Improved TinyTIM Models for WFC3/IR

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ABSTRACT

We use TinyTIM version 7.4 to model a star image near the center of the WFC3/IR detector, subtract the model from the observed star, examine the residuals, and suggest changes to the TinyTIM parameters to improve the fit. The largest errors appear related to the pupil cold mask parameters and we derive improved values for those. We also suggest setting the x- and y-coma parameters to zero, at least until better coma parameters can be derived in the future.

Introduction

The TinyTIM package has been used for many years to simulate and model images produced by HST (Krist, Hook, and Stoerh 2011). It presents a potentially powerful tool for modeling and subtracting bright stars while searching for faint companions such as planets and disks -- since the models can be made to an arbitrarily small pixel scale, they are not subject to the usual undersampling problems which occur when subtracting observed stars from each other.

The WFC3/IR camera onboard HST covers a wavelength range from 0.98 to 1.66 microns, and has a 1024 x 1024 pixel detector array with ~0.13 arcsecond pixels. This instrument was incorporated into TinyTIM by Hook and Stoerh (2008) using a pre-launch ZEMAX model of the camera aberrations. Our goal here is to compare these TinyTIM models against on-orbit data, and begin the process of improving the models where needed.

A previous report (Biretta 2012) investigated the accuracy of TinyTIM for modeling and subtracting stellar point spread functions (PSFs) from on-orbit WFC3/IR images, and noted several deficiencies in the models. The present report investigates improvements to the TinyTIM model to correct those issues. The next sections discuss our procedure for improving the TinyTIM parameters, our results, and potential causes for some of the incorrect parameters. Appendix A gives TinyTIM parameter files (wfc3_ir.tab and wfc3_ir.pup) including the improved parameters.

Procedure for Improving Parameters

We use TinyTIM version 7.4 to generate a model PSF for the observed star image, and then use the procedure described in Biretta (2012) to align and scale it relative to the observed image. Finally the model is subtracted from the observed image, the residuals are displayed, and the RMS of the residuals is computed.

Our approach to improving the model parameters is one of manually adjusting the parameters until the best model is obtained. We examine the residuals of the subtraction, use our knowledge of optical aberrations to decide which parameter(s) to adjust, make some adjustment, and then repeat the modeling procedure. We continue iterating and adjusting the parameter(s) until no further improvement is seen in either the residual image or RMS. We then study the residual image again, possibly choose a different parameter to adjust, and the repeat the iterative procedure.

Once several parameters have been adjusted, we go back to the first ones adjusted and see whether some further improvement could be made. For example, there could be some correlation or interaction of the parameters, and adjusting one parameter might affect others. It is also possible that as the residuals decreased, we might be able to discern smaller errors that were previously obscured, and hence make finer adjustments. In total, about 200 models were run while the parameters were tested and adjusted.

Uncertainties in the derived parameters were estimated by seeing what range of values was possible around the "best" value, before the model got noticeably worse. Uncertainties derived in this way are only approximate, and do not have the same exact meaning as uncertainties that might be determined through some non-linear least-squares fit. [1]

Most of the work was performed on a single image, IABL01D7Q_flt.fits, which is a well-

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[1] It would be interesting to use a multi-parameter non-linear least-squares fit for the TinyTIM parameters, but that is beyond the scope of the present work.

