Imaging Terrestrial Planets with a Free-Flying Occulter and Space Telescope: An Optical Simulation

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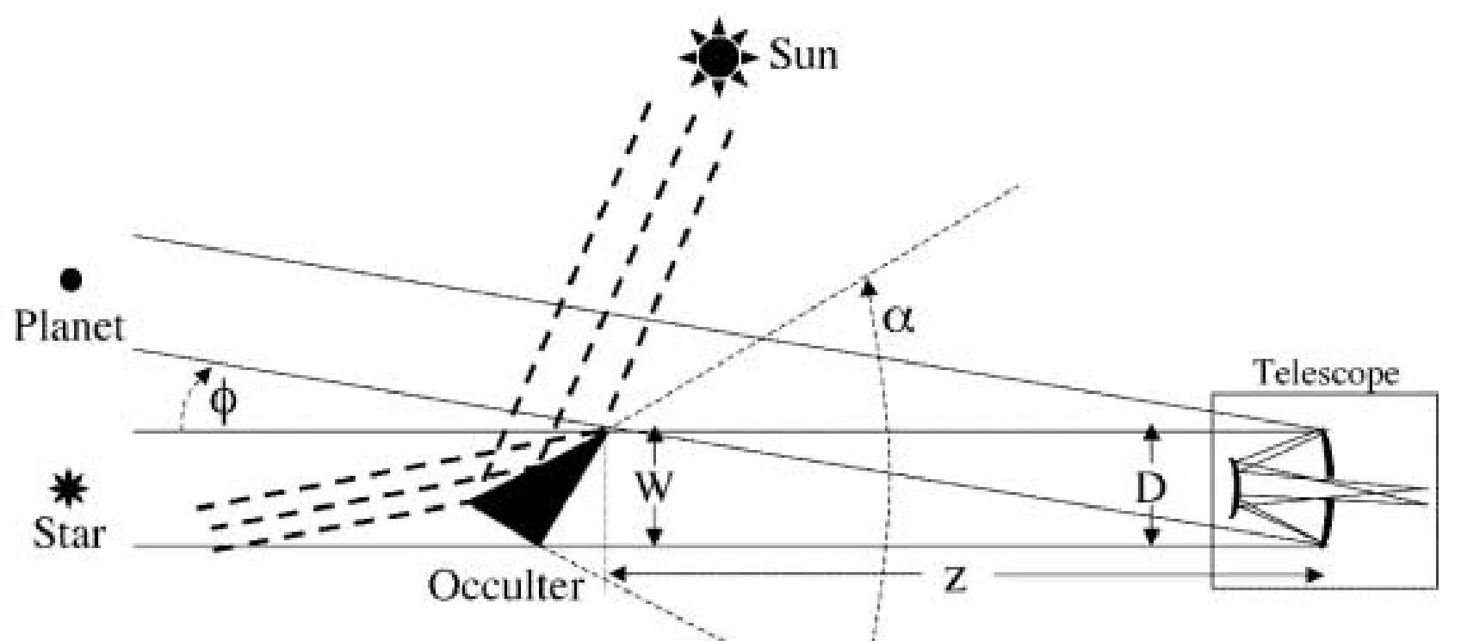
Abstract:

In this paper, we further develop our concepts for the free-flying occulter space-based mission, Umbral Missions Blocking Radiating Astronomical Sources (UMBRAS). Our optical simulations clearly show that an UMBRAS-like mission designed around a 4-m telescope and 10-m occulter could directly image terrestrial planets. Such a mission utilizing existing technology could be built and flown by the end of the decade. Moreover, many of the other proposed concepts for Terrestrial Planet Finder could significantly benefit by using an external occulter.

We present optical simulations for an optical design comprising a square aperture telescope plus square external occulter. We show that the entire diffraction pattern, from occulter to telescope and through telescope to focal plane, may be characterized by two parameters, the Fresnel number and the ratio of the telescope diameter to the occulter width, *D/W*. In addition, combining the effects of a square occulter with apodization provides a much more rapid roll-off in the PSF intensity between the diffraction spikes than may be achieved with an unapodized telescope aperture and occulter. We parameterize our results with respect to wavefront quality and compare them against other competing methods for exo-planet imaging. The combination of external occulter and apodization yields the required contrast in the region of the PSF essential for exo-planet detection. An occulter external to the telescope (i.e., in a separate spacecraft, as opposed to a classical coronagraph with internal occulter) reduces light scatter within the telescope by approximately 2 orders of magnitude. This is due to less light actually entering the telescope. Reduced scattered light allows significant relaxation of the constraints on the mirror surface roughness, especially in the mid-spatial frequencies critical for planet detection. This study, plus our previous investigations of engineering as well as spacecraft rendezvous and formation flying clearly indicates that the UMBRAS concept is very competitive with, or superior to, other proposed concepts for the Terrestrial Planet Finder (TPF) mission.

