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Description of Fixed-Pattern Noise in CCD's Using the Spatial Power Spectrum

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Abstract

Characterization of fixed-pattern noise is an important aspect in evaluating the performance of a staring array. The usual method of quantifying the effect of this artifact on the image is to state the variance of the pixel levels. However, this implicitly assumes that the fixed-pattern noise is spatially "white", that is, it has an equal effect at all spatial frequencies of interest. Usually, fixed-pattern noise has a nonrandom spatial distribution, which violates the assumption of white noise. A more complete characterization is provided by the spatial power spectrum of the fixed-pattern noise. This descriptor quantifies the effect of fixed-pattern noise on image data, both in terms of its frequency content, as well as its magnitude. Consideration of the noise spectrum is seen to yield additional insight into the nature of the fixed-pattern noise present on the array.

Introduction

Fixed-pattern noise is a generic term used to describe the variations in gain and offset levels observed over an array of detector elements, such as a CCD. Variation of offset levels is an additive noise, and is discernible even with no flux incident upon the array. Variation of gain (responsivity) is a multiplicative effect, which varies with the amount of scene flux.

Such detector non-uniformity can be a severe problem, especially in the infrared[1], where images are of inherently low contrast to begin with. Fixed-pattern noise can be partially corrected for digitally, but for large array sizes, such a correction represents a large number of addition and multiplication operations[2].

This paper will concentrate on the characterization of fixed-pattern noise artifacts by means of the spatial power spectrum. It will be seen that the spatial noise on the array is non-white, and that additional insight is gained into the effect of the noise at the different spatial frequencies of interest. This additional insight would be useful in the intercomparison of various arrays or correction algorithms, and as a frequency-domain viewpoint on the performance of the CCD array as a processor of optical signals.

Mathematical foundations

The usual means of characterizing fixed-pattern noise is by specifying the variance, σ^2, of the pixel levels.

$$\sigma^2 = \frac{\sum_i \sum_j \left[I(x_i, y_j) - M \right]^2}{\text{number of pixels}} \quad . \tag{1}$$

The variance computation is often written (schematically) as:

$$\sigma^2 = \overline{(I - M)^2} = \overline{I^2} - M^2 \ , \tag{2}$$

the array data being denoted by $I(x,y)$ and the mean by M.

Variance is the average square difference of the array values from the mean, usually measured with a uniform (or zero) input flux distribution. A relatively larger variance is seen for arrays exhibiting an appreciable amount of fixed-pattern noise. However, a specification of variance alone gives no indication as to how the nonuniformities are distributed over the array, essentially assuming that there is an equal contribution from the fixed-pattern noise at all spatial frequencies (white noise). We will present examples of array data for which this assumption does not hold, and hence motivate the description of the array data in a more complete manner.

Relationship between variance and power spectrum

This section will develop the relationship between the two descriptors of array performance, variance and spatial power spectrum. The two dimensional Fourier transform of the array data may be written as

$$\mathcal{F}(\xi,\eta) = \iint I(x,y)\, e^{-j\,2\pi\,(\xi x + \eta y)}\, dx\, dy. \tag{3}$$

Operating on the transform data to produce its absolute value squared, one obtains the power spectrum of the array data, $|\mathcal{F}(\xi,\eta)|^2$.

The autocorrelation of the image data is defined as

$$R(x_{shift},\, y_{shift}) = \frac{\iint I(x,y)\; I(x-x_{shift},\, y-y_{shift})\; dx\; dy}{\iint dx\; dy} . \tag{4}$$

The following relationship[3] exists between the value of the autocorrelation at zero shift and the variance

$$\sigma^2 = R(x_{shift}=0,\; y_{shift}=0) - M^2 . \tag{5}$$

By the Wiener-Khinchine theorem, the autocorrelation and the power spectrum are a Fourier transform pair.

$$R(x_{shift},y_{shift}) \xrightarrow{\mathcal{F}} |\mathcal{F}(\xi,\eta)|^2 . \tag{6}$$

Using the central ordinate theorem for Fourier transforms,

$$R(0,0) = \iint |\mathcal{F}(\xi,\eta)|^2\; d\xi\;\; d\eta\; . \tag{7}$$

Finally, using equations 5, 6 and 7, we obtain a relationship between the variance and the power spectrum

$$\sigma^2 = \iint |\mathcal{F}(\xi,\eta)|^2\; d\xi\;\; d\eta\; - M^2 . \tag{8}$$

The variance is seen to equal the integral of the spatial power spectrum of the array data over all frequencies (within an additive constant equal to the square of the mean of the pixel values). Thus, a specification of σ^2 alone assumes that the power spectrum is constant over the spatial frequencies of interest.

Experimental Verification

In this section, experimental data (in one dimension) is provided for a specific array which demonstrates that the noise power spectrum is not necessarily flat, and that there is additional insight into the imaging process to be gained from a spectral representation of the fixed-pattern noise.