exposed image of standard star GD153 taken through the F098M filter in 1024x1024 format on 2009-07-31. The star is located near the detector center.[2] A short wavelength was chosen, since the wavefront errors will have the most obvious impacts. Some work was also done on image IABL01D8Q_flt.fits which was taken through the F160W but is otherwise identical. Similar results were obtained for both images. Both data sets are from proposal 11439 (Hartig 2009).
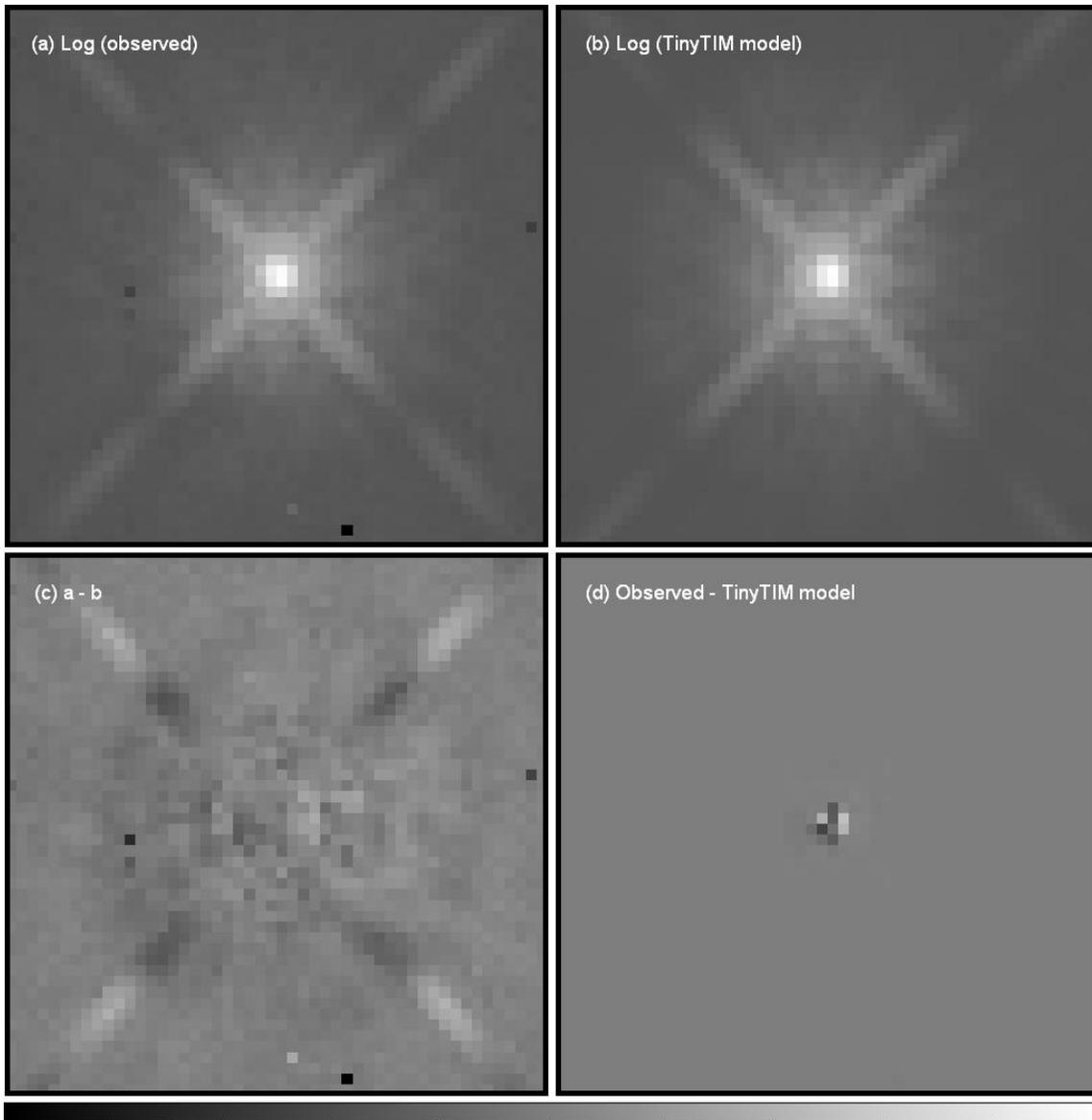
Results

Figure 1 shows the results of a TinyTIM model fit and subtraction using the original parameters. Figure 2 points out some of the more-obvious systematic residuals in the subtracted image.

The largest errors are along the image diagonals – these are subtraction errors in the spider diffraction spikes. The minima in the observed brightness of the spikes are about 20% farther from the star in the model, as compared to the observed image. The position of these minima is generally related to the width or thickness of the OTA secondary support spider, or in this case, the width of the cold pupil mask spider, which is used to mask-off or block the warm OTA spider. The cold mask is a physical mask inside the detector dewar, which lies near the position of the re-imaged OTA pupil (c.f. Figure 2.1in Dressel, et al., 2014). The fact that the position of the minima is about 20% too large, tells us that the spider thickness is about 20% too low in the TinyTIM model. We increased the cold mask spider thickness from 0.061 to 0.074 and a significant improvement in the model immediately resulted. Further tests and exploration of this parameter showed that the best value was 0.077 with an uncertainty of about + or - 0.001. Values outside this range gave significantly larger residuals.

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[2] The default WFC3/IR apertures, which is where observers typically place targets, are mostly located near the detector center. Notable exceptions are some of the grism apertures which are located up to ~140 pixels from the detector center.

