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FPA#64 and new substrate removed FPAs for WFC3-IR: a trade-off study

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Abstract

Recent tests indicate that the flight detectors selected for WFC3-IR may be subject to higher than expected background due to radiation effects. In this document I compare the performance of the FWC IR channel assuming FPA#64 with higher background versus the new substrate removed detectors currently under development at Rockwell Science Center. I also use as current benchmark the performance of NICMOS in the F110W, F160W and F126N filters, and of ACS in the F850LP filter. The analysis is based on the model and metrics (speed and discovery efficiency) of Stiavelli and Robberto (2003), with a newly introduced efficiency factor, the ultra-deep sensitivity, that represents the limiting magnitude reached in a HUDF-like project. The main results are: 1) the worst case scenario of high extra background (~1e/s/pix) on FPA#64 has a major impact on the sensitivity of WFC3-IR; 2) the factor of ~2 improvement in quantum efficiency at short wavelengths provided by the substrate removed parts offers a substantial increase of sensitivity in the F110W filter; 3) also with substrate removal, a rather pessimistic increase of readout noise up to ~40e for correlated double sampling does not significantly affect the sensitivity of deep surveys performed in broad band filters; 4) WFC3 with substrate removed detector in the F098M band is approximately 2 times more efficient than ACS in F850LP for deep imaging, a gain that comes at the price of coarser sampling (130mas/pixel vs. 50mas/pixel).

1. Introduction

After the selection of the flight candidates detectors for WFC3-IR (FPA#64 as prime and FPA59 as backup) and in parallel with the integration and system level tests carried out at Ball and at the Goddard Space Flight Center (GSFC), the WFC3 team has carried out further test activities aimed to fully characterize the performance of these devices in space environment.

In particular, the sensitivity of WFC3-IR devices to cosmic ray radiation has been evaluated in two runs at the UC Davies. A few FPAs similar to those selected for flight have been exposed to proton beams of different energy and fluency while they were operated in standard data acquisition mode

A most surprising result of these tests has been the appearance of an extra background that seems to be related to the passage of protons through the ZnCdTe detector substrate. It is estimated that in space environment the extra background may add between ~0.25 e/s/pixel and ~1 e/s/pixel of "dark" signal, leading to a serious degradation of the sensitivity of the instrument.

Following this discovery, contacts have resumed with Rockwell to find ways to mitigate the problem. Rockwell suggested that removing the entire ZnCdTe substrate should eliminate the problem. Substrate removal also offers the advantage of increasing the quantum efficiency in the J-band and pushing the blue cut-off of the detector down to 0.4μm.

The substrate removal operation has been attempted by RSC on two WFC3 detectors (FPA#94 and FPA#95) build in late 2004 from lots grown and processed during the previous development phases. The tests made at U.C. Davies on these parts have demonstrated that the extra background is virtually disappeared. Recent measures made at the GSFC confirm the expected increase of QE at shorter wavelengths (Fig.1), up to ~70% level.

