Disruptive Technology: How to eliminate (almost) Diffraction "noise" in Telescopes[a]

Physical optics issues in terrestrial exoplanet coronagraphy

interim report

James B. Breckinridge[1], James E Harvey[2], Tony Hull[3]

[1]Caltech and College of Optical Sciences, U of A

[2]Photon Engineering, Tucson AZ

[3]University of New Mexico, Albuquerque, NM

[a].. Breckinridge was supported by NASA Contract:

NNX17AB29G awarded by SMD TDEM15 exoplanet program office to the U of A and

NNX17AD08G awarded by STMD Early Stage Innovation program to S. Pellegrino @ Caltech

Outline

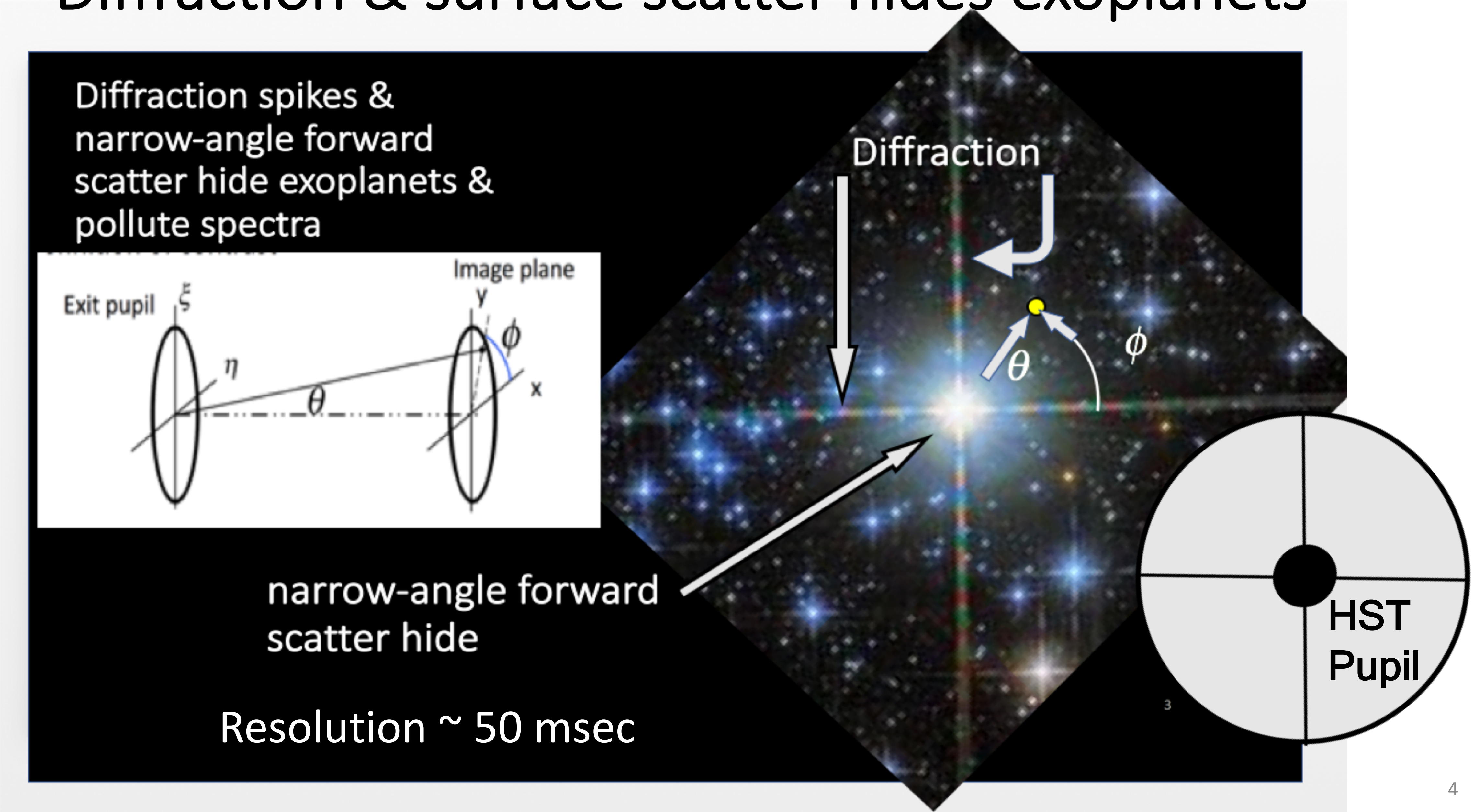
- Where are the terrestrial exoplanets (earth-twin) we want to image?
- Diffraction from Cassegrain 2nd ary supports will mask exoplanets
- Method to smooth out diffraction to reveal exoplanets
  - Re-discover 1934 amateur telescope making (ATM) technology
  - Minimizes unwanted diffracted light at the image plane
- Terrestrial exoplanets need >4-m apertures => require segmented telescopes
- Show that hexagonal segments hide exoplanets
- Segment topologies for large apertures to reveal terrestrial exoplanets
- Implications for: spectroscopy, image processing, & observatory operations.
- Fabrication of curved (pinwheel) segments – Tony Hull

Where are the terrestrial exoplanets?

- **Exoplanet candidates as a function of distance**
- **Range in angles is 10 to 50 masec.**
- Range in aperture size is ~2 to 30 meters

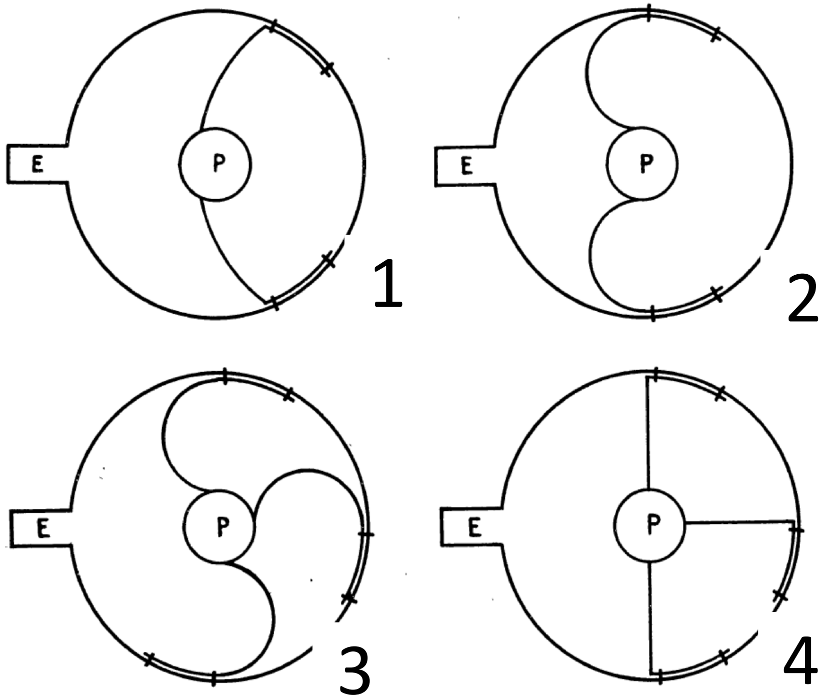
Distance Parsecs PC	Angle between star & earth twin in masec	Aperture (m) Diffraction limited at 500nm	Aperture (m) third Airy diffraction ring
10	100.0	1.2	3.7
20	50.0	2.5	7.5
30	33.3	3.7	11.1
40	25.0	5.0	15.0
50	20.0	6.2	18.6
60	16.7	7.4	22.2
70	14.3	8.7	26.1
80	12.5	9.9	29.7

Diffraction & surface scatter hides exoplanets –



C. H. Werenskiold, (1941) *Improved telescope spider design*, J. R. Astron. Soc. Can. 35, 268–273 1941.
75 years ago!

Looking into his telescope from object space; he experimented with 4 different 2nd ary support structures and concluded:



For visual observations of Jupiter's belts, number 4 gives the *lowest quality image.*

That *curving the support structure* "appears to remove the diffraction spikes from visual images to increase the contrast of Jupiter's belts"

Richter, J. L. (1984) Spider diffraction: a comparison of curved and straight legs, AO, 23 1907-1913

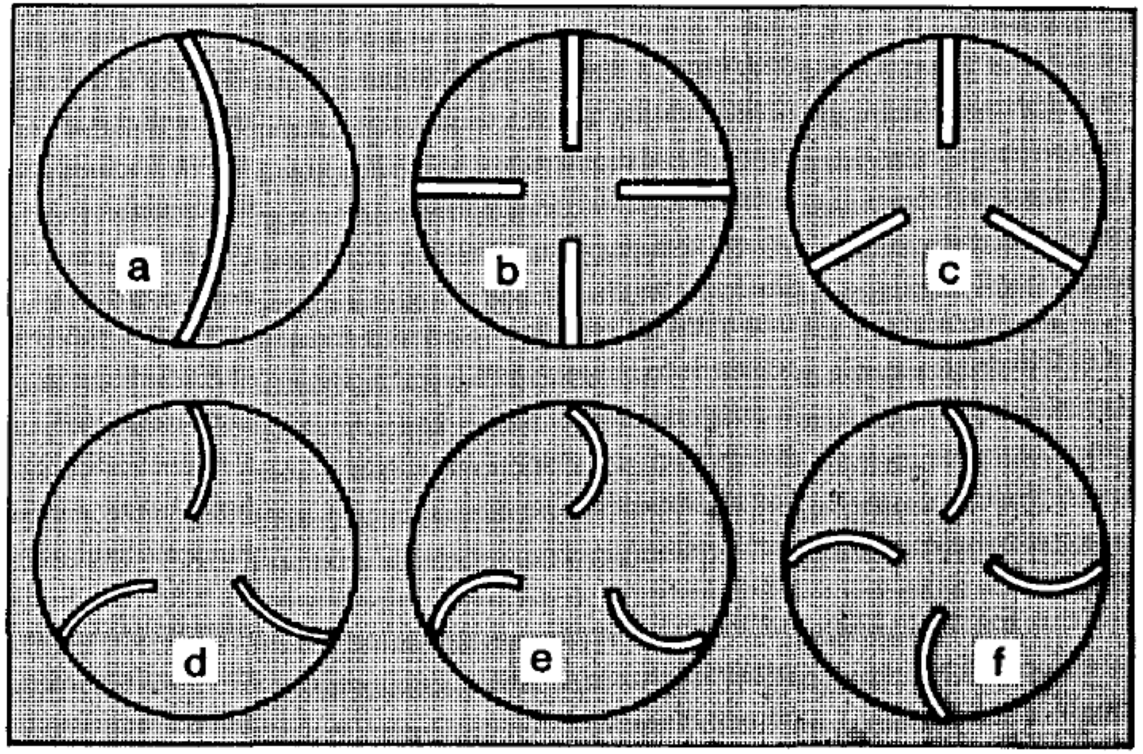


Fig. 15. Diffraction masks. The six masks were used in front of the lens to form the images shown in Fig. 14. The largest extent of any actual mask is 50 mm.