Figure 1. Results for the F098M filter with star GD153 placed near the detector center (archive image iabl01d7q). Displays and brightness ranges are as follows: (a) $\log_{10}$ display of the observed image with the peak pixel scaled to unity and display range -6 to 0; (b) same as panel (a) but for the TinyTIM model, (c) difference of panels (a) and (b) with display range -1 to +1, (d) simple ratio of the observed image divided by the TinyTIM model with display range -10% to +10%. Each image is 51 x 51 pixels in size, or ~7 arcseconds wide by ~6 arcseconds high; the different horizontal and vertical scales are due to geometric distortion. Dark pixels in (a) and (c) are detector artifacts.

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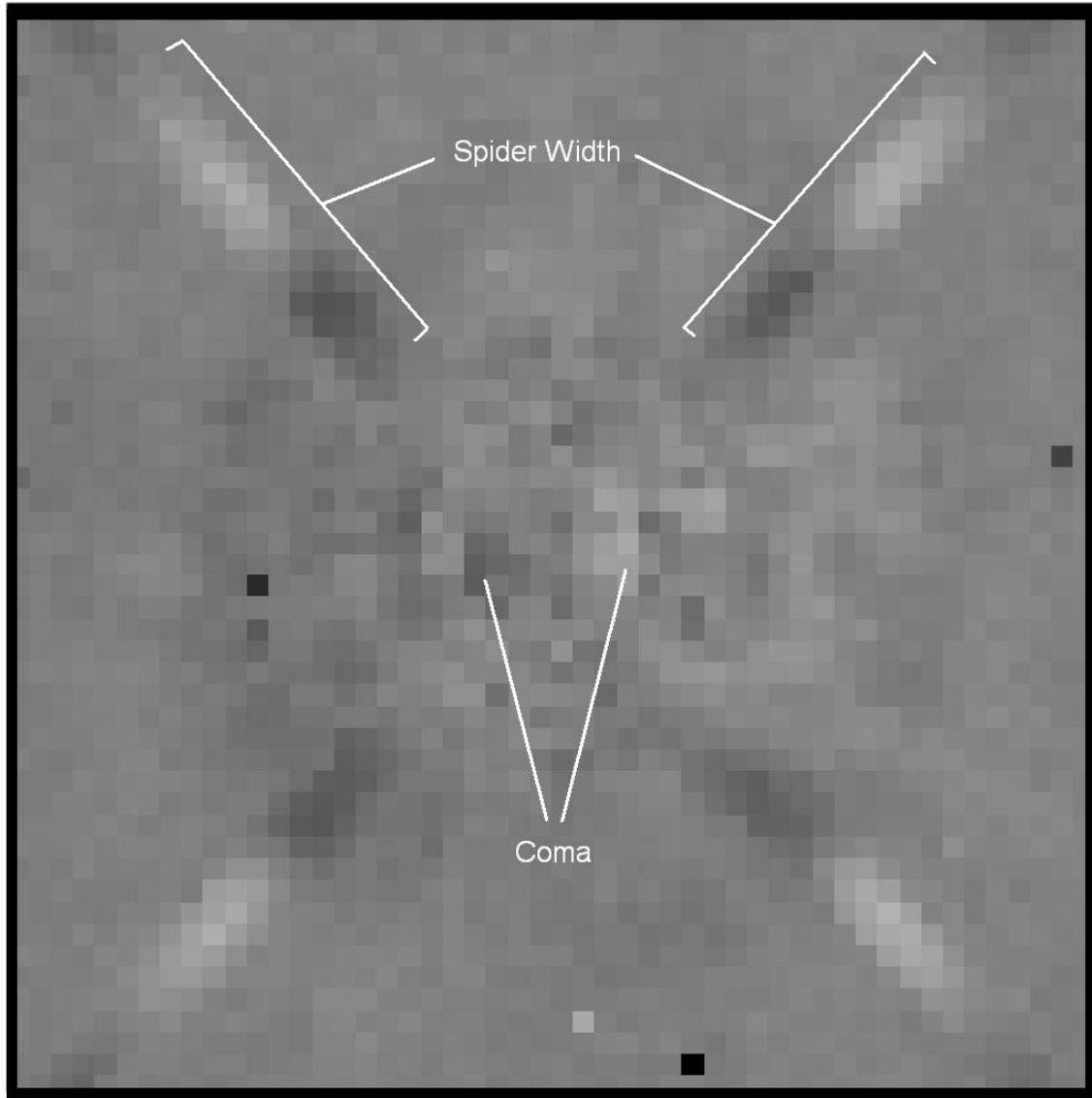
Figure 2. Difference between $\log_{10}$ of the observed image and $\log_{10}$ of the TinyTIM model for image **iabl01d7q. Residuals due to problems with the cold mask spider width and coma aberrations are labeled. This is same image as Figure 1c – see Figure 1 for details.**

Since adjusting the cold mask width gave a noticeable improvement, we investigated varying its other parameters, and found that increasing the secondary size, and introducing a small offset gave further reduction in the model subtraction residuals. In this case the improvements appeared as a reduction in the residuals in the form of a dark ring approximately 4.2 arcseconds in diameter. We also examined the cold mask outer diameter, but adjusting it did not give any significant improvements. Similarly we adjusted the hold-down pad parameters, but no improvements we obtained. The improved cold mask parameters are summarized in Table 1.

