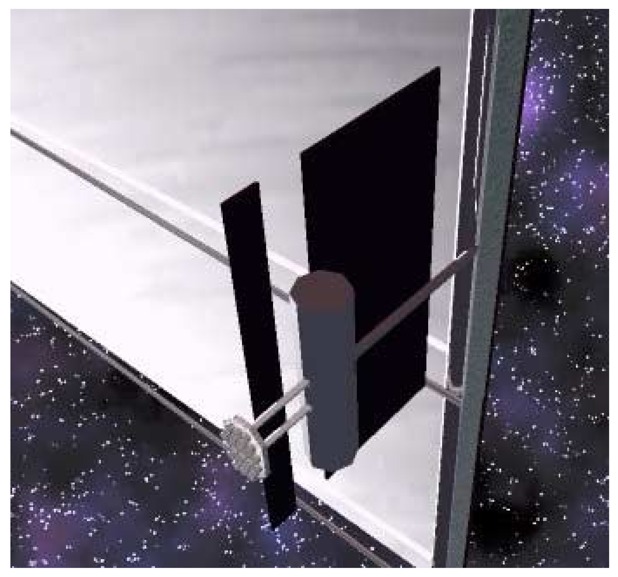
Imaging Terrestrial Planets



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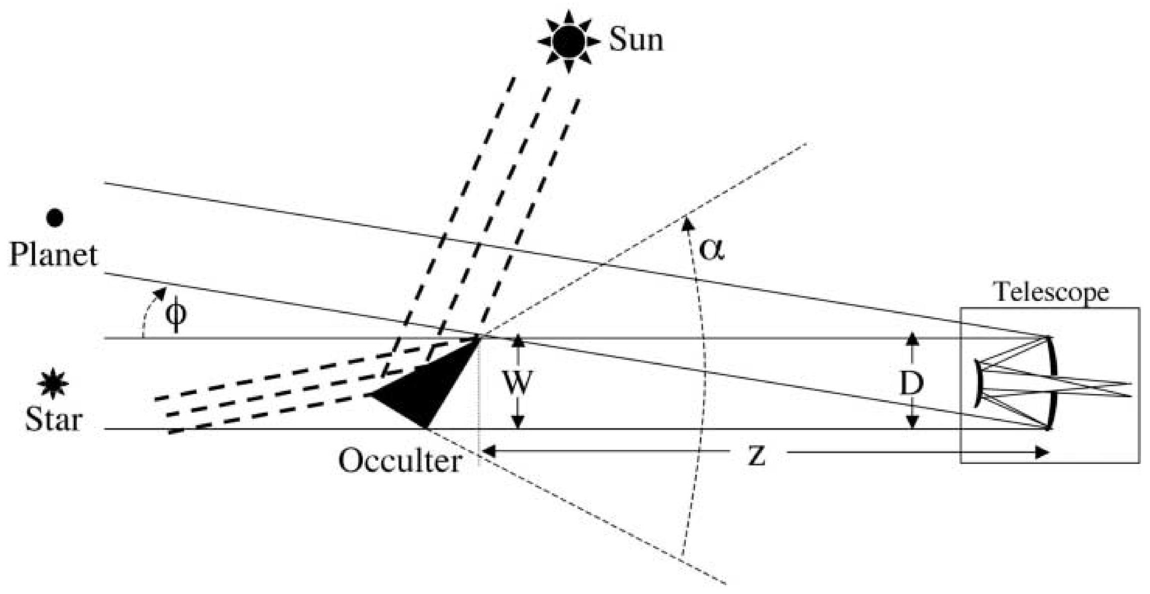
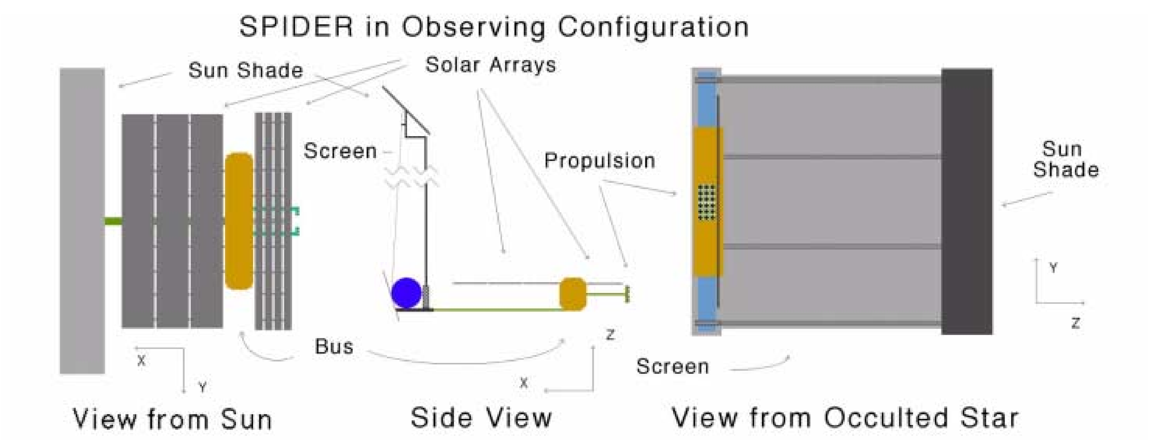
Abstract:

Direct images of terrestrial planets around nearby stars will be spectacular and profound, one of the great scientific accomplishments of the 21st Century. Current direct imaging capabilities are limited to ground-based coronagraphic and adaptive optics (AO) imaging with 8-m or larger telescopes and with the instruments onboard the Hubble Space Telescope (HST). None of these platforms has imaged any verifiable exo-planet. To date, radial velocity studies of nearby solar-type stars have discovered over 100 Jupiter-sized planets. Some systems are unlike our own Solar System in that they are dominated by giant, Jupiter-like planets, orbiting within a fraction of an A.U. of the primary. A terrestrial planet, in reflected light, is typically 10 orders of magnitude dimmer than the central star, i.e., the luminosity ratio of the planet to star is 10^{-10}. NASA's Terrestrial Planet Finder (TPF) program is investigating two concepts, detection using interferometry and coronagraphy for imaging. We present optical simulations approach to directly image terrestrial planets. Our simulations show that the combination of external occulter and apodization yields the required contrast in the region of the PSF essential for exo-planet detection.

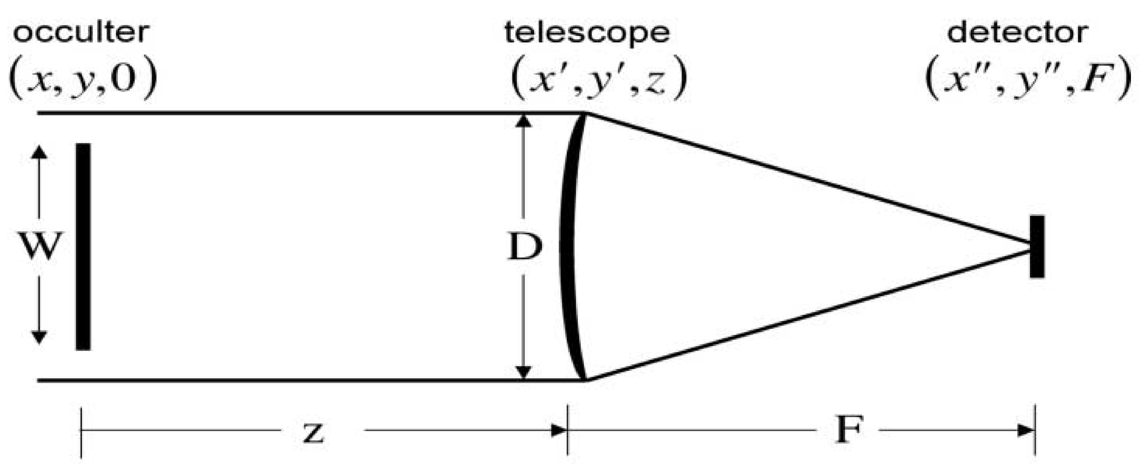


Introduction:

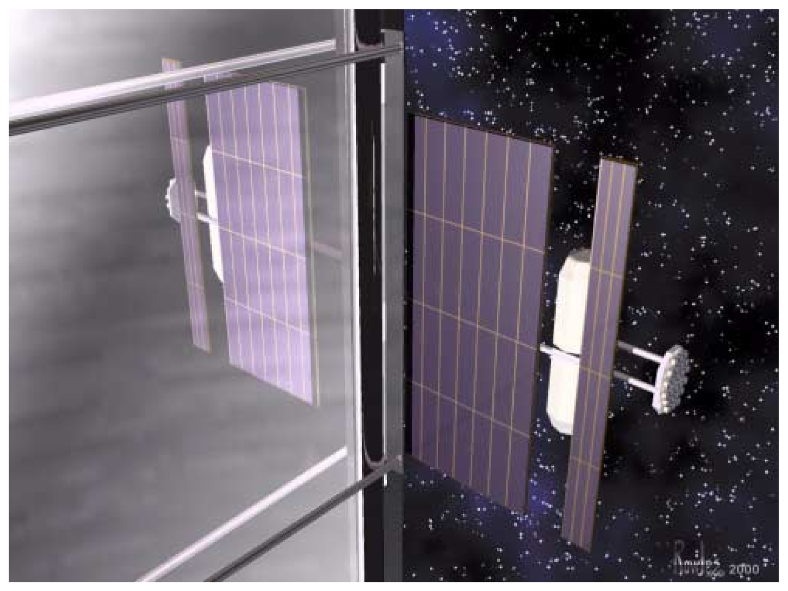
We have explored combining an apodized space telescope with an external occulter, which we call the Umbral Missions Blocking Radiating Astronomical Sources (UMBRAS) project. Relative configuration of an external occulter operating with a space telescope is depicted in the figure above. The telescope points at the target as the occulter craft interposes itself between the target and telescope. Imaging of the field is used to locate the target, map the star field, locate the occulter, and to support formation control once the occulter is in the target-telescope line-of-sight (TTLOS).



The physical size of the occulter, its distance from the telescope, observing wavelength, and ability to maintain alignment are major factors in the resulting on-axis light reduction. Velocity matching and formation control of the Solar-Powered Ion-Driven Eclipsing Rover (SPIDER) with the telescope are achieved with smaller impulse thrusters and communication between telescope and SPIDER. The automated SPIDER tasks are implemented by the Attitude and Translational Control System (ATCS). The figure above depicts a conceptual design for the SPIDER.