Introduction:

One of the "Holy Grails" of astrophysics is the detection of earth-like planets around nearby stars. So far, radial velocity studies of nearby solar-type stars have discovered over 100 Jupiter-sized planets (see papers by Mayor, Queloz, Marcy, Butler, Fisher, Noyes, Cochran, Hatzes, and many more investigators, too numerous to be listed here). Thus, there are more than 10 times the number of known planets outside as inside our solar system. These systems are unlike our own Solar System in that they are dominated by giant, Jupiter-like planets, some orbiting within a fraction of an A.U. of their primary.



Direct imaging has the potential to detect both Jupiter and Earth-like planets at large distances from their primaries. Visually, planets shine by reflected starlight, making them difficult to image against the glare of their parent stars. Current direct imaging capabilities are limited to ground-based coronagraphic and adaptive opttics (AO) imaging with 8-m or larger telescopes and with the instruments onboard the Hubble Space Telescope (HST). To date, none of these platforms has imaged any verifiable exo-planet.

Our previous studies have shown free-flying occulters in combination with a space-based telescope are a promising means to image and study nearby exo-planets. The figure at right presents the formation configuration of a coronagraphic system consisting of an external free-flying occulter and space telescope. At optical wavelengths, conventional Lyot coronagraphs have, at best, achieved contrast enhancements of ~10^4 in the 5-10 Airy ring annulus. Simulations of an apodized square aperture space telescope suggest that a contrast enhancement of ~10^6 could be achieved in the same annular region. Further simulations of an apodized square aperture telescope in combination with a free-flying occulter indicate that the contrast enhancement could be boosted to >10^8. Thus, a space-based apodized telescope plus external occulter system will be able to directly image exo-planets.

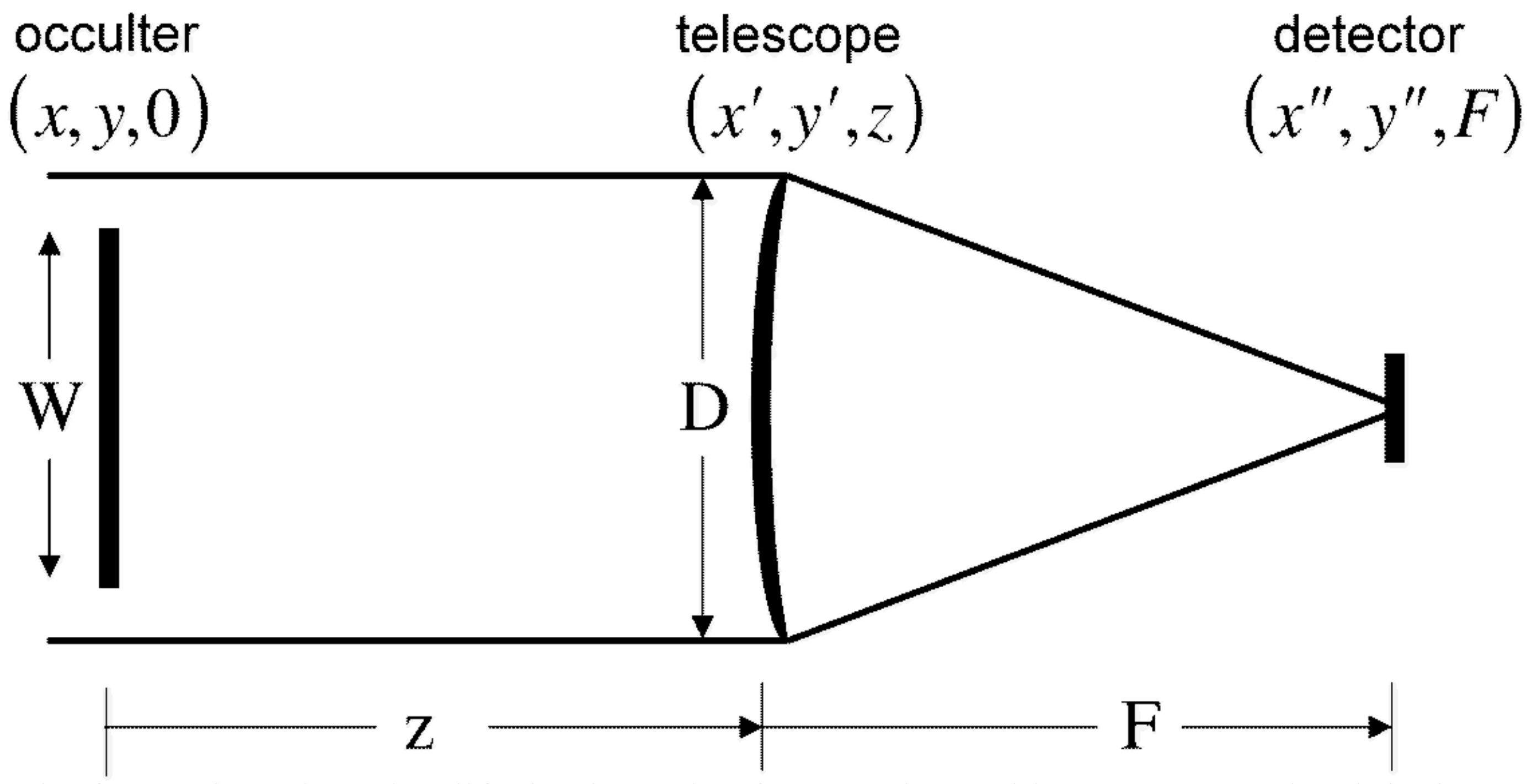
Optical Modelling:

Propogation of the electric field from the occulter to the telescope entrance pupil is given by Fresnel diffraction. Fresnel diffraction occurs because the diffracting obstruction (occulter) is at a finite distance from the telescope entrance plane. Propogation of the electric field from the entrance pupil to the focal plane is accomplished by Fraunhofer diffraction.

Free space propogation of the scalar electric field is described by the spatial Helmholtz wave equation with appropriate boundary conditions:

$$\nabla^2 E(\vec{r}) + k^2 \varepsilon E(\vec{r}) = 0$$

where $\vec{r} = (x,y,z)$ is a point in space, $E(\vec{r})$ is the scalar electric field at that point, $k = 2\pi/\lambda$ and $\varepsilon = 1$ are the wavenumber and permittivity in free space, respectively, where λ is the wavelength. We reduce the 2nd order partial differential equation to a 2nd order ordinary differential equation for planar boundary conditions and apply circular and square symmetry.



The figure above is a Simplified Schematic of External Occulting Coronagraph. Light from a stellar source is diffracted by the occulter and is intercepted by the telescope entrance pupil. The telescope both changes the phase and amplitude, then focuses the source at the detector plane.

The electric field at the telescope entrance pupil is seen to be the difference of two terms: (i) a plane wave that would exist without the occulter, and (ii) a defocussed (quadratic phase factor in integral) Fourier transform of the occulter shape function.

The electric field at the telescope's entrance pupil is a combination of Fresnel integrals which can be evaluated by standard numerical methods. The shape of the field at the telescope is dependent only on the Fresnel number defined by