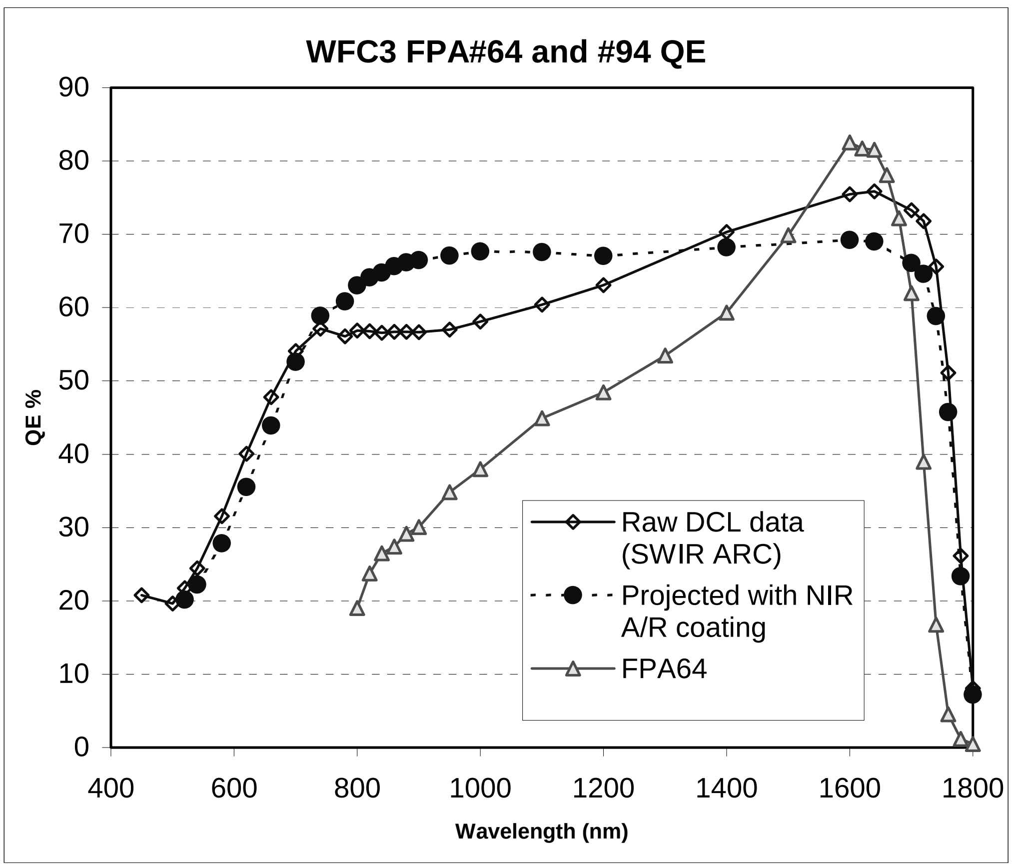

Figure 1: QE curve of the prototype substrate-removed FPA#94, measured at GSFC/DCL.

Following the success of these prototypes, two new lots of detectors have been commissioned to RSC. A lot will contains 8 wafers, each one providing up to 4 devices.

Whereas the baseline plan is to reproduce the FPA#64 recipe for the detector material and FPA#94 for the substrate removal process, small variations will be implemented in some wafers to explore different annealing, buffer and passivation strategies. These variations have the potential of improving somewhat the detector performance. In-situ passivation, in particular, may substantially reduce the readout noise, as demonstrated in the previous lot 7B, when a readout noise of ~16e DCS was reached. Unfortunately, the quantum efficiency showed in the same parts a dramatic drop to a few percent level, making them unsuitable for flight. Now, the combination of substrate removal and in-situ passivation could provide both low readout noise and high QE. On the other hand, one has to remember that FPA#64 represents the best detector produced so far, with excellent stability and relatively low readout noise (~25 e per double correlate read). There is no guarantee that low values of readout noise will be reached again in the new devices.
There is therefore a range of production strategies that may lead to vastly different detector performance. Decisions on the growth and processing of detector material will need to be taken soon, balancing the benefits in performance, the risks and the schedule constrains.
To support this process, I compare in this document the performance attained by WFC3 with the current detectors and with various types of substrate removed parts. I will refer in particular to a limited but representative number of cases:

1) FPA#64 and WFC3 as-built This is the reference case assumed for all current estimates of the WFC3 IR sensitivity.
2) FPA#64 with an extra background of 1 e/s/pixel due to cosmic ray events. This represents the worse case scenario if WFC3 had to fly with the current flight devices.
3) FPA#64 with an extra background of 0.25 e/s/pixel due to cosmic ray events. This represents the most probable scenario if WFC3 had to fly with the current flight devices.
4) New FPA with substrate removed, providing high QE and RON equal to FPA#64
5) New FPA with substrate removed, with high QE but high RON (pessimistic case)
6) New FPA with substrate remove, with high QE and low RON (in-situ passivated, optimistic case)

I compare the WFC3 performance with two other instruments:

a) NIC-3 after the NCS (Nicmos Cooling System) installation, with the F110W, F160W and F126N filters, using the same parameters of Stiavelli & Robberto (2003, hereafter SR03).
b) ACS/WFC with the F850LP filter.

The parameters assumed for each individual model are detailed in the next section.

2. Input parameters

The input parameters for this study are in general the same used by SR03 to estimate the performance of the WFC3-IR channel with FPA#64. Referring hereafter to WFC3 "as built", I refer to the model based on the pre-thermal vacuum values for the instrumental throughput. Concerning the detectors I explore the following combinations:

1. FPA#64 baseline
2. FPA#64 with extra background, assumed to produce an effective dark current of:

2.1. DC = 1.0 e/s/pix
2.2. DC = 0.25 e/s/pix
3. New FPA with substrate removed (SR). I assume QE=0.7 constant between 0.8 and 1.7micron and readout noise equal to:
3.1. RON = 25.6 e/pix (same as FPA#64)
3.2. RON = 40 e/pix (high)
3.3. RON = 15 e/pix (low)

Following SR03, I will refer to a point source of m_{AB}=28 mag arcsec^{-2} corresponding to 22.91nJy (1nJy=31.4 ABmag) in both F110W and F160W, and m_{AB}=25 mag arcsec^{-2} (361.1nJy) in F126N. In the Vega system these values correspond to 27.2 mag arcsec^{-2} in F110W, 26.6 mag arcsec^{-2} in F160W and 24.2 mag arcsec^{-2} in F126N.
The point source is assumed to fall over 5.83, 8.20 and 6.53 pixels ("equivalent noise area") at F110W, F160W and F126N, respectively. The reciprocal of these values (0.172, 0.122, 0.153) is the PSF "sharpness" used by SR03.

