# Modelling the fringing of the ACS WFC and HRC chips 

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#### Abstract

The fringing of CCD detectors occurs because of interference between the incident light and the light internally reflected at the interfaces between the thin layers of the CCD chip. Knowing the construction of the CCD, namely the materials composing the layers, their refractive index variation with wavelength and their thicknesses, the resulting fringe amplitude can be calculated from geometrical optics. Malamuth et al. (2003) have applied this technique to the STIS CCD. The topmost layer, which is the detection layer and composed of Silicon, defines the most varying fringing with wavelength; the lower layers control the envelope of the fringing amplitude with wavelength. Modelling of the layer structure of the ACS HRC and WFC CCD's is described. The HRC (SITe) chip is a copy of the STIS one and so has a similar structure, but the WFC (also SITe) chip has proprietary construction. During the ACS ground testing at Ball Aerospace, a series of narrow band flat fields at wavelengths from 7000 to 10000 A were observed to provide the primary data for the modelling. The modelling procedure is described. The observed fringe amplitude across the CCD is used to predict the spatial variation of the thickness of the top layer, whilst the thicknesses of the lower layers are kept fixed. By applying the model maps of the layer thicknesses to ground or in-orbits flats, the observed fringing in ACS can be reduced by a factor $\sim 4$ to the level of a few percent rms. Application of the fringe model to the correction of extracted spectra is outlined.


## 1. Introduction

Interference of light in an optical CCD detection layer occurs between incident light and that back-reflected from the thin multi-layer. In a back-illuminated CCD, if the detection layer becomes transparent then the contribution of the reflected light can become a large
fraction of the incident power. The result is a modulation of the signal by fringes whose amplitude depends on the optical properties of the layers, which are a function of wavelength. Modulation of the signal by fringing can approach $40 \%$ of the signal level in the red region. The fraction of light internally reflected depends on the number of layers of the CCD, their thicknesses and material, which enters through the layer refractive index. Since Silicon, which composes the detection layer, becomes more transparent with wavelength beyond about 6000A, the resulting fringe amplitude typically increases dramatically in the far-red / near-infrared spectral region.
Fringing is a common bane of astronomical detectors in the 7000-10000A region. In astronomical imaging, flat-fields are taken through the same filter and used to remove the fringing as a function of detector position. In spectroscopic applications with a fixed slit, flat-fields are also employed using continuum lamp exposures (e.g. off the inside of the dome). For slitless spectrometry, each pixel of the CCD can receive light of any wavelength over the passband of the instrument, and the flat-field must be replaced by a series of flat-fields at many wavelengths - a flat-field cube.
Knowing in detail the bulk construction of the CCD, the resulting fringe amplitude can be calculated from geometrical optics. The refractive index varies as a function of wavelength for most materials (see Handbook of Optical Constants of Solids, Palik 1998), and is a key ingredient for the optical modelling. Malamuth et al. (2003) successfully applied this technique to the STIS SITe CCD. Here we describe this approach for the ACS WFC and HRC CCD chips which are both employed as detectors for the G800L grism (see Pavlovsky et al. 2002). A series of flat fields at many wavelengths in the red were obtained on the ground with a monochromator illuminating the ACS. The reduction and analysis of these data to derive the thicknesses of the CCD layers is described. Application of the modelled layer structure to the correction of real data is outlined.

## 2. Ground fringe flat data collection

While ACS was at Ball Aerospace labs during February 2001, a series of tests were conducted to illuminate the ACS with the HST Refractive Aberration Simulator (RAS/ HOMS) and a monochromator. The monochromator was adjusted to have a slit width to produce monochromatic light of wavelength extent 20 or 10 A , chosen to be less than the pixel width in the dispersion direction for the G8000L grism ( $\sim 40 \mathrm{~A}$ for WFC and $\sim 24 \mathrm{~A}$ for HRC; Pasquali et al. 2003). Table 1 summarises the collected data for the WFC and Table 2 for the HRC. The Catalog No. refers to the $\log$ in the ACS IDT calibration database (see http://adcam.pha.jhu.edu/instrument/calibration/). The data were taken by George Hartig, Zlatko Tsvetanov, Frank Bartko, Don Lindler and Andre Martel.