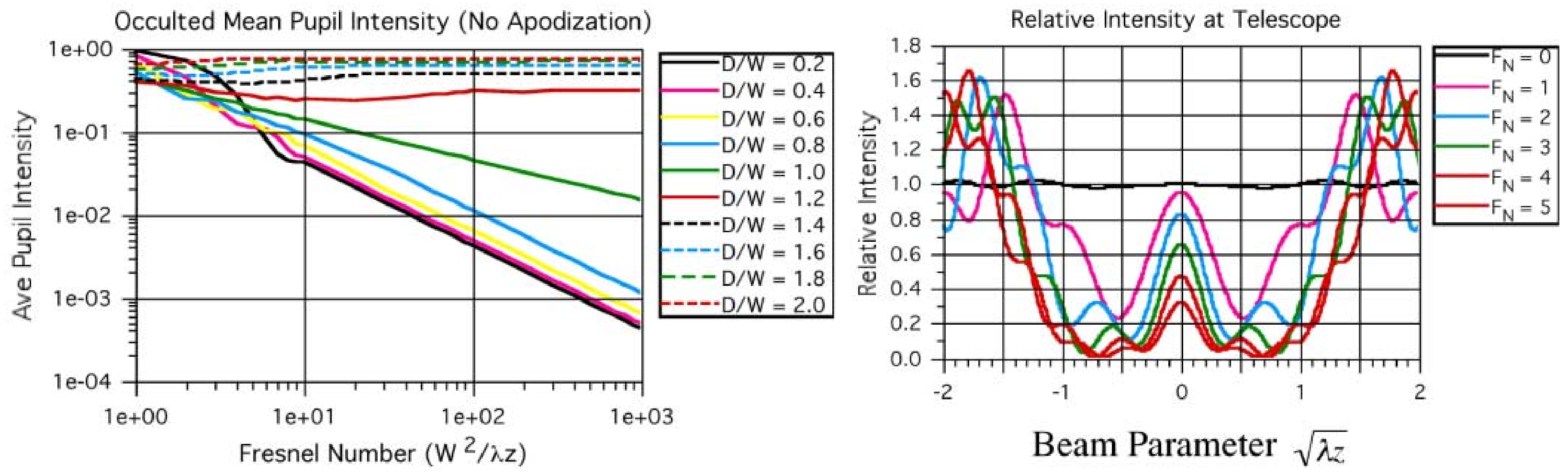
$$F_N = W^2 / 2\lambda z.$$

The Fresnel number is a dimensionless parameter where W is the characterstic width of the mask ("occulter"), λ is the wavelength, and z is the distance of the occulter from the aperture. The $F_N < 1$ regime is called Fraunhoffer diffraction, while $F_N \geq 1$ produces Fresnel diffraction. Intermediate regimes require more difficult analysis, but can be treated using scalar diffraction theory. The relative intensity at the focal plane is given by:

$$\frac{I}{I_0} = \left| -1 + 2i \left\{ C\left(\sqrt{\frac{W^2}{2\lambda z}}\right) - iS\left(\sqrt{\frac{W^2}{2\lambda z}}\right) \right\}^2 \right|^2$$

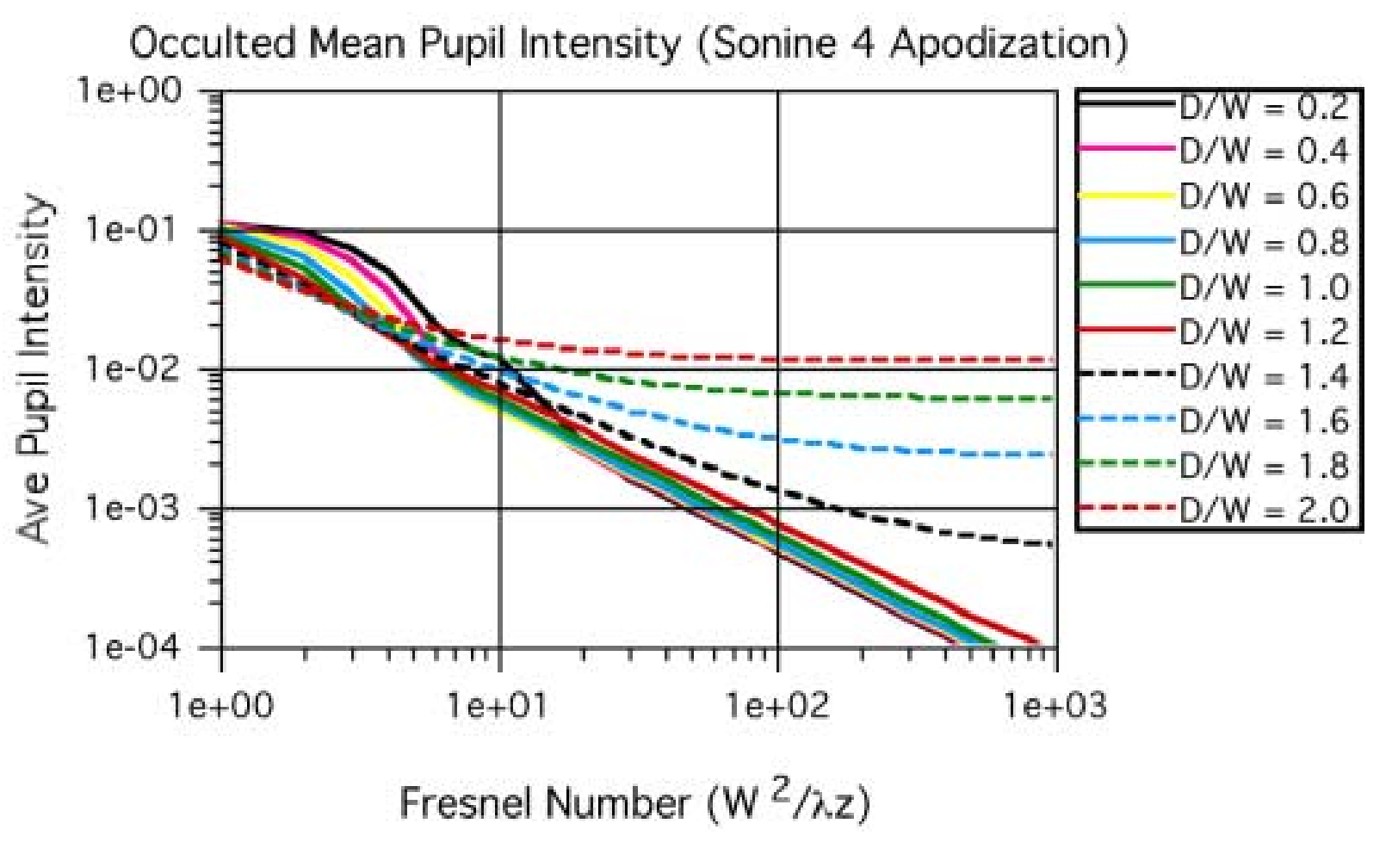
where I_0 is the intensity of the plane wave incident on the occulter.

