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Impact of the SPIRIT III sensor design on algorithms for background removal, object detection, and point source extraction*

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ABSTRACT

This paper describes background removal, point source detection, and position and irradiance extraction data processing algorithms that have been developed for the Spatial Infrared Imaging Telescope (SPIRIT) III design. The SPIRIT III sensor is the primary instrument on the Midcourse Space Experiment (MSX) satellite and is scheduled for launch in early 1996. The sensor consists of an off-axis reimaging telescope, and, among other instruments, a six-band scanning radiometer that covers the spectrum from midwave infrared to longwave infrared. The radiometer has five arsenic-doped silicon (Si:As) focal plane detector arrays with 8×192 pixels. The angular separation between adjacent pixels is $90 \mu\text{rad}$. A single axis scan mirror can operate at a constant 0.46 deg/sec scan rate to give programmable fields of regard of 1×0.75 , 1×1.5 , and 1×3 degrees or can remain fixed. Scanned images are non-uniformly sampled because of non-linear scan mirror motion, array misalignment, optical distortion, detector readout ordering, and satellite rotation. In addition, three of the five arrays contain multiple cross-scan aligned columns of pixels that give scanned images that have spatially overlapping in-scan data. Algorithms for processing data sampled on a uniform grid, such as data obtained from a CCD array, are enhanced and applied to the SPIRIT III radiometer where scanned images are non-uniformly sampled and have spatially overlapping data. The performance of these algorithms are evaluated with point source data acquired during ground measurements.

Keywords: SPIRIT III, point source, background subtraction, non-uniform sampling

1. INTRODUCTION

The Spatial Infrared Imaging Telescope (SPIRIT) III sensor is the primary instrument on the Midcourse Space Experiment (MSX) satellite, which is scheduled for launch early in 1996. SPIRIT III consists of an off-axis reimaging telescope with a 35 cm-diameter unobscured aperture, a six-channel Fourier-transform spectrometer, a six-band scanning radiometer, a cryogenic dewar/heat exchanger, and instruments to monitor contamination levels and their effects on the sensor.^{1, 2}

The radiometer has five arsenic-doped silicon (Si:As) focal plane detector arrays of 8×192 pixels each, operating at between 10K and 12K. The detector geometry is shown in Figure 1. Note that left side detector columns are offset from the right side by one half of a pixel. Also, although each array is fully populated, not all detector columns are recorded. The number of active columns is 8 for array A, 2 for array B, 4 for array C, 4 for array D, and 2 for array E. The radiometer collects data in six color bands covering the spectrum from the midwave infrared ($4.22 \mu\text{m}$) to the very longwave infrared ($26.0 \mu\text{m}$), and has a spatial resolution of $90 \mu\text{rad}$. The radiometer scan mirror can remain fixed or can operate at a constant 0.46 deg/sec scan rate with programmable fields of regard of 1×0.75 , 1×1.5 , and 1×3 degrees.

This paper describes how the SPIRIT III sensor design has influenced data processing algorithms for determining the position and irradiance for each point source identified in a scene of data. This process will be referred to as point source extraction (PSE). The PSE operation consists of position tagging, background subtraction, object identification, point source discrimination, and determining a position and amplitude for each identified point source. This process extracts point sources from data collected with the scan mirror in either stare mode or scanning mode. A block diagram of the PSE operation is shown in Figure 2. For the purposes of this paper, we will assume that the following pixel-response corrections have been ap-

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Figure 1. Geometry of the SPIRIT III radiometer.

plied: dark offset correction, linearity correction, integration mode normalization, non-uniformity correction, and that dead or anomalous pixels have been removed.³

One of the primary goals for these algorithms is to provide a baseline against which other, perhaps more sophisticated, algorithms may be compared. Because they are intended to be used in this way, the goal for these algorithms is to produce position estimates to within 0.05 pixels (about 5 μ rad), and radiometric uncertainties of about 1% under the following conditions:

1. No objects (point sources) are closer than six detectors.
2. The signal-to-noise ratio (SNR), defined as the point source peak amplitude divided by the noise standard deviation, is greater than or equal to 10.
3. Spacecraft rotation relative to the object must be less than 1/50 detector/(minor frame) in scanning mode.
4. Spacecraft rotation relative to the object must be constant in the in-scan direction and near zero in the cross-scan direction and there must be no rotation about the boresight axis in stare mode.

