Instrument Science Report WFC3 2017-05

Variable He I emission in grism data

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February 20, 2017

Abstract Previous work has demonstrated how the grism background can be decomposed into two main background components and how these can be estimated and removed. In this work, we show how the variability of one of these components negatively affects the data products produced by CALWF3. Using both simulated observations as well as real observations, we demonstrate that this effect can be mitigated. Our approach combines a multiple background component approach with up-the-ramp fitting to offer the best possible grism background subtraction while retaining the efficient cosmic ray rejection and lower effective read-out noise offered by up-the-ramp fitting.

1. Introduction

The background level in WFC3 IR imaging observations can vary during the course of an exposure (ISR-2014-03), and a recent ISR (ISR-2016-16) describes how these imaging ob-

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Table 1:: WFC3/IR Background Subtraction Approaches

	Background	
	constant	time-variable
imaging	default	ISR-2016-16
grism	ISR-2015-17	**This work**

servations should be handled. The source of the quick variation was identified to be scattered light from the Earth's atmosphere and a multi-component (Zodiacal and HeI components) approach to the background need to be used in the case of grism observations (ISR-2015-17). The different cases are summarized in Table 1 where we show which study relates to the issue of background in imaging or grism data when the background is constant or variable. The Zodiacal component is not expected to vary significantly during the course of an exposure, but the amount of scattered HeI light can however vary greatly, especially during long exposures. While this problem can be mitigated by padding slitless observations with direct imaging either at the end or beginning of a visit (when the likelihood of being affected by the bright Earth limb and the associated HeI emission is greater). WFC3 observations are taken as a series of non-disruptive reads, recording the mean count rates of pixels several times during the course of the exposure. Up-the-ramp fitting is used to combine these multiple reads and to derive an optimal count rate for each pixel. In the process, the effect of saturation and cosmic rays are accounted for. This is handled by the task CALWF3, which takes the initial multiple-read data (RAW file), applies detector corrections such as bias subtraction, dark, flat-fielding to produce a multiple-read reduced dataset (IMA file), which the up-the-ramp fitting process uses to produce a final two dimensional image (FLT file). This process is described in detail in Chapter 3 of the WFC3 Data Handbook.

2. Effect of variable background

Several components to the grism background have been identified: a Zodiacal light component, which varies spatially on the sky but does not vary temporally; an HeI emission component from the Earth's atmosphere which can quickly become the dominant contribution to the background and which temporally varies during the course of a visit, as the angle between the line-of-sight and the Earth limb changes. This has been described in detail in ISR WFC3 2015-17. The main problem with strong temporal variation of the background is that it directly violates a basic assumption that is made about the data by the CALWF3 up-the-ramp fitting process. The latter assumes that the background rate is constant during the multiple no-destructive readouts of an exposure. A varying background causes the end product (the FLT file) to look superficially normal but the the final combined FLT file is actually much noisier than it should be. Figure 1 shows two different cases. The first one is a dataset (`icoi4bnhq`) with little variation in its background level (as measured directly from each of the IMSET in the IMA file produced by CALWF3). The second case is a dataset (`icoi4aspq`) where the background is observed to vary by a factor of 1.8 during the course of the exposure. As Figure 1 shows, a combination of Zodiacal and HeI background components successfully models the observation in the first case, but fails to properly do so in the second case, when the background varies significantly. The left panels of Figure 1 show the background subtracted FLT files. The middle panels shows a histogram of the background (masking out bright spectra). One would expect a good background subtraction to lead to a spatially flat FLT image with a distribution of background pixel values that is described by a zero-centered Gaussian distribution. This is clearly not the case when the background varies significantly, as the bottom row of Figure 1 shows. Figure 1 also shows (rightmost panels) the distribution of pixels with residuals greater than 0.1 e^{-}/s (masking out the spectra in the image). While, cosmetically, the two final products (i.e. top and bottom rows of Figure 1) appear superficially similar, there is nevertheless a large number of pixels with significant residuals (positive or negative) when the method is applied to an exposure with a varying background.

3. Simulations

Using realistic simulations, we now verify that a strongly variable background rate negatively affects the quality of the FLT files produced by CALWF3. We simulated WFC3 IMA files by replacing the data in each IMSET of the dataset `icoi4bnhq` with the sum of a Zodiacal background, a HeI background and some simulated spectra. We added the noise contribution of the Dark Current (taken to be $0.1e^{-}/s$) and readout noise ($20e^{-}/s$). We also populated the error extensions of the IMA file. Different amount of HeI variation was considered: First, we allowed only a moderate amount of variation in the HeI level, as was the case in the original `icoi4bnhq` observations. Second, we allowed for a significant variation in the HeI background rate, as was the case in the original `icoi4aspq` observations.