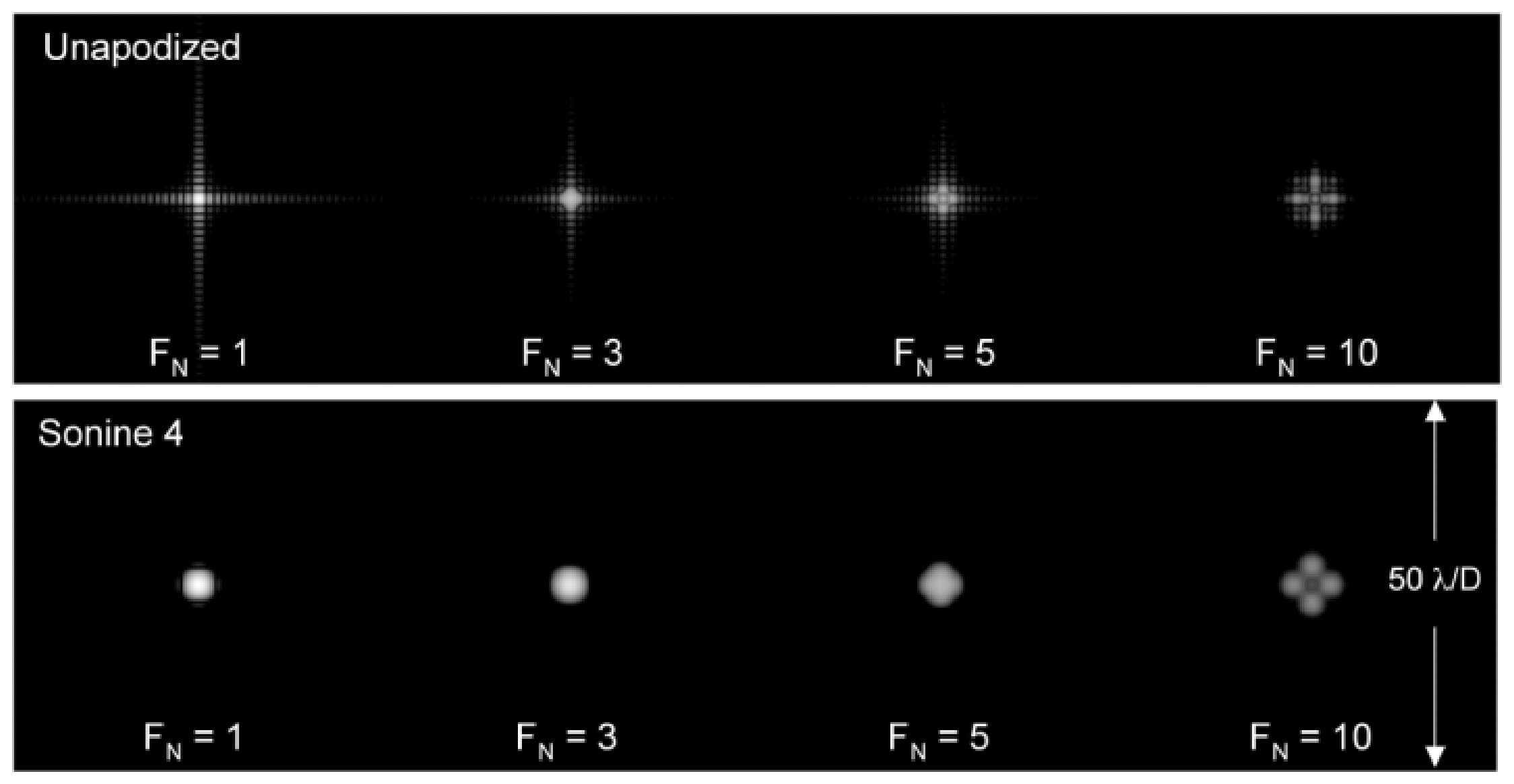
Results from Model Simulations:



