JWST Near-Infrared Detectors: Latest Test Results

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ABSTRACT

The James Webb Space Telescope, an infrared-optimized space telescope being developed by NASA for launch in 2013, will utilize cutting-edge detector technology in its investigation of fundamental questions in astrophysics. JWST's near infrared spectrograph, NIRSpec utilizes two 2048 x 2048 HdCdTe arrays with Sidecar ASIC readout electronics developed by Teledyne to provide spectral coverage from 0.6 microns to 5 microns. We present recent test and calibration results for the NIRSpec flight arrays as well as data processing routines for noise reduction and cosmic ray rejection.

Keywords: infrared arrays, astronomy

1. INTRODUCTION

The James Webb Space telescope (JWST) will be a cutting edge general-purpose astronomical observatory in the tradition of the Hubble Space telescope and Spitzer Space telescope. The JWST instrument suite will enable photometry and spectroscopy from 1 to __ microns opening the earliest stages of star and galaxy formation to astronomical investigation. One of these instruments, NIRSPEC, is a moderate resolution 1 to 5 micron multi-object spectrograph utilizing cutting-edge neat-infrared detector technology to meet the ambitious instrumental and scientific requirements set by the JWST science case.

This is an incredibly busy time for the NIRSPEC detector System (DS) team. We have made 2 flight detector selections, have achieved detector total noise requirements under lab conditions and have just recently completed Pathfinder testing at Goddard Space Flight Center's Detector Characterization Laboratory (DCL). Additionally, testing using the instrument cryostat and test detector electronics has begun at Astrid EAS in Ottobrun, Germany. This article focuses on Pathfinder testing and preliminary flight hardware test results. For a more detailed look at DS architecture and readout patterns readers are encouraged to refer to precious articles and references therein. [1-4]

Previous papers on JWST NIR detectors concentrated largely on testing performed at Teledyne Imaging Systems (TIS) at Camarillo, CA and data from such testing made available for analysis by the DCL. This paper focuses on data obtained in-house in the DCL.

2. DCL FACILITY

The Detector Characterization Laboratory is a state of the art facility at Goddard Space Flight Center, which specializes, in the testing and development of low background infrared detectors. The DCL is responsible for final testing and calibration of the near-IR sensors for the NIRSpec detector system. Previous papers detailed testing of H2RGs performed at Teledyne Imaging Systems (TIS). This testing was used in the selection of flight grade, flight spare and flight analogue devices, while testing at the DCL more extensively characterizes the selected devices. The DCL also tests the detector system electronics, cables, thermal control and other DS hardware.

DCL equipment consists of several cryogenic vacuum enclosures that have been baffled and light-sealed for extremely sensitive dark current, total noise and fain measurements. Two sets of electronics have been used in these measurements, the ETU electronics and the Pathfinder electronics. The ETU system was used in basic test and readout electronic development, as well as for basic understanding of H2rg behavior in the DCL test dewar. The Pathfinder configuration was designed to use flight-like electronics and is being used to simulate array behavior as installed in the final NIRSpec system. For both the configurations the same H2RG arrays were used, S042 and S040.

3. H2RGS

The NIR arrays used in JWST are Teledyne Imaging System's Hawaii II devices (H2RG's). NIRSpec utilizes two H2RGs, each with a 2048x2048 pixel format. The NIRSpec detectors have a wavelength sensitivity range of 0.6 microns to 5 microns. Two other instruments also utilize H2RGs: the Fine Guidance Sensor (FGS) and NIRCam, although NIRCam uses a mixture of short wavelength (1-2.5 micron) and long wavelength (1-5microns) devices. H2RGs are read out by TIS-developed ASICs, which enable signal amplification and digitization at cryogenic temperatures. Each H2RG is read out by its own ASIC. H2RG and ASIC development has been the product of a close collaboration between Goddard and TIS. A Goddard-built FPE powers the H2RGs and ASICs. Early testing utilized the well-characterized ETU FPE, while recent tests have used the Pathfinder FPE, which operates identically to the FPE that will fly on JWST. Goddard computers process array outputs. Like the FPEs, early testing was performed using a well-characterized system (SWTS), while recent pathfinder tests were performed using a flight-like system (STIS). Test results reported here will specify whether they were in the ETU/SWTS or Pathfinder/STIS configuration. The SCA/ASIC pairs remained unchanged for all tests.