The remainder of the paper is organized as follows. Section 2 describes time and position tagging of the pixel data. In this step, each pixel in all columns of an array is time tagged and then position tagged, creating a non-uniformly sampled scene of data. Section 3 describes the algorithm for removing background from the scene. The process of determining which areas of a scene are responses to objects, and which of those objects are likely to be the instrument response to a point source is described in Section 4. Section 5 describes the algorithm for determining the position and irradiance of each point source, Section 6 gives results based on ground calibration data, and Section 7 provides a summary.

Figure 2. Point source extraction block diagram.

2. TIME AND POSITION TAGGING

The first step in the point source extraction algorithm is to organize the data from each detector column into a column “scene”. We begin by tagging each detector pixel with a time. There is a slight time lag from the time when a detector is sampled until the beginning of the minor frame in which it is read out. The detector sample time is given by the following equations. For the Rockwell arrays, arrays C, D, and E, the detector sample time $t_{a,r,c}$ for array a , detector row r , detector column c is given by

$$t_{a,r,c} = t_m - a_1^{\text{det}} N - a_0^{\text{det}}, \quad (1)$$

where t_m is the minor frame time in milliseconds, N is the telemetry ordered pixel row number, and a_0^{det} and a_1^{det} are readout period and offset coefficients which are integration mode and array dependent.⁴ For the Aerojet arrays, arrays A and B, $t_{a,r,c}$ is given by

$$t_{a,r,c} = t_m - a_1^{\text{det}} \left\lfloor \frac{N}{2} \right\rfloor - a_0^{\text{det}}, \quad (2)$$

where the notation $\lfloor N/2 \rfloor$ denotes the largest integer less than or equal to $N/2$. The readout period and offset coefficients were determined based on an analysis of the SPIRIT III electronics. The coefficients are integration mode and array dependent.

Next we determine the scan mirror position at the time the scan mirror was sampled for each minor frame by evaluating a scan-mirror transfer function $F_{scn}(enc)$. The scan-mirror transfer function relates the scan mirror encoder readout enc to scan mirror angle in what we will refer to as the focal plane coordinate (FPC) system. The FPC system is not corrected for array coalignment or optical distortion.⁵

A slight time lag exists from the time when the scan mirror encoder count is sampled until the beginning of the minor frame in which it is read out. To account for this time lag, each scan mirror position is time tagged using

$$t_{sm} = t_m - a_0^{sm} - C a_1^{sm}, \quad (3)$$

where t_{sm} is the scan mirror sample time in milliseconds, t_m is the minor frame time in milliseconds, a_0^{sm} is the mirror readout offset coefficient, a_1^{sm} is the mirror position counter, and C is the output of a mirror position counter that counts the amount of time that has elapsed between the minor frame time and scan mirror sample time.

The mirror position $MP(t_m)$ at the minor frame time t_m is interpolated by evaluating a linear fit of time tagged scan mirror positions at time t_m . The linear fit uses only valid minor frames within a window of 5 minor frames before and 5 minor frames after t_m . If the scan mirror is at either edge of the scan, then as few as 6 minor frames are used in the linear fit. Given $MP(t_m)$ the in-scan FPC position is computed using:

$$in_{a,r,c}^{fpc} = MP(t_m) - v(t_m - t_{a,r,c}), \quad (4)$$

where v is the approximate scan velocity, taken as $v = -8.1$ $\mu\text{rad/sec}$ for a forward scan and $v = 8.1$ for a reverse scan, or as the spacecraft rotation rate about the X axis if the scan mirror is in hold mode. The cross-scan FPC position is given by:

$$cr_{a,r,c}^{fpc} = (C_{ref} - r) S_{pix} + C_c, \quad (5)$$

where $C_{ref} = 95$ denotes the index of the reference detector in the column, $S_{pix} = 90$ $\mu\text{rad/detector}$ is the nominal pixel spacing, and C_c is the stagger for column c ; $C_c = 45$ μrad for columns on the right side of the stagger, and $C_c = 0$ μrad for columns on the left side of the stagger.