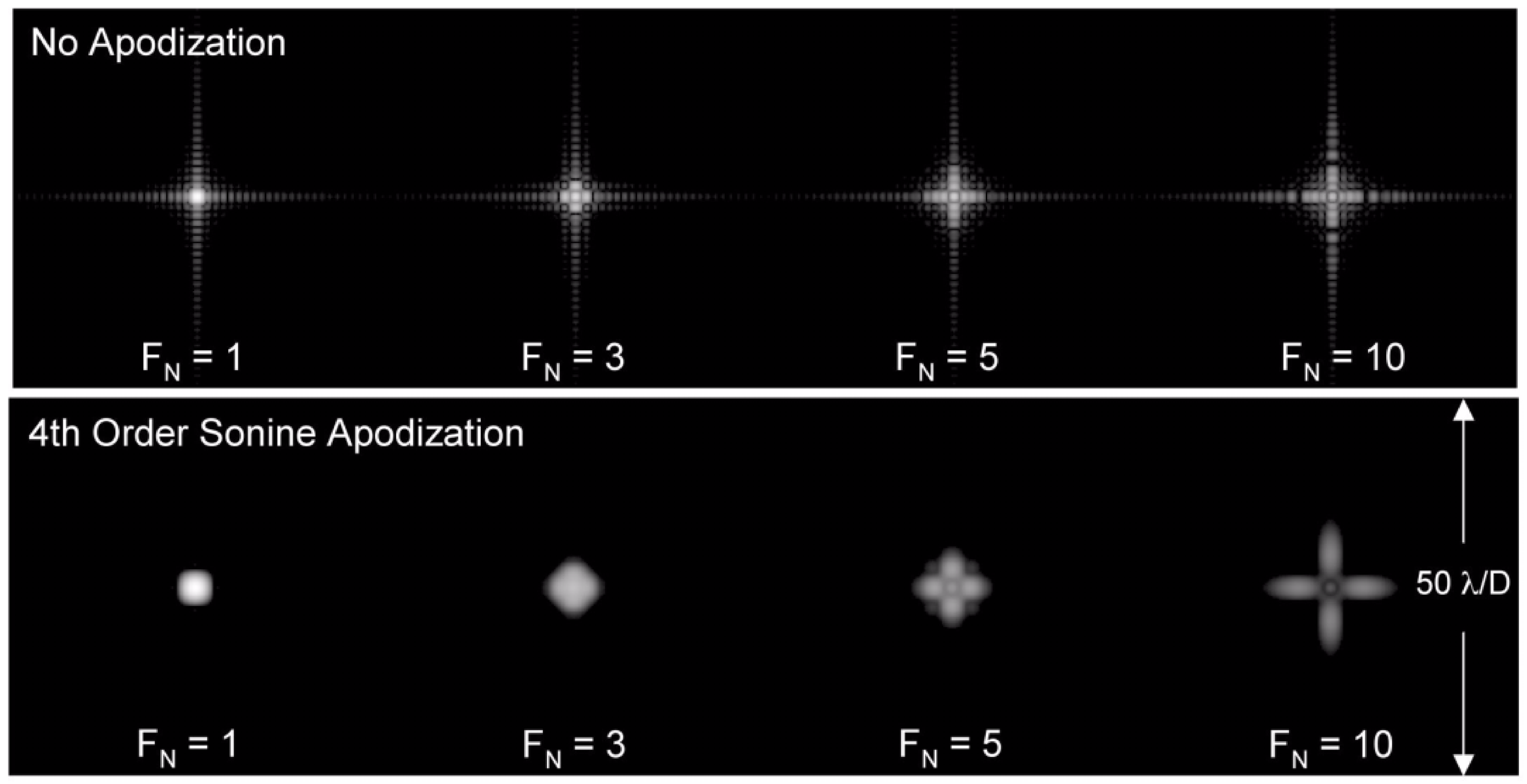


The diffraction of light from the occulter to telescope is Fresnel, and from aperture to focal plane is characterized by Fraunhofer diffraction.