The most natural performance comparison is the one against NIC3_NCS. However, the increase of QE with substrate removed detectors increases the scientific interest of another WFC3 filter, F098M, not originally considered by SR03. The idea here is to compare the performance of WFC3 with F098M with that of ACS with the F850LP filter, which covers a similar wavelength range. There are obvious differences in pixel size between ACS (50mas) and WFC3-IR (130MAS) and in field of view (11.65 square arcmin for ACS against 4.77 square arcmin for NIC3-IR). In this study I will neglect the difference in pixel size, following the same approach already taken by SR03 when WFC3-IR with NIC3 were compared regardless of the finer WFC3 sampling. For the F098M filter with WFC3, I assume again a point source with m_{AB}=28 mag arcsec^{-2} with an equivalent noise area of 5.26 pixels (sharpness = 0.19). I also assume a background flux of 0.0027photons/HSTarea/s/A/arcsec^2. The parameters for ACS with the F850LP filter are directly taken from the current Exposure Time Calculator with default parameter (in particular Gain=2 and CR-split=2). The only exception is the background flux which is estimated with minimum Earth shine and OH airglow contributions, in order to make it equal to the thermal-only background assumed for WFC3 and NIC-3, albeit slightly optimistic.
In the analysis of the Signal to Noise (SNR) ratio, I consider the standard sources of noise: 1) the detector readout noise; 2) the background signal, a combination of the instrumental thermal emission and detector dark current; 3) the sky background; 4) the source signal, typically negligible at the faintest flux levels. The relative weights of these contributions depend on the basic detector parameters. They are reported in Table 1 for the nominal case 1), i.e.WFC3 as-built with FPA#64, for our assumed AB magnitudes, per pixel and in 2400 sec of exposure time.

	RON	*DARK*	*SKY*	*SOURCE*
F110W	*15.600*	*17.901*	*34.023*	*8.287*
F160W	*15.600*	*27.704*	*26.081*	*6.867*
F126N	*15.600*	*18.267*	*6.349*	*5.815*

Table 1: noise contributions (standard deviation) in the standard case.

Table 1 shows that the F110W filter is dominated by the sky background noise, for the F160W filter the instrumental thermal background becomes also a major noise source, whereas in the F126N filter the sky background is negligible and the readout noise becomes important.

The other cases explore different parameter spaces. For example, if one assumes case 2.1 with FPA#64 under the pessimistic combination of high dark current at 1 e/s/pix, one obtains the values presented in Table 2:

	RON	*DARK*	*SKY*	*SOURCE*
F110W	*15.600*	*49.804*	*34.023*	*8.287*
F160W	*15.600*	*54.106*	*26.081*	*6.867*
F126N	*15.600*	*49.937*	*6.349*	*5.815*

Table 2: same as Table 1 for the case with Dark Current = 1 e/s/pix.

Here the dark current becomes the main limiting factor in all three filters, and in particular dominates over the sky background also in the F110W filter.
Vice-versa, in the optimist case 3.3 of Substrate Removed detector with low readout noise, the noise values are those presented in Table 3:

	RON	*DARK*	*SKY*	*SOURCE*
F110W	*9.642*	*19.349*	*43.976*	*10.711*
F160W	*9.642*	*27.704*	*26.081*	*6.867*
F126N	*9.642*	*19.349*	*7.604*	*6.964*

Table 2: same as Table 1 for the case with substrate Removed FPA and readout noise of 15 e/pixel (DCS).

In this case the increase of QE causes an increase of sky noise especially in the F110W filter, and marginally of the dark signal due to the increased efficiency in detecting the thermal background of the detector environment. Readout noise remains negligible also in the narrow band F126N filter.
Finally, for comparison, in Table 4 I give the noise contributions estimated with the current parameter of NIC3:

	RON	*DARK*	*SKY*	*SOURCE*
F110W	*20.271*	*17.483*	*45.922*	*7.769*
F160W	*20.172*	*26.193*	*29.394*	*6.405*
F126N	*20.271*	*16.513*	*7.657*	*5.157*

Table 4: same as Table 1 for NIC3 (with NCS).

In the next section I will examine how the variations of detector parameters affect the performance of WFC3-IR.

