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NICMOS Detector Performance in the NCS Era

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Abstract. After a three-year hiatus following the exhaustion of its solid nitrogen coolant, NICMOS was revived with the installation of the NICMOS Cooling System (NCS) during the *HST* Servicing Mission 3B in March 2002. NICMOS now operates at about 77.1 K, some 15 K warmer than during its initial operating period. In this paper, we briefly describe the on-orbit performance of the NCS. In addition, we use results from the early NICMOS calibration program to characterize the impact of the higher operating temperature on the behavior of the NICMOS detectors, with a focus on those parameters that are relevant to the scientific performance of the "new" NICMOS.

1. Introduction

The Near Infrared and Multi-Object Spectrometer (NICMOS) provides the *Hubble Space Telescope* (*HST*) with its only means to study the universe at infrared wavelengths. Installed on *HST* during the second Servicing Mission in February 1997, NICMOS suffered from a shortened lifetime because of a thermal anomaly that led to an increased sublimation rate of the solid nitrogen coolant used to maintain a detector temperature of $\approx$ 61 K. Following the nitrogen exhaustion in January 1999, the NICMOS instrument warmed up to temperatures around 260 K, much too high for scientifically useful observations. NICMOS thus lay dormant for about three years, awaiting the installation of the NICMOS Cooling System (NCS), a mechanical cooler using a closed-loop reverse-Brayton cycle (Cheng et al. 1998).

Since the NICMOS detectors show a number of subtle effects that are sensitive to temperature, both the value of the operating temperature and its stability are crucial parameters for the scientific performance of NICMOS. Prior to the NCS on-orbit installation, the evaluation of the thermal performance of the NICMOS/NCS system had to rely on models, because for obvious reasons, the NICMOS dewar was not available for ground testing. Therefore, various aspects of the NCS performance remained rather uncertain, including the parasitic heat load that the NCS had to overcome and its ability to react to environmental changes during the orbital (and seasonal) cycle of *HST*. However, the results from the early NICMOS calibration program and the NCS telemetry during the first few months of on-orbit operation indicate that all is well with the revived NICMOS. In what follows, we describe the stable and efficient performance of the cryocooler, and the impact of the higher operating temperature on detector parameters such as dark current, quantum efficiency, and readout noise.

