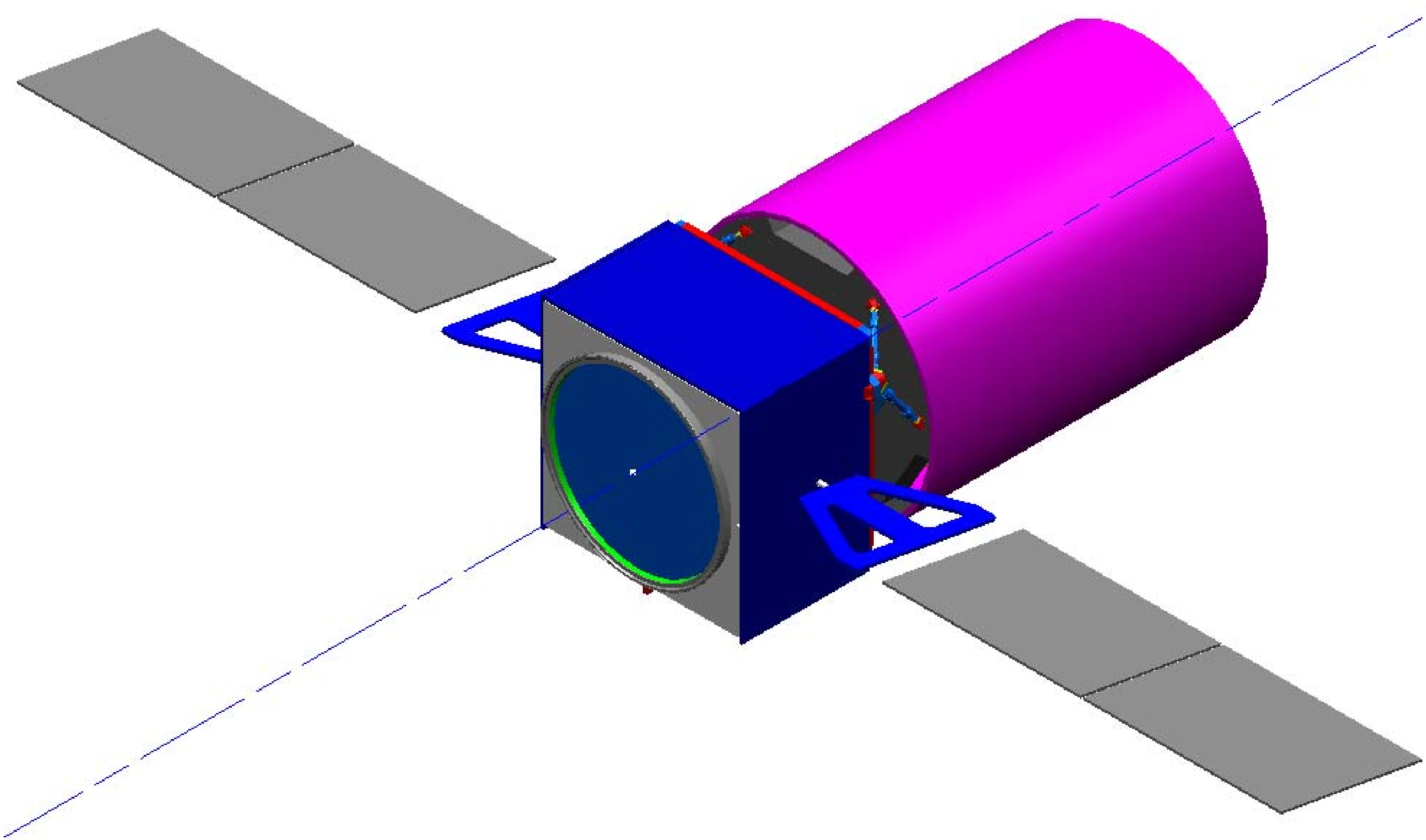


Fresnel Coronagraph Concept

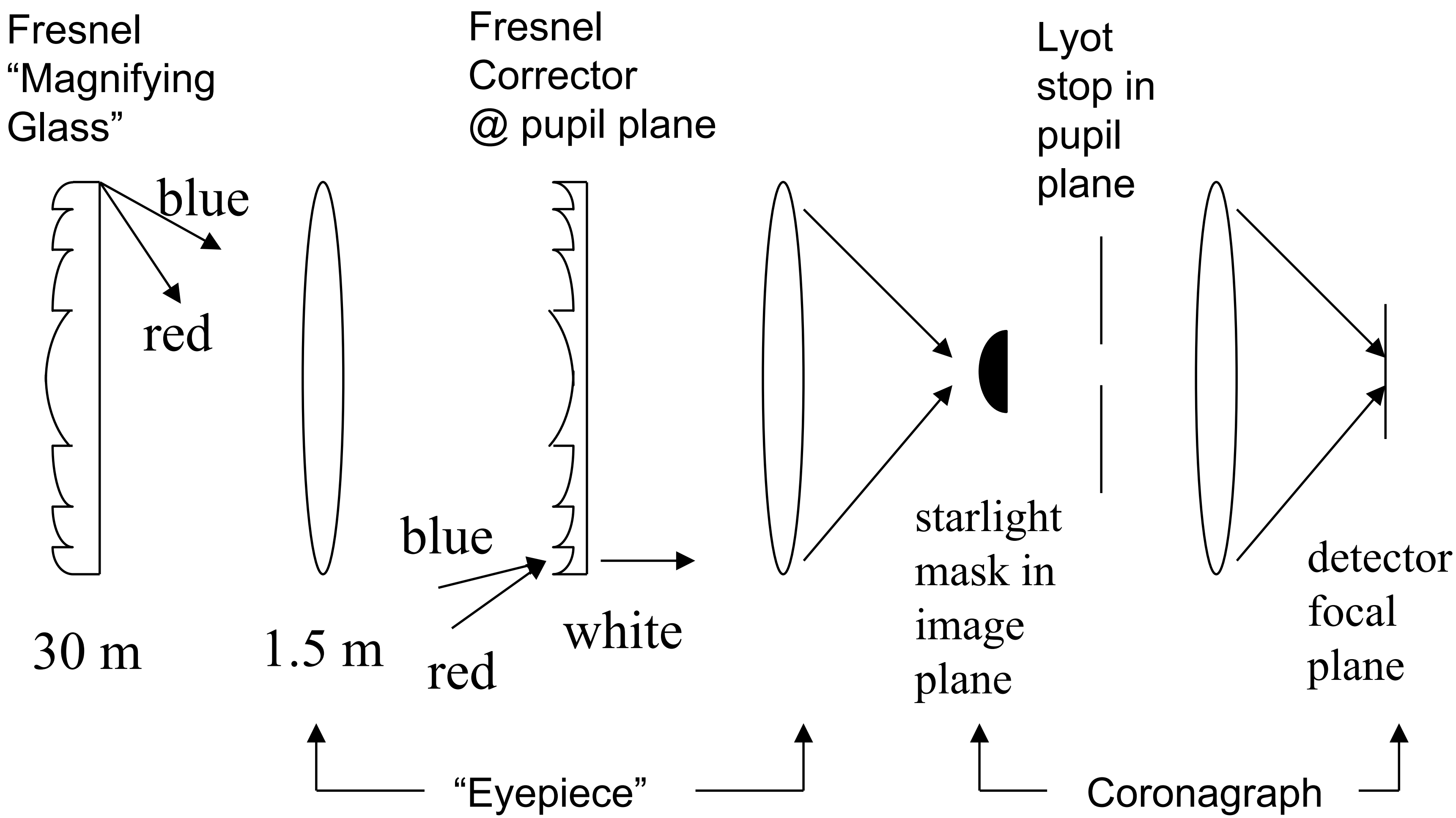
TRW



"Eyepiece" Satellite



Fresnel Coronagraph Functional Block Diagram

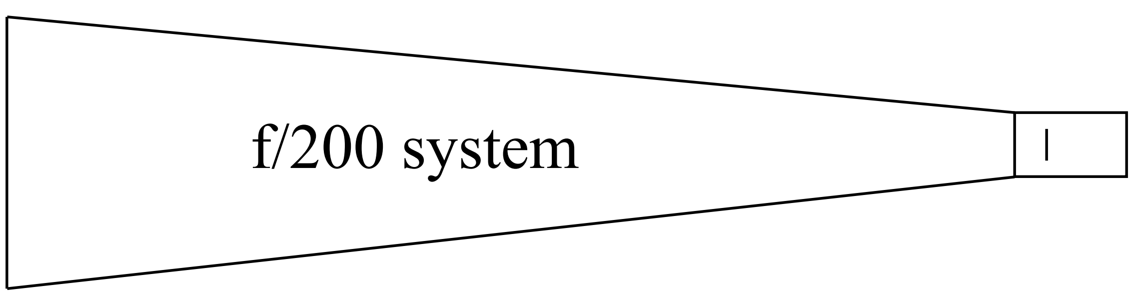


Chromatic aberration of Fresnel Magnifying Glass is removed with Fresnel Corrector