3. Results

The basic computation estimates the time needed to reach S/N=10 in each filter. This time can be expressed in seconds or in HST orbits, under the assumption that one orbit is 2400s long. When time is expressed in number of orbits, its inverse is called **Speed**.

Comparing WFC3 with NICMOS, the exposure time, or the speed, does not take into account the larger field of view of WFC3. A second figure of merit, the **Discovery Efficiency**, is therefore defined as the product of the speed times the field of view (FOW), in square arcminutes. Let me remind that it is FOW=4.772 for WFC3, FOW=0.728 for NIC-3 and FOW=11.65 for ACS.

I introduce here a third figure of merit, based on the HST experience on large programs like the UDF. Planning a UDF-type program, the typical questions are of this type: assuming one has 600 orbits of HST time, what is the limit magnitude one can reach spending e.g. 200 orbits in the F160W, F110W and F098M bands over the WFC3 field? Also, one may consider the goal of reaching the same AB magnitude in all filters, adjusting the number of orbits in each of them according to the system efficiency at the two wavelengths. In this case one has the advantage of dealing with a single value, the limit sensitivity, or **ultra-deep sensitivity** for AB magnitudes measured in the three filters with SNR=10 in 600 orbits total.

The results relative to speed, discovery efficiency and ultra-deep sensitivity are reported in the following subsections.

3.1 Speed

Table 3 lists the speed (1/nr. of orbits) for our 7 cases. The first 6 are those defined in Section 2, the lat one (NIC3/ACS) is a hybrid, including the NIC3 performance for the F110W, F160W and F126M filter comparison, and ACS for the F098M/F850LP comparison. The speed normalized to the baseline WFC3+FPA#64 is presented in Table 4, whereas in Table 5 the speed is normalized to the current NIC 3 performances.

SPEED

	FPA#64 BL	FPA#64 +1.0 e/s	FPA#64 +0.25 e/s	SR BL	SR- highRON	SR- lowRON	NIC3 ACS
F110W	*1.54*	*0.70*	*1.25*	*2.88*	*2.49*	*3.05*	*0.74*
F160W	*1.05*	*0.47*	*0.72*	*1.05*	*0.85*	*1.15*	*0.73*
F126N	*1.15*	*0.27*	*0.71*	*2.12*	*1.35*	*2.68*	*0.64*
F093M	*0.39*	*0.11*	*0.28*	*1.08*	*0.82*	*1.23*	*0.20*

Table 3: absolute speed of the different configurations for 2400s integration time, SNR=10, for m_{AB}=28 (F110W and F160W) and m_{AB}=25 (F126N). The columns indicate: 1) WFC3+FPA#64 (baseline case); 2) WFC3+FPA#64 with 1.0 e/s extra-background; 3) WFC3+FPA#64 with 0.25 e/s extra-background; 4) WFC3+Substrate removed FPA with high QE; 5) WFC3+Substrate removed FPA with high QE and high Readout noise; 6) WFC3+Substrate removed FPA with high QE and low readout noise; 7) NICMOS camera 3 (filters F160W, F110W and F126M) and ACS (F850LP).

SPEED NORMALIZED TO FPA#64-BL

	FPA#64 BL	FPA#64 +1.0 e/s	FPA#64 +0.25 e/s	SR BL	SR highRON	SR lowRON	NIC3 ACS
F110W	*1.00*	*0.45*	*0.81*	*1.87*	*1.62*	*1.99*	*0.48*
F160W	*1.00*	*0.45*	*0.69*	*1.00*	*0.81*	*1.09*	*0.70*
F126N	*1.00*	*0.23*	*0.62*	*1.85*	*1.17*	*2.34*	*0.56*
F093M	*1.00*	*0.29*	*0.71*	*2.75*	*2.08*	*3.12*	*0.50*

Table 4: same as Table 3, but normalized to FPA#64.

SPEED NORMALIZED TO NIC-3 (ACS for F098M)

	FPA#64 BL	FPA#64 +1.0 e/s	FPA#64 +0.25 e/s	SR BL	SR-highRON	SR-lowRON	NIC3 ACS
F110W	*2.09*	*0.95*	*1.70*	*3.91*	*3.38*	*4.14*	*1.00*
F160W	*1.43*	*0.64*	*0.98*	*1.43*	*1.15*	*1.56*	*1.00*
F126N	*1.80*	*0.42*	*1.11*	*3.33*	*2.11*	*4.20*	*1.00*
F093M	*2.00*	*0.58*	*1.42*	*5.52*	*4.16*	*6.25*	*1.00*

Table 5: Same as Table 3, but normalized to NIC3 or ACS.

In Figure 2 I plot the speed normalized to NICMOS camera 3 as a column diagram.