3.1 S040 and S042

The overall goal of testing at the DCL was to achieve familiarity with the NIRSpec detector system prior to flight integration. As such the SCAs used in the DCL tests were not flight-selected devices, but were selected to be operationally flight-like. For DCL testing we used 2 TIS SCA/ASIC pairs: S040 and S042. Both arrays were selected from the same 'batch' as the selected flight arrays so as to provide accurate comparison in behavior. S042 is actually of relatively high quality, with few hot pixels, low dark current and hi DQU as measured by Teledyne. However, it has a large Photo Emissive Defect (PED) that disqualified it from flight consideration. S040 is of lower quality, but is a useful operational check against S042. Because of its high quality, when ignoring the PED, S042 makes and excellent test device for NIRSpec detector system calibration. See figure 1. H2RGs are read out in 4 columns of 512x2048 pixels referred to as outputs 1-4 in this document. Each output has its own ROIC, necessitating separation of the outputs for noise and dark current measurements.

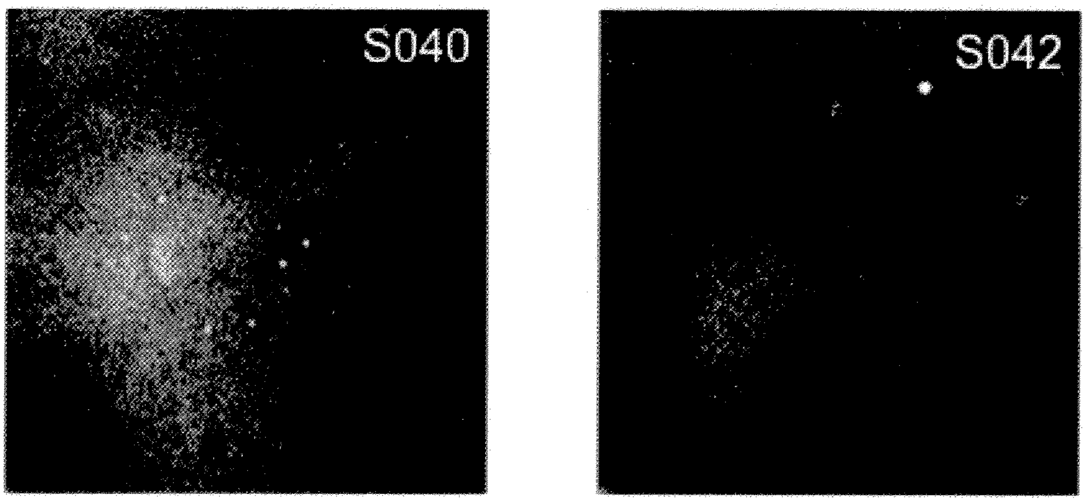

Figure 1: Dark ramp exposures of S040 (left) and S042 (right)

3.2 Sampling up-the-ramp (SUTR)

The primary method of data acquisition for NIRSpec will be as 88 frame sampling up the ramp exposures. Sampling up the ramp uses a series of equally spaced non-destructive reads to create one exposure. Flux levels in each pixel are subsequently found through iterative slope-fitting routines, making the method especially efficient for the sparse, low flux targets that NIRSpec will most commonly examine. SUTR has the added benefit of allowing Cosmic Ray rejection without loss of data.

Sampling up the ramp utilizes buildup of charge on each pixel to measure flux (see figure 2). The entire array is reset at the beginning of the exposure. Each pixel is read out at regular intervals throughout the ramp, creating a signal measured as a slope for each pixel. The H2RGs used in NIRSpec are read out every 10.6 seconds for a total of 88 frames. NIRSpec further structures the data into 22 groups of four frames each. NIRSpec arrays are 2048 x 2048 pixels, resulting in data cubes of dimensions 2048 x 2048 x 22. Using iterative slope-fitting on each pixel this data cube is processed to produce an overall slope image for the duration of the exposure.

