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High Contrast Imaging using WFC3/IR

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ABSTRACT

We present results from the IR component of the HST/WFC3 calibration proposal 12354 in this instrument science report. The proposal was designed to test the high-contrast imaging capability of the HST/WFC3 IR channel to detect faint companions at close angular separation. We observed a bright young star (V=6.9 mag) at nine orients in the F128N narrowband filter over 3 orbits. For our analysis we injected companions with 30 degrees rotation in each successive orient. The data were then reduced using both classical PSF subtraction and the "Locally Optimized Combination of Images" (LOCI) algorithm. We find that with 9 orients, we can detect faint injected companions with magnitude differences of 10 mag at 0.5 arcsec, 11 mag at 1 arcsec, and 12.5 mag at 2 arcsec, with a confidence level of 5-σ.

Introduction

The Wide Field Camera 3 (WFC3) is the workhorse imaging instrument on the Hubble Space Telescope. With the NICMOS instrument currently disabled, the IR channel on WFC3 is the only near-IR camera on the telescope. Because there is no coronagraphic capability in WFC3, we have studied the feasibility of high-contrast imaging using roll deconvolution (Mueller, M. and Weigelt, G. 1987), or angular differential imaging (Marois, C. et al 2006), together with advanced PSF subtractions. We present the results of the three-orbit calibration proposal 12354 in the F128N narrow band filter.

Observations

The WFC3 IR camera is a 1k x 1k detector with 0.13 arcsec/pixel and 15 filters covering a wavelength of $\sim$ 800 to 1700 nm. Directly imaging bright targets is challenging for a couple of reasons; the camera does not have a coronagraph, or a shutter and additionally suffers from persistence (Knox et al. 2010). We chose a fairly bright star, HD165459 which is a young A dwarf (V = 6.9 mag). This experiment would be easier to reproduce with fainter targets.

When designing the proposal there were two primary considerations. We wanted deep exposures to reach appropriate signal to noise ratio at the location of potential nearby companions. To do this we saturated the inner 0.5 arcsec of the PSF. Also we wanted to incorporate the maximum number of rolls in our three-orbit allocation in order to enable roll deconvolution or angular differential imaging.

Even allowing the inner 0.5 arcsec to saturate, the computed exposure times for the medium (e.g. F127M) and wide band filters (e.g. F160W) were under $\sim$2s and $\sim$1s respectively. The IR detector has a reset time of $\sim$2.9s which when combined with the lack of a shutter makes very short exposures of bright stars problematic, potentially resulting in bright persistence features. To get around this we designed our observations using the narrow band filter F128N which permitted relatively long exposure times of 10.23s per image.

To maximize the number of rolls per orbit we limited the total number of dithers to four exposures per orient. Additionally the IR pixel size is 0.13 arcsec/pixel resulting in a WFC3 PSF that is only half-Nyquist sampled. We used small sub-pixel dithers to mitigate this problem while maintaining optical stability of the PSF. Since this is a calibration proposal we were able to fit three orients per orbit. However, this created considerable scheduling difficulties, and GO's should expect to get a maximum of two orients per orbit.

The scheduling constraints for this program were such that we did not have successive rolls, but three orients with 0, -5 and +5 degree rotations, which were reproduced three times in each orbit of our calibration program. Using this dataset we simulated an observing scenario where successive rolls were performed. Because we do not rotate the PSFs and simply inject fake companions at different positions angles, the assumed rotation angle does not impact the final subtracted image, but it does impact the inner working angle (IWA). For a rotation of 5 degrees the IWA would be $\sim$1.5 arcsec, where the IWA is defined by the separation at which the rotation corresponds to the PSF FWHM.

We decided to use a larger roll angle than 5 degrees (30 degrees obtained successfully in HST proposal 7226) to explore the detection at small IWA, where we would be limited by the PSF stability and not by the rotation of the companion PSF. However, this scenario is not completely realistic because it implicitly assumes that the PSF maintains the same stability over 30 degree rolls as it does over 5 degree. Also due to scheduling constraints to reach such large rolls the data would be obtained over several months and the PSF correlation would decrease. However it has been shown using NICMOS data (Lafrenière et al. 2009) that it is possible to use reference PSFs that are spread in time with the "locally optimized combination of images" or LOCI algorithm (Lafrenière et al. 2007), and even from other stars, but the required number of reference PSFs is larger.

