

## A Multiwavelength Differential Imaging Experiment for the High Contrast Imaging Testbed

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**ABSTRACT.** We discuss the results of a multiwavelength differential imaging lab experiment with the High Contrast Imaging Testbed (HCIT) at the Jet Propulsion Laboratory. The HCIT combines a Lyot coronagraph with a Xinetics deformable mirror in a vacuum environment to simulate a space telescope in order to test technologies and algorithms for a future exoplanet coronagraph mission. At present, ground-based telescopes have achieved significant attenuation of speckle noise using the technique of spectral differential imaging (SDI). We test whether ground-based SDI can be generalized to a nonsimultaneous spectral differential imaging technique (NSDI) for a space mission. In our lab experiment, a series of five filter images centered around the O<sub>2</sub>(A) absorption feature at 0.762  $\mu\text{m}$  were acquired at nominal contrast values of  $10^{-6}$ ,  $10^{-7}$ ,  $10^{-8}$ , and  $10^{-9}$ . Outside the dark hole, single differences of images improve contrast by a factor of  $\sim 6$ . Inside the dark hole, we found significant speckle chromatism as a function of wavelength offset from the nulling wavelength, leading to a contrast degradation by a factor of 7.2 across the entire  $\sim 80$  nm bandwidth. This effect likely stems from the chromatic behavior of the current occulter. New, less chromatic occulters are currently in development; we expect that these new occulters will resolve the speckle chromatism issue.

### 1. INTRODUCTION

While over 300 exoplanets have now been discovered indirectly via radial velocity, transits, or gravitational lensing, to date only a handful of planets have been directly imaged around a main-sequence or pre-main-sequence star (Kalas et al. 2008; Marois et al. 2008). Most other detection methods (e.g., radial velocity and transit) are more sensitive to close-in planets than those at greater distance from their stars. Direct imaging is the only method currently capable of detecting planets  $>10$  AU from their parent stars. Numerous adaptive optics and space-based surveys to directly image young Jupiter mass planets in the near-IR (Biller et al. 2007; Lafrenière et al. 2007; Farihi et al. 2007) have recently been completed; these surveys have placed strong statistical limits on extrasolar planet distributions but have produced no planet detections. Clearly, directly imaging planets is a nontrivial undertaking—and one that becomes even more difficult for terrestrial planets.

In order to successfully image a planet, one must first overcome: (1) the huge contrast difference between star and planet (the very youngest Jovian planets will be  $10^{-5}$  times fainter than

their parent star, while a terrestrial planet will be  $\sim 10^{-10}$  times fainter). Modern approaches to planet-finding often employ a Lyot coronagraph to achieve these contrasts (e.g., Kuchner & Traub 2002). (2) Even once the initial star-planet contrast has been achieved, residual superspeckles remain (from errors in the wavefront due to imperfect optics) and produce a limiting “speckle” noise floor which prevents planet detection. This is seen both from the ground and space (e.g., the “breathing” effect seen by the *Hubble Space Telescope*, *HST*).

A number of instrumental speckle suppression techniques have been suggested and implemented on ground-based telescopes (and in testbed scenarios for space-based telescopes), including azimuthal differential imaging (ADI, a.k.a. roll subtraction, see, e.g., Marois et al. 2006; Lafrenière et al. 2007), simultaneous spectral differential imaging (SDI, see e.g., Marois et al. 2005; Biller et al. 2007; Lenzen et al. 2004; Chun et al. 2008), imaging polarimetry (Perrin et al. 2008; Thalmann et al. 2008; Oppenheimer et al. 2008), various methods of focal plane wavefront sensing (Guyon et al. 2006, 2009; Codona et al. 2008; Kenworthy et al. 2006), and the use of Integrated Field Spectrographs (IFS) to separate speckles (which modulate with wavelength) from real companions (which do not) (Larkin et al. 2006; McElwain et al. 2007; 2008; Claudi et al. 2008). In this article we focus on the possible application of the SDI technique to a space-based telescope platform.

From the ground, the SDI technique has been used after adaptive optics (AO) correction to remove residual speckle noise without removing planet light. SDI has been implemented

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on the TRIDENT device at the CFHT (Marois et al. 2005), on the Simultaneous Differential Imager at the VLT and MMT (Biller et al. 2007; Lenzen et al. 2004) and, more recently, with a coronagraph, on the Near-Infrared Coronagraphic Imager at Gemini South (Chun et al. 2008). SDI attenuates speckle noise by exploiting a spectral feature in the desired target (previous implementations utilize the  $1.6 \mu\text{m}$  methane absorption feature robustly observed in substellar objects cooler than 1400 K). Images are taken simultaneously both within and outside the chosen absorption feature. Due to the simultaneity of the observations, the star and the coherent speckle pattern are largely identical in both filters, while a faint companion with that absorption feature is bright in the continuum filter and faint in the absorbed filter. Subtracting the absorbed filter image from the continuum filter image thus removes the starlight and speckle patterns, while a real companion with the chosen absorption feature remains in the subtraction image. In other words, the off-absorption band image acts as an ideal reference point spread function (henceforth PSF) for the absorption band image. Utilizing a signature spectral feature of substellar objects greatly reduces the number of false positives detected (e.g., a faint background object, while real, will drop out of the SDI subtraction since it will not have methane absorption). From the ground, significant attenuation of speckle noise has been achieved with SDI. For example, Biller et al. (2007) achieved H band contrasts  $>25000(5\sigma\Delta F1[1.575 \mu\text{m}] > 10 \text{ mag}, \Delta H > 10.8 \text{ mag}$  for a T6 spectral type) at a separation of  $0.5''$  from the primary star. With this degree of attenuation, it is possible to image ( $5 \sigma$  detection) a  $2 M_J$  planet at 5 AU around a 10 Myr M0 star at 10 pc (Biller et al. 2007; Fortney et al. 2008).

SDI on ground-based telescopes provides significant speckle attenuations down to star-planet contrasts of  $\sim 0.3\text{--}1 \times 10^{-4}$ . To test the classical SDI technique at contrasts of  $10^{-6}$  to  $10^{-9}$  and to determine whether such a technique would be applicable for the detection of terrestrial planets for a possible exoplanet coronagraph, e.g., a Terrestrial Planet Finder mission, we implemented a similar multiwavelength differential imaging scheme for the High Contrast Imaging Testbed (henceforth HCIT, described in detail in the supplemental material to Trauger & Traub 2007) at the Jet Propulsion Laboratory. The HCIT combines a band-limited Lyot coronagraph with a  $32 \times 32$  actuator Xinetics deformable mirror in a vacuum environment (Trauger et al. 2004) to simulate a space telescope in order to test technologies and algorithms for future coronagraph missions. The HCIT has demonstrated extremely high contrasts and very fine wavefront control; contrasts of  $10^{-10}$  have been achieved, sufficient to image an Earth-like extrasolar planet (Trauger & Traub 2007).

## 2. EXPERIMENTAL DESIGN

Five 2% bandwidth filters were selected near the prominent  $\text{O}_2(\text{A})$  absorption feature at  $0.762 \mu\text{m}$  (seen in Earth's atmosphere and expected for any terrestrial extrasolar planet with

an oxygen atmosphere, Woolf et al. 2002) with approximate central wavelengths of  $F1(768 \text{ nm})$ ,  $F2(784 \text{ nm})$ ,  $F3(800 \text{ nm})$ ,  $F4(816 \text{ nm})$ , and  $F5(832 \text{ nm})$ . Exact filter wavelengths and bandwidths are presented in Table 1—however, approximate wavelengths are used to refer to the filters throughout the text. Two sets of images were taken in each filter—a long set, with 90 s exposure time per filter, and a short set, with 5 s exposure time per filter. The filter set was spaced across a considerable bandwidth in wavelength in order to measure speckle chromatism as a function of wavelength. The light source used for this experiment is a passively Q-switched Nd:YAG 1060 nm laser. This laser delivers subnanosecond pulses into a single-mode supercontinuum photonic crystal fiber, producing light with a relatively smooth spectrum from 600 nm to 1600 nm and providing sufficient bandwidth and stability to conduct this experiment (Trauger & Traub 2007). Coronagraph setup was similar to that used in Trauger & Traub (2007).