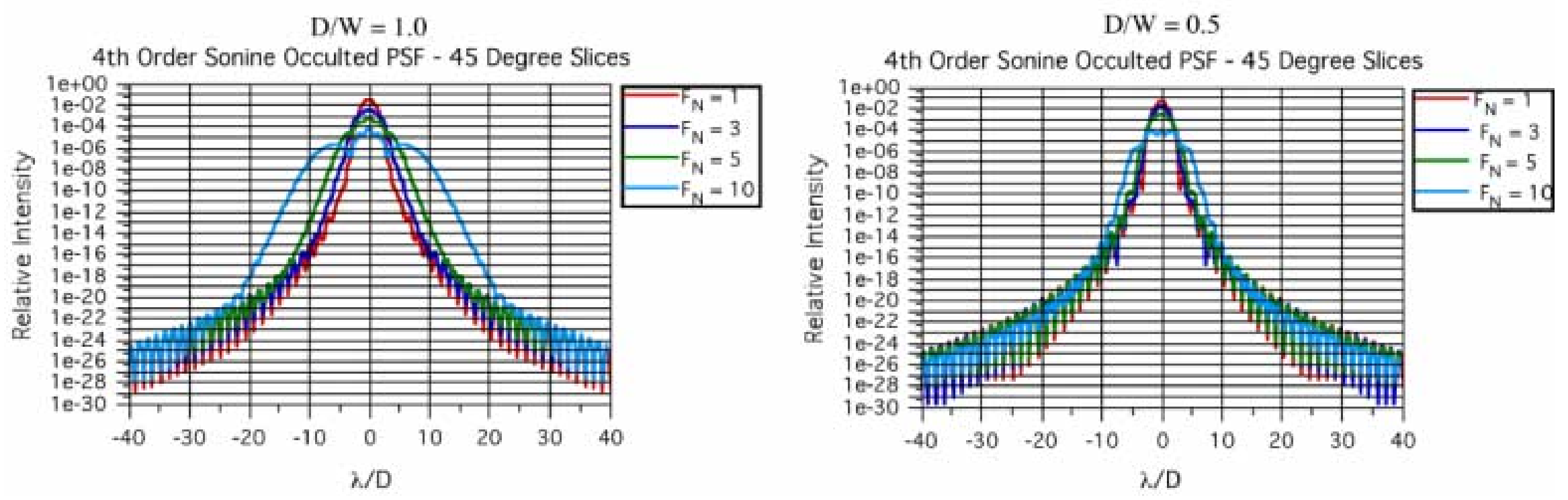
The figure above left is the mean relative intensity at the telescope entrance pupil vs. Fresnel number for various telescope-aperture-to-occulter-width ratios. The figure to the right above is the relative intensity at the telescope entrance pupil vs. beam parameter. Intensity is nearly uniform in the far-field (F_N~1) and shows increasingly complex behavior as the occulter and telescope are moved increasingly into the Fresnel domain (closer spacing).