| Catalog. ID. | Date | Filter | Lambda (A) | Width (A) | Exp.(s) |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 25670 | 2001-02-23 | F606W | 7000 | 20 | 60 |
| 25671 | 2001-02-23 | F814W | 7500 | 20 | 60 |
| 25672 | 2001-02-23 | F814W | 7820 | 20 | 54 |
| 25673 | 2001-02-23 | F814W | 7860 | 20 | 55 |
| 25674 | 2001-02-23 | F814W | 7902 | 20 | 57 |
| 25675 | 2001-02-23 | F814W | 7910 | 20 | 57 |
| 25676 | 2001-02-23 | F814W | 7920 | 20 | 57 |
| 25677 | 2001-02-23 | F814W | 7930 | 20 | 58 |
| 25679 | 2001-02-23 | F814W | 7940 | 20 | 58 |
| 25680 | 2001-02-23 | F814W | 7980 | 20 | 60 |
| 25682 | 2001-02-23 | F814W | 8560 | 20 | 89 |
| 25683 | 2001-02-23 | F814W | 8250 | 20 | 71 |
| 25684 | 2001-02-23 | F814W | 7940 | 20 | 58 |
| 25685 | 2001-02-23 | F814W | 8600 | 20 | 91 |
| 25686 | 2001-02-23 | F814W | 8610 | 20 | 92 |
| 25687 | 2001-02-23 | F814W | 8620 | 20 | 101 |
| 25688 | 2001-02-23 | F814W | 8630 | 20 | 102 |
| 25689 | 2001-02-23 | F814W | 8640 | 20 | 103 |
| 25690 | 2001-02-23 | F814W | 8680 | 20 | 107 |
| 25691 | 2001-02-23 | F814W | 9000 | 20 | 150 |
| 25692 | 2001-02-23 | F850LP | 9150 | 20 | 177 |
| 25693 | 2001-02-23 | F850LP | 9320 | 20 | 220 |
| 25694 | 2001-02-23 | F850LP | 9360 | 20 | 231 |
| 25695 | 2001-02-23 | F850LP | 9400 | 20 | 244 |
| 25696 | 2001-02-23 | F850LP | 9440 | 20 | 258 |
| 25697 | 2001-02-23 | F850LP | 9480 | 20 | 273 |
| 25698 | 2001-02-23 | F850LP | 10000 | 20 | 623 |
| 25701 | 2001-02-23 | F814W | 8620 | 20 | 101 |
| 25702 | 2001-02-23 | F814W | 8630 | 20 | 102 |
| 25703 | 2001-02-23 | F814W | 8630 | 20 | 102 |
| 25704 | 2001-02-23 | F814W | 8600 | 10 | 200 |
| 25705 | 2001-02-23 | F814W | 8610 | 10 | 200 |

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| Catalog. ID. | Date | Filter | Lambda (A) | Width (A) | Exp.(s) |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 25706 | $2001-02-23$ | F814W | 8620 | 10 | 200 |
| 25707 | $2001-02-23$ | F814W | 8630 | 10 | 200 |
| 25708 | $2001-02-23$ | F814W | 8640 | 10 | 200 |
| 25709 | $2001-02-23$ | F814W | 8680 | 10 | 220 |
| 26007 | $2001-02-25$ | F814W | 8850 | 20 | 120 |
| 26008 | $2001-02-25$ | F814W | 8630 | 20 | 102 |
| 26009 | $2001-02-25$ | F850LP | 9750 | 20 | 400 |
| 26010 | $2001-02-25$ | F850LP | 9410 | 20 | 250 |
| 26011 | $2001-02-25$ | F850LP | 9420 | 20 | 250 |
| 26012 | $2001-02-25$ | F850LP | 9430 | 20 | 250 |
| 26013 | $2001-02-25$ | F850LP | 9450 | 20 | 250 |
| 26014 | $2001-02-25$ | F850LP | 9460 | 20 | 250 |
| 26015 | $2001-02-25$ | F850LP | 9100 | 20 | 160 |
| 26016 | $2001-02-25$ | F850LP | 9150 | 20 | 180 |
| 26017 | $2001-02-25$ | F850LP | 9900 | 20 | 500 |
| 26018 | $2001-02-25$ | F850LP | 9800 | 20 | 450 |

Table 1: Log of the ACS WFC monochromator flat field data.

| Catalog ID | Date | Filter | Lambda (A) | Width (A) | Exp. (s) |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 25815 | $2001-02-24$ | F606W | 7000 | 20 | 341 |
| 25816 | $2001-02-24$ | F814W | 7500 | 20 | 465 |
| 25817 | $2001-02-24$ | F814W | 7820 | 20 | 580 |
| 25618 | $2001-02-24$ | F814W | 7860 | 20 | 597 |
| 25619 | $2001-02-24$ | F814W | 7900 | 20 | 615 |
| 25820 | $2001-02-24$ | F814W | 7910 | 20 | 464 |
| 25821 | $2001-02-24$ | F814W | 7920 | 20 | 467 |
| 25822 | $2001-02-24$ | F814W | 7930 | 20 | 471 |
| 25823 | $2001-02-24$ | F814W | 7940 | 20 | 474 |
| 25824 | $200-1-02-24$ | F814W | 7980 | 20 | 489 |
| 25825 | $2001-02-24$ | F814W | 8250 | 20 | 605 |
| 25826 | $2001-02-24$ | F814W | 8560 | 20 | 791 |