3.1. Case with moderate HeI variation

We ran CALWF3, using up-the-ramp fitting, on the `icoi4bnhq` simulated file to produce an FLT file and we fitted and subtracted a combination of the Zodiacal light and (constant) HeI light components. The result is shown in Figure 2. The bottom panel of this Figure shows the background residuals in the same manner as the ones shown in Figure 1. The top panel shows a plot of the background count rate (e^{-}/s) in each in the IMA IMSET, plotted in red. The estimated Zodiacal plus HeI background levels are shown in blue. Since these background levels were determined from the single science extension of the FLT file (which combines all of IMSET from the IMA file), the measured background rate is constant, and equal to the final background level in the last IMSET of our simulated IMA. This Figure 2 shows that in the case of constant HeI emission the residuals are as expected, zero-centered

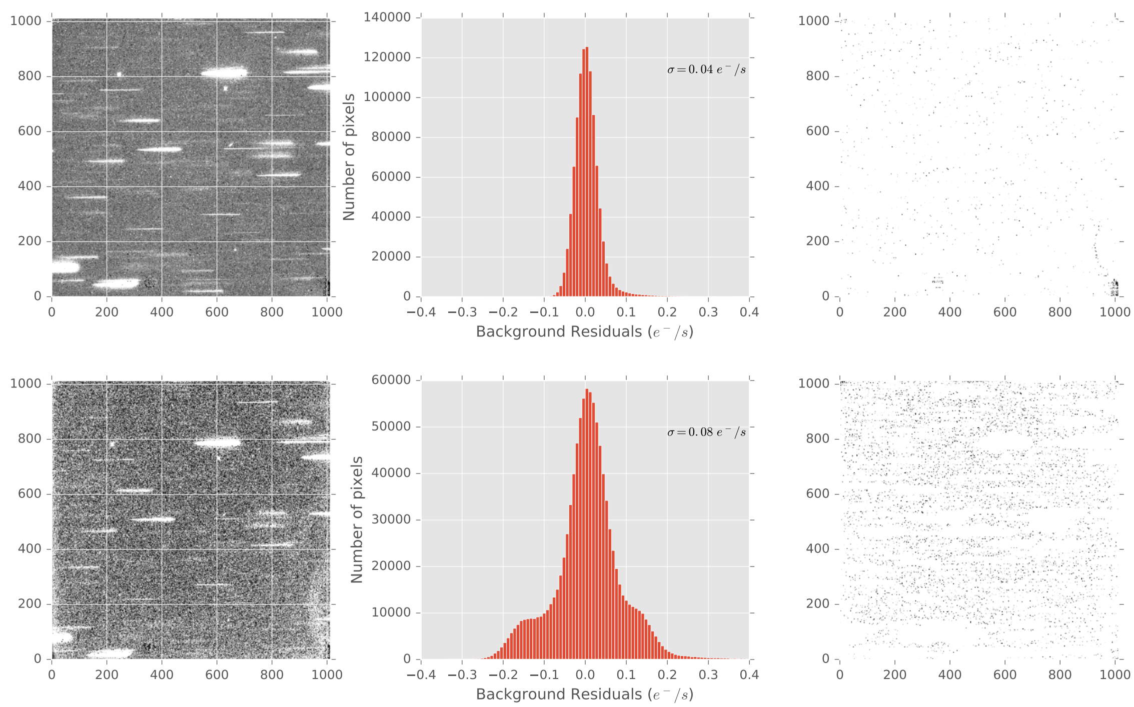

Fig. 1.—: Fitting and subtracting a combination of Zodiacal and HeI background to an FLT file produced by CALWF3 leads to different results when the background is nearly constant during the course of the exposures (Top panels) and when it varies by significantly, by a factor of 1.8 in this case (Bottom panels). The left panels show the background subtracted FLT images. The middle panels present histograms of the background residuals, which should be centered on zero and Gaussian-like. The right panels show (black) the pixels with higher than expected ($> 0.1e^-/s$ in this case) deviations. The latter are peppered all over the image.

Gaussian in shape and with a standard deviation of 0.04 e^{-}/s.

3.2. Case with significant HeI variation

The same test was then done on a simulated `icoi4aspq` dataset where the background rate slowly increased from 0.5 e^{-}/s to $2e^{-}/s$. The results, when using up-the-ramp fitting are shown in Figure 3 and show a significant non-Gaussian nature of the background residuals. The standard deviation of the background residuals is 0.13 e^{-}/s and we successfully reproduce the effect shown in Figure 1.

3.3. Turning off up-the-ramp fitting

As was the case with the real observations discussed in Section 2, we obtain much better results when turning off the up-the-ramp fitting of CALWF3 to produce a "last minus first" FLT file. This is shown in Figure 4. The standard deviation of the background residuals in the case of a significantly varying HeI simulated observation is reduced 0.05 e^{-}/s when up-the-ramp fitting is switched off.

4. Description of solution

4.1. Turning up-the-ramp fitting off

One possible solution is, as has been the case with direct imaging, to simply turn of the up-the-ramp fitting portion of CALWF3. This has the important drawbacks of not allowing for the detection of cosmic rays (a very important benefit of using up-the-ramp-fitting) as well as to result in a higher effective read out noise ($20e^{-}$ versus a nominal $12e^{-}$ when sampling the signal multiple times along the ramp).