The next step in the position tagging process is to adjust the position of each sample to account for the spatial orientation of the array. This adjustment coaligns the pixels for all detectors, but does not account for optical distortion. This step also defines the boresight, which is the midway point between arrays A and C at the cross-scan center of the arrays. The in-scan coaligned position for array a , detector row r , column c is given by:

$$in_{a,r,c}^{co} = in_{a,r,c}^{fpc} + a_a^{tilt} cr_{a,r,c}^{fpc} + a_{a,c}^{in}, \quad (6)$$

where a_a^{tilt} is a coefficient relating to the physical tilt of array a , and $a_{a,c}^{in}$ is the in-scan offset coefficient for array a , column c . The cross-scan coaligned position is given by:

$$cr_{a,r,c}^{co} = a_a^{scale} cr_{a,r,c}^{fpc} + a_a^{cr}, \quad (7)$$

where a_a^{scale} is the cross-scan scale factor for array a and a_a^{cr} is the cross-scan offset coefficient for array a .

The last step in the position tagging process is to correct for optical distortion. This correction is given by

$$in_{a,r,c}^{sp3} = D_a^{in}(in_{a,r,c}^{co}, cr_{a,r,c}^{co}), \quad (8)$$

and

$$cr_{a,r,c}^{sp3} = D_a^{cr}(in_{a,r,c}^{co}, cr_{a,r,c}^{co}), \quad (9)$$

where D_a^{in} and D_a^{cr} denote the in-scan and cross-scan distortion functions for array a . These functions are approximated using a 5th order polynomial in the in-scan direction, and a 6th order polynomial in the cross-scan direction. We will refer to this distortion-corrected coordinate system as the *SPIRIT III coordinate system*.

The result of this sequence of operations is a non-uniformly sampled scene for each detector column of each array. The scenes are coaligned, and the goniometric effects of optical distortion have been removed.

3. BACKGROUND REMOVAL

Background subtraction is performed on one detector row of data in a scene at a time. A detector row is defined as all samples $\hat{d}_t$ from a given detector in a scene, ordered with respect to in-scan position x_t , where t denotes time. Given window width w , let the local mean, μ_t , be defined as

$$\mu_t = \left(\frac{1}{N_t} \right) \sum_{\tau \in T_w(t)} \hat{d}_\tau, \quad (10)$$

where $T_w(t) = \{\tau \mid |x_\tau - x_t| < w\}$ and where N_t is the number of samples,

$$N_t = \sum_{\tau \in T_w(t)} 1. \quad (11)$$

Let the local standard deviation, σ_t^2 , be defined as

$$\sigma_t^2 = \left(\frac{1}{N_t} \right) \left(\sum_{\tau \in T_w(t)} \hat{d}_\tau^2 \right) - \mu_t^2. \quad (12)$$

The detector row of data is divided into two sets. Given some threshold T , the first set contains samples which are thought *not* to be responses from point sources, and is defined as:

$$R_B = \{\hat{d}_t \mid \sigma_t < T\}. \quad (13)$$

The second set contains samples which are thought to be responses from point sources with a background, and is defined as:

$$R_P = \{\hat{d}_t \mid \hat{d}_t \notin R_B\}. \quad (14)$$

The background b_t for any sample $\hat{d}_t \in R_B$ is given by $b_t = \mu_t$. The background for each sample $\hat{d}_t \in R_P$ is determined by linearly interpolating, using the determined background of the samples in the first set which are closest to the given sample. Specifically, for any sample $\hat{d}_t \in R_P$ let

$$\tau_t^L = \operatorname{argmax}_\tau \left(\{x_\tau \mid \hat{d}_\tau \in R_B \text{ and } x_\tau < x_t\} \right), \quad (15)$$

and let

$$\tau_t^U = \operatorname{argmin}_\tau \left(\{x_\tau \mid \hat{d}_\tau \in R_B \text{ and } x_\tau > x_t\} \right). \quad (16)$$

Then

$$b_t = \left(x_t - x_{\tau_t}^L \right) \left(\frac{\mu_{\tau_t}^U + \mu_{\tau_t}^L}{x_{\tau_t}^U + x_{\tau_t}^L} \right) + \mu_{\tau_t}^L. \quad (17)$$

The background subtracted data are given by:

$$d_t = \hat{d}_t - b_t. \quad (18)$$

The threshold T is set to the n th quantile of σ_t computed over all t for a particular pixel. This allows the threshold to self-adjust according to the noise on a particular detector. This technique assumes that the background is slowly changing, and uses a linear model for the background in regions likely to be responses to point sources. This is only a slight extension of a similar technique which has been used successfully to analyze data from the Brilliant Eyes Proof Of Principal (BEPOP) instrument.⁶

4. POINT SOURCE DETECTION

After the background subtraction step, all samples from an array are combined into one set. We denote the in-scan position, cross-scan position, and amplitude of the i th sample of the set using x_i , y_i , and d_i respectively.

