Reciprocity Failure In 1.7μm Cutoff HgCdTe Detectors

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Introduction

The IR channel of the Hubble Space Telescope (HST) Wide Field Camera 3 (WFC3) instrument employs a 1024x1024 HgCdTe detector supplied by Teledyne Imaging Systems. The detectors were designed to have a 1.7μm red cutoff to permit the use of thermoelectric cooling and thereby avoid the need for on-board cryogens. Comprehensive testing of candidate detectors for WFC3 was performed at the NASA/GSFC Detector Characterization Laboratory (DCL).

IR Detector Features

- 1024x1024 pixel format, hybridized to a Hawaii-1R multiplexer
- Five rows and columns of reference pixels to track bias level drift
- Substrate removed to eliminate radiation-induced luminescence (also provides short wavelength response)
- Wavelength range: 350-1700nm (The WFC3 application uses 850-1700nm)
- Operating temperature 145K
- CDS read noise typically 20-25e^- rms
- Dark Current typically 0.02-0.05e^-/pix/sec at 145K
- QE ~80%

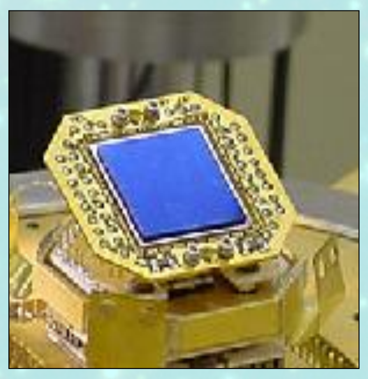


Figure 1. The flight packaged WFC3 IR detector.

Besides the standard detector performance tests, several detectors underwent additional testing to investigate the non-linear behaviors exhibited by these detectors. In addition to the well-known non-linearity of their response depending on the total signal measured in a given pixel, we found that the detected signal also depends on the rate of accumulation of charge in the pixel. This flux dependent response is usually referred to as reciprocity failure.

Understanding the effect of reciprocity failure on science data is very important in applying a correct calibration to photometric data. The HST photometric calibration sources are often several orders of magnitude (by up to a factor of 10^6) brighter than the (typically fainter) scientific sources of interest. Without a proper correction for reciprocity failure, it is possible to make significant systematic errors in determining the brightness of low flux sources.

The Experiment

The DCL has designed an experiment intended to characterize the reciprocity failure of the WFC3 IR detectors. The experimental setup is shown in Figure 2. All of the testing described here was performed using 1.0μm illumination.

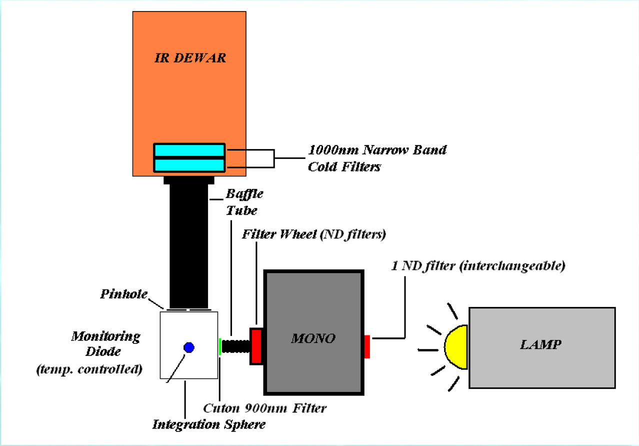


Figure 2. The experimental setup for characterizing reciprocity failure

The incident flux on the detector is controlled by varying the size of the pinhole and by varying the combinations of neutral density filters positioned at the entrance and exit ports of the monochromator. In this manner it is possible to obtain high quality data spanning almost five orders of magnitude in flux (0.1-10^4 photons/second). The lower limit is imposed by the background rate (~0.1 photon/sec) in the setup.

Several aspects of the experiment must be closely controlled in order to obtain an accurate measurement of reciprocity failure. The most important of these is the linearity correction.

Linearity Correction

The response of the IR detector to constant flux changes as the signal in a given pixel accumulates. Therefore, applying a single value for the gain of the detector at all signal levels is not appropriate. This departure from linearity must be accounted for in order to make a proper measurement of the reciprocity failure. As an example, the correction needed for one the detectors measured is shown in Figure 3.

