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Subtraction of Well-Exposed NICMOS 2 PSFs

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1. Introduction

A SNAP program (7420) proposed by David Golimowski (JHU) and Todd Henry (CfA) is underway to search for companions to nearby stars using NICMOS 2 (f/45, 0.″076/pix). Well- to over-exposed star images are obtained at the center of the detector in four filters: F110W, F180M, F207M, and F222M. The stars are typically saturated to allow for the detection of faint companions. The point spread function (PSF) often fills the entire field of view, with diffraction rings visible out to a radius of 10″.

The program was designed with the expectation that a large number of the stars would not have any companions or material around them, making them suitable for use as reference PSFs to subtract from other star images. The reference PSF would be shifted and intensity scaled to provide the best subtraction.

In addition to the possible discoveries of companions, the high signal-to-noise structures in the wings of these PSFs have provided new, unexpected information on the optical characteristics of the NICMOS 2 camera which cannot be obtained from the current PSF monitoring program.

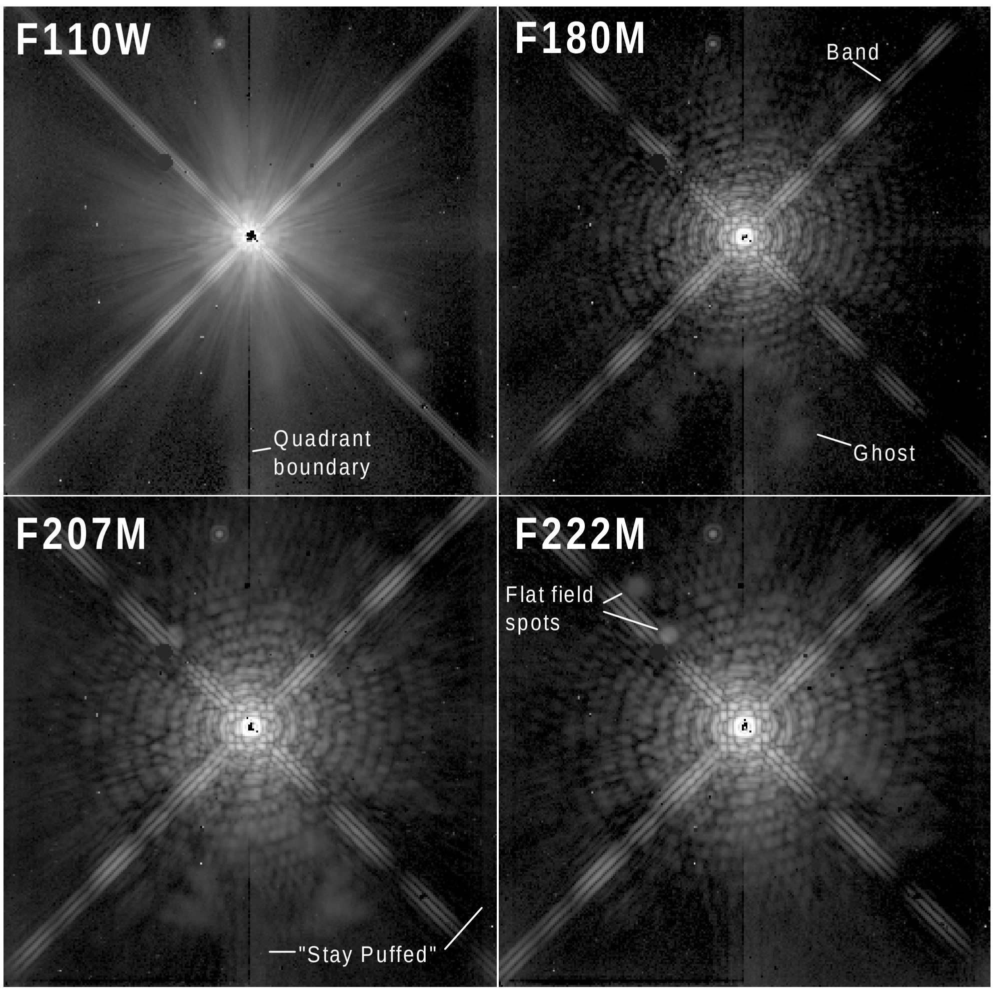
2. Observations

Figure 1 shows a star from our program in each of the four filters. These are standard pipeline-processed images obtained from the HST archive. A stellar companion is 7.″7 away. The wings in the F110W image appear relatively smooth because the PSF structure expands with increasing wavelength, blurring the diffraction rings over the range of the wide-band filter. The PSF does not change as much over the wavelength range of the medium-band filters, so the diffraction rings are plainly visible in the those images.

