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 imaging detection concepts: interferometry and coronagraphy. We present an 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.

Spacecraft Occulters

We have explored combining an apodized square aperture space telescope with an external occulter (Kochte, et al. 2002), which we call the Umbral Missions Blocking Radiating Astronomical Sources (UMBRAS) project, for the purpose of observing extrasolar terrestrial planets (Schultz, et al. 2003; Schultz, et al. 2002; Schultz, et al. 2000). Relative configuration of an external occulter operating with a space telescope is depicted in Figure 1. The telescope points at the target as the occulter craft interposes itself between the target and the telescope. The occulter, a Solar Powered Ion-Driven Eclipsing Rover (SPIDER), is autonomous and coordinates its activities with the telescope. Imaging of the field is used to map the star field, locate the target, locate the occulter, and support formation control once the occulter is in the target-telescope line-of-sight (TTLOS).

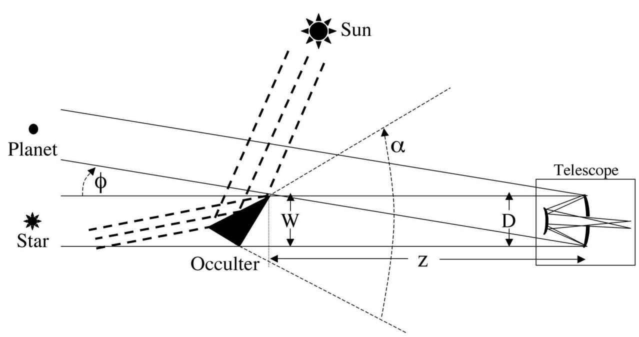

Figure 1: Constellation of spacecraft

The physical size of the occulter (W), its distance from the telescope (z), observing wavelength (λ), and ability to maintain alignment are major factors in the resulting on-axis starlight reduction. Velocity matching of the SPIDER with the telescope and formation control are achieved with small impulse thrusters on the SPIDER and communication between the telescope and the SPIDER (Hart, et al, 2000). The automated SPIDER formation control tasks are implemented by the Attitude and Translational Control System (ATCS). Figure 2 depicts a conceptual design of the occulter spacecraft.

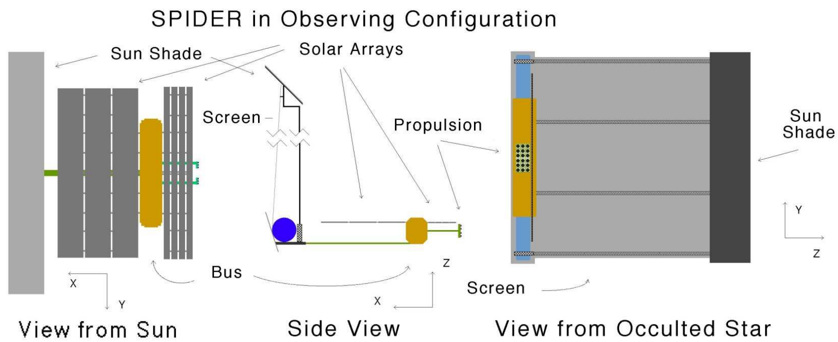

Figure 2: Three views of the SPIDER (Jordan, et al., 2000)

Apodized Square Aperture Telescopes

Apodized square aperture telescopes have been studied by Schultz, et al (1984), Nisenson and Papaliolios (2001), and Gezari, et al (2002). They have the advantage of redirecting much of the diffracted starlight along preferred orthogonal spikes. Apodization reduces the resolution, but increases the depth of the nulls between diffraction spikes. We combine these techniques with an external occulter.

Optical Analysis and Simulations

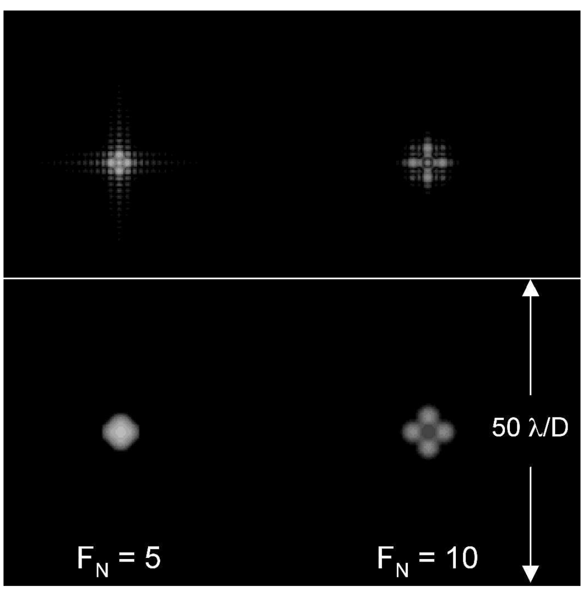

Figure 3: Focal plane simulation of a square occulter with a square aperture telescope where D/W=0.5

Optical analysis 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; see also Figure 1). Figure 3 illustrates model PSFs expected at the focal plane, with and without telescope apodization (upper pane is unapodized, lower pane is with crossed 4th order Sonine apodization applied), for a D/W=0.5. Note that if occulter width is held constant for a given wavelength, as the Fresnel number increases then the occulter is, in effect, moving closer to the telescope. Two simulations are provided to show the effect on the PSF for different separations between the occulter and the telescope.

Occulter Effectiveness

Figure 4 shows the “in-pixel contrast”, i.e., the ratio of the star flux to the planetary flux in a $(\lambda/D)^2$ pixel, as a function of angular separation between the planet and star. In reflected visible light, the luminosity ratio of a terrestrial planet to the host star is typically in the range of 10^{-10} (corresponding to “10” on the y-axis in Figure 4), while Jupiter-like planets have contrast ratios of 10^{-8} (“08” on the y-axis in Figure 4).