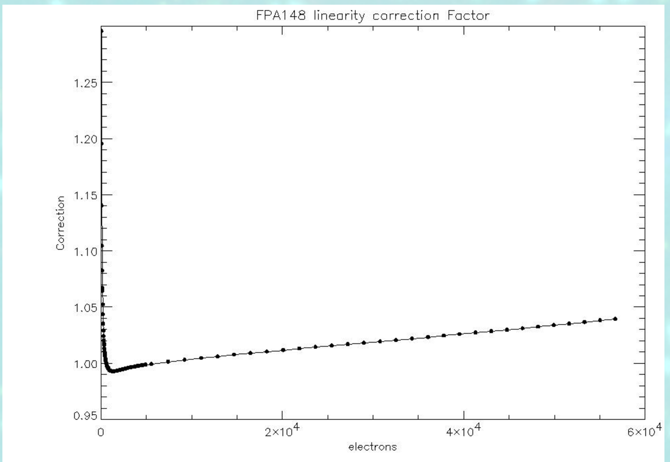


Figure 3. The linearity correction as a function of signal level

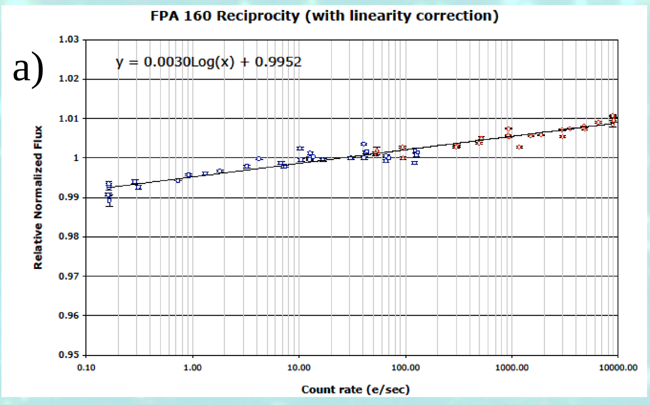
The correction is most important at high signal levels, where it can amount to a few percent (although the percentage correction is large at low signal levels, it amounts to a small number of electrons). If not properly accounted for, the non-linearity of the detector response can swamp the reciprocity failure effect we hope to measure.

Other experimental effects that must be controlled are the temperature stability of the monitoring diode, the uniformity of the flat field illumination and the minimization of the effects of persistence.

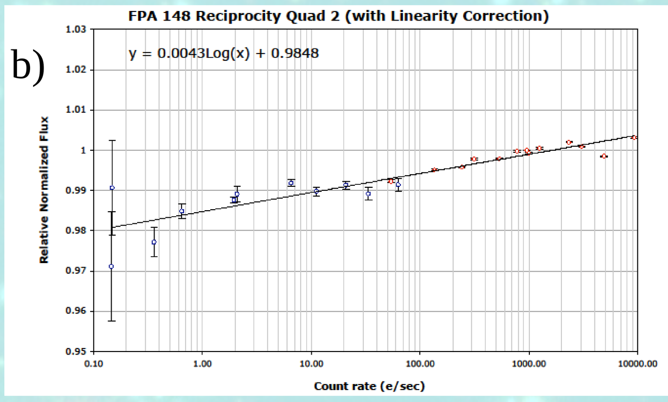
Reciprocity Failure

Reciprocity failure was characterized in three different detectors. The results are shown in Figures 4a-c. In all three cases, the reciprocity failure can be characterized by a power law, with the detector response increasing with increasing incident flux. The power law holds over the full range of flux measured (almost 5 orders of magnitude). However, each detector obeys a power law with a different slope, and thus the effect must be measured independently for each detector.

a)



b)



c)

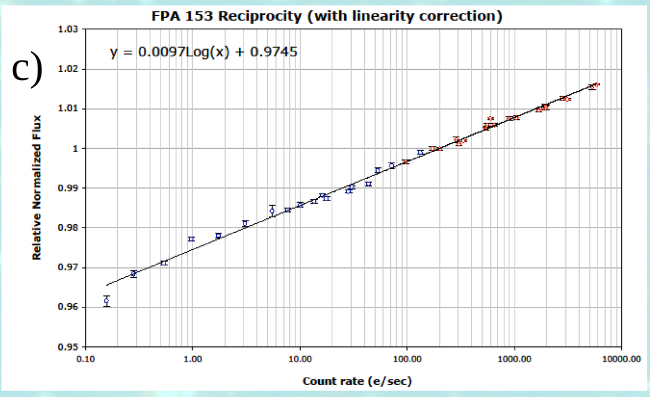


Figure 4a-c. The reciprocity failure observed in three different detectors: a) FPA160, b)FPA148, and c) FPA153. In all cases, the flux-dependent response obeys a power law over the range of fluxes tested, although the slope varies from detector to detector.