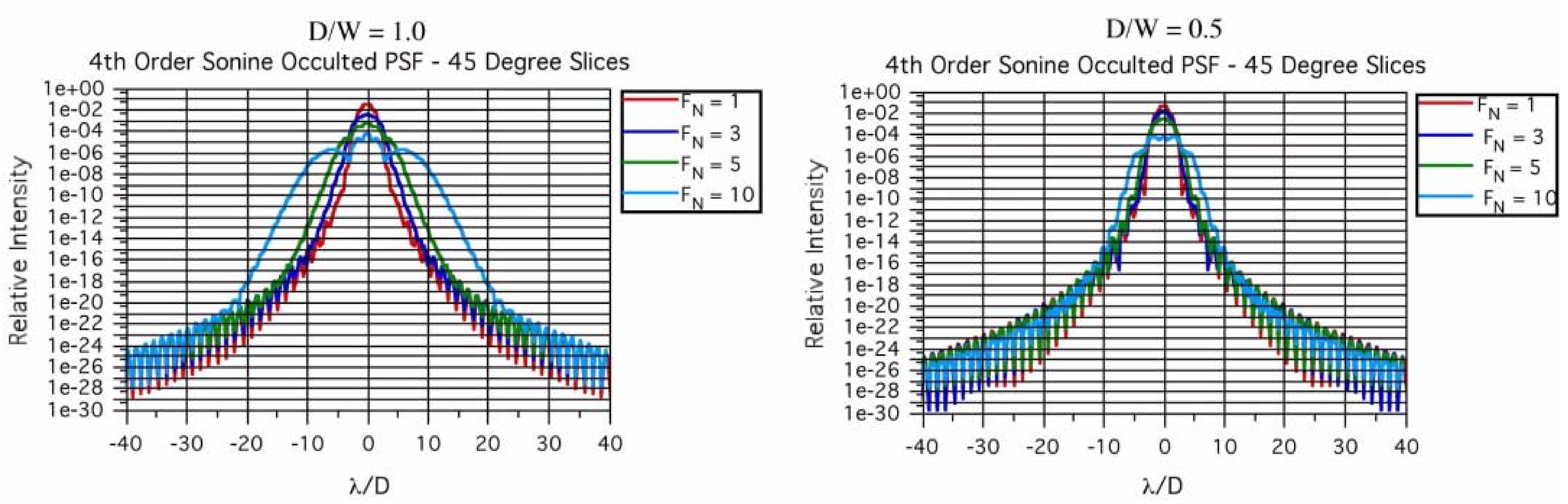


Optical Simulations:

Optical simulations of a square aperture telescope with a square external occulter show that the diffraction pattern can be characterized by two parameters: the Fresnel number ($F_N = W^2/\lambda z$) and the ratio of the telescope diameter to the occulter width (*D/W*). Below are presented model telescope point spread functions (PSF), with and without telescope apodization.



The above figure illustrates 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 (where *D/W* is the ratio of the telescope diameter to the occulter width). 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.



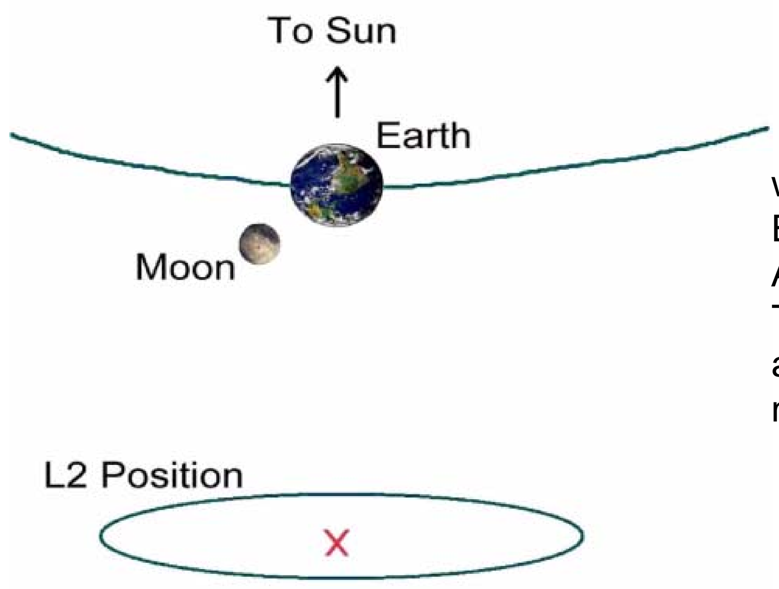
The two graphs above present slices through the PSFs that clearly show that the contrast increases as the *D/W* decreases.

Advantages:

Desirable features of using an external coronagraphic vehicle include the ability to obtain coronagraphic data with any instrument on the telescope - imaging, spectroscopic, or interferometric. Advantages over conventional coronagraphs to achieve high-contrast imaging are:

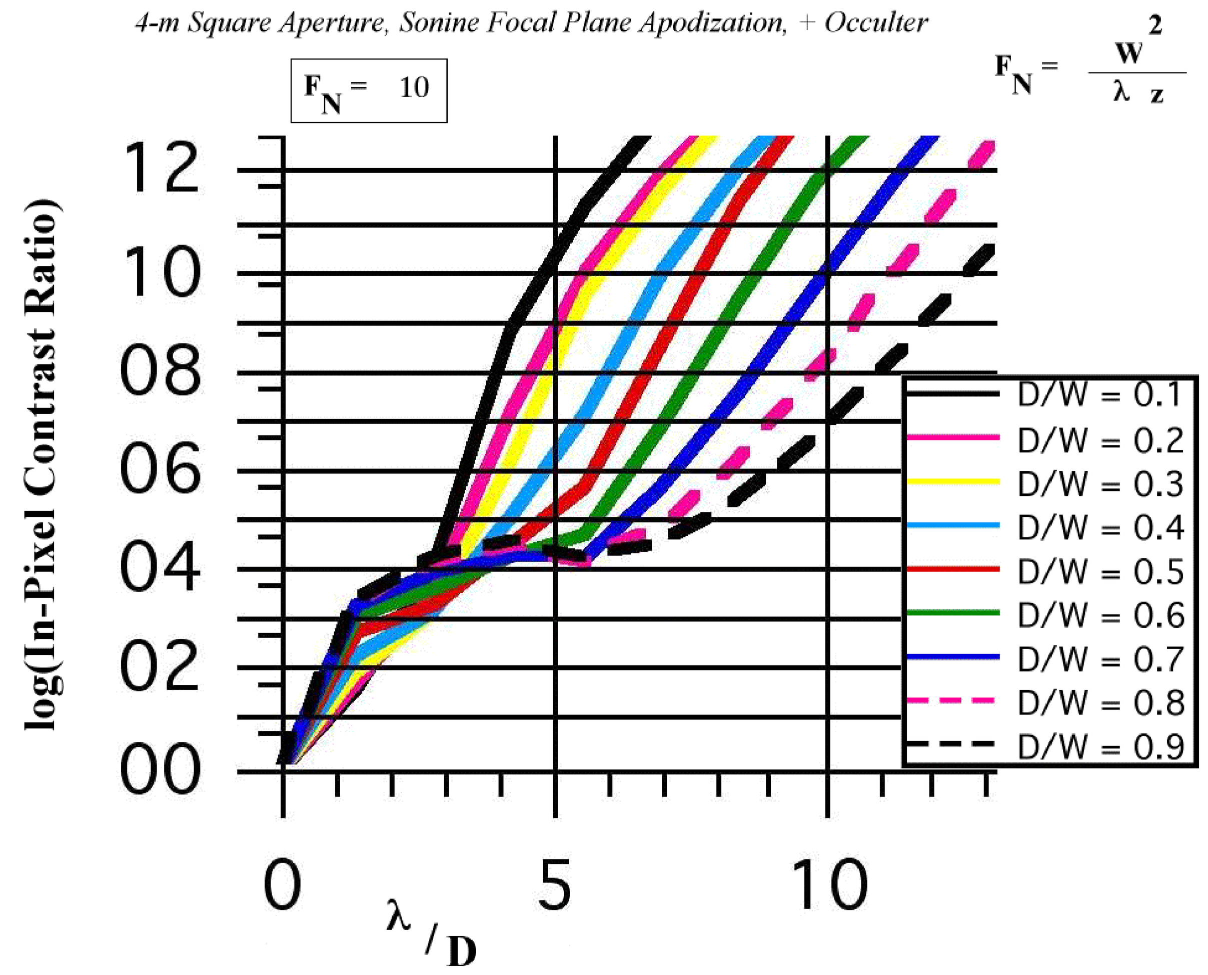
- Fewer internal telescope obstructions
- Less on-target light entering the telescope
- Mirror polishing tolerances less stringent
- Fewer diffraction spikes
- Lower technological readiness

http://umbras.org



A mission of this type might be flown at the Earth-Sun L2 position, which is four times further away from Earth than the Moon. However, a 1 A.U. fall away orbit (similar to SIRTIF) would be preferable, as in such an orbit the Earth tides become dramatically smaller than Solar tides.

Occulter Effectiveness: Relative Contrast:



The graph above shows the star-to-planet contrast (in-pixel contrast ratio) achievable for different primary mirror-to-occulter width ratios as a function of the wavelength-normalized telescope resolution (λ/D). In reflected light, the luminosity ratio of a terrestrial planet to the host star is 10^{-10} and 10^{-8} for Jupiter-like planets.

The actual detection contrast for terrestrial planets is obtained by multiplying the luminosity ratio by the "in-pixel contrast". For D/W=0.1, at 6 Airy rings (6λ/D), we expect a contrast of ~100. At 5 Airy rings, we expect a contrast ~1-10.

Using a 4-meter telescope at 5500A, λ/D=0.026". With the addition of a 10-meter occulter (D/W=0.4), at 20,000 kilometers from the telescope, an in-pixel contrast ratio of 10^{10} is achievable at λ/D=7; i.e., 0.18" from the target star.