For ground-based observing with adaptive optics (AO), quasistatic superspeckles due to residual instrumental errors remain even after AO correction (Marois et al. 2005; Masciadri et al. 2005). These superspeckles are stable on timescales of minutes to hours, but still vary quickly enough over a typical observation (1–2 hours; see, e.g., Hinkley et al. 2007; Marois et al. 2006) that a reference PSF must be built on similar timescales in order to overcome the stochastic speckle noise floor. (To build this PSF, ADI uses rotation on the sky to decorrelate speckles from real objects, SDI uses wavelength diversity, and imaging polarimetry uses images taken in different polarization states.) Thus, on the ground, simultaneous imaging in several bandwidths is desirable to successfully implement spectral differential imaging (SDI). For space-based observing, however, speckles are stable on much longer timescales of hours to days, making simultaneity of imaging less necessary (e.g., Sparks & Ford 2002). While proposed instrument designs (such as those for the *Terrestrial Planet Finder* and the *Eclipse* mission) utilize simultaneous imaging via either an integral field unit or dichroic beamsplitter, no multispectral backend imager was available at the HCIT.

Trauger & Traub (2007) demonstrated extreme speckle stability at the HCIT during a “movie experiment” where 480 individual snapshot images were recorded over a 5 hour period. They found that the change in speckle contrast in HCIT during this period (where the apparatus was allowed to drift freely) was

TABLE 1  
FILTER WAVELENGTHS AND BANDWIDTHS

Filter	Center Wavelength	FWHM
$F1$ .....	768.1 nm	15.1 nm
$F2$ .....	782.5 nm	15.6 nm
$F3$ .....	798.9 nm	15.9 nm
$F4$ .....	814.8 nm	16.3 nm
$F5$ .....	830.9 nm	15.5 nm

$\sim 0.1 \times 10^{-10}$  per 5 hours. This demonstrated speckle stability allowed the current experiment to be conducted nonsimultaneously with valid results. Additionally, the use of the same imaging channel avoids noncommon path wavefront errors between images and thus allows for a cleaner determination of inherent speckle chromaticity. The present multiwavelength differential imaging experiment measures speckle evolution as a function of wavelength and contrast level. We test whether the ground-based simultaneous spectral differential imaging technique can be generalized to a nonsimultaneous spectral differential imaging technique for a space mission.

By using a 5 filter set, we can attempt to correct for speckle chromatism using both single differences of images and the double difference technique pioneered by Marois et al. (2000). Since the radial position of the speckle pattern in each filter image is proportional to  $\frac{\lambda}{D}$ , the platescale of each image must be scaled so that the speckles in each filter fall at the same radii despite chromatic differences. After this scaling, a number of single differences as well as a double difference of images in the  $F1$  through  $F5$  filters are calculated:

$$I_{31} \equiv (F3 - F1) \quad (1)$$

$$I_{32} \equiv (F3 - F2) \quad (2)$$

$$I_{34} \equiv (F3 - F4) \quad (3)$$

$$I_{35} \equiv (F3 - F5) \quad (4)$$

$$I_{4332} \equiv (F4 - F3) - (F3 - F2) \quad (5)$$

$$I_{5331} \equiv (F5 - F3) - (F3 - F1). \quad (6)$$

In this document, we discuss preliminary results using the classical SDI data reduction method (i.e., no Fresnel propagation is considered.)

### 3. DATA ACQUISITION AND REDUCTION

Data were acquired in 2007 January. A series of five filter images was acquired, one at each nominal contrast value ( $10^{-6}$ ,  $10^{-7}$ ,  $10^{-8}$ , and  $10^{-9}$ ). High contrasts were achieved via speckle nulling in the  $F3$  800 nm filter. Speckle nulling iteratively removes speckles locally by correcting the wavefront with the deformable mirror. Speckles are “dialed out” one by one by programming in the appropriate antispeckle with the deformable mirror (Malbet et al. 1995; Trauger et al. 2002; Bordé & Traub 2006; Trauger et al. 2006). The HCIT operates at such high contrasts that speckles due to both phase errors and amplitude errors in the wavefront must be corrected. (From the

ground, at contrasts of  $\sim 10^{-4}$ – $10^{-5}$ , phase errors dominate so completely that amplitude errors can effectively be ignored; see, e.g., Guyon 2005; Soummer et al. 2007). However, only phase speckles can be dialed into the deformable mirror. This creates a symmetry issue when removing amplitude speckles (Bordé & Traub 2006). In the image, both phase and amplitude speckles will appear as a pair of symmetric point sources around the central PSF. However, when inspected in image plane electric field instead of image amplitude, phase and amplitude speckles appear rather different. Phase speckles are antisymmetric, while amplitude speckles are symmetric. Adding the opposite phase speckle on the deformable mirror (DM) will completely cancel out a phase speckle, but will only cancel out one side of an amplitude speckle. The other side of the amplitude speckle will be intensified (Bordé & Traub 2006). In our optical system, phase speckles dominate to contrasts of  $10^{-7}$ —up to these contrasts, a symmetric dark hole can be generated (Trauger et al. 2004). At contrasts better than  $10^{-7}$ , speckles are produced by a mix of phase and amplitude aberrations in the wavefront and the dark hole becomes asymmetric.

In this manner, the scattered light producing the speckles can be removed locally, however, the speckle solution is inherently asymmetric; high contrasts are achieved only in the right-side dark hole region. (Fig. 1 shows a schematic of the darkest portion of the dark hole region on the right and a comparison region on the left.) This is quite clear in our images (Fig. 2–Fig. 5)—at a contrast of  $10^{-6}$ , a slight dark hole is seen on both sides of the image but at contrasts of  $10^{-7}$  or better when amplitude errors must be taken into account, the dark hole appears only on the right side of the image. The size of this dark region is determined by the control radius of the deformable mirror, which

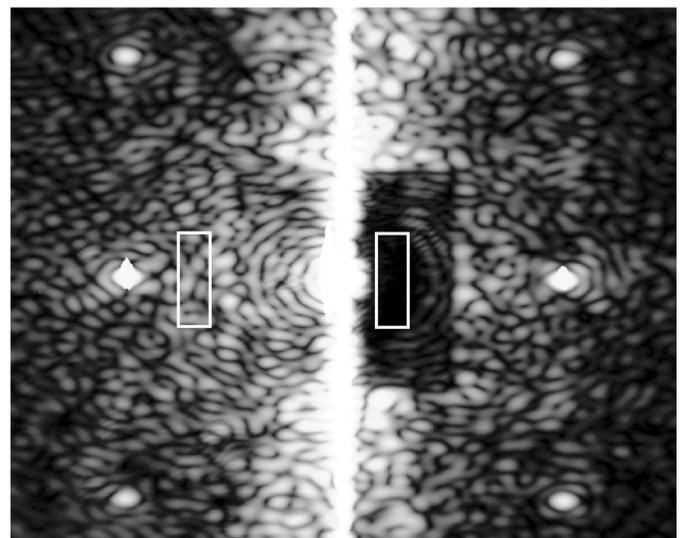


FIG. 1.—Boxes used for speckle RMS calculation (Table 2). See the electronic edition of the *PASP* for a color version of this figure.

