Pointing Accuracy Improvement using Model-Based Noise Reduction Method

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ABSTRACT

A new method for improving centroid accuracy, thereby pointing accuracy, is proposed. Accurate centroid estimation is critical for free-space optical communications where the number of photons from the reference optical sources such as stars or an uplink beacon is limited. It is known that the centroid accuracy is proportional to the SNR. Presence of various noise sources during the exposure of CCD can lead to significant degradation of the centroid estimation. The noise sources include CCD read noise, background light, stray light, and CCD processing electronics. One of the most widely used methods to reduce the effects of the noise and background bias is the thresholding method, which subtracts a fixed threshold from the centroid window before centroid computation. The approach presented here, instead, utilizes the spot model to derive the signal boundary that is used to truncate the noise outside the signal boundary. This process effectively reduces both the bias and the random error. The effectiveness of the proposed method is demonstrated through simulations.

Key words: pointing, centroid estimation, optical communications

1. INTRODUCTION

Accurate centroid estimation is a critical task for a beacon based pointing system. A recent study shows that the centroid error (random and bias error) for deep space optical communications needs to be less than $1/20^{th}$ pixel whereas the total pointing error allowed (1 sigma) is $1/16^{th}$ pixel [4,5]. Two types of centroid errors, random and bias, are affected by various sources. A random error is caused by noises such as CCD read noise, shot noise, dark current, and ADC quantization noise. A bias error occurs when non-uniform background light such as straylight and Earth background image exists.

Conventional methods to reduce the noise and bias include the thresholding and centroiding of the normalized zero-crossings [2,3]. For the thresholding method, an estimated threshold is subtracted from the centroid window, which equivalently performs a bias subtraction and eliminates the noise. This method can be effective when the threshold value takes out most of the bias and the noise. However, a simple threshold, in general, is not effective since the threshold value is dependent on the brightness of the image and the number of pixels forming the object may be altered by the thresholding process [2]. To avoid this problem, the use of zero-crossings for centroid estimation was proposed [2]. The limitation of this approach is that it is only applicable to the center of mass estimation and assumes equal weighting on every pixel.

For the same objective of reducing the effects of noise, there were suggestions to use only nine pixels around the signal peak [7,8,9]. This truncation simplifies and speeds up the centroid calculation without affecting the centroid accuracy only if the signal is limited to this small local region. As was indicated in [6], however, the truncation of the wide signal considerably affects the accuracy of centroid estimation. Therefore, the number of pixels used in centroid estimations needs to be carefully selected so as not to sacrifice the centroid accuracy.

In this paper, we propose to use a spot model to determine which pixels are used for centroid estimation. A spot model can be constructed from the characterization of optical systems (PSF of optical system). On the centroid window, which is usually several pixels larger than beacon spot size to allow beacon motion, the approximate signal boundary of a beam spot can be estimated from the spot model and the measured noise level. Once the boundary is identified, the pixels to the signal boundary can be set to zero, effectively eliminating all the noise and bias outside the beam spot.

The organization of the paper is as follows. In section 2, we will present the effects of noise on centroid accuracy. In section 3, the model-based noise reduction method is presented. In section 4, simulation results are presented.

2. EFFECT OF NOISE AND BIAS ON CENTROID ACCURACY

The equations for centroids (center of brightness) for spots on CCD type of focal plane arrays is well known [5]:

$$C_x = \sum_i i p_{ij} / \sum_{ij} p_{ij} \ , \ C_y = \sum_j j p_{ij} / \sum_{ij} p_{ij} \qquad (1)$$

where i and j is x and y axis coordinates, P_{ij} is the output of $(i,j)^{th}$ pixel value of CCD.

From Eq.(1), it is clear that the noise or bias closer to the edges of the centroid window dominates the centroid error due to larger weighting factor as coordinates increases toward the edges. This is one of the most important motivations of this paper.