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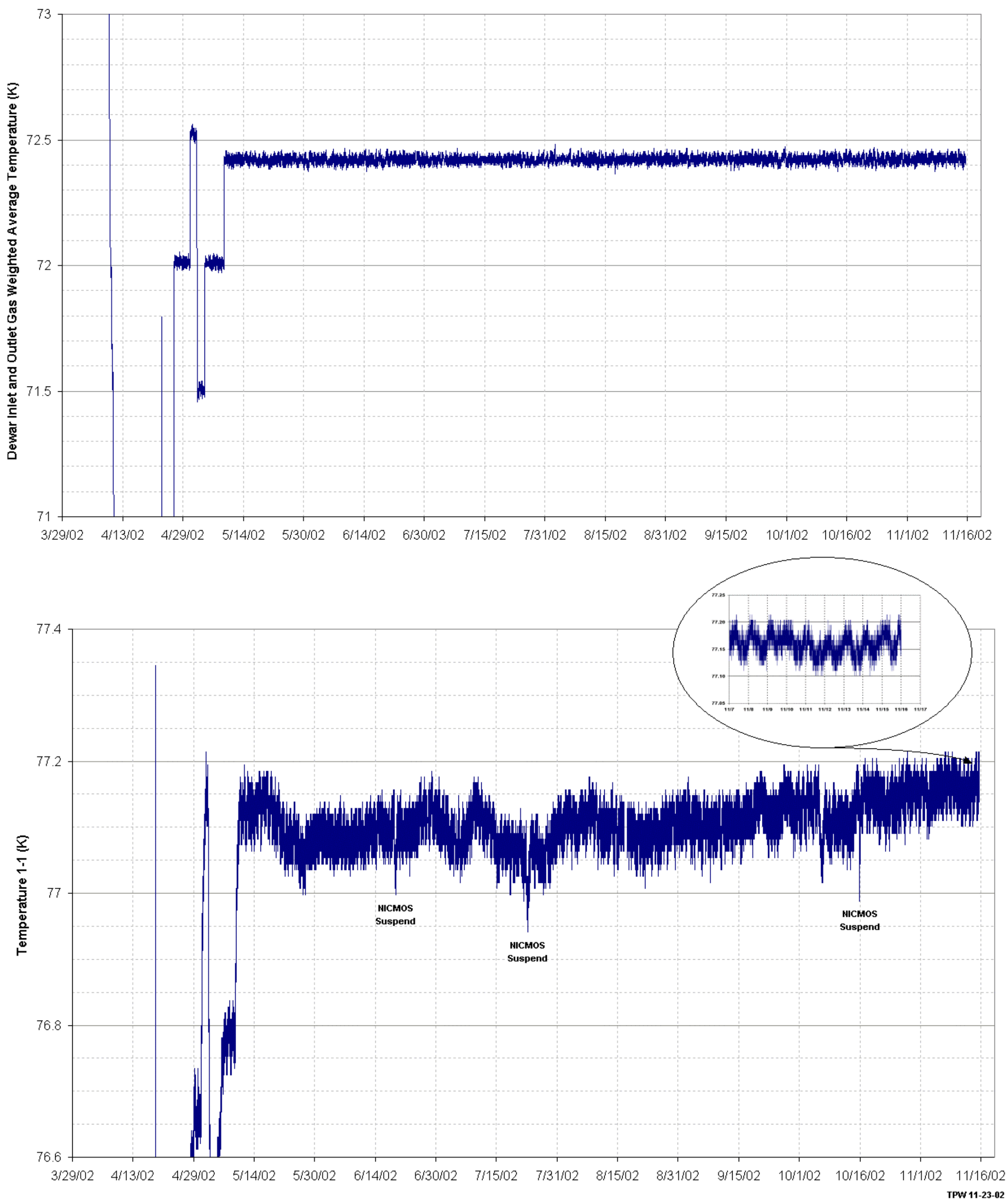

Figure 1. Thermal history of the NCS. Top: weighted average of the Neon inlet and outlet temperature sensors. Bottom: Camera 1 mounting cup sensor which closely traces the actual detector temperature.

2. NICMOS/NCS Performance in 2002

2.1. The Cooling System Performance

Much effort had been spent over the last few years to understand the thermal performance of the NICMOS/NCS system. The latest pre-launch models had predicted a cooldown time of about 10 days. However, it became clear very soon that the NICMOS dewar was cooling much slower than expected, which triggered frequent revisions to the SMOV timeline, not only for NICMOS, but also for the other *HST* instruments. What made matters worse, early extrapolations of the cooldown profile indicated that the target temperature of around 77 K for the NICMOS detectors might not be reached. A number of options to increase the NCS cooling capacity or to reduce the parasitic heat load were discussed in a flurry of status meetings. The more drastic of these proposals included disabling the safety heaters that provide leakage protection of the cryogenic Neon lines.

Finally, a decision was made to temporarily safe the NICMOS instrument in order to reduce the heat load from its electronic boxes. A consequence of this decision was the loss of all telemetry data from within NICMOS, and the interruption of the dark current monitoring program which was supposed to provide early indications of the NICMOS performance in the NCS era. However, the NICMOS safing resulted in an accelerated cooldown and, after about 4 weeks of continued cooling, the Neon gas inside the NCS circulator loop finally reached the target temperature of 72 K. NICMOS was switched on again, and the dark current measurements resumed while the system was stabilizing.

Since the start of NCS operations, STScI has continously monitored the system performance. The thermal history of a few key temperature sensors until mid-November 2002 is summarized in Figure 1. The plots show that over the first 6 months of operation, the NCS has maintained the NICMOS detectors to within 0.1 K of their target temperature. The slight increase in the average detector temperature over the last month is probably a reflection of the hotter season for *HST*, as the earth currently is closer to the sun and hence the mean temperature of the *HST* aft shroud is slightly increased. STScI is currently investigating whether this trend is significant enough to warrant adjustments to the NCS control law.