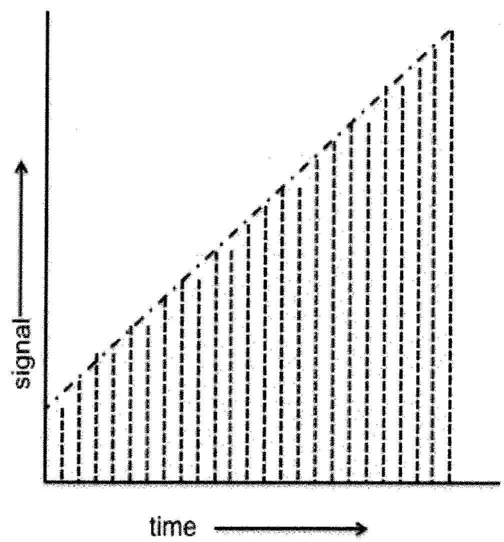

Figure 2:One 'ramp'. Each dotted line represents a non-destructive read or 'frame'. The slope of the dashed line is equal to the flux seen by the pixel.

Noise in a SUTR exposure is not calculated in the same manner a correlated double sample (CDS) or Fowler sampling. Instead the noise in a SUTR exposure is given by:

$$\sigma_{\text{total}}^2 = \frac{12(n-1)}{mn(n+1)}\sigma_{\text{read}}^2 + \frac{6\left(n^2+1\right)}{5n(n+1)}(n-1)g_c^{-1}t_g i_{\text{dark}} - \frac{2(2m-1)(n-1)}{mn(n+1)}(m-1)g_c^{-1}t_f i_{\text{dark}}$$

Where i_{dark} is the flux, g_c is the conversion gain, n is the number of frames per group (4 for NIRSpec) and m is the number of groups (22 for NIRSpec). For complete derivation and discussion of this noise equation, see Mott et al.[5]

3.3 Reference Pixel Subtraction

Teledyne H2RGs utilize a 4 pixel wide frame of non-light responsive pixels for reference correction, meaning the photo-sensitive portion of the SCA is 2040x2040 pixels. The reference pixels are electrically identical to the photosensitive pixels, so they can be used to remove a large portion of the electronic noise from the array images. The DCL had been utilizing a simplified reference pixel subtraction method based on testing performed at the University of Hawaii[7]. This simple reference pixel subtraction only used the horizontal reference pixels in the correction, ignoring the columns of reference pixels along outputs 1 and 4. While the horizontal reference pixels correspond to the 'fast scan' direction of the array, they cannot correct for 1/f noise or other noise appearing as horizontal bands across the detector. In response to this the DCL has developed a reference pixel subtraction method that initially corrects using the horizontal reference pixels, but performs a secondary correction utilizing the vertical reference pixels. This approach yields noise reductions of 2% to 8% over the simplified, horizontal reference pixel method.

4. SCA TESTING RESULTS

This section presents the results from DCL testing of S040 and S042. All tests were performed in the DCL dark dewar under cryogenic conditions. As the overall goal wad to characterize the flight ready detector system. The presented results are from the Pathfinder FPE and STIS configuration except for the ETU total noise result, which is presented as an illustration of the potential gain from ASIC tuning.