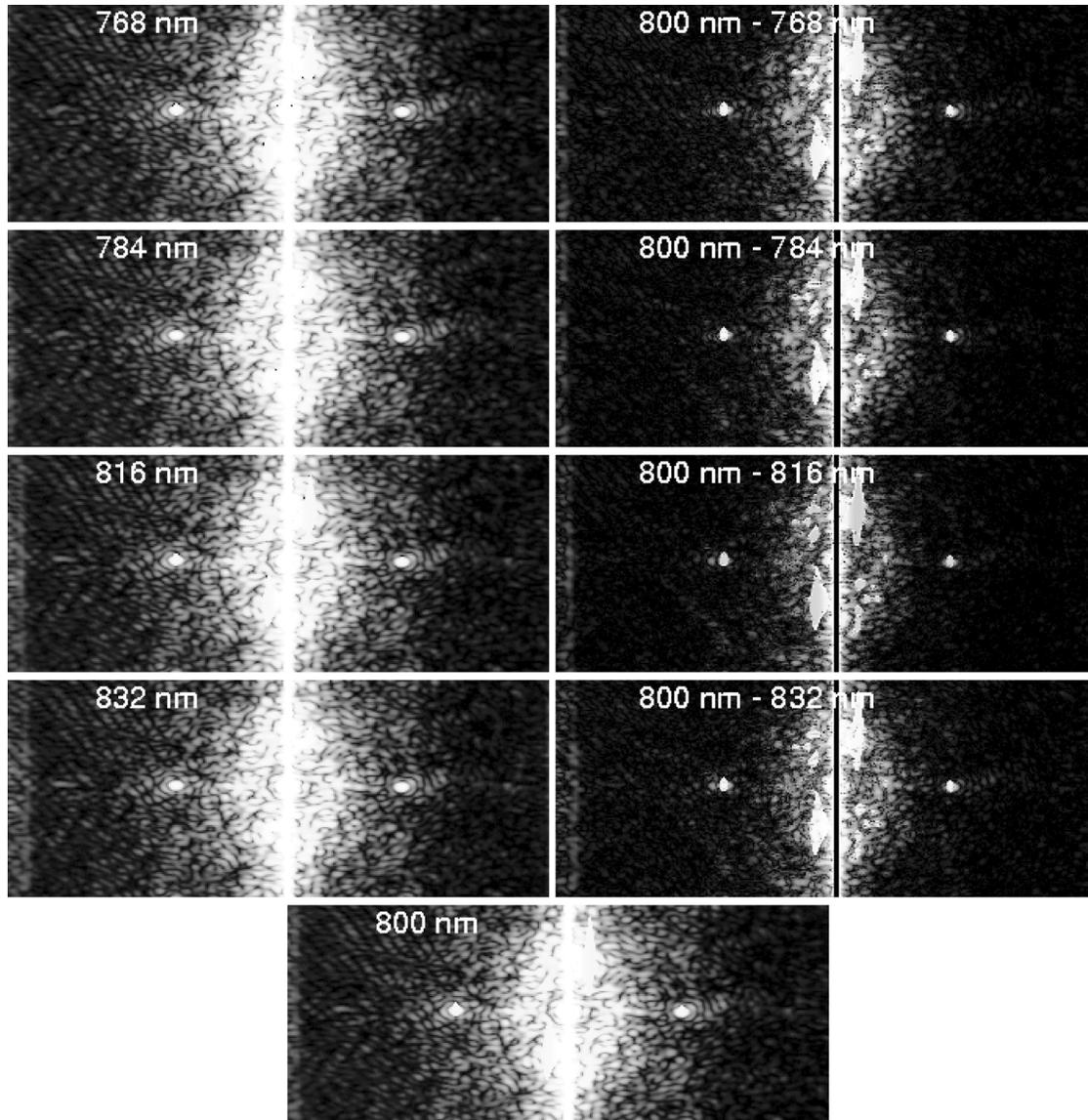


FIG. 2.—*Left*: Single wavelength image, *right*: NSDI. Gallery of single wavelength images and single differences with a nominal contrast level of  $10^{-6}$ . All images are shown with the same logarithmic stretch from contrasts of 0 to  $10^{-5}$ . The single subtractions suppress the speckles outside the dark hole by a factor of 5–50. The bright point sources outside the dark hole are ghosts produced by aliasing outside the control radius of the DM. See the electronic edition of the *PASP* for a color version of this figure.

is in turn determined by the total number of DM actuators and actuator spacing.

Once each contrast level was achieved via speckle nulling, two images (with exposure times of 90 s and 5 s) were acquired at each of the five filter wavelengths. Per-pixel S/N ratios (for pixels representative of the average contrast value in the image dark hole) are presented in Table 2. The gain of the CCD was 2.5 electrons  $\text{DN}^{-1}$ , with a read noise of 6 electrons  $\text{pixel}^{-1}$  rms. The total noise per pixel is a combination of shot noise and read noise

$$N = \sqrt{N_{\text{shot}}^2 + N_{\text{read}}^2}. \quad (7)$$

We focus on the 90 s dataset, since its signal-to-noise ratio (S/N) is considerably higher (by a factor of  $>4$ ) than that of the 5 s dataset. Unfortunately, significant saturation within the dark-hole region ( $\sim 5\%$  of pixels) occurred in the  $10^{-6}$  contrast images. We display these images since their qualitative features are still of interest, but exclude them from further analysis. Some saturation is seen in the  $10^{-7}$  to  $10^{-9}$  contrast images, but only far outside the dark hole and comparison regions. In fact, for these images, only ghost point sources considerably outside the dark hole were saturated. (These ghost point sources are produced by aliasing outside the control radius of the DM and are  $31 \lambda/D$  from the occulted star—in other words, far from

