

A Test of non-Standard Gain Settings for the NICMOS Detectors

Chun Xu & Torsten Böker
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ABSTRACT

We report on the results of a test program to explore the potential scientific benefit of using non-standard gain settings in NICMOS observations. While this capability had originally been included in the NICMOS design, it has never been used on orbit. We present our analysis of the test data, discuss the potential scientific benefits, and outline the necessary modifications to planning, implementation, and pipeline calibration of NICMOS data taken with non-standard gain settings.

1. Introduction

For image processing, the photo-electronic signal generated in the NICMOS detector pixels (after on-chip amplification) must be converted into machine-readable, digitized format. This conversion from electrons (e^-) to data numbers (DN) occurs in a set of analog-to-digital converters (ADCs) which have 16-bit accuracy and therefore a dynamic range of $2^{16}=65,536$ DN. In NICMOS data, this range is mapped from -32,767 DN to +32,768 DN. The standard conversion factor (the “gain”) for the three NICMOS cameras of $\sim 6 e^-/\text{DN}$ has been selected such that the full well of the detector pixels of $\sim 150,000 e^-$ comfortably fits into this range.

Unfortunately, the last bit of the ADC output is unstable, thus rendering the information contained in that bit useless. Signal levels in all NICMOS data therefore carry an inherent uncertainty of 1 DN, effectively adding an additional noise component which is usually referred to as “digitization noise”.

The importance of digitization noise can be judged by comparison to typical read noise levels of $\sim 27e^-$, or ~ 4.2 DN per read pair at the current gain setting of $\sim 6.5 e^-/\text{DN}$ for NIC3 (for cameras NIC1 and NIC2, the gain is $\sim 5.4 e^-/\text{DN}$). It can also be compared to the added signal from detector dark current and thermal background. As an example, we use the NICMOS Hubble Deep Field observations during which typical dark current levels

were $0.15 \text{ e}^-/\text{s}$ and the combined background from sky and telescope was $0.55 \text{ e}^-/\text{s}$ in NIC3 or about 1 DN in a 64 s readout of a MULTIACCUM sequence. Digitization noise therefore is a non-negligible noise contribution in background-limited observations, and reducing the gain for such observations is potentially beneficial for the NICMOS sensitivity. In addition, a reduced digitization noise should improve the identification and rejection of low-level cosmic rays during pipeline processing of NICMOS data.

With this in mind, the NICMOS electronics were designed with an ability for variable gain settings. However, non-standard gain settings have never been used for NICMOS observations and have neither been tested nor calibrated after the installation of NICMOS on HST. In order to gauge the benefit of a reduced gain setting for deep NICMOS images and to test the operational procedures, we have undertaken calibration program 9324, the results of which are described in this report. In Sec. 2, we describe the design of the proposal and the data analysis. Section 3 summarizes the results and some implications for the handling of NICMOS data taken with non-standard gain settings. We discuss the scientific benefits of such data in Sec. 4. Finally, we list some necessary modifications to the implementation and processing of NICMOS observations with alternate gain in Sec. 5, and conclude in Sec. 6.

2. Observations

With an eye on HST orbit cost, program 9324 was designed to obtain a (not necessarily complete) impression of the usefulness of NICMOS data obtained with non-standard gain settings. Most importantly, the data should enable a test of the expected readnoise reduction in long integrations of faint signal levels. In addition, the program should allow an assessment of whether the pipeline reference files can be used to calibrate NICMOS data taken with non-standard gain, or whether a separate set of reference files needs to be constructed and maintained in order to support such data.

Currently, the header keyword ADCGAIN in the science header is not updated to reflect the use of non-standard gain (see Sec. 5). Rather, this information is contained in the keyword ND1GAIN in the `_spt` file. Use of the nominal gain is indicated by `ND1GAIN=x2`, while using $1/2$ and $1/4$ of the standard conversion factor causes the header to be set to values of `x4` and `x8`, respectively. Currently, the instruction to execute a gain change has to be uplinked via special commanding.

To measure the electronic noise in data taken with non-standard gain, a number of long (~ 1.6 ksec) dark frames were obtained in all three cameras, both with `ND1GAIN=x2` and `x8`. In order to verify the relative change in the conversion factor, flat-field frames in the H-band filter (F160W) were taken in all three cameras (plus associated background observations) for all three gain settings (`x2`, `x4`, and `x8`). This part of the test should also verify that the standard flat field reference files can be used to support alternate NICMOS gain settings. Similar scope is assigned to the observation of P330E in NIC2 (F160W) at gains

x2 and x8. Table 1 summarizes the different data sets. In order to avoid any complications introduced by the CALNICA pipeline (see Sec. 5) we base this analysis on the uncalibrated datasets (“_raw” files).