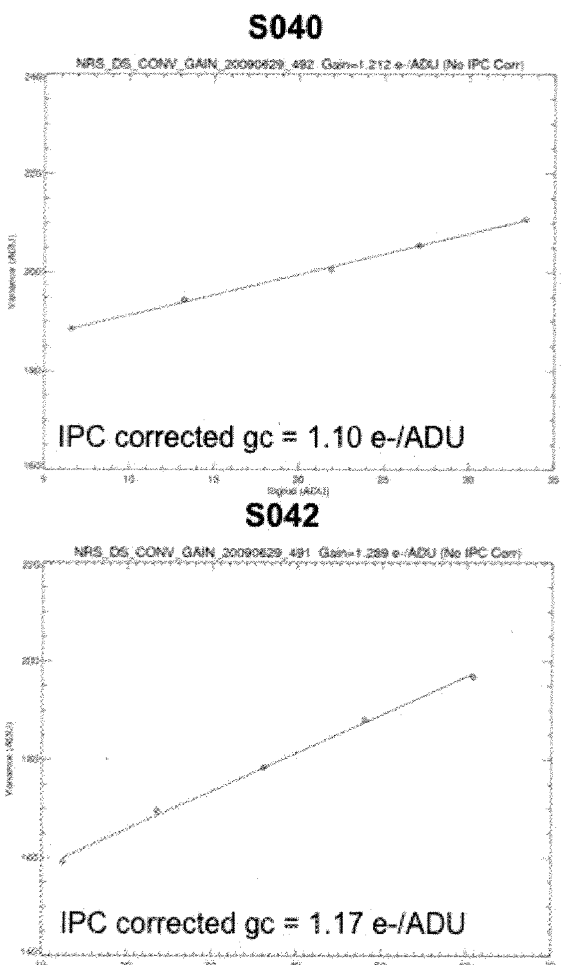

Figure 3: Conversion gain results for S040 (top) and S042 (bottom)

4.1 Conversion Gain

Con version gain is of obvious importance to any astronomical detector system. Each SCA has a different gain, as does each experimental configuration, thus gain must be determined for each SCA/ASIC pair during the experiment. Conversion gain is also subtly affected by signal level, requiring the determination of gain for the NIRSpec DS at extremely low signal levels not only because total noise measurements are performed at the dark current flux limit, but also because NIRSpec's primary astronomical targets will be distant, faint objects in the early universe. We utilize the noise signal squared technique for gin determination. This method uses a very faint, calibrated light source to illuminate the SCA over the course of a series of multiple frame rams. We then create a series of CDS images at different flux levels by comparing each frame to the first frame of the ramp. With a series of ramps we can also find the noise on the signal. We then use the relation

$$\sigma_{total}^2 = \sigma_{CDS}^2 + \frac{1}{g_c} S$$

and find the conversion gain by plotting the noise^2 vs. the signal[6]. The slope of the liner regression is the conversion gain. With conversion gains from multiple signal levels we interpolate back to a conversion gain for the zero-flux case. This gin does not take into account the IPC factor, which, for the H2RGs we are using has been shown to be 12% in the low signal case. Including this factor yields the gains reported here and used in the dark current and total noise measurements. For S042 in the ETU configuration we found g_c=1.21 e^-/ADU. For the pathfinder configuration we found S042's gain to be g_c=1.17e^-/ADU. Figure 3 shows the pathfinder gain measurements for S040 and S042.

4.2 Dark Ramps

The Dark Current and total noise measurements both require a large number of long-duration dark SUTR exposures. Each dark ramp is taken as 88 10.6-second duration non-destructive reads. These 88 frames are then re-structured into 22 groups of 4 frames each. This is called a 22x4 MULTI ramp. While taking such a long dark exposure likely overestimates the dark current, data is taken using this method to accurately mimic the primary observing mode for NIRSpec. Experiments in altering the dark ramp procedure will be undertaken during NIRSpec flight calibration to more fully investigate the tradeoffs involved.

In general 50 of these ramps is obtained for each dark current and total noise measurement. Once the series of dark ramps has been acquired, each ramp is converted into a slope image using the least-squares slope fitting found in the astro library DJS-ITERSTAT procedure. Reference pixel subtraction and 3-sigma clipping is also applied to the data. Since these darks are often taken overnight, after a full day of experiments the first 10 ramps are discarded from further processing in order to ensure only data from a fully stabilized system is included. The slope images are combined into a mean slope image. This procedure also generates records the standard deviation from the mean slope at each pixel as a 'sigma' image. In the dark ramp case, the mean slope image is the dark current, while the sigma image yields the total noise. Figure 4 shows the mean slope and sigma images for S042 in the pathfinder configuration.