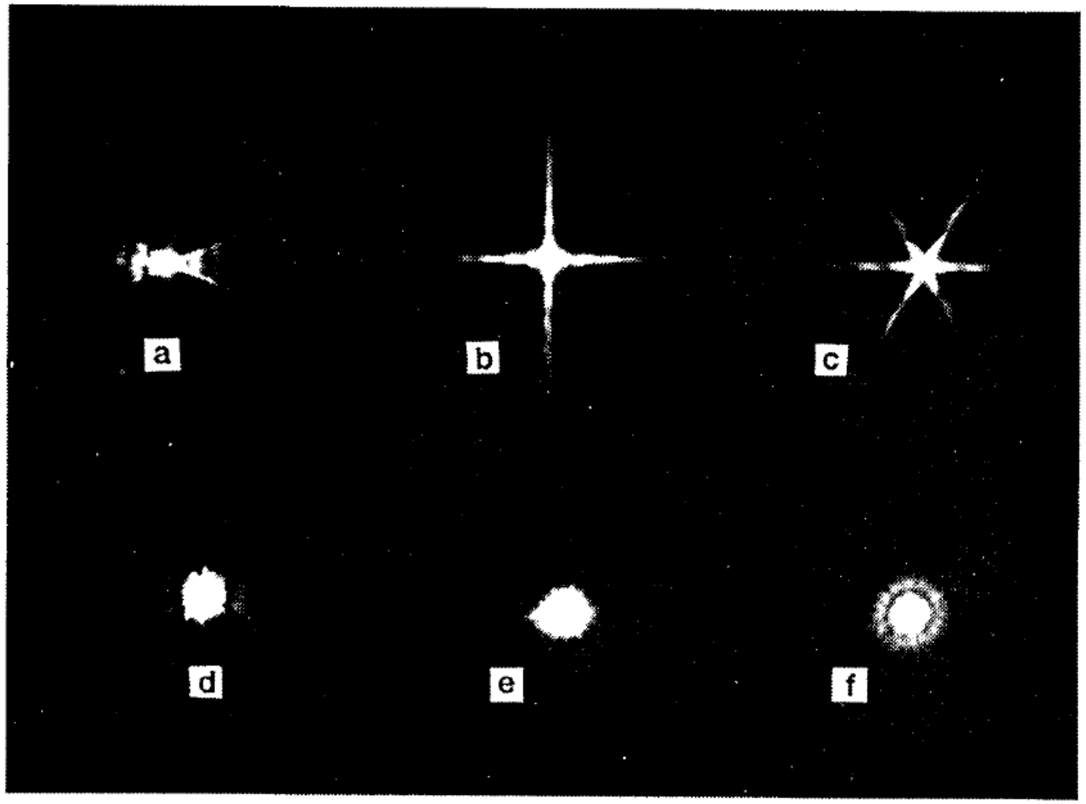
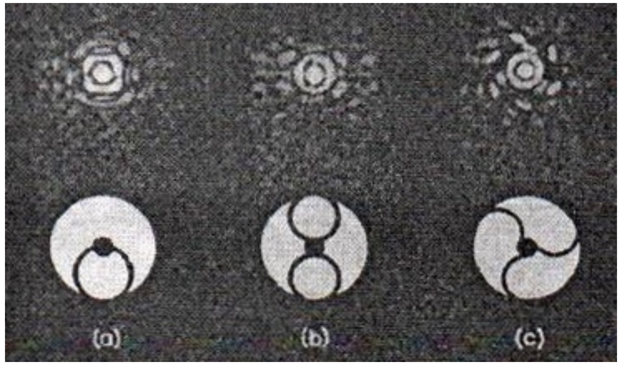


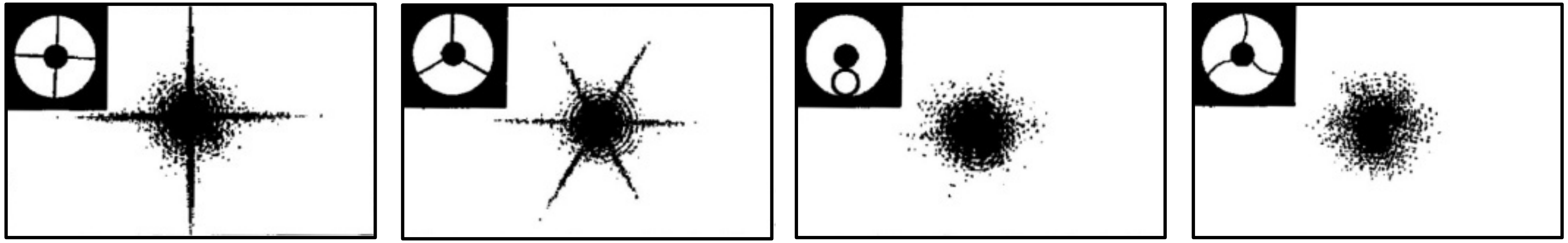
Fig. 14. Diffraction photographs. The six diffraction images were taken of a distant pinhole light source with the masks shown in Fig. 15 in front of the 305-mm EFL lens. The separation between the unenlarged image centers of (b) and (c) is 3.6 mm.

More papers

E. Everhart and J.Kantorski (1959) Diffraction effects produced by obscurations in reflecting telescopes of modest size, Astron. J. **64**, 455-463



J. E. Harvey and C. Ftaclas (1995) Diffraction Effects of Telescope Secondary Mirror Spiders upon Various Image Quality Criteria Appl. Opt. **34**, 6337-6349

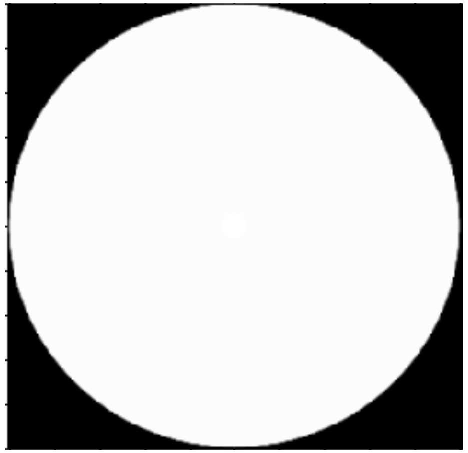


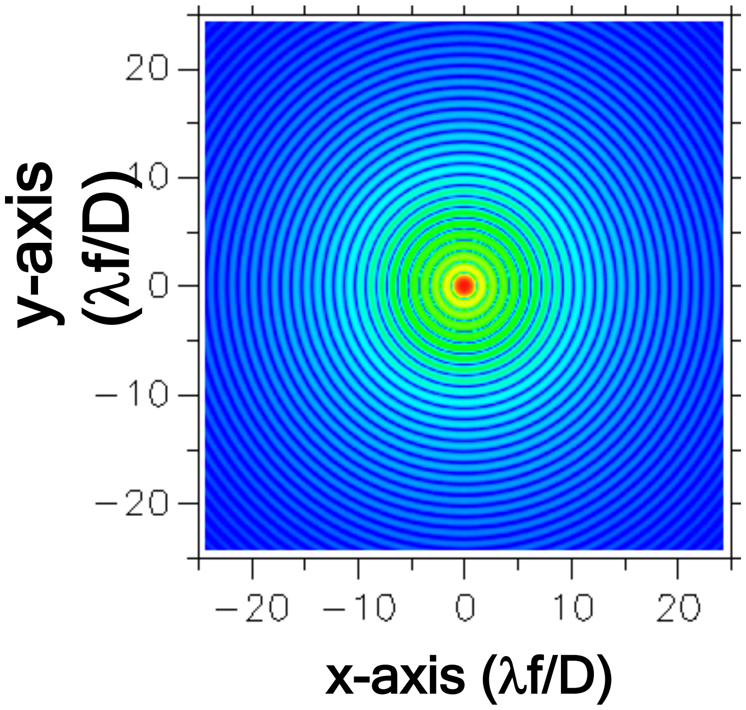
Calculation of Diffraction Effects @ 500 nm

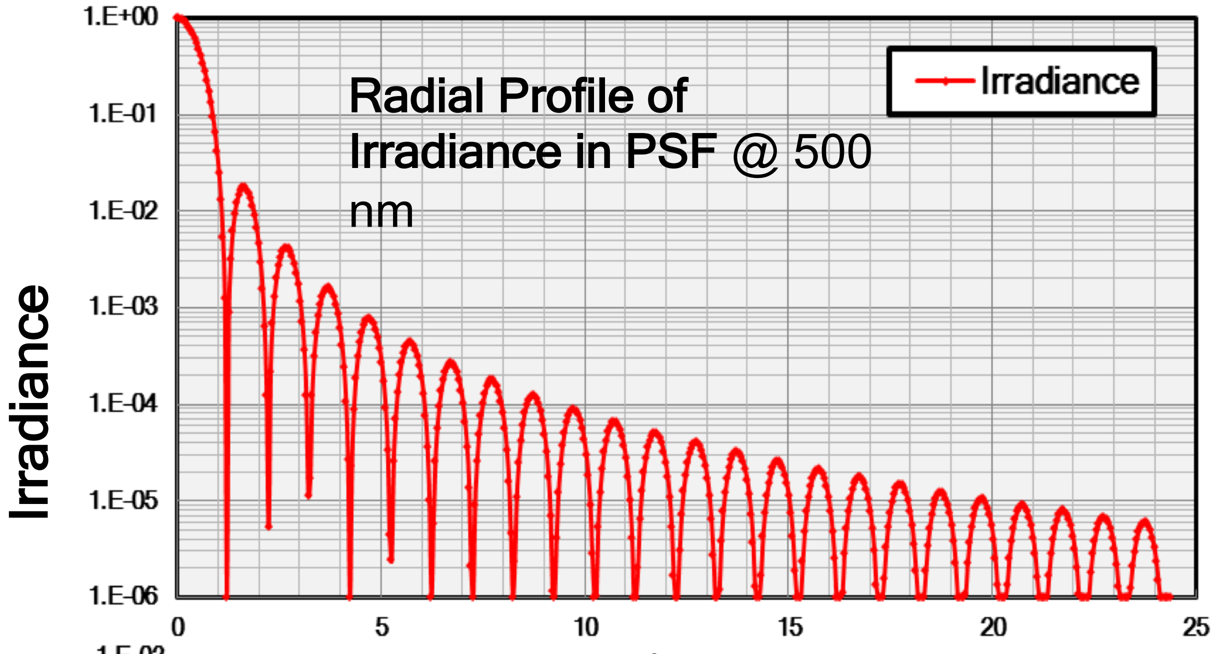
Circular Pupil: No Obscuration, No Struts

