ATLAS Internal Note

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Pixel CCD RASNIK

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Introduction

This note compares the performance of the established Video CCD version of the RASNIK instrument with that of the proposed Pixel CCD version. A RASNIK (Red Alignment System of NIKhef) [1] instrument consists of a chessboard mask, a lens, and a two-dimensional image sensor. The mask is illuminated by infra-red light. Its squares are between 85 and 170 μm wide, depending upon the mask. The image sensor is a CCD (Charge-Coupled Device). The lens focuses an image of the mask onto the plane of the CCD. The CCD is smaller than the image. It does not see the entire mask. But the part that it does see is rendered unique by a sparse, mask-wide pattern superimposed over the chessboard. A computer analyzes the image and determines which point in the mask is projected onto the top left corner of the CCD. The position of this point, measured in the coordinate system of the mask itself, is the standardized RASNIK x-y measurement.

We intend to use the RASNIK instrument as a three-point monitor in the global alignment system [1]. The line between the origin of the mask and the top-left corner of the CCD is the three-point axis. The displacement of the lens from this axis is proportional to the RASNIK x-y measurement. If the lens is midway between the mask and the CCD, its displacement is half the RASNIK x-y measurement.

A "video CCD RASNIK" instrument uses a video camera with its lens removed to detect the mask image. The image is focused directly onto the camera's CCD. The camera transmits the CCD image as a video signal, one line at a time, along a coaxial cable to a frame grabber. The frame grabber translates the signal into an array of pixel intensities, which is analyzed by a computer. Results obtained with video CCD RASNIK instruments are presented in [2] and [3].

One disadvantage of the video CCD RASNIK instrument is that its x-measurement is subject to several electrically-generated offsets. The camera introduces an offset when it combines the pixels of a CCD row into a continuous 64-μs video line. We cooled one camera with chlorofluorocarbon spray, and the x-measurement decreased by 27 μm. The frame grabber introduces its own offset into the x-measurement when it converts the video line back into individual pixels. The frame grabber need not, and rarely does, convert the video line into the same number of pixels as were present in the original CCD row. When one frame grabber is exchanged for another, the x-measurement can change by 100 μm [4].

In a "pixel CCD" RASNIK instrument, the CCD image is transmitted one pixel at a time (instead of one line at a time). Because the pixels are transmitted separately, the CCD driver can construct a geometrically exact representation of the CCD image in its memory. There is no electrical offset in the x-coordinate measurement. At Brandeis University, we have a CCD imaging system suitable for pixel CCD RASNIK instruments. We designed it to take x-ray images of muon tubes.

Apparatus

Table 1 compares the video and pixel CCD apparatus used in our study. We had three platforms mounted at 4-m intervals along a wall. Upon the leftmost platform we put a RASNIK mask illuminated by diffuse infra-red light. The mask squares were 170 μm wide. The light was produced by a light-emitting diode (LED). The LED (Hewlette Packard, HSDL-4230) has its peak emission at 875 nm. Immediately in front of the LED was an opal glass diffuser (Edmund Scientific, A43,717). The diffused light was directed towards the mask by a 30-mm diameter plastic fresnel lens of focal length 25 mm (Edmund Scientific, A32,588). This lens was mounted with its flat surface facing the LED. Adequately uniform illumination of the mask could not be obtained with the lens facing the other way. The mask was mounted upon a micrometer stage. The stage allowed the mask to be moved in the x-direction, parallel to the platform and perpendicular to the wall.

Upon the central platform was a 50-mm diameter lens of focal length 2 m (Melles Griot, 01LMP059). There was also an iris with which the effective aperture of the lens could be reduced from 50 mm to 25 mm. The lens focused an image of the mask onto a CCD mounted on the rightmost platform.

Part	Pixel CCD RASNIK	Video CCD RASNIK
light source	875-nm infra-red LED	
diffuser	opal glass	
field lens	25-mm focal length fresnel lens	
mask	170 µm squares	
lens	2-m focal length glass lens	
lens aperture	50-mm or 25-mm diameter	
optical filter	infra-red only black glass	
image sensor	CCD head	video camera
exposure control	LED switch	electronic shutter
image readout	CCD driver	frame grabber
image storage	on disk	
image analysis	Brandeis University RASNIK analysis program	

