(NASA-CR-196287) A STUDY OF A MULTI-PINNED PHASE CCD DETECTOR FOR USE AS A STAR TRACKER Final Report (JHU) 10 p

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P. 10

A Study of a Multi-Pinned Phase CCD Detector for Use as a Star Tracker

Final Report - July 21, 1994

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This grant has supported studies of the use of CCDs in star trackers in a number of different areas. Among the tasks we have pursued are the following.

1) Radiation modeling and the increase in noise equivalent angle as a result of exposure to protons and bremsstrahlung gamma rays.
2) The development of pattern matching software to identify field locations from a CCD image and a pre-existing map of the local area.
3) Observations of various stellar fields from the 24 inch telescope at the Offit Observatory at JHU, primarily to test the pattern matching software. These included crowded fields as well as moving objects, like comets.
4) Tracking of very faint objects, to determine the faint limit of the CCD system.

This final report concludes with a more complete description of some of the above activities.

There were two studies conducted which employed the Photometrics PM-512 Camera. The first study validated two models for the Noise Equivalent Angle (NEA) expected on a CCD based star sensor. The second study demonstrated the principle of star scene identification by means of correlation with the Hubble Guide star catalog. Both studies were very successful, important to the FUSE project and could not have been performed without the CCD camera.

1. NEA Models. A key performance parameter for a star sensor is the Noise-equivalent angle which is a measure of the distribution of measurements of a star's position. Noise inherent in the measurement leads to variances in star's measured position, an important quantity for driving spacecraft attitudes. Design studies for the FUSE star sensor, the Fine Error Sensor (FES), require models which relate design parameters and predict performance. Two models for the FES NEA have been built. One model is a

Monte-Carlo simulation of the noise imposed on a star's image at the sensor. The second model is a parametric function derived from statistical theory.

A simple laboratory configuration permitted the collection of data for validating the NEA models. An incandescent lamp connected to a rheostat illuminated a 200 micron pinhole. The pinhole was imaged onto a Photometrics PM-512 CCD camera at about 2 meters from the lamp. The typical image width was about 1 pixel RMS. The apparatus was set up in a photographic dark room to minimize background light on the detector. The camera is cooled and exposures were typically about 1 sec to minimize the thermal noise. Seven intensities spanning the range expected in the FES were selected. For each intensity a series of 30 images were captured and filed on disk. The position of the spot was measured for each image. The NEA was related to the standard deviation of the position measurements.

Results of the validation experiments were very successful. Both the simulation and the parametric models accurately tracked the measured data. The NEA models are being used in design studies with confidence. Several technical memos have been written and distributed to the FUSE team. One of these memos is attached to this report. A paper for journal submission is in preparation.

2. Star Field Identification. The FUSE FES has a second purpose: providing visible imagery of the star field surrounding the FUSE target. The imagery will be used to verify the target scene and to compute small spacecraft slews to center the target in the center of the instrument's entrance aperture. The field of the view of the FES is small and scene verification may be difficult.

The faint limit of the sensor is about at the magnitude limit of the Hubble Guide Star Catalog (HGSC). A procedure was developed which correlates the catalog to CCD images. The procedure involves taking images of the star field with the camera and analyzing the image for star positions. The star positions are put into a list and compared to a list of positions derived from the guide star catalog. The algorithm for correlating the two lists was taken from a procedure employed in the attitude control system on spacecraft.

A series of measurements were made to demonstrate the correlation algorithm. The Photometrics camera was attached to the JHU Offit Telescope and about six different star fields were imaged. The images were then correlated in near real time (within 1 minute) with the HGSC to about 1 arcsec accuracy. A technical paper is in preparation describing the algorithm and its application to FUSE problem. The application of the algorithm is being considered for implementation in the FUSE Science and Missions Operations Center.

Validation of a Model for the Noise-Equivalent Angle in a CCD Sensor

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Jul 20, 1994

A model has been derived for the NEA of a CCD Sensor. This model should be useful in design and performance studies for the FUSE Fine Error Sensor. This note reports the results of a validation study for the model. Results from laboratory measurements and Monte-Carlo simulations were used to validate the model. The model appears to accurately predict the NEA in CCDs where the primary noise sources are photon counting noise and read-out noise. It appears that the model can be easily extended to include other noise sources such as background light.