An object is defined as the set of samples in a scene that exceed a threshold, and which are within some radius of another sample in the object. Given some constant a , and the standard deviation σ and mean μ of the samples within a scene, the threshold is calculated as

$$T_B = a\sigma + \mu. \quad (19)$$

The set of samples that exceed the threshold is defined as:

$$D_b = \{d_i | d_i > T_B\}. \quad (20)$$

For each sample, $d_i \in D_b$, determine the set of samples S_i that lie within some radius r of that sample:

$$S_i = \{d_j | (x_i - x_j)^2 + (y_i - y_j)^2 < r^2, d_j \in D_b\}. \quad (21)$$

Identify each sample in S_i using the same object identification. Also, recursively identify each sample in S_j , where $d_j \in S_i$ with the same object identification as those samples in S_i .

To determine which objects are likely to be the response of the instrument to a point source, we compute the following statistics for each object: total intensity I_i , total square intensity I_i^2 , in-scan centroid x_i , cross-scan centroid y_i , in-scan second moment $\mu_{0,2}$, cross-scan second moment $\mu_{2,0}$. These statistics are used to determine how spherical the object is, as well as its size and an estimate of its irradiance. Each object whose statistics pass the point source criteria are flagged as point sources and extracted. In principle, this is only a slight extension of a similar technique which is used to determine objects in uniformly sampled images, such as that obtained from a CCD array. In practice, however, the computation is made much more difficult by the fact that the position of each pixel has to be checked to determine its distance from any other pixel. The result of this step is a list of point sources in each scene that contains a rough estimate of the position and irradiance of each point source.

5. POSITION AND IRRADIANCE EXTRACTION

The position and irradiance of a point source are extracted by minimizing a cost function J that quantifies differences between a scaled, shifted point response function (PRF) $P(x, y)$, and the *local* data, the data within $270\text{ }\mu\text{rad}$ of the centroid of a point source. The cost function is given by

$$J(x, y, a) = \sum_{i=1}^N w(i) (d_i - aP(x_i - x, y_i - y))^2, \quad (22)$$

where x , and y are the in-scan and cross-scan position of the point source respectively, a is the amplitude, in counts, and $w(i)$ is a weighting function.

By setting to 0 the derivative of J with respect to a , the optimal value of a as a function of x and y , under the conditions of (22), is found to be:

$$a(x, y) = \frac{\sum_{i=1}^N w(i) d_i P(x_i - x, y_i - y)}{\sum_{i=1}^N w(i) P(x_i - x, y_i - y)^2}, \quad (23)$$

where N is the number of samples within the local window. Substituting (23) into (22) and eliminating terms which are constant with respect to x and y yields a simplified cost function to minimize:

$$J'(x, y) = - \frac{\left(\sum_{i=1}^N w(i) d_i P(x_i - x, y_i - y) \right)^2}{\sum_{i=1}^N w(i) P(x_i - x, y_i - y)^2}. \quad (24)$$

Powell's method is used to minimize (24) yielding a point source position x, y in SPIRIT III coordinates. The amplitude is then found using (23). The position error using this minimization was found (using simulation data) to be slightly better than that obtained using the centroid.^{7, 8} Also, this technique does not seem to require the correction described in Reference 9 for CCD arrays using the centroid to obtain sub-pixel accuracy. That no correction is required may be due partially to the increased sampling in the cross-scan direction provided by the offsetting columns. In addition, based on simulation data, results using this technique were found to be very near the optimal predicted by the Cramer-Rao bound.¹⁰ There is, of course, the disadvantage that a model PRF must be known for the instrument. It should also be noted that for the special case of $w(i) = 1$, the result of minimizing (24) is the same as that obtained by maximizing a continuous cross-correlation function.