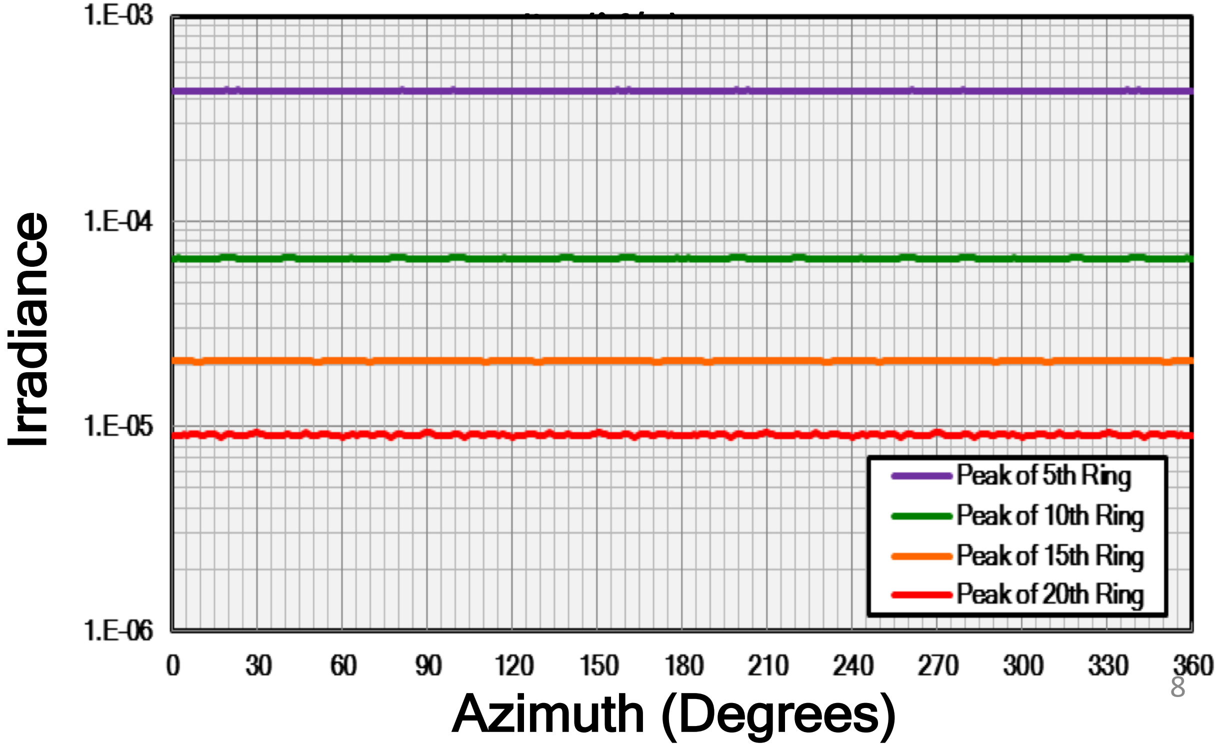
D = 10m

f = 20D





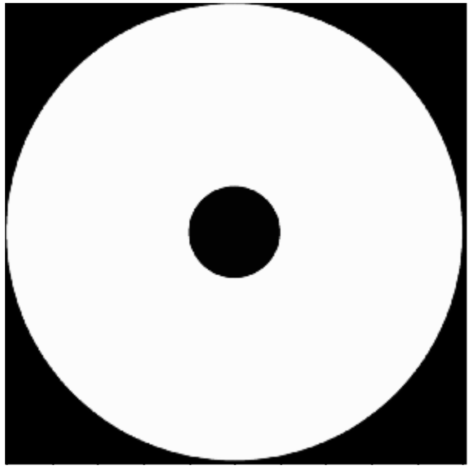


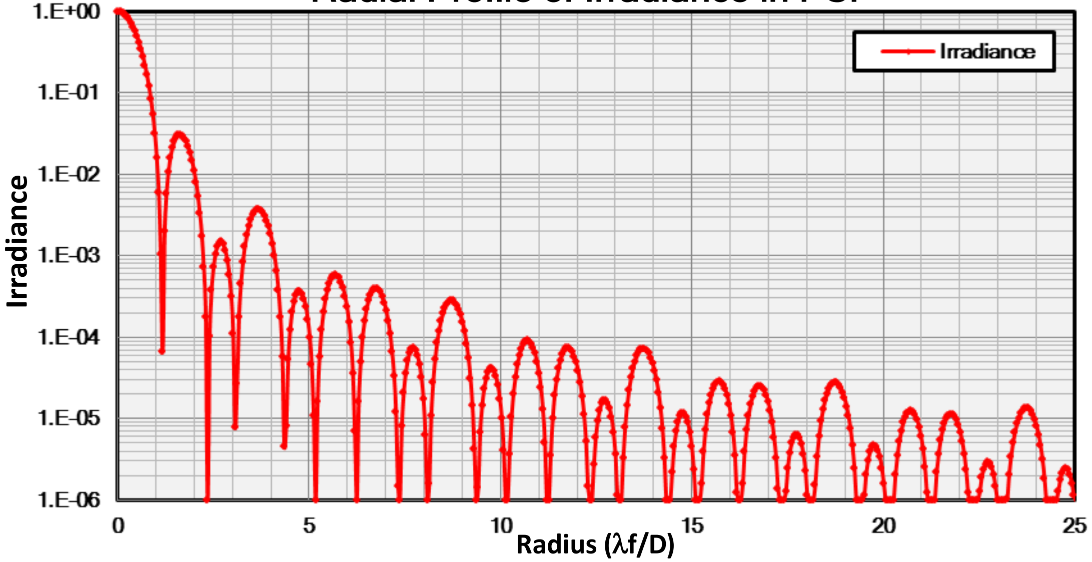


Calculation of Diffraction Effects
(Annular Pupil: ε = 0.20, No Struts)

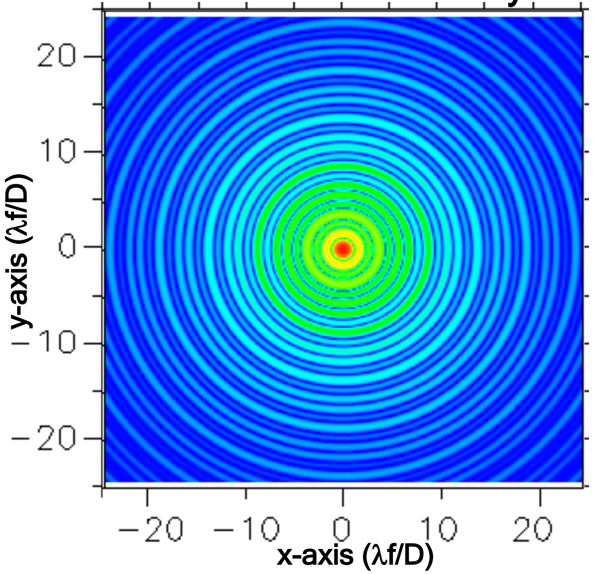
Annular Pupil: No Struts.

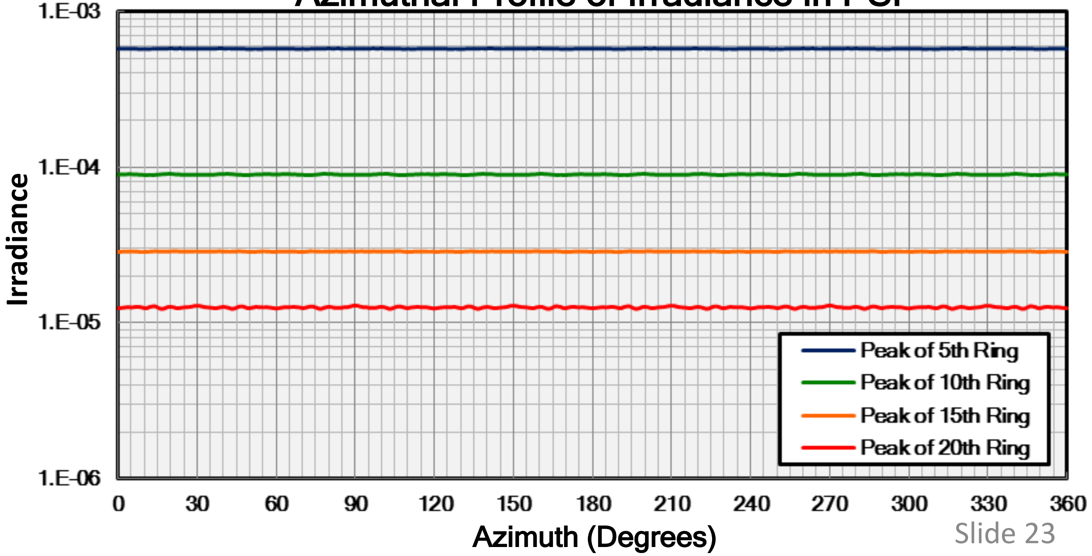
D = 10m
f = 20D
ε = 0.2





Color-coded PSF calculated by FRED.

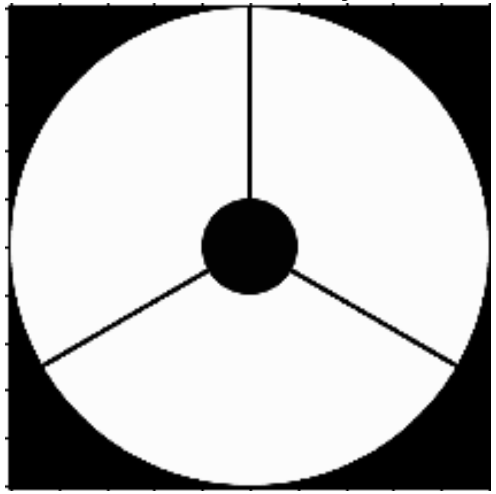




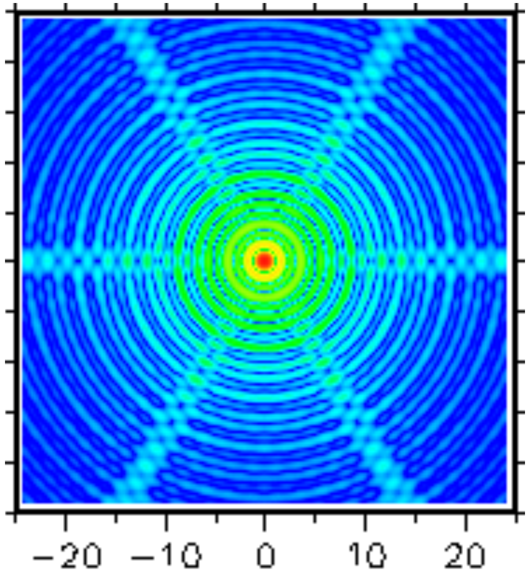
Calculation of Diffraction Effects
(Three Straight Secondary Mirror Struts)

Pupil with three secondary mirror struts.

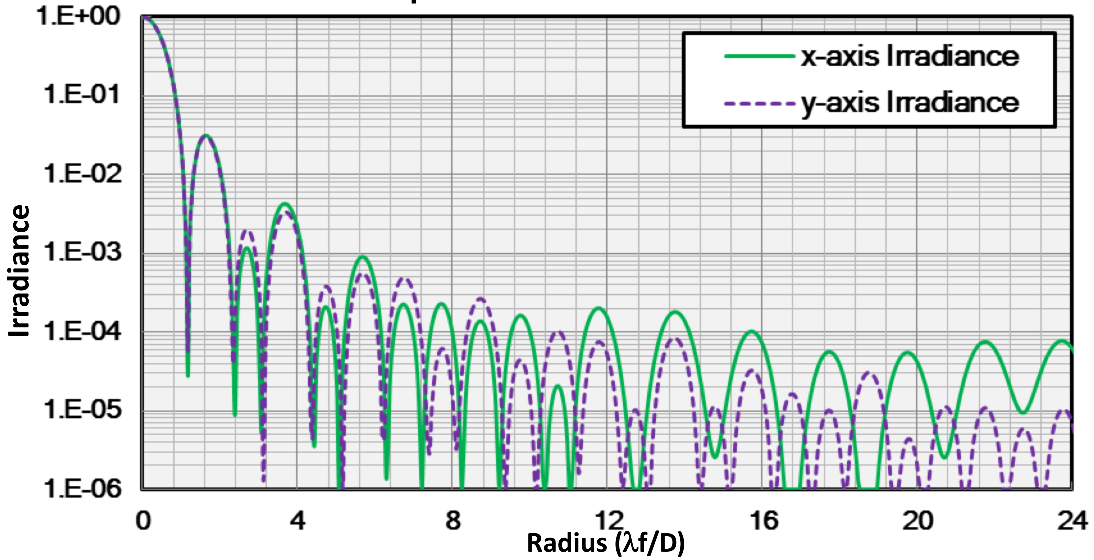
D = 10 m
f = 20 D
ε = 0.20
w = 0.01



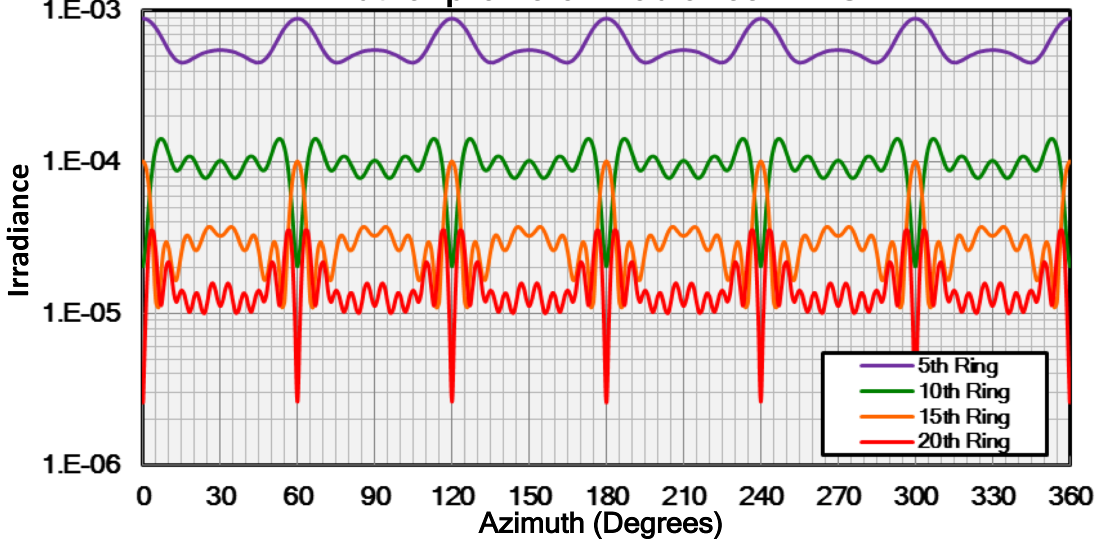
Color-coded PSF calculated by FRED.



