Review of NICMOS Performance

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ABSTRACT
We summarize the performance of the NICMOS instrument and compare the observed
with the expected (pre-launch) capabilities. A discussion on the measured sensitivity, the
observed sky and thermal backgrounds, the photometric performance and stability, and
the image quality is presented. NICMOS has achieved or exceeded the pre-launch perfor-
ance in most areas, with substandard performance occurring only in some specialized
modes of operation. As an example, typical 3 $\sigma$ detection limits for a 5 orbit observation
with NIC2 are 1.47 $\mu$Jy arcsec$^{-2}$ in F110W, 1.67 $\mu$Jy arcsec$^{-2}$ in F160W, and 12.6 $\mu$Jy arc-
sec$^{-2}$ in F222M.

1. Instrument Overview
NICMOS, the Near Infrared Camera and Multi-Object Spectrometer, is the only instru-
ment onboard the Hubble Space Telescope (HST) that is capable of infrared observations
at wavelengths of 1-2.5 $\mu$m. NICMOS was installed as part of the second HST servicing
mission in February 1997 and has been taking scientific data since the end of orbital veri-
fication in May 1997.
NICMOS provides near-infrared imaging capabilities in broad, medium, and narrow band
filters, broad-band imaging polarimetry, coronographic imaging, and slitless grism spec-
troscopy, in the wavelength range 0.8-2.5 $\mu$m. NICMOS is an HST axial instrument and
has three adjacent but not contiguous cameras, designed to operate independently and
simultaneously, although the physical deformations of the detector assembly experienced
after launch have compromised the parfocality of the three cameras. Each camera has a
different magnification scale, and is equipped with a dedicated 256x256 HgCdTe (“mer-
cad telluride”) Rockwell array. The arrays are divided into four quadrants, each served by
an independent read-out amplifier located near the outside corner of each quadrant. Each
of the three cameras carries 19 independent optical elements providing a wide range of fil-
ters including wide and narrow bandpasses. Cameras 1 and 2 have polarimetric filters.
Camera 2 has a 0.3 arcsec radius coronographic spot and a cold mask. Camera 3 has three
separate grisms providing slitless spectroscopy over the full NICMOS wavelength range. The main characteristics of each of the three cameras (NIC1, NIC2 and NIC3) are summarized in Table 1 below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NIC1</th>
<th>NIC2</th>
<th>NIC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Current (e⁻/s/pix)</td>
<td>0.1</td>
<td>0.08</td>
<td>0.1</td>
</tr>
<tr>
<td>Read-out noise (e⁻/pix)</td>
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<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Gain (e⁻/ADU)</td>
<td>5.4</td>
<td>5.4</td>
<td>6.5</td>
</tr>
<tr>
<td>Angular Resolutionᵃ</td>
<td>0.09&quot;-</td>
<td>0.15&quot;</td>
<td>0.4&quot;</td>
</tr>
<tr>
<td></td>
<td>0.15&quot;</td>
<td></td>
<td></td>
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<td>0.043&quot;</td>
<td>0.075&quot;</td>
<td>0.2&quot;</td>
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<tr>
<td>Diffraction Limited λ</td>
<td>1.0 mm</td>
<td>1.75 mm</td>
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</tr>
<tr>
<td>Field of View</td>
<td>11&quot; x 11&quot;</td>
<td>19.2&quot; x 19.2&quot;</td>
<td>51.2&quot; x 51.2&quot;</td>
</tr>
<tr>
<td>1.6 μm Limiting Sensitivityᵇ</td>
<td>199 nJy</td>
<td>59.0 nJy</td>
<td>27.8 nJy</td>
</tr>
<tr>
<td></td>
<td>m&lt;sub&gt;AB&lt;/sub&gt;=25.7</td>
<td>m&lt;sub&gt;AB&lt;/sub&gt;=27.0</td>
<td>m&lt;sub&gt;AB&lt;/sub&gt;=27.8</td>
</tr>
<tr>
<td></td>
<td>H=24.2</td>
<td>H=25.5</td>
<td>H=26.3</td>
</tr>
<tr>
<td>Background (F160W)ᶜ</td>
<td>0.066</td>
<td>0.219</td>
<td>1.608</td>
</tr>
<tr>
<td>Achieved</td>
<td>(0.325)</td>
<td>(0.975)</td>
<td>(6.750)</td>
</tr>
<tr>
<td>(Anticipated)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photometric Stability</td>
<td>1-2%</td>
<td>1-2%</td>
<td>1-2%</td>
</tr>
<tr>
<td>Achieved</td>
<td>(5%)</td>
<td>(5%)</td>
<td>(5%)</td>
</tr>
<tr>
<td>(Anticipated)</td>
<td>(5%)</td>
<td>(5%)</td>
<td>(5%)</td>
</tr>
<tr>
<td>Absolute Photometryᵈ</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Achieved</td>
<td>(10-15%)</td>
<td>(10-15%)</td>
<td>(10-15%)</td>
</tr>
<tr>
<td>(Anticipated)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Angular resolution depends on wavelength for wavelengths longer than the diffraction limit. The NIC3 PSF is undersampled at all wavelengths. Dithering allows some recovery of resolution in NIC3 and in NIC1 and NIC2 at wavelengths shorter than the diffraction limit.