| Catalog ID | Date | Filter | Lambda (A) | Width (A) | Exp. (s) |
| :---: | :---: | :---: | :---: | :---: | :---: |
| 25827 | 2001-02-24 | F814W | 8600 | 20 | 820 |
| 25828 | 2001-02-24 | F814W | 8610 | 20 | 827 |
| 25829 | 2001-02-24 | F814W | 8620 | 20 | 834 |
| 25830 | 2001-02-24 | F814W | 8630 | 20 | 842 |
| 25831 | 2001-02-24 | F814W | 8640 | 20 | 850 |
| 25832 | 2001-02-24 | F814W | 8680 | 20 | 882 |
| 25833+4 | 2001-02-24 | F814W | 9000 | 20 | 600 |
| 25835+6 | 2001-02-24 | F850LP | 9150 | 20 | 700 |
| 25837+8 | 2001-02-24 | F850LP | 9320 | 20 | 800 |
| 23839+40 | 2001-02-24 | F850LP | 9360 | 20 | 850 |
| 25841+2 | 2001-02-24 | F850LP | 9400 | 20 | 850 |
| 25843+4 | 2001-02-24 | F850LP | 9440 | 20 | 850 |
| 25845+6 | 2001-02-24 | F850LP | 9480 | 20 | 850 |
| 25847+8 | 2001-02-24 | F850LP | 10000 | 20 | 1200 |
| 28020+1 | 2001-02-25 | F850LP | 9750 | 20 | 1000 |
| 26022+3 | 2001-02-25 | F850LP | 9410 | 20 | 800 |
| 26024+5 | 2001-02-25 | F850LP | 9420 | 20 | 800 |
| 26026+7 | 2001-02-25 | F850LP | 9430 | 20 | 800 |
| 26028+9 | 2001-02-25 | F850LP | 9450 | 20 | 800 |
| 26030+1 | 2001-02-25 | F850LP | 9460 | 20 | 800 |
| 26032+3 | 2001-02-25 | F850LP | 9100 | 20 | 650 |
| 26034+5 | 2001-02-25 | F850LP | 9200 | 20 | 700 |
| 26036+7 | 2001-02-25 | F850LP | 9900 | 20 | 1000 |
| 26038+9 | 2001-02-25 | F850LP | 9800 | 20 | 1000 |
| 26040+1 | 2001-02-25 | F814W | 8850 | 20 | 500 |
| 26042 | 2001-02-25 | F814W | 8630 | 20 | 842 |

Table 2: Log of the ACS HRC monochromator flat field data.

The wavelengths at which the narrow band flat fields were obtained were a compromise between covering the whole wavelength range at 20 or 40A steps, in order to adequately sample the fringe cycle of about 80A, and time limitations. Thus a few narrow wavelength ranges ( $\sim 200 \mathrm{~A}$ ) were well sampled (e.g. 10 or 20A steps) with a selection of isolated data points at other wavelengths over the range 7000 to 10000 A . Below 7000A the fringe
amplitude is very low ( $<1 \%$ ); above 10000A the CCD DQE is very low, so flat field exposure times become prohibitively long. Fringe amplitude (expressed in \% or fractional) is defined as the absolute value of the unity subtracted ratio of the signal in a pixel of an image which has been normalised by the mean over a spatial scale much larger than the fringing.
Tables 1 and 2 list the exposure times. The times were derived by taking a few test exposures at four wavelengths and then determining the exposure time to reach a given signal level (typically $\sim 20000$ DN for the WFC flats (GAIN=1) and $\sim 7500 \mathrm{DN}$ for the HRC ones, at GAIN=2). For many of the HRC flats, a repeat exposure to enable cosmic-ray (CR) rejection was performed (see entries in Table 2).

## 3. Basic data reduction

Bias frames were taken during the course of the narrow band flat field calibration programme. The bias frames were averaged for each chip (WFC Chips 1 and 2 and HRC) and simply subtracted from the flat field exposures as the bias changed by less than 2DN over the course of the data taking. A correction for the wrap of the 16 bit integer data was made before bias subtraction (if the pixel value was $<0$, then 65536 was added to the value). The IDT data format for WFC consists of two 2 kx 2 k pixel reads for each chip and these were reformed into a single 4kx2k image. The bias-subtracted image was then smoothed by a broad Gaussian to form a large-scale flat field. The width of the Gaussian was chosen to be much larger than the spatial frequency of the fringing. The final value was determined by examining the rms as a function of smoothing sigma in a number of areas over the chips on the image normalised by the smoothed flat. The rms on the normalised flat increases as a function of increasing width of the smoothing Gaussian and then levels off as the largerscale variations are modelled., leaving the fringing as the measured rms. For the HRC a sigma of 35 pixels was adopted, 40 for the WFC chips. This procedure ensures that the fringe flats are normalised to 1.0 on spatial scales larger than the fringing (i.e. $>10$ pixels). The final stage of the basic reduction was to set header keywords MONOWAVE and MONOWID for the monochromator wavelength and width of the flat field illumination, as specified in Tables 1 and 2.