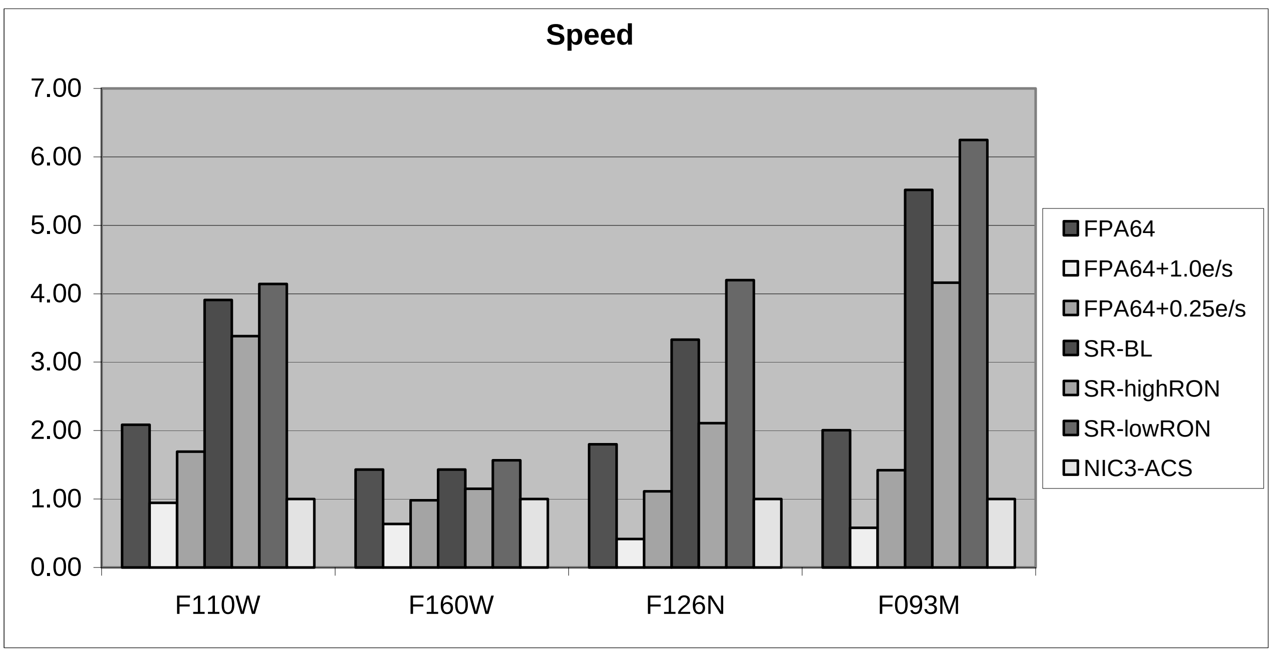

Figure 2: speed relative to NICMOS camera 3 (same data of Table 5).

The tables show that with substrate removed FPAs the speed improves by a factor ~2 at F110W and F093M due to the higher QE. The variations of the readout noise produce a more moderate effect in this band, dominated by the instrumental background. On the other hand, the speed remains basically unchanged in F160W since here the QE is already near its theoretical limit. In the F126W narrow band filter, the speed improvement with substrate removal FPAs can also be a factor ~2 or more due to the higher QE, but it is necessary to keep the readout noise low otherwise the QE advantage is lost.

3.2 Discovery efficiency

In Table 6 I list the absolute values of the discovery efficiency. The same values normalized to FPA#64 and to NIC3/ACS are shown in Table 7 and 8, respectively. In Figure 3 I plot the discovery efficiency normalized to NIC3/ACS as a column diagram.

DISCOVERY EFFICIENCY

	FPA#64 BL	FPA#64 +1.0 e/s	FPA#64 +0.25 e/s	SR BL	SR-highRON	SR-lowRON	NIC3 ACS
F110W	*7.33*	*3.32*	*5.97*	*13.74*	*11.88*	*14.56*	*0.54*
F160W	*5.00*	*2.23*	*3.44*	*5.00*	*4.03*	*5.48*	*0.53*
F126N	*5.48*	*1.27*	*3.40*	*10.13*	*6.43*	*12.79*	*0.46*
F093M	*1.88*	*0.55*	*1.34*	*5.17*	*3.90*	*5.85*	*2.29*

Table 6: discovery efficiency, absolute values.