Because the NICMOS detectors react sensitively to temperature variations, the superb stability of the cooling system is extremely positive news for the scientific performance of NICMOS. In what follows, we discuss in some more detail the characteristics of the NICMOS detectors in the NCS era.

2.2. The Early NICMOS Calibration Program

NICMOS datasets consist of a series of non-destructive detector readouts, with varying time intervals (Δ-times) between reads. The observer can choose from a number of pre-defined sequences that are designed to optimize the dynamic range for a variety of science projects. For details about the readout sequences, we refer to the NICMOS instrument handbook at *http://www.stsci.edu/hst/nicmos/documents/handbooks/v5/*. A number of proposals using different readout sequences were executed early in the SMOV process to assess the NCS performance and to obtain essential information about the NICMOS health and detector performance. Table 1 summarizes the programs that were used to derive the results presented in this paper. To a large extent, the data analysis procedures follow those of the NICMOS warm-up monitoring program after the cryogen depletion in early 1999. The analysis has been discussed in detail in Böker et al. (2001), and hence will not be repeated here.

2.3. Detective Quantum Efficiency

The detective quantum efficiency (DQE) of the NICMOS detectors changes as a function of temperature, in the sense that higher operating temperatures result in higher sensitivity.

Table 1. Summary of Early NICMOS SMOV Programs

Program #	Purpose	Filter	Readout Sequence
8944	Filter wheel functional	All	ACCUM
8945	Dark current monitor	Blank	SPARS64
8975	Readnoise & Shading	Blank	SCAMRR & STEP256
8985	DQE	All	many

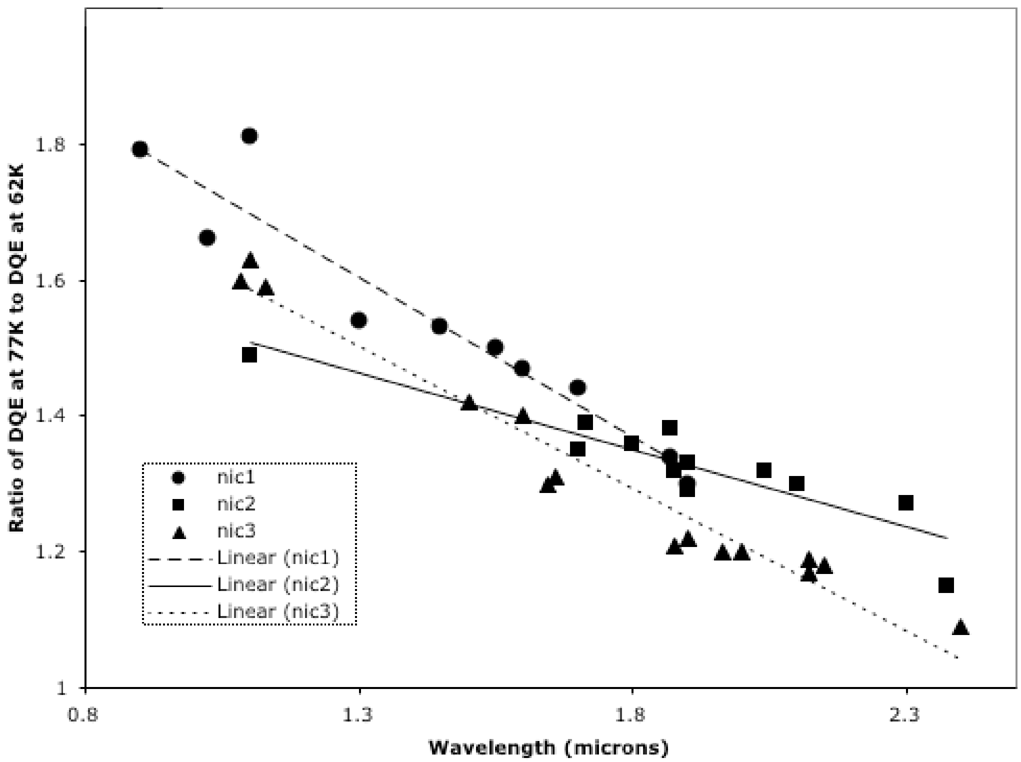

Figure 2. NICMOS DQE: comparison between post-SM3B (at operating temperature of 77 K) and 1997/1998 (62 K) eras.