Table 1. Summary of program 9324. A gain setting of ND1GAIN=x4 (x8) should reduce the conversion factor (in e^-/DN) by a factor of 2 (4)

Obs.	Sequence	NSAMP	#	Cam.	ND1GAIN	Filter
Darks	SPARS64	26	7	all	x2, x8	BLANK
Flat Fields	STEP2	23	4	NIC1	x2, x4, x8	F160W
	STEP1	15	4	NIC2	x2, x4, x8	F160W
	SCAMRR	26	4	NIC3	x2, x4, x8	F160W
P330E	SCAMRR	26	4	NIC2	x2, x4	F160W

3. Results

Verification of analog-to-digital gain

In Fig. 1, we plot the response curves of the three NICMOS cameras to illumination by the internal flat field lamps. Note that the signal level at $t=0$ s is not zero, because no 0th read subtraction has been performed in the raw data. For each detector quadrant, the ratio of slopes is a measure of the relative change in the conversion factor from e^- to DN, i.e. the analog-to-digital gain. As can be seen from the results of linear fits to those parts of the ramps that are below the ADC limit of 32,768 (Table 2), the conversion factors for ND1GAIN=x4 and x8 are very close to their predicted values of 1/2 and 1/4 of the standard value. This is also evident from the diagonal lines in Fig. 1. These are **not** fits to the higher gain ramps, but replicate the fit to data taken with the standard gain, and scaled by factors of 2 and 4, respectively (after adjusting the y-axis intercept).

Reset voltage and dynamic range

For the default gain setting, NICMOS signal levels never reach the ADC limit of 32,768 DN because the standard conversion factor was selected to map the full well of the detector pixels onto the dynamic range of the ADCs. This is no longer the case for the alternate gain settings, because fewer electrons are converted into a DN. This, in effect, reduces the dynamic range by factors of 2 and 4 for ND1GAIN values of x4 and x8, respectively. However, this reduction should not pose any problems for deep exposures of faint signals which are the most likely to employ alternate gain settings.

Figure 1: Flat-field response curve for all NICMOS detector quadrants at different gain settings. For each quadrant, we plot the median signal levels. The slope of the ramps is determined by the conversion from e^- to DN. For each gain, the slightly different slopes of the four quadrants are due to DQE variations across the array, any offsets at $t=0$ s are due to the reset voltage being converted to different count levels.