Radial profile of Irradiance in PSF

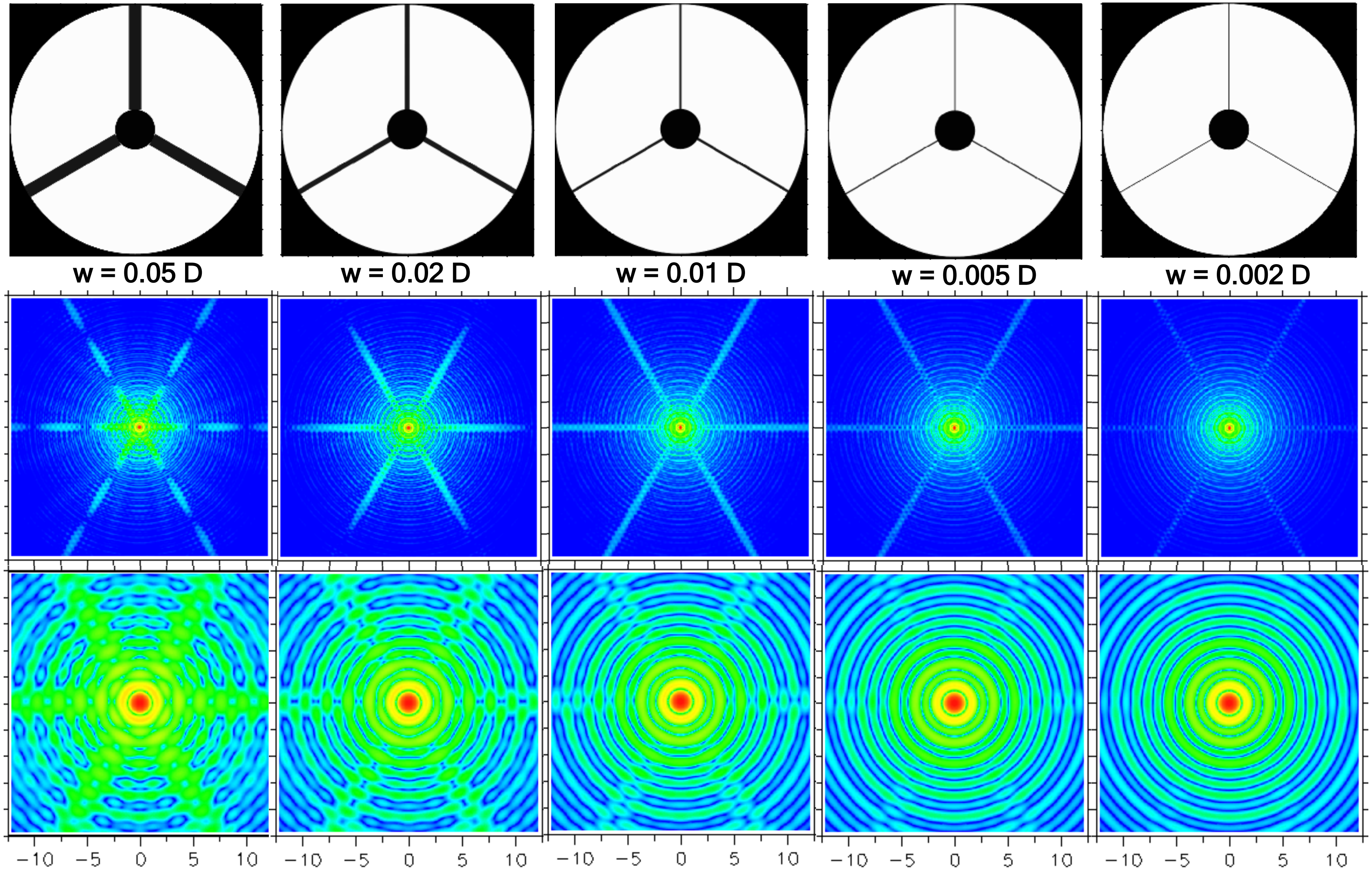


Azimuthal profile of irradiance in PSF



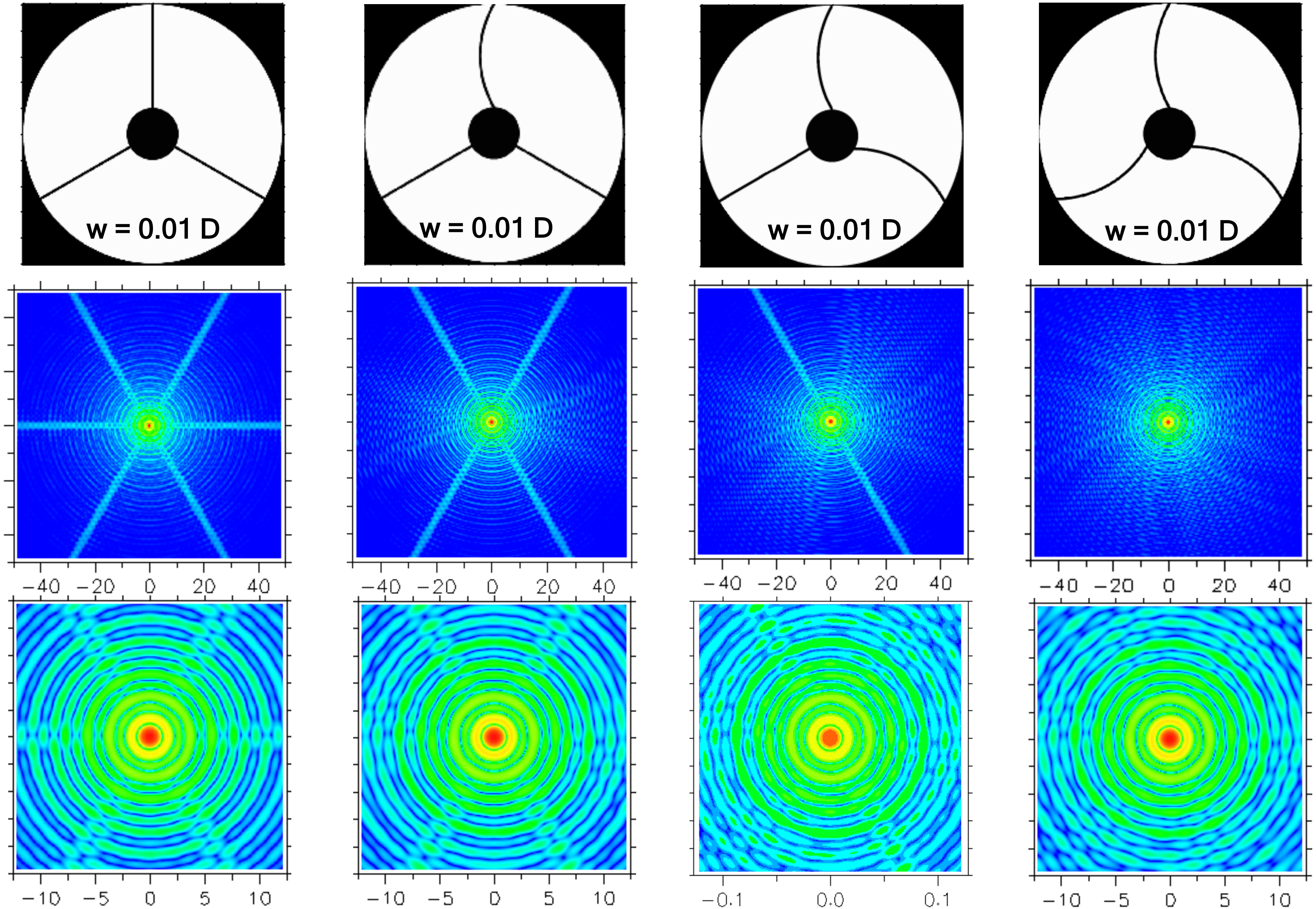
Sensitivity of Diffraction Effects to Strut Width

(Three Straight Secondary Mirror Struts)



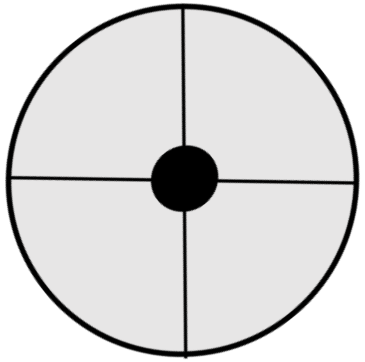
Substituting Curved Struts for Straight Struts

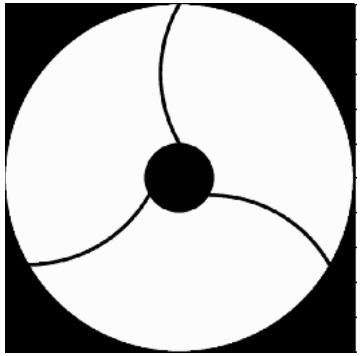
(Effects of Curved Secondary Mirror Struts)