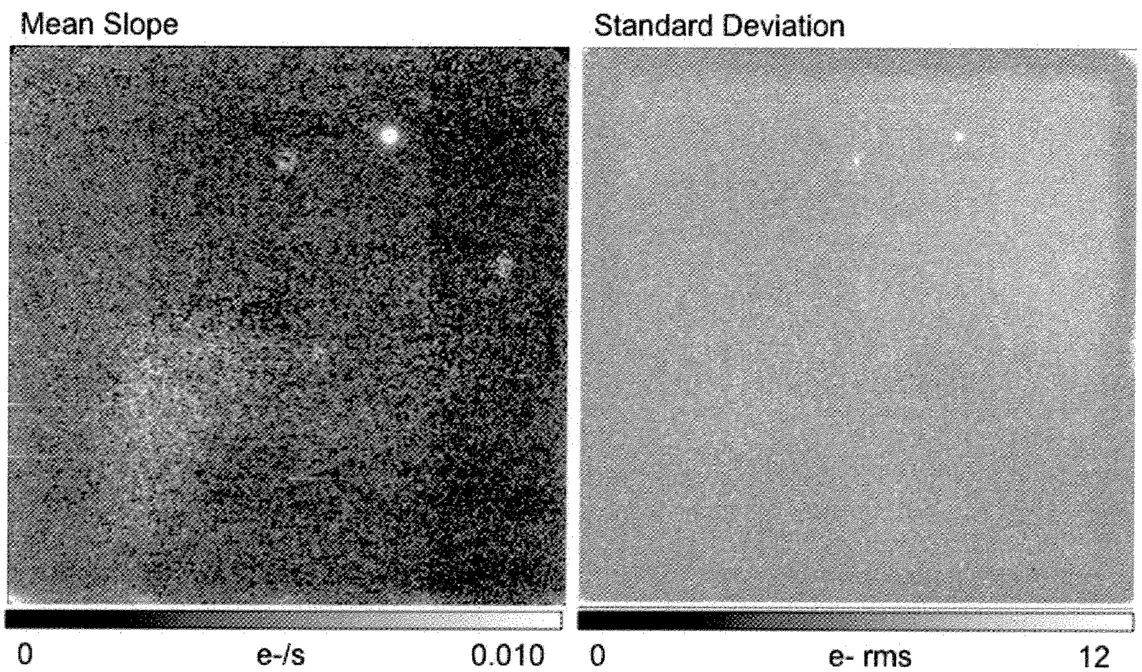

Figure 4: S042 Mean Slope (left) and standard deviation images after reduction of 50 ramps.

4.3 Dark Current

Dark current is the measurement of the inherent signal in a given detector. At the NIRSpec operating temperature of 37K dark current for the H2RG is dominated by quantum tunneling, which is sensitive to thermal stability, ROIC stability and input voltages, this the dark current must be measured at each new configuration. These devices have extremely low dark current, so dark current measurements are taken only after the detector has been dark for at least 24 hours. The majority of pathfinder tests (ASIC tuning, thermal stability, etc) are done with the dewar completely dark, allowing accurate dark current measurements, but gain, DQE and flat field measurements require light sources capable of creating persistence in the detector leading to dark current over estimation[8].

The mean slope image found from the dark ramp series is a measure of the dark current at each pixel. Plotting the distribution of these dark currents gives the mean dark current for the entire array. Figure 5 shows he dark current measured in the pathfinder configuration for both S040 and S042, separated by output. Table 1 summarizes the pathfinder dark current results.

