National Aeronautics and Space Administration

Modelling optimal nulling configurations for characterizing exoplanets inside the coronagraphic regime

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Objective: To find optimal single-telescope nulling-interferometry configurations for visible/near-infrared exoplanet observations that could increase the exoplanet yield of NASA's future coronagraphic exoplanet flagship mission. Nulling options range from classical single- and multiple-baseline nullers to novel vortex fiber nullers that apply a spiral phase ramp to a pupil prior to nulling in a single-mode fiber. Our objective here was to compare the sensitivity of potential nulling configurations on a common basis, so as to identify optimal cases.

Background: Exoplanet imaging and spectroscopy is the top priority of the recent Astronomy Decadal Report. However, coronagraphic exoplanet observations are typically limited to star-planet separations > a few diffraction beamwidths, leaving most exoplanets unobservable. To increase future exoplanet mission yield, it is imperative to reach smaller separations, where reflected-light exoplanets should be brighter and more numerous. This can be done with cross-aperture nulling interferometry (nulling starlight between different parts of a single telescope aperture). As many nulling configurations within a single large telescope aperture are possible, it is important to find optimum configurations.

Approach and Results: We developed a model of single-mode nulling interferometer configurations that calculates optical point spread functions and efficiencies (throughputs). A systematic examination of nulling options has led to three results - a topological viewpoint that unites multi-aperture nullers and single-aperture phase-based coronagraphs in a common geometrical framework (Fig. 1), a new type of phase-mask ("split-ring") coronagraph (Fig. 1), and a clear identification of optimal nulling configurations (Fig. 4). (An optimal configuration has both a small inner working angle and a high throughput for exoplanet light.)

Our systematic comparison of nulling configurations (Figs. 2 & 3) shows that single-mode nullers all have very small IWAs, with peak throughputs roughly one diffraction beamwidth off the star, and an inner working angle ~ half that (Fig. 4). We also found that subaperture-based nullers have lower efficiencies than those using the entire telescope aperture, such as the vortex and phase-knife fiber nullers (in the latter, an achromatic pi-radian phase shift is applied to half the pupil prior to focusing onto a single-mode fiber). We specifically focused on the large family of "circular" nulling configurations, with the number of (also circular) subapertures ranging from 2 to 6, but also included the vortex and phase-knife nuller cases. Clear optimal pupil configurations emerged from this analysis (Fig. 4), with the highest efficiency (~ 35% for a circular telescope aperture) found for the aperture-plane phase-knife nuller, almost double that of the next best case, the vortex fiber nuller (~ 19%). The phase-knife nuller's angular response also allows for locating exoplanets in azimuth, whereas the vortex fiber nuller does not. The former thus has best sensitivity for exoplanets at known azimuths, while the latter allows (lower sensitivity) spectroscopy even without azimuthal information. Both of these configurations thus have useful roles to play.

Significance/Benefits to JPL and NASA: The number of exoplanets accessible to high-contrast imaging and spectroscopy with a large space telescope can be increased by increasing the telescope diameter or by decreasing the separation from stars at which planets can be observed. Nulling interferometry within a telescope pupil can see in to smaller separations than a coronagraph, and here we have identified optimal cases (the phase-knife fiber nuller for exoplanets at known azimuths, and the vortex fiber nuller for exoplanets with unknown azimuths). Both enable observations in to roughly half a diffraction beam width from a star. These optimal small-angle nulling configurations should be of great interest to NASA, as they could increase the exoplanet yield of future exoplanet space telescopes.

