Compensation for gain nonuniformity and nonlinearity in HgCdTe infrared charge-coupled-device focal planes

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Abstract. Infrared CCD arrays generally require a compensation for the effect of gain and offset variation among the individual detectors of the array. Linear compensation techniques do not suffice for focal planes that exhibit a large nonlinearity of response combined with order-of-magnitude variations in threshold and saturation flux levels. This situation is common among hybrid architecture CCDs, particularly when HgCdTe is the detector material. This paper reports on a multipoint piecewise-linear correction scheme employed on a HgCdTe infrared CCD focal plane. This technique allows a compensated response to be obtained in a computationally efficient manner. An experimental relationship between the number of calibration points and the amount of residual fixed-pattern noise is presented and compared to previous analytical models.

Subject terms: charge-coupled devices; charge-transfer devices; focal plane arrays; fixed-pattern noise; nonuniformity compensation; nonlinearity compensation; flat-field test.

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CONTENTS

1. INTRODUCTION

Compensation for the effects of fixed-pattern noise and artifacts of array nonuniformity is a particularly important problem for detector arrays operating in the infrared region of the spectrum. Several factors combine to make this so. Infrared scenes are inherently of low contrast, so pertinent detail can be easily masked by pattern noise. The state of development of the detector materials is immature, particularly for the long wavelength region of the IR, encompassing the 8 to 12 μm atmospheric window. The developmental nature of the materials processing techniques contributes to the nonuniformity of response. The necessity for hybrid architectures for these detector materials is another source of nonuniformities, resulting from the coupling of the detectors themselves to the CCD structure fabricated of another material.

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The measurements and characterizations presented in this paper were performed on a hybrid focal plane array, with HgCdTe detectors gate-coupled to a silicon CCD structure. The responsivity function of the individual detectors (voltage output per unit of flux input) is a nonlinear function, generally of an "S" shape. The detectors exhibit a response region that is approximately linear in the middle, with noise floor and threshold effects at the low end and saturation effects at the high end of their response range. The usual technique for compensation of such detectors is a gain and offset correction, amounting to a linear interpolation between the measured response at two calibration values of input flux. This technique has seen wide application for compensation of IR focal plane responses.[1,2]

The problem to be addressed in this paper arises when the low and the high calibration flux values chosen for this compensation are not in the linear region of all of the detectors of the array, due to nonuniformity of the functional form that describes the individual response curves of the elements. For example, if the "hot shutter" value of flux, which is supposed to be near the high end of the usable dynamic range of the device, places a significant number of the detectors of the array into saturation, then the user is faced with two choices: either restrict the operating range of the device, in terms of incoming flux levels, or use a more complex calibration technique to compensate for this nonuniformity in detector nonlinearity.

The use of a piecewise-linear approximation for the input/output curve[2,3] allows the user to more adequately sample the response of each element. Their individual nonlinearities can be mapped more closely, so as not to require the assumption of a linear response for all elements