4.2. Fitting and removing the varying HeI component

We have developed an approach that allows us to account for the varying HeI background while still allowing a user to make full use of the up-the-ramp-fitting and its benefits. Our approach is based on our previous work (ISR WFC3 2015-17). When dealing with grism data however, it is a multiple step process, which starts with the RAW images themselves:

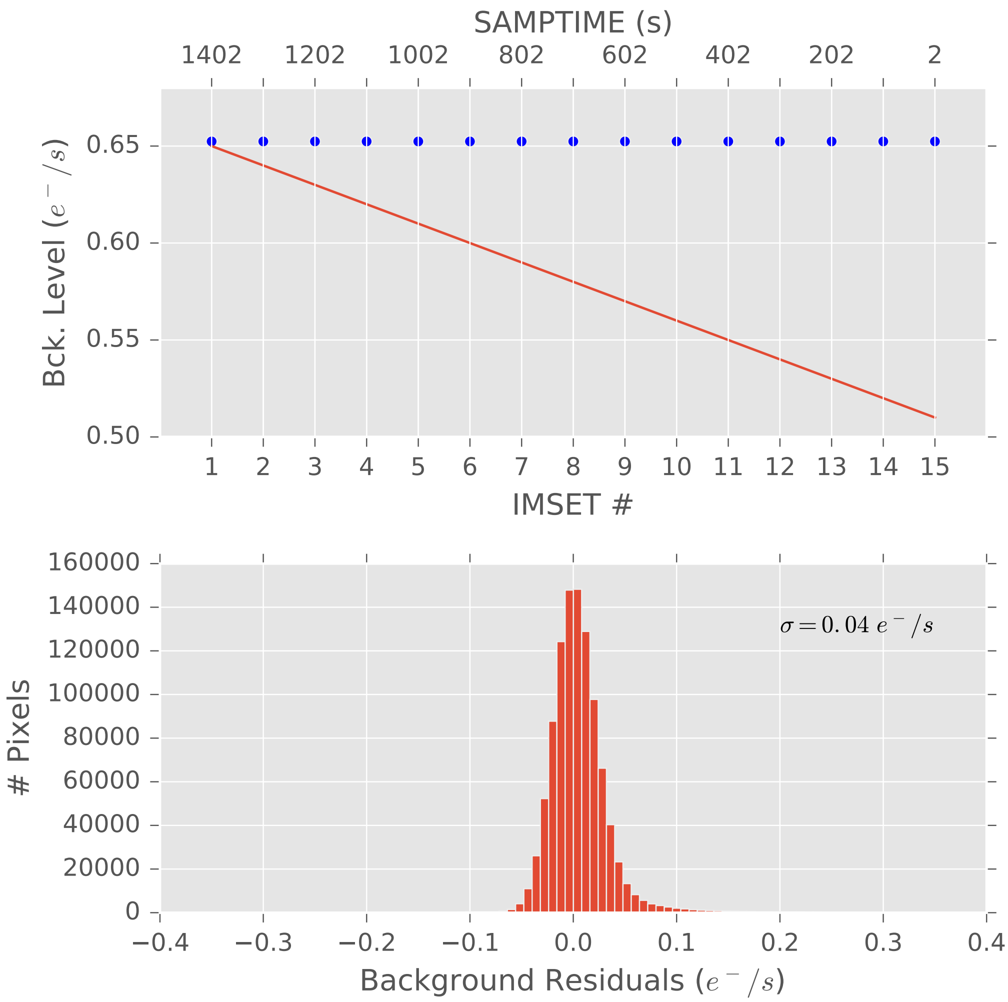

Fig. 2.—: **Moderate background variation**. Top panel: Background levels in a simulated WFC3 grism IMA file, as a function of IMSET and exposure time (SAMPIME). The background level in each IMA read is allowed to vary from $0.5e^-/s$ at the beginning of the exposure (IMSET 15) and rises to $0.65e^-/s$ at the end of the exposure (IMSET 1, 1402 seconds later). The estimated background level from the fit (blue dots) is shown in blue ($0.64e^-/s$). Since the process assumed a constant background level, the same average background levels are assumed for each IMA read. Bottom Panel: A histogram of the background residuals (bright simulated spectra are masked out), gaussian like as expected and with a standard deviation of 0.04 e^-/s. The very small departure from gaussianity on the positive side of the histogram is caused by faint spectra ($< 0.005e^-/s$) not having been masked out.