Equation for the random centroid error (or NEA, noise equivalent angle) from [5] is summarized here:

$$\mathrm{NEA} = \mathrm{sqrt}(\ (S + N_P(\mathrm{Var}(R_F) + \Delta t\ R_T))/S^2)N(N + 1)/3\ ) \qquad (2)$$

Where S = total signal.
Δt = the exposure time.
N = Truncated half width of centroiding area.
N_P = Number of pixels involved in the centroiding area, $N_P = (2N+1)^2$
R_F = Fixed per pixel noise (1σ), such as read noise.
R_T = Per pixel background signal (including straylight and dark current).

EQ.(2) indicates that NEA is inversely proportional to SNR. Therefore, either the signal needs to be increased or the noise needs to be decreased in order to reduce the NEA. This implies that the effect of the noise is small if the signal is relatively larger than the noise and vice versa. To illustrate this, let's take an example where the spot signal is low. For deep space optical communications that may require stars as a beacon source, the minimum signal available from 11^{th} star with 30cm telescope is 10,000 photons with 25% system efficiency [5]. Assuming CCD QE of 50%, this translates to 5000 electrons. In this example, the reduction of the centroid window size improves the centroid accuracy significantly if that does not truncate the signal notably. The allocated error for NEA in [5] is $1/25^{th}$ of the pixel. Plots of the NEA vs. the number of pixels used in centrod estimation were shown in Figure 1. The assumptions are the same fixed per pixel noise ranging from $5e^-$ to $20e^-$ with no background signal. Figure 1 shows that NEA increases more rapidly with larger fixed per pixel noise as the number of pixels (used in centroid estimation) increases.

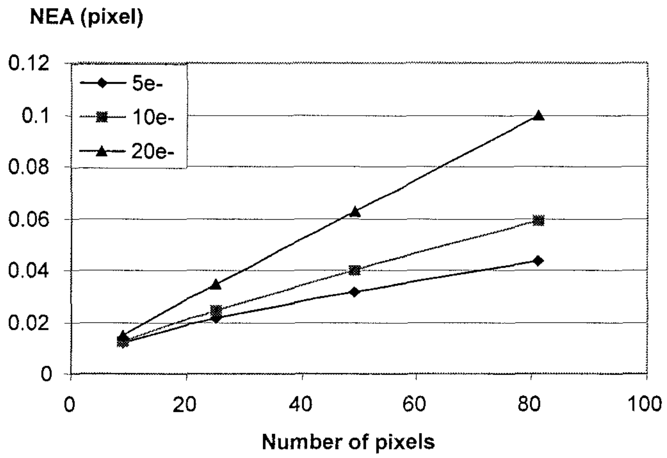
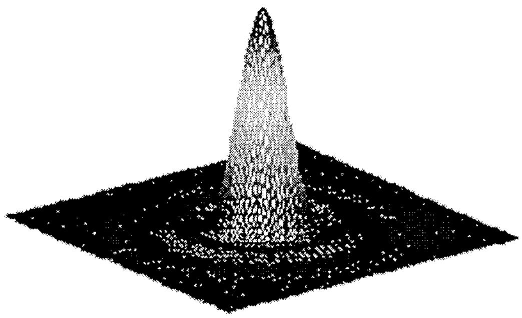
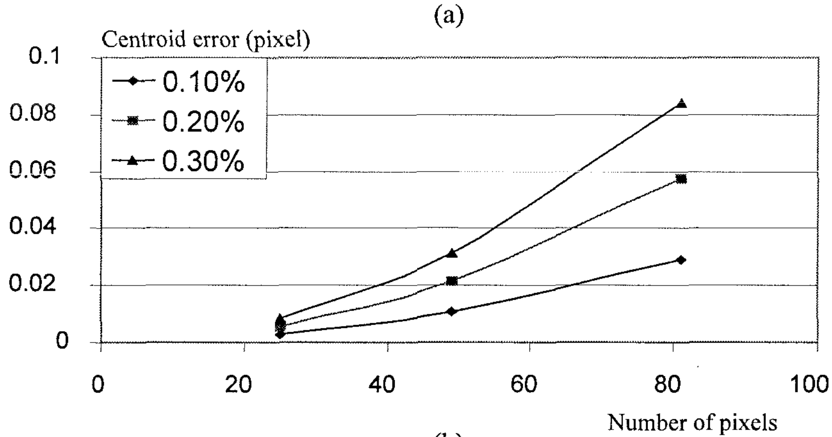