This is one of the reasons why the re-instated NICMOS under NCS control was expected to be more efficient than during the solid cryogen era—at least for some science programs. This section quantifies the gain in DQE at the new operating temperature.

Relative changes of the NICMOS DQE can be measured from "flat-field" exposures generated from a pair of "lamp off" and "lamp on" exposures. Both are exposures of the (random) sky through a particular filter, but one has the additional signal from a flat field calibration lamp. Differencing these two exposures then leaves the true flat-field response. The countrate in such an image is a direct (albeit relative) measure of the DQE. The DQE increase of the three NICMOS cameras between 77 K and 62 K as a function of wavelength is presented in Figure 2.

From the DQE monitoring program during the 1999 instrument warmup, we were able to construct a model that predicts the DQE as a function of wavelength and temperature. This model—together with dark current predictions—provided the basis for the sensitivity calculations in the NICMOS exposure time calculator (ETC), a widely used web tool for NICMOS users. With the new post-SM3B data, we are now able to test the accuracy of

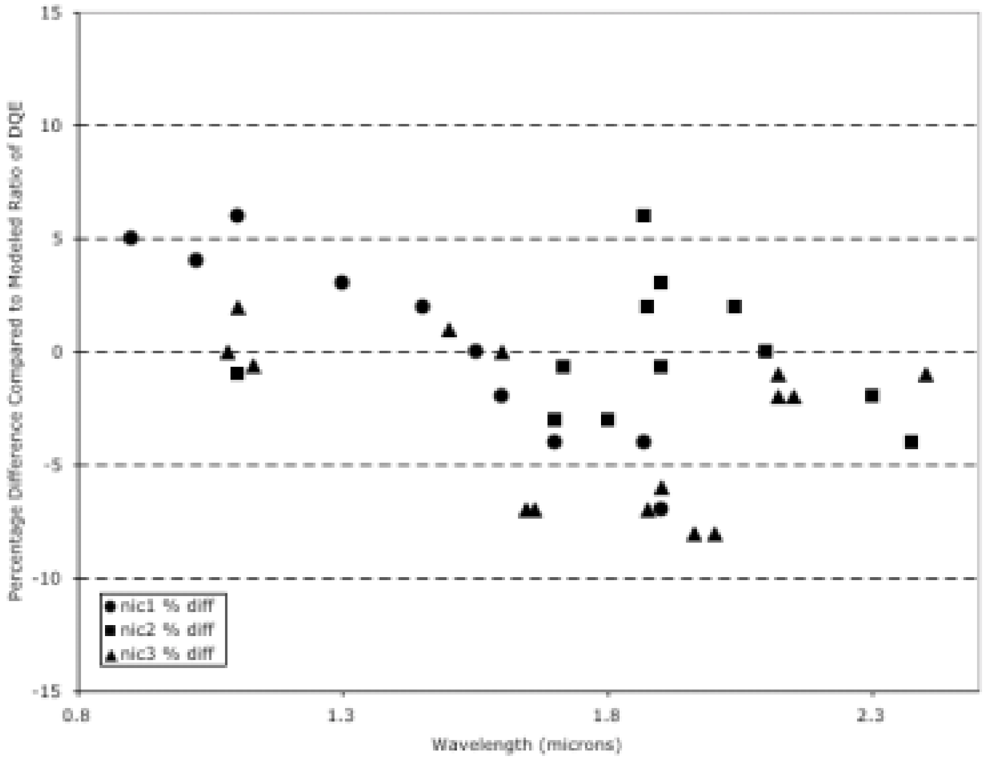

Figure 3. Comparison of NICMOS DQE as measured during April 2002 to predictions based on data from the 1999 instrument warmup.

this model, and to verify that the predicted exposure times for all NICMOS science projects are correct. In Figure 3, we compare the new DQE measurements through the NICMOS filter set to the model predictions. The plot demonstrates that the new data agree with the model predictions to within a few percent, which means that earlier sensitivity calculations are indeed accurate for the revived NICMOS.