TPF Fresnel Lens Specifications

TRW

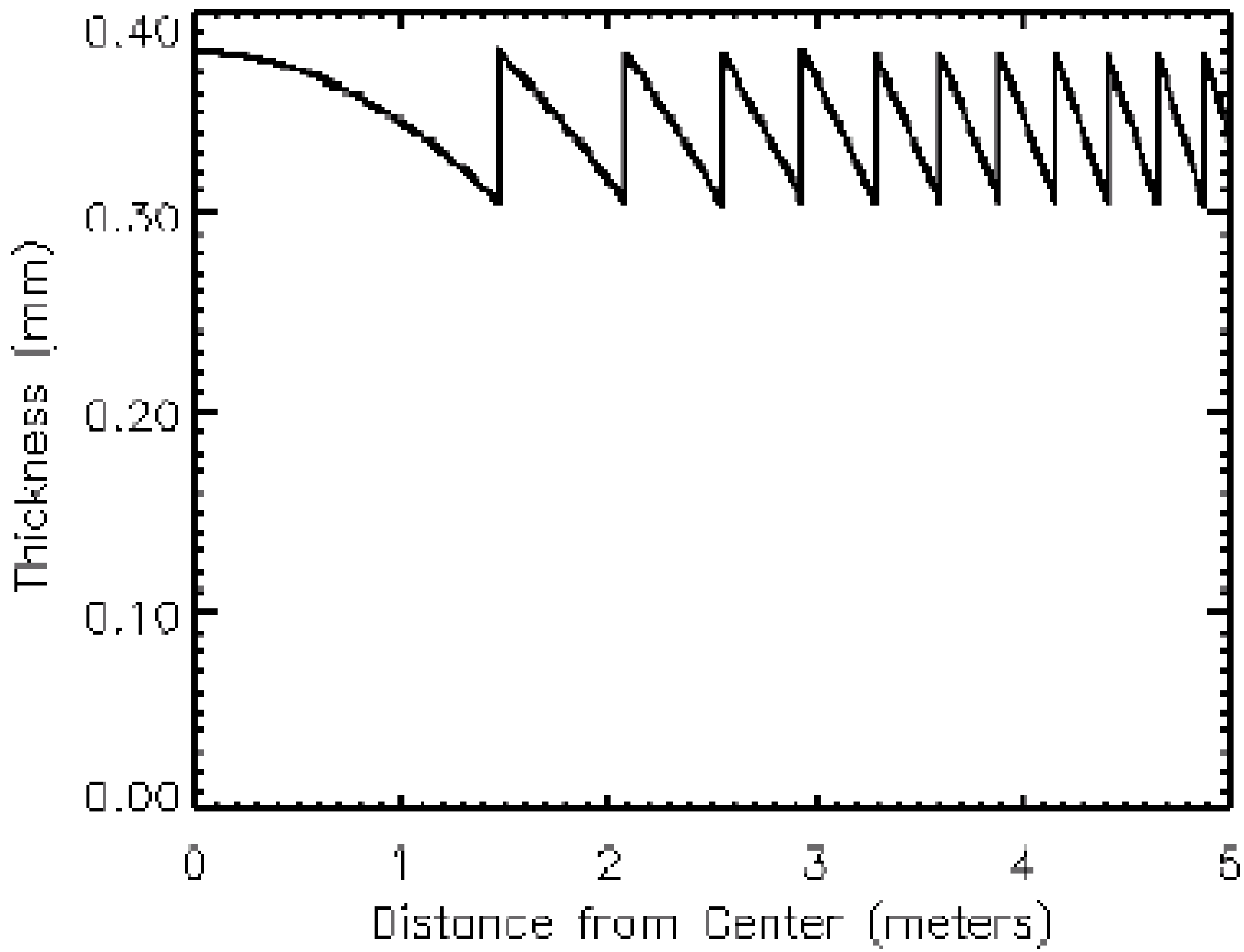
- Covers spectral range 1-25 μm except 9±0.2 μm and 16.4±0.4 μm
- Mass of primary lens: 750 kg
- Aperture: 30 m
- Number of zones: 104
- Focal length: 6,000 m
- Secondary aperture: 1.5 m
- Primary may be slowly spun to provide stabilizing tension
- Remainder of optical train is in separate free-flyer
- 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



30 m Aperture for 1-17 μm Operation

TRW

Profile of innermost 5 meters of “Magnifying Glass” lens



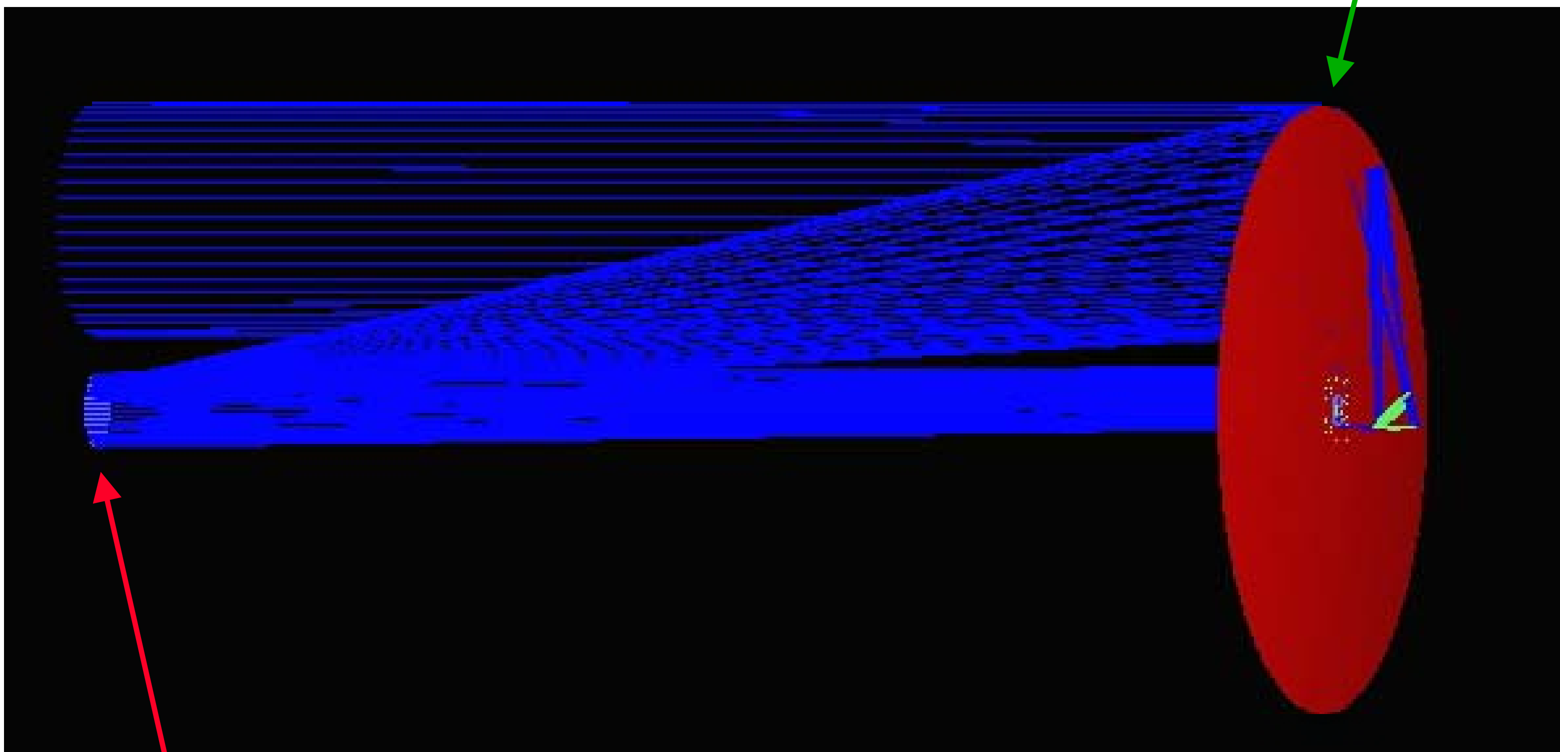
TRW

Eyepiece Design Features

- 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 Design

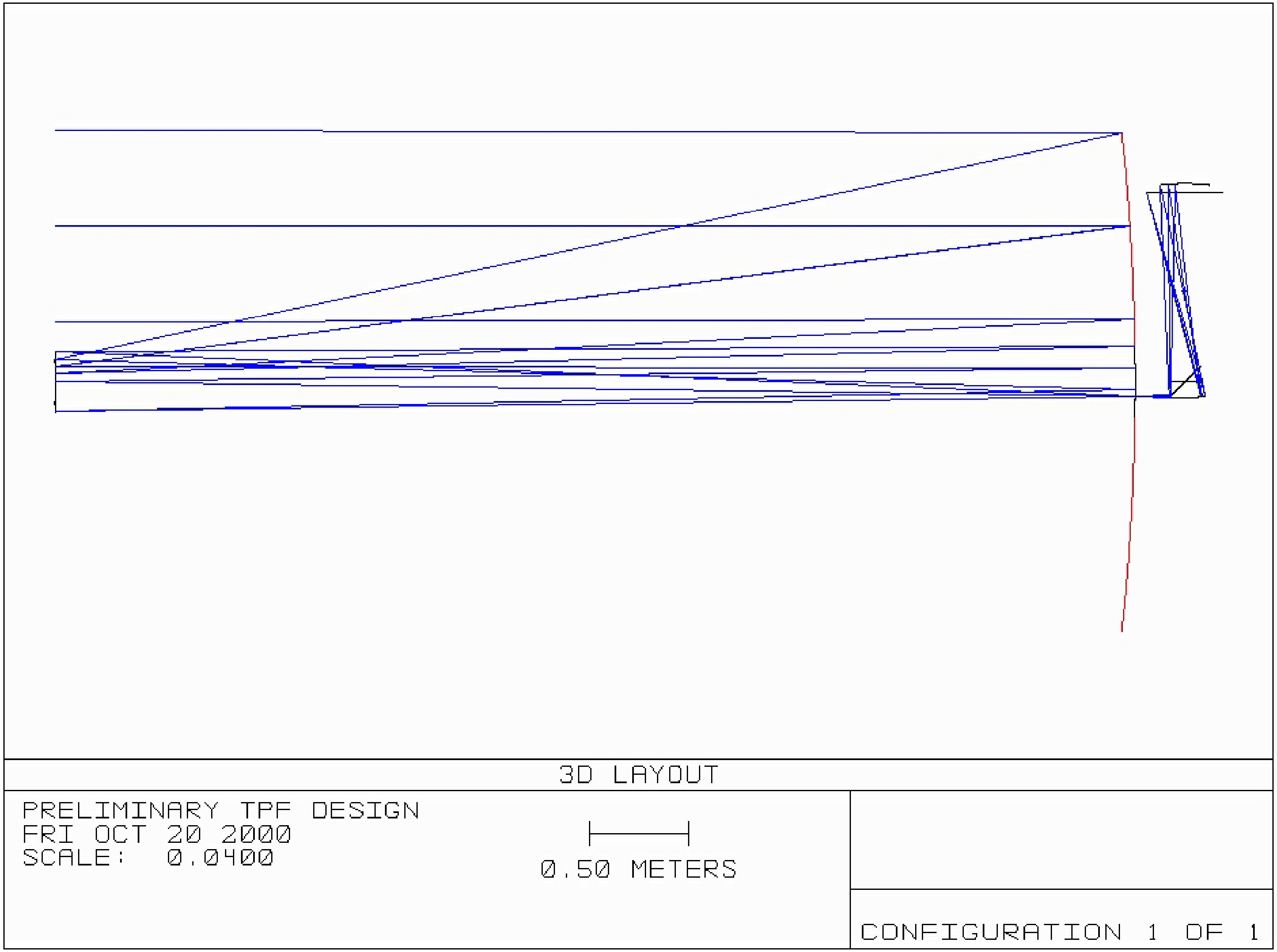
Eyepiece primary mirror is also the tertiary