## 4. Fringe optical modelling

A CCD detector behaves very similarly to a multi-layer stack and can be treated through wave propagation in stratified conducting media (see for example Born \& Wolf, Chapter 13). In the case of the ACS CCD's, manufactured by SITe, both are backside-thinned devices, and the Silicon detection layer is at the top of the stack and intercepts the incident radiation (in vacuo). Figure 1 shows a sketch of the layer construction of the ACS HRC chip. This chip has very similar contruction to the STIS chip and the approximate thicknesses and material of the layers are available from SITe (see Table 1 of Malamuth et al., 2003).

The amplitudes of the transmitted and reflected waves at a boundary are given by Fresnel equations. At the interface between two media $i$ and $j$ the amplitude reflection coefficient is given by

$$
\mathbf{R}_{\mathbf{i} \mathbf{j}}=\frac{\left(\mathbf{n}_{\mathbf{i}}-\mathbf{i} \mathbf{k}_{\mathbf{i}}\right)-\left(\mathbf{n}_{\mathbf{j}}-\mathbf{i} \mathbf{k}_{\mathbf{j}}\right)}{\left(\mathbf{n}_{\mathbf{i}}-\mathbf{i} \mathbf{k}_{\mathbf{i}}\right)+\left(\mathbf{n}_{\mathbf{j}}-\mathbf{i} \mathbf{k}_{\mathbf{j}}\right)}
$$

and the amplitude transmission coefficient by

$$
\begin{equation*}
T_{i \mathbf{j}}=\frac{2 \sqrt{\left(\mathbf{n}_{\mathbf{i}}-\mathbf{i} \mathbf{k}_{\mathbf{i}}\right) \times\left(\mathbf{n}_{\mathbf{j}}-\mathbf{i} \mathbf{k}_{\mathbf{j}}\right)}}{\left(\mathbf{n}_{\mathbf{i}}-\mathbf{i} \mathbf{k}_{\mathbf{i}}\right)+\left(\mathbf{n}_{\mathbf{j}}-\mathbf{i} \mathbf{j}_{\mathbf{j}}\right)} \tag{2}
\end{equation*}
$$

where the complex refractive index is
$\mathbf{n}=\mathrm{n}+\mathrm{ik}$
which is a tabulated function of wavelength (Palik 1998). Some fraction of the light reaching the $\mathrm{Si}-\mathrm{SiO}_{2}$ interface in Figure 1 is reflected and it is the intensity of this reflected light $\left(=\mid\right.$ Amplitude $\left.\left.\right|^{2}\right)$ that contributes to the fringing. The fraction transmitted through the $\mathrm{Si}-\mathrm{SiO}_{2}$ layer is then absorbed in the $\mathrm{SiO}_{2}$ layer and undergoes reflection at the SiO 2 -
$\mathrm{Si}_{3} \mathrm{~N}_{4}$ layer. The reflected light is then transmitted back through the $\mathrm{SiO}_{2}$ layer and through the $\mathrm{SiO}_{2}-\mathrm{Si}$ interface to contribute to the fringing. A similar effect occurs for the $\mathrm{SiO}_{2}-\mathrm{Si}_{3} \mathrm{~N}_{4}$ interface and the $\mathrm{Si}_{3} \mathrm{~N}_{4}-\mathrm{Si}$ interface. The subtrate $\left(\mathrm{Si}_{3} \mathrm{~N}_{4}\right)$ is assumed to be infinite and have an appropriate reflectivity. The doubly reflected beams in each layer were neglected.
The transfer of radiation can be expressed in terms of the electric vector for a plane harmonic wave:

$$
\begin{equation*}
\mathbf{A}=\mathbf{A}_{\mathbf{0}} \mathrm{e}^{-\mathbf{i}\left(\mathbf{x}-\frac{2 \pi \pi_{i} \mathrm{~d}_{\mathrm{i}}}{\lambda}\right)} \mathbf{e}^{\frac{2 \pi \mathrm{k}_{\mathrm{i}} \mathrm{~d}_{\mathrm{i}}}{\lambda}} \tag{3}
\end{equation*}
$$

where $x$ is some arbitrary initial phase, and the second exponential term accounts for the absorption in the $i$ th layer dependent on the absorption coefficient $k$ and the thickness of the layer $d_{\mathrm{i}}$. The detected signal amplitude is then the sum of the incident and the four reflected waves (from each of the interfaces). Since the beams are F/24.9 for the WFC and F/72 for the HRC, they can be treated, to a fair approximation, as having the same incident
angle across the detector. Using a beam tilted by 2.3 degrees, to simulate the WFC beam, showed a fringe amplitude differing only by $0.5 \%$ compared to the zero incidence case. Malamuth et al. (2003) also considered the anti-reflection coating on the incident surface of the Si detection layer. This layer is very thin with respect to the wavelength of the light causing the fringing and so effectively provides only a very slowly varying modulation with wavelength; the anti-reflection layer was neglected in this treatment but from the quality of the correction of fringing that can be achieved, its inclusion is clearly not of paramount importance. Malamuth et al. (2003) also discuss the contribution of the roughness of the various layers (see Windt, 1998). Since these are small with respect to the wavelength, the net effect is a loss of specular reflectance leading to reduced fringe contrast. In our treatment the combined fringe contrast loss by all layers was fitted by a single, wavelength independent, parameter at each pixel, subsequently called fringe amplitude efficiency.