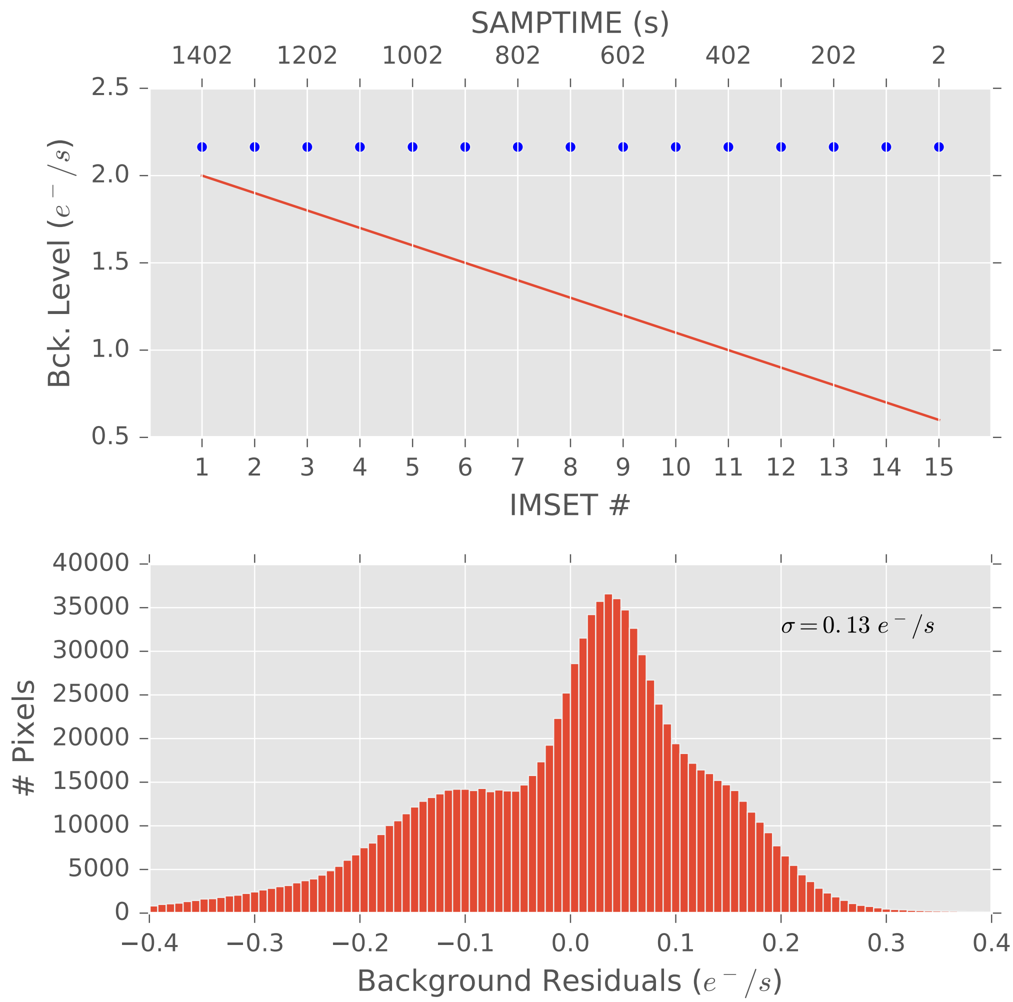

Fig. 3.—: **Significant background variation**. Same as Figure 2 but with a HeI background that varies significantly more ($0.5e^-/s$ at the beginning of the exposure (IMSET 15) and rises to $2e^-/s$). The fit once again assumes a constant background but the derived value is now incorrect ($2.1e^-/s$ versus $2e^-/s$) and the resulting background is highly non-gaussian (Bottom Panel). The standard deviation of the residuals is $0.13e^-/s$.