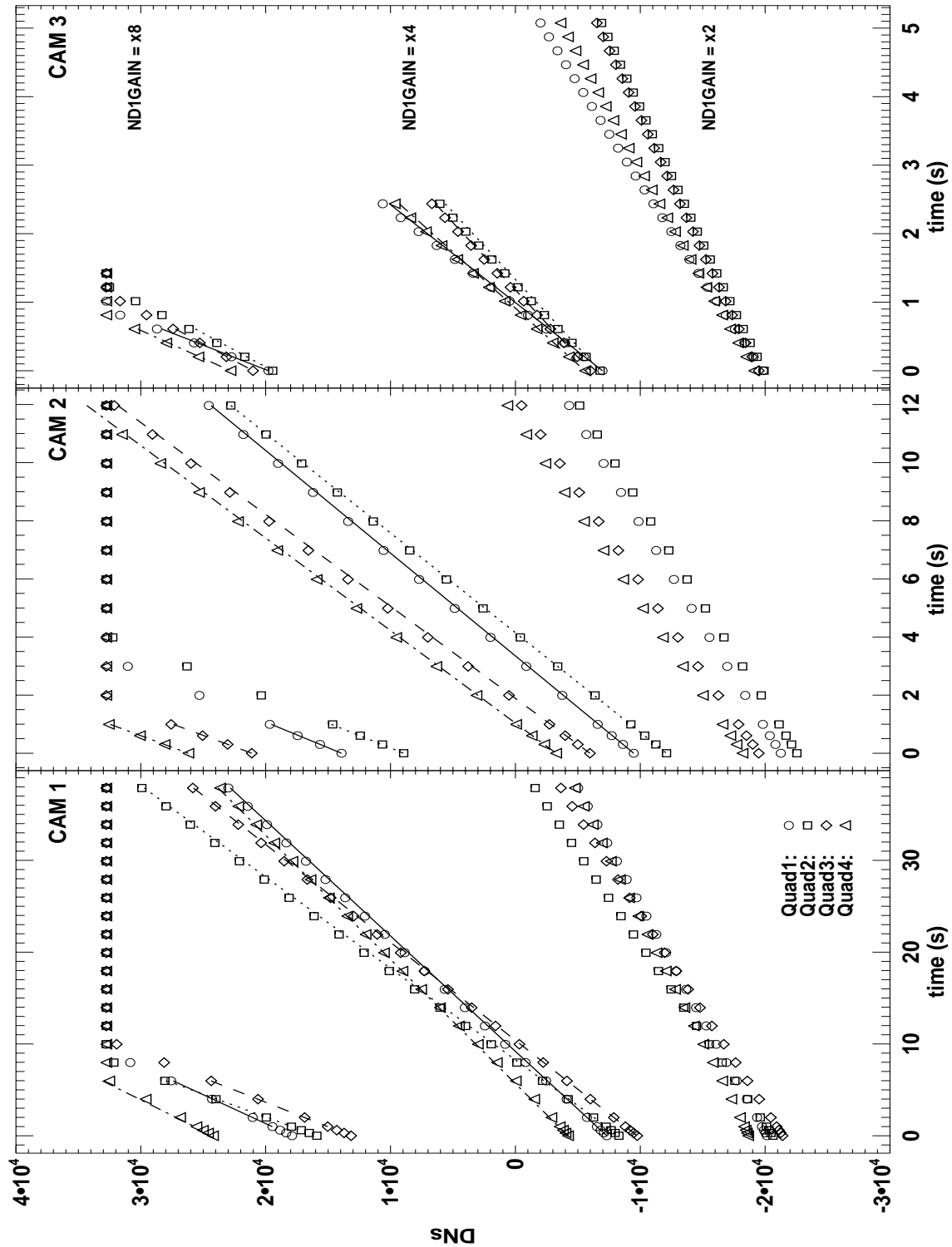


Table 2. Relative change in (inverse) analog-to-digital gain for all NICMOS detector quadrants. The nominal gain is $5.4 \text{ e}^-/\text{DN}$ for NIC1 and NIC2, and $6.5 \text{ e}^-/\text{DN}$ for NIC3. Numbers are derived from linear fits to the ramps plotted in Fig. 1 (excl. the first few reads which are affected by shading). The quoted uncertainties for ND1GAIN=x8 are estimates for the systematic error. Because of the small number of reads below the ADC limit, these fits include the shading-impacted first reads.