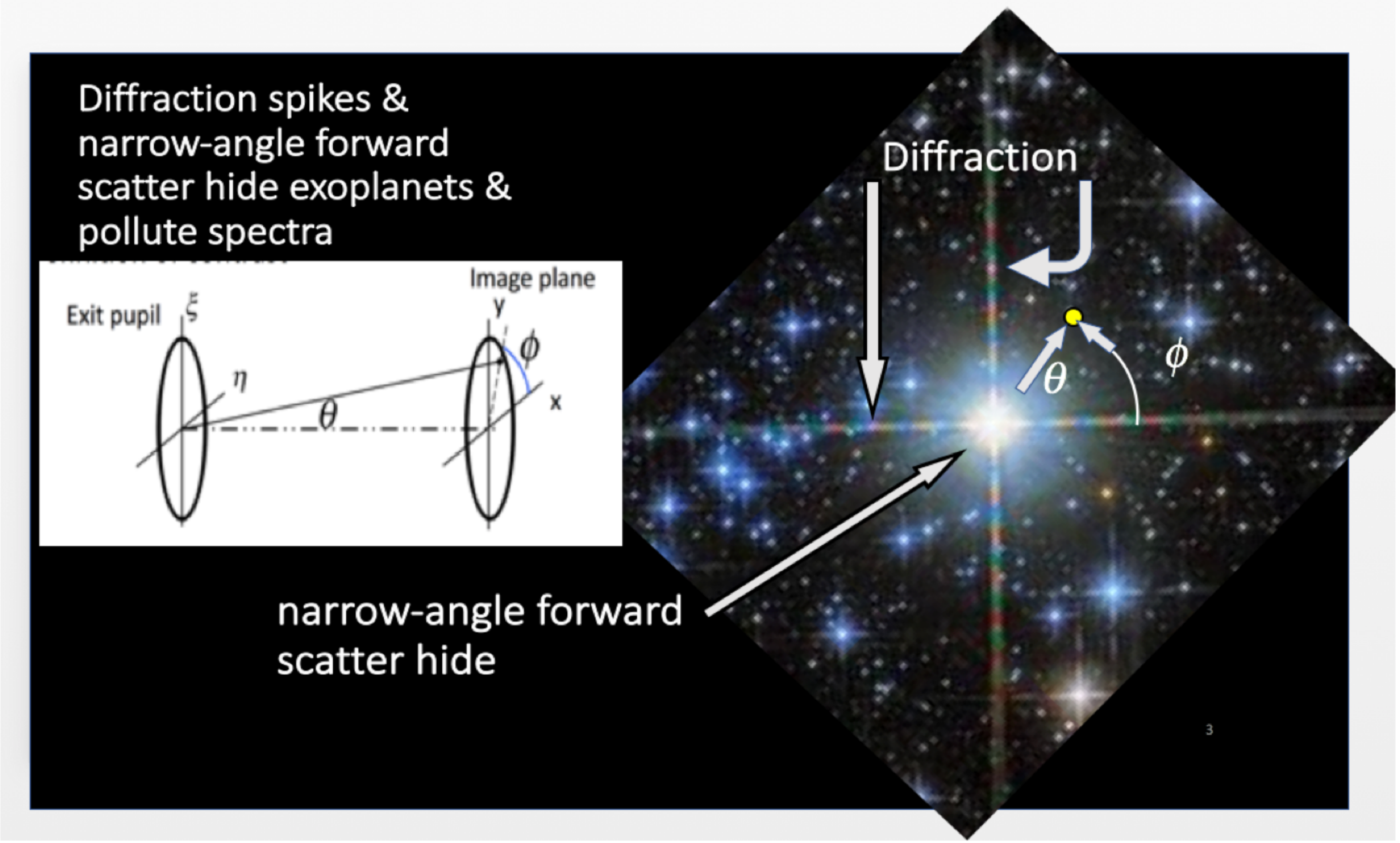


Conclusion on how to control diffraction from spiders

- **Problem:**







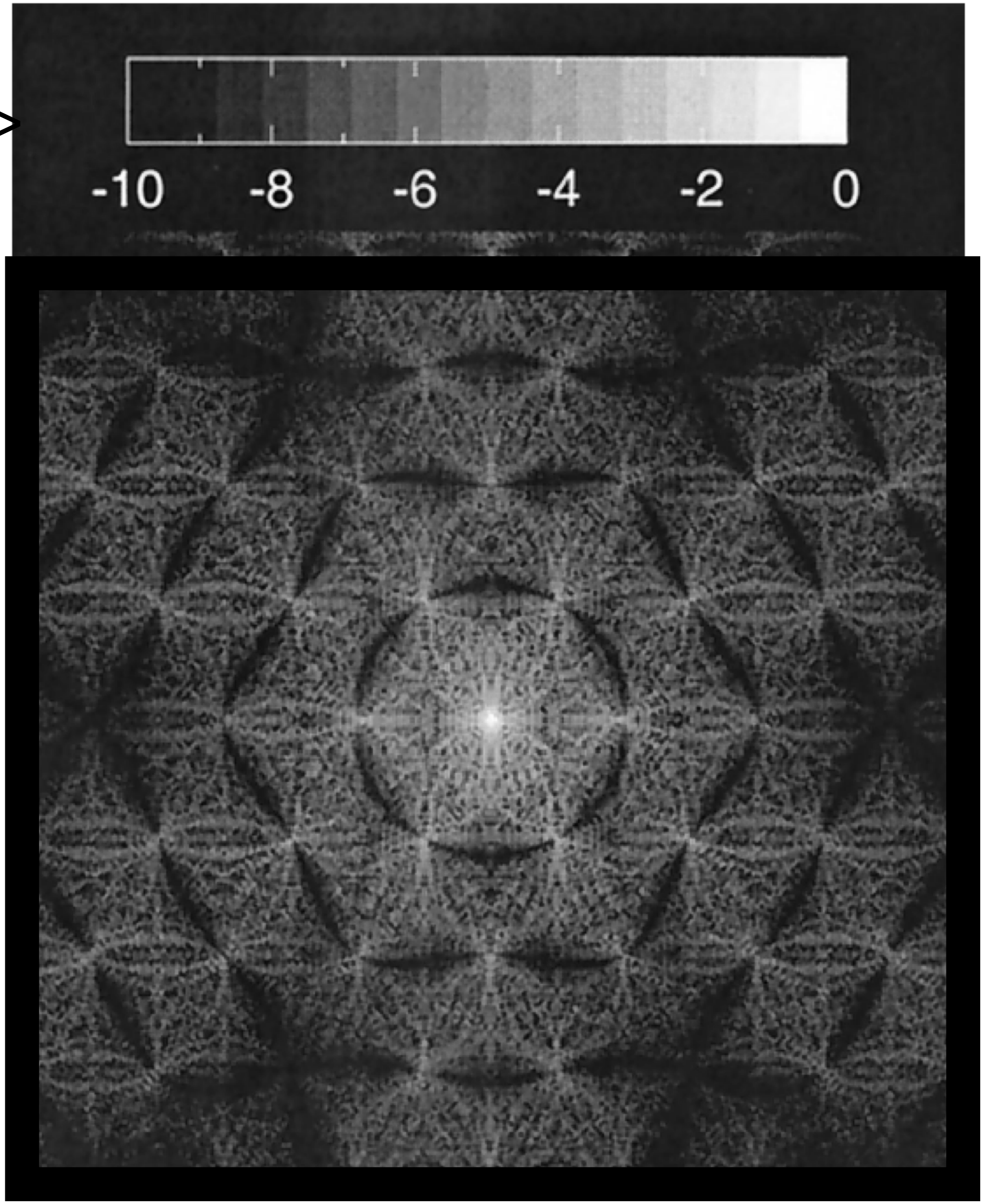
- **Solution:**
  - **Re-discover 1934 amateur telescope making (ATM) technology**

But: Terrestrial exoplanets need >4-m apertures => require segmented telescopes

- **Most large astronomical telescopes use hexagonal segments**
- **Remind ourselves, where within (θ,ϕ) are the terrestrial exoplanets we want to image?**
- **Hexagonal segment diffraction pattern hide exoplanets**
- **Present new segment topologies for large apertures to reveal terrestrial exoplanets**
- **Fabrication of curved (pinwheel) segments**
- **Implications for: spectroscopy, image processing, & observatory operations.**

Typical hexagonally segmented primary

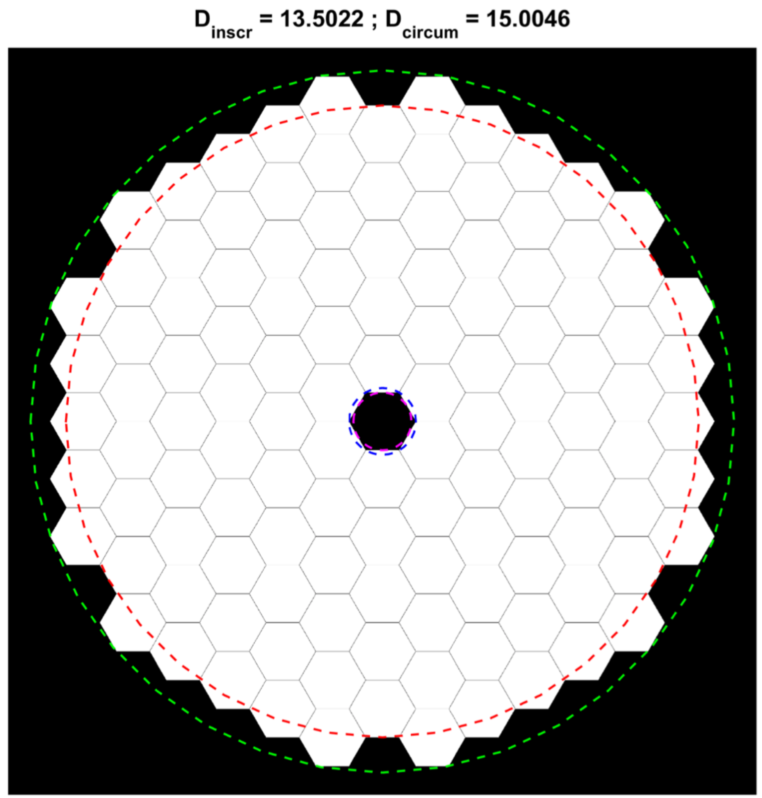
$$\frac{I(\theta,\phi)}{I(0)} \Rightarrow$$

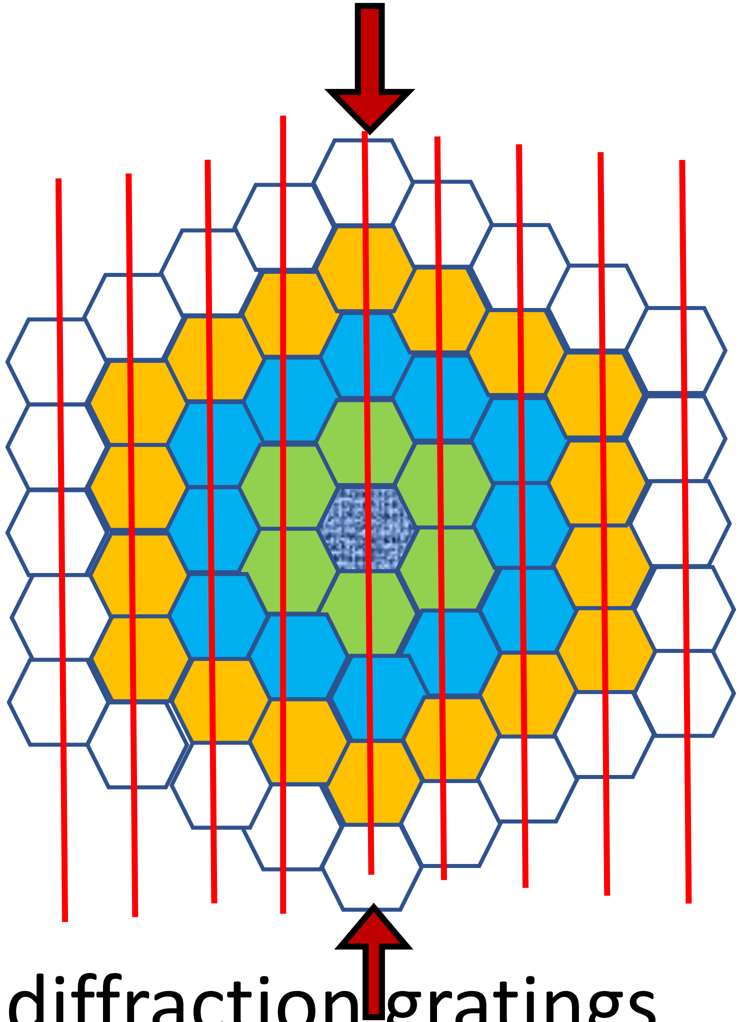


- M. Troy & G. Chanan (2003) Diffraction effects from giant segmented-mirrors **42** 3745-3753 Applied Optics
- **Image to the right occupies 1x1 arcsec**
- **Monochromatic wavelength = 1 micron**
- **ExoPlanets hide within the multiple-harmonic diffraction-induced structure**
- **10^{-7} exoplanet contrast difficult**