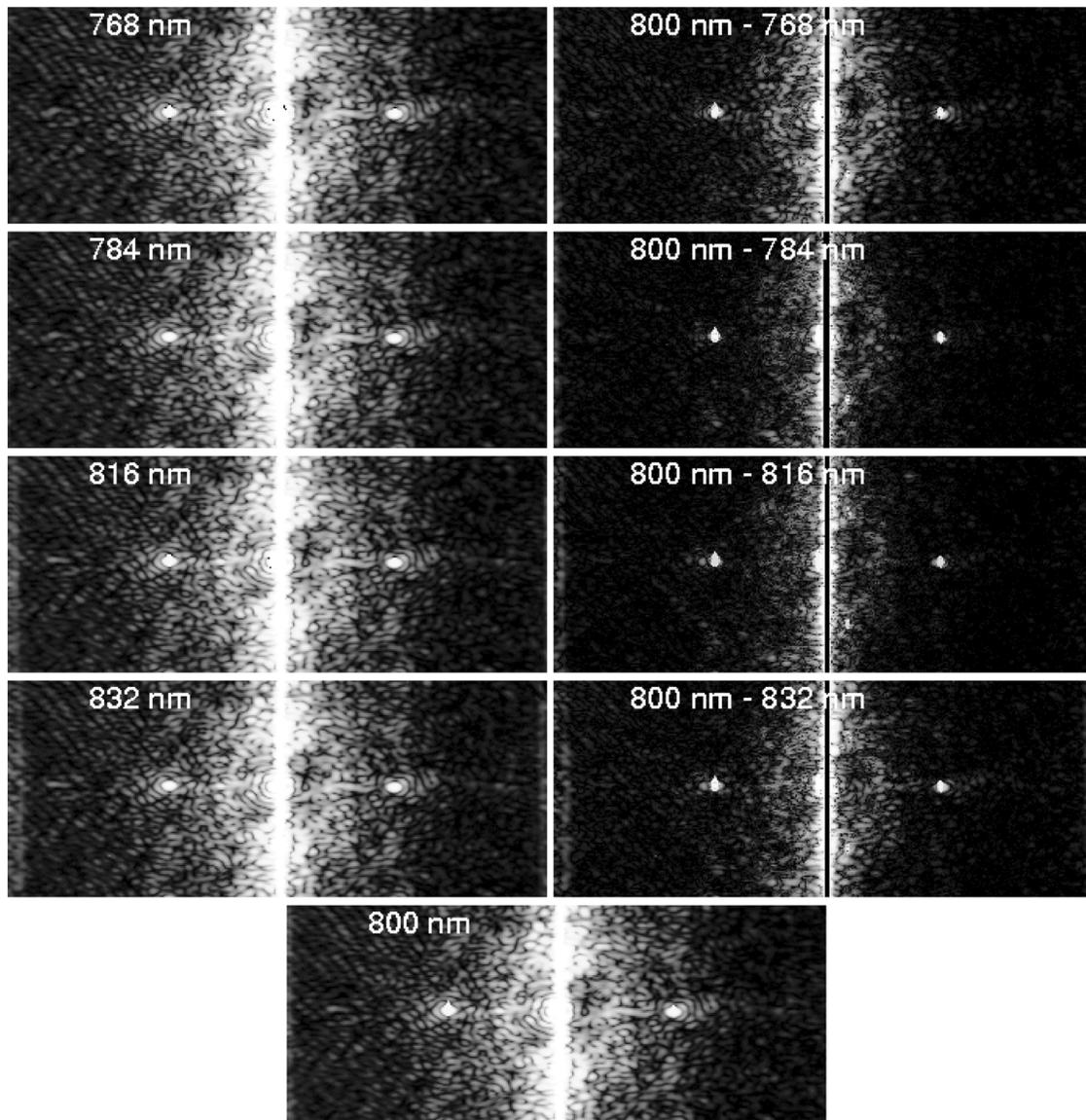


FIG. 3.—*Left*: Single wavelength image, *right*: NSDI. Gallery of single wavelength images and single differences with a nominal contrast level of  $10^{-7}$ . All images are shown with the same logarithmic stretch from contrasts of 0 to  $10^{-5}$ . The single subtractions suppress the speckles outside the dark hole by a factor of 5–50. The bright point sources outside the dark hole are ghosts produced by aliasing outside the control radius of the DM. See the electronic edition of the *PASP* for a color version of this figure.

any analysis region). Coronagraph images were bias and dark corrected, but no flat fielding was performed, as the CCD already exhibits a pixel-to-pixel DQE uniformity of better than 1% (Trauger & Traub 2007). Since the images in the nulled wavelength are of the highest quality and are the most reliable, the F3 800 nm filter image was used as the “master” image (for adjustment of platescale and alignment purposes) in this analysis.

Fluxes in each wavelength image were converted to the equivalent contrast via the following steps: (1) a “stellar PSF” was derived by offsetting the coronagraph mask by  $144 \mu\text{m}$  to the first maximum in transmission (in other words,

moving the star off the mask) and taking a  $30 \mu\text{s}$  snapshot image, (2) the “stellar peak” was estimated from the snapshot image and scaled to the appropriate peak signal for a 90 s data image, (3) each 90 s image was divided by the estimated peak signal to convert to contrast units, and (4) each peak signal corrected image was then divided by the analytic attenuation profile of the coronagraph mask (known to closely match the measured attenuation profile) to correct for attenuation. For more details on this process, see the supplemental material from Trauger & Traub (2007).

Since the radial position of the speckle pattern in each filter image is proportional to  $\lambda$ , the platescale of each image was

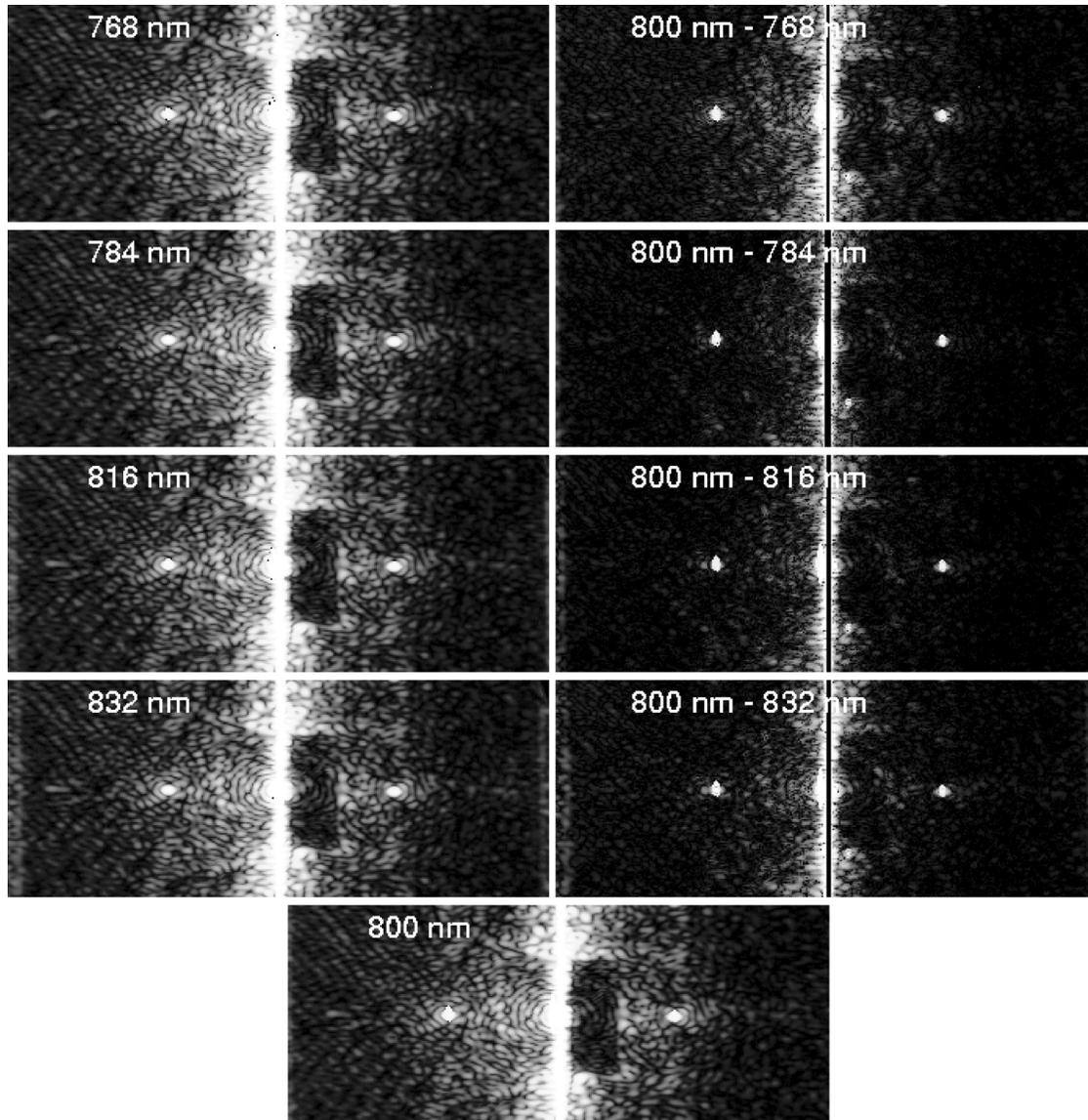


FIG. 4.—*Left*: Single wavelength image, *right*: NSDI. Gallery of single wavelength images and single differences with a nominal contrast level of  $10^{-8}$ . All images are shown with the same logarithmic stretch from contrasts of 0 to  $10^{-5}$ . The single subtractions suppress the speckles outside the dark hole by a factor of 5–50. The bright point sources outside the dark hole are ghosts produced by aliasing outside the control radius of the DM. See the electronic edition of the *PASP* for a color version of this figure.