Because the flat-field lamps inside NICMOS have not been calibrated in an absolute sense, these data can not be used to determine the absolute DQE of the NICMOS detectors. This is a notoriously difficult problem, which typically relies on observations of standard stars with a well-known energy distribution over the NICMOS wavelength range. This calibration program is currently still under analysis. For the purpose of this paper, we show in Figure 4 the absolute DQE of the three NICMOS detectors—measured during NICMOS ground-testing at ≈ 60 K—compared to the same curve scaled by the linear fits to the relative DQE increase from Figure 2. This gives another impression of the sensitivity improvement under the NCS.

2.4. Read-out Noise

Each NICMOS detector has four independent readout amplifiers, each of which reads a 128×128 pixel quadrant. The noise associated with the amplification process, commonly referred to as read-out noise, has been shown to be independent of temperature (Böker et al. 2001). However, it is important to answer whether the three-year hiatus in space has in any way degraded the performance of the NICMOS electronics.

Subtracting the first two reads of a SPARS64 sequence eliminates all effects of bias variations or shading. The effective integration time of this difference image is only 0.3 s, too short for the linear dark current signal to become important. Therefore, the RMS deviation of the pixel values across the detector array is an accurate representation of the

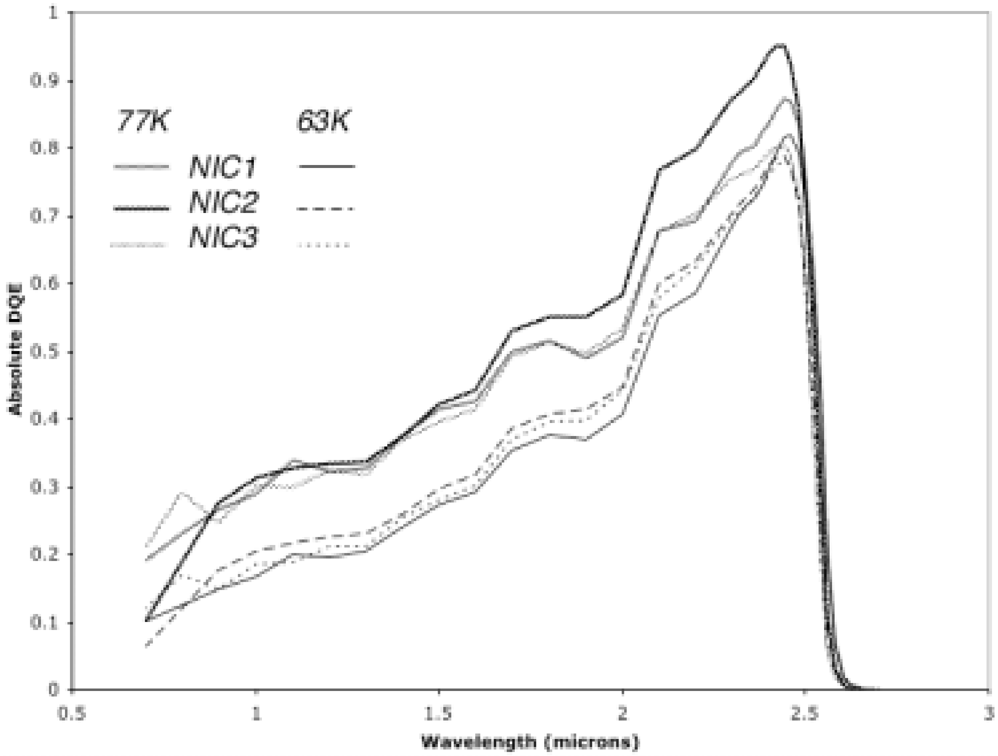

Figure 4. Approximate improvement of absolute DQE of the NICMOS detectors. Here, the pre-launch measurements have been scaled by the relative DQE increase as shown in Figure 2.

intrinsic read-out noise of the detectors. From a series of about 400 such first-difference images, we determined the average RMS pixel-to-pixel variation across the three NICMOS detector arrays. The results, which are summarized in Table 2, indicate that the NICMOS noise levels are not in any way degraded from the pre-NCS values.