Fresnel pattern etched on Eyepiece 4th mirror

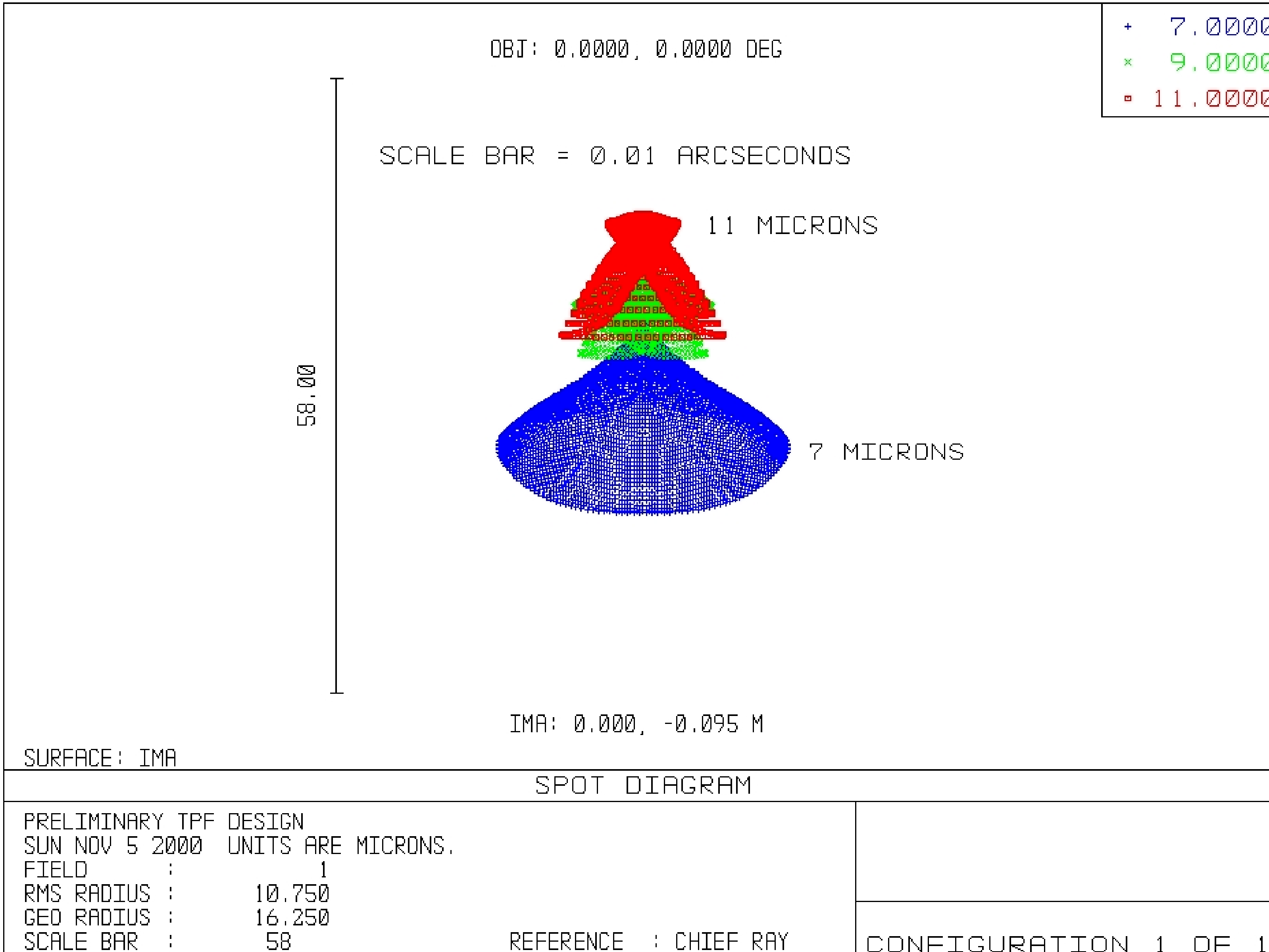
Coronagraph behind Eyepiece Primary

Eyepiece Ray Trace Example



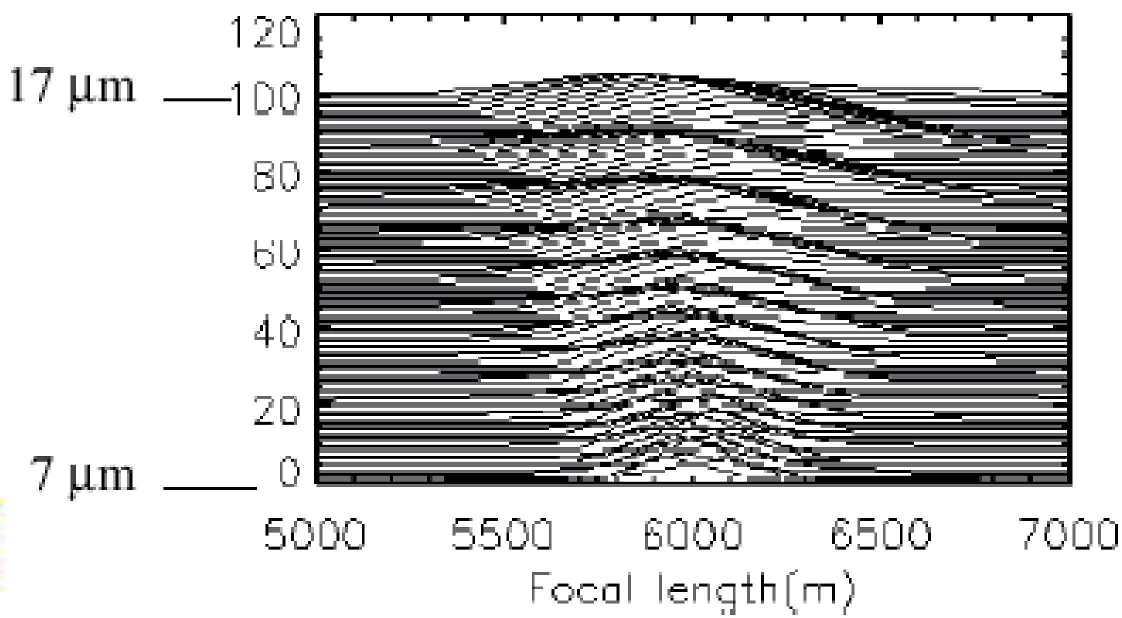
Spot Diagram

TRW



Intensity for Individual Orders vs. Wavelength

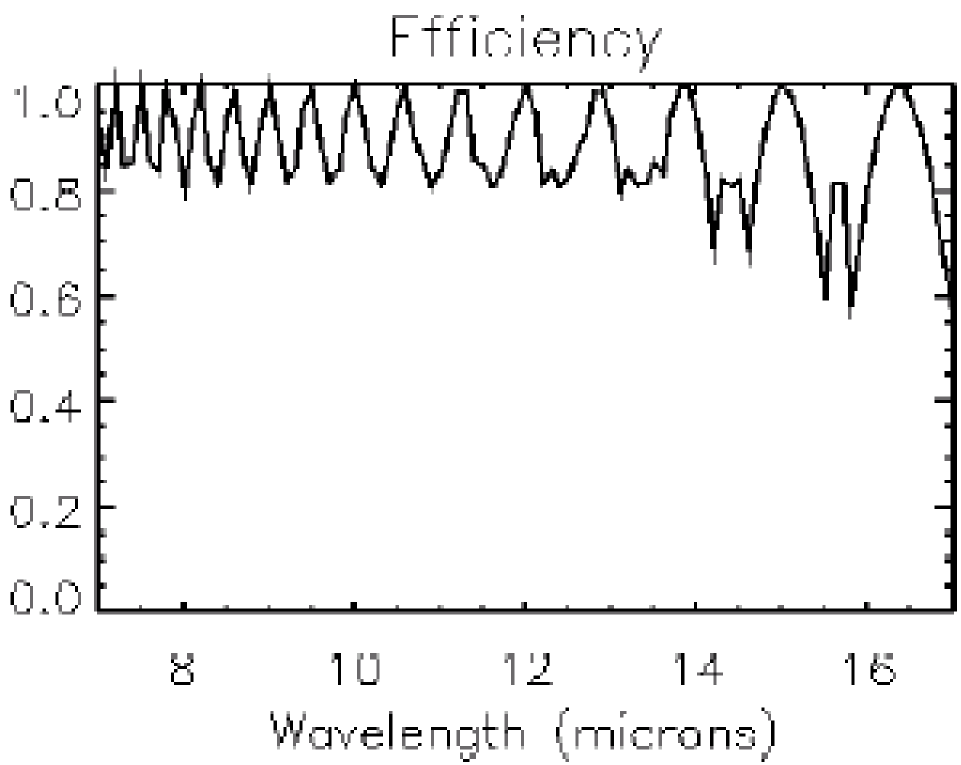
- Each wavelength has a different distribution of intensity vs. diffraction order, as indicated in the plot below
  - At steps of 0.1 μm over the range 7 to 17, a series of profiles of the intensity vs. mode number are plotted
  - The focal length for each mode number is: $f_n = f_1/n$
  - Total efficiency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