Table 1: Comparison of the Pixel and Video CCD RASNIK Apparatus

To detect the mask image in the pixel CCD instrument, we used one of the CCDs with which have taken x-ray images of muon tubes (Eastman Kodak, KAF-0400). Its active area is 5 x 7 mm, and its pixels are 9.00 µm square. The CCD was part of a circuit we named the "CCD head". The CCD head was connected by 20-way ribbon cable to a VME-based circuit we named the "CCD driver". The 20-way ribbon cable can be up to 20 m long, but in this study it was 3 m. The CCD driver controlled the CCD head and stored the retrieved pixel intensities in its own memory. Both the CCD head and the CCD driver were designed and built at Brandeis University. A computer (Macintosh, Power PC 7100/66) retrieved the CCD image from the CCD driver by means of a Macintosh-VME interface (Sparrow, MacVEE). The time for which the CCD was exposed to the mask image was controlled by turning on and off the LED.

To detect the mask image in the video CCD instrument, we used a video camera (Chinon, CX-060). Its CCD has an active area of 4 x 3 mm and its pixels are 6.70 µm square. We removed the wide-angle lens that came with the camera. The camera transmitted the CCD image across 3 m of coaxial cable to a frame grabber (Scion, LX-3). The frame grabber was plugged into the same computer we used for the pixel CCD instrument. The time for which the CCD was exposed to the mask image was controlled by the video camera's own electronic shutter.

During our experiments, we turned off the lights in the laboratory and fixed a black glass infra-red-only filter (Melles Griot 03FCG112) over both CCDs. Images were analyzed by the Brandeis University RASNIK program [3, 5].

Mask Images

Figures 1 and 2 are pixel and video CCD images respectively. Both were obtained with a lens aperture of 50 mm. The pixel CCD exposure was 100 ms. The video CCD exposure was 17 ms, which was the longest exposure possible with our camera.

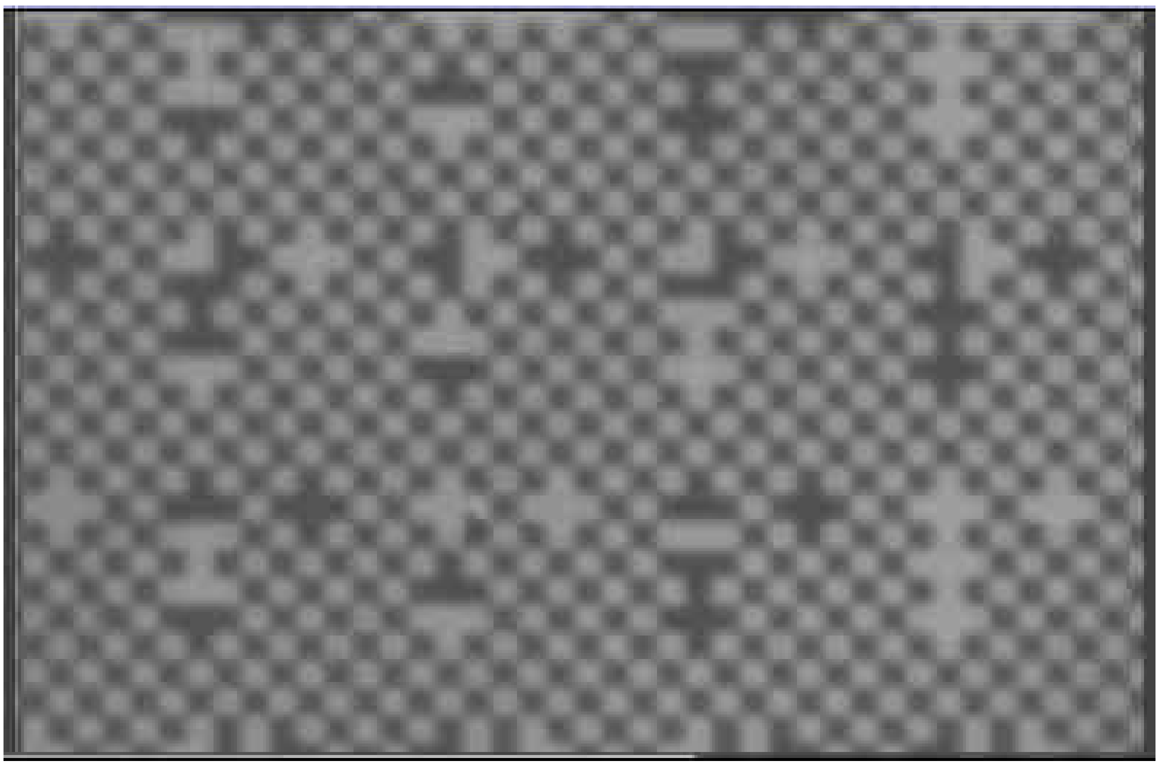

Figure 1: A Pixel CCD RASNIK Image (50-mm lens aperture)