Table 1. Improved TinyTIM Cold Mask Parameters. [3]

Parameter	Old Value	New Value	Approx. Uncertainty
Secondary Radius	0.354	0.370	0.007
Spider Width	0.061	0.077	0.001
Mask Position	0.00, 0.00	0.02, -0.02	0.01

Coma is the next most obvious error in Figures 1 and 2. Coma errors will typically manifest themselves as bright areas within the inner Airy rings which are present only on one side of the star (i.e. asymmetric about the star image center). Such an error appears in the subtracted model residuals as a bright area on the right side of the star, and a dark area on the left, at a radius that corresponds roughly to the first Airy ring of the point spread function. In this case the error appears in the detector "X" direction, but this does not necessarily imply the TinyTIM "X coma" parameter is solely at fault. The TinyTIM model is in the OTA frame of reference, which is rotated by ~135 degrees to that of the detector. Hence both the TinyTIM model "X coma" and "Y coma" parameters are likely to be involved. The coma parameters are not a single value, but rather a 36-term polynomial with describes the variation in the coma across the two-dimensional detector. In the current models for WFC3/IR only the 6

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[3]Units are fraction of the OTA primary mirror pupil radius as re-imaged at the cold pupil mask.

lowest-order parameters are used. From Figure 1 it is apparent that the models had too much coma, so we tried making small reductions in the coma parameters. But eventually we found the best model resulted from setting all the coma parameters to zero. Apparently the pre-launch ZEMAX model used in TinyTIM (Hook and Stoehr 2008) contains significant coma which is not seen on orbit.

The final model utilizing the improved parameters is shown in Figure 3, and a side-by-side comparison is shown in Figure 4.