Efficiency vs. Wavelength

TRW

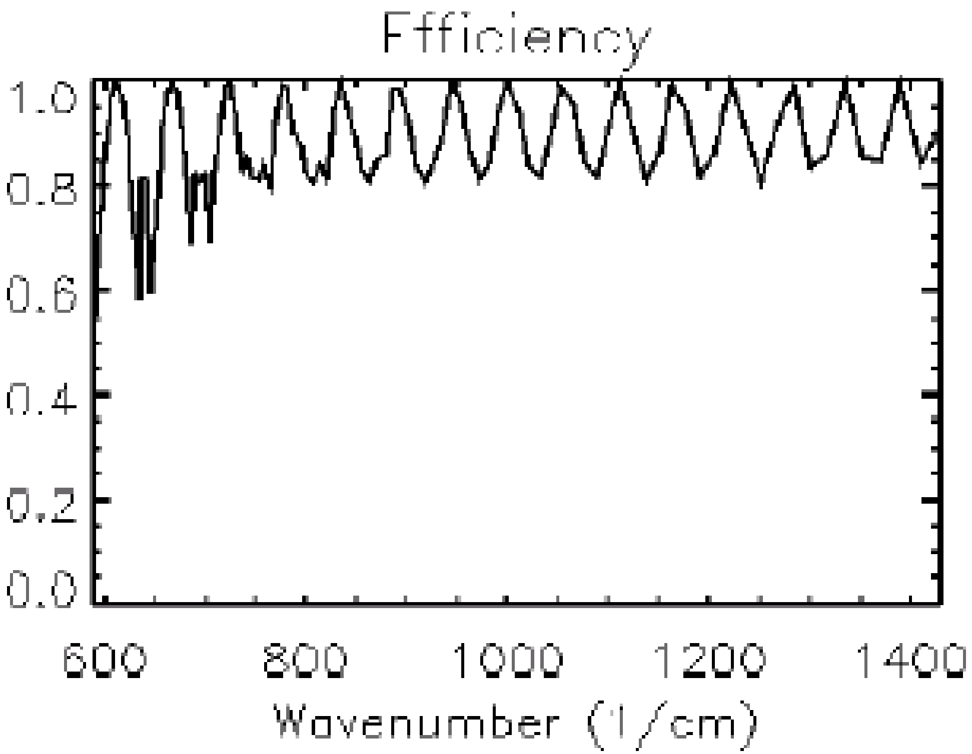
- The efficiency for collection of diffracted light vs. wavelength for the 30 m primary "Magnifying Glass" and 1.5 m aperture "Eyepiece" telescope is displayed below



Efficiency vs. Wavenumber

TRW

- 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



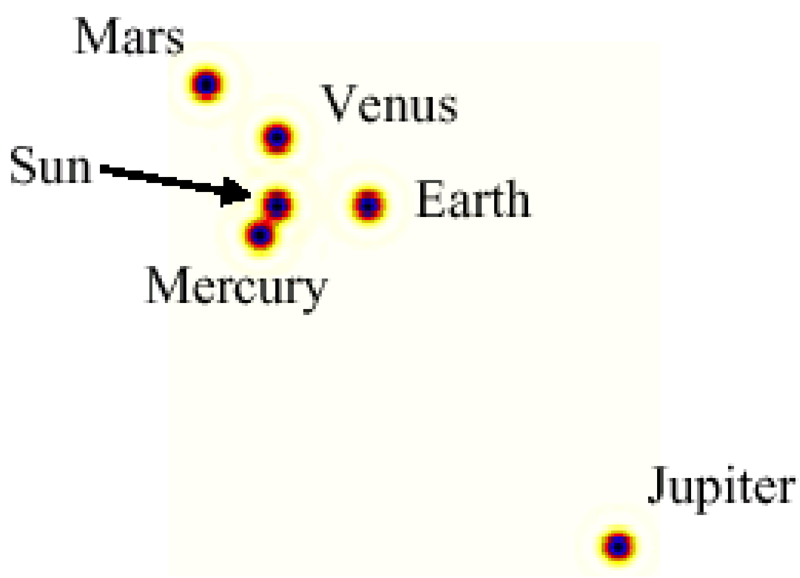
Planet Detection Performance Model Assumptions

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



Typical Simulation Results Follow

TRW

- 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)

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

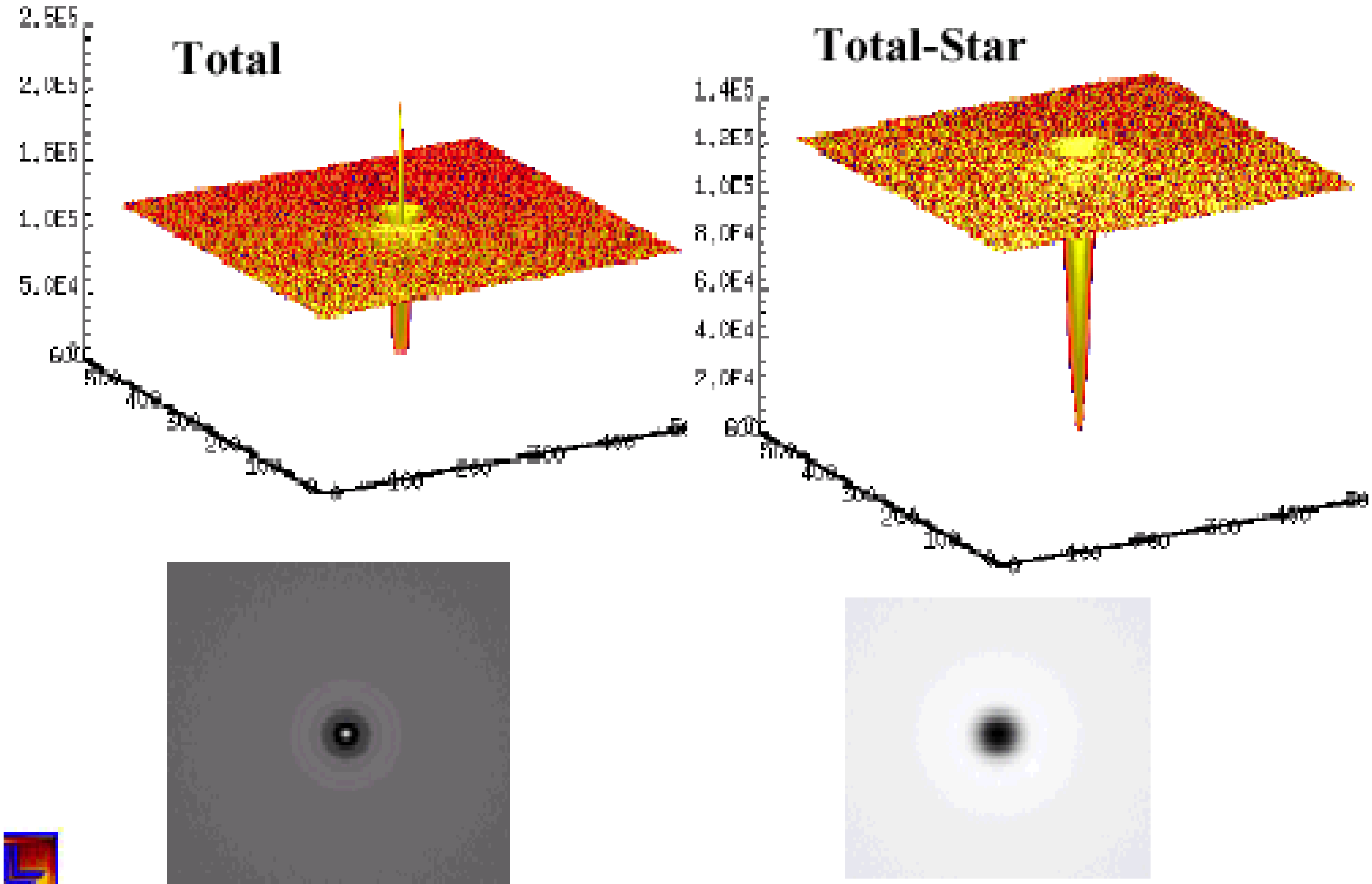
- Lyot-stop “diffuseness”=0.5 m
- 0.01” per pixel
- 2 hour exposure time at spectral resolution R=3

- Signal to Noise Results for Individual Planets

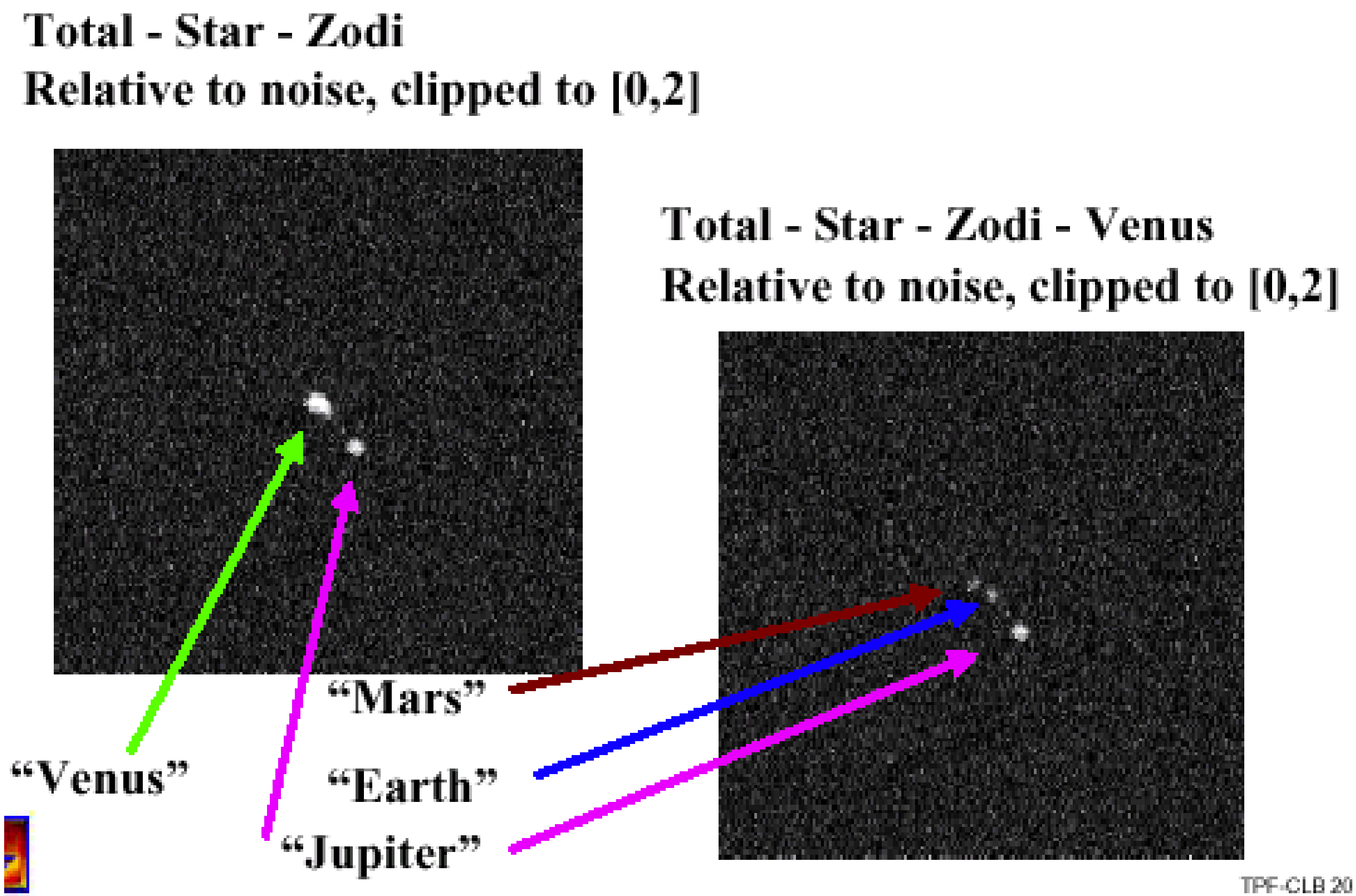
Venus	Earth	Mars	Jupiter
59	11	7	31

(Other planets not detected)