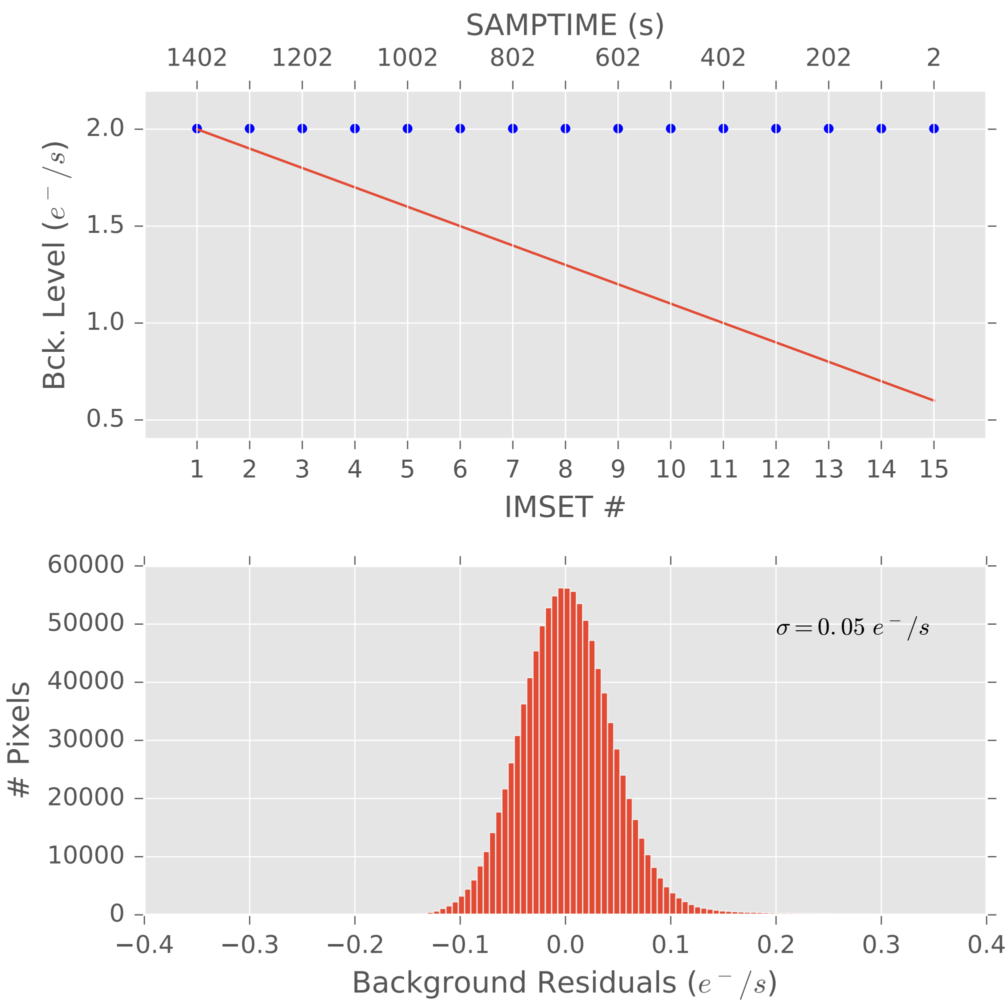

Fig. 4.—: **Significant background variation, "Last minus First" reduction**. Same simulated dataset as Figure 3 but now processing without up-the-ramp fitting. The estimated backgound level is now correct and the residuals are gaussian with a standard deviation of $0.05e^-/s$.

- We begin by running CALWF3 on the RAW images to produce IMA images. At this stage, the data is still split in multiple non-destructive readouts (IMSETs), but each read has been corrected for the WFC3 instrumental effects such as bias and dark current corrections.

- We consider each of the IMSETs to have a background that is the sum of the different possible background components (Zodiacal and HeI), and use the iterative thresh-holding method described in ISR WFC3 2015-17 to estimate the constant part of the background (i.e. Zodiacal) as well as the varying component (i.e. the HeI). In each IMSET, the HeI contribution that we compute (and which is allowed to be different for each IMSET as we just described), is subtracted from the signal. This process results in an IMA file with a background that has been linearized since the variable HeI component has been removed from each IMSET.

- We run CALWF3 on the modified/HeI subtracted IMA file, with the CRCORR option switched on, to perform the final up-the-ramp-fitting and produce cosmic ray free FLT files.

- The Zodiacal level of the final (and therefore higher signal-to-noise) FLT file is estimated and subtracted using the same iterative fitting thresh-holding algorithm but using only a Zodiacal component.

Figure 5 shows the result of applying this approach to the same simulated datasets used earlier in Figures 3 and 4.

5. Application to real observations

We conclude by applying this method to the real dataset `icoi4aspq` and showing the results in Figures 6 to 7. We also show the alternative results, obtained by simply fitting and subtracting the background (a mix of Zodiacal and HeI background components) from the FLT produced by CALWF3 when up-the-ramp fitting is switched on in Figure 7 and when it is switched off (last minus first) in Figure 8.
The method described in this document successfully removed the HeI and Zodi components and allows the use of UTRF. In some cases however, these two components are not sufficient to completely remove the background from grism observations (to a level below 0.01 e^{-}/s. When this is the case, careful modeling of the dispersed field can be used to create a mask that is more accurate than the thresholding mask used above. Averaging the rows of the masked image, smoothing the resulting one dimensional estimate of the background residuals and