We performed similar, though less extensive, tests on the F160W image IABL01D8Q_flt.fits. The same set of improved parameters was found to give good results on the F160W data as well. The full set of final TinyTIM parameters, including these improvements, is listed in Appendix A.
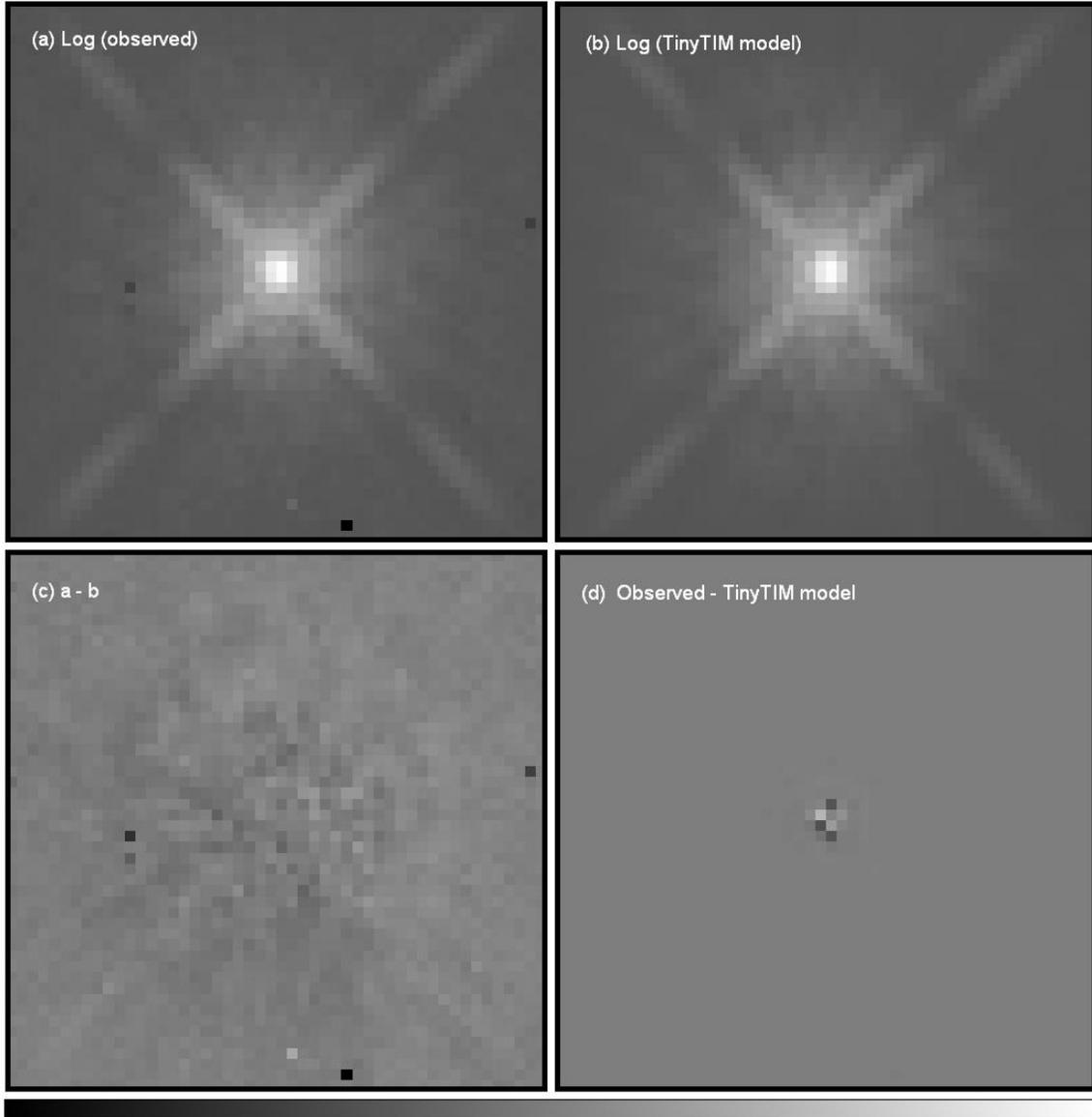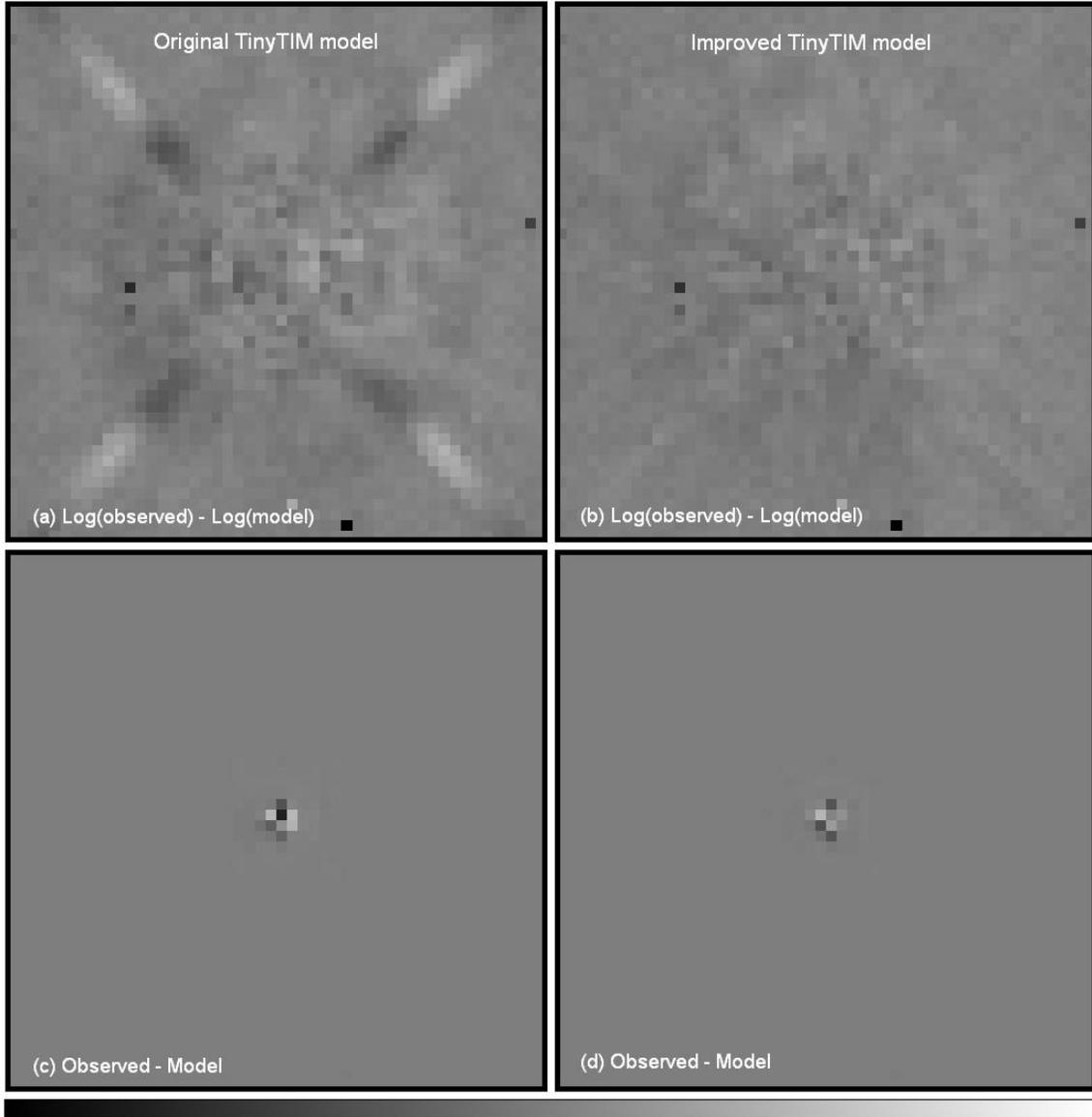
Figure 3. Similar to Figure 1, but using improved TinyTIM model parameters.