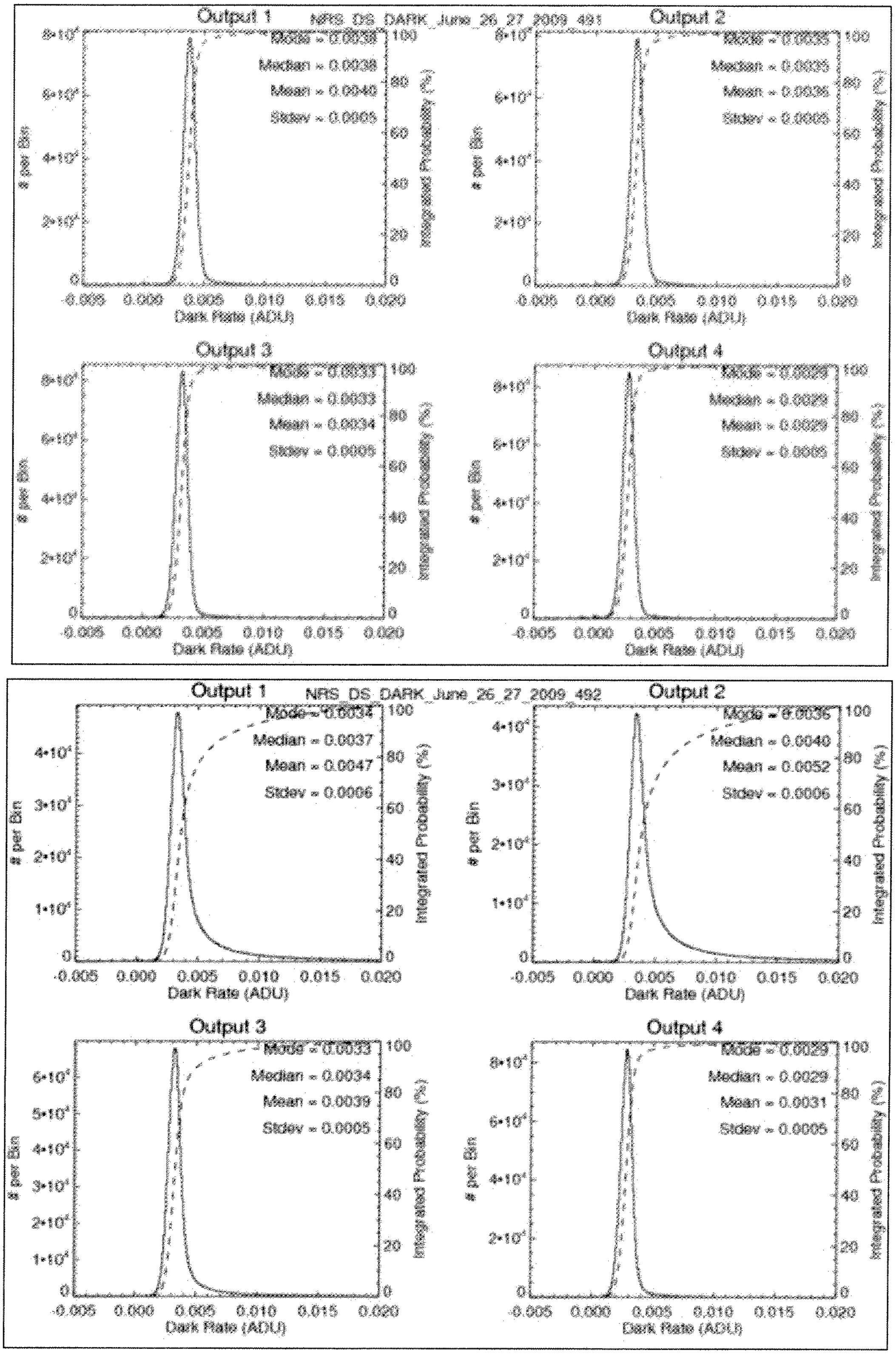

Figure 5: Dark Current for S040 (top) and S042 (bottom)

Table 1: Pathfinder Dark Current Results

		Dark Rate (ADU/Sec)	Gain /ADU)	Dark Rate e-/Sec
SCA040	1	0.0038	1.21	0.0046
	2	0.0040	1.21	0.0048
	3	0.0031	1.21	0.0038
	4	0.0025	1.21	0.0030

		Dark Rate (ADU/Sec)	Gain /ADU)	Dark Rate e-/Sec
SCA042	1	0.0036	1.17	0.0042
	2	0.0030	1.17	0.0035
	3	0.0028	1.17	0.0033
	4	0.0024	1.17	0.0028

4.4 Total Noise

The 6-electron total noise requirement is potentially the most difficult specification for the NIRSpec detector system to achieve. Theoretically, the total noise in a 22x4 MULTI ramp is given by equation 1 in section 3, but in reality, achieving this goal requires a well-understood, well-tuned system. The noise per second per pixel is given by the sigma image from the series of dark ramps discussed in section 4.2. Fitting a Gaussian to the distribution of these noise measurements gives the total noise for the entire detector. To convert from ADUs to electrons we multiply by the IPC-corrected conversion gain, g_c.

We have achieved the 6-electron noise goal in the ETU configuration with S042, and are progressing steadily towards 6 electrons in the pathfinder configuration. We have found that the majority of the total noise is contributed by the Sidecar ASIC readout electronics. These contributions can be minimized by careful adjustment of the ASIC. A great deal of ETU testing at the DCL concentrated on tuning the detector system through small modifications to the ASIC microcode and personality file. Each ASIC is subtly different, and requires individual tuning and adjustment for optimal noise performance. During flight integration and test the flight hardware will be put through the same tuning process as the ETU and pathfinder configurations have been. Figure 6 shows the noise results for S042 in the ETU configuration, while figure 7 shows the total noise results for S040 and S042 in the pathfinder configuration. Table 3 summarizes the total noise results for the pathfinder configuration.