There are some optical and calibration artifacts in the data. A ghost is visible in the lower half of the image, most notably in the first three filters, and its position varies with the location of the star and the filter used. Two spots in the upper left portion of the images (best seen in F222M) are caused by flat field errors. The flat fields were generated by combining pre-launch and on-orbit data. At those times, the coronagraphic occulting spot was at a different position in the field, so there are two "ghost" masks in the flats. The leftmost spot is the current location. The dark spot located on the upper left spider (most visible in the F110W image) is the mask location in the linearity file.

The dark, vertical line at the center of the image is the boundary between quadrants on the detector. The diffuse, vertical band, most visible in F222M, is the "Stay Puffed" anomaly, which also causes the brighter columns on the right sides of the images, especially in F110W. A horizontal trail of unknown origin can be seen to the right of the PSF center, especially in the F180M image. Individual bright points may be dark pixels not corrected by the pipeline. The cores of the stars appear black because they are saturated.

Figure 1. An example SNAP program target in four filters, with optical and calibration artifacts marked.



3. Initial PSF Subtraction Method

At the onset of the program, the quality of the PSF subtractions was expected to be dependent mostly on the focus stability of the telescope/camera. The differences among star images with various spectral energy distributions (SEDs) were expected to be negligible, since neither the PSFs nor the SEDs varied much over the filter bandpasses, especially in the medium-band filters.

The initial procedure was to subtract a star with each of the previously observed PSFs in each filter and choose the one which provided the best subtraction. An IDL program was developed to allow experimentation with the PSF shifts, background levels, and normalizations.

The program first computes the median values within two boxes on the extreme right and left sides of the star image and takes the minimum of the two as the initial background estimate, which is subtracted from the image. The same is done for the reference PSF.

Normalizing the reference PSF is complicated by the fact that most of the star images in our program are saturated in the core, so direct determinations of total stellar flux are not possible. Instead, the medians are computed in two boxes to the left and right of the core of the image and then averaged. The same is done for the reference PSF, which is then multiplied by the ratio of the intensity values to normalize it to the star.

The final step is image registration by shifting the PSF at the subpixel level using interpolation. Cubic convolution interpolation is performed using the `interpolate` function in IDL, which offers better results with the narrow diffraction rings than bilinear interpolation. Cubic convolution approximates sinc interpolation, which is appropriate since NICMOS 2 is nearly critically sampled at longer wavelengths.

The PSF shift is adjusted manually until the residuals in the subtraction appear symmetric. This method is sensitive to shifts of less than 0.05 pixels (4 mas). The image and PSF backgrounds, as well as the PSF normalization factor, can be adjusted interactively along with the shifts.

The quality of a subtraction is subjective, based on a visual examination of the residuals. The goal is to produce a result that provides the best chance for detecting a faint companion, which is not necessarily provided by a minimum chi-squared subtraction due to differences between the PSF structures (diffraction rings, spider patterns, etc).