Figure 1. The construction of the ACS HRC CCD chip as modelled.

### 4.2 Fitting the observed fringing

The input data consists of a fringe flat cube at the finite number of wavelengths sampled. The incident light from the monochromator has a finite range of wavelengths so the fringe amplitude for a pixel is computed as an average over the range of wavelengths appropriate to the monochromator width (column 4 of Tables 1 and 2). It was found to be accurate enough to compute the average fringe amplitude from at least six wavelength steps per fringe flat. Calculating the fringe amplitude, for a 20A wide monochromatic beam, at 6
wavelength points across the beam, as opposed to 20 values at 1 A spacing, produced a difference of less than $1 \%$ in the computed fringe amplitude for a value of $15 \%$.
The optimization problem is to choose the thickness of the four layers given their compositions and the tabulated refractive index with wavelength which minimizes the rms on the observed - model fringe amplitude for the set of normalized flat fields. The high frequency fringing with wavelength is caused by the thickest ( Si ) layer, whilst the lower (thinner) layers modulate the amplitude only relatively slowly with wavelength. Small changes in thickness of, say, the $\mathrm{Si}_{3} \mathrm{~N}_{4}$ layer (Figure 1) have a very small effect on the rms of the observed-fitted fringe amplitude, less than the typical errors on the fringe flats. The operational procedure was to choose a number of small regions across the chip and seek a fit in terms of the thicknesses of the four layers. To improve the signal-to-noise this procedure was performed on a coadded region of $3 \times 3$ pixels; by coadding increasingly large regions, it was found that $3 \times 3$ pixels was the maximum size allowed which did not decrease the fringe amplitude through summing pixels with significantly differing fringe phase and amplitude. Figure 2 shows an example of such a fit for the centre of the HRC (pixels 527:529,527:529). The optimization of the layer thickness, by minimizing the rms on the observed-model fringe amplitude with wavelength, was performed using the NAG quasiNewton minimization routine E04JAF. The error bars in the plot are determined from the rms on the mean over the 9 pixels in the summed area. The fitted thicknesses of the layerwere: $13.38,0.26,0.24$ and 0.83 micron and the rms on the fit was 0.012 for the fringe flats at 37 wavelength points (see Table 2).
The most rapidly varying component of the fringing, attributable to the Si detection layer (see Figure 1), varies in amplitude and phase on a spatial scale of $<4$ pixels. Therefore to adequately model the fringing of the chips, the thickness of the upper Si layer should be fitted for each pixel of the CCD. For the HRC this is $1024^{2}$ pixels, but for the WFC it is $4096^{2}$ pixels. The behaviour of the rms of the observed-model fringing for the top Si layer, with the other layer thicknesses held fixed, shows a highly periodic behaviour with seperation between minima of about 0.13 micron for the HRC. The behaviour of the rms on the observed-model fringe flats, as a function of the thickness of the other layers, was much more shallow and well behaved, with only the bottom Si layer showing a periodic behaviour. Also the fitted fringe amplitude efficiency factor showed a smooth behaviour with no well defined minimum. This periodic function of the rms as a function of the Si layer thickness proved hard to minimize with an automatic minimum finding routine.


Figure 2. The model fringing (continuous line) fis shown for a position at the centre of the HRC CCD (9 pixels centred on pixel 528,528 ). This is compared with the observed fringing averaged over the same 9 pixels from the fringe flats (crosses with error bars). The model fringing, but binned to the same wavelength range as the fringe flats, is shown by filled triangles.

A phased approach was adopted to deriving the pixel-by-pixel Si layer thickness. Sampling the fringing averaged over a $3 \times 3$ pixel box stepped every 5th pixel, and searching
for the minimum rms over a wide range in thickness, a coarse map of the thickness of the upper Si layer was constructed. This was then binned onto the CCD array extent and used as an initial value for a finer sampling but with a narrower search range in thickness. This was repeated until the final step was an output pixel-by-pixel thickness map with a fine search step and small range. The minimum rms was located to a precision of $+/-$ 0.01 micron for the thickness of the Si layer. At each step the image of the thickness of the Si layer was examined and any obvious "bad" pixels, where an adjacent minimum had been located, or there were bad pixels in some of the flat field images (cosmic ray affected), were manually substituted using the local mean value (employing IRAF task boxinterp) or a purpose written routine to replace a pixel with an outlier thickness by the median value of the local group of pixels. The supposition that there are no discrete jumps of more than 0.1 micron in the thickness of the Si layer between adjacent pixels is implicit here and was bourne out by the behaviour of most of the detector pixels.