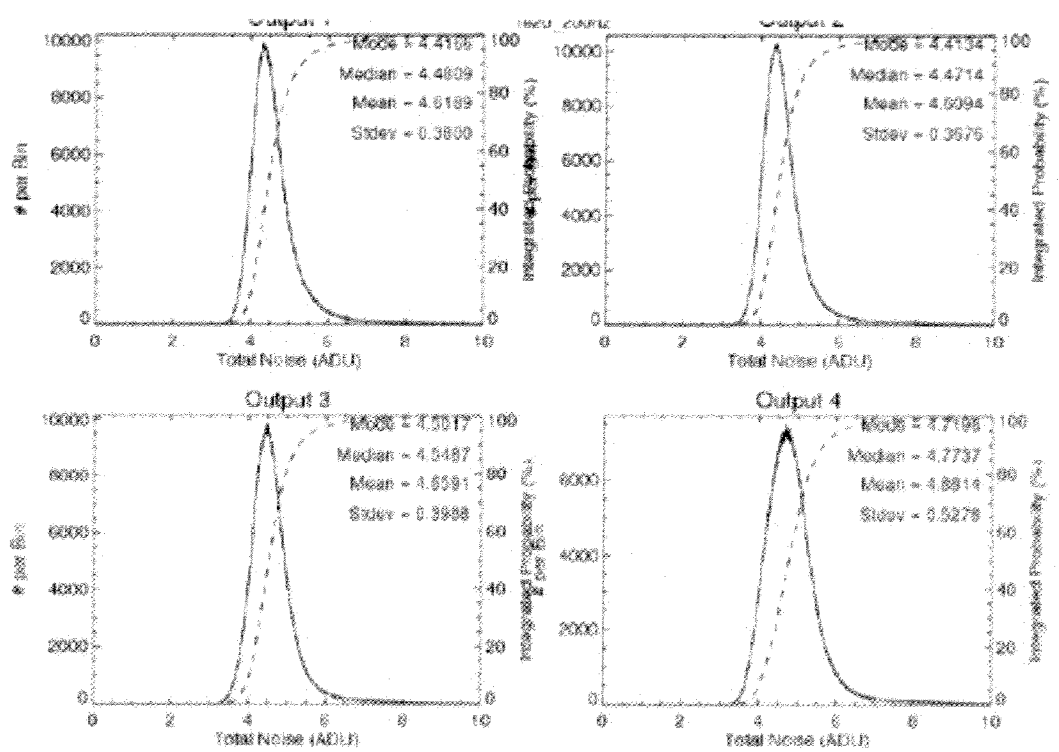

Figure 6: Total Noise for S042 in ETU configuration (gain= 1.21 e/ADU --> 5.8 e- avgas)

Table 2: Pathfinder Total Noise Results

		Total Noise (ADU)	Gain (e^-/ADU)	Total Noise e^-			Total Noise (ADU)	Gain (e^-/ADU)	Total Noise e^-
SCA040	1	6.47	1.21	7.83	SCA042	1	5.45	1.17	6.38
	2	6.94	1.21	8.40		2	5.52	1.17	6.46
	3	6.33	1.21	7.66		3	5.77	1.17	6.75
	4	6.19	1.21	7.49		4	5.74	1.17	6.72

5. SUMMARY

Pathfinder testing for a set of H2RGs has been completed at the DCL at Goddard Space Flight Center. These tests have established a baseline measurement for detector gain, dark current and total noise in a flight-like configuration. Although testing non-flight grade components, we have achieved the NIRSpec DS requirements for gain and dark current in the pathfinder configuration, and have achieved the total noise specification in the ETU configuration. Pathfinder testing has yielded a comprehensive process for tuning the Sidecar ASIC readout electronics, which will be the critical component in final flight integration, calibration and test. Likewise, the lessons learned in this testing are widely applicable, not only to the other near-IR JWST instruments NIRCAM and FGS, but will also be useful to other NIR space missions, as well as ground-based instrumentation currently under development for large observatories like Keck and Gemini. We are confident that the H2RG devices, as well as the Sidecar ASIC readout electronics can be sufficiently tuned and calibrated to meet or exceed even the stringent requirements of the NIRSpec science case, providing a state-of-the-art detector system and spectrometer capable of probing the most fundamental questions of the early universe.