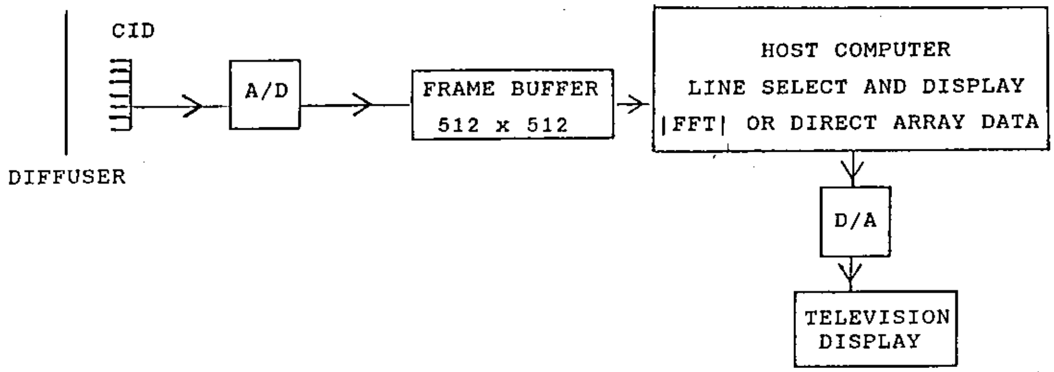

Figure 1. Experimental Setup

The following equipment was used: General Electric TN2505 CID camera (248-V x 388-H), Imaging Technology IP-512 Frame Buffer and D/A & A/D board, and an Intel model 310 host computer.

The host computer software and frame grabber hardware allow a complete frame of data to be displayed, and also allow the selection and display of any line of the data set. The magnitude of the FFT of that line is then calculated and displayed on the TV monitor.

The diffuser was used with a uniform light source in order to make the fixed-pattern noise (primarily areas of low responsivity - "dead cells") appear with a higher contrast on the display and in the data.

In this system, the magnitude of the Fourier transform, not the power spectrum, has been displayed. Thus, the area under a given spectrum plot will be proportional to the standard deviation of the pixels, rather than the variance.

We now consider a representative frame of data, two particular lines of that frame, and their associated Fourier transforms.

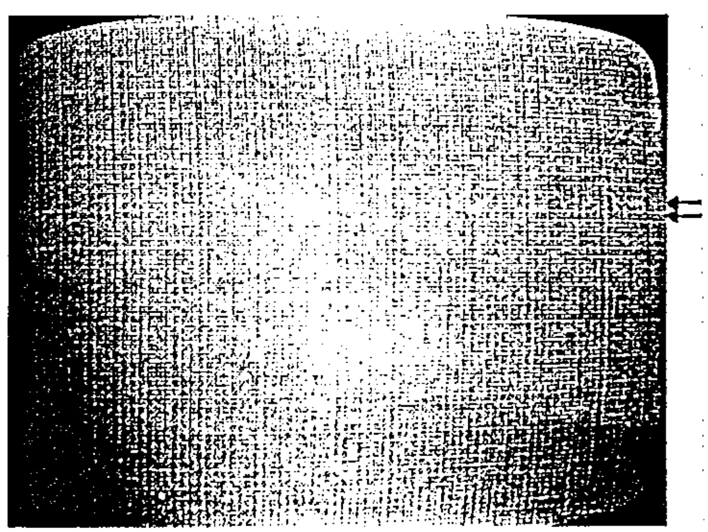

Figure 2. Typical frame of fixed-pattern noise data.
Top arrow is line 180, bottom arrow is line 185.

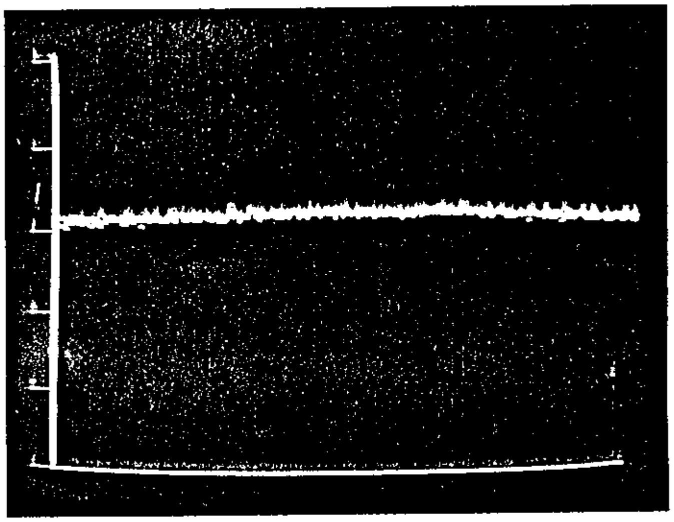

Figure 3. Plot of $I(x, y = 180)$.