Even if our video camera could expose for longer, it would still be unable to produce an image with as much contrast as we see in the pixel CCD image. Every CCD suffers from "dark current", the accumulation of charge in its pixels that takes place even when no light is incident upon the CCD. After 17 ms, the video camera CCD pixels are 10%-filled by dark current. If the CCD were exposed for 100 ms, the pixels would be 60%-filled. Although the mask image would be proportionally brighter, the image contrast would not improve. In fact, pixels in the white squares of the mask would be over-filled. Their charge would spread to neighboring pixels (a phenomenon known as "blooming"). The KAF-0400 is designed to have low dark current. The pixels of our particular KAF-0400 took 10 minutes to become 10%-filled by dark current.

Figure 2: A Video CCD RASNIK Image (50-mm lens aperture)

When we reduced the lens aperture to 25-mm, the video CCD images could not be analyzed. The mask squares were too faint. On the computer screen, or on paper, we could not discern them. As mentioned above, we were unable to increase the exposure time used by the video CCD instrument. We did, however, increase the exposure time used by the pixel CCD instrument (Figure 3). The images we obtained with 400 ms exposure through a 25-mm aperture were as bright as those taken with 100 ms exposure through a 50-mm aperture. The most noticable difference between images taken through the two different apertures is that the mask squares appear blurred when seen through the narrower aperture. With the help of an optical simulation program, we determined that the blurring of the squares was due to diffraction at the narrower aperture.

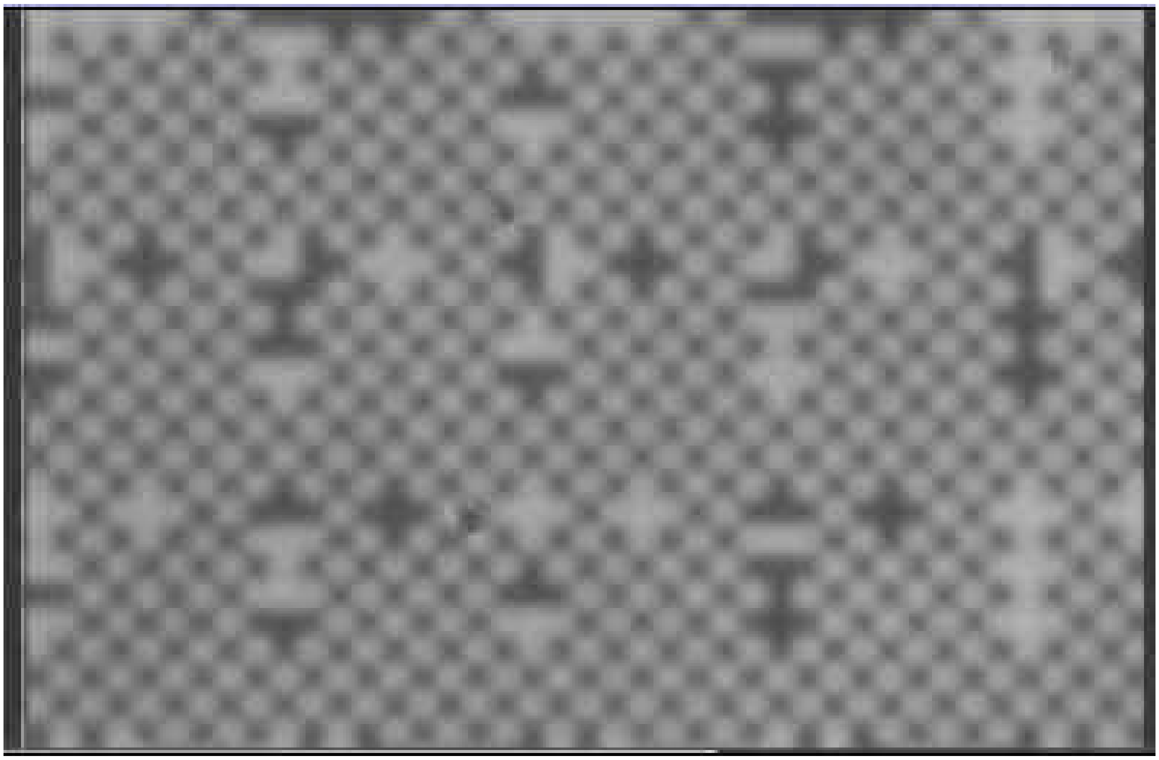

Figure 3: A Pixel CCD RASNIK Image (25-mm lens aperture)

Experimental Results

Table 2 compares the results obtained with the pixel and video CCD instruments.