The NEA Model

The noise-equivalent angle is a measure of the distribution of the positions [centroids] of a series of images of a stationary star. NEA is defined in terms of the variance of the centroids, C_X, and usually specified in units of angle [arcsec] at the 99%tile confidence level (3σ).

$$NEA_x = 3\sqrt{\mathrm{Var}(C_x)}$$

NEA is functionally dependent on the brightness of a star's image, the detector integration (exposure) time, and the several sources of the noise inherent in the detector system. The read-out noise has been found to be the dominant source of detector noise.

Using statistical theory a model for the centroid variance has been derived[1]:

$$NEA_x = 3\left[\frac{W_x^{\ 2}}{I} + \frac{R^2}{I^2}\alpha\right]^{1/2}$$

[1] C.P. Holmes: "Model for the NEA of the FUSE Fine Error Sensor", (In Preparation).

where for measurements with respect to the x axis of the CCD array:

W_x is the RMS width of the star image

I is the intensity [electrons] of the integrated star image

R is the read-out noise for the CCD

α is a geometric factor related to the size of the subarray containing the star image and is defined as

$$\alpha = \left(m \sum_{i=1}^{n} (x_i - C_x)^2 \right)$$

x_i is the coordinate of the ith pixel in the subarray,

C_x is the measured centroid of the image, where

$$C_x \equiv \langle x \rangle = \frac{1}{I} \sum_{i=1,j=1}^{n,m} x_i F_{i,j}$$

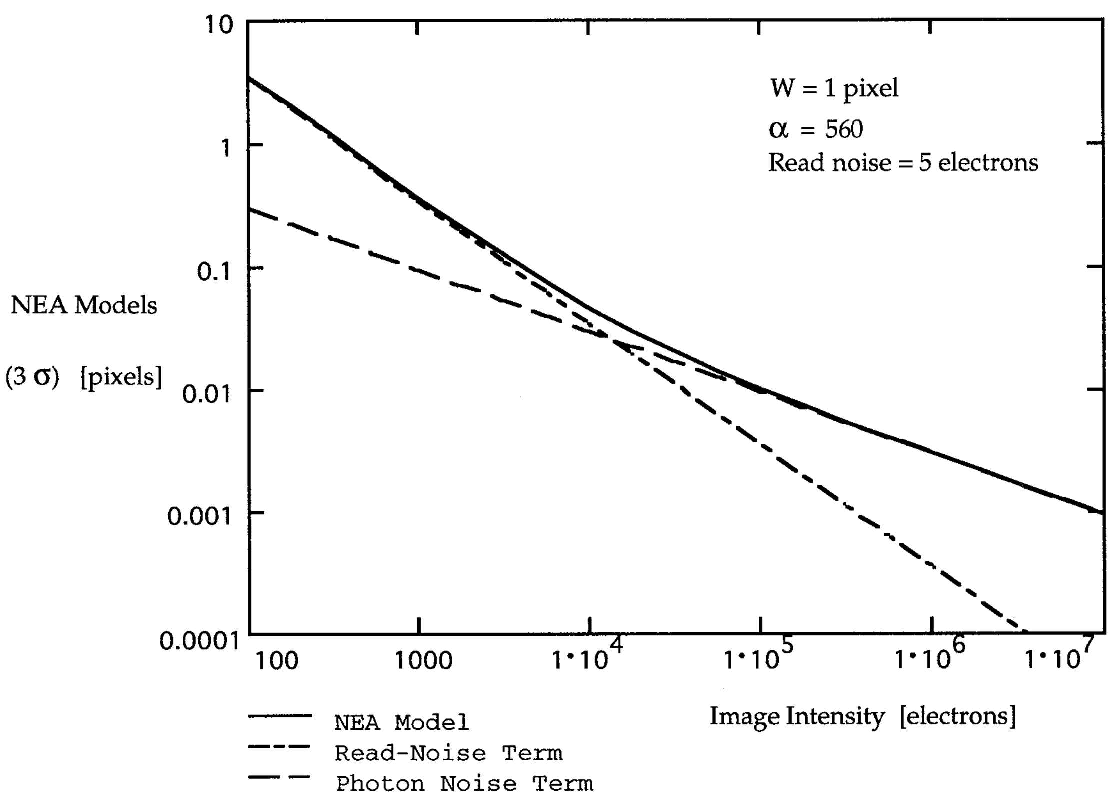
n and m are the x and y dimensions of the subarray, and