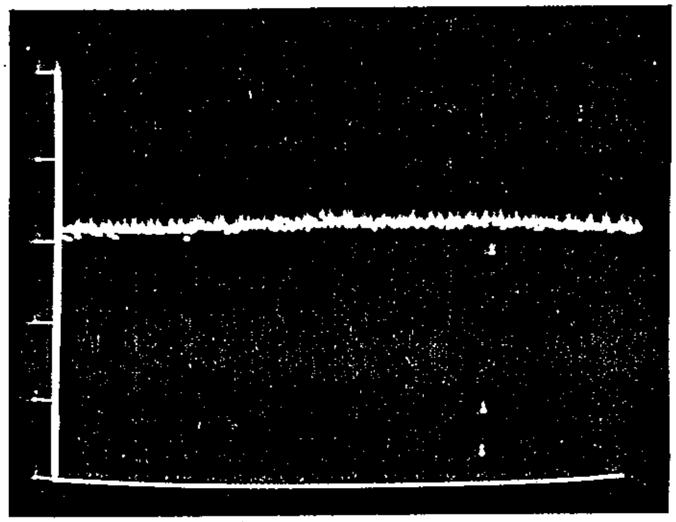

Figure 4. Plot of $I(x, y = 185)$.
Note the region of low responsivity at right.

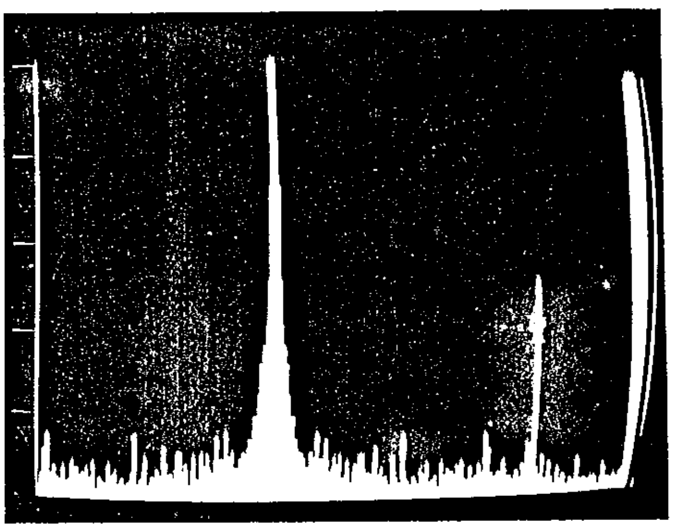

Figure 5. Plot of $|\mathcal{F}(\xi, y = 180)|$.

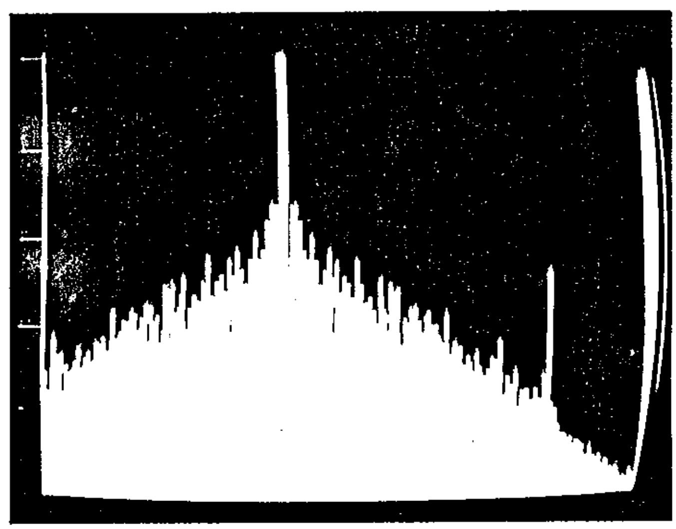

Figure 6. Plot of $|\mathcal{F}(\xi, y = 185)|$.

Both plots to same scale

Observations

In the plots, the location corresponding to zero spatial frequency occurs at the central spike. The spatial Nyquist frequency is located at the white bar at the right of the plot. The localized "dead cell" region raises the noise spectrum at all frequencies, proportional to the magnitude of its Fourier transform. We thus have a descriptor for spatial noise which characterizes the effect, both in terms of magnitude and frequency content.

In each of the plots there is harmonic content visible at $\approx$ 0.75 times the Nyquist frequency. Its origin appears to be related to a spatial beat frequency between the sampling lattice of the detector array (388 samples horizontal) and the sampling performed (512 samples horizontal) by the A/D harware which converts the analog video to digital form.

Conclusions

The characterization of fixed-pattern noise by means of the power spectrum has several advantages over the use of the variance. The primary advantage is that additional insight is gained into the effects of the noise on the different spatial frequencies which make up the image data.

The fixed-pattern noise is seen to be nonwhite. For cases where the spatial distribution of nonuniformities is not random, the noise spectrum has a definite frequency dependence. The use of variance as a spatial noise descriptor provides no such information.

The additional insight provided by this method is best evidenced by the display of the harmonic content at ≈ 0.75 times the Nyquist frequency. This points out a performance characteristic of the overall system, which is not seen by inspection of the direct image data, and which was unexpected initially. Such harmonic content would likely be important to transmission of image data at that spatial frequency.

Acknowledgements

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References

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