DISCOVERY EFFICIENCY NORMALIZED TO FPA#64

	FPA#64 BL	FPA#64 +1.0 e/s	FPA#64 +0.25 e/s	SR BL	SR-highRON	SR-lowRON	NIC3 ACS
F110W	*1.00*	*0.45*	*0.81*	*1.87*	*1.62*	*1.99*	*0.07*
F160W	*1.00*	*0.45*	*0.69*	*1.00*	*0.81*	*1.09*	*0.11*
F126N	*1.00*	*0.23*	*0.62*	*1.85*	*1.17*	*2.34*	*0.08*
F093M	*1.00*	*0.29*	*0.71*	*2.75*	*2.08*	*3.12*	*1.22*

Table 7: discovery efficiency normalized to FPA#64.

DISCOVERY EFFICIENCY NORMALIZED TO NIC-3

	FPA#64 BL	FPA#64 +1.0 e/s	FPA#64 +0.25 e/s	SR BL	SR-highRON	SR-lowRON	NIC3 ACS
F110W	*13.68*	*6.20*	*11.13*	*25.63*	*22.16*	*27.16*	*1.00*
F160W	*9.37*	*4.18*	*6.43*	*9.37*	*7.55*	*10.26*	*1.00*
F126N	*11.78*	*2.73*	*7.31*	*21.80*	*13.83*	*27.52*	*1.00*
F093M	*0.82*	*0.24*	*0.58*	*2.26*	*1.70*	*2.56*	*1.00*

Table 8: discovery efficiency normalized to NICMOS camera 3.

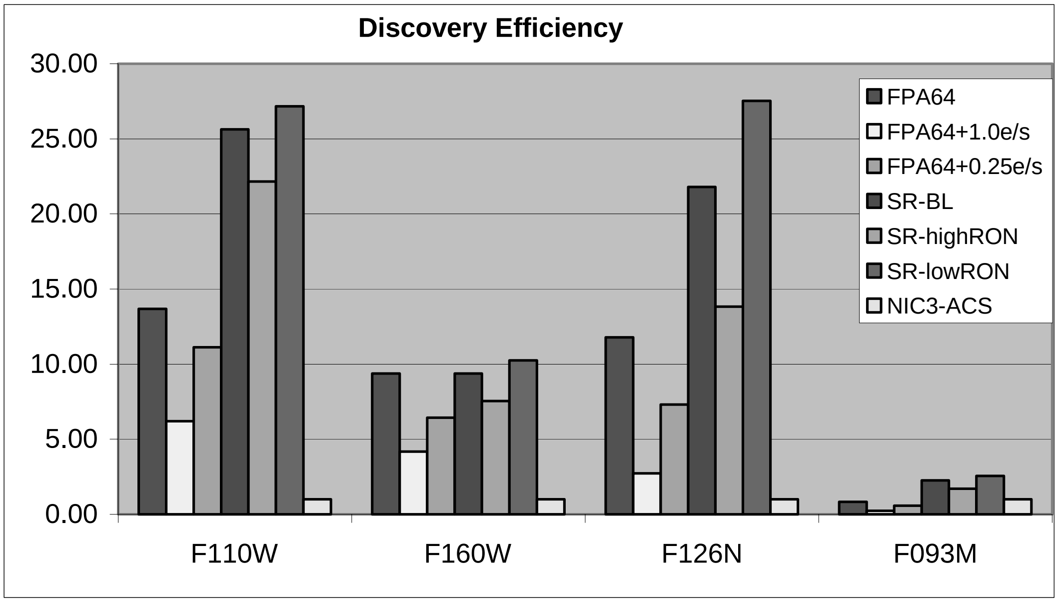

Figure 3: discovery efficiency normalized to NIC3/ACS

Table 7 (discovery efficiency relative to FPA#64) coincides with the speed relative to FPA#64 (Table 4) with the only exception of the last column, since the area is the same for all the first 6 columns. With reference to the case normalized to NIC3/ACS, passing from FPA#64 to a substrate removed device increases the discovery efficiency by a factor ~2 in F110W, raising from a factor ~13 of ~22-27. It remains nearly constant around ~7-10 in F160W. Again, in the narrow band filter the gain depends on the readout noise In the F093M filter the discovery efficiency also doubles with thinned devices, but remain within a factor of two from the ACS+F850LP filter. From a scientific point of view, when the gain is marginal ACS may still be preferred due to its finer sampling.