## 5. Modelling the HRC

There were 37 fringe flats covering the wavelength range from 7000 to 10000 A inclusive, all with 20A monochromator beam width (see Table 2). Figure 3 shows the observe fringe flat at a wavelength of 9200A, near the wavelength of maximim fringe amplitude (see Fig. 2 ). The region of the detector (top left) obscured by the coronographic finger cannot be modelled. There is clear trend from top left to bottom right and with distinct regions where the fringes are less bunched together to the top left and lower right (i.e a saddle from lower left to upper right).
In the set of ground flats (Table 2), there were two regions in wavelength space where fringe flats closely separated in wavelength were observed in order to well-sample the fringe phase and amplitude. These are the regions at 8640A and 9400A where the monochromator wavelengths are separated by 10 or 20A only. Adopting the tabulated refractive index values from Palik (1998) for all the materials, showed in particular that it was not possible to reconcile the phase of the fringing at both 8640 and 9400 with the tabulated Si refractive index. This problem was also encountered by Malamuth et al. (2003) and is discussed in detail in their Section 3.3. The modified tabulation of refractive index adopted by them was also tried for the ACS HRC chip (similar in construction to the STIS CCD). This led to much improved results for the two well sampled regions but still did not reconcile the observed and model fringe phase below 7500A and above 9600A. On the basis that impurities and dopants in the Silicon can alter its refractive index, we adopted a fudged Si refractive index in which the real value was increased by around 0.018 in the wavelength range 6600-7400A and by 0.003 beyond 9600A (both regions were very poorly sampled in wavelength - see Figure 2). An alternative explanation could be that the absolute values of the monochromator wavelengths are not accurate.


Figure 3. The observed fringe flat at a wavelength of 9200A for the HRC detector. The greyscale range is 0.85 to 1.15 .

The final fitting of the HRC fringe flats was made with this modified Si refractive index data. The result for the map of the Si detection layer is shown in Figure 4. The mean rms on the observed-fitted amplitude is 0.026 for this image. The variation of the Si layer differs significantly from the map of the STIS CCD which showed a wedge in the thickness, whereas the HRC has a valley from lower left to upper right. The majority of the pixels are between 12.8 and 15.5 micron thickness compared to the 13.2 to 14.8 range for the inflight STIS chip. Figure 5 shows the modelled fringe amplitude produced by running the model in reverse to predict the fringe amplitude and phase based on the pixel-by-pixel thickness of the Si detection layer (Figure 4), the fixed thicknesses of the lower layers and the fringe amplitude efficiency. The wavelength extent of the monochromatic flat field is taken into account in this model fringe image.


Figure 4. The modelled map of the thickness of the upper Si detection layer for the HRC chip. The greyscale range is 12.49 to 16.03 microns (thickest $=$ white).

The assumption that the thickness of the lower layers does not significantly affect the result for the upper Si layer was tested by using the image of the upper Si layer as input and holding the thickness of the Si3N4 and lower Si layer fixed but fitting for the thickness of the SiO 2 layer. The results showed only a marginal improvement in the rms of the fit over the chip. In Figure 6 are shown cuts across the CCD (rows 511 and 512 averaged): the observed fringe amplitude is shown at the top. The result of correcting the observed fringe flat at 9440 A by the model is shown in the middle trace; the result should be flat. The result of using the fit to the Si detection layer and the lower SiO 2 layer is shown at the bottom. Little improvement is discernible. Formally the rms of middle plot is $3.25 \%$ to be compared with the observed fringing which has an rms of $8.67 \%$. The rms of the two layer fit (lower) is $3.37 \%$. The peak-to-peak fringe amplitude is reduced from 0.27 to 0.07 , a factor of almost four.


Figure 5. Modelled HRC fringe amplitude at a wavelength of 9200A, to be compared with Figure 3.


Figure 6. The observed HRC fringe amplitude (unity subtracted) is shown at the top for rows $511+512$ averaged. The middle plot shows the result of dividing the observed fringing by the fringing predicted by the model with the upper Si layer fitted on a pixel-bypixel basis and the thickness of the other layers fixed. The lower plot shows the same result but using the fringe map calculated from fitting the upper Si and $\mathrm{SiO}_{2}$ layers. Any improvement resulting from fitting the $\mathrm{SiO}_{2}$ layer is seen to be marginal.

