Characterisation of NICMOS array flat-field response.

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ABSTRACT
This ISR describes the likely flat-field performance of the NICMOS array detectors. A series of tests of one of the flight spare arrays are described, and then the results of these are presented, along with some initial analysis.

1. Introduction
Initial characterisations of the flight arrays for NICMOS indicated that there are substantial variations in flat-field response across the arrays which may involve a significant colour term. Unfortunately, these initial results only encompassed two measurements per array, through broadband J and K filters. Thus to determine the flat-field response for any other wavelength it was necessary to interpolate or extrapolate, rendering estimates of the colour sensitivity of the flat-field response highly uncertain.

A set of multi-wavelength flat-field response measurements were therefore required. By this stage, unfortunately, the flight arrays had been installed into the NICMOS dewar in preparation for the System Level Thermal Vacuum Testing. Therefore we have made a series of new measurements of the flat-field response at many wavelengths, using one of the flight spare arrays. The complete flat-field characterization of the flight arrays is expected to be performed during the 1996 SLTV testing.

The remainder of this ISR describes the tests made, and their results. It must be borne in mind that the results do not define the flat-field response of the NICMOS arrays: they should be treated only as a characterisation of the response, which can be used to establish policy and advice for the GO in the Cycle 7 NICMOS Handbook, and to assist with software development. Better data should become available following SLTV. When the data on the flight arrays is fully reduced and analysed we shall make the results available to NICMOS users through updates to the Instrument Handbook and via the World Wide Web pages for NICMOS.
2. Flat-field response tests.

The tests were carried out at the Steward Observatory during the period August-28 to September-12 1995.

**Table 1. Log of Observations**

<table>
<thead>
<tr>
<th>Filter</th>
<th>Observe date</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8μm</td>
<td>Sep-02-95</td>
</tr>
<tr>
<td>0.9μm</td>
<td>Aug-28-95, Sep-08-95</td>
</tr>
<tr>
<td>1.1μm</td>
<td>Sep-03-95</td>
</tr>
<tr>
<td>1.2μm</td>
<td>Aug-28-95, Sep-08-95</td>
</tr>
<tr>
<td>1.3μm</td>
<td>Sep-02-95</td>
</tr>
<tr>
<td>1.4μm</td>
<td>Sep-02-95</td>
</tr>
<tr>
<td>1.5μm</td>
<td>Aug-28-95, Sep-08-95</td>
</tr>
<tr>
<td>1.6μm</td>
<td>Sep-03-95</td>
</tr>
<tr>
<td>1.7μm</td>
<td>Sep-04-95</td>
</tr>
<tr>
<td>1.8μm</td>
<td>Aug-29-95, Sep-09-95</td>
</tr>
<tr>
<td>1.9μm</td>
<td>Sep-04-95</td>
</tr>
<tr>
<td>2.0μm</td>
<td>Sep-04-95</td>
</tr>
<tr>
<td>2.1μm</td>
<td>Aug-29-95, Sep-01-95</td>
</tr>
<tr>
<td>2.2μm</td>
<td>Sep-01-95</td>
</tr>
<tr>
<td>2.3μm</td>
<td>Sep-01-95, Sep-12-95</td>
</tr>
<tr>
<td>2.4μm</td>
<td>Sep-01-95, Sep-12-95</td>
</tr>
<tr>
<td>2.5μm</td>
<td>Aug-29-95, Sep-09-95</td>
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<tr>
<td>J</td>
<td>Aug-31-95, Sep-07-95</td>
</tr>
<tr>
<td>H</td>
<td>Aug-31-95, Sep-07-95</td>
</tr>
<tr>
<td>K</td>
<td>Aug-31-95, Sep-07-95</td>
</tr>
<tr>
<td>2.415μm</td>
<td>Sep-12-95</td>
</tr>
</tbody>
</table>

Flat-field response measurements were made using a large variety of filters. Three ‘standard’ broad-band J, H, and K filters were used. Additionally a set of 10% bandwidth filters were used, with central wavelengths spaced every 0.1μm from 0.8μm to 2.5μm, the full spectral bandpass of NICMOS. Finally, one narrow bandwidth filter, with approximately 2% bandwidth and a central wavelength of about 2.415μm, was tested. Many of the filters were tested on two dates, allowing the consistency of results to be checked.