3.2 Ultra-deep sensitivity

I report in Table 9 the limiting magnitude reached in 200 orbits in F110W, F160W and F098M. In Table 10 I list the number of orbits one should allocate to each filter, out of a total of 600, to reach the same sensitivity in all three filters and the corresponding ultra-deep sensitivy m_{AB}(UD) (row 5). I present two cases for NIC3, one in which the entire complement of orbits is used on the same tile for ultimate depth (NIC3 deep) and one in which it is split to mosaic an area equal to the WFC3-IR field of view (NIC3 large FOW). Due to its particular combination of detector parameters, in particular QE and readout noise, and to the width of its F160W filter, NICMOS provides in its J and H filters an almost perfectly balanced combination of sensitivity, enabling to reach the same AB magnitude in approximately the same time. In comparison WFC3 appears unbalanced, with the J band channel more efficient due to the narrower passband of the F160W filter. The variations in detector performance I am considering, dominated by the QE increase at shorter wavelengths, do not offset, but rather increment the unbalance. The request of reaching the same AB magnitude (flux per unit frequency) in the three filters with the same SNR, makes necessary to spend more time integrating on the slower channels. At the moment this is the F098M, but for substrate removed parts F098M and F160W will require nearly the same amount of time. If one neglects F098M, F160 is always slower. This partially offsets the advantage of increasing the blue QE and makes the difference in ultra-deep sensitivity less prominent than what one may have expected, at least with this type of metric.

The variations of ultra deep sensitivity are therefore within ~1mag, ranging typically between 28.8 and 29.8. The comparison with NICMOS clearly depends on the area covered by NICMOS. For the substrate removal, baseline case one gains 0.4 mag with respect to a deep field made with NICMOS and 1.4 mag with respect to a deep NIC 3 field covering the same field in the same number of orbits.

AB MAGNITUDE REACHED IN 200 ORBITS

	FPA#64	FPA#64 +1.0 e/s	FPA#64 +0.25 e/s	SR BL	SR highRON	SR lowRON	deep NIC3 ACS	Wide NIC3 ACS
m_{AB}(F110W)	*29.86*	*29.43*	*29.75*	*30.20*	*30.12*	*30.23*	*29.46*	*28.44*
m_{AB}(F160W)	*29.65*	*29.21*	*29.45*	*29.65*	*29.54*	*29.70*	*29.46*	*28.44*
m_{AB}(F098M)	*29.12*	*28.45*	*28.93*	*29.67*	*29.52*	*29.74*	*28.74*	*28.74*

Table 9: Ultra-deep sensitivity: m_{AB} reached in 200 orbit exposure

FILTER SPLIT FOR A 600 ORBIT HUDF

	FPA#64	FPA#64 +1.0 e/s	FPA#64 +0.25 e/s	SR BL	SR highRON	SR lowRON	deep NIC3 ACS	Wide NIC3 ACS
Nr of orbits F110W	*94.2*	*69.9*	*83.4*	*93.7*	*85.9*	*97.7*	*104.3*	*233.0*
Nr of orbits F160W	*138.0*	*104.1*	*144.6*	*257.2*	*252.7*	*259.5*	*104.7*	*233.7*
Nr of orbits F098M	*367.8*	*426.0*	*372.0*	*249.1*	*261.5*	*242.8*	*391.0*	*133.3*
m_{AB} (UD)	*29.45*	*28.86*	*29.27*	*29.79*	*29.66*	*29.84*	*29.11*	*28.52*

Table 10: Ultra-deep sensitivity results.