The figure at right shows the relative intensity averaged across the entrance pupil of the telescope, when apodization is applied at the telescope entrance pupil. As expected, apodization lowers the mean intensity ~1 order of magnitude. Although the light from a planet is also reduced by the same amount, there is a net gain since the diffracted light outside the stellar PSF core is reduced. Combining an occulter with apodization allows us to redistribute the energy, reshaping the final image and concentrating more energy into the core of the stellar PSF.

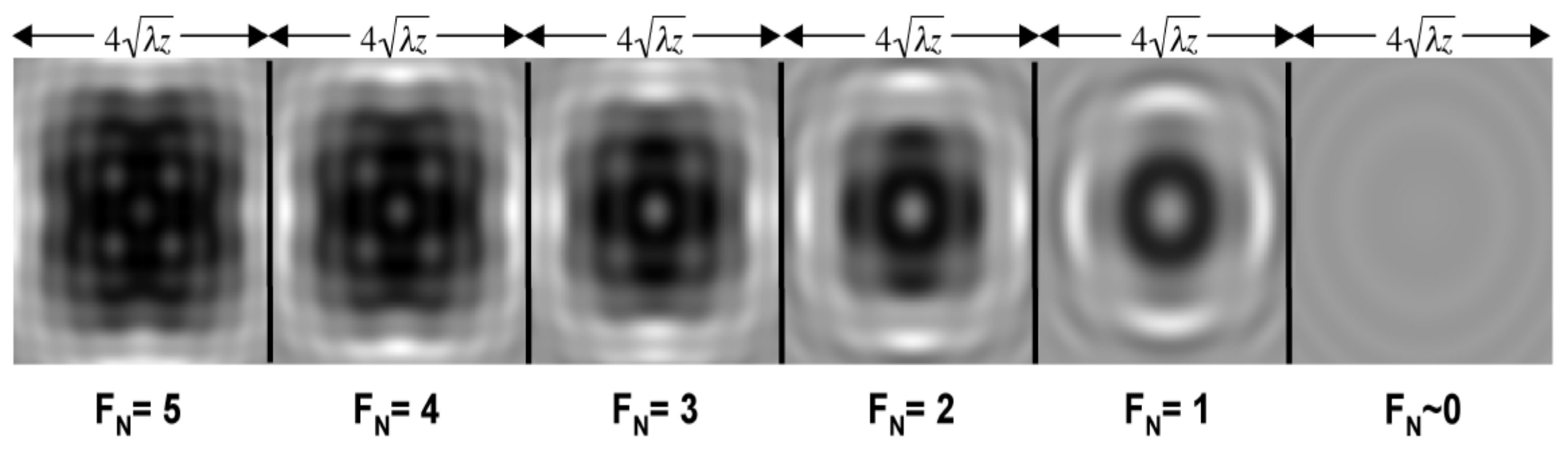


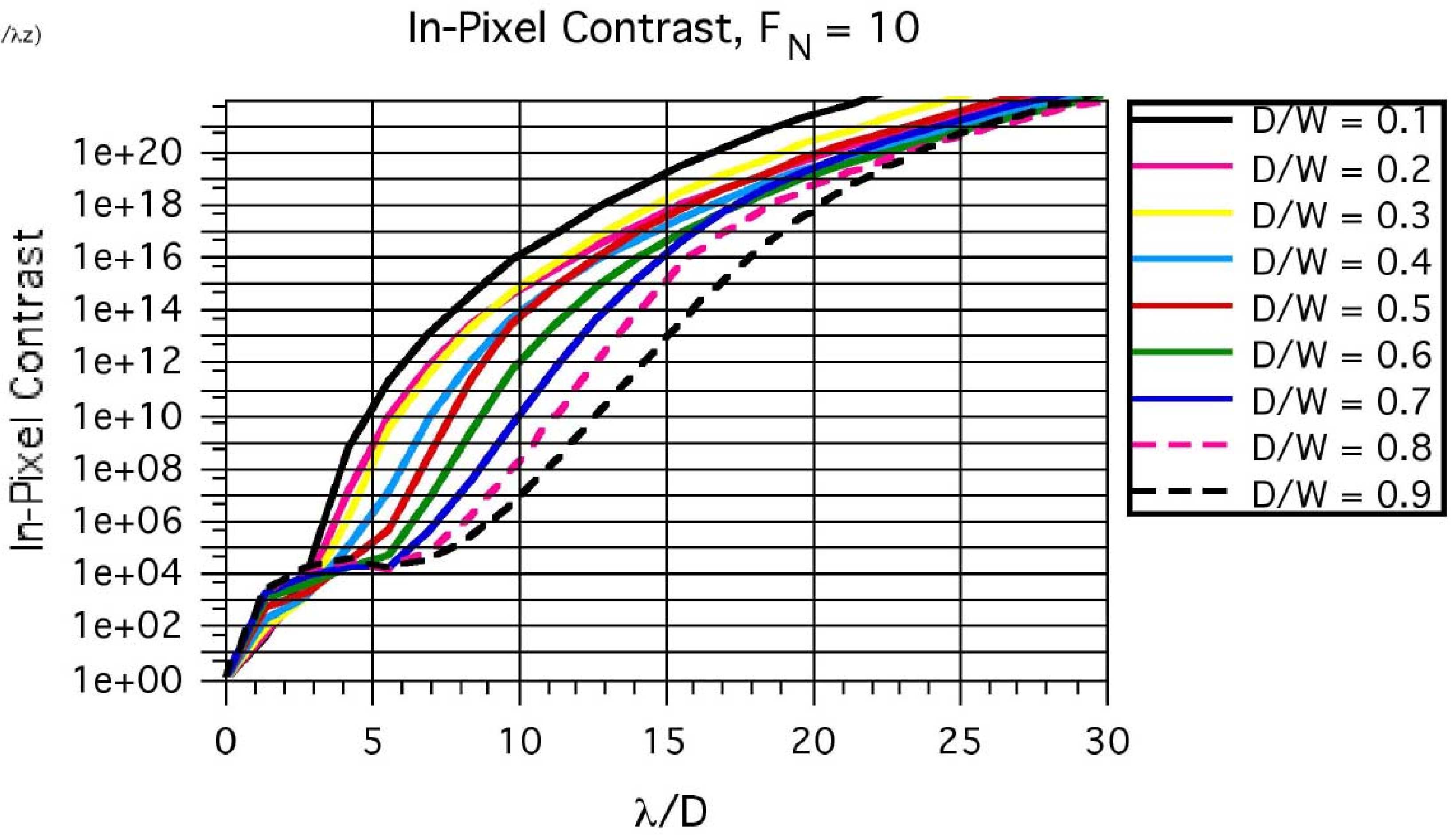


The above figure illustrates the model PSFs as observed at the focal plane. The top and bottom rows show the PSFs without and with apodization for a *D/W* = 0.5. The Fresnel number varies from 1 to 10 from left to right. Note that as the Fresnel number increases the occulter is in effect moving closer to the telescope.



The two graphs above show the PSF at the focal plane of a square telescope with a square occulter. You can clearly see that the contrast increases as the *D/W* decreases. The image string below shows images of the calculated wavefront at the telescope entrance pupil. For larger F_N (where the occulter is closer to the telescope), the shadow of the square occulter emerges. However, the wavefront becomes more uniform with decreasing F_N, as the occulter moves further away from the telescope.





The actual detection contrast for terrestrial planets is obtained by multiplying the luminosity ratio by the "in-pixel contrast" (see above figure). Thus at 6 Airy rings (6λ/*D*), we would expect a contrast of ~100; the terrestrial planet would appear to be ~100 times brighter than the stellar background due to diffracted and scattered light. At 5 Airy rings, we would expect a contrast of ~1-10. For a 4-m telescope at 5500 A, λ/*D*=0.028".

Summary & Conclusions:

The analytical and computational modeling were performed at NASA, Goddard Space Flight Center (GSFC), Greenbelt, MD, using the Optical Systems Characterization and Analysis Research (OSCAR) software package. The results presented here are for perfect optics, i.e., no deformations, misalignments, light scatter, micro-roughness, transmission errors, or polarization effects are included. A space-based free-flying occulter-type mission has several important advantages when compared to the existing proposed missions; (i) star light is reduced before entering the telescope, (ii) light scatter within the telescope is reduced due to less star light entering the telescope as well as fewer obstructions within the telescope, and (iii) the optical tolerances are reduced to existing HST-type optics which are well understood and can be achieved with current technology.