Scalar Vortex Masks for Exoplanet Direct Detection

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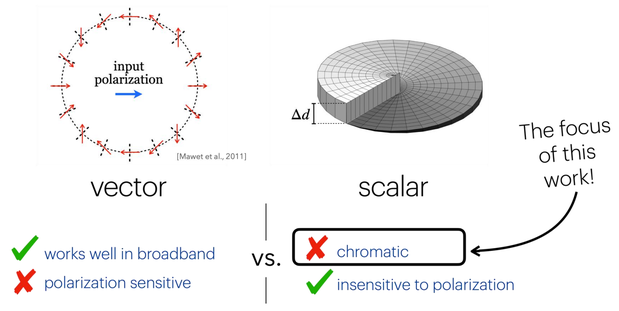
Background:

Direct detection and characterization of Earth-like exoplanets requires efficient starlight suppression at high contrast and small angular separations. Scalar vortex phase masks are applicable to both coronagraphy and fiber nulling to achieve this goal. They offer a promising alternative to vector vortex masks due to their inherent dual-polarization operation and lower cost. These advantages make them attractive for both space-based missions and ground-based on-sky demonstrations; motivating the development of scalar vortex masks capable of broadband performance.

HWO: The current starlight suppression architectures being considered for NASA's Habitable Worlds Observatory (HWO) are limited by their coronagraphic masks, and none have demonstrated the required 10^{-10} contrast in broadband light at their inner working angle. The scalar vortex coronagraph (SVC) has shown the potential to reach HWO level performance and is being tested in JPL's High Contrast Imaging Facility (HCIT).

HiSPEC: Direct imaging of close companions is limited by the inner working angle of coronagraphs. Vortex fiber nulling (VFN) provides an alternative that enables detection at separations < 1 λ/D. HiSPEC is a single-mode fiber-fed spectrograph (R~100,000) being built at Caltech for Keck Observatory that will include a VFN mode and could enable the first on-sky demonstration of scalar VFN.

Two flavors of vortex phase mask:

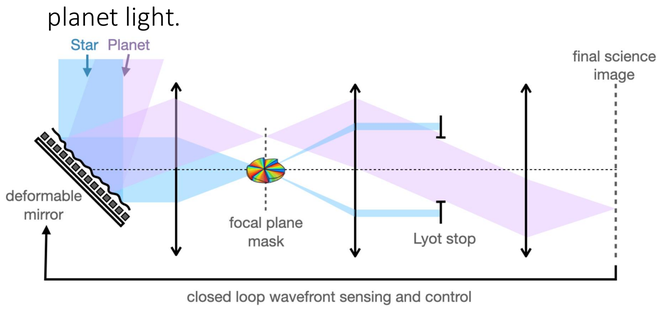


Scalar vortex masks offer dual-polarization performance but need to be made broadband-capable.

Scalar Vortex Coronagraphs for HWO:

How a vortex coronagraph works:

A vortex phase mask imprints a spiral phase pattern on the PSF and clips the `ring of fire' with a Lyot stop: rejecting on-axis starlight while transmitting off-axis planet light.

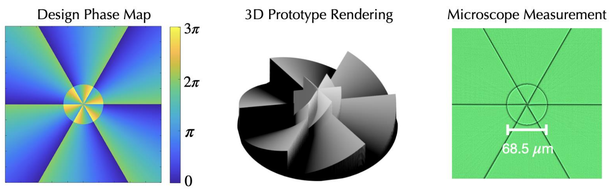


Objective:

Develop an achromatic charge 6 scalar vortex phase mask and demonstrate it on a high contrast imaging testbed to measure the deepest possible contrast in 3-10 λ/D in 10% broadband light.

Approach:

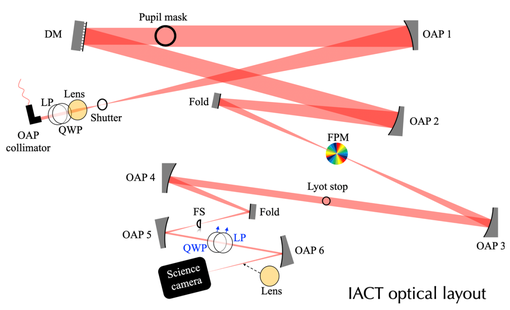
We fabricated new SVC designs combining a sawtooth scalar vortex and central π phase shift to address chromatic leakage. These dimpled vortex masks predict 10^{-9} level contrast across a 10% bandwidth.