The filters were installed in a standard IR Labs dual reservoir dewar, the outer tank con-
taining LN2 and the inner solid N2 at 58K. Three filters could be mounted in the dewar at any one time, in a sliding mount with detents. The dewar contains simple camera optics for imaging a small field close to the entrance window. The dewar was mounted in a dark tent. A white painted wall at the far end of the dark tent was illuminated with a flashlight to provide the flat-field source. A square pupil was employed to define the input beam. A simple procedure was followed to obtain the images. The dewar was moved to align it with the pupil (by using the edges of the pupil, which was in focus). With the aid of alignment marks on the far wall, a plane mirror external to the dewar was used to adjust the beam such that the illuminated far wall defined a plane orthogonal to the dewar optical axis. The flash-light was adjusted so that images yielded a signal in each pixel which would provide a large S/N, but small enough to be in the linear portion of the detector’s sensitivity curve. Flat-field images were then taken, typically ten images for each of the three filters in the dewar. The flash-light was switched off, and another ten images taken through each image, in order to remove any background radiation.

Whether or not any of the 10% bandpass filters had any red or blue leaks under cryogenic conditions had not been established. Therefore some tests were carried out, installing three 10% bandwidth filters in the dewar, and placing another 10% bandwidth filter, with a different central wavelength, at the pupil position. With no overlap between the bandpasses of the filters internal and external to the dewar, this test should result in zero signal. However, in the event that a filter leak coincided with the bandpass of the external filter, a positive signal with the characteristic flat-field response pattern should be observed.

Previous flat-field data obtained using these techniques had yielded fairly large global variations in response, generating some concern over the uniformity of the illumination (is the ‘flat-field’ really ‘flat’?), and whether any other elements in the optics might generate some fraction of the perceived variation in response. A number of tests were made to address these concerns. Firstly, the flashlight was moved laterally, and then defocussed, to investigate the sensitivity to variations in the illumination source itself. Secondly, the filter slide in the dewar was shifted in either direction, to look for any filter transmission effects. Finally, results of these tests were compared with results of similar tests carried out in mid-June 1995, as an independent test of long-term repeatability.

### 3. Results

**General Character**

Figure 1 shows the measured flat-field response at a number of wavelengths. There are global variations in response much as determined in the earlier tests, with a change of almost a factor of four between the most and least efficient regions, if we consider a region as being the mean of a 10x10 group of pixels. Between the most and least sensitive individual pixels in the array (disregarding ‘bad’ or dead pixels) there is a variation in
response by a factor of almost eight at the shortest wavelengths. The flight arrays exhibited very similar variations in the earlier tests using only broad J and K filters. In order to assess the amplitude of pixel-to-pixel variations in response, we generated a version of the flat-field response smoothed by a 4x4 pixel kernel, then divided the original flat-field response image by this. The result is displayed in several ways in Figure 2, for a wavelength of 1.5\(\mu m\), and is seen to be essentially random and uniform across the array, with an amplitude (1\(\sigma\)) of about 8%. The pixel-to-pixel variations do not appear to get systematically smaller where the global response is worse.

At 0.8\(\mu m\), the most sensitive areas on the array are a little more than twice as sensitive as the mean, and the least sensitive areas a little less than half as sensitive. Thus there is a variation by a factor of about five in the relative response across the array, ignoring any pixel-to-pixel variations. This declines to about a factor of three at a wavelength of 2.2\(\mu m\), and at 2.5\(\mu m\) the array is almost flat. All of the above results are more or less consistent with the values estimated for the flight arrays from J and K broadband flat-field response measurements.

### Wavelength Variation

An indication of the variation with wavelength of the flat-field response has already been given above. From Figure 1 it can be seen that the variations are greatest at 0.8\(\mu m\), at 1.5\(\mu m\) they are smaller, at 2.1\(\mu m\) they are similar to the variations at 1.5\(\mu m\), and at 2.5\(\mu m\) the array is almost flat. This would seem to indicate that while there is some steady change in the flat-field response between, say, 1.0\(\mu m\) and 2.1\(\mu m\), between 2.1\(\mu m\) and 2.5\(\mu m\) there is a drastic change in behaviour. There also may be significant changes at the short wavelength end of the NICMOS waveband.

To characterise this, we have generated spectra of the relative response of individual pixels, and these are displayed in Figure 3. To do this we have selected four groups of three pixels. Each group of three consisted of adjacent pixels, either in a line or in an ‘L’ shape. Two of the groups were in areas which were clearly of relatively high sensitivity, and the other two in areas of relatively low sensitivity. The sensitivity of the pixel relative to the mean for the array at that wavelength is plotted against wavelength, using all of our 10% bandwidth measurements. It is very important to note that this does not give any information on the Quantum Efficiency (QE) as a function of wavelength - only on the relative QE of the pixel compared to the mean for the array. The results clearly show that for many pixels, at wavelengths between 1.0\(\mu m\) and 2.2\(\mu m\) the variation in response changes fairly slowly, but that at a wavelength around 2.2-2.3\(\mu m\) there is a turnover, past which the change with wavelength is dramatic. It is at once evident that in the earlier broadband J and K measurements, the largest part of the variation in response between the two wavelengths arose inside the bandpass of the K filter. This is not to say that there are no significant colour terms at wavelengths shorter than 2.2\(\mu m\) - the data do show that there
are also variations at intermediate wavelengths, but they are smaller than we might have
expected based on the J and K band data alone, and we will quantify the likely effects of
these in a subsequent ISR. Also, there is a suggestion that the flat-field response may also
change quite rapidly shortwards of 1.0\(\mu\)m, though this appears less extreme than the
changes in behaviour at long wavelengths.