b. The limiting magnitude for a typical 5 orbits observation of a point source in the F160W filter as described in detail in section 3.3. Units are Jansky, AB mag, and H mag. A Jansky is defined as $10^{-23}$ erg s⁻¹ cm⁻² Hz⁻¹.

c. The sky background observed in the F160W filter (centered at 1.59 μm) is given in photons sec⁻¹ μm⁻¹ pix⁻¹.

d. The uncertainty in absolute calibration is dominated by uncertainties in the absolute fluxes of the calibration stars.

The HgCdTe detectors of NICMOS must be cooled to cryogenic temperatures in order to operate. NICMOS was launched with a supply of 240 pounds of solid N₂ designed to allow operation of the detectors at T = 58-60 K for up to 4.5 years. A thermal short that
developed soon after launch has substantially increased the evaporation rate of the solid N$_2$, and therefore has shortened the useful lifetime of NICMOS to about 2 years. The expected end of the useful scientific life for the instrument is mid-November 1998.

2. Summary of Achieved Capabilities

NICMOS was designed to be a multipurpose infrared instrument for HST and included both imaging and spectroscopic capabilities. The primary design features were selected to take advantage of the high sensitivity afforded by the low and stable background of the orbital environment, the inherent photometric stability of HST, and the high angular resolution possible with diffraction-limited optics. All of these three important areas of performance are discussed in detail in separate sections that follow. They are also summarized briefly along with other relevant performance parameters in Table 1.

The performance of NICMOS is based on evaluation of data taken on-orbit and can be compared to the performance anticipated on the basis of testing before launch. Observations with NICMOS began soon after launch in February 1997. Engineering qualification tests occupied the first two months of NICMOS’s on-orbit lifetime. Routine calibration programs are ongoing. Some limited science observations began as early as May 1997. By September 1997 the decision to accelerate NICMOS observations resulted in NICMOS using between 40% and 50% of the available orbits on HST. As of mid-April 1998 approximately 60% of NICMOS proposals, including those accepted as part of a supplemental call for proposals in September 1997, had been completed. Current thermal models of the dewar predict exhaustion of the cryogen by mid-November 1998 at which time science observations with NICMOS will cease. Thus, our understanding of NICMOS’s performance on-orbit, summarized in Table 1, is based on analysis of data from general observer (GO), guaranteed time observer (GTO), and calibration programs and represents a mature understanding of the properties of the instrument. In the most important areas, NICMOS’s on-orbit performance has met or exceeded the capabilities of the instrument as understood by the Cycle 7 Time Allocation Committee. Differences between expected and actual performance have mostly been minor, the most serious being the loss of the ability to focus all three cameras simultaneously which has impacted parallel science. Substandard performance has occurred for several specialized modes of operation, but in essentially all cases, adequate alternative procedures have allowed a recovery of all important capabilities. These special cases are discussed separately below.

The HgCdTe detectors are performing optimally as indicated by the low dark current and read noise in Table 1. The pixel scale, field of view, and diffraction-limited wavelength are unchanged from pre-launch values, except that there is a small vignetting of the fields of view as discussed below. The photometric performance has exceeded prelaunch expectations. In its most important performance criterion, overall sensitivity, NICMOS has met and even exceeded prelaunch estimates reaching a limiting sensitivity of $\lesssim 2.5 \times 10^{-9}$ Jy (1
\(\sigma\) in observations of the Hubble Deep Field (HDF) at 1.6 \(\mu m\) (comparable to the limits reached by WFPC2).

3. Sensitivity

NICMOS is uniquely sensitive at near infrared wavelengths where it takes advantage of the very low natural background available on orbit. In the subsections below we discuss separately the backgrounds, both from zodiacal light and thermal radiation, and describe in more detail the achieved sensitivities of the three NICMOS cameras for both point sources and extended sources. Throughout this document we have described NICMOS sensitivities in units of Janskys, where 1 Jy = \(10^{-23}\) erg s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\).