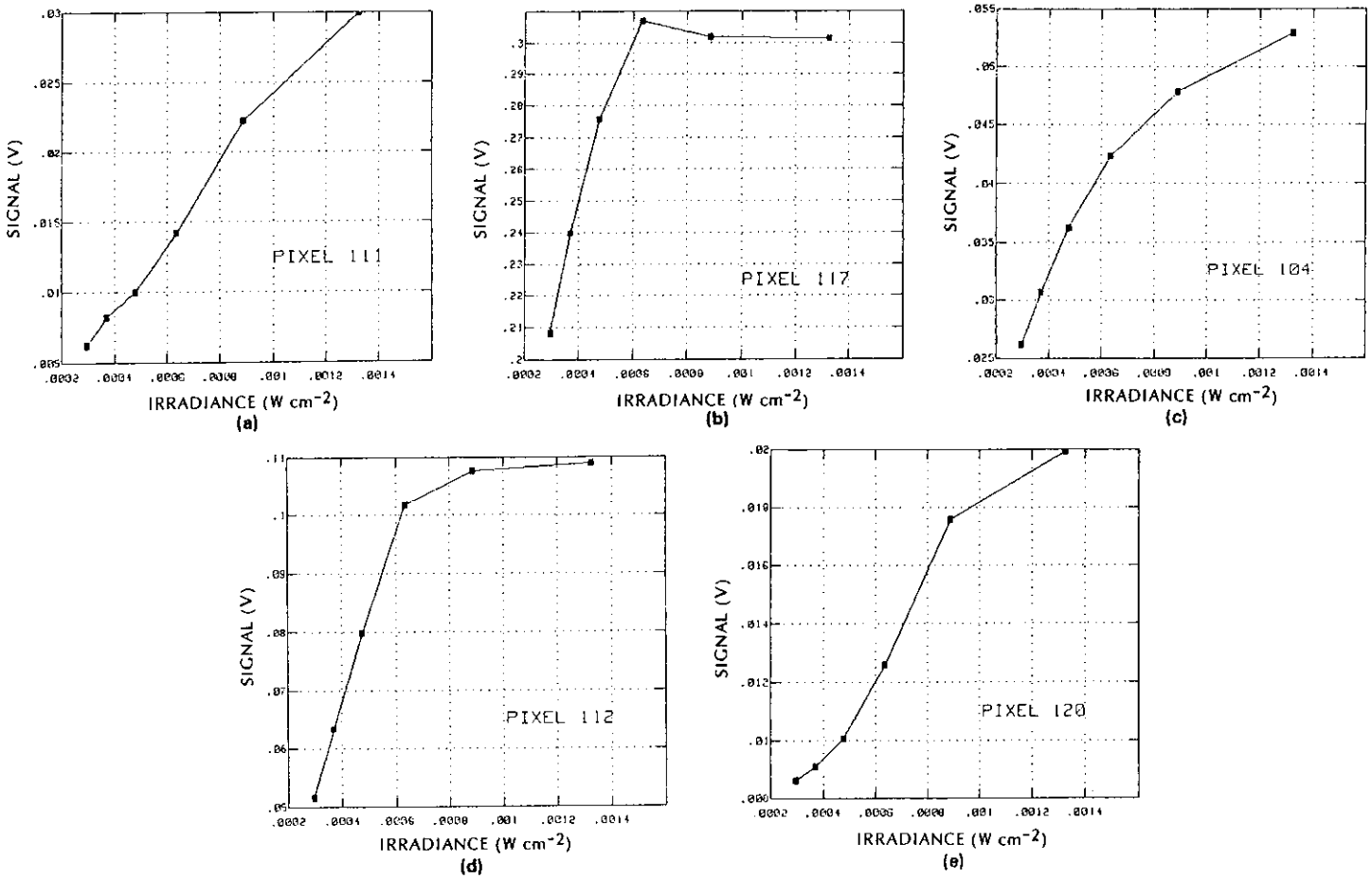

Fig. 1. Output voltage versus input irradiance for pixels (a) 111, (b) 117, (c) 104, (d) 112, and (e) 120.

between only two calibration values of input flux. It will be seen that this technique significantly reduces the variance of a "flat-field" response, that is, the compensated response of an array with a uniform flux scene input. The piecewise-linear technique is compatible with the computationally efficient algorithms necessary for IR focal plane applications and also may be of particular utility for scenes with higher than normal dynamic range. The paper also presents a comparison between previous analytical models and the experimental results, regarding the amount of residual fixed-pattern noise as a function of the number of correction points.

2. EXPERIMENTAL PARAMETERS

The architecture of the focal plane under test was two separate, staggered arrays, each with 120 columns and 16 rows. The array was intended for use in a time-delay-and-integration scanning mode. The array was operated in a staring mode, which allowed the collection and analysis of data sets corresponding to one row of 120 elements. The detectors themselves were HgCdTe, with a cutoff wavelength of 9.5 μm. These detectors were gate coupled into a silicon CCD structure. This input method by itself[1] would indicate the need for a nonlinear compensation scheme. The operating temperature was held within $\pm 2°$ of 76 K. The master clock frequency of the drive electronics was 1.6 MHz.

Digitization of the signal to 8 bits was accomplished with a TRANSIAC transient digitizer. Temporal noise on the pixels produced a time variation with $\sigma \approx 0.01$ V. A 10 frame average was performed for each of the data sets discussed herein to reduce the effect of random noise.

The experimental apparatus consisted of a 900 °C blackbody, with effective source diameter of 0.5 cm. The source was moved longitudinally along a linear track, and pixel response data were collected at various distances. Data cited in this paper were collected at distances of 48, 43, 38, 33, 28, and 23 cm from the source to the detector. The geometry was such that for all data collected, the blackbody was effectively a point source; that is, its irradiance across the focal plane was uniform and followed a $1/r^2$ falloff with range.