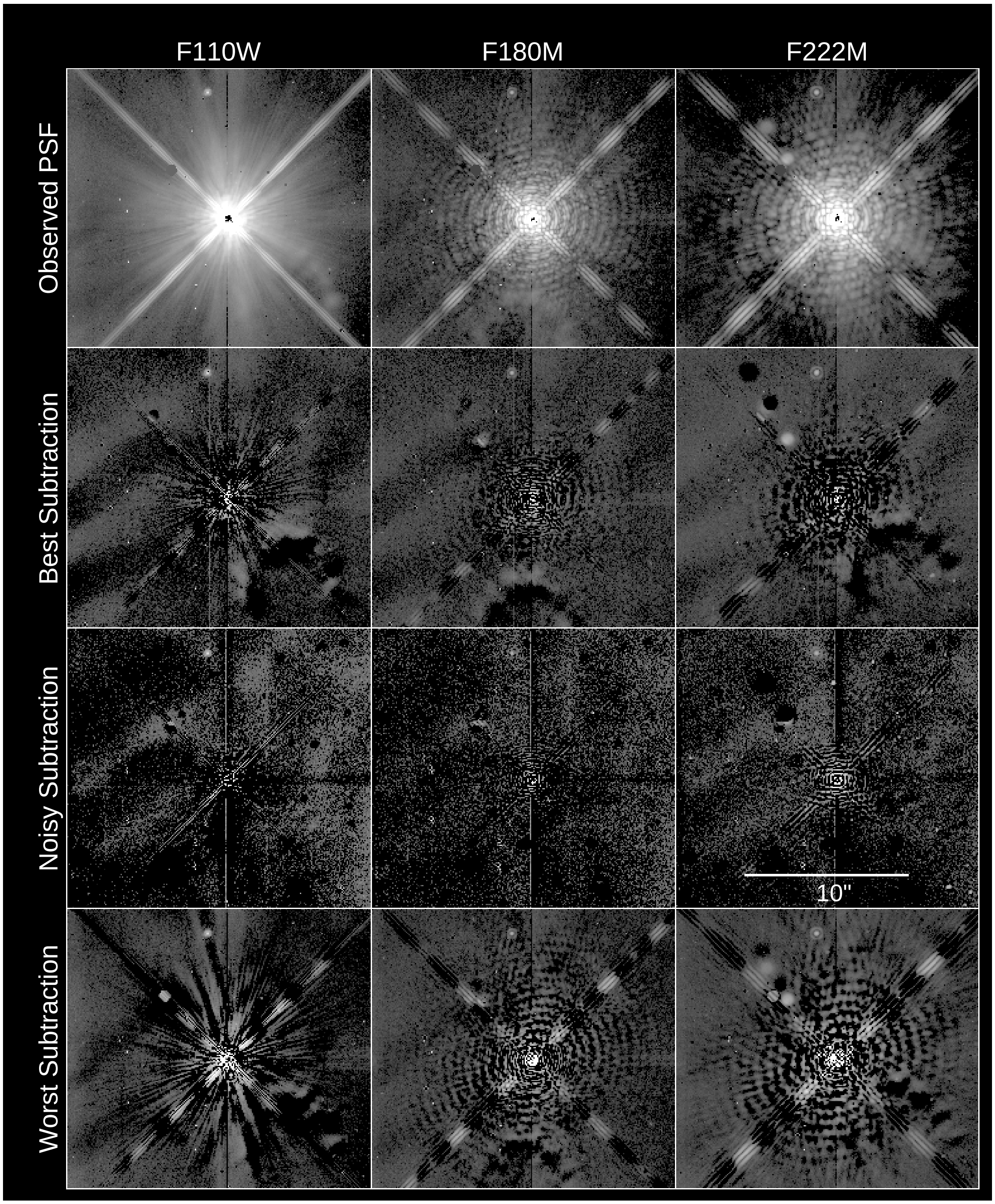
4. Initial Subtraction Results

Using the procedure described above, subtractions were performed on most of the targets available at the time (about 20). These included a variety of star brightnesses and colors, from spectral type F to M. In some cases up to three targets were observed on the same day, which provided important information on the time variability of the NICMOS PSF. The PSFs were all located near the center of the field.

The subtractions ranged from very good to very poor. As expected, the largest residuals were near the core, where interpolation errors and PSF mismatches combined with the high data values. In most cases the diffraction spikes did not subtract out well, and there were large variations in how well they did from image to image. The subtraction of the diffraction rings in the wings also varied greatly. Figure 2 shows examples of both good and poor subtractions.

When the registered, normalized PSFs were blinked against each other, it was apparent that something was causing the diffraction structure to vary in unexpected ways. The largest changes were evident in the banding patterns in the diffraction spikes. Bands along one diagonal spike would move towards the PSF core while those along the other diagonal would move away. At the same time, the diffraction rings would move slightly in various

Figure 2. NICMOS 2 PSF Subtractions. The noisy subtractions used PSFs that were about eight times fainter than the star but with a similar band ratio. The poor subtractions used PSFs with similar exposure levels which were not good band ratio matches.



directions. In some cases the bands and rings would not move between two PSFs, and these cases provided the best subtractions.