3.1 Background, \(\lambda<1.6\ \mu m\)

The single most important factor in the high sensitivity of NICMOS is the much lower level of background radiation encountered on-orbit compared to a ground-based observatory. From the ground, the infrared background is dominated by both absorption bands and emission lines from gases in the terrestrial atmosphere. This time-variable background produces a fundamental limitation on the depth of astronomical imaging possible from the ground.

The location of HST above the atmosphere completely removes these terrestrial effects and NICMOS readily reaches the natural background provided by the scattering of sunlight from zodiacal dust at wavelengths of 1.6 \(\mu m\) and less (at longer wavelengths thermal emission becomes important as described below). The zodiacal background is strongly dependent on the ecliptic latitude and longitude; at a position 45\(^{\circ}\) out of the ecliptic the zodiacal background can be approximated as:

\[
Z(\lambda) = 5.0 \times 10^8 / \lambda^{1.09} + 6 \times 10^{-8} B(\lambda)(T) \quad \text{photons cm}^{-2} \mu m^{-1} \text{(sr)}^{-1}
\]

Where \(\lambda\) is the wavelength in \(\mu m\) and \(B(\lambda)(T)\) is the blackbody function for the zodiacal dust temperature \(T\) (roughly 265 K). The contribution of zodiacal light was overestimated prior to launch so that the actual performance on orbit has been better than originally advertised.

In Figure 1, a comparison of measured backgrounds on HST and a representative ground-based telescope, it can be seen that the orbital environment provides HST with a background that is as much as 300 times lower at 1.6 \(\mu m\). The ground-based background is due to emission from molecular oxygen and hydroxyl radicals located high in the Earth’s atmosphere (\(z\sim87\) km) that produce a prodigious number of emission lines concentrated in
the 1-2 \(\mu m\) range. In addition, water vapor in the Earth’s atmosphere produces strong absorption bands near 1.4 and 1.9 \(\mu m\) that limit sensitivity in these regions.

**Figure 1:** Comparison between ground-based and on-orbit IR backgrounds. The sum of the zodiacal and thermal backgrounds “seen” by HST is shown as a function of wavelength (continuous line) for the NICMOS range. The ground-based IR background (filled triangles) was measured from J (1.25 \(\mu m\)), H (1.65 \(\mu m\)), and K\(_s\) (2.14 \(\mu m\)) observations obtained at the Las Campanas 2.5-m telescope with a NICMOS3 array, during dry weather. The background observed by NICMOS is free of the molecular absorption bands and the OH+O\(_2\) emission which limits the sensitivity of ground-based IR detectors, via both intensity and instability.

### 3.2 Background, \(\lambda > 1.6 \mu m\)

The thermal emission from the HST’s primary and secondary mirrors can be approximated as a blackbody with an effective temperature of 290 K; the analogous emission from the NICMOS foreoptics has temperature \(T \sim 270\) K. Before launch, the emissivity of a mirror like HSTs in the space environment was unavailable. Conservative estimates put the emissivity as high as 10-20%. Comparison of the expected thermal emission and the known zodiacal background indicated that the thermal component of the background would dominate the total background at wavelengths longer than approximately 1.6 \(\mu m\).

Measurement on orbit, however, have shown that background count rates are between factors 2 to 5 (going from 1.6 \(\mu m\) to 2.4 \(\mu m\)) lower than expected before launch, revealing that the HST primary and secondary mirrors’ emissivity is closer to 5% and resulting in a gain in sensitivity at longer wavelengths compared to pre-launch expectations. The HST thermal emission still dominates the NICMOS long wavelength background (Figure 1), but with almost one order of magnitude reduction factor compared to pre-launch expecta-
tions. In addition, monitoring of changes in the thermal background have shown it to be stable with an amplitude of less than 5% over orbital timescales and of ~8% (peak-to-peak) over timescales of several months; the lack of significant variations within orbits has removed the necessity for rapid dithering and chopping. This has resulted in a significant gain in efficiency since fewer background measurements must be made.

### 3.3 Detailed Sensitivity Calculations

A detailed summary of NICMOS sensitivities in the three cameras and at different wavelengths is given in Tables 2 and 3 below. Table 2 gives the limiting flux (and corresponding magnitudes) for a point source detected in 250 minutes total integration time. This time was chosen to be representative of an “average” HST observation. Significantly deeper observations can be and have been made and have achieved even fainter limiting magnitudes. Table 3 similarly reports the limiting fluxes (and corresponding surface brightnesses) for extended sources detected with the same criteria as in Table 2.