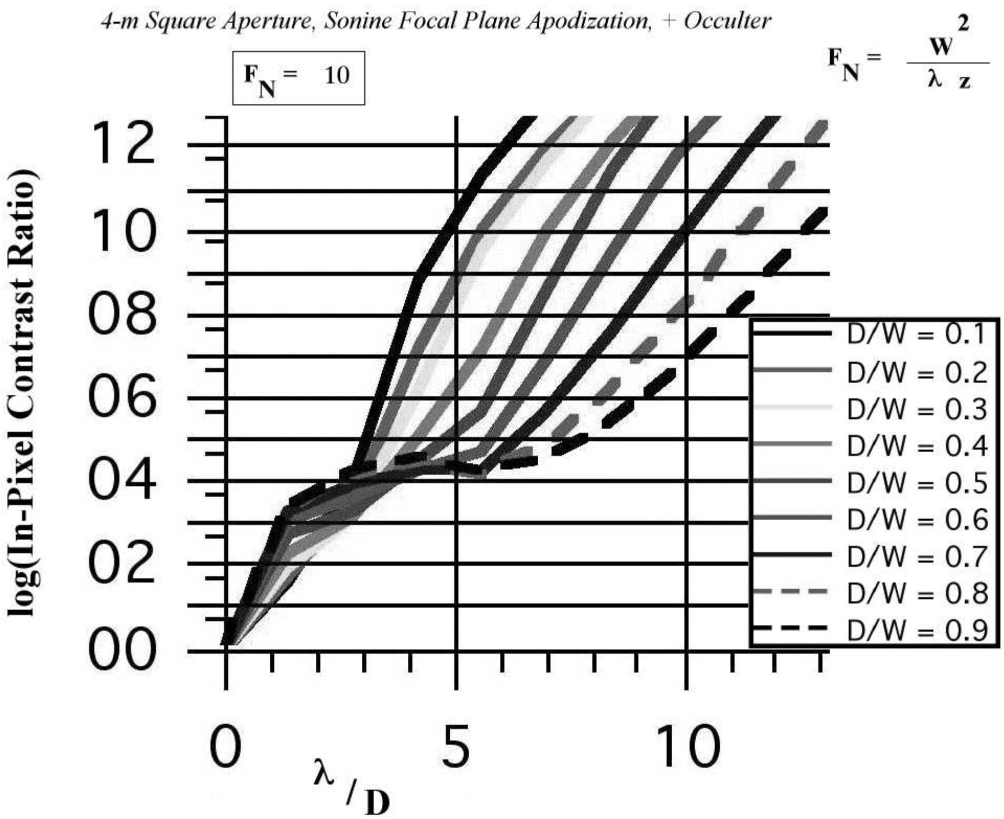

Figure 4: Contrast ratio in the focal plane PSF wavelength normalized to aperture.

The actual measured contrast is obtained by multiplying the luminosity ratio by the in-pixel contrast that is plotted in Figure 4. By intersecting the expected terrestrial planet contrast (a horizontal line on the y-axis) with one of the plotted contrast ratio curves (D/W), one can determine the angular separation needed to detect the planet.

Using a 4-meter telescope at 5500A, $\lambda/D=0.026''$. For D/W=0.5 (8-meter occulter) at 12,800 kilometers from the telescope, the in-pixel contrast ratio of 10^{10} is achievable at ~7.5 λ/D (0.19”). If instead a 10-meter occulter (D/W=0.4) is used at 20,000 kilometers from the telescope, an in-pixel contrast ratio of 10^{10} is reached at $\lambda/D=7$; i.e., 0.18” from the target star.

Occulter Advantages

An external occulter has a number of advantages over an onboard conventional coronagraph. These advantages are:

- Less on-axis starlight entering the telescope
- Mirror polishing tolerances can be less stringent
- Lower technological readiness
- Ability to utilize any instrument on the telescope – imaging, spectroscopic, or interferometric

References

1. Schultz, A., et al. 2003 SPIE Meeting, San Diego, CA, *Imaging Terrestrial Planets with a Free Flying Occulter and Space Telescope: An Optical Simulation*
2. Gezari, D.Y., et al. 2002, SPIE Conference, Waikoloa, HI, *ExPO: A Discovery-class Apodized Square Aperture (ASA) Exo-Planet Imaging Space Telescope Concept*
3. Schultz, A, et al. 2002, SPIE Conference, Waikoloa, HI, *UMBRAS: A Matched Occulter and Telescope for Imaging Extrasolar Planets*
4. Kochte, M, et al. 2002, 199th AAS Conference, Washington, D.C., *Free-flying Occulters for Use with Space Telescopes*
5. Nisenson, P., Papaliolios, C., 2001, ApJ, 548, L201, *Detection of Earth-like Planets Using Apodized Telescopes*
6. Jordan, I.J.E., et al. 2000, AIAA Space 2000 Conference & Exposition, Long Beach, CA,*UMBRAS: Design of a Free-Flying Occulter for Space Telescopes*
7. Hart, H.M, et al. 2000, SPIE Meeting Quebec City, Canada, *Imaging Planets About Other Stars with UMBRAS: Target Acquisition and Station Keeping*
8. Schultz, A. et al. 2000, SPIE Meeting, San Diego, CA, *Imaging Planets About Other Stars with UMBRAS II*
9. Schultz, A., Frazier, T.V., Kosso, E., 1984, Applied Optics 23, 1914, *Sonine’s Bessel Identity Applied to Apodization*