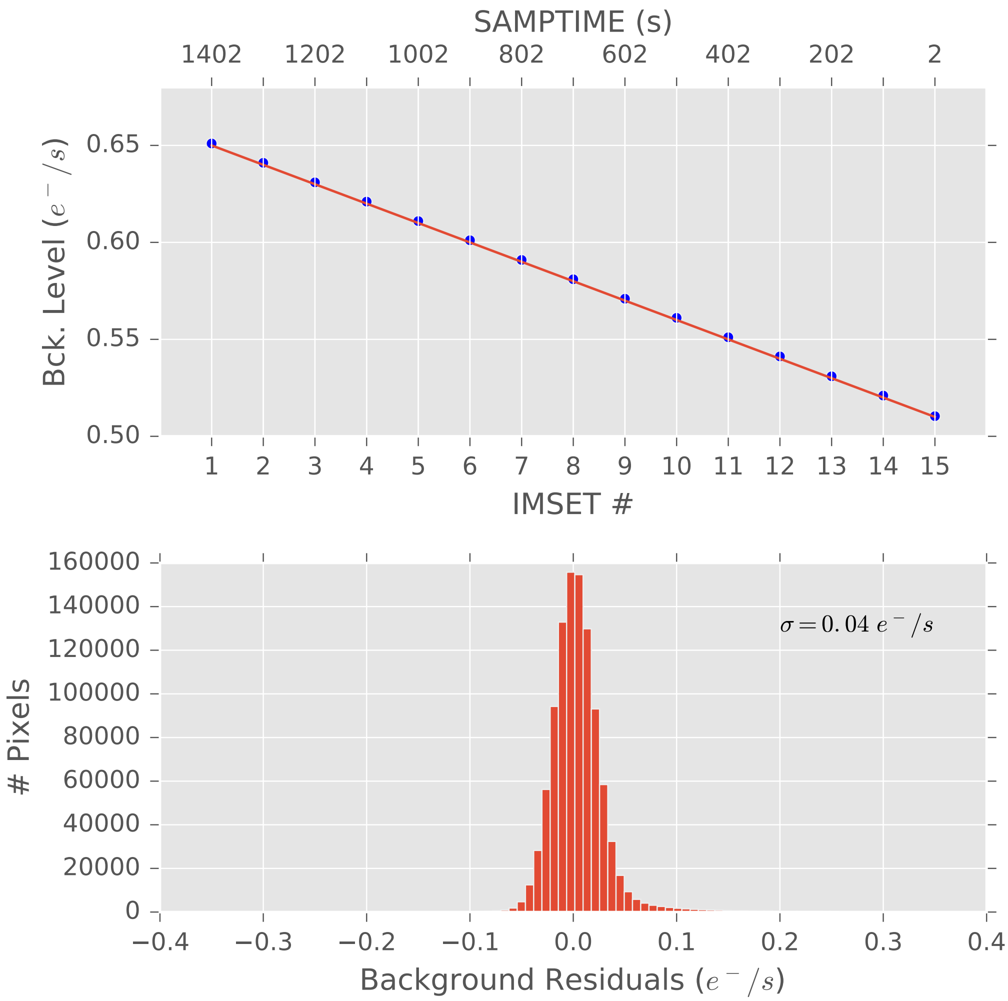

Fig. 5.—: **Significant background variation, variable HeI based reduction**. Same simulated observations as shown in Figures 3 and 4 but we now estimate individual HeI levels for each IMSET of the IMA file, while a single Zodical value is used across the whole observation. The input/true model background levels are shown in red in the top panel and the estimated levels are shown using blue dots, demonstrating a very good agreement. The background residuals, shown in the bottom panel are now as expected and have a standard deviation of $0.04e^-/s$, reflecting the use multiple non-distructive reads and of up-the-ramp fitting to increase the signal-to-noise of the final FLT file.

subtracting this estimate from all the rows in the data can further improve the background subtraction.

6. Application to mutiple datasets

We have demonstrated that a varying background can adversely affect the results the up-the-ramp process, using both simulations and real observations. We demonstrated this process using a single dataset (RAW file) containing multiple non-destructive reads (IMSETs). Since the Zodiacal component is constant on small time scales, this method can be used with multiple IMA files at the same time, as long as these are observations taken during a single HST Visit/Pointing. When doing this, we simply solve for all the HeI levels simultaneously while keeping the Zodiacal level constant across all the observations. For example, four exposures taken during a single Visit, each taken using 16 readouts (NSAMP), are used to compute NSAMP*4 HeI background levels and one single Zodiacal level. Four FLT files are then generated, each using CALWF3 and up-the-ramp-fitting and a single Zodical background can be derived for all four observations at once, leveraging the higher signal to noise available when using four images instead of one. The higher signal-to-noise provided by these four images can then be leveraged to provide a better estimate of the Zodiacal light level during these exposures.

7. Conclusion

It has been previously shown that the IR background observed using HST can be decomposed in at least two distinct components, and that one of these components can vary substantially during the course of an HST exposure. We have since found evidence that accurately subtracting a two components from some grism FLT files processed using up-the-ramp fitting is not possible. We identified the cause to be the the combination of strongly varying background levels and the use of up-the-ramp fitting and the assumption that the count rate of an exposure is constant during the course of an observations. While this problem can be mitigated using a simpler "last minus first" readout approach, this unfortunately implies that cosmic rays cannot be removed during the up-the-ramp fitting process. We have shown that we can estimate the HeI contribution in individual readouts in a multiaccum (IMA) dataset and can therefore linearize the background level of the IMA dataset by subtracting this varying component. The resulting linearized IMA file can then be processed normally using CALWF3 and the up-the-ramp fitting to produce cosmic ray free FLT images.