Figure 1. Effect of the number of pixels used in centroid estimation. NEA increases as the number of pixels increases and more rapidly with larger noise level.

Bias error, which can be mitigated by centroiding algorithm, is caused by non-uniform signal distribution, which include straylight and background image. This corresponds to the cases where the telescope is pointing toward the Earth or close to the Sun. Even if background subtraction were applied, there would be some bias left, especially if the threshold is below the maximum of the background signal. As Figure 2 shows, even 0.1% of the peak spot value as the maximum bias value, can cause considerable bias error if the centroid window size is large, 9x9 pixels in this example.



(a)



(b)

Figure 2. (a) Airy pattern spot used in the simulation, (b) Bias centroid error vs. the number of pixels used in centroid estimations at bias values from 0.1% to 0.3% of the peak pixel value

3. MODEL-BASED NOISE REDUCTION

The two key issues in our approach are construction and the use of the spot models in centroid estimations. This is summarized in block diagrams in Figures 3 and 4, respectively.

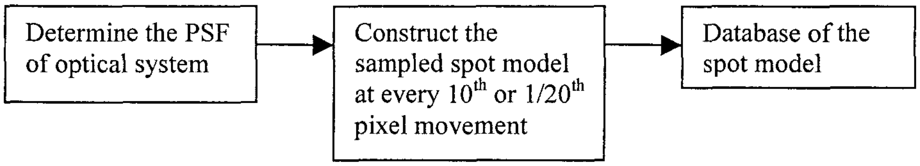


Figure 3. Construction of Spot Model

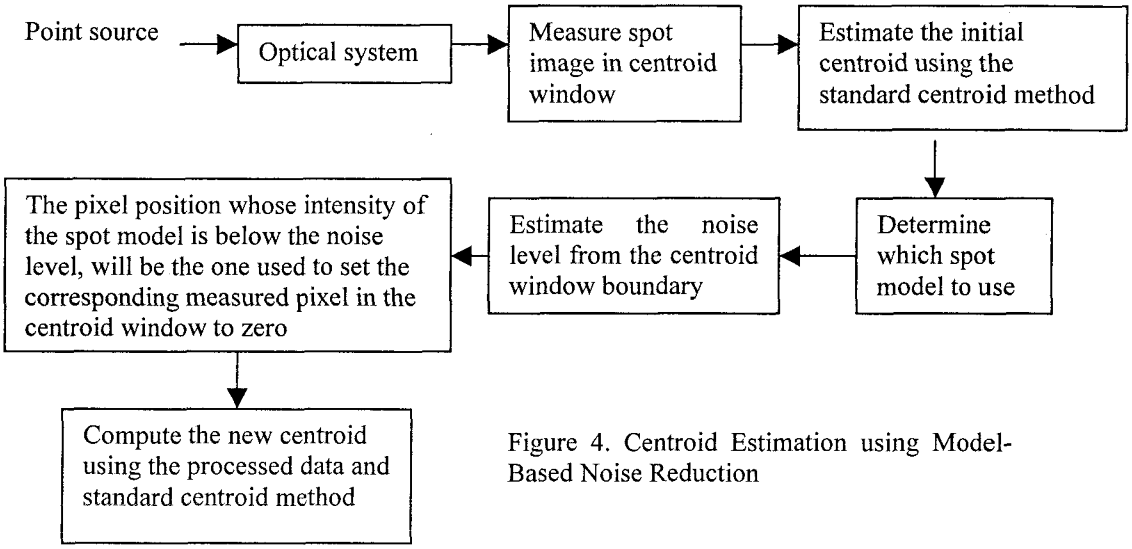


Figure 4. Centroid Estimation using Model-Based Noise Reduction

In construction of spot models, the PSF is sampled (spatially quantized) at every $1/N^{th}$ pixel movement. This forms a spot model at the specific location of PSF relative to the sub-pixel positions. Beyond a certain resolution, the benefits of finer resolution are expected to diminish. In this paper, N=10 was used.

Once the database of spot models is constructed, each model can be used to determine which pixels in the measured spot image (corrupted by noise) should be truncated. As illustrated, the rough centroid estimate is obtained using the standard (center of brightness) centroid algorithm. This centroid is used to determine which spot model should be used. If the error in the rough centroid estimate exceeds the pixel movement determined by N, then the incorrect spot model can be selected. The effect of incorrect spot models is presented in section 4. Once the