1-arc second

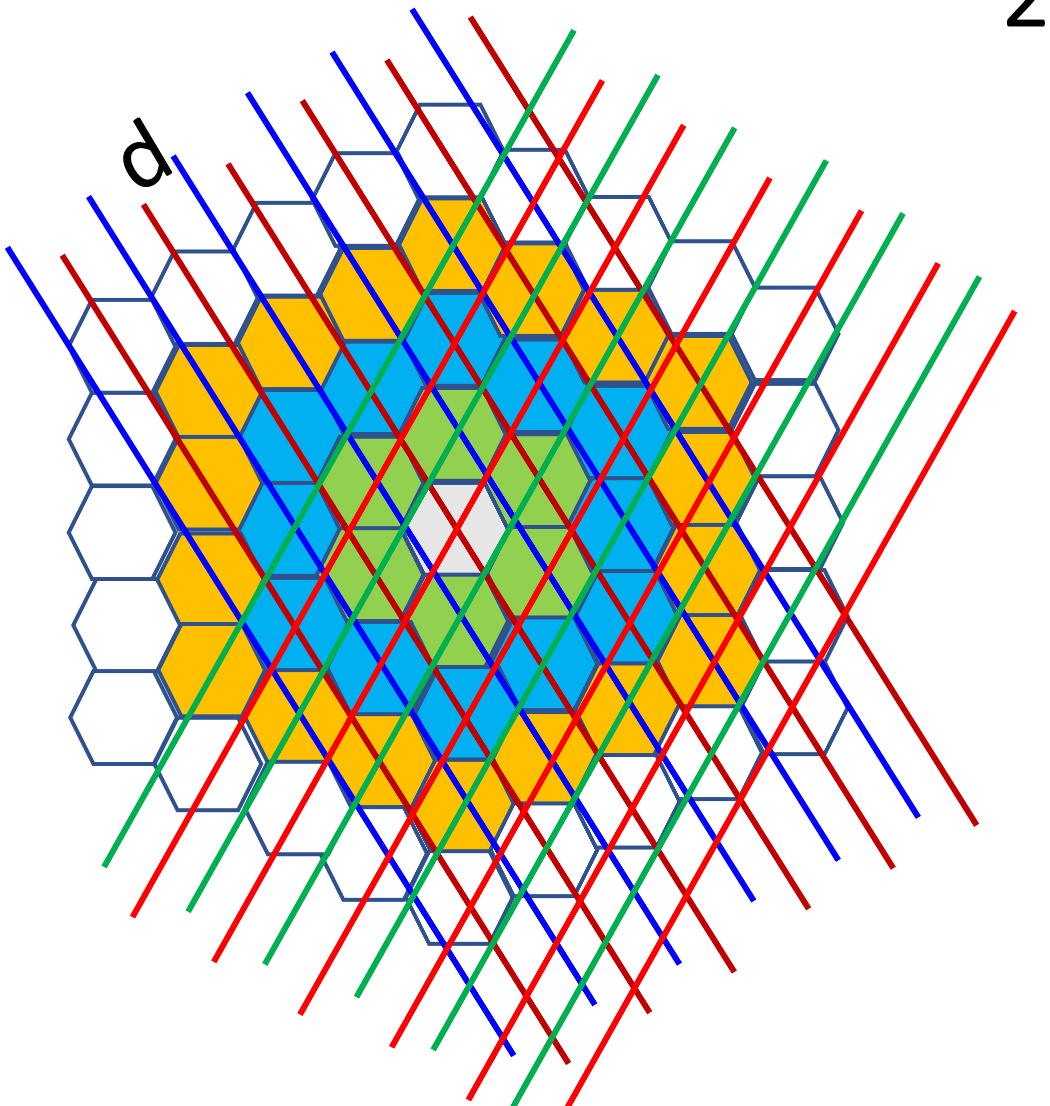
The LUVOIR pupil has several-rings of Hex's





The pupil is covered with 3 diffraction gratings, each clocked 60 degrees relative to the other

The LUVOIR pupil is covered by 3 diffraction gratings: calculate the diffraction angle.



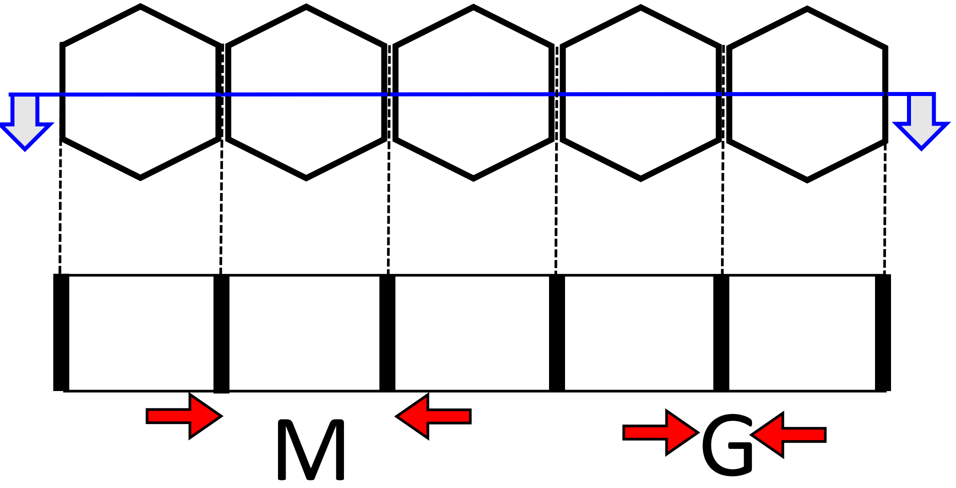
2d is the flat to flat segment size.

Diffraction causes a structured background across the image plane to

- Block exoplanets and
- May introduce polarization aberrations

To simplify: Estimate the diffraction pattern from a row of segments to Location & Brightness

Intensity put into the diffraction orders



Location of the diffraction orders

Let $\lambda =$ wavelength

$n =$ diffraction order

$d =$ ruling spacing, then

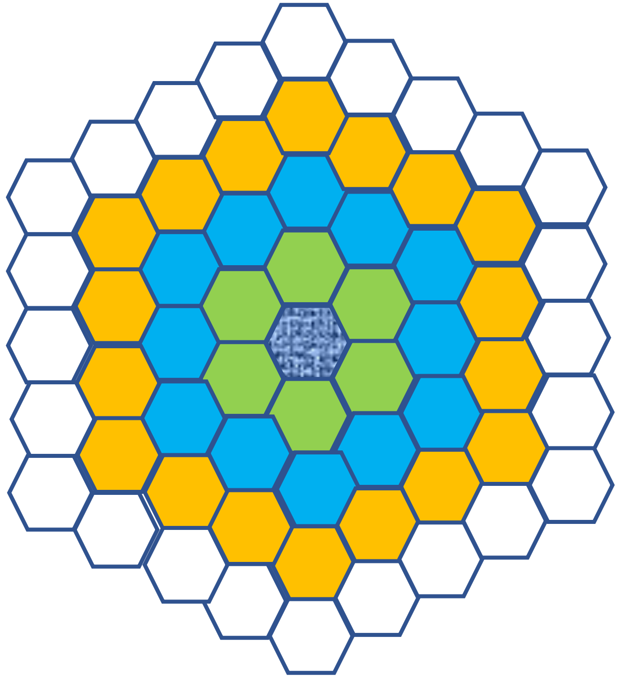
$$n\lambda = 2d\sin(\theta)$$

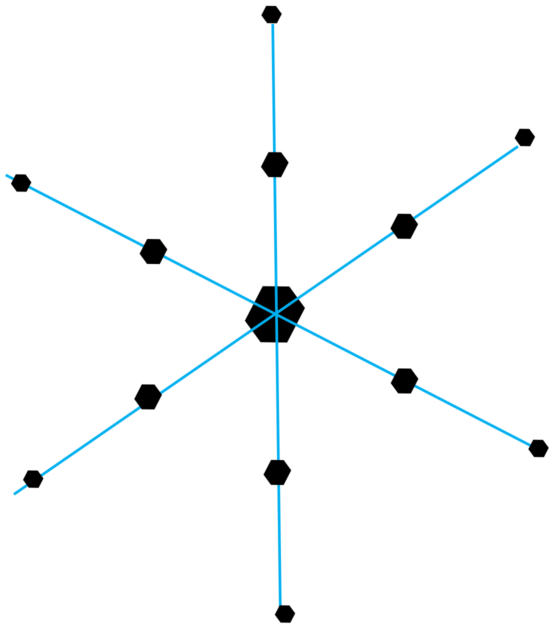
$$\sin(\theta) = \frac{n\lambda}{2d} = \frac{n\lambda}{a}$$

$$\frac{I(n=1)}{I(n=0)} \approx \frac{\text{Total reflecting area of the gaps}}{\text{Total reflecting area of the mirror segments}} = \frac{A_G}{A_M}$$

Compare this diffraction angle & intensity to those for exoplanets

PSF for a 500 nm monochromatic star: multiple images of the parent star appear because of diffraction





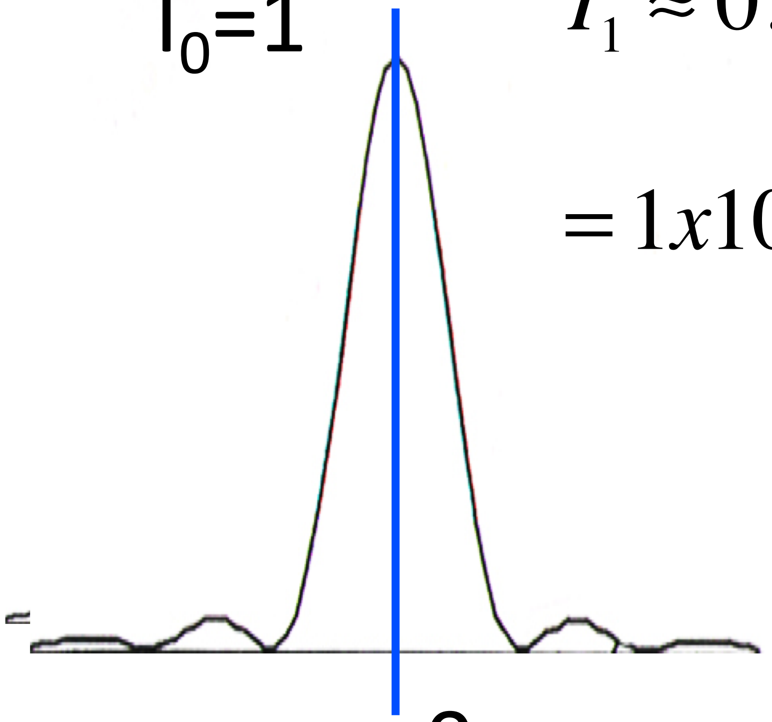
Distance between n=0 and n=1

1-m F to F seg. => 103 msec
2-m F to F seg. => 52 msec
3-m F to F seg. => 17 msec

***Simple coronagraph mask suppresses only the zero order of the diffraction grating, letting the other orders pass to add background*.**

How bright are the n=1 orders? Compared to exoplanet brightness: Rough order of Magnitude calculation