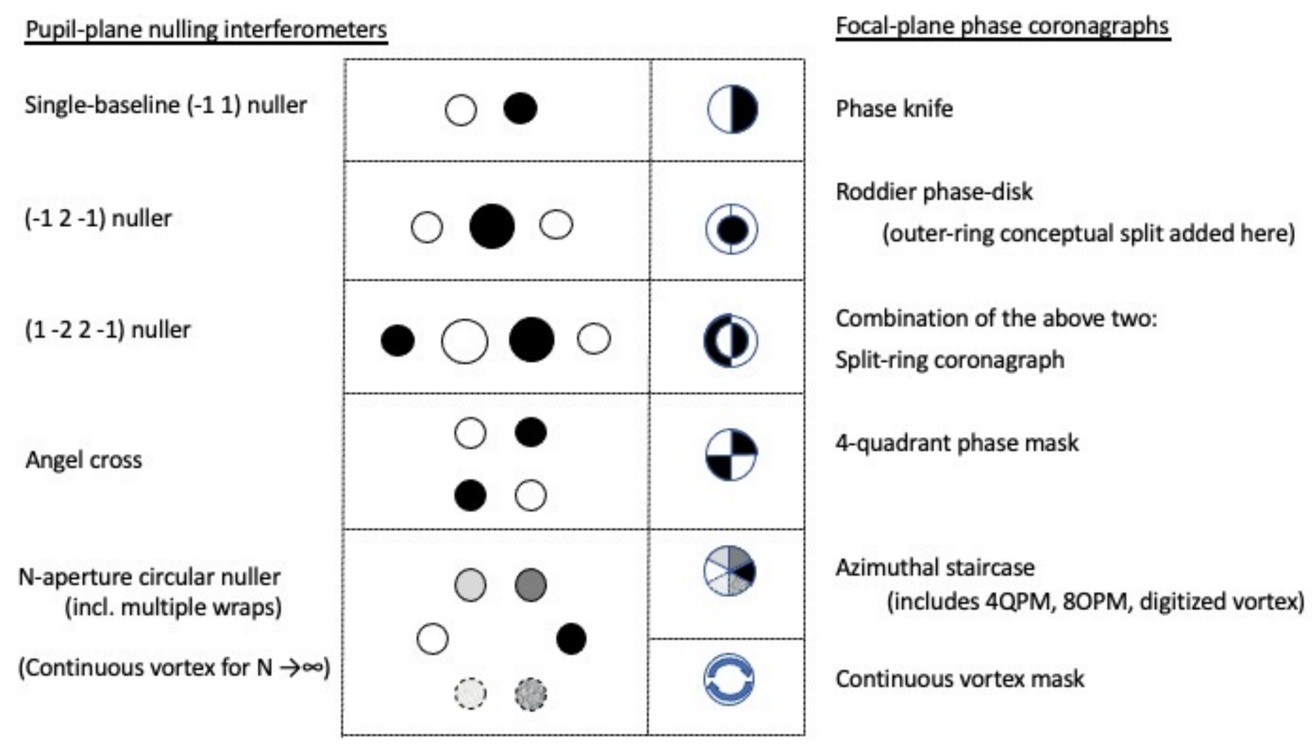

Fig. 1. Comparison of separated-aperture nulling interferometer configurations (left) with focal-plane phase mask configurations used in phase coronagraphy.

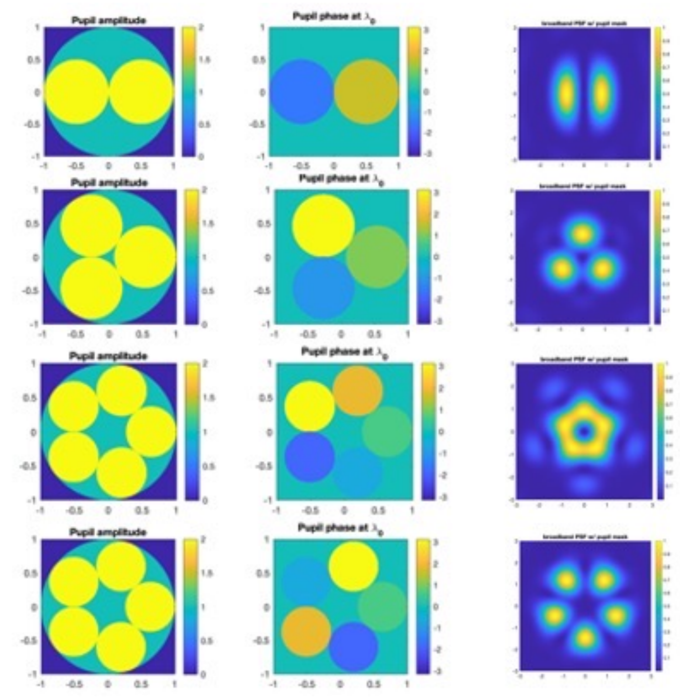

Fig. 2. Comparison of aperture intensities and phases, and resultant point spread functions for the cases of 2, 3 and 5 maximal subapertures within a circular telescope aperture. For > 3 apertures, multiple phasings are possible.