scaled to the 800 nm image so that the speckles in each filter fall at the same radii despite chromatic differences. The exact filter central wavelengths presented in Table 1 were used for this scaling. To estimate the resampling noise introduced by wavelength scaling, we rescaled 20 randomly chosen  $40 \times 60$  pixel subimages from within each of the dark holes of the  $10^{-7}$ ,  $10^{-8}$ , and  $10^{-9}$  images (4 wavelengths  $\times$  3 contrast levels, so 240 subimages total were considered in this analysis). We then calculated the standard deviation in each subimage (using the `robust_sigma` algorithm in IDL) before and after scaling ( $\sigma_{\text{orig}}$  and  $\sigma_{\text{scaled}}$ , respectively). Resampling noise was estimated to be

$$N_{\text{resamp}} = \text{stddev}(\sigma_{\text{orig}} - \sigma_{\text{scaled}}). \quad (8)$$

We found values for the resampling noise of  $3.5\text{--}6.6 \times 10^{-11}$ , which, even at our best contrasts of  $10^{-9}$ , are negligible.

Finally, each wavelength image was aligned to the 800 nm image using a custom shift-and-subtract alignment algorithm (alignments are to 0.1 pixel precision, Biller et al. 2007). The resulting aligned images were subtracted from the master 800 nm image. Galleries of each aligned image and the resulting subtraction are presented for each nominal contrast level in Figures 2–5. These images are shown with a logarithmic stretch from contrast levels of 0 to  $10^{-5}$ . Speckle rms measured in

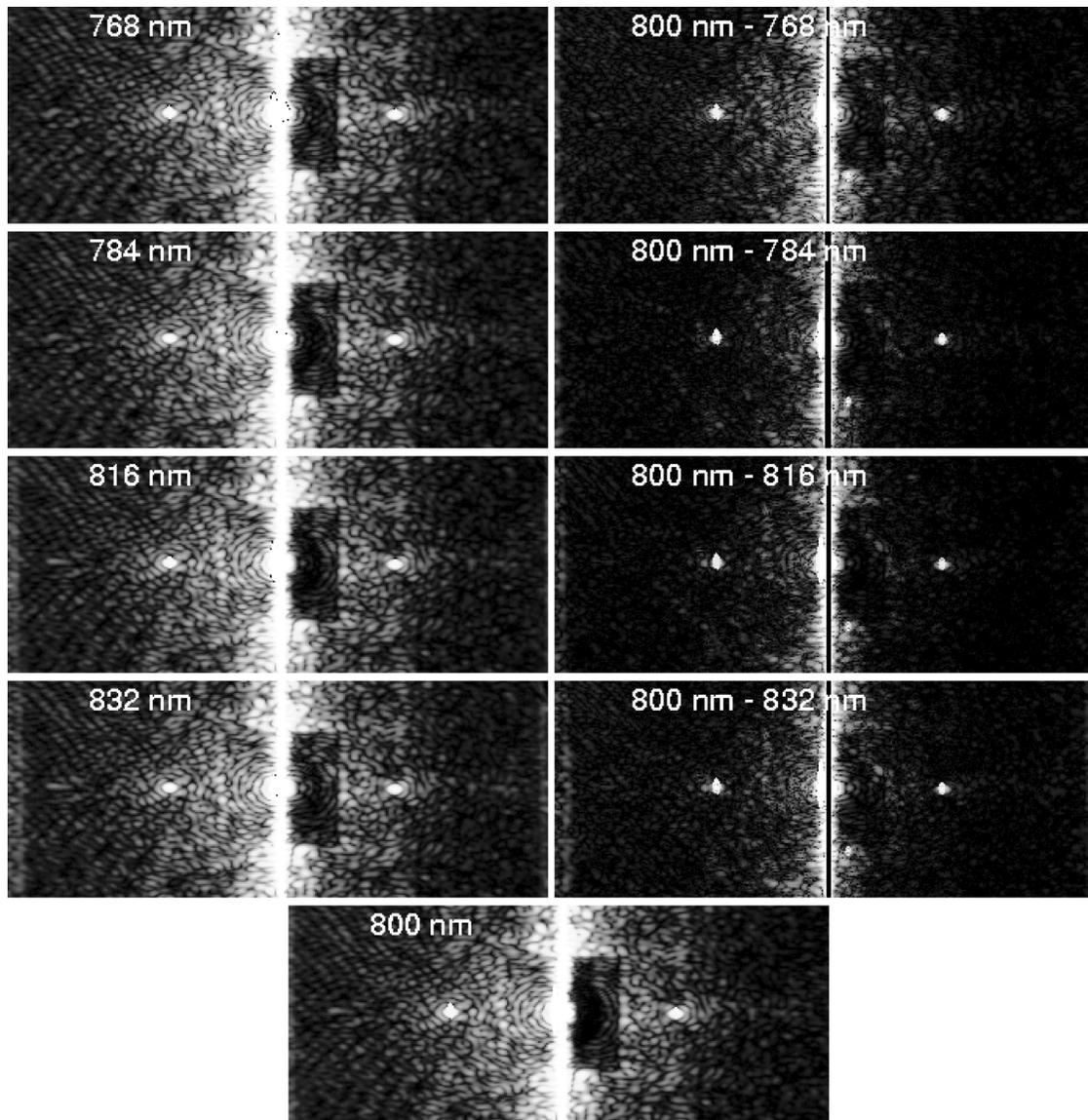


FIG. 5.—*Left*: Single wavelength image, *right*: NSDI. Gallery of single wavelength images and single differences with a nominal contrast level of  $10^{-9}$ . All images are shown with the same logarithmic stretch from contrasts of 0 to  $10^{-5}$ . The single subtractions suppress the speckles outside the dark hole by a factor of 5–50. The bright point sources outside the dark hole are ghosts produced by aliasing outside the control radius of the DM. See the electronic edition of the *PASP* for a color version of this figure.

several regions outside the dark hole were reduced by a factor of 5–50 after subtraction (for details on speckle rms/contrast calculations, see § 4). Speckle rms values inside and outside of the dark hole are presented in Table 3. Two double differences were also calculated and are shown for  $10^{-9}$  contrast in the dark hole (same logarithmic stretch, also by nominal contrast level) in Figure 6.