spot model is determined, the next task is to estimate the noise level present in the centroid window. There can be many ways to best estimate the noise level. In this paper, we used simple mean of four edge lines. This noise level is compared with the spot model. If the pixel value of the spot model is smaller than the noise level, the pixel position is used to truncate the pixel in the centroid window. Once this process is completed over the entire pixels of both spot model and the centroid window, truncation of the noise is complete. The final task is to apply the standard centroid algorithm to the truncated centroid window to obtain the new centroid value. The process of forming signal boundary is illustrated in Figure 5 using one-dimensional, continuous signal.

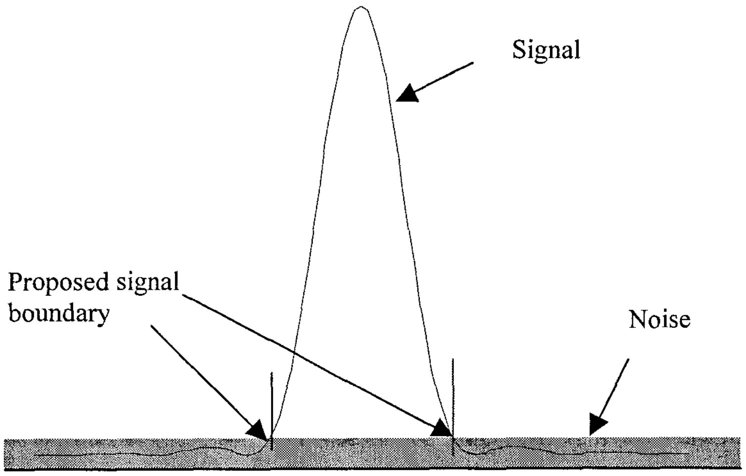


Figure 5. Proposed signal boundary to reduce noise

4. SIMULATION RESULTS

The objective of the simulation is to show the effectiveness and robustness of the model-based noise reduction method in centroid estimation. For this objective, three cases were investigated.
These are:

(a) Comparison of three centroiding algorithms (including model-based) at various noise levels given the total signal equivalent to $5000e^-$.
(b) Comparison of three centroiding methods on the bias error.
(c) Three scenarios of using incorrect spot models were used: incorrect models at 0.1 pixel, 0.2 pixel, and 0.3 pixel used to show the robustness of the model-based method.

4.1 Comparison of three centroiding algorithms

Three algorithms were run 100 times for a fixed noise value and the noise was increased from $10e^-$ equivalent to $100e^-$ equivalent (Gaussian noise with 1 sigma value from $10e^-$ to $100e^-$ equivalent). The 1sigma error and mean error were computed and plotted in Figure 6. As is shown, the model-based algorithm outperforms the other two methods: standard centroid and thresholding method. The strength of the model-based method is not only the much smaller centroid error but also its immunity to the noise as demonstrated in both plots. As the noise increases, the centroid error from the standard and thresholding methods also increases. However, the model-based method exhibits almost steady error.