Table 2. Read-out Noise of NICMOS Detectors

Camera	RMS [DN]	Gain	Readnoise [e^-/readpair]
NIC1	5.1±0.15	5.4	27.5±0.8
NIC2	5.1±0.15	5.4	27.5±0.8
NIC3	4.6±0.15	6.5	29.9±0.9

2.5. Linear Dark Current

The linear dark current (i.e., that component of the signal in a "dark" exposure that accumulates linearly with time) of the NICMOS detectors had been the subject of much debate and speculation over the last few years. The reason for this was an anomalously high dark current in the temperature range between 78 and 85 K that was observed during the 1999 warmup (Böker et al. 2001). The elevated dark current would have compromised NICMOS sensitivity (if it had to be operated in this temperature regime), and hence the question of whether or not the anomaly would be present after the cooldown was an important one.

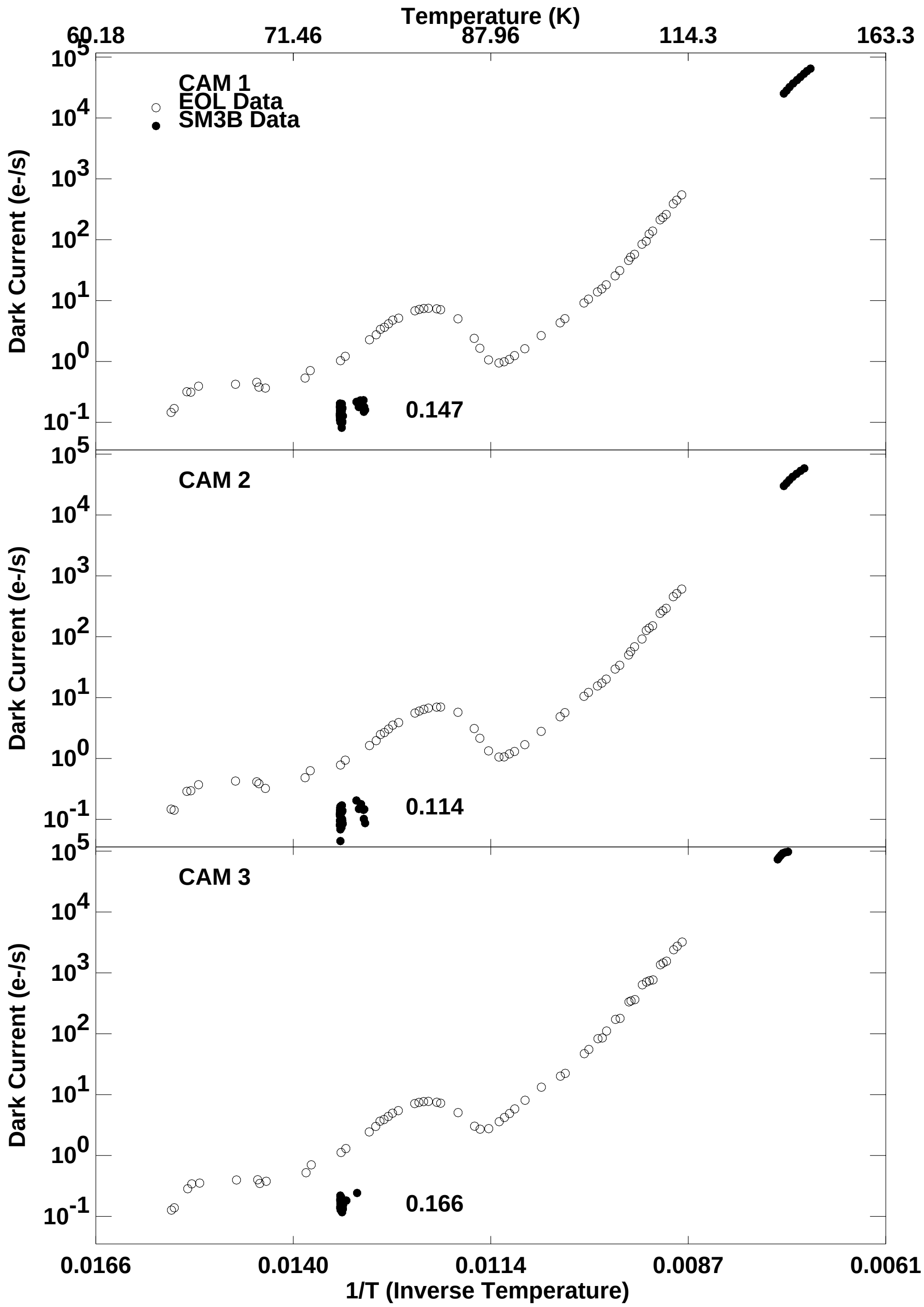

Figure 5. Linear dark current of all three NICMOS cameras as a function of temperature. The open symbols are from the 1999 instrument warm-up, while the closed symbols mark the new data obtained during and after the NCS cooldown. Note the good agreement in the exponential increase towards high temperatures, and the fact that the mean dark current at the new operating temperature of 77 K (plotted in $e^{-}s^{-1}$) is significantly lower than during the warm-up.

The safing of the NICMOS instrument prevented dark current measurements for the better part of the cooldown. However, some non-saturated datasets were taken before the NICMOS safing, and the measurements resumed as soon as the NCS had reached its target temperature. These new measurements are shown in Figure 5, compared to the results of the 1999 warm-up monitor. It is clear that while the exponential increase at high temperatures is fully consistent between the two datasets, the anomalously high dark current around 82 K is absent in the new data.

One minor concern is the fact that all three NICMOS arrays show an increased number of "hot" pixels, i.e., pixels with higher-than-average linear dark current. This is not entirely unexpected because the warmup monitor did show a similar behavior, although it was unclear at the time whether this was a transition effect that would disappear once the detectors stabilize in temperature. The new data show that the hot pixels are indeed a genuine feature of the new operating temperature. However, they can be fully corrected for by dithering NICMOS observations.