## 6. Modelling the WFC chips

In principle an identical procedure can be applied to the WFC chips as for the HRC, with the difference that the number of pixels is 16 times larger over the Chips 1 and 2 of the WFC. However the structure of the SITe WFC 4096x2048 chips differs from the HRC: the chips are also thinned and back-side illuminated but of different architecture (SITe ST002 A ), and the material and layer structure is proprietary. However it was decided to try to model the behaviour of the fringe flats (Table 1) using the same layer structure as for the HRC. Given that it is the Si detection layer that determines the amplitude and phase of the high spatial frequency fringing and the lower layers the envelope of the amplitude with wavelength, then a non-unique model for the lower layers can yet well represent the fringing behaviour. Figure 7 shows the observed fringing at a wavelength of 9400A. The plotted range is 0.9 to 1.1 and the extremes of the data range are $+/-0.14$ about unity. The pattern of fringes is quite different from the HRC with a distinct area of nearly concentric fringes to the bottom left of Chip 1 (upper), extending into Chip 2 (lower). Both chips were cut from the same Si wafer, so the continuity in fringing across the gap between the two chips (about 50 pixels extent) is expected. The range of the fringing at $+/-0.14$ is lower than for the HRC. The sampling strategy for the fringe flat measurements as a function of wavelength was again a compromise between regular coverage of the whole wavelength range and time limitations. Three regions were covered by closely separated fringe flats, around 7900, 8600 and 9400 A with a spattering of sampled wavelengths between (see Figure 8).
The fringing with wavelength was extracted at a few selected positions in both chips and starting from the solution for the HRC layer structure, a match was sought by minimizing the rms on the observed - model fringe amplitude for the 46 fringe flats (Table 1) as a function of the layer thicknesses. A satisfactory solution was easily found and the rms on the fit was smaller than for the HRC (the signal level was higher and there were more fringe flats). Figure 8 presents the fit for a $3 \times 3$ pixel region at the centre of Chip 2 in terms of the fringing as a function of wavelength. As for Figure 2, the errors bars on the observed points are the rms on the mean of the 9 values. Figure 9 shows the fitted structure for the WFC. No claim is made that this is a real representation of the layer thicknesses or material composition; the only assumption is that it is a back-illuminated device.


Figure 7. The observed fringing of the WFC CCD chips at a wavelength of 9200A is shown. Both chips have been butted together in this display, with Chip1 the upper and chip 2 the lower half. The greyscale range is 0.9 to 1.1 .

The pixel-by-pixel fit of the thickness of the upper Si detection layer was completed in a similar manner as for the HRC. Blocks of $3 \times 3$ summed pixels were fitted at steps of 7 pixels initially and the resulting maps of the Si layer thickness inspected and any badly fitted pixels replaced by the local median. The step size was reduced to 3 and then the thickness used as the initial starting point for a $1 \times 1$ pixel search for the minimum rms as a function of the thickness, locating the minimum to within $+/-0.01$ micron. Figure 10 shows the resulting map of the thickness of the Si layer. The map of the rms on the fit was also produced and the mean value is 0.017 micron (Chip 1) and 0.018 micron (Chip 2). The match provided by the standard tabulation of the Si refractive index from Palik (1998) proved to be entirely adequate to match the fringe pattern, in marked contrast to the HRC.


Figure 8. The model fringing (continuous line) is shown for a position at the centre of the WFC Chip2 ( 9 pixels centred on pixel 1021,1021). This is compared with the observed fringing averaged over the same 9 pixels from the fringe flats (crosses with error bars). The model fringing, but binned to the same wavelength range as the fringe flats, is shown by filled triangles


Figure 9. The modelled layer structure of the WFC chips is shown.

The effectiveness of the fringe model is demonstrated by ratioing the observed fringe flat by one generated by the model for the same range of wavelengths. Figure 11 shows the result at a wavelength of 9440A, around the peak of the fringe amplitude (see Figure 8). The fringe amplitude is reduced from a peak-to-peak of 0.24 to 0.07 , a similar factor as for the HRC.
Krist (2003) showed that the PSF width is increased by CCD charge diffusion. In a back-side-illuminated CCD such as the WFC, this blurring is dependent on the thickness of the photosensitive layer. On account of the lower transmission for blue photons in Silicon, the effect of charge diffusion is greater at lower optical wavelengths. By fitting the blur of the PSF with field position, Krist (2003) showed that increased diffusion is directly correlated with the thickness of the detection layer (i.e. top layer in Figure 9), as demonstrated in the Appendix of Krist (2003). The resulting map of the Si layer thickness (Figure 11) has been used in the TinyTim modelling of the WFC PSF.


Figure 10. The map of the thickness of the Si detection layer for the WFC chips. The greyscale range is 12.6 to 17.1 micron (thickest $=$ white) and both chips have been butted together.


Figure 11. The observed fringing across two rows averaged for the centre of the WFC Chip2 is shown in the upper plot. Below is shown the observed fringing corrected by the model.

## 7. Comparing filter flat fields with fringe models

The most promising filter flat field to show fringing is the methane filter F892N (central wavelength 8917 A , width 154 A ) which is centred close to the peak of fringe amplitude for both the HRC and WFC CCD's. Indeed the CDBS flats for this filter in both channels show visible fringing as shown in Figure 12 (m9b12224j_pfl.fits for HRC) and in Figure 13 (m820832qj_pfl.fits for WFC). The F892N filter is designed to cover the whole of the HRC field and for the WFC appears as a square tilted by 45 degrees; it is situated in the right quadrant of Chip 1 and the left quadrant of Chip 2 (i.e. taken with Amp B).