Figure 4. Comparison of subtraction residuals for the original TinyTIM model (left) and the improved model (right). Panels (a) and (b) show the differences between the $\log_{10}$ of the images, and panels (c) and (d) show the simple differences of the images. These are the same data as Figures 1 and 3.

Discussion

The cold mask properties should be well-known as they are simply machined into a piece of metal (unlike some complex optical surface which might have difficult-to-measure curves and surface errors). The cold mask properties used in TinyTIM are discussed by Hook and Stoehr (2008), which references Telfer (2006) for the detailed measurements. They give a value of 0.432mm for the spider widths. The TinyTIM model expresses the properties of the cold mask in units of the OTA pupil radius, which by design is 7.13mm at the cold mask. Hence Telfer's value of 0.432mm appears in TinyTIM as 0.061. Discussions with Hartig (2012) uncovered a Ball Aerospace memo which gives a larger value of 0.526mm, or about 20% larger, for the cold mask spiders. A large part of the cold mask error can be accounted for in the difference between the Telfer and Ball Aerospace values. Additional errors in the cold mask properties could arise from on-orbit focus adjustments made to WFC3. These might have moved the image plane of the OTA pupil away from the cold mask, and thereby changing the scale of the OTA pupil at the cold mask (Hartig 2012).

Regarding the coma parameters, it was surprising that simply setting them to zero would result in better models. We investigated whether these might be incorrectly implemented in TinyTIM. We created a copy of wfc3_ir.pup with large coma aberrations with specific variations across the detector, and then used it to generate test PSF models. In all cases the resulting models had the expected amounts of coma and distribution across the detector, so we feel that the TinyTIM software itself is correct. Apparently the coma parameters themselves, which are derived from pre-launch ZEMAX models (Hook and Stoehr 2008), are incorrect or have changed since launching the instrument. We note that a second set of pre-launch aberrations have been published by Hartig (2008). These were based on measurements during the Thermal Vaccuum #3 test. These indicate a smaller amount of coma -- about half as much -- at the field center, but we have not attempted to implement this alternate model in TinyTIM.

The poor fit given by the pre-launch ZEMAX model of the optical aberrations, as well as discrepancy found in the cold mask parameters, are causes for concern. Apparently there are significant errors in the current TinyTIM model for WFC3/IR. While we have made some modest effort here to improve the situation, a larger effort is probably needed to re-derive the full TinyTIM model for WFC3/IR using on-orbit data.

Our previous (Biretta 2012) work found excess "speckle pattern" residuals around the center of the PSF. We have examined this effect, but cannot yet find any improvements to rectify the situation. The residuals in the PSF core are decreased somewhat by the improvements already discussed (Figure 4b and 4c) but more work remains to be done in this area.

We thank George Hartig and John Krist for helpful discussions.

References

Biretta, J. 2012, "TinyTIM Modeling of WFC3/IR Images," ISR WFC3 2012-13.

Dressel, L., et al., 2014, "WFC3 Instrument Handbook," v. 6.0.

Hartig, G. F. 2008, "WFC3 Optical Wavefront Error Characterization in Thermal-Vaccum Test #3," ISR WFC3 2008-31.