It is difficult to define a single number which adequately quantifies the behaviour of the
flat-field response over the entire array. The standard deviation of the individual pixel
responses from the mean is sometimes used for this, but does not really convey the nature
of the array well. For example, at 0.8\(\mu\)m the array we tested has a standard deviation in its
response of 34\%, which does not convey well the fact that there is a variation of a factor of
five between the least and most sensitive regions. However, the standard deviation can be
used to display the general manner in which the flat-field response varies with wavelength.
In Figure 4, we plot the standard deviation of the smoothed flat-field response as a func-
tion of wavelength, and we see the same behaviour as demonstrated by the individual
pixels in Figure 3. The dramatic change in the 2.2-2.5\(\mu\)m region is shown very convinc-
ingly, and it is also clear that there is some steepening at the short wavelength end, mainly
shortwards of 1.1\(\mu\)m.

We have also investigated how the pixel-to-pixel noise varies with wavelength. We find
that it tends to vary with wavelength in just the same way as the global flat-field response
variations do. At 0.8\(\mu\)m the standard deviation of the pixel-to-pixel noise component is
about 11\%, at 1.5\(\mu\)m it is about 7\%, at 2.1\(\mu\)m 6\% and at 2.5\(\mu\)m it is less than the uncer-
tainties on our measurements (see later). This behaviour is also displayed in Figure 4,
where we see that the variation with wavelength of the high frequency (HF), or pixel-to-
pixel, response variations follows very closely the behaviour of the global flat-field
response. This provides confidence that the measured HF flat-field response variations are
not just measurement error, but really do reflect the nature of the array.

**Out-of-band Leaks**

To within the accuracy of our measurements, we were unable to detect any red or blue
leaks in any of the filters we tested. Therefore the effects of any possible leaks on any of
the measurements we report here must be negligible. We should emphasize, however, that
the filters used in these tests are *not* the same as the ones which will be flown aboard NIC-
MOS. These tests were carried out solely to check the validity of the other tests reported
here, and do not reflect in any way on the NICMOS filters.
Figure 1: flat-field response images obtained through 10% bandwidth filters centered on wavelengths of (a) 0.8µm, (b) 1.5µm, (c) 2.1µm and (d) 2.5µm. The images have been normalised to the mean response for each wavelength. The contours and grey-scales are linearly spaced in each image between normalised responses of 0.4 and 2.2. Significant areas of the array span this whole range at 0.8µm, while at 2.5µm the array is almost flat.
Figure 2: high spatial frequency noise measured at 1.5µm. This was measured by dividing the image in Figure 1(b) by a smoothed version of itself (see text). The greyscale version in (a) is scaled between 0.9 and 1.1 (defined as in Figure 1). Slices through the image are plotted in (b) along row 100 and in (c) along column 100. The distribution of data is plotted as a histogram in (d).
**Figure 3**: relative response as a function of wavelength of a number of pixels. These diagrams basically show the response of a given pixel relative to the mean for the array at each wavelength, for groups of pixels in relatively insensitive (top) and sensitive (bottom) areas. These figures show that the response flattens rapidly longwards of 2.2μm.
Reproducibility

To investigate how much errors in positioning of the filter slide might be affecting the results, images were taken with the filter slide deliberately moved a few mm either side of the detents into which the slide is intended to click. These reflect about the largest positioning errors that could have occurred. The results of these images were divided by images taken with the filter slide correctly positioned, and the results were very smooth gradients across the images, with standard deviations of 2.7%. This result indicates that

Figure 4: the amplitude of the flat-field response variations as a function of wavelength. The solid line shows the global flat-field response, defined as the standard deviation of the individual pixel responses, while the dashed line shows the pixel-to-pixel variations. The two follow the same behaviour very closely.
errors in the position of the filter slide generate a readily visible effect, which probably reflects some small amount of vignetting of the beam. Since the effect was limited to very smooth gradients, and no spatial structure was generated, it is clear that the filters are not themselves generating any of the spatial structure we see in the flat-field response.

Moving the flashlight beam around and dividing the resulting images by one another revealed that the technique for locating the flashlight beam is also sufficiently accurate, once again generating gradients in response with a standard deviation of about 1.5%. Defocussing the flashlight beam generated gradients with a standard deviation of about 1.4%.

Finally, after these tests the entire optical set-up was returned to the standard conditions, and further flat-fields images taken. Dividing these by images taken before the various reproducibility tests discussed above generated images comprising random noise with a standard deviation of 1.2%.