2.6. Amplifier Glow

Amplifier glow is a well-known feature of NICMOS-3 arrays. It manifests itself as a spatially variable, but highly repeatable signal component in every detector read-out. The signal is highest in the corners of the array, i.e., closest to the read-out amplifiers, and gets fainter towards the center of the array. Typical values for the amplifier glow are 2 DN/read in the center of the array, and up to 15 DN/read in the corners, independent of detector temperature. The signal is extremely repeatable and can be well modeled and removed during pipeline calibration.

The amplifier glow is measured by subtracting the first two reads in a STEP64 sequence which are only 0.3 s apart, thus making the signal contribution from the linear dark current negligible. In agreement with expectations, the amount and structure of amplifier glow is unchanged compared to NICMOS data obtained in 1997/1998.

2.7. Reset Level and Self-Calibration

The reset level (i.e., the count level immediately following a detector reset) of the NICMOS detectors is extremely sensitive to temperature. With proper calibration, this fact can be exploited to use the reset level as a detector thermometer. In the absence of other reliable information, e.g. from diode sensors, this method can provide a means to correct for various temperature-dependent effects.

Prior to the on-orbit testing of the NCS, estimates of its performance remained highly uncertain, both in terms of final operating temperature and stability. In addition, there was a real possibility that the operating temperature would fall above 78 K in which case the internal temperature sensors would become unusable due to the limits of their analog-to-digital converters. For these reasons, the STScI NICMOS group spent a significant amount of work in order to use the reset levels to essentially enable self-calibration of NICMOS data.