Hartig, G. F. 2009, "WFC3 SMOV Programs 11437/9: IR On-orbit PSF Evaluation," ISR WFC3 2009-37.

Hartig, G. F. 2012, private communication.

Hook, R. and Stoehr, F. 2008, "WFC3 Support in TinyTIM," ISR WFC3 2008-14.

Krist, J. E., Hook, R. and Stoehr, F. 2011, Proc. SPIE, vol. 8127

Telfer, R. 2006, "A Nominal Geometrical Calculation of the Throughput of the WFC3 IR Channel Cold Mask," unpublished internal memo.

Appendix A: TinyTIM v. 7.4 WFC3/IR Improved Model Parameters.

Below we list the improved aberration tables for WFC3/IR in TinyTIM version 7.4. Note the values for Zernikes Z4 – Z8 in the wfc3_ir.tab file are not used, but instead the values of 1e-12 instruct the software to use field-dependent Zernikes in the wfc3_ir.pup table.

File wfc3_ir.tab

```
# Zernike file for WFC3 IR Channel
# March 2008  Initial implementation (no aberrations)
# March 2011  Set Z4-Z8 terms to non-zero to activate coeffs in .pup file
 547.     # Reference wavelength (nm)
 22       # Last Zernike in file
 0.       # Z1 = (Not used)
 0.       # Z2 = X (V2) tilt
 0.       # Z3 = Y (V3) tilt
 1e-12    # Z4 = Focus
 1e-12    # Z5 = 0 degree astigmatism
 1e-12    # Z6 = 45 degree astigmatism
 1e-12    # Z7 = X (V2) coma
 1e-12    # Z8 = Y (V3) coma
 0.       # Z9 = X (V2) clover
 0.       # Z10 = Y (V3) clover
 0.       # Z11 = 3rd order spherical
 0.       # Z12 = 0 degree Spherical astigmatism
 0.       # Z13 = 45 degree Spherical astigmatism
 0.       # Z14 = X (V2) Ashtray
 0.       # Z15 = Y (V3) Ashtray
 0.       # Z16
 0.       # Z17
 0.       # Z18
 0.       # Z19
 0.       # Z20
 0.       # Z21
 0.       # Z22 = 5th order spherical
```