$F_{i,j}$ is the measured intensity in pixel [i,j] less bias and background.

For bright sources the photon noise term, $\frac{W_x}{\sqrt{I}}$, dominates. For faint sources the read noise term dominates. This can be seen from the Figure 1 where the contributions from the two terms has been isolated.

Figure 1

NEA Model for Range of Star Image Intensities

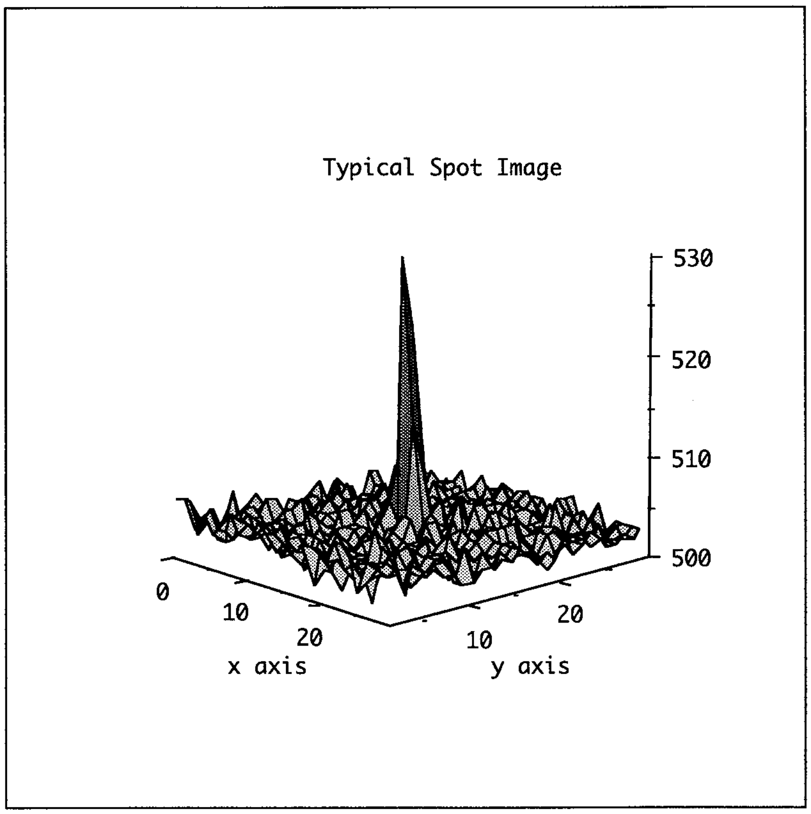


Laboratory Measurements

A simple laboratory configuration permitted the collection of data for validating the NEA model. An incandescent lamp connected to a rheostat illuminated a 200 micron pinhole. The pinhole was imaged onto a Photometrics PM-512 CCD camera at about 2 meters from the lamp. The typical image width was about 1 pixel RMS. The apparatus was set up in a photographic dark room to minimize background light on the detector. The camera is cooled and exposures were typically about 1 sec to minimize the thermal noise

Seven intensities spanning the range in Figure 1 were used. For each intensity a series of 30 images were captured and filed on disk. Figure 2 is a typical "raw" image of the pinhole. The measured pixel intensities shown in the figure are in ADUs where for this measurement 1 ADU = 8.5 electrons. The integrated intensity corresponds to about 900 electrons. The centroids are at 14.4350 (x) and 15.7041 (y) and image widths are 1.11832 (x) and 1.20692 (y) pixels. Each pixel has a bias of about 503 ADUs. The background noise is the read-out noise. The read noise was about 1 ADU or about 8.5 electrons/pixel. As mentioned before the background contains negligible electrons from thermal or stray-light sources.