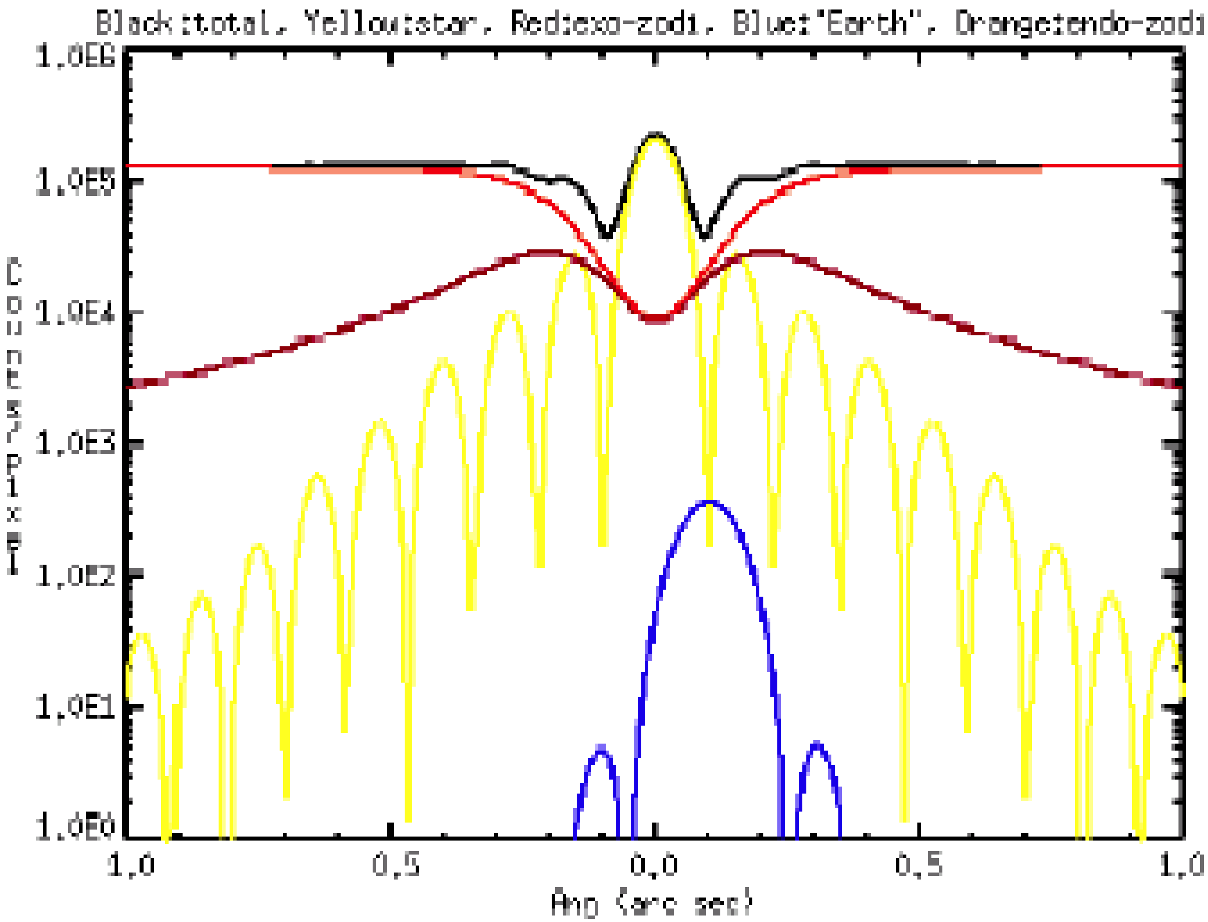
Images


Total
2.5E5
2.0E5
1.5E5
1.0E5
5.0E4
Total-Star
1.4E5
1.2E5
1.0E5
8.0E4
6.0E4
4.0E4
2.0E4

Images (Cont'd)



Line Across System Through "Earth"



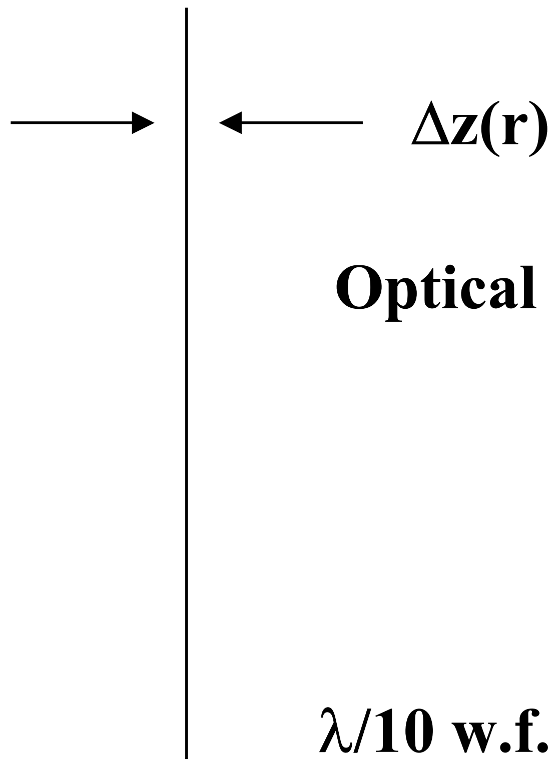
Fresnel Lens Tolerancing

TRW

- 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

Magnifying Glass Tolerances (Out-of-plane)

TRW



30 m Diameter primary
f=6000 m, λ=10 microns

Optical path error for displacement Δz(r):

$$\Delta l = (1 - \cos(\theta(r))\Delta z$$

$$\approx \frac{r^2}{2f^2}\Delta z < \frac{r_{max}^2}{2f^2}\Delta z$$

λ/10 w.f.e. tolerance requires Δz <32 cm

CONCLUDE:
Extremely loose tolerances for out of plane errors

Magnifying Glass Tolerances (In-plane)

TRW

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

$\Delta y(r)$

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

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

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

CONCLUDE:

Quite loose tolerances for in plane errors

TPF Terrestrial Planet Finder

Magnifying Glass Tolerances (Surface Thickness)

TRW

Optical path error for thickness error Δt:

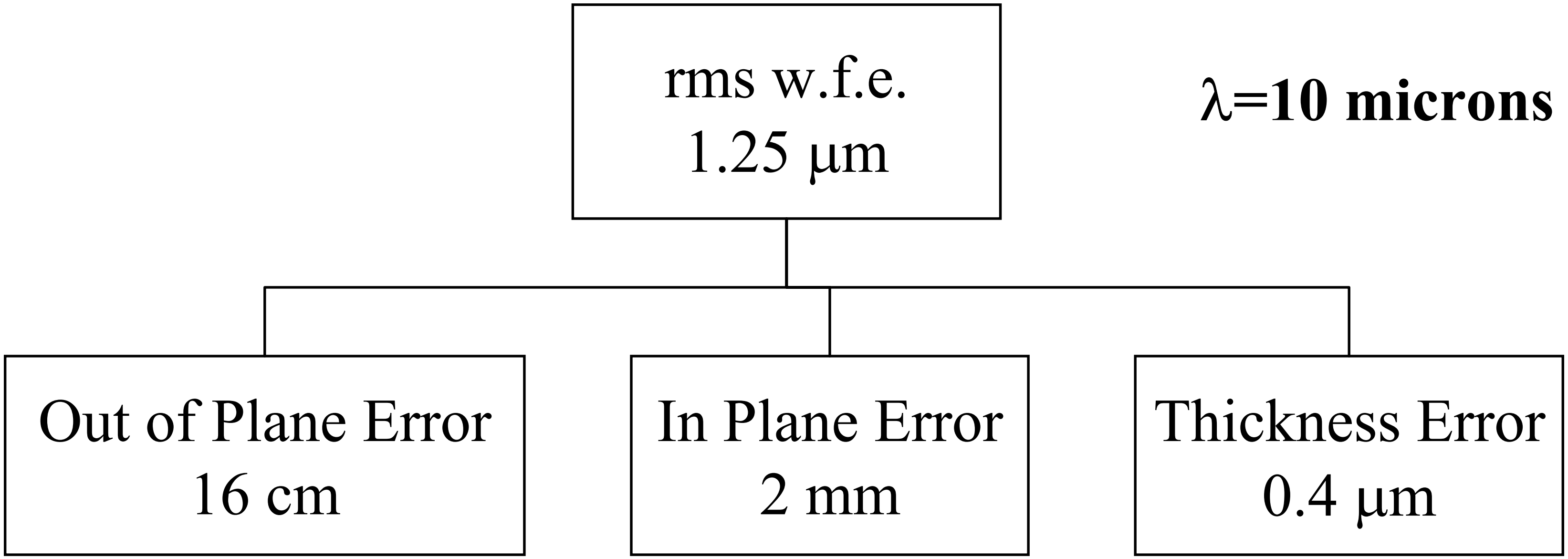
$$\Delta l = (n - 1)\Delta t$$

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

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

TRW

Magnifying Glass Error Budget*



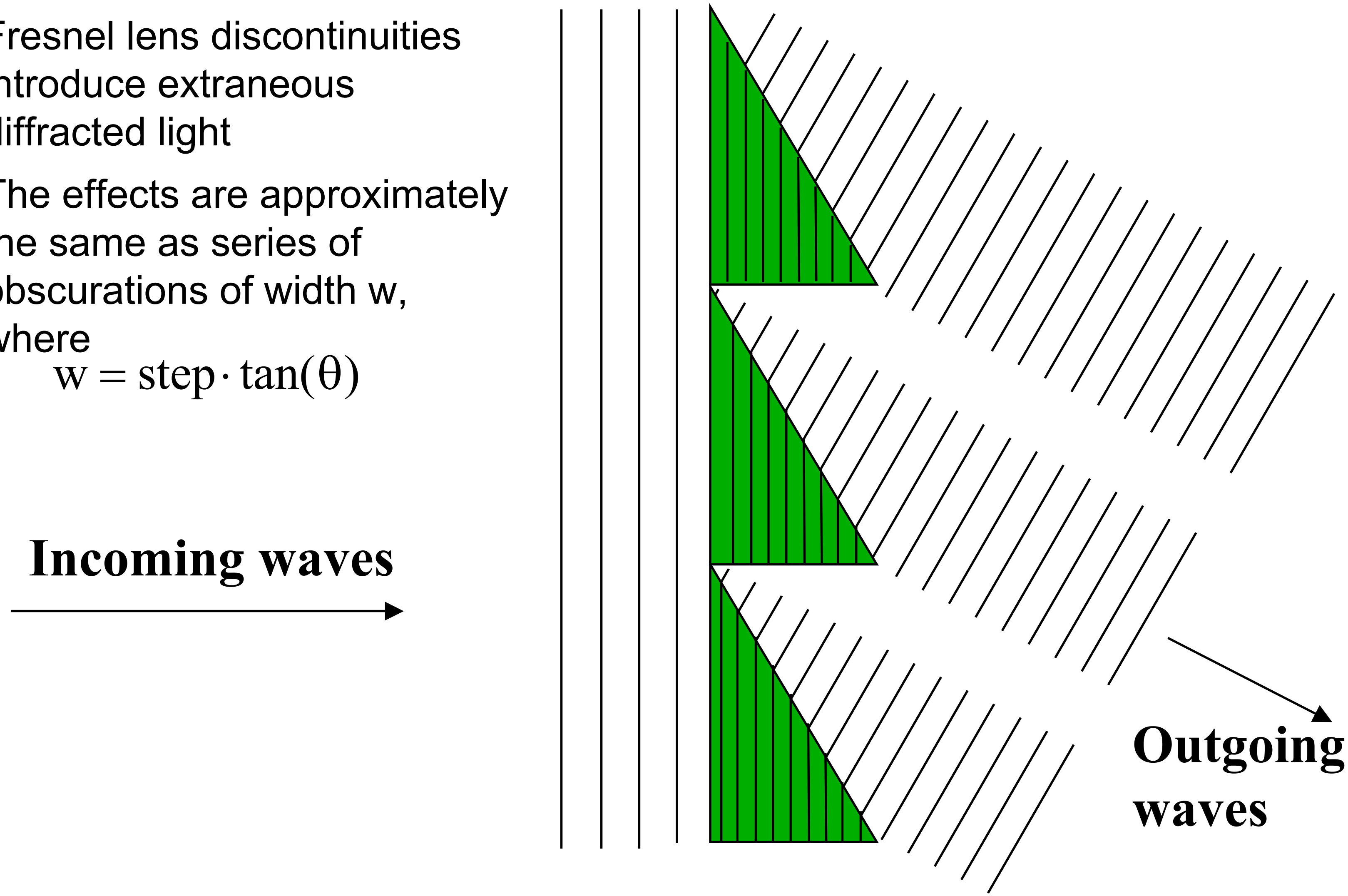
λ=10 microns

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

Fresnel Lens Scattering

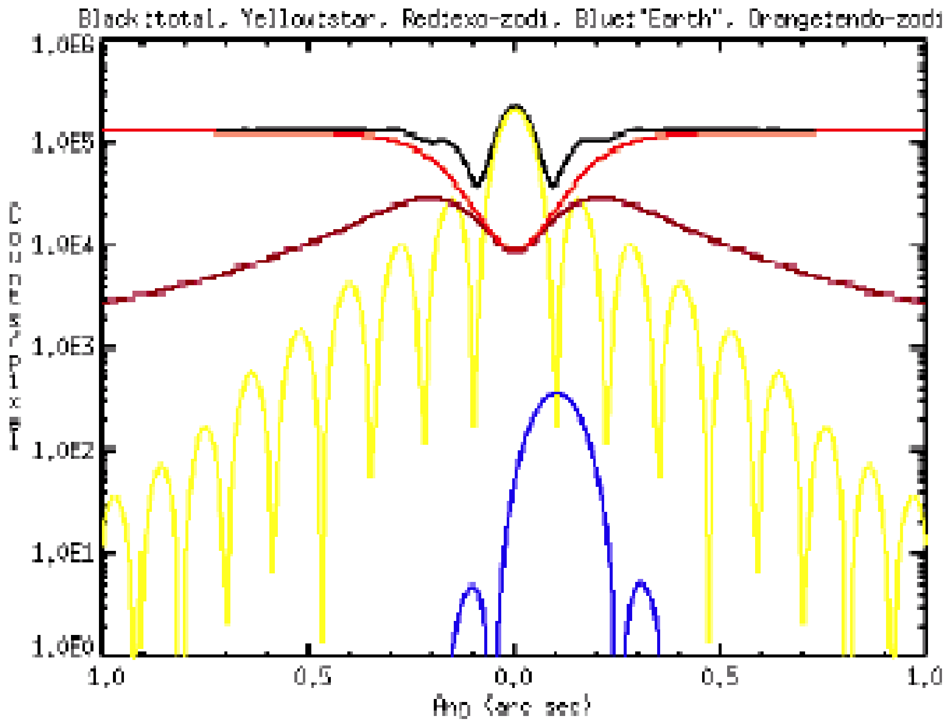
- Fresnel lens discontinuities introduce extraneous diffracted light
- The effects are approximately the same as series of obscurations of width w, where

$$w = step \cdot \tan(\theta)$$



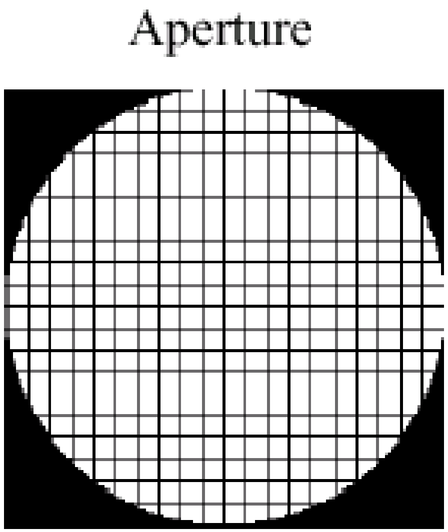
Fresnel Lens Scattering

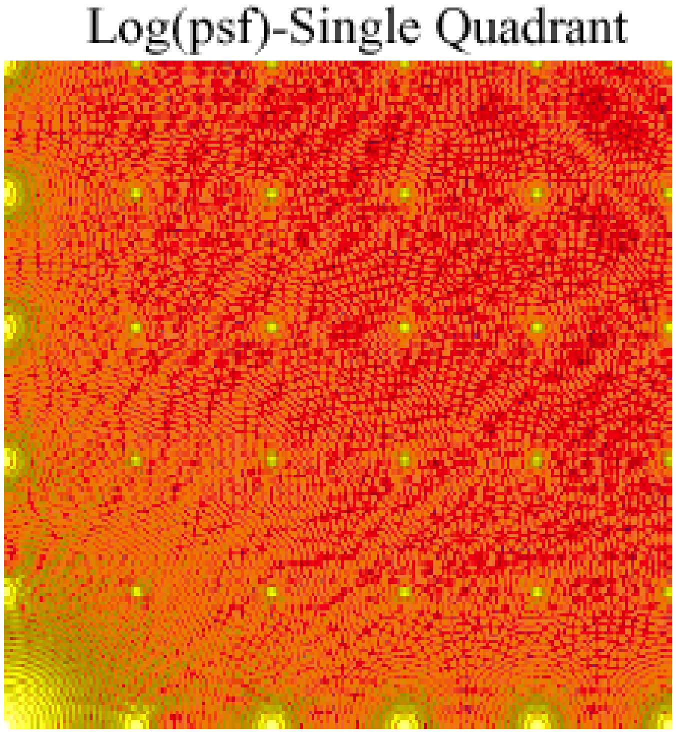
- For the current design, the “Magnifying Glass” produces almost no scattering, while the “Fresnel Corrector” scattering produces a contribution to the Strehl ratio of 0.9875 (Need to modify this for the new higher order design)
- The plot below displays the intensity of the psf from normal diffraction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