6. RESULTS

One concern with any method is the position and irradiance accuracy for point sources positioned at various locations within a detector. To explore the accuracy of these algorithms, 20 scans of a point source were obtained from ground measurements at each of 33 positions spaced $22.5\text{ }\mu\text{rad}$ (one fourth of a detector pixel) apart in the cross-scan direction. The previously described algorithms were then used to determine the position and amplitude of the point source for each scan. The ensemble standard deviation for each set of the 20 scans and 33 positions are shown in Table 1.

To investigate the specific sources of errors shown in Table 1, the mean and standard deviation for each set of 20 irradiances and cross-scan positions were determined. Figure 3 illustrates the point source mean irradiance as a function of cross-scan position for array A using this data set. In the figure, the sample standard deviation is shown using error bars; each error bar

Figure 3. Irradiance as a function of cross-scan position for array A.
Error bars indicate mean plus or minus 1 standard deviation.

PSE Error (1 σ)	Array				
	A	B	C	D	E
Irradiance (%)	1.5%	1.9%	0.5%	1.0%	1.9%
In-scan position (μ rad)	2.0	1.3	1.2	2.1	2.3
Cross-scan position (μ rad)	2.8	4.3	4.2	2.7	2.5

Table 1. Sub-pixel PSE errors

represents one standard deviation above, and one standard deviation below the sample mean. From this figure it is clear that, for array A, there seems to be a small irradiance bias which is a function of the point source position within a detector pixel. This bias is unusual because it has a period of approximately 180 μ rad, (2 detectors), which is approximately 4 times the sample rate in the cross-scan direction for array A. A similar, but smaller, bias occurs for array B, and a bias with a period of approximately 90 μ rad occurs for array D. Very little, if any, if this type of error occurs for arrays C and E, indicating that this phenomenon might be caused by small errors in a calibration coefficient, rather than a problem with the algorithm itself. We will investigate further this phenomenon using on-orbit data. It should also be noted that this type of error was not observed using simulation data.

Plots of in-scan and cross-scan position error as a function of cross-scan position are given in Figures 4 and 5. The noise seen in these figures is of the same order of magnitude as the short-time positional uncertainty of the calibration chamber.

Figure 4. In-scan position error as a function of cross-scan position for array A.
Error bars indicate mean plus or minus 1 standard deviation.

Figure 5. Cross-scan position error as a function of cross-scan position for array A.
Error bars indicate mean plus or minus 1 standard deviation.

From these plots it is clear that little, if any, systematic error results from the use of these algorithms for point sources positioned at various locations within a detector.

We next describe the accuracy of these algorithms over the SPIRIT III $1^\circ \times 3^\circ$ field of regard (FOR). For this experiment, four scans were obtained of a point source positioned at each location in an 11×17 grid pattern over the SPIRIT III FOR.

The ensemble amplitude percent error, in-scan position standard deviation, and cross-scan position standard deviation are shown in Table 2. In this table we see that the amplitude percent error for this test ranges between 3.2% and 7.1% depending on the array. Observation of this error within the SPIRIT III FOR shows that amplitude is clearly a function of position. This change in irradiance over the SPIRIT III FOR seems to result mainly from changes in the model PRF over the SPIRIT III FOR. By modeling the amplitude as a function of position, the amplitude percent error can be reduced by a factor of about 2. A better model will be developed using on-orbit data.

PSE Error (1 σ)	Array				
	A	B	C	D	E
Irradiance (%)	4.8%	6.7%	3.2%	4.2%	7.1%
In-scan position (μrad)	8.5	8.3	8.0	8.2	8.5
Cross-scan position (μrad)	11.5	11.2	11.1	11.4	11.8

Table 2. PSE errors for entire field of regard (FOR)

The position standard deviation lies between about 11.0 and 11.8 μrad in the in-scan direction, and between about 8 and 8.5 μrad in the cross-scan direction. This position standard deviation is dominated by the known medium and long term jitter of the calibration chamber. Thus, the on-orbit position error due to the algorithm is expected to be near the 5 μrad goal (i.e., larger than the sub-pixel position errors shown in Table 1 and smaller than the FOR position errors shown in Table 2).

7. SUMMARY

This paper has described background removal, object detection, and point source extraction algorithms for the SPIRIT III sensor design. These algorithms have accounted for non-linear scan mirror motion, array misalignment, optical distortion, detector readout ordering, and satellite rotation. They have been shown to be quite robust, yielding position and irradiance estimates near the best that can be expected when the uncertainties of the calibration chamber are considered.

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