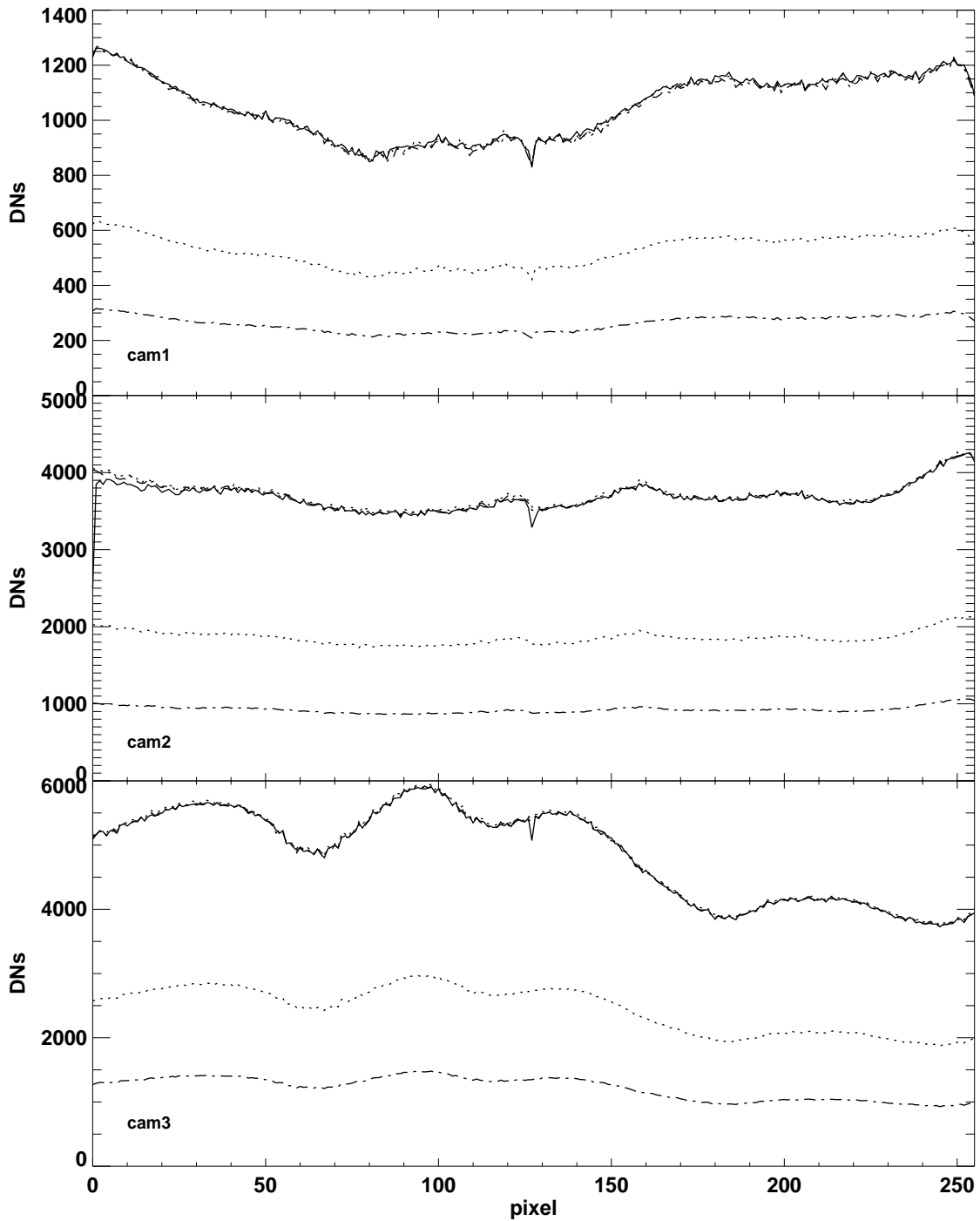
Quadrant	ND1GAIN=x2	ND1GAIN=x4	ND1GAIN=x8
NIC1-Q1	1	2.004 (0.006)	4.0 (0.3)
NIC1-Q2	1	2.005 (0.006)	4.0 (0.3)
NIC1-Q3	1	2.005 (0.006)	4.0 (0.3)
NIC1-Q4	1	2.005 (0.006)	3.7 (0.3)
NIC2-Q1	1	2.012 (0.006)	4.1 (0.3)
NIC2-Q2	1	2.013 (0.009)	4.0 (0.3)
NIC2-Q3	1	2.012 (0.008)	4.1 (0.3)
NIC2-Q4	1	2.015 (0.008)	4.1 (0.3)
NIC3-Q1	1	2.057 (0.007)	4.2 (0.3)
NIC3-Q2	1	2.051 (0.009)	4.3 (0.3)
NIC3-Q3	1	2.043 (0.005)	4.1 (0.3)
NIC3-Q4	1	2.047 (0.005)	4.2 (0.3)

In addition, Fig. 1 shows a second effect which further reduces the dynamic range of the test data: the MULTIACCUM sequences start at higher DN numbers, i.e. closer to the ADC limit of +32,768 DN. The reason for this is of merely technical nature. In all NICMOS data, the offset count level is set to $\sim 15,000$ counts above the bottom of the ADC range at -32,767 DN. This "footroom" is also amplified by the higher gain, which causes the ramps in Fig. 1 to start at different count levels. In order to maintain the same offset levels in amplified counts, the NSETVLT/NOPRVLTL flight software macros need to be used in concert with the NDETGAIN macros for each detector. These macros are routinely used every time the detectors are switched "off", e.g. as NICMOS enters the SAAOPER state. These routines are Operate/Observe macros, and can be executed "on the fly", their use is described in SER OPS 02.

Morphology of flat fields

Because a change in the conversion factor from e^- to DN should simply be a mathematical procedure, there is no reason to believe that the morphology of the DQE variations across the NICMOS detectors should vary between the various gain settings. This is confirmed in Figure 2 which compares the column-collapsed DQE profile across the NICMOS detectors for the different conversion gains. After multiplying the ND1GAIN=x2 (x4) profiles by 2 (4), all profiles accurately match each other, as expected.

Figure 2: Comparison of DQE morphology for all NICMOS detectors at different gain settings. For each camera, we plot a column-collapsed profile through a flat field exposure taken with ND1GAIN=x2 (dashed), x4 (dotted) and x8 (solid). After multiplying the first two curves by factors of 2 and 4, respectively, they accurately match the x8 profile.



This suggests that a simple scaling of the standard flat field reference files is sufficient to calibrate NICMOS data taken with non-standard gain.