Combining all the above sources of error, we estimate that the likely uncertainties of the flat-field response measurements are about 4%. As a final test, measurements of the same array which had been made during June 1995 were compared with the measurements reported here, giving an indication of the long-term repeatability. The standard deviations for the J and K filter measurements obtained in this way were 3.6% and 4.6%, confirming that the uncertainties in these measurements are likely to be of order 4%. These error estimates are summarised in Table 2.

**Table 2. Uncertainties in flat-field response measurements**

<table>
<thead>
<tr>
<th>Source of error</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter slide position</td>
<td>2.7%</td>
</tr>
<tr>
<td>Flashlight beam position</td>
<td>1.5%</td>
</tr>
<tr>
<td>Flashlight beam focus</td>
<td>1.4%</td>
</tr>
<tr>
<td>Combined short term repeatability</td>
<td>~4%</td>
</tr>
<tr>
<td>Measured long term repeatability</td>
<td>~4%</td>
</tr>
</tbody>
</table>

An example of the accuracy of the measurements is displayed in Figure 5. Here we show the ratio of two flat-field response measurements, at a wavelength of 1.8\(\mu\)m, made about three days apart. The greyscale shows that there is some structure in the image, but this does not correlate with any structure in the measured flat-field response. The histogram of the data (Figure 5b) shows that the FWHM of the distribution is at about the 3% level, which provides a reasonable estimate of the uncertainties of our measurements. Only a few percent of the pixels show differences of more than 5%.
Long Wavelength Behaviour

The rather dramatic change in the flat-field response at long wavelength deserves some mention, since it seems likely that this may have some impact on observations made using the longer wavelength NICMOS filters. A number of comparisons of data in this wavelength region can be made. First we have tried comparing the K band flat-field response with the 10% bandwidth 2.2 µm flat-field response: the results are shown in Figure 6. It can be seen that the two flat-field images differ by almost 10%, which emphasises how rapidly the response is changing inside the K bandpass. We also tried comparing the flat-field response images obtained through the 10% bandpass 2.4 µm and the narrow-band 2.415 µm filters. In this case the two images were very similar, only differing by a few percent, close to the uncertainties in the data. This probably reflects the fact that the change in flat-field response between 2.3 µm and 2.5 µm is more or less linear, and the narrow-band filter lies almost at the center of the 10% bandwidth filter’s bandpass. Finally, we have used the long wavelength 10% bandpass flat-field response images to construct a simulated K band flat-field response file. Comparing this with our measured K band response image, we find that the two differ by roughly 4%, which is our estimate of the

Figure 5: an illustration of the repeatability of the measurements. This is the ratio of two 1.8 µm flat-field response measurements made a few days apart, shown in greyscale (a) and as a histogram (b). The differences are seen to be generally better than 3%, and in almost all pixels better than 5%.
measurement uncertainties. Only a few percent of the pixels differ by more than about 6%, thus giving us confidence in the measurements and the analysis we have presented here. Finally, we repeat that there is also some fairly rapid change in response at the shortest wavelengths, but as mentioned before the changes in this region are much less extreme than those exhibited at long wavelengths, and so we do not discuss them any further here.

4. Conclusions

We have presented a large variety of measurements of the flat-field response as a function of wavelength of the principal NICMOS flight spare array. The results indicate that

- the flat-field response variations are large and wavelength dependent.
- The difference in response between the most and least sensitive areas is almost a factor of 5 at the shortest wavelengths, and only a factor of about 1.1 at the longest wavelengths.
- The variation with wavelength is not linear, the largest variations occurring in small wavebands shortwards of 1.1µm and longwards of 2.2µm. The variations in response longwards of about 2.2µm are much more extreme than those shortwards of 1.1µm.
The arrays also exhibit wavelength dependent pixel-to-pixel response variations, ranging from an amplitude of order 10% at the shorter wavelengths to less than our measurement uncertainties at the longest wavelengths. The variation with wavelength of the pixel-to-pixel response variations is almost identical to the behaviour of the global flat-field response variations.

The combination of the size of these flat-field response variations and their wavelength dependence suggests that they will probably have an effect on the accuracy of single wavelength photometry using NICMOS in at least some filters. However, since the greatest wavelength variations occur at either end of the NICMOS operating waveband, it is likely that the most frequently used filters, which will probably be those whose passbands lie in the region where the flat-field response is not changing very rapidly, will not be seriously affected. We will quantify these effects in a subsequent ISR.

**Figure 6:** comparison of the measured flat-field responses through K band and 2.2\(\mu\)m 10% bandwidth filters. The structure which is evident in the ratio image (a) is well correlated with the structure in the flat-field response images, and the two images are seen to differ by almost 10% in the histogram (b).