Thus the observer will have to choose between observing with larger rotation angles and having the orbits executed successively, and prioritize whether to reduce the IWA or to ensure a better correlation between the PSF through all the orients. The contrast estimates we provide in this report for separations <1.5 arcsec depends on some optimistic assumptions and more reference PSFs may be required to achieve this performance.

Analysis

For our image analysis we made use of the FLT images retrieved from the archive at STScI using the 'On-The-Fly-Reprocessing' which uses the most recent reference files for bias, dark and flat field correction. Since the inner 0.5 arcsec of the PSF is saturated, we registered the images by cross correlating the diffraction spikes to each other. In this process we ignored the fact that the PSF is significantly under-sampled, and that shifting and resampling the image would produce aliasing effects. More sophisticated registration techniques could also be used (e.g. Fruchter & Hook 2002) but are beyond the scope of this report.

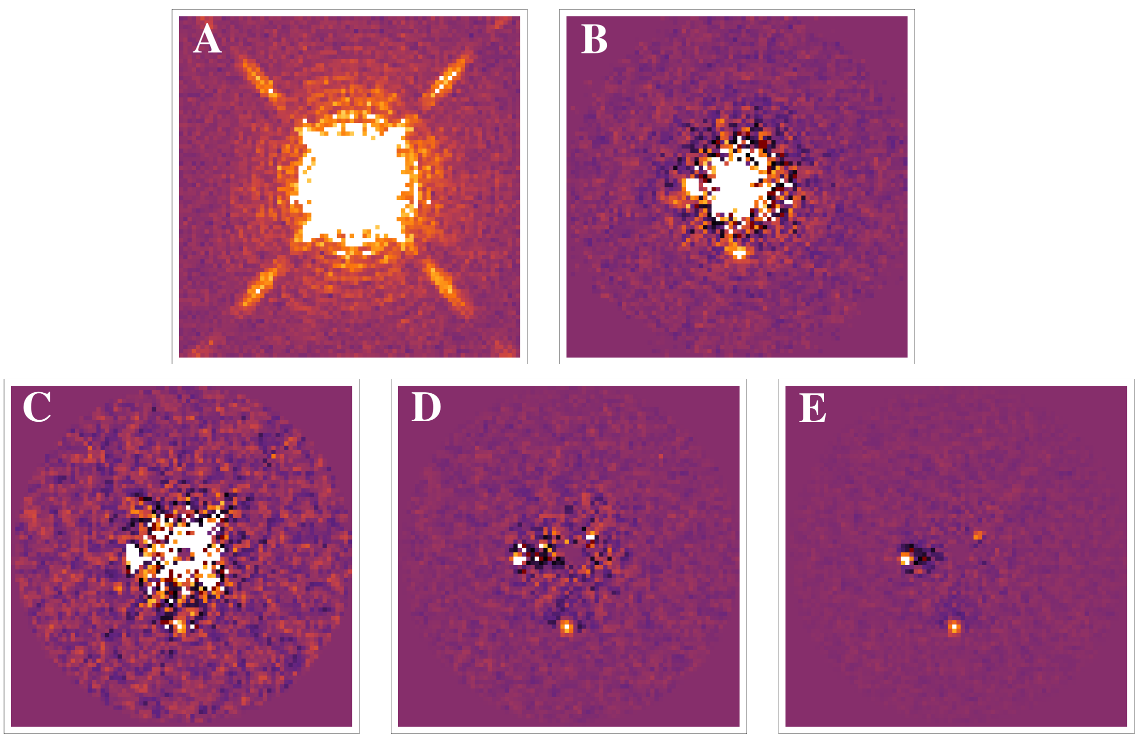

Figure 1. A: target star with three fake companions with magnitude difference of 10.7 mag, 9.1 mag, and 9.3 mag respectively at 0.7 arcsec, 1.4 arcsec, 2.0 arcsec. B: result of a classical PSF subtraction using all nine orients (36 images). C, D, and E: result of LOCI reduction using two, five and nine orients respectively.

We reduced the images using two different methods, namely classical PSF subtraction and the LOCI algorithm. We generated three different observing scenarios from our complete set of 36 observations (nine orients, four dithers):

- The first scenario simulates two orients, which could potentially correspond to a single orbit (SNAP) proposal.
- The second scenario simulates five orients, which was roughly half our sample data set and would require three orbits.
- The final scenario simulates nine orients, our complete data set, and would require five orbits.

We injected reference PSF's that we extracted from a previous WFC3 observation as fake companions in each exposure, assuming a rotation of 30 degrees between successive orients, to simulate actual rolls of 30 degrees by the telescope. For each of the three different data sets we carried out both PSF and LOCI subtraction, the resultant images for which are presented in Fig. 1.