Dark current and shading profile

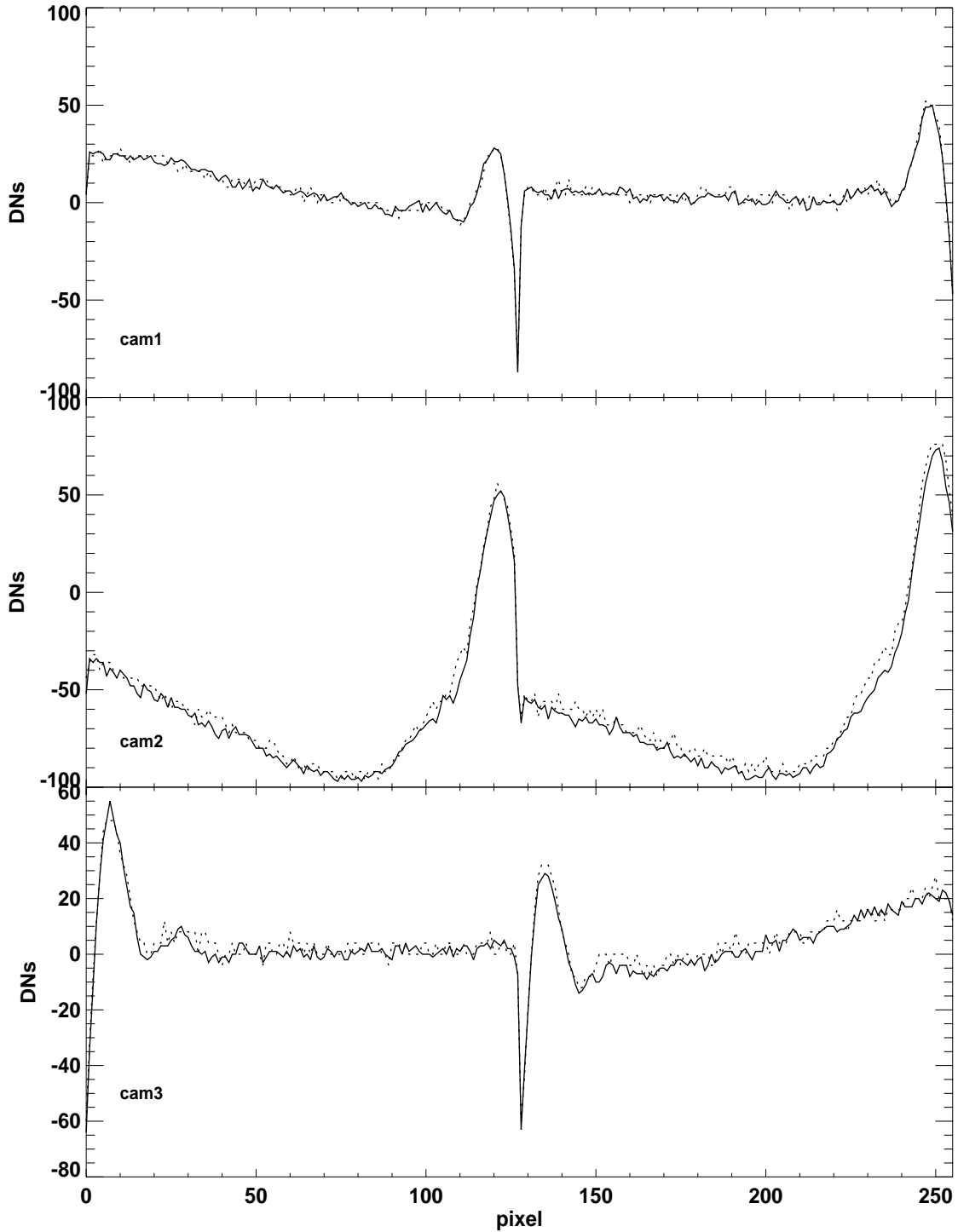
Similar to the discussion of the DQE morphology, a gain change should neither affect the dark current morphology of the NICMOS detectors nor alter the behavior of the detector electronics. It should therefore be possible to simply scale the dark current reference files according to the gain used in much the same way as demonstrated for the flat field reference files. In principle, this is confirmed by Figure 3 which compares the shading profile for gains x2 and x8 for all NICMOS detectors. More specifically, we plot the column-collapsed profile of a (0th read subtracted) sample from a SPARS64 sequence. After multiplying the x2 profile by a factor of 4, both profiles agree to within the noise, thus confirming that the **structure** in dark current images taken with non-standard gains does not change, and hence appropriate scaling of the standard reference darks should be sufficient for calibration of most science data.