Figure 12.The pixel flat field for the HRC and F892N filter is shown (left); the greyscale range is $+/-0.005$ and the flat has been smoothed by a Gaussian of sigma 1.5 pixels to enhance the fringe visibility. The model F892N fringe image is shown at right with the same greyscale range.

Using the maps of the Si layer thickness and the adopted structure of both HRC and WFC CCD chips (Figures 1 and 10 respectively), the model fringe amplitude for this filter was constructed by integrating the fringe contribution (at 2 A steps) across the band using the tabulated filter passband (CDBS file acs_f892N_hrc_003_syn.fits for the HRC and acs_f892N_wfc_003_syn.fits for the WFC). Figure 12 shows the result for the HRC and Figure 13 for the WFC. In the WFC the F892N filter only covers part of the field, so the fringing can only be compared well away from the edges. The spatial agreement of fringing in the model and observed fringe flats is good, attesting to the ability of the model to reproduce the observed effects.


Figure 13. The pixel flat field for the WFC (Chip 2) and F892N filter is shown (left); the greyscale range is $+/-0.005$ and the flat has been smoothed by a Gaussian of sigma 1.5pixels to enhance the fringe visibility. The right panel shows the model F892N fringe image with the same greyscale.

The amplitude of the model fringing is however not exact and was found to require a maximum scaling by $10 \%$ in order to best match (in terms of the rms on the observed-model fringing) the observed fringe amplitude. Figure 14 shows the comparison between the F892N observed and modelled fringing for WFC, Chips 1 and 2 for three rows averaged. The plotted extent in Figure 14 avoids the edges of the filter where the observed amplitude increases. The differences in the modelled and observed fringe amplitude may be attributable to, aside from inadequacy of the model, differences in filter passband across the field or to a slightly different filter profile than in the SYNPHOT data base, perhaps caused by aging of the filter, leading to transmission of a different number of fringe peaks across the passband.

## 8. Fringe correction of extracted spectra

The fringe amplitude at a given pixel is specified by the wavelength of the light incident on that pixel and the thickness of the Si detection layer, the thickness of the other layers being assumed constant across the chip. Thus an image of the upper Si layer thickness is required together with the refractive index tabulations with wavelength in order to uniquely determine the fringe amplitude. In slitless spectroscopy with the ACS a direct image of the field is employed to determine the zero point of the spectrum produced by a given object. This then sets the mapping of the wavelength and the detector pixels. Once the wavelength of a pixel has been assigned by application of the dispersion solution, the
model fringing at the pixel can be determined and the data point normalised by the fringe amplitude. This procedure will be implemented in the ACS slitless extraction package aXe (Pirzkal et al., 2001a; see http://www.stecf.org/software/aXe/ ) enabling correction of fringing.


Figure 14. Comparison of the observed (bold line) and modelled (dashed line) fringe amplitude for WFC chips 1 and 2 with the F892N filter for rows 1130-1032 averaged.

From the available data taken with the ACS WFC, no clear evidence of fringing in continuum objects has been found. This is attributable to the slitless nature of the spectra - the "slit" is the direct image, and the point spread function has a FWHM of about 2.5 pixels. At the dispersion of the WFC, this is 100 A and the period of the fringing is around 70A for the WFC, so the point spread function smoothes out the fringe signature for continuum sources. For a compact emission line source the fringing will modulate the signal of the detected emission line depending on its wavelength. Simulations using the ACS spectral
simulator SLIM (Pirzkal et al. 2001b) show that the fringe amplitude is reduced from $12 \%$ to below $2 \%$ by this effect. However for the HRC, where the fringe period is about 65A and the dispersion is higher ( $\sim 24 \mathrm{~A} /$ pixel), the effect should be observable. Examination of SMOV data for the standard star GD153 extracted with a slit width of two pixels shows a maximum possible residual fringing of $6 \%$ peak-to-peak over the range $8800-9600 \mathrm{~A}$ (rms on mean $1.5 \%$ ), compared with the $25 \%$ peak-to-peak fringe amplitude in this wavelength range (Figure 2). However this is based on data which have not been flat fielded, so pixel-to-pixel variations will also contribute.

## Conclusions

1. Models of the fringing of the four-layer CCD structure for ACS HRC and WFC, using Fresnel equations, have allowed adequate fits to ground calibration fringe flats as a function of wavelength and position over the chips. This match is despite a marked difference between the in-flight and ground flats fields attributed to a non-uniform illumination pattern for the ground flats. The fringing analysis should be insensitive to this mis-match since normalised flats were used in the analysis.
2. Application of the model allows the rms of the observed fringing to be reduced by a factor of about 4 based on tests with the ground flats and in-orbit flat fields.
3. The projected size of the point spread function of the ACS in the slitless spectra reduces the measured fringing at the detectors. This effect is greatest for the WFC on account of the wavelength extent of the pixels. Future tests on in-orbit high signal-to-noise stellar spectra will be made to determine the level of fringing in extracted spectra and the efficacy of its removal based on the model.

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