Classical PSF Subtraction

For each orient, we generate one target image from the median of the four dithers. All other orients form the reference stack and are median combined to give a single reference image, which is subtracted from the target image.

For example in the five orient scenario, this results in five subtracted images where the companions are rotated by 30 degrees with respect to each other. We then de-rotate the subtracted images and combine them into a unique final image.

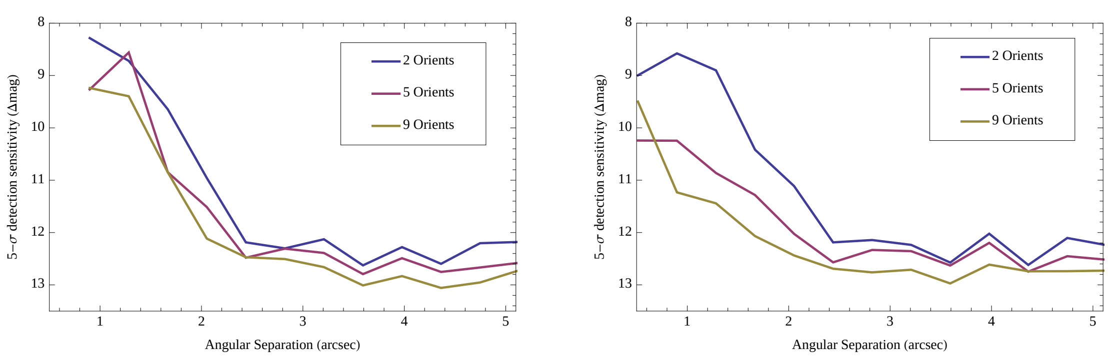

Figure 2. 5-σ detection sensitivity for the Classical PSF subtraction (left), and the LOCI subtraction (right). The Y-axis for both figures shows the contrast between the companion and the star measured in a 3 pixel box, the X-axis is the angular separation in arcseconds.

LOCI Subtraction

The methodology used to combine the LOCI subtracted images is identical to the one described above for classical PSF subtraction. However, it differs greatly in the way we create each individual subtracted image. LOCI is designed to produce an optimal reference PSF to suppress speckle noise, by using a linear combination of the reference images. We follow the implementation of LOCI as described in Lafrenière et al. (2007). This algorithm involves a few parameters that need to be optimized for best results. For the purpose of this study we explored a large parameter space, and determined a set which provides satisfactory results over the entire image. Note that because LOCI is a local algorithm, the optimal parameters change for different angular separations.

Results

In Fig. 2 we show the 5-σ detection sensitivity obtained from the classical PSF subtraction and the LOCI subtraction. The most striking point to note is the effectiveness of LOCI at close inner working angles. LOCI significantly outperforms the classical PSF subtraction in the inner two arc seconds. In both figures, we calculate the contrast for the companion assuming a a 5-σ detection sensitivity, using aperture photometry for the signal, and measuring the noise in an annulus centered on the companion.

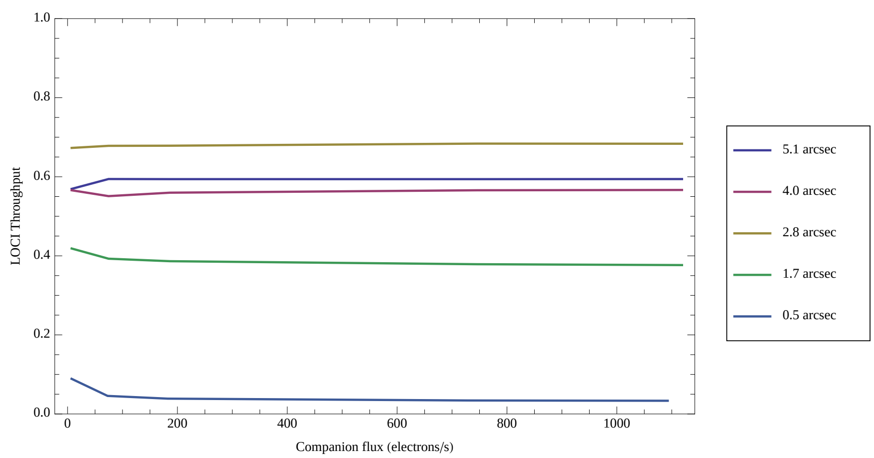

Figure 3. Measured throughput from the LOCI processing as a function of the true companion flux of the injected companions. LOCI affects the throughputs of the companions identically based on the angular separation, irrespective of brightness of the original companion.