The limiting sensitivities in Tables 2 and 3 were calculated using the NICMOS exposure time calculator (ETC) tool. This tool, in turn, has been calibrated to match the observed performance of NICMOS, mainly relying on data from calibration programs. Thus, the ETC reflects the current performance of NICMOS. Examples of the accuracy of the ETC are given by observations of faint targets. The first example are NIC2 observations of distant galaxies in the F160W filter, from the GO program 7714. The observed 1σ detection limit, for exposures not contaminated by cosmic ray persistence (see section 6.1), is 864 nJy arcsec⁻² (AB=24.1 arcsec⁻²), for the sum of 9 dithered exposures totalling 7680 sec of exposure time. The ETC predicts a detection limit which is a factor 5.6% better than measured, for the same observing conditions. Observations of faint targets in NIC3 with the F160W filter (GTO program 7224) yield similar results: the 1σ detection limit for a total exposure time of 8040 sec, divided into six dithered exposures, is 180 nJy arcsec⁻² (AB=25.8 arcsec⁻²), while the exposure time calculator predicts a detection limit of 150 nJy arcsec⁻². Thus, two independent programs yield agreements between predicted and observed detection limits between 6 and 20%. The detection limits of the observations in the two GO programs are courtesy of M. Dickinson (The Johns Hopkins University).

The current sensitivity limits differ only slightly from those predicted before launch. In some cases, the sensitivity is higher and in others lower than before launch. A specific comparison between the promised sensitivity in Cycle 7 (i.e., before launch) and the measured sensitivity is given in Table 4 for the case of NIC2.

Several characteristics of the performance of NICMOS on-orbit make the instrument less sensitive under certain conditions. Cosmic ray persistence, increased dark current in initial readouts, and cross-camera inductance during readouts are discussed in more detail in section 6. However, all of these effects are small in most situations and can be further
minimized or eliminated by proper observing procedures and/or scheduling. Thus, we conclude that science that requires the sensitivity advertised for NICMOS can be achieved as promised.

### Table 2: NICMOS Sensitivity for Point Sources (nJy)

<table>
<thead>
<tr>
<th>Filter</th>
<th>NIC1a</th>
<th>NIC2a</th>
<th>NIC3a</th>
</tr>
</thead>
<tbody>
<tr>
<td>F110W</td>
<td>92.5</td>
<td>28.8</td>
<td>22.2</td>
</tr>
<tr>
<td>F160W</td>
<td>199</td>
<td>59.0</td>
<td>27.8</td>
</tr>
<tr>
<td>F222M</td>
<td>...</td>
<td>804</td>
<td>399</td>
</tr>
</tbody>
</table>

a. Limiting sensitivities for point sources are given as total fluxes (in nJy) for 3 $\sigma$ detections in the central (brightest) pixel in 5 HST orbits, where each orbit is split into 3 independent exposures of 1,000 s each (for a total of 15 exposures). The point source is assumed to be centered on a pixel.

### Table 3: NICMOS Sensitivity for Extended Sources ($\mu$Jy arcsec$^{-2}$)

<table>
<thead>
<tr>
<th>Filter</th>
<th>NIC1a</th>
<th>NIC2a</th>
<th>NIC3a</th>
</tr>
</thead>
<tbody>
<tr>
<td>F110W</td>
<td>5.65</td>
<td>1.47</td>
<td>0.327</td>
</tr>
<tr>
<td>F160W</td>
<td>6.02</td>
<td>1.67</td>
<td>0.365</td>
</tr>
<tr>
<td>F222M</td>
<td>...</td>
<td>12.6</td>
<td>3.96</td>
</tr>
</tbody>
</table>

a. Limiting sensitivities for extended sources are given as surface brightnesses (in $\mu$Jy arcsec$^{-2}$) for 3 $\sigma$ detections in each pixel in 5 HST orbits, where each orbit is split into 3 independent exposures of 1,000 s each (for a total of 15 exposures).

### 3.4 A Brief Example of NICMOS High Sensitivity

Of the thousand gamma ray bursts that have been recorded so far, only a handful have been located accurately enough to enable images of the sources at optical wavelengths. The gamma ray burst 970228 was the first such source. The optical transient was imaged from ground-based observatories for up to a month after the burst. HST’s superior sensitivity allowed the optical transient to be detected up to 6 months after the event when it was detected with STIS at a V magnitude of ~28 (Fruchter et al. 1998a, astro ph/9801169). More importantly, HST was able to detect a low surface brightness galaxy coincident with the optical transient, presumably the host galaxy for this source. Observations from the ground have been unable to discriminate the optical transient from the 0.7”x0.7” host gal-
axy. Observations with NICMOS have been able to detect the host galaxy with S/N~10 and an estimated surface brightness of $22.5 \text{ mags arcsec}^{-2}$ at 1.6 $\mu$m in about 2.2 hours of total integration with NIC2 (Fruchter et al. 1998b, in prep.). The host galaxy for 970228 is thought to lie at redshift $z=0.8$, but others may be as far as $z=3$ or greater. For a galaxy at $z=3$ observations in the H band correspond to a rest wavelength in the B band, extending measurements of the spectral energy distribution into an important regime.