HCI Testbed Results:

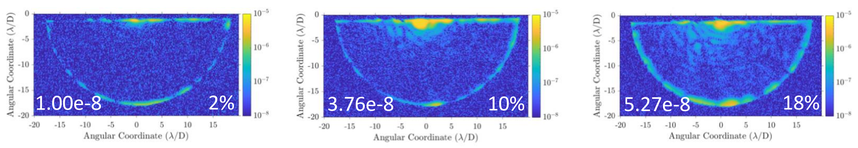
In-Air:

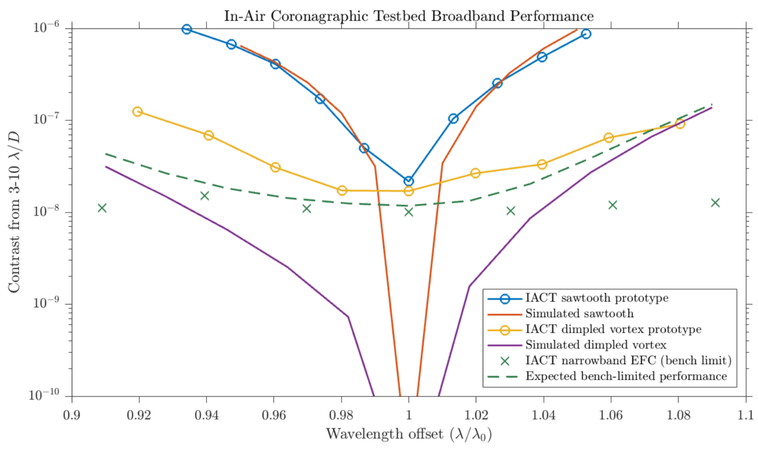
The new dimpled vortex prototypes were first tested on the In-Air Coronagraphic Testbed (IACT) with wavefront control with a single DM.



IACT optical layout

Narrowband dark hole contrasts from 3-10 λ/D reach the contrast floor of the bench. Comparing the simulated and lab-measured contrast as a function of wavelength allows for model validation of SVC designs.





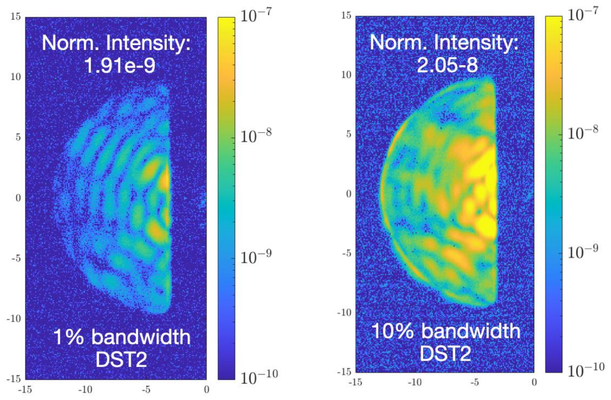
Narrowband EFC runs [x] at each wavelength across the full 20% band all reach ~1e-8 contrast. This estimate of the IACT contrast floor is added to the theoretical performance to provide an expected bench-limited contrast performance.

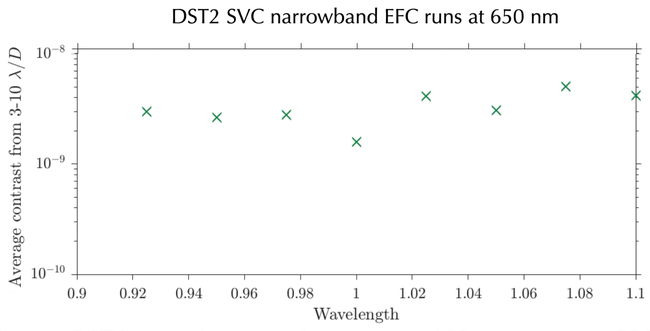
In 10% and 18% broadband light, the new dimpled vortex shows a great improvement in contrast over the previous sawtooth prototype and matches the model-predicted performance within a factor of 2.

In-Vacuum:

Ongoing testing with the Decadal Survey Testbed 2 (DST2) has achieved an order of magnitude improvement in SVC narrowband contrast and SVC narrowband EFC runs reach the 10^{-9} bench limit across the full 20% band!