#### 4. ANALYSIS

To quantify the level of speckle attenuation available through the differential imaging technique both inside and outside the

dark hole, we calculated the contrast levels before and after subtraction in two  $20 \times 60$  pixel regions of the chip for all our reduced images. Contrast (or more simply, residual speckle rms) is estimated as the standard deviation over the region, an approach adopted from Biller et al. (2007). One major caveat is attached to this approach—it assumes Gaussian statistics, whereas speckles have been shown to follow a Rician probability density function (Aime & Soummer 2004; Fitzgerald & Graham 2006). Using Gaussian statistics will seriously overestimate the confidence level of a point source detection (Marois et al. 2008b). However, this approach has been used robustly as

TABLE 2  
PER-PIXEL S/N RATIO IN THE DARK HOLE

Contrast	Exp. time	<i>F1</i>	<i>F2</i>	<i>F3</i>	<i>F4</i>	<i>F5</i>
10 <sup>-6</sup> pixel in 10 <sup>-6</sup> image	90 s	179.9	182.4	179.9	187.9	142.2
10 <sup>-7</sup> pixel in 10 <sup>-7</sup> image	90 s	45.6	47.1	45.8	68.3	68.8
10 <sup>-8</sup> pixel in 10 <sup>-8</sup> image	90 s	21.2	21.5	19.2	19.2	18.1
10 <sup>-9</sup> pixel in 10 <sup>-9</sup> image	90 s	4.4	2.5	2.7	2.5	2.7
10 <sup>-6</sup> pixel in 10 <sup>-6</sup> image	5 s	42.0	42.6	42.0	43.9	33.0
10 <sup>-7</sup> pixel in 10 <sup>-7</sup> image	5 s	9.5	9.9	9.5	15.2	15.3
10 <sup>-8</sup> pixel in 10 <sup>-8</sup> image	5 s	3.4	3.5	2.9	2.9	2.7
10 <sup>-9</sup> pixel in 10 <sup>-9</sup> image	5 s	0.3	0.2	0.2	0.2	0.2

a diagnostic of contrast performance (Trauger et al. 2004; Lafrenière et al. 2007; Hinkley et al. 2007). For this testbed experiment, where we are simply concerned with speckle residuals and not detections of actual point sources, this method is appropriate for our use.

Regions used for this analysis are shown in Figure 1. The dark-hole region lies at 4–9  $\lambda/D$  from the occulted stellar image, while the left-side “comparison region” lies 19–24  $\lambda/D$  to the left of the occulted stellar image ( $\lambda/D = 4.67$  pixels at 785 nm for the HCIT, Trauger & Traub 2007 supplemental material). One major caveat exists regarding our choice of the left-side “comparison region”—we chose a comparison region outside the control radius of the deformable mirror, since the speckle nulling algorithm adds speckle noise to the left side of the image when removing an amplitude speckle from the

right side of the image. Before nulling, we note that a radial trend in speckle intensity exists—there are more and brighter speckles closer to the center of each image. Thus, the speckle noise within the left-side region is somewhat lower than the pre-null speckle noise in the dark-hole region. For this reason, it is not instructive to compare speckle noise between the right and left side regions, but instead to compare the degree of attenuation provided by the differential imaging technique in both of these regions. Contrast information is presented in Table 2 and is plotted for the dark-hole region as a function of  $\Delta\lambda$  from the nulling wavelength (800 nm) in Figure 7. Outside the dark hole, the single differences improve contrast by a factor of  $\sim 6$ , meaning that the NSDI method will be highly applicable in moderate ( $10^{-6}$ – $10^{-8}$ ) contrast systems without a DM to iteratively remove speckles (for instance, this technique might be very

TABLE 3  
SPECKLE RMS IN RIGHT-SIDE DARK HOLE (DH) AND LEFT-SIDE COMPARISON REGION (OH)

Image	Region	10 <sup>-7</sup>	10 <sup>-8</sup>	10 <sup>-9</sup>
<i>F1</i> 768.1 nm	dh	$7.1 \times 10^{-8}$	$1.4 \times 10^{-8}$	$1.2 \times 10^{-8}$
	oh	$4.0 \times 10^{-8}$	$4.7 \times 10^{-8}$	$5.4 \times 10^{-8}$
<i>F2</i> 782.5 nm	dh	$7.0 \times 10^{-8}$	$1.1 \times 10^{-8}$	$3.7 \times 10^{-9}$
	oh	$3.7 \times 10^{-8}$	$4.3 \times 10^{-8}$	$5.0 \times 10^{-8}$
<i>F3</i> 798.9 nm (nulled $\lambda$ )	dh	$6.9 \times 10^{-8}$	$7.3 \times 10^{-9}$	$7.9 \times 10^{-10}$
	oh	$3.7 \times 10^{-8}$	$4.4 \times 10^{-8}$	$4.9 \times 10^{-8}$
<i>F4</i> 814.8 nm	dh	$7.7 \times 10^{-8}$	$1.0 \times 10^{-8}$	$3.0 \times 10^{-9}$
	oh	$3.6 \times 10^{-8}$	$4.2 \times 10^{-8}$	$4.7 \times 10^{-8}$
<i>F5</i> 830.9 nm	dh	$7.8 \times 10^{-8}$	$1.3 \times 10^{-8}$	$8.9 \times 10^{-9}$
	oh	$3.5 \times 10^{-8}$	$4.1 \times 10^{-8}$	$4.7 \times 10^{-8}$
798.9 nm–768.1 nm	dh	$1.7 \times 10^{-8}$	$1.0 \times 10^{-8}$	$1.2 \times 10^{-8}$
	oh	$6.4 \times 10^{-9}$	$6.8 \times 10^{-9}$	$9.3 \times 10^{-9}$
798.9 nm–782.5 nm	dh	$7.5 \times 10^{-9}$	$3.9 \times 10^{-9}$	$3.0 \times 10^{-9}$
	oh	$2.6 \times 10^{-9}$	$2.9 \times 10^{-9}$	$3.5 \times 10^{-9}$
798.9 nm–814.8 nm	dh	$7.6 \times 10^{-9}$	$3.8 \times 10^{-9}$	$2.5 \times 10^{-9}$
	oh	$2.7 \times 10^{-9}$	$3.4 \times 10^{-9}$	$4.0 \times 10^{-9}$
798.9 nm–830.9 nm	dh	$1.3 \times 10^{-8}$	$8.6 \times 10^{-9}$	$8.5 \times 10^{-9}$
	oh	$4.7 \times 10^{-9}$	$5.3 \times 10^{-9}$	$5.8 \times 10^{-9}$
(814.8 nm–798.9 nm)	dh	$8.0 \times 10^{-9}$	$3.7 \times 10^{-9}$	$4.8 \times 10^{-9}$
	oh	$5.2 \times 10^{-9}$	$5.2 \times 10^{-9}$	$5.4 \times 10^{-9}$
(798.9 nm–782.5 nm)	dh	$1.8 \times 10^{-8}$	$1.3 \times 10^{-8}$	$1.9 \times 10^{-8}$
	oh	$9.0 \times 10^{-9}$	$1.1 \times 10^{-8}$	$1.4 \times 10^{-8}$