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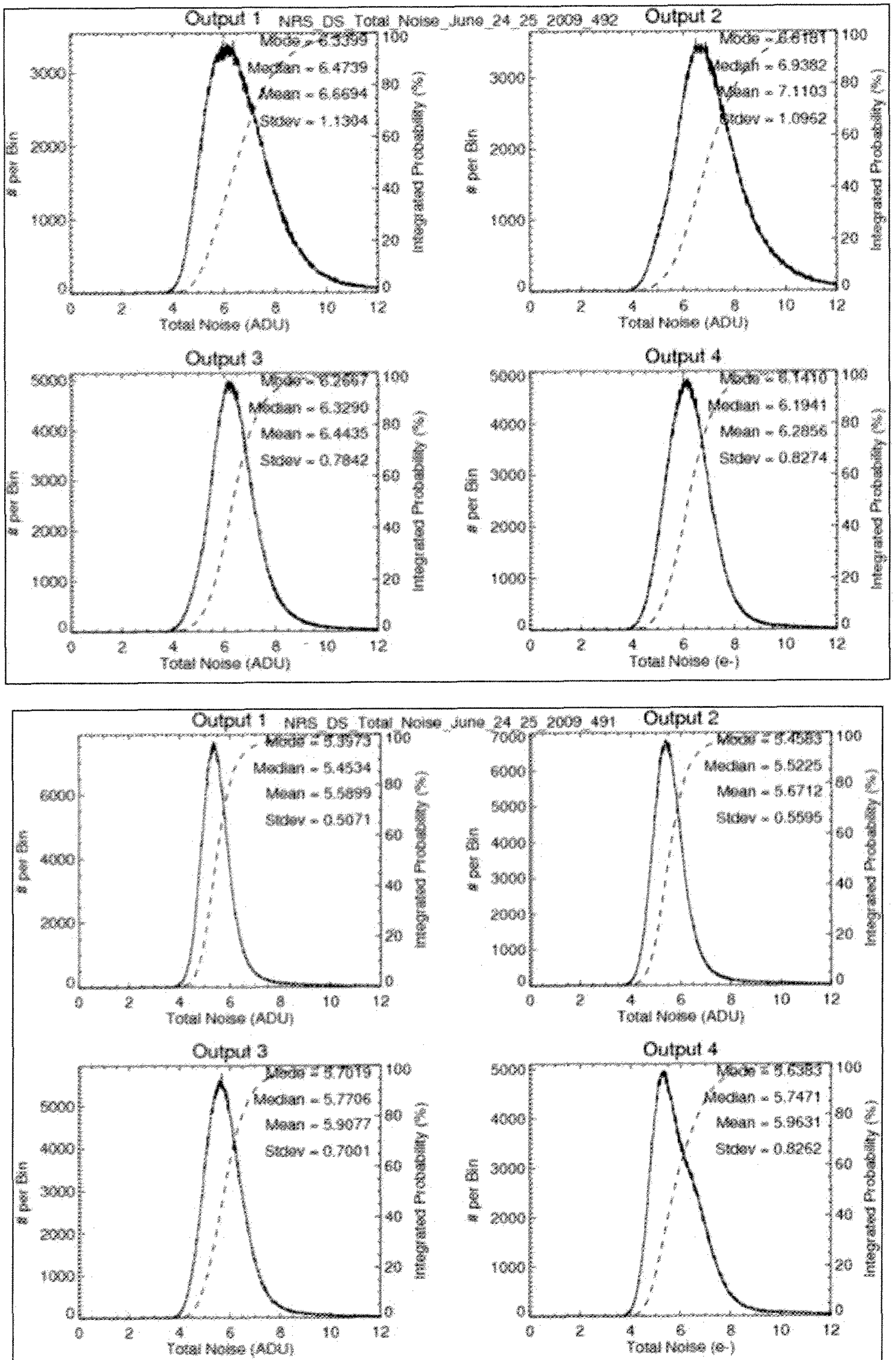

Figure 7: Total noise for S040 (top) and S042 (bottom) in the pathfinder configuration