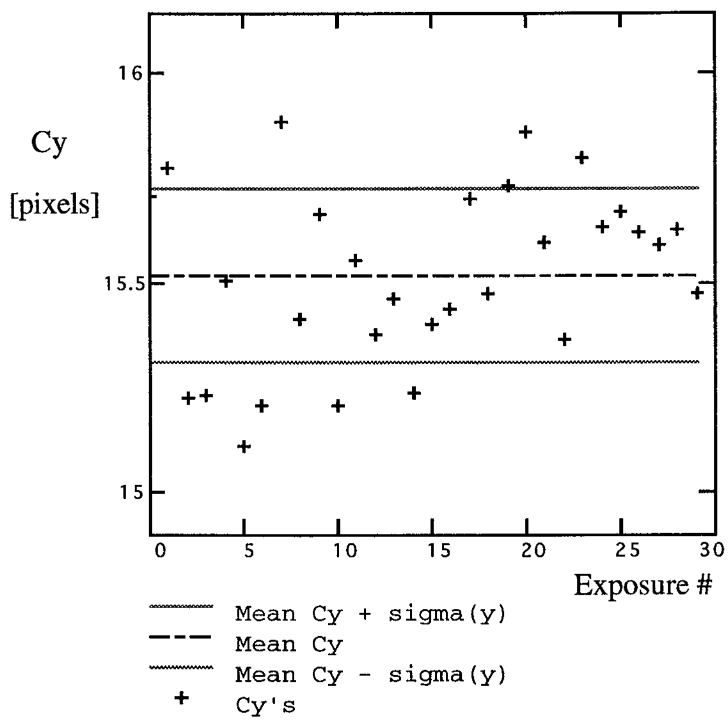
Figure 2



For each series, the x and y centroids were found for each image. The centroids were found using a 9x9 subarray centered on each image. The standard deviation of the series of centroids was then computed. The results are shown in Figure 3.

Figure 3

Distribution of Measured Centroids



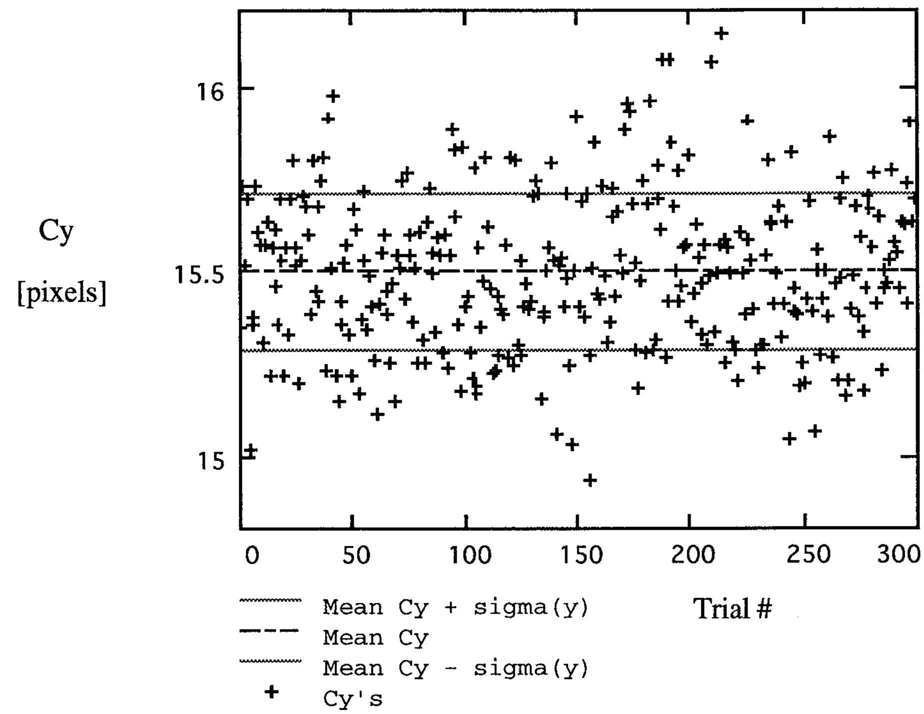
Simulations

A Monte-Carlo model was created to simulate the NEA measurement. The model starts with an image array and repetitively applies photon and read noise to each of the pixels of the array. Centroid calculations are made for each repetition. At the end of the loop, the mean and standard deviation are computed for the series of centroid values.