The size of the effect ranges from 0.3%/dex in FPA160, which is the detector most similar to the WFC3 flight detector, to 0.97%/dex for FPA153. This is much smaller than the 6%/dex (measured at 1.1μm) effect seen for NICMOS detectors on HST, which are an earlier generation of HgCdTe detectors with a different long wavelength cutoff (2.5 μm). Despite its smaller magnitude, reciprocity failure is still a very important effect in the calibration of photometry because of the typically large difference in flux between the standard sources and the scientific sources of interest.

The NICMOS detectors exhibited a larger effect at shorter wavelength. The DCL is thus pursuing new measurements of reciprocity failure at shorter wavelengths (0.85μm) in these detectors.

Non-Persistence Afterimages

A flat field image taken with WFC3 immediately after an early observation of the galaxy M81 showed an afterimage of the galaxy (see Baggett et. al. poster). The core of the galaxy was saturated in the original image. The intensity of the afterimage was as high as 8e-/pix/sec, amounting to a 2.6% signal enhancement over the surrounding flat. Also, the rate increased as the signal in the flat field image increased beyond zero bias. The effect was neither entirely additive or multiplicative. The source of the afterimage can therefore not be entirely explained by persistence, an additive effect, which in any case would be too small (< 1e-/pix/sec) to account for it.

The DCL has attempted to replicate the phenomena by illuminating an extended spot to signal levels as high as 20x saturation and then looking for afterimages in flat fields taken immediately after. An afterimage of the spot was seen in the post-illumination flat field and at signals below zero bias (~60ke^-), the behavior was similar to that seen in the WFC3 image (Figure 5). However, at signals beyond zero bias, the increased, the large increase in afterimage intensity was not seen. The rapid rise starting at ~75ke^- is related to the saturation of the detector rather than an enhanced afterimage.

Testing is continuing in the DCL in an attempt to understand this phenomena. However, this result does further point out the risk associated with attempting to use data extending to signal levels beyond zero bias in these detectors.

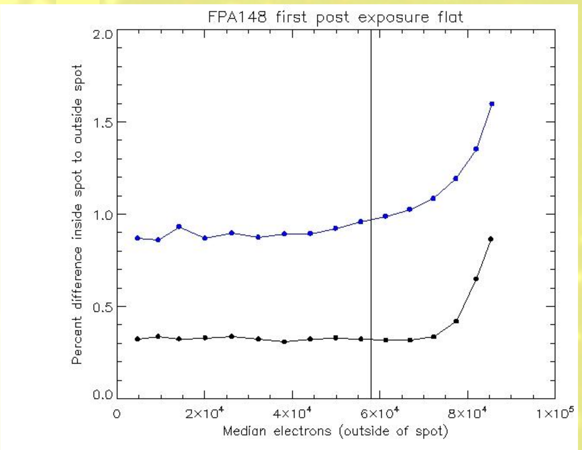


Figure 5. The percent difference in the signal in the post-illumination flat seen in the spot illuminated region compared to a non-illuminated region. The blue and black curves show this ratio in samples-up-the-ramp for regions illuminated to 20x and 2x full well, respectively. The vertical line shows the signal at which zero bias is reached.

Conclusions

- Reciprocity failure has been observed in 1.7μm cutoff HgCdTe detectors.
- The reciprocity failure follows a power law behavior over the range of fluxes tested (0.1-104 photons/second).
- The slope of the power law varies among detectors.
- Accounting for reciprocity failure is important in the photometric calibration of WFC3 data.

Other WFC3 Papers

Talk on Friday at 10:10 -- R. Kimble et. al., "In-flight Performance of the Detectors on HST/WFC3"

Poster – S.M. Baggett et. al., "The Wide Field Camera 3 Detectors"