Fresnel Lens Primary Aperture

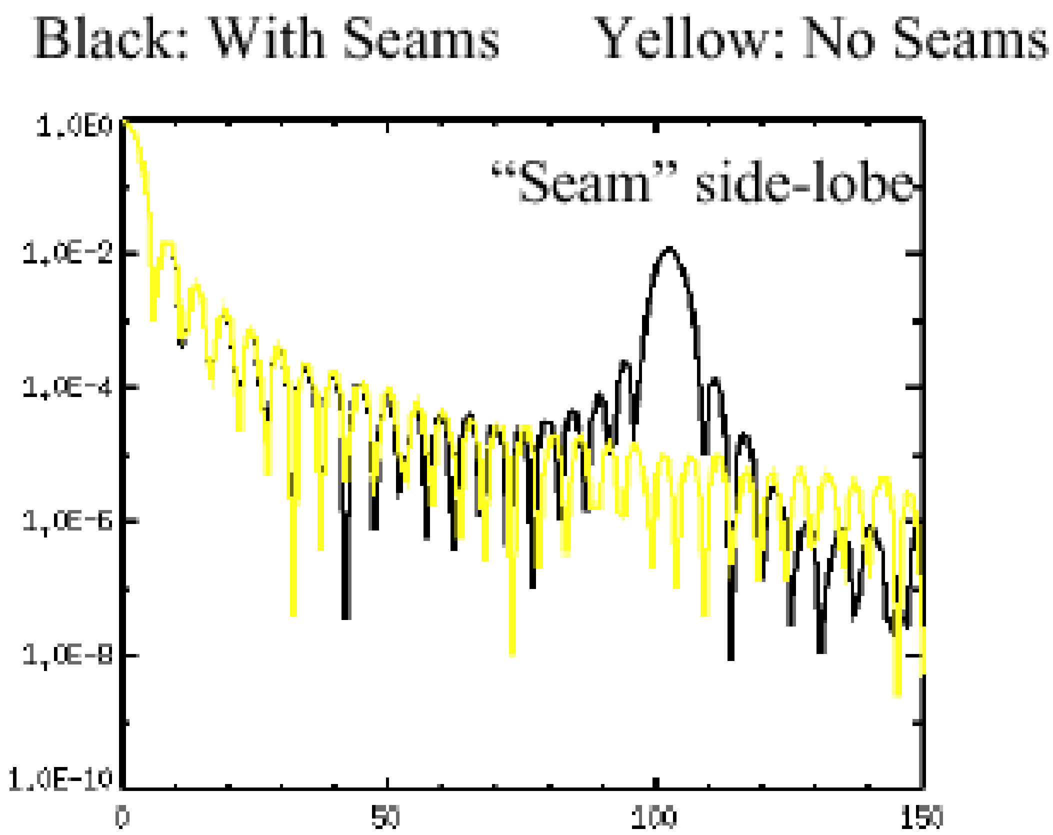
- Full aperture is constructed of identical segments
  - As an example, the effect of square segments on the diffraction limited psf is illustrated
  - Little impact on the "core" of the psf is seen





Segment Affect on PSF

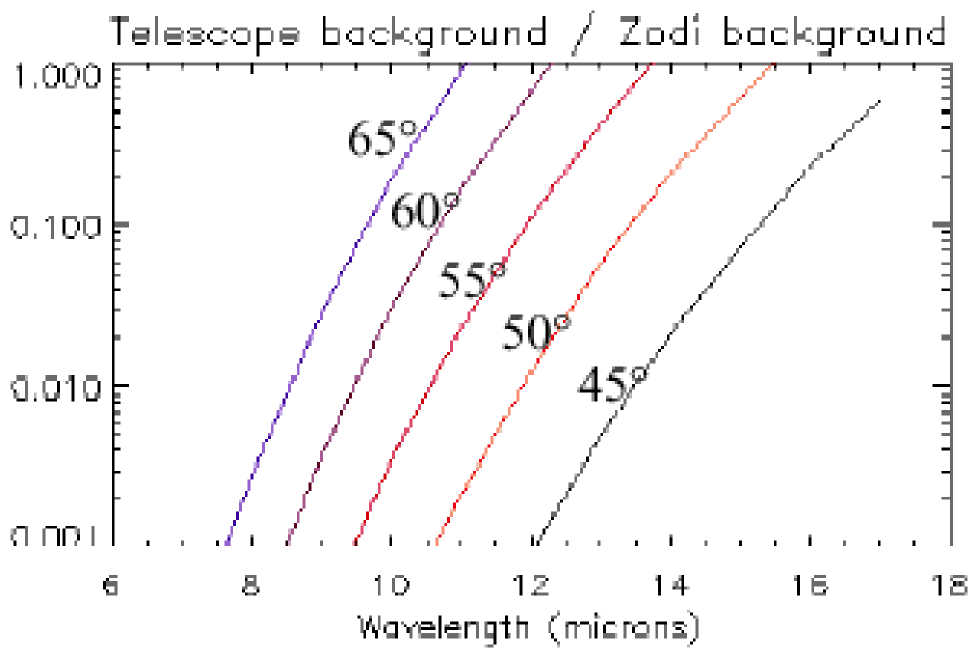
- Along the “x” direction, having the worst side-lobe structure, the change in psf near the core is displayed in the plot below



Temperature Requirements

TRW

- 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°K



Surface (and Bulk) Count

TRW

- 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

Transmission + Efficiency Budget*

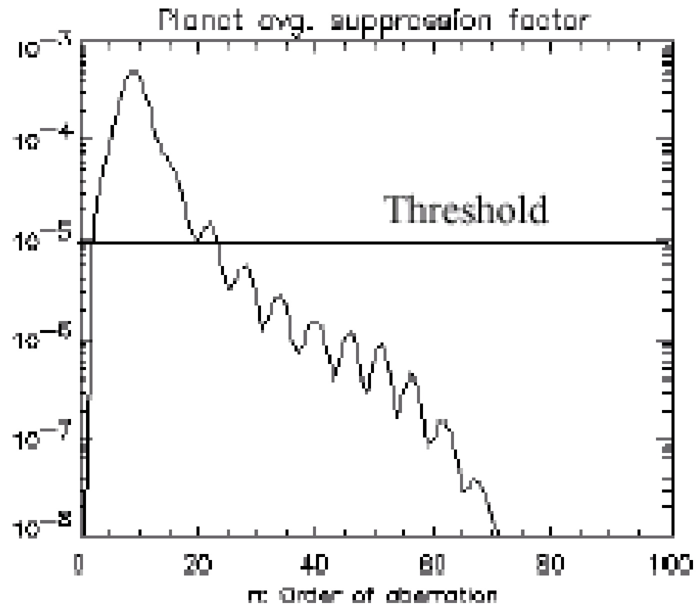
- Overall Efficiency 44%
  - Optics 76%
    - Reflectance 77%
      - 13 surfaces @ 98%
    - Obscurations 99%
  - Diffractive Efficiency 90%
  - Detector QE 65%

*Excluding position dependent transmission of Coronagraph

Impact of Aberrations

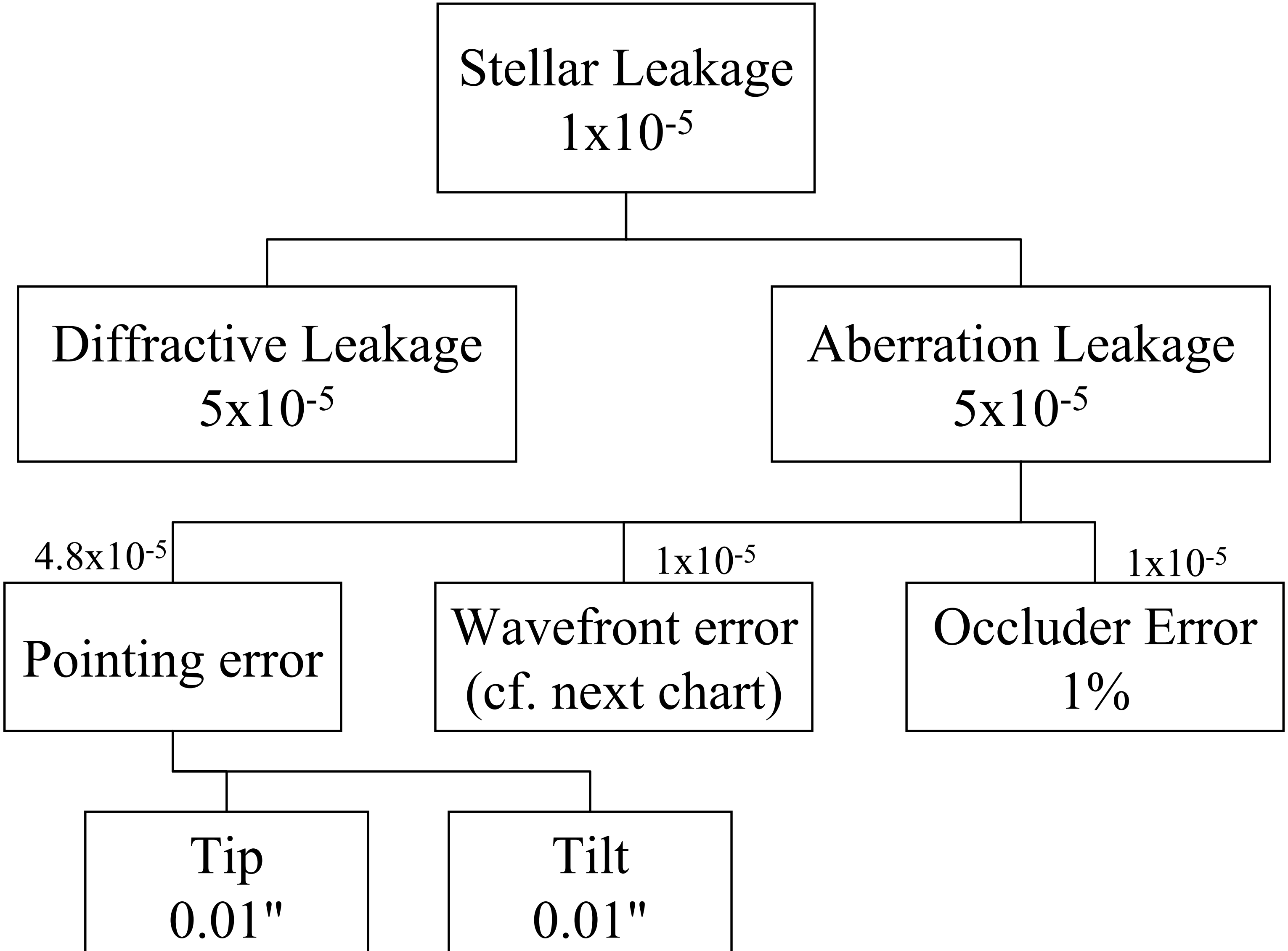
TRW

- 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 coronographic rejection performance



TRW

Coronagraph Error Budget



State-of-the-Art for Fresnel Optics

TRW

- 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 ~ $(\text{diameter})^{1.5}$
  - so 30 m cost est. 50 M$

Conventional Optics vs. State of the Art

TRW

- 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 ~ 1 wave or more)