NEW SVC CONTRAST RECORD!!



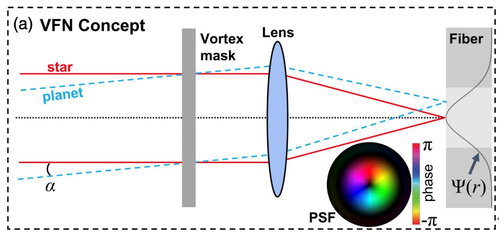


Future DST2 experiments will tune the 10% broadband EFC parameters (regularization) to measure the limit of the single dielectric SVC in vacuum.

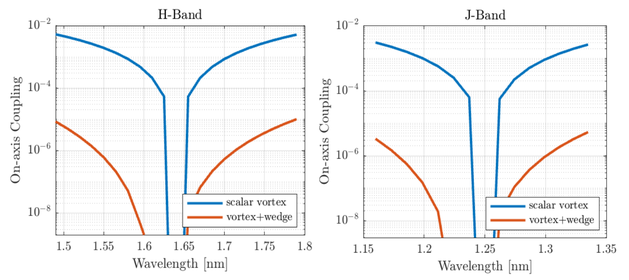
Scalar VFN for HiSPEC

How vortex fiber nulling works:

A vortex phase mask can be placed in the *pupil plane* to null on-axis star light and couple only off-axis planet light into the output fiber.



HiSPEC Simulations:

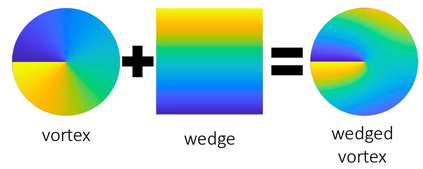


Objective:

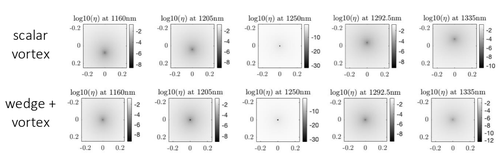
Demonstrate scalar VFN by developing and validating achromatic charge 1 scalar vortex masks for HiSPEC that achieve broadband average nulls below 10^{-4} for 20% bandwidth.

Approach:

A simple scalar vortex with VFN leads to a chromatic displacement in the null. Since the dispersion is roughly linear, we counteract the null shift with an optimized wedge.



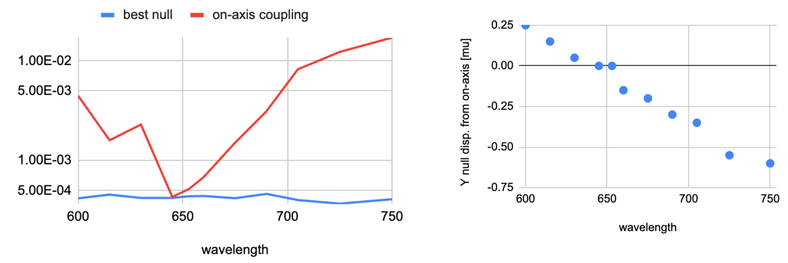
Simulations of the scalar vortex+wedge show the null positions are restored to on-axis.



Specifically, for HiSPEC, integrating a wedge into the phase of a scalar vortex improves H band and J band broadband nulling by 3-4 orders of magnitude!

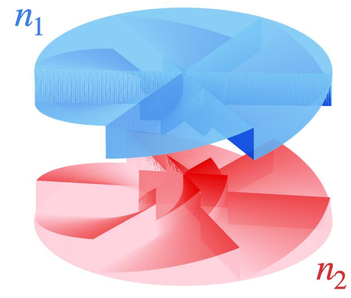
PoRT Bench Results:

Preliminary measurements of a 650 nm scalar vortex on the Polychromatic Reflective Testbed (PoRT) at Caltech show the null is preserved and shifted off-axis as a function of λ.



Future Work: the Dual Layer SVC

Reaching broadband contrast at 10^{-10} for HWO relies on moving from single layer dielectric SVC designs to dual layer optics. By matching materials with dissimilar dispersion properties, we have found new manufacturable dual layer designs that show predicted contrast < 10^{-10} level.



Fabrication will be underway at JPL's MDL soon!