Table 4: NICMOS Camera 2 Sensitivity for Extended Sources ($\mu$Jy arcsec$^{-2}$)

<table>
<thead>
<tr>
<th>Filter</th>
<th>Expected</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>F110W</td>
<td>2.07</td>
<td>1.47</td>
</tr>
<tr>
<td>F160W</td>
<td>2.67</td>
<td>1.67</td>
</tr>
<tr>
<td>F222M</td>
<td>40.7</td>
<td>12.6</td>
</tr>
</tbody>
</table>

The expected sensitivities are derived from read noise and backgrounds that appeared in the NICMOS Instrument Handbook, Version 1.0, June 1996 and were used in the original version of the exposure time calculator used by cycle 7 proposers. Limiting sensitivities for extended sources are given as surface brightnesses (in $\mu$Jy arcsec$^{-2}$) for 3 $\sigma$ detections in each pixel in 5 HST orbits, where each orbit is split into 3 independent exposures (for a total of 15 exposures).

4. Photometric Performance

The absence of time dependent backgrounds makes infrared photometry from NICMOS highly stable. Photometry can be divided into two separate categories of activity, relative photometry and absolute photometry. Both require stable and well-understood backgrounds, darks, and flat fields. NICMOS darks are now well characterized (NICMOS ISR-97-026, by C.J. Skinner & E. Bergeron); ‘synthetic’ dark reference files are routinely used for calibration of NICMOS images and afford high accuracy in the dark subtraction (apart from the DC pedestal, see section 6.1). Flat-fields obtained with internal lamps have accuracies that are now around 2% peak-to-peak. Cross-correlation between internal lamps and Earth flat fields indicate global accuracies also around 2%; Earth flats, however, have revealed presence of low-level ‘fringing’ at the edges of the detectors with a peak-to-peak variation of ~3%; this effect is still under investigation.

Here we discuss the performance of aperture photometry with relatively large (>3-4 pixels) apertures. The special cases of photometry in crowded fields or photometry done with fitting of the point-spread-function (PSF) are not considered, although the next section on image quality is relevant to these methods, and comparatively high performance are obtained thanks to the NICMOS high dynamic range and PSF stability.

4.1 Absolute Photometry

NICMOS absolute calibration has been accomplished with a combination of a solar analog star (P330E), that has been well observed from the ground, and a white dwarf standard
star (G191-B2B), observed at optical wavelengths with WFPC2 and for which UV and optical spectra had been obtained with FOS. At present the limiting factor in the absolute photometric calibration is the ability to model the spectra of the white dwarf and solar analog standards. The uncertainty in determining absolute fluxes is estimated to be 5% based on the combined results from the two standards. The comparison between predicted and observed fluxes shows that the absolute throughput of NICMOS is within 10-20% of the pre-launch predictions. Table 5 reports the current values of the calibrations for the subset of filters closest to the ground-based J, H, and K bands.

### Table 5: NICMOS Photometric Calibrations

<table>
<thead>
<tr>
<th>Filter</th>
<th>NIC1 PHOTFNU(^a) (Jy sec ADU(^{-1}))</th>
<th>ZP(Vega)(^b) (Jy)</th>
<th>NIC2 PHOTFNU(^a) (Jy sec ADU(^{-1}))</th>
<th>ZP(Vega)(^b) (Jy)</th>
<th>NIC3 PHOTFNU(^a) (Jy sec ADU(^{-1}))</th>
<th>ZP(Vega)(^b) (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F110W</td>
<td>2.24 E-6</td>
<td>1897</td>
<td>1.82 E-6</td>
<td>1898</td>
<td>2.58 E-6</td>
<td>1904</td>
</tr>
<tr>
<td>F160W</td>
<td>2.39 E-6</td>
<td>1112</td>
<td>2.07 E-6</td>
<td>1113</td>
<td>2.83 E-6</td>
<td>1111</td>
</tr>
<tr>
<td>F222M</td>
<td>...</td>
<td>...</td>
<td>5.28 E-6</td>
<td>653</td>
<td>5.44 E-6</td>
<td>653</td>
</tr>
</tbody>
</table>

\(a\) Conversion factor from ADU/sec to Jy  
\(b\) Zeropoints for magnitudes based on the Vega system; it is assumed that Vega has magnitude equal to 0.02 in all NICMOS bandpasses, as per the calibration of Campins et al. (1985, AJ, 90, 896)

### 4.2 Relative Photometry

Relative photometry refers to the ability to obtain consistent and repeatable results when observing the same object at different locations on the detector. Measurements obtained as part of photometric calibration programs show that differential photometry can be obtained with an accuracy of ~1-2% across each camera’s FOV, for NIC1 and NIC2, and for the red filters (>1.6 μm) of NIC3.