With classical PSF subtraction, we observe limited improvement from using additional orients, and the gain is one magnitude from two to nine orients. With LOCI subtraction, we observe progressive improvement from two to nine orients, which suggests that we have not reached the limitation from the systematics, and that further improvement might be achievable with more orients. At a separation of one arcsec the improvement is about three magnitudes from two orients to nine orients.

At the shortest possible separation of 0.5 arcsec, we detect companions with a 10 magnitude difference in our experiment. At large angular separations both techniques reach the limitations of the data, and perform comparably.

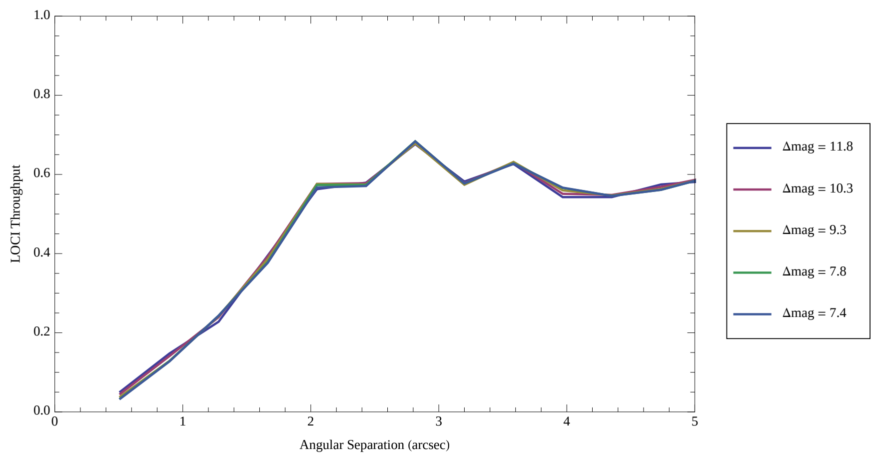

Figure 4. Measured throughput for the injected companion at different angular separation from the star for five different magnitude differences of companions with respect to the star.

Since LOCI is designed to aggressively suppress speckle noise, the algorithm tends to subtract the flux from the companion as well, resulting in incorrect photometry measurements for the companion if measured directly from the LOCI output images. To help properly characterize the behavior of LOCI on the companions, we measured how it affects the throughput in the output images for companions injected at different angular separations.

The LOCI throughput is the ratio of the affected companion flux to the true companion flux. We generated Fig. 3 by measuring the flux for companions with increasing brightness and by placing them at increasing angular separation. Fig. 3 shows that at a particular angular separation the throughput remains stable for a large range of companion fluxes from a few electrons per second to more than 1500 electrons per second, viz. magnitude difference of $\sim$12 mag to $\sim$7 mag. Fig. 4 shows some fluctuation in the throughput curve which results in the line for the companion at 2.8 arcsec being higher than ones located at larger angular separations. Similarly we plotted the throughput as a function of the angular separation (Fig. 4). The figure shows that at small separations LOCI acts aggressively and the companions flux is reduced to a few percent of its original flux, and at larger separations the companions only have about half their original flux. Combining the negative effect of LOCI on the throughput with the increased time for processing of images can be a reason to prefer classical PSF subtraction at larger angular separations, where the two methods are comparable in performance.

Conclusion

We have shown that high contrast imaging is possible using the IR channel of the Wide Field Camera 3 using two different methods of data reduction (classical PSF subtraction and LOCI). We generated several observing scenarios to simulate the improvement with increasing number of orbits, using roll deconvolution.

We find that faint companions with a range of magnitude differences from 10 to 13 can be detected at the 5σ level at separations larger than 0.5 arcsec. More importantly, we find that despite the absence of a coronagraph and the undersampling of the PSF, we observe continuous performance improvement in the 0.5-2.5 arcsec region by increasing the number of orbits. This suggests that with further optimization of the observations, including finer dithering and a larger reference data set, the detection limits could possibly be pushed further. Combining the effect of PSF under-sampling and LOCI's effect on the throughput and PSF shape a signal-to-noise ratio of five might not be sufficient depending on the application (photometry and astrometry).

Additionally we observed a bright star (V=6.9) which pushed the detector close to the edge in terms of saturation, but were still successful in detecting objects at 0.5 arcsec. Observations of fainter targets should be significantly easier to plan where the full suite of filters on the camera would be available.

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