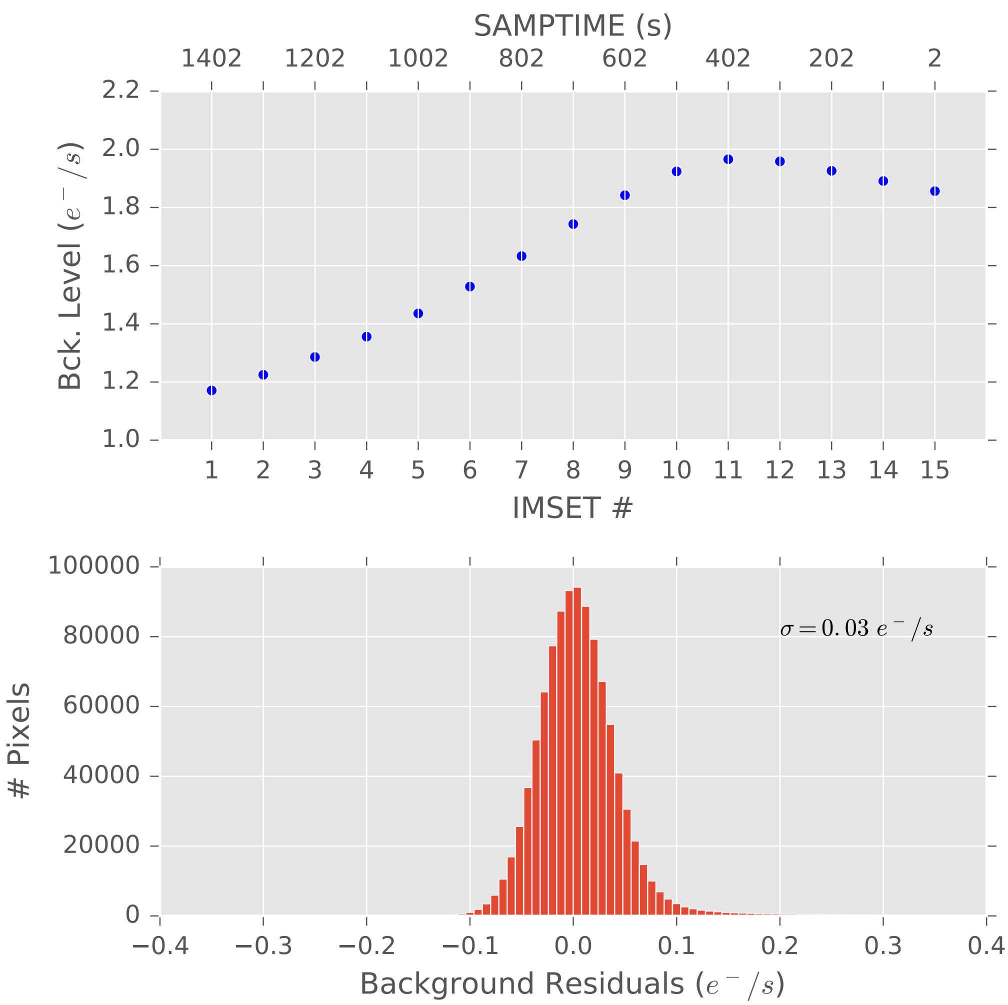

Fig. 6.—: **Significant background variation in real data, variable HeI based reduction**. This Figure is similar to Figure 5 but we now use the real dataset `icoi4aspq`. The Top Panel shows the estimated HeI level as a function of IMSET and SAMPTIME and the Bottom Panel shows the histogram of the background residuals. A smooth variation of the HeI is detected, although we put no constrains on the HeI level in each individual IMSET. The standard deviation of the background residual is $0.05e^-/s$.