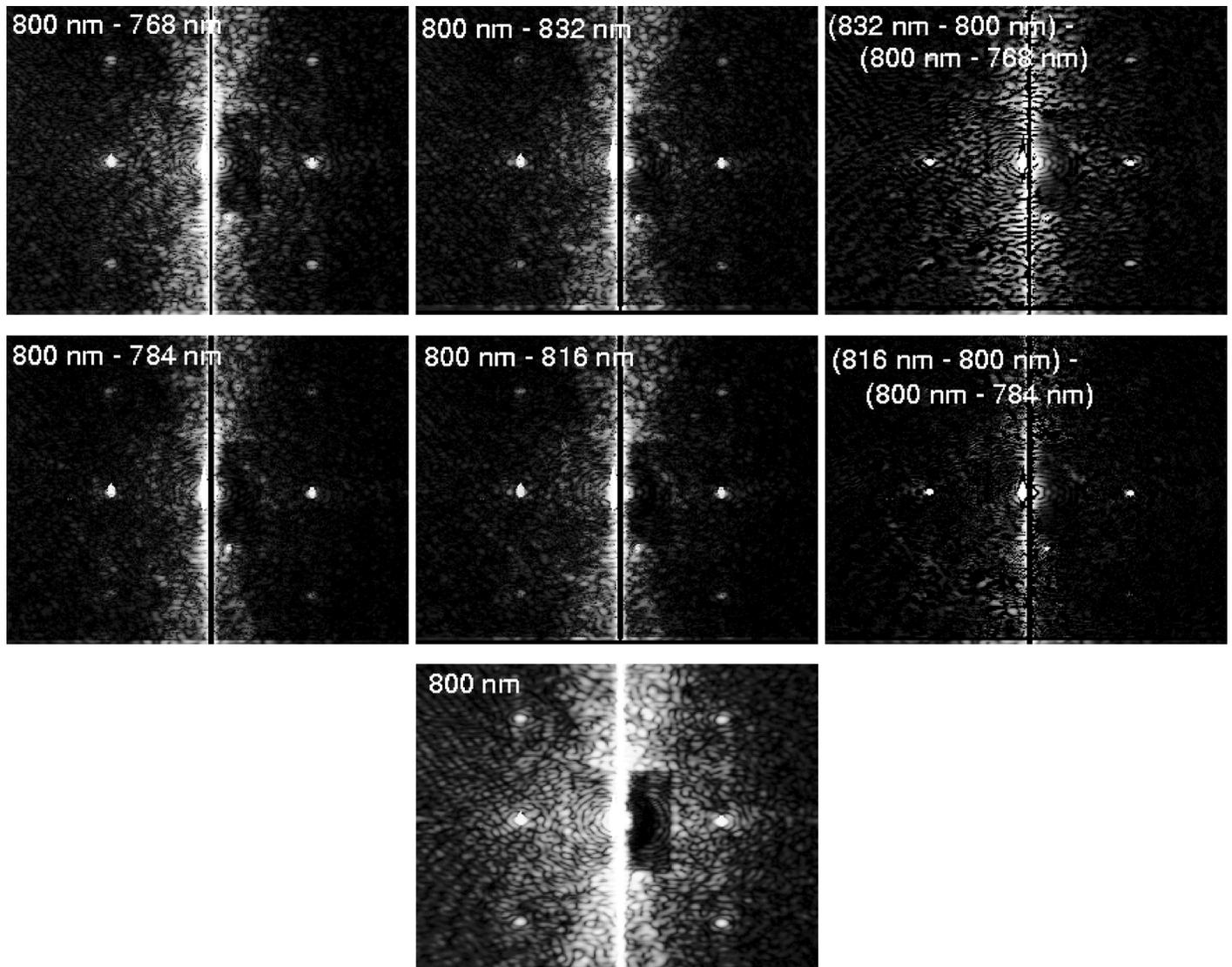


FIG. 6.—Double differenced images— $(F_4-F_3)-(F_3-F_2)$  [ $(F_3-F_2)-(F_2-F_1)$ ] and  $(F_5-F_3)-(F_3-F_1)$  for a nominal contrast level of  $10^{-9}$ . These images are shown with the same logarithmic stretch from contrasts of 0 to  $10^{-5}$  as in Fig. 2. Significant speckle residuals are present compared to the single differenced images. In contrast to theory (Marois et al. 2000), the double difference method is less effective at suppressing speckle noise than a single difference. The bright point sources outside the dark hole are ghosts produced by aliasing outside the control radius of the DM. See the electronic edition of the *PASP* for a color version of this figure.

appropriate to utilize with a coronagraphic Jovian planet imager without a DM). Inside the dark hole, contrast appears to depend strongly on  $\Delta\lambda$  from the nulling wavelength, especially at higher contrasts. For lower contrast levels, a similar speckle suppression with single subtraction is also observed within the dark hole. At high contrasts ( $10^{-8}$ ,  $10^{-9}$ ), however, apparent chromatic variation becomes very important and the speckle pattern appears to decorrelate. For instance, significantly more speckle noise appears in the 832 nm versus the 800 nm image, meaning that a subtraction of these two images degrades the achieved contrast relative to the 800 nm image alone. For the same reason, the double differences do not provide an advantage

over the single differences—contrast inside and outside of the dark hole is not decreased compared to the single differences.

Increased speckle noise in the dark hole as image wavelength differs from the nulling wavelength translates to a lower contrast in that image relative to the image at the nulled wavelength. Our multifilter experiment lets us simulate the variation in achieved contrast as a function of wavelength that we would expect within a wideband image. Our filters cover a wavelength range of  $\sim 80$  nm—equivalent to a 10% bandwidth filter. At an 800 nm contrast of  $10^{-8}$ , contrast is degraded by a factor of 1.7 at the red end (830.9 nm) compared to the nulled wavelength (798.9 nm), and contrast is degraded by a factor of 2 at the blue end

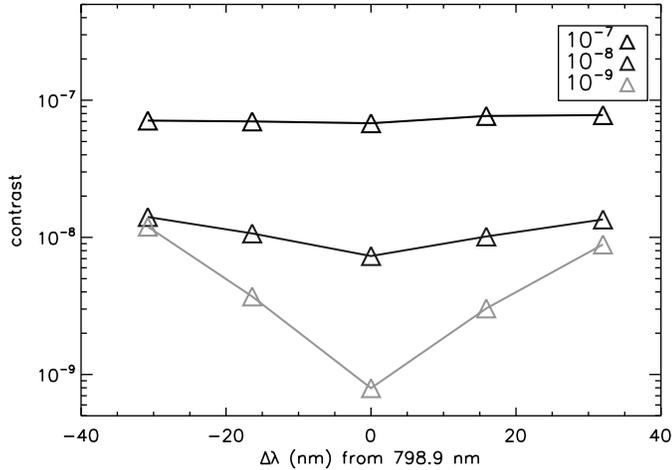


FIG. 7.—Single image contrast as a function of wavelength ( $\Delta\lambda$  in nm from 798.9 nm) inside the dark hole. Contrast is degraded by a factor of  $\geq 2$  at wavelength differences of  $\pm 30$  nm from 798.9 nm. The degradation of contrast as a function of wavelength is most pronounced at the highest nulling wavelength contrast level ( $10^{-9}$ ). See the electronic edition of the *PASP* for a color version of this figure.

(768.1 nm) compared to the nulled wavelength. Over the entire  $\sim 80$  nm bandwidth, contrast is on average degraded by a factor of 1.5 compared to contrast at the nulled wavelength (and, hence, the contrast would be degraded by a factor of  $\sim 1.5\times$  over a 10% bandwidth filter than over a 2% bandwidth filter.) At the highest contrasts ( $10^{-9}$ ) in the 800 nm image, contrast over the entire bandpass is considerably diminished—at the red end (830.9 nm), contrast is degraded by a factor of 11 compared to the nulled wavelength (798.9 nm), and at the blue end (768.1 nm), contrast is degraded by a factor of 15 compared to the nulled wavelength. Over the entire  $\sim 80$  nm bandwidth, contrast is degraded on average by a factor of 7.2 compared to the nulled wavelength. Thus, apparent speckle chromatism in these images is sufficient to predict considerable contrast degradation in a wide band ( $\sim 80$  nm) filter.

To determine the source of speckle chromatism in these images, we must take into account various sources of wavefront error in the HCIT. There are three main categories of wavefront errors we must consider:

1. *Wavelength scaling phase errors in the pupil plane.* These speckles scale according to  $\lambda$  and thus can be aligned across different wavelengths. Additionally, they are antisymmetric and can be completely removed by the deformable mirror.