5. NICMOS 2 PSF Variations with Time

The opposite motions of the spike bands could not be explained by focus or wavelength effects, as experiments with Tiny Tim models proved. Focus changes, such as those caused by breathing or dewar shrinkage, barely alter the position of the bands, even with large focus offsets. And as with wavelength-induced alterations, the bands would move together, either towards or away from the core. Variations like those seen can only be caused by changes in the obscuration pattern of the optical system — namely, changes in the positions of the spiders which generate the diffraction spikes.

Additional evidence pointed towards a change in the obscuration pattern. Close examination of the diffraction rings showed that they are actually elliptical. While astigmatism in the optics might be the easy explanation as the cause, the aberrations in NICMOS 2 have been well measured using phase retrieval, and are included in Tiny Tim PSF models. With the measured amount of astigmatism, those models had visually circular rings, and no amount of astigmatism could be added to make them elliptical without significantly distorting the PSF.

In addition, the banding in the diffraction spikes was not symmetric - one spike had more bands, and at different places, than the other. This indicated that the spiders in the obscuration pattern are not symmetrical and probably misaligned.

As described by Krist and Hook (1997), each NICMOS camera has a mask at the entrance of the dewar which is intended to block thermal emission from the telescope obscurations (spiders, primary mirror edge, secondary mirror baffle); hence it is called a cold mask. Optimally, the mask and telescope obscurations would be aligned, producing a PSF with essentially circular diffraction rings and symmetrical spike banding patterns.

However, by shifting the cold mask with respect to the telescope obscurations in Tiny Tim, the observed PSF anomalies could be reproduced. The diffraction rings and the positions of the spike bands were matched.

The elliptical diffraction rings are caused by an elliptical central obscuration, a result of the offset of the NICMOS central mask relative to the telescope's secondary mirror obscuration. The asymmetry in the spike bands are caused by the offsets of the mask spiders relative to the telescope's. Along one direction the spiders are barely separated, while along the other they are offset by about 10% of the pupil radius (which is defined by the outer edge of the mask or telescope primary). The widely separated spiders cause the greater frequency of banding along one spike diagonal. Other implications of the mask shift are described in Krist & Hook (1997).

A mask offset can also explain the variations seen among the observed PSFs, if the mask moved with time. This was verified with Tiny Tim. If the mask was moved so that the separation of the spiders along one direction increased while the separation along the other direction decreased, the in-and-out changes in the spike bands could be reproduced well. Subtracting model PSFs generated with two slightly different mask shifts also reproduced the sort of residuals seen in the observed PSF subtractions. Further experiments showed that the mask moves randomly around the general offset amount by up to 0.5% of the pupil radius. Differences between PSFs taken on the same day indicate that the mask shift varies on orbital timescales.

6. Revised PSF Subtraction Method

Since obscuration shift is the largest contributor to PSF errors in our program, a method of determining the closest matches was devised. For each target, the distances from the core to the second bands in the upper right and lower right spikes in the F222M image are measured. The ratio of these two values, the *band ratio*, provides a measure of the banding asymmetry. The same ratio is assumed for the PSFs in the other filters.

PSFs with the closest ratios tend to be better matches to each other and provide better subtractions. Using this method, only the closest three or four PSFs need be subtracted before finding the best result. This is important in a program with 120 targets (and even more if the Cycle 7.5 program is accepted).

7. Other Subtraction Considerations

In one case, a companion star was located in the brightest portion of the ghost mentioned earlier. Rather than choosing the PSF that provided the best overall subtraction, one was selected which was at the same position. This placed the ghost at the same location, which subtracted out well.

Except for the ghosts, the PSFs do not show any significant field dependence. The cold mask shift does not vary with position, since the mask is in a plane conjugate to the entrance pupil.

Some of the target stars are considerably fainter than the others. These make poor reference PSFs, since the noise in the images will be multiplied by the normalization factor. Examples are shown in Figure 2.

Good subtractions can be obtained using different spectral types, at least in the filter used in this program. A G8 star subtracts well from a M1V, though residuals are high when using F-types.

With plenty of observed PSFs available, Tiny Tim models are not useful for subtractions. Considerable work would be required to fine-tune the obscuration shifts for each PSF, and even then high-order aberrations and distortion would introduce significant residuals in the wings. They are, of course, useful for diagnosing optical problems.

Experiments with Tiny Tim models demonstrate that changes in the PSF wings caused by focus variations (breathing) are less than from mask shifting.

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References

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