However, the **noise** properties will be different for darks obtained with different gains (see next section). Contrary to the case of flat field exposures which are Poisson-limited, the read noise is an important limitation for dark current images. While the reference “superdarks” for NICMOS pipeline processing have been constructed from many dark current exposures (and thus should not be readnoise-limited), for science observations that require additional (contemporary) dark current exposures, the latter should certainly be taken at the same gain setting as the science observations in order to fully benefit from the reduction in read noise.

Noise levels

Ideally, the readout noise (incl. the contribution from digitization noise) in NICMOS data is measured from a large number of short dark current exposures using the SCAMRR readout sequence. Such data are routinely obtained as part of the dark current monitoring program (9636) and have demonstrated that the total readout noise (incl. digitization noise) in NICMOS data obtained with the standard gain is $\sim 27e^-$ (Böker & Xu, ISR in preparation). While the SPARS64 dark current exposures of this test program are not ideal for this purpose, they nevertheless allow to gauge the impact of alternate gain settings on the noise properties. This is because the Poisson noise contribution from dark current accumulated in a 64s long exposure is small compared to the readout noise. In addition, the signal from cosmic rays is relatively small, since the data were obtained in orbits that are free from passage through the South-Atlantic Anomaly, and therefore the SPARS64 darks are adequate for our purposes.

Figure 3: Comparison of dark current/shading morphology for all NICMOS detectors at different gain settings. For each camera, we plot a column-collapsed profile of a single read (here, we arbitrarily chose the 3rd read) in a SPARS64 dark exposure (after 0th read subtraction). After multiplying the ND1GAIN=x2 profile by a factor of 4 (dotted line), it accurately matches the profile taken with ND1GAIN=x8 (solid line).



In order to gauge whether the use of a non-standard gain indeed reduces the noise in NICMOS data, we took the following approach. We calculated first differences from all 7 SPARS64 sequences, and “stacked” the resulting 154 64s dark exposures into a (256 x 256 x 154) datacube. For each detector pixel, the RMS variation around the mean value (after removing outlying values due to cosmic rays at the 4σ level) is a measure of the pixel noise. After application of the nominal conversion factor, we plot in Fig. 4 (top row) the histogram of noise levels in e^- per read-pair for all three NICMOS detectors derived from the SPARS64 dark exposures taken with the standard gain.