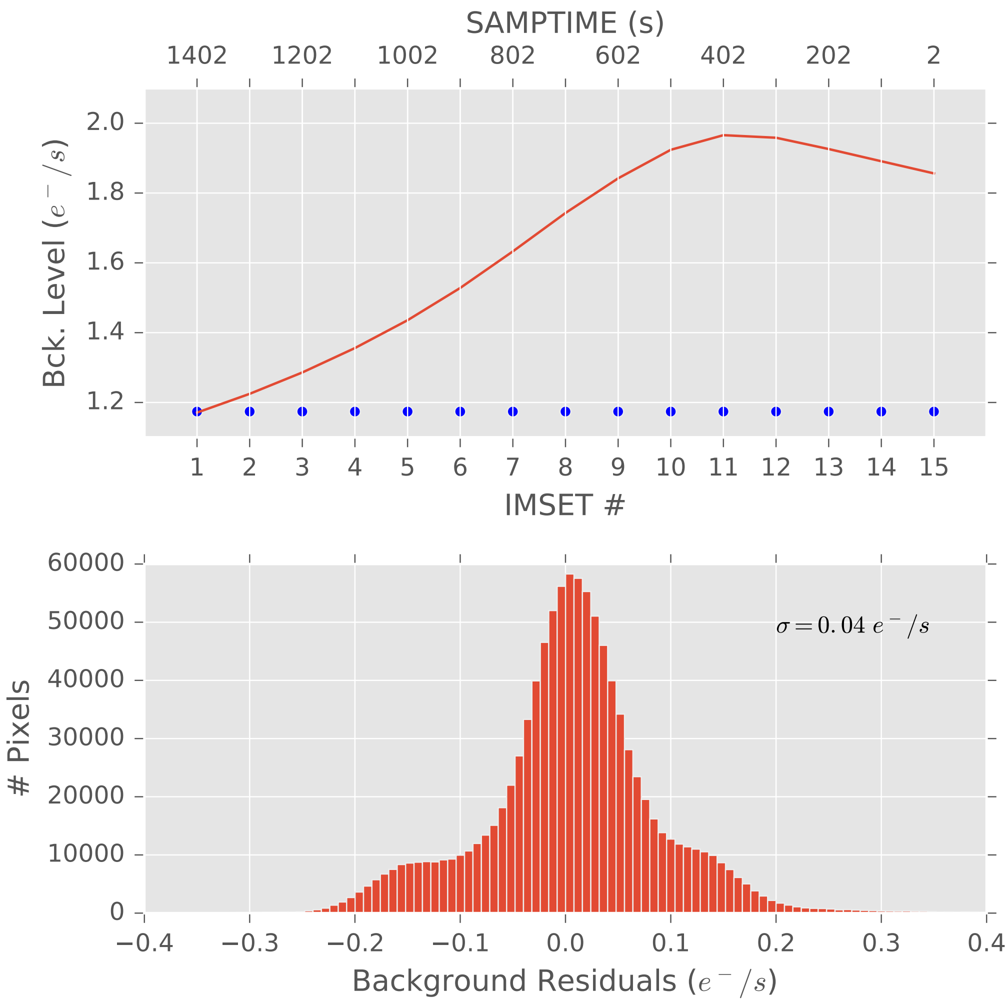

Fig. 7.—: **Significant background variation in real data with up-the-ramp fitting**. Result of processing dataset `icoi4aspq` using up-the-ramp fitting and then trying to fit a two components model to the resulting FLT file. As expected, and as we already demonstrated above using simulated data, the resulting FLT is negatively affected by the varying HeI background, leading to a much noisier image.

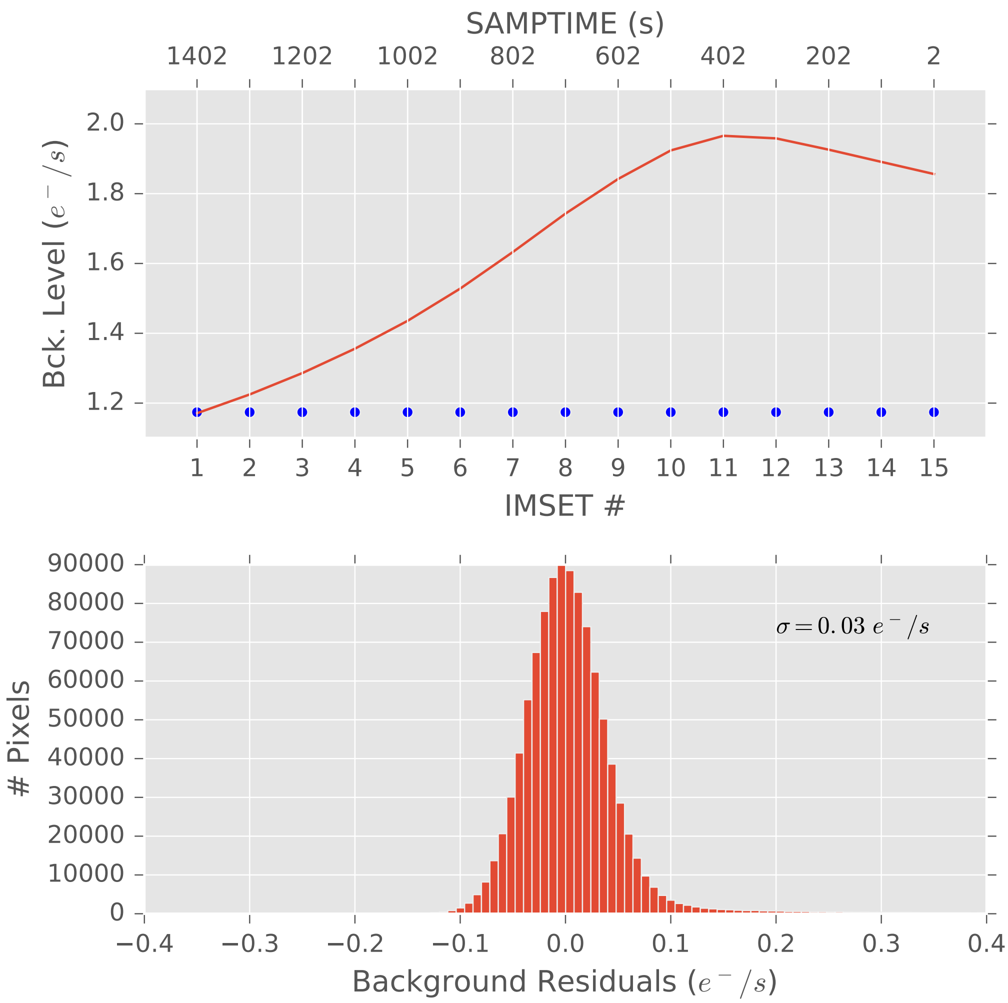

Fig. 8.—: **Significant background variation in real data, "Last minus First" reduction**. Result of processing dataset `icoi4aspq` without up-the-ramp fitting and then trying to fit a two component model to the resulting FLT file. As with our simulated datasets, the background subtraction works well, but at the expense of not being to use the up-the-ramp fitting process to remove cosmic rays. The latter do not show in these plots as their numbers are relatively small with variations that can be larger then $0.4e^-/s$ which is the range we show here.

References

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8. Acknowledgments

We would like to thank Jay Anderson for his review of this document.