The set of pixels chosen for analysis was a subset of the 120 pixels contained in the digitized data sets. Seventeen contiguous pixels (Nos. 104 through 120) were chosen on the basis of their response uniformity, freedom from permanently saturated or permanently dead cells, and freedom from undue temporal noise.

3. RESPONSIVITY DATA

We begin by considering representative curves of output voltage versus irradiance, shown in Fig. 1, for some individual HgCdTe detectors in the array. One can readily see that there is a wide variation in gain and offset among the

detectors. This could be largely corrected with a standard linear interpolation scheme, but the *shapes* of the response curves show an effect that is harder to correct. There is a wide variation in the functional form of the curves and a variation in the flux level at which the individual pixels begin to saturate.

We now briefly consider representative examples of some of the specific forms seen in the individual response curves. Pixel 111, shown in Fig. 1(a), exemplifies a nearly linear response between the calibration points. Pixel 117, shown in Fig. 1(b), has a form that rises rapidly to a saturation level, past which the response decreases. This type of pixel cannot be accurately compensated for flux values past the initial saturation due to the lack of a single-valued mapping. Pixel 104, shown in Fig. 1(c), has a slowly varying curve of approximately parabolic form, which would exhibit its maximum error in the midflux range if modeled by a straight line. Pixel 112, shown in Fig. 1(d), exhibits three different slope regions, with some useful gain available even in the saturation region. This was the most common form of response curve seen on the array tested. Pixel 120, shown in Fig. 1(e), behaved in the classic "S" shape, exhibiting both floor and saturation effects.

If the responses of this set of pixels are required to conform to a linear curve between any two calibration values for irradiance, there will be a great deal of residual pattern noise remaining after correction due to the *variation* in nonlinearity exhibited. To be sure, a better correction could be achieved if each curve were individually fitted to a two-point linear interpolation, with its own region of validity. However, this is precluded in the usual linear compensation procedure for an array of detectors, which dictates a choice of two flux calibration values that are within the linear region for "most" pixels. A multipoint piecewise-linear correction scheme allows the user to adequately sample the individual response curves over the entire dynamic range of interest. This results in a much more accurate compensation model while still retaining the inherent simplicity of the linear compensation algorithm.

4. ANALYSIS

In this section, we compare the states of correction obtained by two compensation schemes. A "flat-field" test is performed on the 17 pixel data set under a standard two-point linear interpolation and under a four-point piecewise-linear interpolation. This yields an experimental relationship between the number of calibration points and the residual fixed-pattern noise in the detector, as measured by the standard deviation of the flat-field pixel values.

4.1. Two-point interpolation

In this paper, we refer to a two-point interpolation as a correction for offset and gain nonuniformity by the standard linear compensation technique. We chose irradiance values for the "cold shutter" and the "hot shutter" that are in the linear region for most of the detectors. As seen in Fig. 2, the "cold shutter" value of irradiance used was 3.0×10^{-4} W/cm^2 and the "hot shutter" value was 8.9×10^{-4} W/cm^2. The equation for the straight line joining these points (different for each pixel) was used to estimate the value of incident irradiance, given the voltage response corresponding to

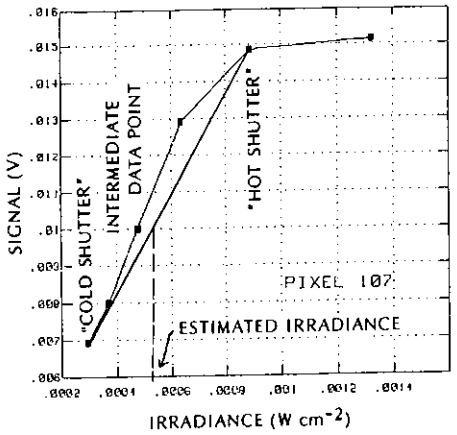

Fig. 2. Two-point interpolation applied to pixel No. 107.

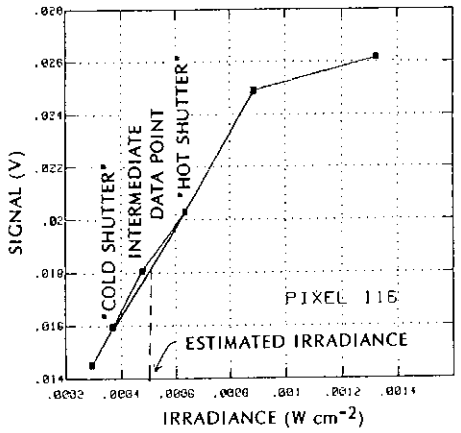

Fig. 3. Four-point interpolation applied to pixel No. 116.

an unknown flux level between the two calibration levels. This estimate of irradiance is in error due to the nonlinearity of the response curve between the "cold shutter" and "hot shutter" values.