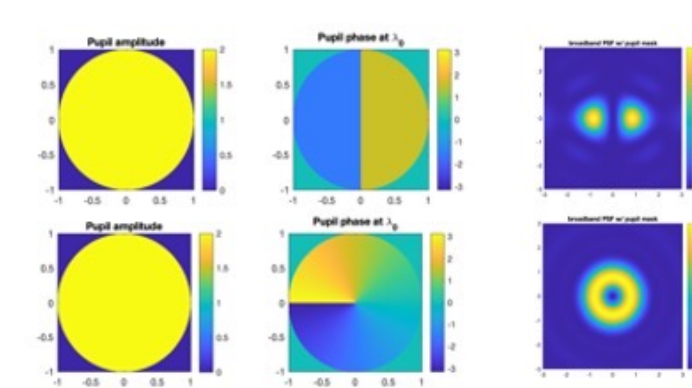

Fig. 3. Aperture amplitudes and phases, as well as resultant point-spread functions, for the phase-knife and vortex fiber nullers.

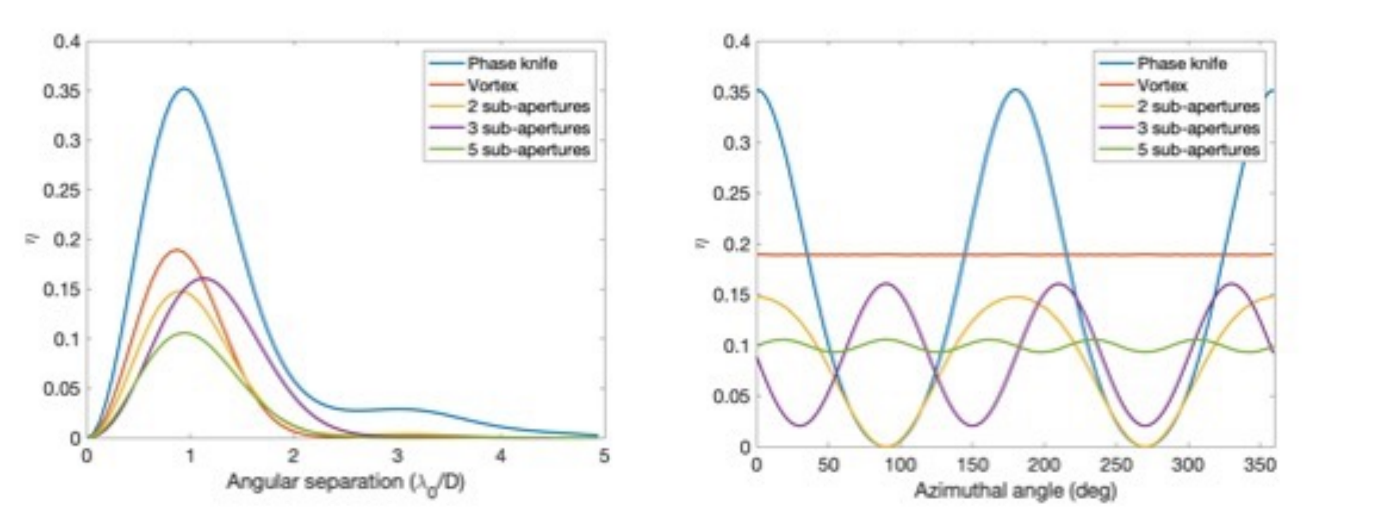

Fig. 4. Left: Transmission efficiencies vs. separation angle for the configurations seen in Figs. 2 & 3. Right: Associated azimuthal response patterns.

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