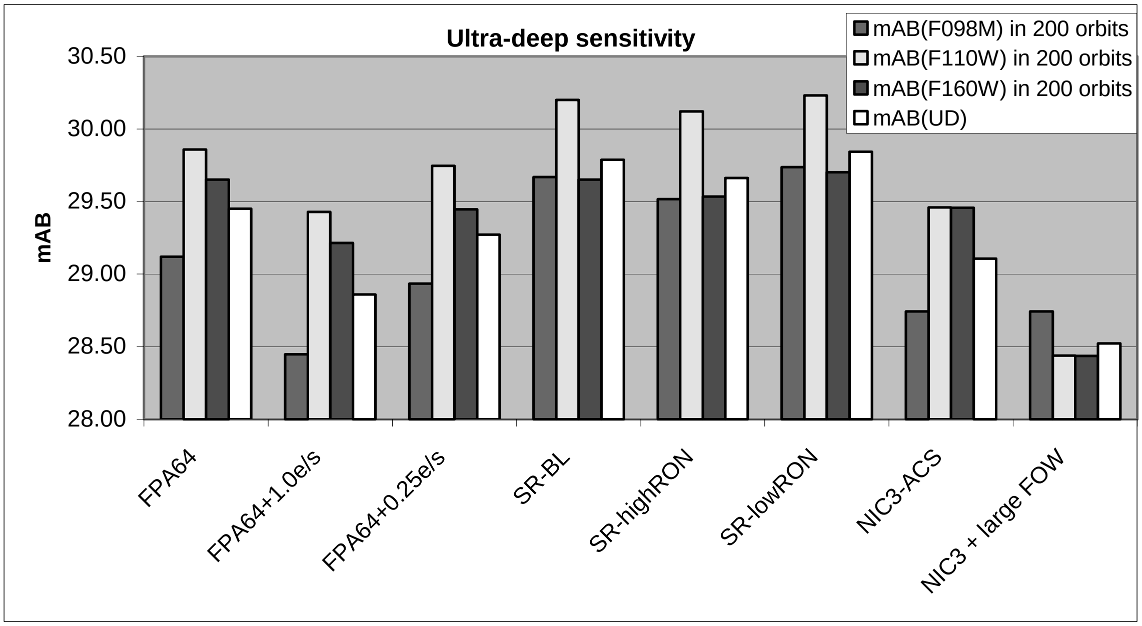

Figure 4: limiting magnitudes and ultra-deep sensitivity

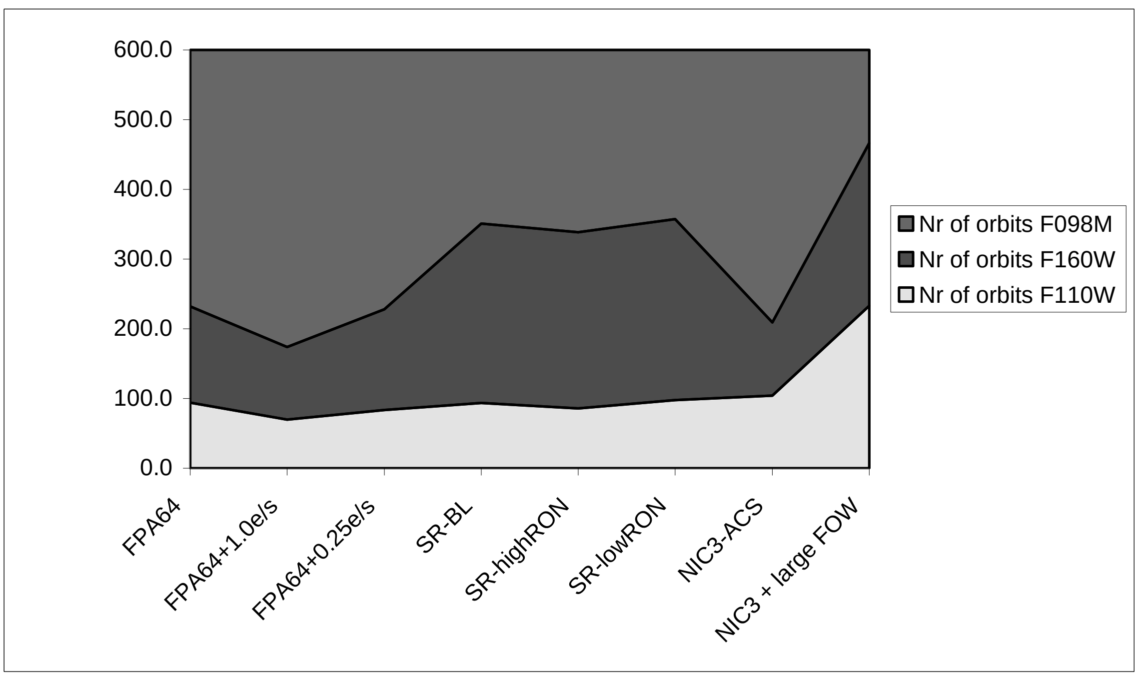

Figure 5: optimal distribution of 600 orbits to reach the same AB magnitude.

4. Conclusion

The comparison of the performance of the FWC IR channel with FPA#64 and with a new substrate removed detector shows a substantial gain in speed at short wavelengths (e.g. F110W band). Substrate removed detectors also provide higher sensitivity in the F098M band where they beat the similar ACS F850LP filter by a large factor (speed) that remains greater than unity even after the difference in field of view has been taken into account (discovery efficiency). It must be remarked, however, that this gain that comes at the price of coarser spatial sampling (130mas/pixel vs. 50mas/pixel). If FPA#64 is affected by extra background induced by cosmic rays, the worse case scenario (~1e/s/pix) would have a major impact on the WFC3-IR sensitivity; vice-versa, a substrate removed part would maintain a clear advantage over nominal FPA#64 (i.e. without cosmic ray induced background) even if it provides a significant increase of readout noise up to ~40e for correlated double sampling. For large survey programs, the gain of sensitivity in the blue bands is mitigated by the little improvements in the red filters (F160W), where the QE is already close to the theoretical limit and the detector band-pass limits the throughput.

References

Stiavelli, M., & Robberto, M. 2003, "Performance of the WFC3-IR channel with FPA#64" Space Telescope Science Institute –Instrument Science Report WFC3-2003-05 (SR03)