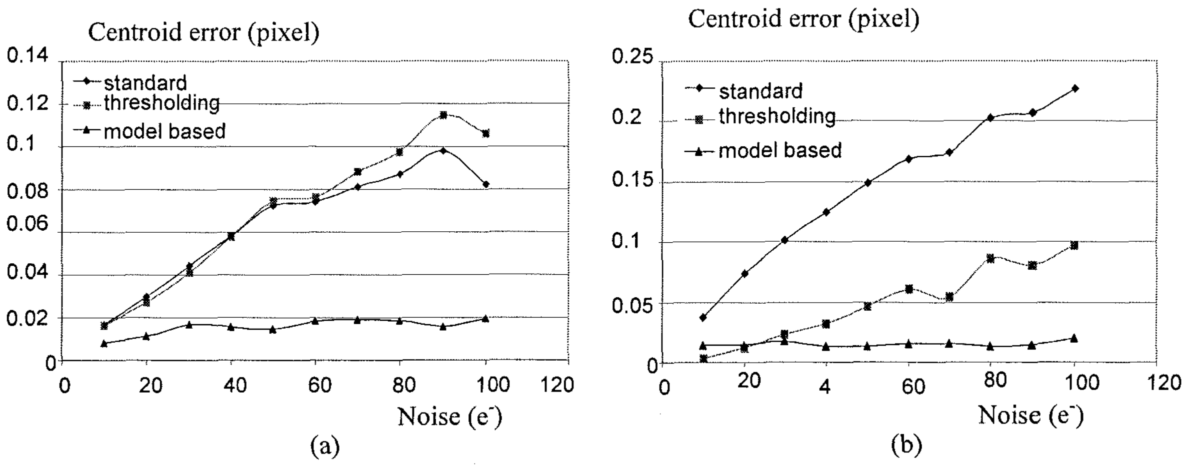


Figure 6. Comparison of three centroid methods: standard centroid, thresholding method, and model based method. Plots shows the centroid error vs. fixed per pixel noise (equivalent to electrons based on total signal of 5000e$^-$): (a) 1 sigma random error, (b) mean error

4.2 Comparison of three centroiding algorithms on bias error

The objective of this simulation is to compare the effect of bias in the spot image on the three centroid methods. As was evident in EQ (1), even the model-based method would be affected by the presence of the background bias unless complete removal of the bias is conducted. In the simulation, bias value was selected based on the peak pixel value that is 28.5% of the total signal. Maximum bias was varied from 0.1% to 1% of the peak pixel value. Figure 7 shows the simulation results. As expected, the model-based method outperforms the other two that exhibits linear relationship between the bias value and the centroid error.

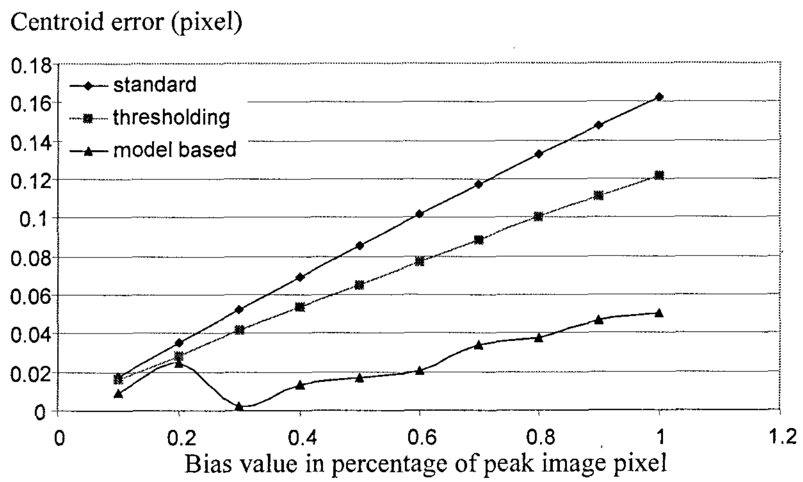


Figure 7. Bias was added to the spot image and three centroid methods were applied. Bias value increases from 0.1 to 1 percent of peak pixel value of the spot image. In this example, the peak pixel value is 28.5% of the total image energy.