File wfc3_ir.pup

```
# Pupil Table :  wfc3_ir.pup
# Do not change the order of these entries!
# Date : April 2008
# Preliminary version of WFC3 IR channel pupil information for Tiny Tim 7.0.
#
# Added preliminary distortion coefficients, from Colin Cox, March 2008
# Added preliminary cold-mask information from George Hartig, March 2008
#
# Date : Feb 2011
#  Swapped X/Y coeffs for astig and coma
#  Using charge diffusion kernel from WFC3 ISR 2008-41
# Date : March 2011
#  Updated V2,V3 (pupil) coordinates for reference position and camera center
#    using uab1537ci_idc.fits
#-----------------------------------------------------------------------------
#
# Optical Telescope Assembly pupil information
#
 0.330  = OTA Secondary Mirror Radius
 0.022  = OTA Spider Width
#
```

```
# Mirror pad positions and radii
#
  0.8921   0.0000 0.065 = OTA Pad 1 (V3, V2, Pad Radius)
 -0.4615   0.7555 0.065 = OTA Pad 2
 -0.4564 -0.7606 0.065 = OTA Pad 3
#
# WFC3 IR wavelength range
#
  900 1700  = min, max detector wavelength (nm)
#
# WFC3 IR cold mask obscuration parameters
# These are from George Hartig, they are close, but not the same as the old
NICMOS ones.
# 0.354 = WFC3 IR Secondary radius
# 0.061 = WFC3 IR Spider width
# 0.9755 = WFC3 IR Outer radius of cold mask
#
# Improved values - Biretta (2013)
 0.37 = WFC3 IR Secondary radius
 0.077 = WFC3 IR Spider width
 0.9755 = WFC3 IR Outer radius of cold mask
#
# Mask position
#
# 0.0 0.0 = Mask X,Y positions
#
# Improved values - Biretta (2013)
 0.02 -0.02 = Mask X,Y positions
#
# WFC3 IR camera rotation (relative to OTA)
#
  135.0  = WFC3 IR camera rotation
#
# Pixel size (arcsecs)
#
   0.13 = WFC3 IR pixel size
#
# Axial offset of WFC3 IR camera
#
  0.0 0.0 = WFC3 IR Camera 2 V2,V3 axial offset
#
#  WFC3 IR field dependent aberration coefficients (in microns)
#
# Focus
#
-1.20318149e-02 -1.01187543e-04 7.07476814e-07 0.0e+00 0.0e+00 0.0e+00
7.69803251e-04 4.23580589e-08 0.0e+00 0.0e+00 0.0e+00 0.0e+00
-7.67207830e-06 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
#
# X astig
# SWAPPED
1.33063083e-03 1.68392660e-04 -8.55061473e-09 0.0e+00 0.0e+00 0.0e+00
-2.58073858e-05 -3.33276120e-06 0.0e+00 0.0e+00 0.0e+00 0.0e+00
-2.00120320e-08 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
#
# Y astig
# SWAPPED
-8.35400173e-03 5.13194852e-04 -3.99141208e-06 0.0e+00 0.0e+00 0.0e+00
2.01150767e-04 -3.92886164e-08 0.0e+00 0.0e+00 0.0e+00 0.0e+00
-1.97495797e-06 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
```

```
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
#
# X coma
# SWAPPED
# coma removed - Biretta (2013)
# 2.31206647e-02 1.81284830e-04 -5.30494748e-06 0.0e+00 0.0e+00 0.0e+00
# -1.39564501e-04 3.97479493e-06 0.0e+00 0.0e+00 0.0e+00 0.0e+00
# -2.06559126e-06 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
#
# Y coma
# SWAPPED
# coma removed - Biretta (2013)
# 1.25930198e-02 -5.80506052e-04 5.25377957e-06 0.0e+00 0.0e+00 0.0e+00
# -5.67486735e-04 4.09168135e-06 0.0e+00 0.0e+00 0.0e+00 0.0e+00
# 2.15934792e-06 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00 0.0e+00
#
# WFC3 IR geometric distortion coefficients; used to convert
# detector X,Y position to telescope V2,V3
#
# V2,V3 (pupil) coordinates of reference position
#
  -1.0190  0.5070     = in arcsec
#
# Detector X,Y coordinates of reference position
#
   507 507  = pixels
#
# V2, V3 (pupil) coordinates of WFC3 IR camera center
#
  -1.0190  0.5070     = in arcsec
#
# X,Y -> V2 transform coefficients (4th order)
#
-7.834721E-6  1.354925E-1  -2.666651E-10  3.238674E-6  -1.381910E-10
3.737046E-14  1.843860E-11  4.087322E-13  3.758686E-12
0.0 0.0 0.0 0.0 0.0
#
# X,Y -> V3 transform coefficients
#
1.210825E-1   8.907462E-6   3.563704E-6   2.909743E-10  8.195221E-7
2.676912E-11 -3.854757E-13  1.336036E-11 -5.999974E-14
0.0 0.0 0.0 0.0 0.0
#
# V2,V3 -> X
#
4.775553E-4    7.380483E0  -7.414314E-8  -1.457858E-3  1.313760E-7
-1.377528E-10  5.729815E-7  -1.438840E-9  5.382542E-8
0.0 0.0 0.0 0.0 0.0
#
# V2,V3 -> Y
#
8.258834E0  -5.429441E-4  -2.009371E-3  1.718983E-7   -3.689799E-4
```

```
8.509658E-7  1.510508E-9   2.749957E-7  1.801569E-10
0.0 0.0 0.0 0.0 0.0
#
# Diffusion kernels to model the IPC effect
#
#  ********* Note - these are based on vac measurements kindly provided
#            by George Hartig in May 2008 - they are empirical and match what
was seen in thermal vac.
#            See WFC3 ISR 2008-41.
#
# These numbers are known to be a function of quadrant and readout, and not
determined as
# a function of wavelength. The values here are averages.
#
1.000  = Wavelength (microns) of kernel 1
#
# Kernel 1
#
0.0007 0.025  0.0007
0.025  0.897  0.025
0.0007 0.025  0.0007
#
1.300  = Wavelength (microns) of kernel 2
#
# Kernel 2
#
0.0007 0.025  0.0007
0.025  0.897  0.025
0.0007 0.025  0.0007
#
1.600  = Wavelength (microns) of kernel 3
#
# Kernel 3
#
0.0007 0.025  0.0007
0.025  0.897  0.025
0.0007 0.025  0.0007
#
# Additional field dependent charge diffusion relation coefficients
# Currently these are just place holders.
#
  2  = number of wavelengths at which coefficients are defined
#
#
  1.000  = wavelength 1
0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0
#
  1.600  = wavelength 2
0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0
```