General Astrophysics

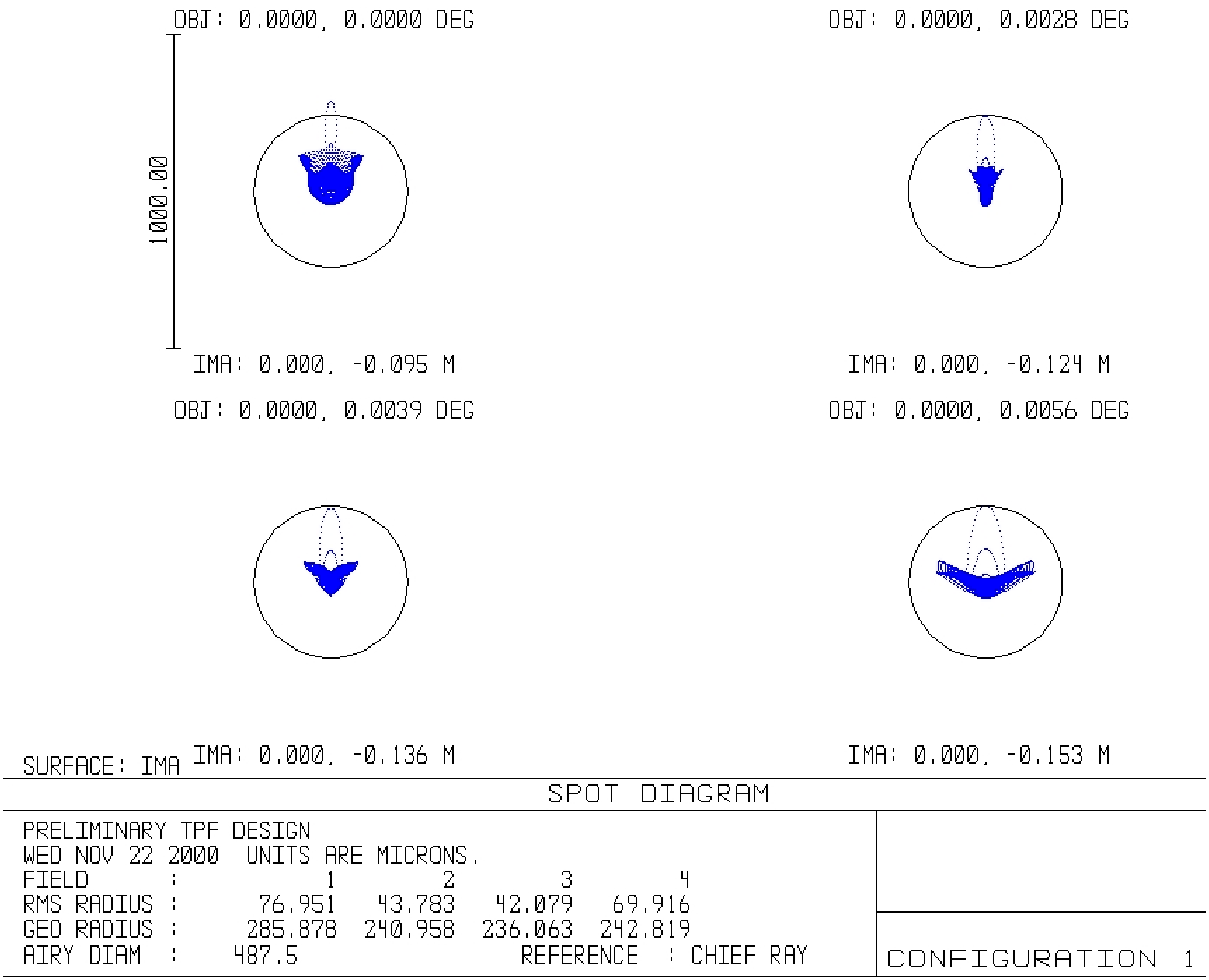
TRW

- 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:

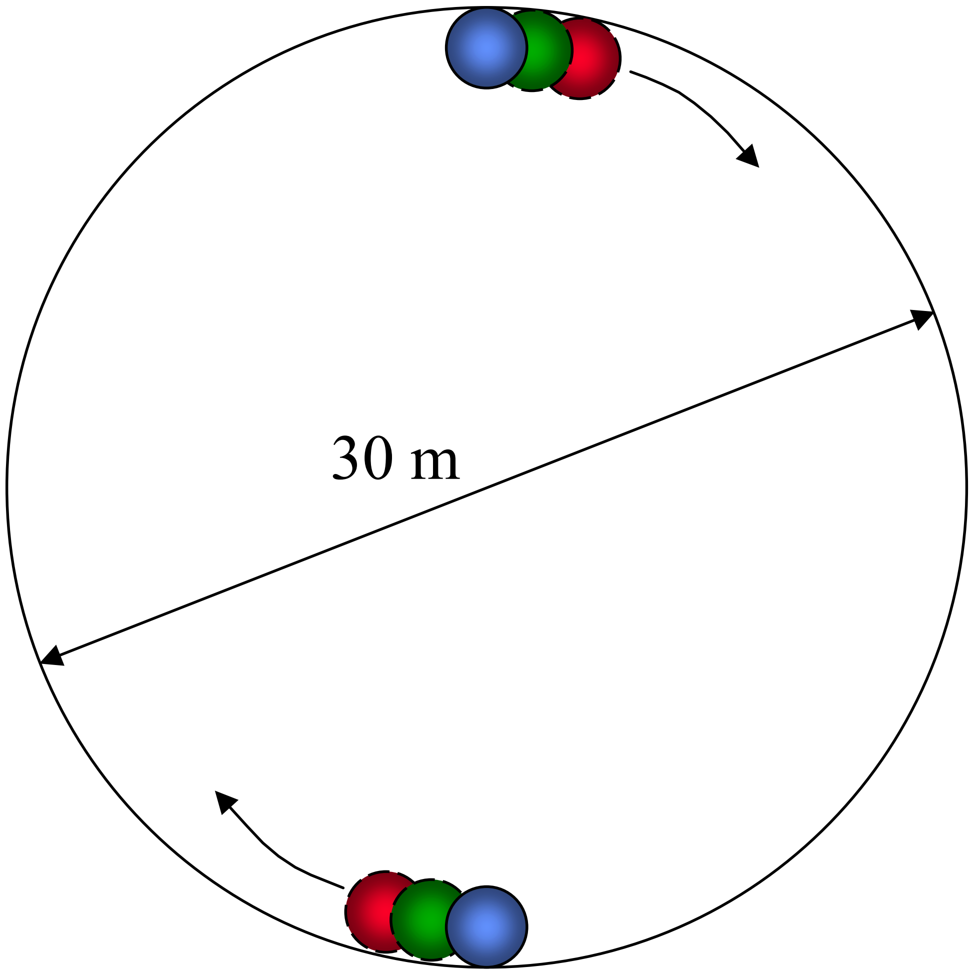
Fresnel Lens	NASA requirement
0.006 μJy	0.3 μJy

Spot Diagram for Imaging



Imaging Speed: Interferometer vs. Filled Aperture

TRW



- 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:

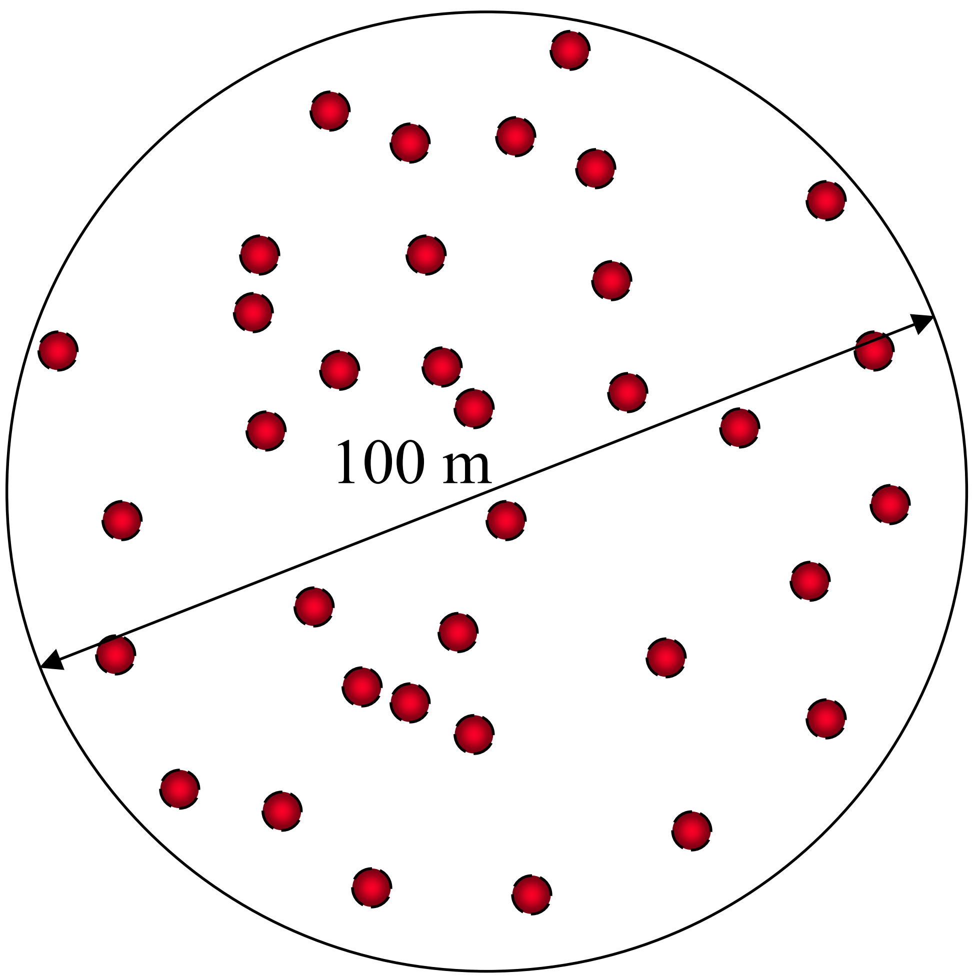
$$(\text{Relative area})^2$$

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

Imaging Speed: Sparse vs. Filled Aperture

TPF Terrestrial Planet Finder

TRW



- 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 x