Figure 4, shows a series of 300 trials of simulated measurements on a spot image. The image was formed from the average of the thirty images each having intensities of about 900 electrons. The NEA of these simulated measurements is 0.63 pixels.

Figure 4

Simulated Distributions of Centroids

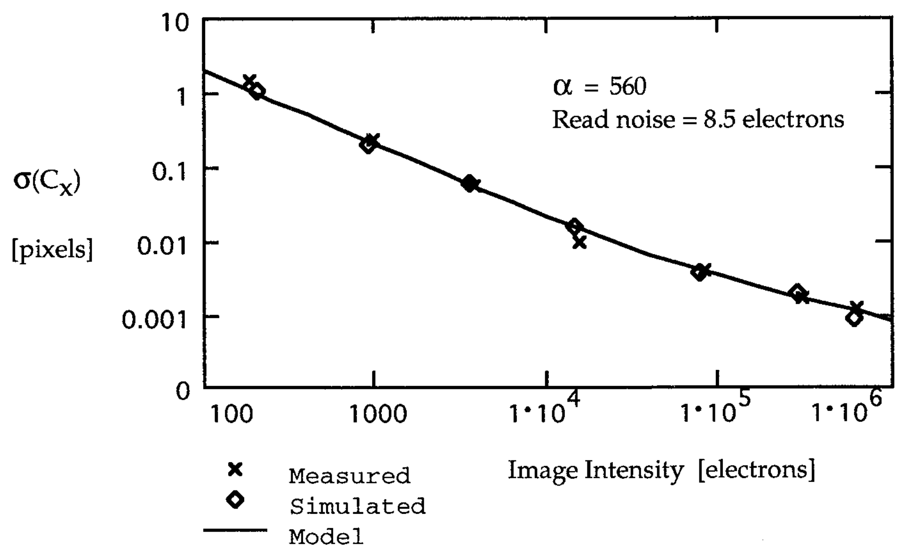


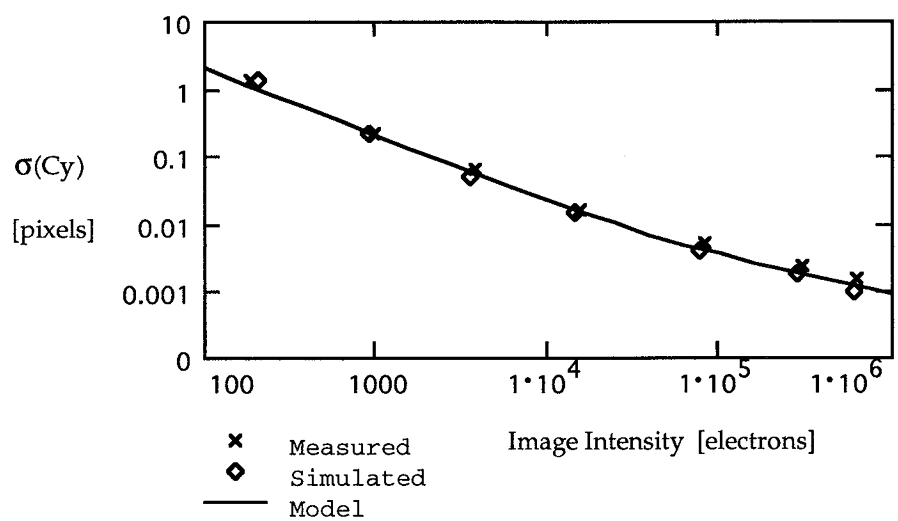
Results

Figure 5 shows the comparison between the NEA model, the measurements, and the simulations. These figures show that the model tracks the measurements and simulations extremely well in both the extremes of the image intensity. This should provide confidence in applying the model to design and performance studies for the FUSE Fine Error Sensor.