2. *Wavelength scaling amplitude errors in the pupil plane.* These speckles scale according to  $\frac{\lambda}{D}$ . They can be removed on one side of the image using the deformable mirror, but will produce an increase in the corresponding speckle on the other side of the image.

3. *Wavelength dependent phase errors in the focal plane due to the occulter.* In other words, each wavelength sees different occulter properties. The current occulter is fabricated from High

Energy Beam Sensitive (HEBS) glass, which varies in transmission according to wavelength and thus will introduce slightly different phase errors at different wavelengths. (The relationship between wavelength and phase shift for HEBS glass is plotted in Fig. 2 of Moody & Trauger 2007) We hypothesize that the HEBS glass in the occulter is responsible for the speckle chromatism observed in this experiment. At lower contrasts, the phase errors due to wavelength dependent transmission in the HEBS glass are negligible, but at  $10^{-9}$  contrasts, they become quite important. These speckles are thus chromatic—they do not scale by  $\lambda$  and are likely the culprit in causing the characteristic “parabola” pattern in contrast seen in Figure 7.

In Figure 8, we compare our results to in-house theoretical predictions for this experiment (at slightly better contrasts of  $10^{-9.5}$  and with somewhat different comparison regions) and find the same qualitative result. The testbed optics are modeled as a series of optical surfaces, each of which has an interferometrically measured surface map (see, e.g. Fang et al. 2005) The occulting mask is assumed to have a profile of intensity transmission that follows a fourth-order sinc<sup>2</sup> function (Kuchner & Traub 2002), and has a transmitted phase that varies as a function of intensity transmission, as measured by Halverson et al. (2005). Wavefront correction is performed using a model of the speckle nulling algorithm, as described in Trauger et al. (2004). To simulate the image recorded on the camera through an

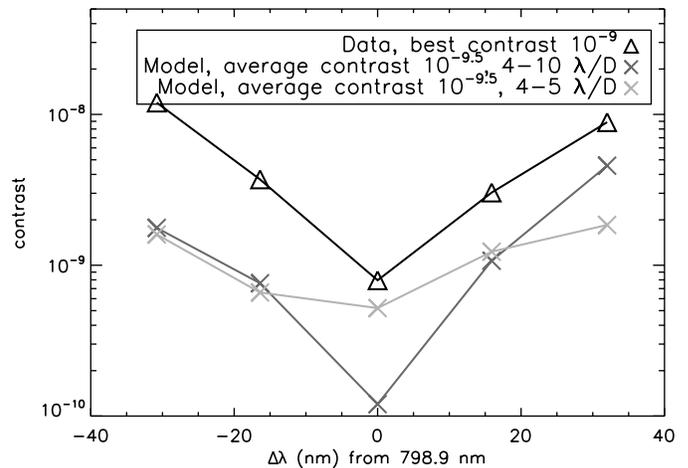


FIG. 8.—Single image contrast as a function of wavelength ( $\Delta\lambda$  in nm from 798.9 nm) inside the dark hole ( $10^{-9}$  average contrast) and from model predictions. Contrast is degraded by a factor of  $\geq 2$  at wavelength differences of  $\pm 30$  nm from 798.9 nm. The degradation of contrast as a function of wavelength is most pronounced at the highest nulling wavelength contrast level ( $10^{-9}$ ). Model predictions for this experiment produce a qualitatively similar result. These models are for slightly higher intrinsic contrast levels and calculate contrast in somewhat different regions than used in the experiment, which is why there is some discrepancy between model and experiment results. The 4–5  $\lambda/D$  model samples only the deepest parts of the dark hole, while the 4–10  $\lambda/D$  model samples a much larger and somewhat less corrected region, hence, the observed degradation in contrast between the models. See the electronic edition of the *PASP* for a color version of this figure.

individual bandpass filter, a number of monochromatic wavelengths (typically at least three wavelengths per filter) are propagated through the model and summed by intensity at the camera. The model iterates the speckle nulling algorithm until the contrast improvements in successive iterations become negligible. More details regarding modeling can be found in Moody & Trauger (2007) and Moody et al. (2008). Models using the current generation of HEBS glass occulter can qualitatively reproduce the speckle chromaticity found in the current experiment.

Moody & Trauger (2007) used this same modeling approach to simulate the contrast performance of next generation hybrid coronagraph mask designs (metallic and dielectric thin films deposited on a glass substrate) using a similar band-limited coronagraph setup and predict considerably less chromatic coronagraph performance from these masks. Thus we suggest that the speckle chromaticity seen in this experiment is due to the  $\lambda$ -dependent behavior of the HEBS glass used in the occulter and not from the intrinsic design of the band-limited coronagraphic mask. Moody et al. (2008) have implemented a metallic thin film mask at the HCIT (and achieved the best published contrasts to date at the HCIT with it). Hybrid masks are just becoming available at the HCIT and have already yielded considerable improvements in contrast over a 20% bandwidth filter (Moody, D., 2009, private communication). When these hybrid masks have been fully implemented at the HCIT, this experiment will be repeated to test this hypothesis.

## 5. DISCUSSION, CONCLUSIONS, AND FUTURE WORK

Using single wavelength speckle nulling with a band-limited Lyot coronagraph and operating at nominal contrasts of  $10^{-6}$  to  $10^{-9}$ , single differences of filter images can reduce speckle noise outside of the dark hole by factors of 5–50. For contrasts of  $10^{-6}$  to  $10^{-8}$ , a similar result is also found within the dark hole, with speckle attenuation achieved through a single difference decreasing as a function of increasing contrast. However, at high contrasts ( $10^{-9}$ ), considerable increase in speckle RMS between filters is observed to “pollute” the dark hole in all of our single differences (where, in each difference, only one of the two wavelengths had undergone optical speckle nulling). At all contrast levels, a double difference of images does not seem to decrease speckle noise relative to the single differences. Significant differences in contrast ( $\sim 2$ – $10 \times$  RMS) are found between filters separated in wavelength by  $\Delta\lambda > 20$  nm. Contrast degradation between filters increases strongly as a function of

increasing contrast at the nulling wavelength. This chromatic speckle noise is likely due to the chromaticity of the materials of the occulter itself.

However, this experiment is only one possible implementation using specific choices of coronagraphic mask/occulter and nulling algorithms available in 2007 January. It is clear that the occulter used in 2007 January possessed significant wavelength dependent phase errors, causing speckle decorrelation between filters. This decorrelation was exacerbated by using a speckle nulling algorithm that calculated a speckle solution at only one wavelength. Since 2007, significant effort has gone into developing nonchromatic coronagraphic focal plane occulter and nulling algorithms for the HCIT. Thus, another implementation of this experiment using these improvements would likely be able to extend NSDI performance to even better contrasts. Specific improvements possible include:

1. The major limiting factor for this experiment is likely chromaticity due to the materials of the occulter itself. However, since 2007 January, a variety of less chromatic occulter options are under development. Moody & Trauger (2007) explore hybrid coronagraph mask designs (metallic and dielectric thin films deposited on a glass substrate) which promise considerably less chromatic coronagraph performance. These masks are still in development but will in principle allow the extension of differential imaging techniques to  $10^{-9}$ – $10^{-10}$  contrasts.

2. Algorithms that produce a multiwavelength speckle solution are now available (e.g., multiwavelength electric field conjugation, Give'on et al. 2007) instead of speckle nulling at a specific wavelength. Utilizing one of these newer algorithms will produce a broadband solution without degradation at either end of the bandpass.

A future iteration of this experiment will be conducted once these improvements are implemented.

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