4.3 Model-based centroid algorithm – when incorrect spot models are used

This time, the model-based algorithm was run 100 times at each noise level for three scenarios: first one using incorrect spot model which is 0.1 pixel different from the true spot model, the second one is 0.2 pixel different, and the third one is 0.3 pixel different. The objective is to verify the robustness of the model-based method. Overall, the performance is affected by the accuracy of the spot model as shown in plot (b) of Figure 8. However, this distinction is not obvious as the noise increases. Furthermore, some improvements are seen for the case of spot models with 0.2 and 0.3 pixel different. This improvement is due to the fact that the added noise increases the noise level, which then limits the number of pixels used in centroid computation. Notice both 1 sigma and mean errors are in the neighborhood of $1/50^{th}$ of pixel!

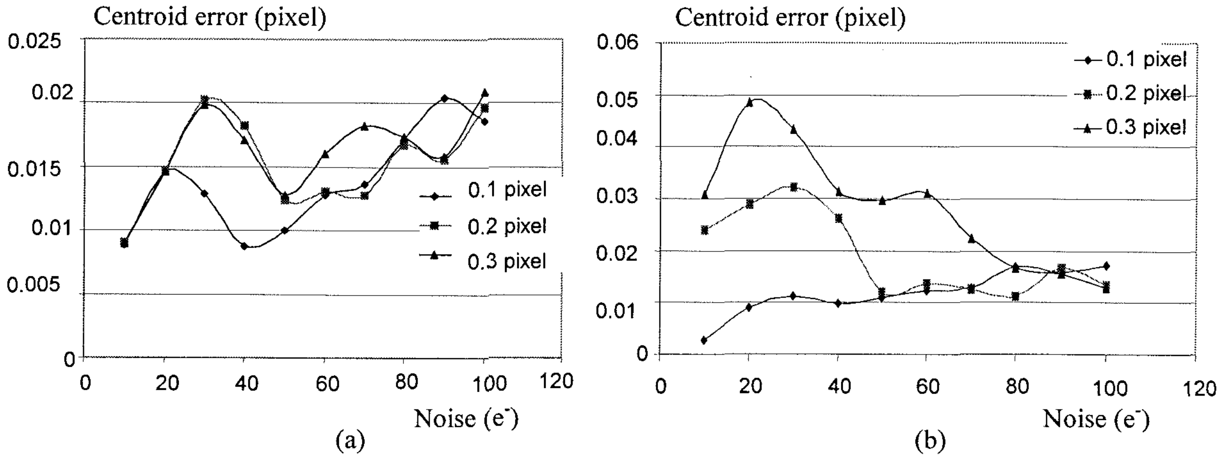


Figure 8. Incorrect spot models were used to see the effects on centroid error. Centroid error vs. fixed per pixel noise (equivalent to electrons based on total signal of 5000e$^-$): (a) 1 sigma error, (b) mean error

5. CONCLUSION

A new method based on the spot model was proposed to improve centroid estimates of a point source image. The new method assumes the spot model can be used to truncate noise and bias in the measured spot, thereby improving centroid estimates. Simulations were performed to demonstrate the effectiveness of the proposed method for noise and bias. Compared with the standard centroiding and the more advanced thresholding method, the model-based method turned out to be superior in accuracy. From the simulation where the incorrect spot models were intentionally used, the effect on its performance was minimal, especially at high noise level. Since this method was intended for low SNR signal, it could prove to be essential for deep space missions, where the strong optical signal is not readily available.

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