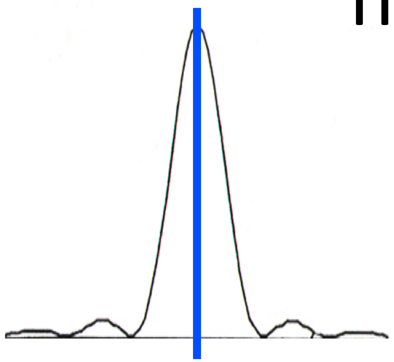
$I_0=1$



n=0

$$I_1 \approx 0.5\left[\frac{A_G}{A_M}\right]$$

$$= 1x10^{-4}$$



n=1

Assume Gap is 2 mm and segment F to F is 1000 mm

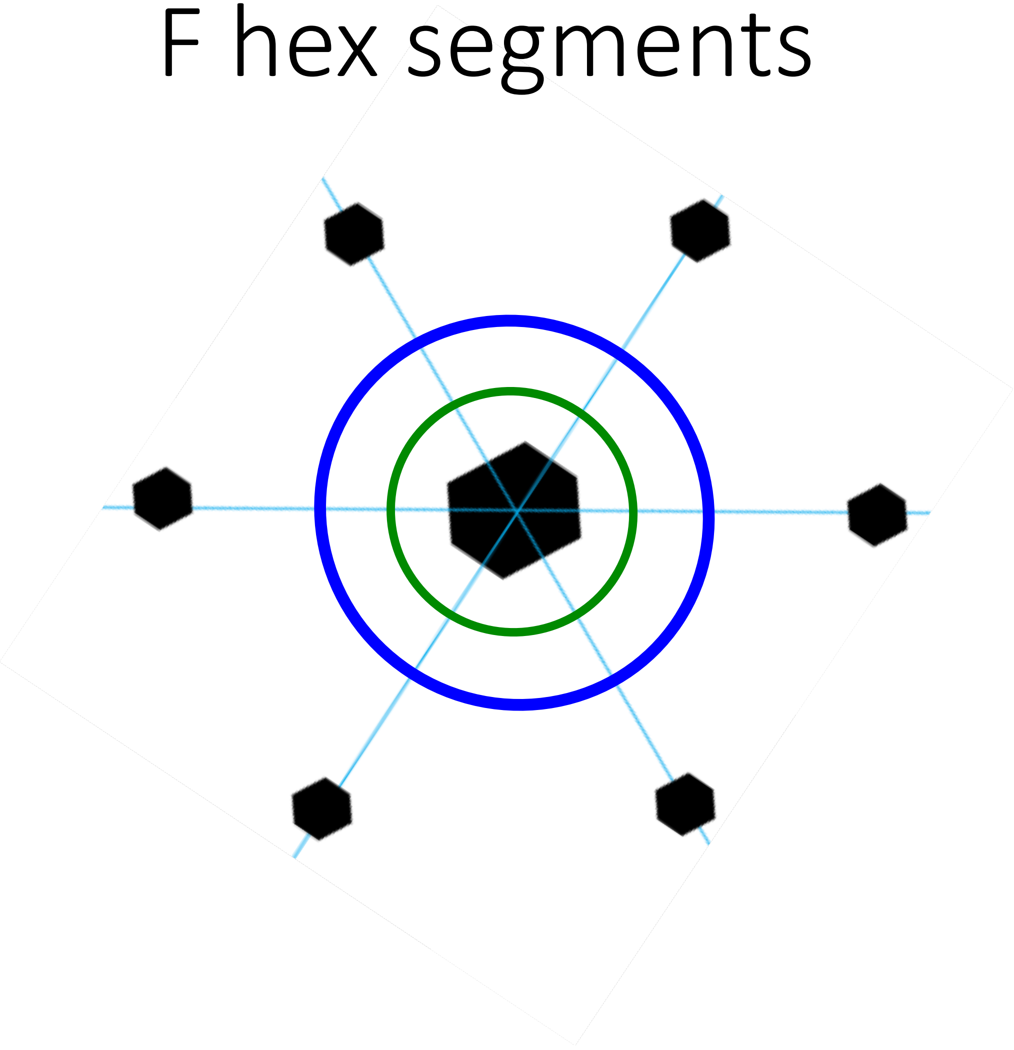
Gap size is determined by the need to deploy segments

Where are the exoplanets? masec

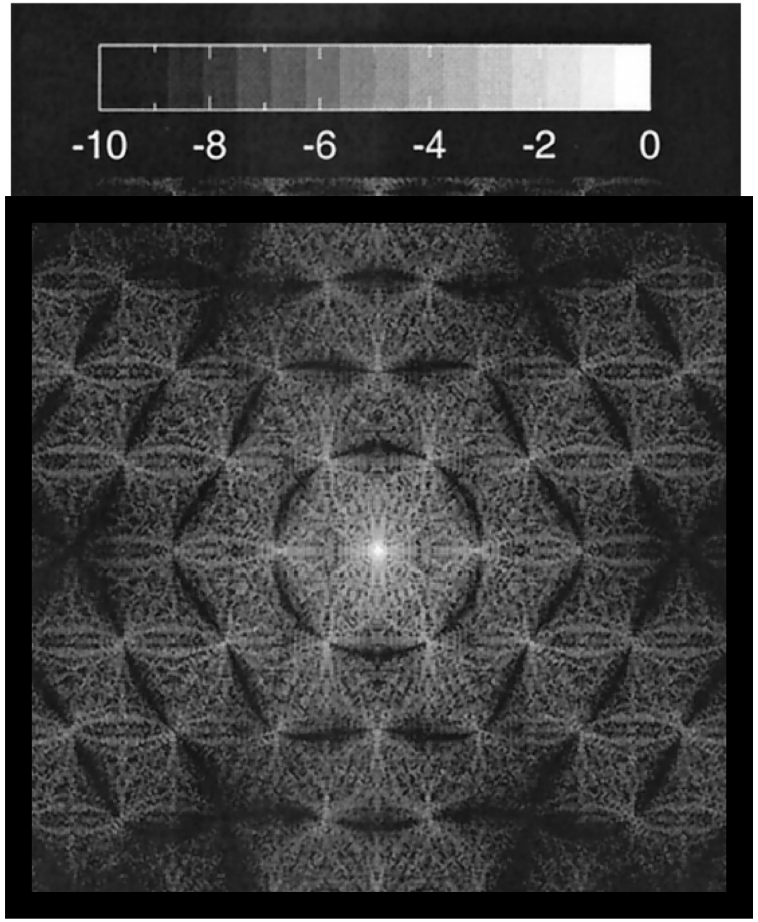
- **Exoplanet candidates as a function of distance**
- **Range in angles is 10 to 50 masec.**
- Range in aperture is 4 to 30 meters

Distance Parsecs PC	Angle between star & earth twin in masec	Aperture (m) Diffraction limited at 500nm	Aperture (m) third Airy diffraction ring
10	100.0	1.2	3.7
20	50.0	2.5	7.5
30	33.3	3.7	11.1
40	25.0	5.0	15.0
50	20.0	6.2	18.6
60	16.7	7.4	22.2
70	14.3	8.7	26.1
80	12.5	9.9	29.7

Locus of the apoapsis of an earth twin at 40 and 80 parsecs [25 and 12.5 msec] in relation to the monochromatic diffraction pattern from 2-m F to F hex segments

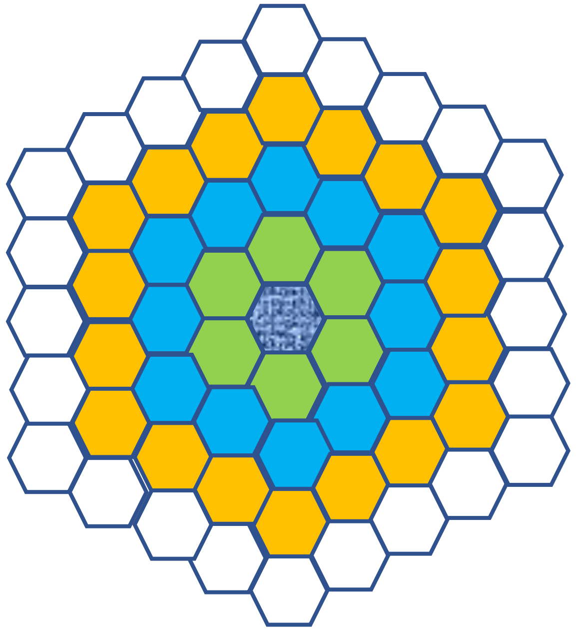


M. Troy & G. Chanan (2003)



1-arc second

PSF for a polychromatic (450 to 550nm) star



Aperture

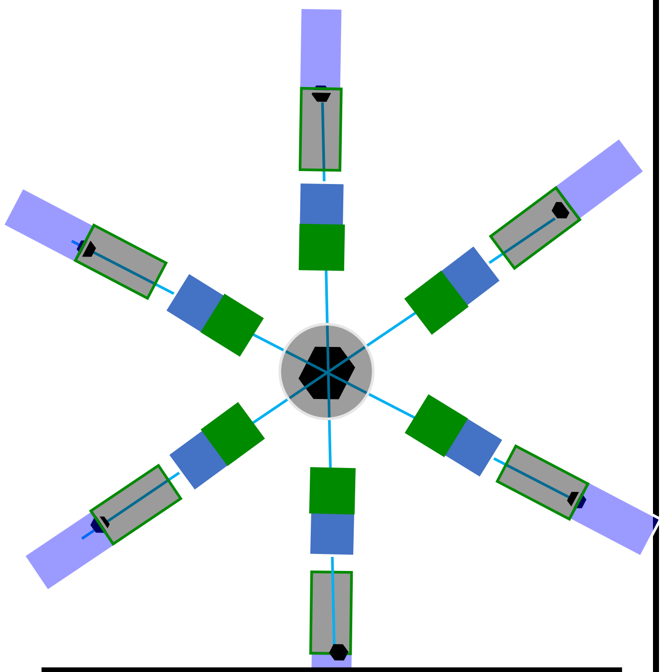


Image plane
n=1,2 spectrum
of the star

Distance between
n=0 and n=1

	500 nm wavelength	450 to 550 nm
1-m F to F =>	103	+-21. msec
2-m F to F =>	52	+-11. msec
3-m F to F =>	17	+- 6.9 msec

Seven masks, one for each diffraction order are needed OR

Can we apodize the aperture to control unwanted light?

Can we mask (apodize) the segments at a relayed aperture (pupil) plane in a polychromatic system?

- Not very well since diffraction is wavelength dependent
- Therefore the location of the exit pupil images are wavelength dependent
- Very difficult to control diffraction after it has taken place
- Very difficult to reassemble the electric field without significant absorption - Kathryn St. Laurent**, et. al (2018)**
- Hexagonal-segmented telescopes [ELT & TMT & JWST] are locked in

Problem & possible solution

- Eliminate the unwanted diffraction orders that “look like” and exoplanets
- Apertures segmented with a periodic structure is not optimum for exoplanets or general astrophysics
- Non-periodic, segmented apertures may be the answer
- Investigate non periodic apertures for large telescopes
- Start with the pinwheel pupil

Disruptive technology: curved sided segments

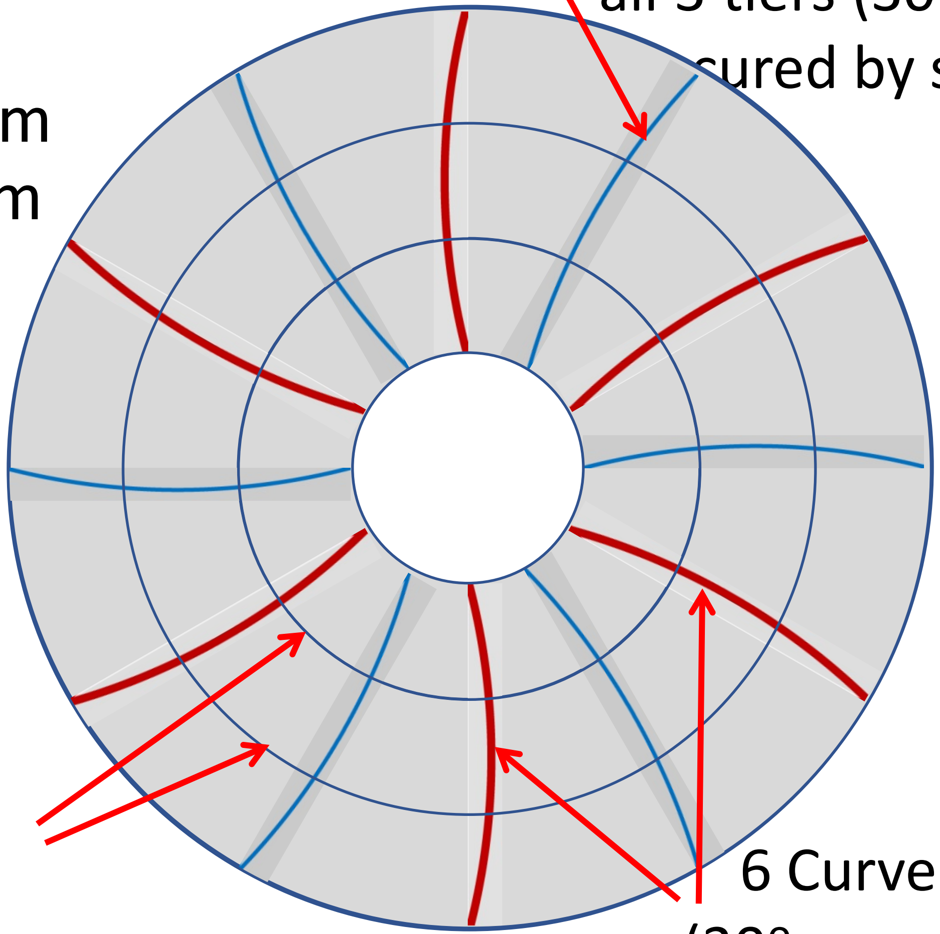
- But LUVOIR and future space segmented telescopes are not locked in to hexagonal segments and straight line support systems for secondary mirrors.
- **We learned that curved shadows from secondary support system corrects diffraction => can we apply the same to segment gaps?**
- **If yes, then**
  - **LUVOIR can be built to characterize 10^{-10} contrast terrestrial exoplanets anywhere in the FOV!**
  - **Following the iSAT architecture: 20 to 50 meter telescopes become possible and the promise of finding life on a terrestrial exoplanet increases dramatically.**