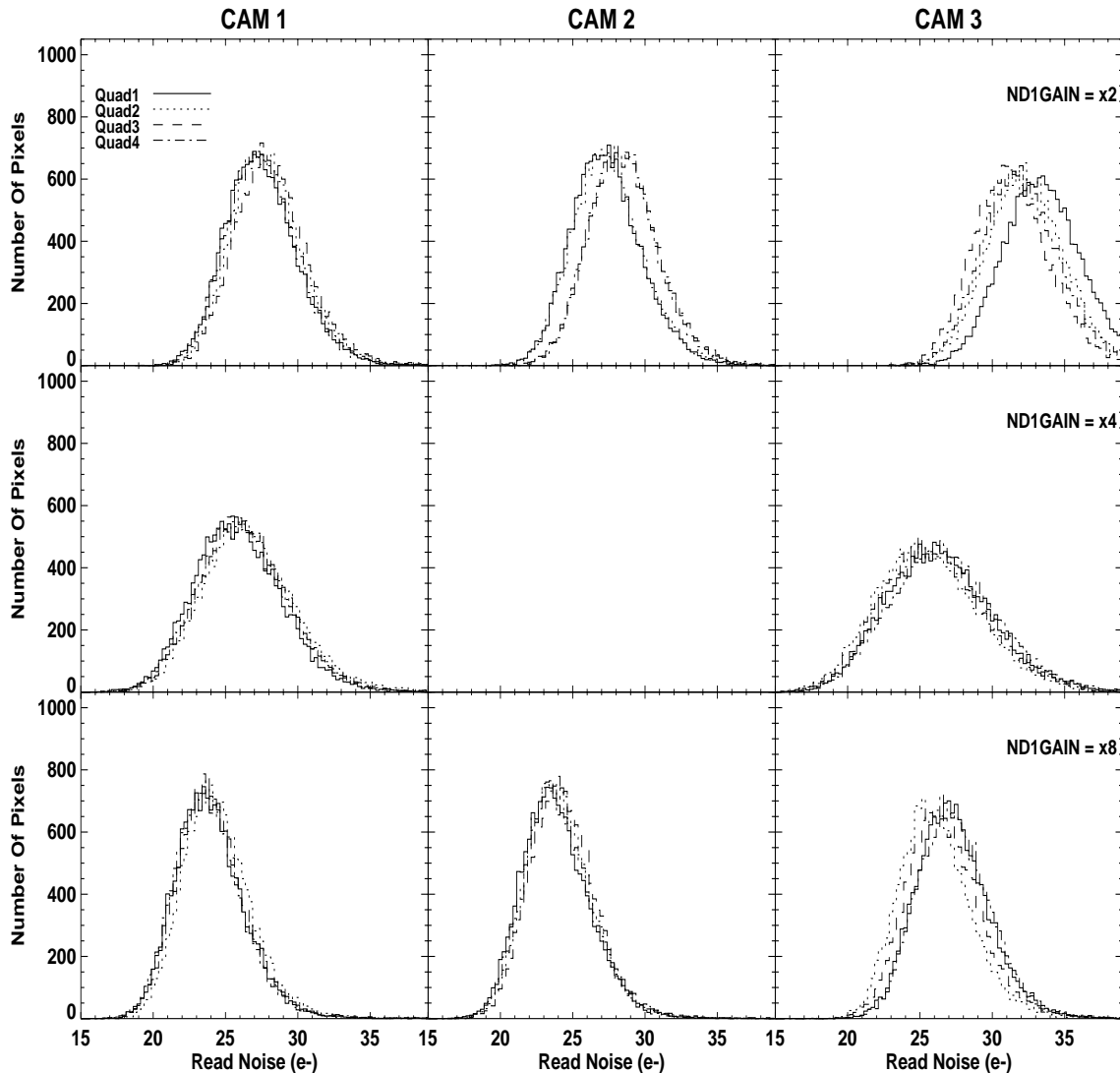
The histograms are fully consistent with results derived from the short SCAMRR darks obtained for the read noise monitoring program (9636, ISR in preparation), demonstrating that the impact of cosmic rays is negligible and that our approach is valid. For comparison, the last row of Fig. 4 shows similar noise histograms obtained from SPARS64 darks taken with $ND1GAIN=x8$ (using the respective conversion factor listed in Table 2). For all three cameras, the mode of the distribution is about $4 e^-$ or $\sim 15\%$ lower than for data taken with the standard gain. This demonstrates that the use of $ND1GAIN=x8$ indeed reduces the noise level of NICMOS faint exposures.

Unfortunately, similar darks taken with $ND1GAIN=x4$ are not available. To compensate for this lack, and as a consistency check, we used the lamp-off exposures taken for all three cameras in conjunction with the flat-field images. These are observations of the empty sky taken through the F160W filter. For cameras NIC1 and NIC3, the combined background from sky and telescope in a 2s exposure is low enough that it does not significantly affect the noise estimates. To verify this, we confirmed that the results from lamp-off exposures taken with $ND1GAIN=x2$ and $x8$ agree with those obtained from the SPARS64 dark current images. The middle row of Fig. 4 then shows noise histograms derived from a stack of 72 first differences of the lamp-off sky exposures taken with $ND1GAIN=x4$. The mode of the noise distribution is almost identical to that reached with $ND1GAIN=x8$. It thus appears that the $\sim 15\%$ noise reduction is already achieved with $ND1GAIN=x4$, and going to $ND1GAIN=x8$ provides only minimal additional benefits.

4. Scientific benefit of reduced readout noise

The data presented here demonstrate that the combined level of readout noise and digitization noise in NICMOS observations can be reduced by 10-15% ($3-4 e^-$ per read pair) using alternate gain settings. For NICMOS exposures with low background from sky and telescope, readout noise becomes an important limitation. While other noise sources such as Poisson noise from dark current and thermal background or the signal from uncorrected, low-level cosmic rays also have an impact on the detection limits, deep HDF-type NICMOS observation should in principle benefit from the reduced digitization noise.

Figure 4: Noise properties of NICMOS data taken with various gain settings. Shown are histograms of pixel noise for all four quadrants in each NICMOS camera. The data for ND1GAIN=x2 and ND1GAIN=x8 are from SPARS64 dark current images, while the ND1GAIN=x4 data are from short exposures of the empty sky. Because of a smaller number of readouts in these datasets, the histograms for ND1GAIN=x4 are somewhat broader. For NIC2, the background signal was too high for a useful comparison, the corresponding panel is therefore left blank. The noise reduction for non-standard gains is clearly visible.