Since the NIC3 PSF is heavily undersampled especially in the bluest filters and because of intrapixel sensitivity variations in the NICMOS detectors, the accuracy of the relative photometry is much lower than 2% below 1.6 μm in NIC3. On-orbit data obtained in the F110W filter give variations in the relative photometry with a r.m.s. of ~11% across the NIC3 FOV.

### 4.3 Temporal Stability of Photometry

The photometric performance of an instrument can change over time due, for instance, to the degradation of filter throughput or quantum efficiency of the detector. NICMOS has been and is being monitored to assess the temporal stability of its photometry, which has been found constant within 1-2%. An example of the photometric stability of NICMOS is given in Figure 2.
Figure 2: The temporal stability of the NICMOS photometry is shown for NIC2 and the filter F160W. The photometry appears stable within ~1-2%. The aperture used for the photometry is 0.5”.

4.4 Linearity and Dynamic Range

Infrared detector arrays differ from charge coupled devices (CCD) used at optical wavelengths in that each pixel is read out independently. Effects common in CCDs such as bleeding of charge to adjacent pixels and along rows in the readout direction do not occur in NICMOS. The NICMOS detectors remain linear to within 2% up to a limit of approximately 160,000 electrons in NIC1 and NIC2 and 200,000 electrons in NIC3. NICMOS does not have any count rate restrictions. When these characteristics are combined with the excellent image quality of HST (i.e. diffraction limited and stable PSF with very high Strehl ratios, see next section and Table 7) the result is to enable observations of very high dynamic range over the entire NICMOS field of view.

5. Angular Resolution and Image Quality

NICMOS delivers diffraction-limited imaging at all wavelengths, and provides full Nyquist sampling down to 1 μm and ~1.7 μm in NIC1 and NIC2, respectively (see Table 1 and Figures 3 and 4). Table 6 lists the radii encircling 85% of the PSF energy for the two Cameras at representative wavelengths.

NIC3 was designed to have a large field of view at the price of having larger pixels and not taking full advantage of the diffraction-limited capabilities of HST, although good resolution can be recovered through dithering in sub-pixel steps. The typical FWHM of NIC3 images (both in and out of focus) is ~1.3 pixels, with small variations between different
wavelengths (NICMOS ISR-98-006, A.D. Storrs); the percent flux within the first PSF minimum goes from 43% in J to 49% in H to 58% in K with NIC3 in focus. Each of the three cameras can be brought into focus using internal adjustments of the pupil adjustment mechanism (PAM), and additional motion of the HST secondary mirror for NIC3. Measurements of encircled energy and point-spread-functions show that the performance goal of images with total wavefront error of $\lambda/14$ or better is being met by all three cameras (except at J in NIC3, where the wavefront error is $\lambda/10$).

**Table 6: NIC1 and NIC2 85% Encircled Energy Radii (in pixels)**

<table>
<thead>
<tr>
<th>Filter</th>
<th>NIC1</th>
<th>NIC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>F110W</td>
<td>6.5</td>
<td>3.5</td>
</tr>
<tr>
<td>F160W</td>
<td>9.0</td>
<td>4.8</td>
</tr>
<tr>
<td>F222M</td>
<td>...</td>
<td>6.0</td>
</tr>
</tbody>
</table>

The high image quality of NICMOS is demonstrated by the Strehl ratio of the PSF, namely by the ratio of the observed-to-perfect PSF peak fluxes. This ratio is between 0.8 and 0.9 for NICMOS images, at all wavelengths and in all Cameras. Representative values are shown in Table 7, where the peak flux of the “perfect PSF” has been derived from Tiny Tim (courtesy of John Krist, STScI).