4.2. Four-point interpolation

In the more exact piecewise-linear compensation technique seen in Fig. 3, we use a "cold shutter" irradiance of 3.7×10^{-4} W/cm^2 and a "hot shutter" irradiance of 6.4×10^{-4} W/cm^2. Again, the voltage response for an unknown flux value is used to estimate the irradiance that caused it, using a linear interpolation between the calibration points. The error incurred in this case is generally smaller due to the more accurate piecewise-linear model.

This technique is termed "four point" even though it still is an interpolation between two response values, since the spacing of the calibration points is determined by the number of calibration data points recorded. This technique could be used to estimate irradiance values even into the saturation region if one used the highest irradiance value taken (1.3×10^{-3} W/cm^2) as a calibration point. The difference between the coarse and fine interpolation schemes then would be even more pronounced. Such a piecewise-linear algorithm does not require more bits of resolution in the data but rather more calibration data to be stored in memory. It is necessary in actual use to partition incoming

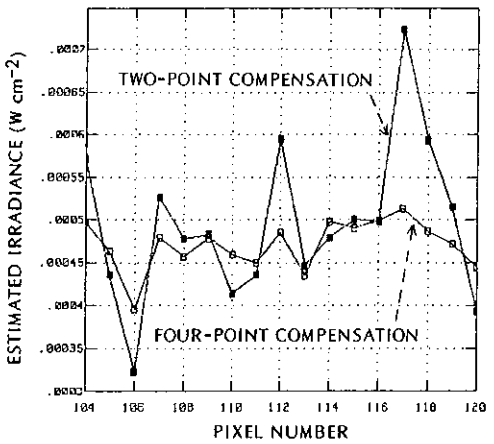

Fig. 4. Comparison of flat-field plots for two-point and four-point compensation.

values of signal to their appropriate linear correction region before performing the compensation.

4.3. Flat-field test

To quantify and display the difference in performance between the two compensation methods, a "flat-field" test was performed on the data. A known, uniform value of irradiance is incident on the array. Ideally, this would produce a flat plot of estimated irradiance versus pixel number, corresponding to the value of the uniform irradiance incident on the array. Figure 4 shows actual plots of estimated irradiance versus pixel number for the two-point and four-point compensation schemes. These plots were done for an actual incident irradiance of 4.8×10^{-4} W/cm^2. Flat-field plots are parametrized on irradiance. As stated previously, the value of irradiance for these plots was in the nearly linear range for most of the detectors. Had the test value of irradiance been higher or lower, into either the threshold or the saturation region, more of the dynamic range of the device would have been used. In that case, the differences between the two compensation schemes would have been even more pronounced.

Data from the two-point test yields an average estimate for irradiance of 5.0×10^{-4} W/cm^2, with $\sigma = 9.3 \times 10^{-5}$ W/cm^2. Data from the four-point test produced a closer estimate of irradiance of 4.7×10^{-4} W/cm^2, with a smaller $\sigma = 2.8 \times 10^{-5}$ W/cm^2.

For the flat-field test, the dependence of σ on the number of calibration points used can be usefully compared with the analytical model presented in Ref. 2. In that model, a parabolic form was assumed for the detector response curves, and it was assumed that there were no inflection points of the responses within the range of flux values used for calibration. Under these conditions, a $1/N^4$ dependence was derived for the σ values in a flat-field test, where N is the number of subintervals. In our comparison, the actual value of improvement in σ seen experimentally between one subinterval and three (a factor of 3.3) is much lower, largely because the detector responses are generally more complex than parabolic.

5. CONCLUSIONS

Experimental data have shown the usefulness of a piecewise-linear algorithm for correcting the nonuniformity and nonlinearity of response of a HgCdTe focal plane array. A decrease in the standard deviation of the irradiance estimates by a factor of approximately 3.3 was obtained in going from a two-point to a four-point correction scheme. This method was shown to be useful to extend the dynamic range of the focal plane. A major advantage of this type of approach is that the calibration values of irradiance need not lie within the linear region for all of the detectors on the focal plane. This is a useful property, considering the variation seen in the individual element responses, as far as threshold and saturation levels are concerned.

6. ACKNOWLEDGMENTS

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