In order to quantify the improvement in NICMOS sensitivity caused by a higher NICMOS gain, we have used software tools developed by the NICMOS IDT group (R. Thompson, private communication). Specifically, we have studied the case of a 1000 s long integration with 15% lower readout noise. The sensitivity of such data is higher by a factor of 1.104, thus enabling detection of objects that are fainter by 0.107 mags with the same intergration time and signal-to-noise ratio. For reference, the number of objects per magnitude per square degree at 28.4 mag is 3.2×10^5 . A gain of 0.107 mags then yields 3.4×10^4 additional objects per square degree, or 7 objects within the camera 3 field of

view. Thus, the use of a higher gain for the Cycle 12 HST treasury program which will obtain deep NICMOS observations of the Ultra-Deep Field (UDF) should result in the detection of about 60 additional objects.

It is expected that the reduced read noise will also slightly improve the ability to identify and correct pixels that have been impacted by cosmic rays. However, this effect is difficult to quantify because it will depend on the exact method used to combine multiple deep exposures. In addition, the limiting factor in deep NICMOS exposures is often the *persistence signal* from cosmic rays, especially after passage through the South Atlantic Anomaly. A different gain will not help in this respect, and hence this additional scientific benefit is unlikely to have a major impact on NICMOS sensitivity.

5. Implications for pipeline processing of NICMOS data

Besides the need for a modified implementation of the gain change resulting from the amplified reset level detailed in Sec. 3, our analysis revealed a few other issues related to the pipeline processing of NICMOS data with non-standard gain settings. These need to be addressed before such data can be routinely used by GOs. In what follows, we simply list the items that have come to our attention, without a claim for completeness.

1) Currently, the header keywords ADCZERO (the offset of the reset count level to the floor of the ADC range, i.e. -32767 DN) and ADCGAIN (the conversion gain from e^- to DN) in the primary FITS header of NICMOS science data are populated with fixed numbers for each camera. In order to populate these keywords correctly, a lookup table should be used that selects the right keywords based on the selected camera **and conversion gain**. A number of CALNICA routines presently make use of this keyword, most importantly, the NOISCALC routine which computes the statistical errors in NICMOS data. This causes a large number of incorrect flags in the data quality files for the data taken with higher gain.

2) The CALNICA routine ZSIGCORR which checks and corrects for signal that has accumulated between the reset and the 0th read in MULTIACCUM data currently assumes that the count level after reset is given by ADCZERO. Because the MULTIACCUM ramps in data taken with non-standard gain start at higher values, all pixels are incorrectly flagged for significant 0th read signal. This issue should be resolved once the correct reset levels are restored by using NSETVLT/NOPRVLT flight software macros when changing the gain as described in Sec. 3.

3) Similarly, because the MULTIACCUM ramps in datasets with ND1GAIN=x4 or x8 quickly reach count levels that exceed the threshold for non-linearity correction, pixels are incorrectly flagged for non-linearity. While restoring the correct reset level will solve part of the problem, the fact remains that because of the lower conversion factor, the NICMOS pixels are **not** approaching their saturation limit even at count levels close to the ADC limit of +32,768 DN. The resolution to this issue would probably require to either select

different linearity reference files based on what gain was used, or to use one linearity reference file **with values in e⁻**, and derive the correct thresholds in DN using the ADCGAIN header keyword (once correctly populated).

6. Conclusions and Recommendations

There is little doubt that if variable gains were offered routinely for NICMOS observations, most deep exposures would use the ND1GAIN=x4 or x8 setting because of the 10-15% reduction in readout noise and the resulting sensitivity improvement of about 0.1 mags. Presently, however, both OPUS and the CALNICA pipeline need a number of modifications before such data can be handled routinely. This is in addition to work required to enable this option for the Phase II planning with the APT, as well as modifications to the exposure time calculator. Although it appears that simple scaling of reference files such as flat field and dark current images should produce accurate pipeline calibration of data taken with non-standard gain, a more thorough test will undoubtedly be required once the necessary changes and updates have been implemented.

Given the incremental increase in sensitivity, the major effort required to offer non-standard NICMOS gains routinely to General Observers (i.e. as an SUPPORTED mode) does not seem justified. However, for some programs, the sensitivity improvement could be important enough to use a higher gain, although it should be obvious that such data cannot be archived in the normal way because OTFR will not work properly unless the changes mentioned above have been implemented. Hence, in such cases, the GO needs to take responsibility for the proper data reduction procedures, and any supporting calibration exposures, if needed.

We would like to thank Rodger Thompson for calculating the sensitivity improvement of data with lower readout noise. We are also grateful to Glenn Schneider for his help in sorting out the correct flight software macros. Finally, we are indebted to Ilana Dashevsky for invaluable help with the implementation of the Phase II proposal.