**Table 7: NICMOS Strehl Ratios**

<table>
<thead>
<tr>
<th>Filter</th>
<th>NIC1</th>
<th>NIC2</th>
<th>NIC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>F110W</td>
<td>0.91</td>
<td>0.89</td>
<td>0.81</td>
</tr>
<tr>
<td>F160W</td>
<td>...</td>
<td>0.90</td>
<td>0.86</td>
</tr>
<tr>
<td>F222M</td>
<td>...</td>
<td>0.90</td>
<td>0.92</td>
</tr>
</tbody>
</table>

The focus and the PSF have a small spatial dependence across each detector’s FOV. By one stringent measure, the energy contained within a 2 pixel radius, a measure relevant to photometric measurements in crowded fields, these spatial variations in image quality can produce differences of as much as 6% in the encircled energy. In larger apertures variations fall to the 1-2% level.

The telescope’s “breathing” results in changes in focus equivalent to approximately +/- 1 mm motions of the NICMOS PAM mirror. Deviations from optimal focus of this size do not significantly degrade NICMOS images. In order to minimize the potential effects of telescope breathing, the nominal PAM positions for both NIC1 and NIC2 have been optimized to be as close as is practical to optimal focus.

All three cameras have some partial obscuration or vignetting in their fields of view. In NIC1 and NIC2 the vignetting is caused by a slight misalignment of the cameras and the cold mask on an internal mirror called the Field Divider Assembly. In both cameras, the
vignetted portion of the detector is limited to approximately 15 of 256 rows at the lower edge of the field. NIC3 has a similar vignetting from the cold mask as NIC1 and NIC2, but also has a significantly larger portion of the detector (approximately 25% of the detector) vignetted by a warm baffle which produces elevated thermal backgrounds and degraded image quality. To eliminate this deleterious vignetting, observations with NIC3 are now done with the field offset mirror (FOM) moved to produce a +16 arcsec translation of the field of view. This has eliminated the warm vignetting and associated image degradation. Moving the FOM has introduced some additional astigmatism which can be measured by phase retrievals, although at 16 arcsec of offset, the astigmatism remains below the $\lambda/14$ criterion for image quality (except at J).

6. Anomalies

Although NICMOS has delivered all the basic capabilities as expected, there have been shortcomings in some special cases and/or situations. They are listed here, together with the implemented workaround, when appropriate.

Updates on the anomalies are in the NICMOS WWW page:


6.1 Dark Current Pedestal

The Dark Current Pedestal appears in almost all NICMOS exposures and is a random, quadrant-dependent, additive signal, with typical amplitude 3-10 ADU (and observed maxima of ~30 ADU). The DC pedestal is roughly uniform across each quadrant and is equivalent to an “excess bias” which appears when the detector has not been observing for some time previous to the current exposure. The larger the “idle” period previous to the observation, the larger the observed Pedestal; the Pedestal decays in many minutes (up to ~30 minutes). Being an additive signal, the most noticeable effect of the pedestal is to leave flatfield residuals in the calibrated images; in other words, the pedestal is a uniform offset without any flatfield variations, and so the flatfield correction during calibration will impose an inverted flatfield response pattern in the final calibrated image.

The DC Pedestal currently measured is much lower than what observed immediately after launch, thanks to a Flight Software modification implemented on August 21st, 1997. Before the modification, the typical pedestal amplitude was around 40-50 ADU, versus the 3-10 ADU measured after the fix. The Flight Software change consisted in keeping the NICMOS amplifiers on at all times (except during passages into the South Atlantic Anomaly). Before the change, the amplifiers were switched on only at the beginning of an observation, otherwise were typically kept turned off.

Because of its random nature, the pedestal cannot be removed as part of the standard calibration pipeline processing. However, being a constant signal in each quadrant, careful
Figure 3: A NIC1 stellar image (left) with the PSF profile (right) taken in the F165M filter. The expected features of fully diffraction limited images can be clearly seen from the image.

Figure 4: Figure from the focus sweeps showing two stars separated by 0.24 arcsec in NIC2 with the F110W filter (indicated by the arrows).

data reduction aimed at pedestal subtraction with observation-dependent procedures entirely removes the problem. In the case of sparsely populated fields, an iterative procedure which minimizes the fluctuations of the flat-field residuals can be successfully implemented. For extended sources (when the detector FOV is completely filled with the astronomical object), removal techniques are more complicated, as modelling of the light profile of the source is required. In summary, appropriate data reduction techniques can
remove completely the DC pedestal, leaving little or no residual on the final calibrated image.

6.2 Cosmic Ray Persistence from the South Atlantic Anomaly

The SAA is a lower extension of the Van Allen radiation belts, energetic particles trapped in the Earth’s magnetic field. HST has a relatively low orbit (~600 km) and an orbital period of about 96 minutes. The precession of the HST orbit around the Earth implies that the telescope traverses the SAA for ~6-7 consecutive orbits out of the 15 orbits in a day. An SAA passage is generally rather short in duration, about 20-30 minutes. During this period no science observations are performed, as NICMOS is flooded with high energy particles. In addition, because of the sensitivity of NICMOS electronics to particle hits, the detectors are turned off during SAA passages.