Parameter	Lens Aperture	Standard Deviation in X-Direction	
		Pixel	Video
fitting time	50 mm	18 s	11 s
fitting error	50 mm	3 µm	6 µm
image error	50 mm	8 µm	7 µm
scan residuals	50 mm	8 µm	11 µm
scan residuals	25 mm	10 µm	fails

Table 2: Comparison of Results Obtained with Pixel and Video CCD RASNIK Instruments

The results are quoted in terms of the standardized RASNIK measurement, not in terms of lens displacement. For our symmetric instruments, an error in the standardized RASNIK measurement must be halved to obtain the corresponding error in the measurement of lens displacement. Thus a 10-μm rms residual in Table 2 corresponds to a 5-μm residual in lens displacement.

The "fitting time" is the time it takes the computer to analyse an image, averaged over 25 runs on the same image. It is greater for the pixel CCD images because they have more squares to analyze. The "fitting error" is the standard deviation of 25 measurements made with the same image. Some images have a greater fitting error than others. The values given in Tables 2 and 3 are the average fitting error over 25 images. The y-direction is perpendicular to both the optical axis and the x-direction.

	Fitting Error		
Instrument	x (μm)	y (μm)	tilt (mrad)
video CCD	6	8	3
pixel CCD	3	5	2

Table 3: Fitting Errors

When we apply the analysis program to an image 25 times, and calculate the average of these 25 measurements, we obtain what we call the "expected measurement" for that image. If we take 25 images consecutively, without moving any part of the instrument, the standard deviation of their expected measurements is the "image error". The image error in our instruments was caused by air turbulence, which causes the mask image to move erratically. We had no tubes enclosing the light path, and we could feel a cold draft along the wall. We hope, therefore, that the image errors in Table 4 represent the worst case for RASNIK instruments in the ATLAS experiment hall.

	Image Error		
Instrument	x (μm)	y (μm)	tilt (mrad)
video CCD	7	5	1
pixel CCD	8	9	0.6

Table 4: Image Errors

Using the micrometer stage, we moved the mask in 0.5 mm steps a total of 15 mm in the x-direction. At each position we recorded one image. Each image was analyzed once to obtain an x-measurement. The "scan residual" in Table 2, given for each instrument, is the standard deviation of the residuals from a straight line fit to the graph of RASNIK x against micrometer x. The scan was performed first with a 50-mm aperture, and then with a 25-mm aperture.

Instrument	Lens Aperture	Scan Residual	Slope (µm/µm)
Video CCD	50 mm	11 µm	1.0014
Video CCD	25 mm	failed	failed
Pixel CCD	50 mm	8 µm	1.0013
Pixel CCD	25 mm	10 µm	1.0009

Table 5: X-Direction Scan Results

Fitting errors, image errors, and errors reading the micrometer all contribute to the scan residual. The error reading the micrometer is approximately 3 µm rms. Adding these errors together in quadrature, we get a total of 9 µm rms for the pixel CCD instrument, and 10 µm rms for the video CCD. The residuals are themselves 8 µm and 11 µm rms respectively, so we conclude that we have observed the largest sources of error in both instruments. By far the most significant source of error is turbulence along the light path. We note that the 10 µm rms residual obtained with the pixel CCD instrument and a 25-mm aperture corresponds to a 5 µm rms residual in the measurement of lens position.

CCDs for the Pixel CCD RASNIK Instrument

All other things being equal, the cost of a CCD increases by more than a factor of three for each doubling of its active area. The KAF-0400, for example, costs $180, while the KAF-1600, which has four times the area, costs $1750.

CCD	Company	Active Area (mm^2)	Pixel Size (μm^2)	10%-Fill Time (s)	Cost in Thousands ($)
KAF-0400	Kodak	7 x 5	9 x 9	200	180
KAF-1600	Kodak	14 x 10	9 x 9	200	1750
TC-237	TI	4.9 x 3.7	7.4 x 7.4	20	50
TC-255	TI	3.2 x 2.4	10 x 10	5	14
CX-060	Chinon	4.3 x 3.2	6.7 x 6.7	0.02	>100

Table 6: Comparison of CCDs

Table 6 describes a selection of CCDs. The last row in the table is devoted the Chinon CX-060 camera. The 10%-fill times are those guaranteed by the manufacturer.