Figure 5

Precision of the Centroid Measurement:
Comparison between NEA model, measurements, and simulation



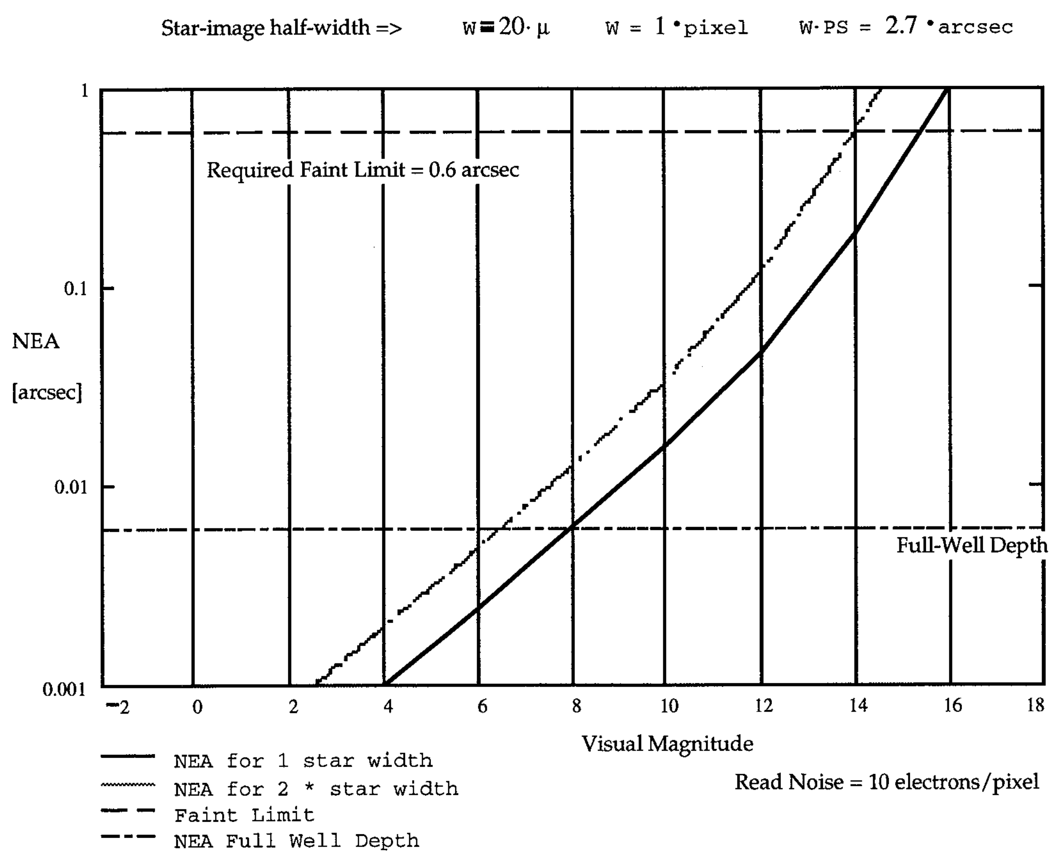


Application of the Model to FUSE

An example of the application of the NEA model is given in Figure 6. This figure shows the relationship between the visual magnitude of a star and the NEA. The calculation uses current design parameters for the FUSE instrument and assumes an exposure time of 1.9 sec. The assumed read-out noise was 10 electrons/pixel which is quite large for FES at the beginning of life. Recent redesign of the FES camera will permit star image widths at the detector of about 2.7 arcsec or about 1 pixel. A second NEA curve is plotted for an image width of twice the first or 5.4 arcsec. These curves can be compared to the required performance of an NEA of 0.6 arcsec for a star with visual magnitude of 13.5. It appears that with current design parameters the FUSE FES will exceed the performance requirements with some margin.

Figure 5

Performance of the FUSE Fine Error Sensor
NEA as a function of visual magnitude



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