Observations taken immediately after passages into the SAA are affected by persistent cosmic rays, which manifest themselves as “CR-noise”, i.e. as granularity from CR hits which increases the global noise level. This noise is non-gaussian, namely a skewed background distribution with a long tail towards positive values. The added noise component decays with a timescale of ~20-30 minutes, and can produce a factor 2-3 increase in the nominal noise level of the detector.

Given the amplitude of the effect, only long exposures (faint target observations) are affected. Thus the workaround for this problem is to schedule bright target observations after the SAA passages and schedule faint targets away from the SAA.

6.3 Operations Inside the South Atlantic Anomaly

In the first few days of the on-orbit NICMOS operations, a susceptibility of the electronics to radiation hits during passages in the deepest parts of the SAA was reported. Sporadic shut-offs of the detectors happened while inside the most cosmic-ray active regions of the SAA. The opto-isolators in the electronic circuit were identified as the culprit. The opto-isolators are optical switches inserted in the circuit to lower the electronic noise of the system. In regions where the cosmic ray density is comparatively high the opto-isolators can be spuriously activated. The change of status causes the system to send a turn off signal to the detectors if they were previously on. Although there were no health and safety issues for NICMOS, these events were likely to produce a loss of operational efficiency. Thus the problem was solved within the two months of NICMOS on-orbit life by introducing a ‘SAA-OPER’ mode in the flight software. The ‘SAA-OPER’ mode turns off the NICMOS detectors while HST is inside the most active parts of the SAA. This operational mode is totally invisible to users, since no scientific data have ever been taken with any of the HST instruments during SAA passages, due to the excessively high rate of cosmic rays.
6.4 Cross-Camera Inductance
When only one of the three NICMOS cameras is used for a particular observation, the interference between the clocking of the used Camera with the autoflush of the unused Cameras produces “electronic bars” in the images. The “bars” resemble bad columns, with the difference that their position changes from one read-out to the next, and are electronic in nature. The amplitude of this effect is very small, ~2 ADU, and is completely removed when all three Cameras are used (e.g., by taking parallel exposures in the cameras which are not used for the primary science).

6.5 The Bright Object Mode
NICMOS was advertised to the astronomical community as being capable of three readout modes: MULTIACCUM, ACCUM, BRIGHTOBJ, each of them targeted to specific situations. MULTIACCUM and ACCUM are actually interchangeable, and the larger amount of information provided by MULTIACCUM has made the latter the mode of choice for most observations.

BRIGHTOBJ mode was designed for observations of bright targets. With this mode, each pixel of the array is reset and read individually before moving to the next pixel. This allows very short short exposure times, circumventing the minimum time allowed by other readout modes. The standard ACCUM or MULTIACCUM operations, for which the entire array is reset and then read, have a minimum exposure time of 0.203 sec, set by the read-out speed. Unfortunately, tests have shown that BRIGHTOBJ mode behaves in a strongly non-linear manner, hampering any reasonable attempt at calibration. This behavior is likely a form of detector persistence.

BRIGHTOBJ mode may still be useable for limited purposes of identifying the location of very bright point sources or for strictly morphological studies. Studies of bright extended objects (e.g. Jupiter) have been possible without using BRIGHTOBJ mode by careful selection of filters. Indeed, an assessment of the science impact due to the non availability of this mode has shown that all astronomical targets are observable with the more general MULTIACCUM readout mode.

6.6 Multiple Initial and Final Reads
When NICMOS was initially advertised, one promised capability was the possibility of reducing the read-out noise (which is significant for faint targets, see Table 1) by using multiple initial and final readouts. This capability was clearly important for faint target observations. Multiple initial and final read-outs are a unique capability of infrared detectors, where the reading of the detector is performed in a non-destuctive manner, and N reads potentially reduce the read-out noise by sqrt(N).

This capability has been proven not to be effective at the expected level on NICMOS, as other contributors to the effective noise of the detectors (e.g., amplifier glow) have almost
erased the advantages of the read-noise reduction. However, the multiple readout information provided by MULTIACCUM still produces some readout noise reduction relative to a single ACCUM with NREAD=1; the reduction factor is around 20-30% in some cases, namely from 30 e− to 20 e−. In addition, a single ACCUM with NREAD=25 shows a reduction in read-noise as high as ~40-50% relative to an ACCUM with NREAD=1.

7. Acknowledgements

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