3 Tier Piewedge 12 Segmented Mirror Concept with Six Curved Secondary Mirror Struts (30º arc of circle)

Ten Meter Diameter Segmented Mirror

Obscuration = ε = 0.25
R1 = radius of 1st zone = 2.5 m
R2 = radius of 2nd zone = 3.75 m
R3 = radius of 3rd zone = 5.00 m

36 Segments



12 Curved Radial Gaps thru all 3 tiers (30° arc of circle): 6 obscured by struts.

2 Centered Circular Gaps Separating the 3 tiers (360° arc of circle).

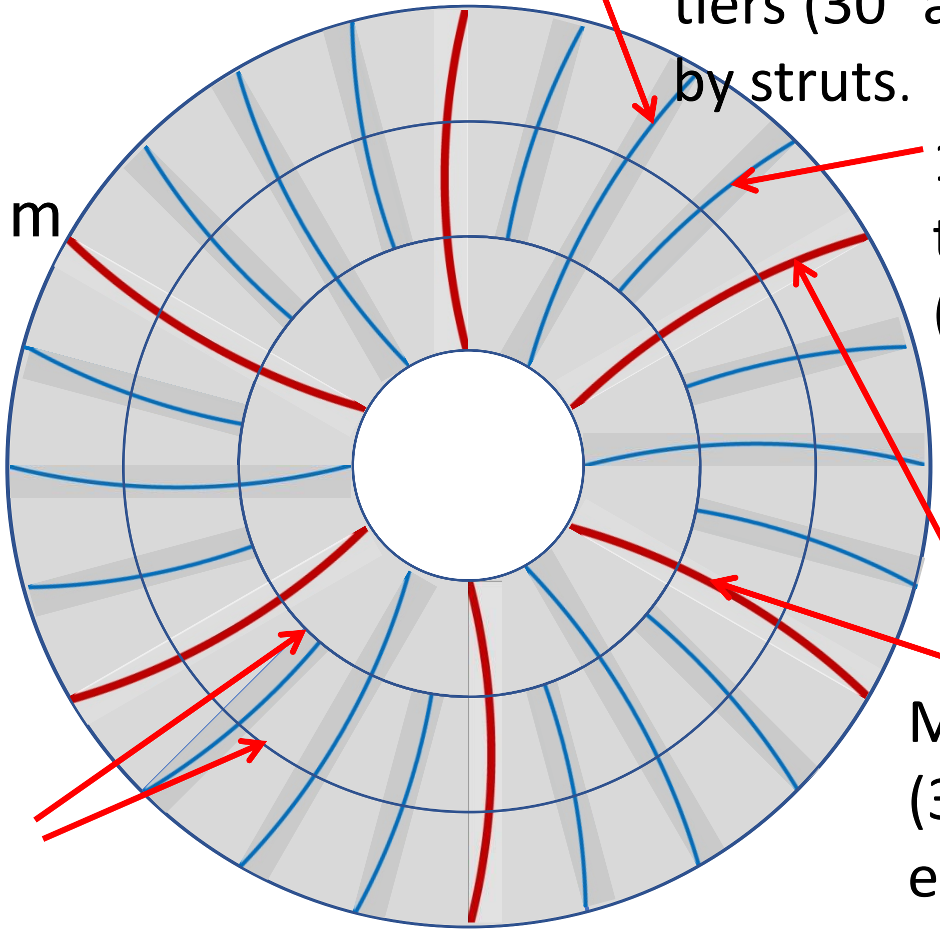
6 Curved Secondary Mirror Struts (30º arc of circle): each obscuring a gap.

3 Tier Keystone 24 Segmented Mirror Concept with
Six Curved Secondary Mirror Struts (30º arc of circle)

Twenty Meter Diameter Segmented Mirror

Obscuration = ε = 0.25
R1 = radius of 1st zone = 5. 0 m
R2 = radius of 2nd zone = 7.5 m
R3 = radius of 3rd zone = 10.00 m

60 Segments



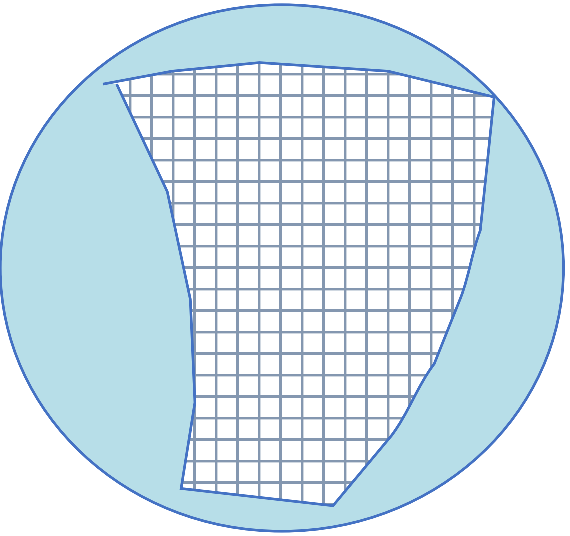
Pinwheel apertures are structured pupils: advantages

- No need to roll the telescope about the bore-sight axis
- Shorter integration times per object
- Image processing
  - Isoplanatic patch is both rotation and translation invariant
- Spectroscopy
  - Reduced spectral contamination from the parent star to the exoplanet.
  - Improved line identification
  - Improved molecular and atomic abundance calculations
- Polarimetry
  - Removes the straight-line segment edges as a possible source of polarization "noise"

Optical Fabrication of Non-Circular Aspheric Segments

- **Keck was an early example, segments were polished by Tinsley using a combination of Stress Mirror Polishing (SMP) and deterministic polishing to remove the residual errors**
- **The SMP techniques have been considered or updated for TMT and E-ELT hexes. One approach is SMP**
  - **With a full size tool, with rapid material removal polish the roundels, removing most of the volume between "nearest sphere" and off axis aspheric form.**
  - **Shape the roundel into a curve-sided segment**
  - **Remove the remaining small volume of surface error with deterministic small tools**
- **Polish directly as a curved-sided segment with deterministic tools as done by Tinsley on the 18 JWST hexagonal primary mirror segments.**

Pinwheel Petal light weighted



- Pinwheel mirrors may be made of a number of different materials.
- SCHOTT offers extremely stable monolithic mirror substrates of ZERODUR® and can provide aggressively light weighted substrates up to 4m in diameter.
- The pinwheel form can be undercut around it's perimeter
- A mirror substrate cost
  1. Material
  2. Cutting roundel
  3. Milling near optical shape
  4. Light weighting (up to 90% material removal) and lands for mounting
  5. Acid etching to mitigate any subsurface damage

- The pinwheel would be light weighted for machining as an isogrid (not the rectangular grid indicated), thus minimizing cost due to waste.
- After optical fabrication as an off-axis segment in roundel form, the petal would be parted out by machining

Pinwheel pupils to control diffraction is not new, 84 yrs

- J. B. Breckinridge (2018) *The pinwheel pupil: exoplanet science and technology* AAS Poster 439.04 Jan
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- A. Couder, (1934) *Dealing with spider diffraction, L'Astronomie*, translation into English is in Amateur Telescope Making, Book 2, A. G. Ingalls, ed. Scientific American, New York, 1996, pp. 357-360.

Recent references

- Breckinridge, J. B., J. E. Harvey, T. Hull & K. Crabtree (2018); *ExoPlanet telescope diffracted light minimized: The pinwheel-pupil solution*, SPIE Proc. 10698-61
- Harvey, J. E., J. B. Breckinridge, R. G. Irvin, K. Crabtree, R. N. Pfister (2018); *Diffraction Analysis of Large Segmented Mirror Concepts for Exoplanet Exploration*, SPIE Proc. 10698-60
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Thank you for listening

The end

jbreckin@Caltech.edu

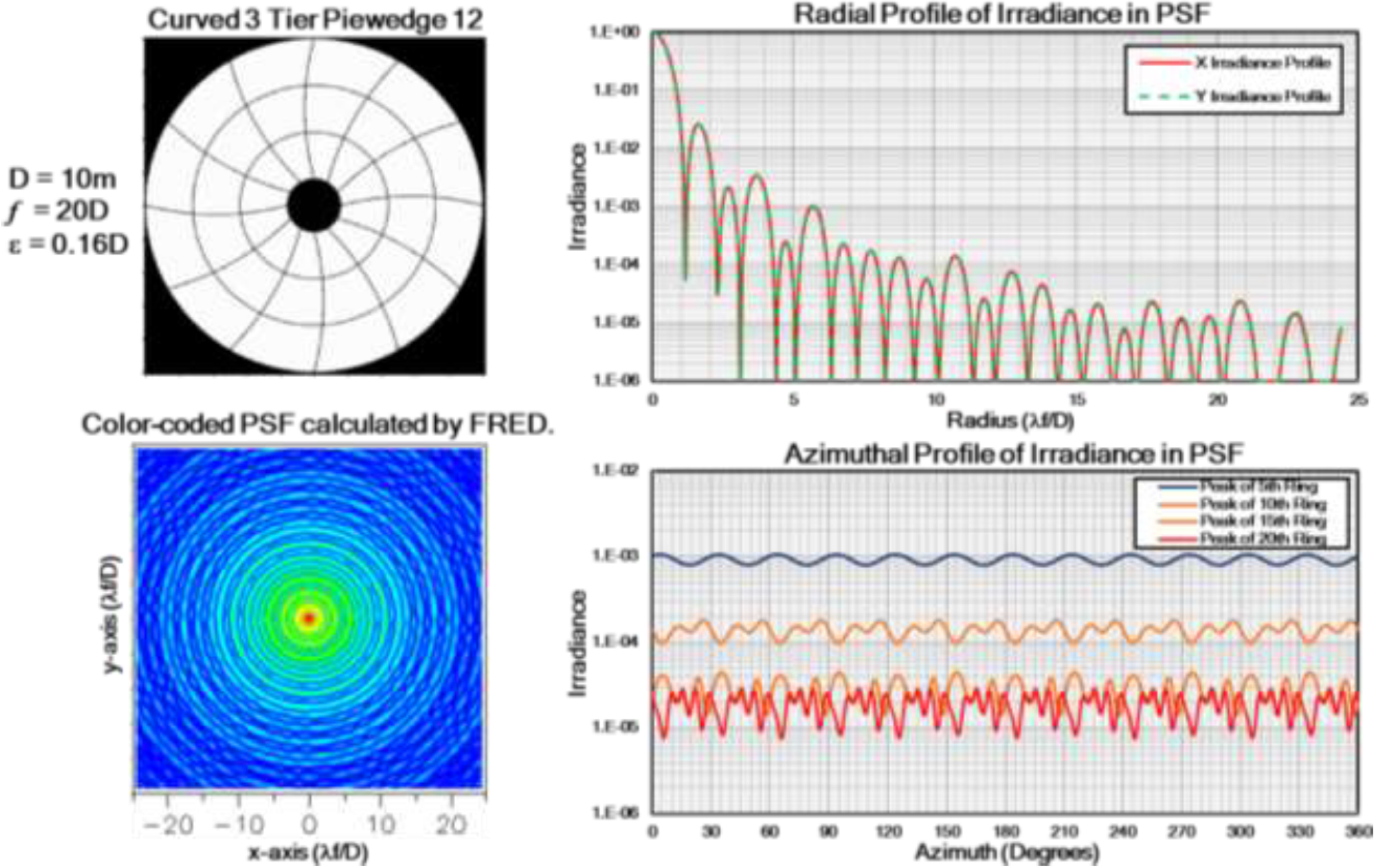

Figure 18. The 3 Tier Piewedge 12 segmented mirror configuration is illustrated with a relative gap width of w = 0.002D. The simulated PSF is devoid of any discrete narrow diffraction flares; however, substantial interference effects are apparent. The x and y-axis radial irradiance profiles and several azimuthal irradiance profiles are also indicated.