The TC-237 is suitable for an ATLAS pixel CCD RASNIK instrument. Its active area is larger than that of a standard video CCD. Its dark current is low enough to allow exposures of several seconds. Unlike the KAF-0400, it contains a "frame store", into which an image may be transferred in less than a millisecond. The frame store allows us to implement an electronic shutter in the CCD head without having to turn on and off the LED.

It may be possible to use the TC-255 instead of the TC-237. It has a frame store, and is less than one third the price. Although it is smaller even than a video camera CCD, it is still large enough for a RASNIK instrument. Provided that the squares in the mask image are smaller than 240 µm, the TC-255 is sure to detect an uninterrupted block of 9 x 9 mask squares. A block of 9 x 9 mask squares is adequate to interpret the RASNIK pattern [6].

CCD Area	Lens Aperture	Scan Residual	Slope (µm/µm)
TC-255	25 mm	13 µm	1.0008
KAF-0400	25 mm	10 µm	1.0009

Table 7: Performance of the Simulated TC-255

We simulated the TC-255 in our pixel CCD instrument by re-analyzing our KAF-0400 images using only the central 355 x 267 pixels (a 3.2 x 2.4 mm area). The results we obtained for the x-direction scan are given in Table 7, where they are compared to the results we obtained earlier using the entire CCD. The fitting error rose to 5 µm. The image error remained 8 µm. The scan residual rose to 13 µm, or 6.5 µm in terms of lens displacement.

Hardware Comparison

Table 8 compares the sensor and data acquisition electronics used by proposed production versions of the video and pixel CCD RASNIK instruments. The proposed video CCD instrument uses a miniature video camera (Supercircuits, PC18XS). The cost of its data acquisition electronics was estimated by NIKHEF. The pixel CCD instruments use CCD heads and data acquisition electronics whose cost was estimated by Brandeis University.

Component	Pixel CCD RASNIK with TC-237	Pixel CCD RASNIK with TC-255	Video CCD RASNIK with PC18XS
Cables	20-way flat	20-way flat	coax & power
Smallest Lens	25 mm	25 mm	50 mm
Sensor Size	25 x 25 mm	25 x 25 mm	40 x 45 mm
Sensor Cost	$65	$29	$60
DAQ Cost	$73	$73	$48

Table 8: Comparison of Pixel and Video CCD Hardware

The quiescent power consumption of the TC-237 and TC-255 CCD heads is less than 100 mW, while that of the PC18XS is close to 1000 mW. Nevertheless, we do not expect the queiscent power consumption of the PC18XS to present a problem. The camera can be turned off when it is not in use, and turned on briefly when a picture is taken.

The TC-237 and TC-255 CCDs are manufactured using a process that has proved itself in space applications to be resistant to radiation doses in excess of 100 krad. The remaining components on the pixel CCD sensor heads are resistors, zenar diodes, capacitors, and an operational amplifier. None of these are vulnerable to a radiation dose of less than 100 krad. The PC18XS radiation resistance has yet to be tested.

Conclusion

The video CCD instrument is sensitive to changes in its readout electronics. The pixel CCD instrument is not. In our study, both instruments were accuarate to better than 5 μm rms in their measurement of lens displacement. When we reduced the lens aperture from 50 mm to 25 mm, the pixel CCD instrument continued to measure lens displacement to an accuracty of 5 μm rms, but the video CCD instrument could not operate with the darker mask image. Our preliminary simulations suggest that we could manufacture a 25 x 25 mm pixel CCD sensor head for $29. The cheapest video CCD sensor head we know of measures 40 x 45 mm and costs $60. We have obtained samples of several inexpensive CCDs. When the newest version of our CCD driver circuit is available, we will test these samples in pixel CCD instruments.

References

[1] ATLAS Collaboration, *Technical Proposal*, CERN/LHCC/94-43

[2] Astrid van der Horst, Harry van der Graaf, *Measurements on RASNIK*, NIKHEF internal report, February 1995.

[3] Kevan S. Hashemi, James R. Bensinger, *RASNIK Image Processing with a Steepest Ascent Algorithm*, ATLAS Internal Note MUON-No-092, August 1995.

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[6] http://www.nikhef.nl/pub/departments/et/ccd_rasnik