However, the surprising stability of the NCS, and the fact that at least some diode sensors within NICMOS are still within their usable range, allow consideration of an alternative strategy for NICMOS calibration. Given temperature variations of less than 0.1 K RMS since the start of active NCS control in mid-April, the NICMOS calibration pipeline could possibly rely on reference files taken at the actual operating temperature, at least for the near future. This possibility is currently under study. However, should the temperature stability of the NCS degrade significantly (RMS $>$ 0.1 K), data self-calibration via the reset levels is the only viable option for the NICMOS pipeline.

2.8. Saturation Levels and Dynamic Range

The saturation level of a given detector pixel is defined by the amount of charge "loaded" onto it during the detector reset (i.e., the well depth). The reset voltages of the NICMOS detectors and—to a much smaller degree—the capacitance of the pixel both vary with temperature, and hence the pixel saturation levels will also depend on the operating temperature. The flat field exposures taken after the cooldown allow us to measure the saturation levels at the new NICMOS operating temperature of 77K. The data suggest that for cameras 1 and 2, the average pixel saturates around 25,000 DN (or $\approx 135,000 e^{-} s^{-1}$) which is about 15% lower than during the nitrogen period. For camera 3, the reduction is only about 7%. This rather small loss in dynamic range of NICMOS data can be compensated for by a proper choice of readout sequences, so that NICMOS will be able to execute the same wide range of science projects as before.

2.9. Cosmic Ray Persistence

The NICMOS detector are susceptible to image persistence from a bright source, for example a luminous star or a cosmic ray hit. Persistence signal from cosmic ray hits is a problem especially for exposures taken soon after an *HST* passage through the South Atlantic Anomaly (SAA), a region in the Earth's atmosphere with higher than average cosmic ray incidence. The random spatial distribution of the cosmic ray "afterglows" is effectively an additional component to the dark current. It increases the noise level in the image and therefore limits faint source detections.

Some of the dark current monitoring data were taken soon after an SAA passage. Our analysis of these datasets indicates that the persistence signal decays exponentially over a period of about 30 min. This is the same timescale as in the solid nitrogen period, and hence new NICMOS datasets will be affected by cosmic rays in much the same way as the old ones did. However, for the upcoming NICMOS science program, STScI plans to automatically schedule a pair of dark exposures immediately following each SAA passage in order to provide a map of the persistent cosmic ray afterglow. Experiments using 1998 NICMOS data have shown that it is possible to scale and subtract such "post-SAA" darks from subsequent science exposures, and thus to significantly reduce the impact of CR persistence. A more detailed advisory on how to use the "post-SAA" darks will be distributed soon.

2.10. Detector Cosmetics

All NICMOS detector arrays have a small number of particulates on their surfaces. These are believed to be flecks of black paint scraped off the baffles during the mechanical deformation that led to the accelerated cryogen depletion. There was some concern that the warmup and subsequent cooldown with their associated mechanical motions could have produced an increased number of these particles. Fortunately, these concerns are not confirmed. Except for one additional particle in the lower right corner of camera 1, no new contaminants are apparent in the SMOV data. Moreover, the number of "bad" pixels (i.e., pixels with significantly degraded responsivity) is roughly the same as before, so that the cosmetic appearance of the NICMOS detectors is as good as in the pre-NCS era.

3. Summary

We have described various aspects of the detector performance of the reinstated NICMOS instrument. All parameters are in line with expectations, and will enable a "better-than-ever" scientific performance of NICMOS. In particular, the DQE increase agrees very well with models derived from the 1999 warmup, and the linear dark current shows no sign of anomalously high levels. Other parameters such as readnoise, amplifier glow, or detector cosmetics are unchanged compared to the "old" NICMOS. Together with the stable and quiet performance of the cooling system, *HST* and NICMOS are in great shape for new, exciting scientific discoveries.

Acknowledgments. It is impossible to name all individuals who have helped to make the idea of a NICMOS revival become a reality. We are indebted to the NCS team at GSFC for making the cooling system a success, to the GSFC thermal group for their continued assistance in modeling the NICMOS/NCS system, and to the NICMOS group at UofA, in particular G. Schneider and R. Thompson, for invaluable help in the design and analysis of the NICMOS verification and calibration program.

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