Postprint of Image Distortion Correction for Wedge-and-Strip Anode Ultraviolet Detector

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Abstract

Based on polynomial correction methods, a formula model for image coordinates was established, and polynomial parameters were obtained using MATLAB' s Surface Fitting Tool to correct imaging distortion in ultraviolet detectors. This paper introduces the causes of distortion in wedge-and-strip anode ultraviolet detectors and the principle of polynomial correction, designs a DLL module for LabVIEW applications, determines the polynomial through pinhole mask template experiments, and applies it to resolution target imaging, thereby achieving distortion correction for resolution target imaging.

Full Text

Image Rectification Algorithms for Wedge and Strip Anode Detectors

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Abstract: A formula model based on polynomial correction method was established for image coordinate transformation. Polynomial parameters were obtained using MATLAB' s Surface Fitting Tool, enabling correction of imaging distortion in ultraviolet detectors. This paper analyzes the causes of distortion in wedge-strip anode ultraviolet detectors and introduces the principle of polynomial correction. A dll module for LabVIEW was designed to determine polynomial coefficients through pinhole mask experiments and apply them to resolution target imaging, successfully achieving distortion correction.

Keywords: wedge; WSZ; single photon; ultraviolet detector; image correction

With the rapid development of space detection technology, satellite-based ultraviolet detection and applications have received increasing attention. Due to the weak radiation intensity in space ultraviolet detection, which approaches single-photon conditions, photoelectric conversion and photon-counting imaging are required. Wedge-strip anode ultraviolet detectors are employed for imaging detection of specific weak light sources due to their high detection sensitivity, high signal-to-noise ratio, and low background noise [1,2]. Currently, wedge-strip anode ultraviolet detectors have been widely used in space detection from near-ultraviolet to X-ray bands. The EUVE satellite launched by the United States in 1992 and the IMAGE satellite launched in 2000 both carried microchannel plate-based wedge-strip anode detectors [3]. While foreign anode detectors have expanded beyond wedge-strip anodes to include delay-line anodes, vernier anodes, and cross-strip anodes [4], wedge-strip anodes remain a domestic research focus due to their simple fabrication, straightforward electronic readout circuit design, and high spatial resolution [5].

Airglow and aurora constitute important Earth radiation backgrounds that are closely related to solar activity cycles, geomagnetic activity intensity, and the state of the upper atmosphere and ionosphere, making them significant for space detection. Imaging detection of airglow and aurora represents a developmental trend in the field, and wedge-strip anode detectors are one of the key components for such imaging. Their imaging quality directly affects the quantitative application of detection data. This paper addresses the image distortion correction algorithm for wedge-strip anode detectors used in aurora and airglow detection.

1. Imaging Principle of Wedge-Strip Anode UV Detectors

The wedge-strip anode detector primarily consists of an optical input window, photocathode, microchannel plate (MCP), Ge sensing layer, wedge-strip anode (WSA), and electronic readout circuit. As shown in Figure 1 [Figure 1: see original paper], single photons enter the detector through the optical input window and strike the photocathode to excite photoelectrons. These photoelectrons are multiplied through Z-stack cascaded microchannel plates, outputting approximately 10 electrons to form an electron cloud [6]. While this electron cloud could be directly collected by the position-sensitive anode, direct anode reception is unsuitable for vacuum devices and suffers from electrostatic field distortion due to drift fields and large electron cloud deviations. Therefore, an inductive collection method is adopted [7]. The electron cloud first strikes a high-impedance semiconductor Ge film, and the charge collected on the Ge film is then capacitively coupled to the wedge-strip anode through charge induction [8]. The wedge-strip anode comprises three electrodes: wedge anode, strip anode, and Z-shaped anode. The centroid position of the electron cloud can be calculated from the charge distribution ratios across these three anodes, thereby determining the position of the single photon [9].

The charge distribution ratios are obtained by converting charge to voltage through the electronic readout circuit and subsequent calculation. The electron cloud size is influenced by multiple factors including MCP gain, distance between MCP and Ge film, ceramic substrate thickness of the Ge film, and anode acceleration voltage, with no precise formula available for calculation [10]. When the electron cloud is small, modulation distortion occurs in the imaging, while larger electron clouds cause "S" -shaped distortion. Additionally, significant inter-electrode crosstalk exists among the three electrodes of the wedge-strip anode, causing compression in both x and y directions [9].

2. Polynomial Correction Method

Imaging from wedge-strip anode UV detectors suffers from multiple distortions including modulation distortion, "S" -shaped distortion, and inter-electrode crosstalk. Although specialized correction treatments have been applied for particular distortions—such as adjusting the distance between MCP and Ge film and modifying position formulas—the final results may still be affected by these combined distortions, necessitating final image correction. Polynomial correction is a commonly used method in remote sensing image distortion processing [11]. This approach can correct images under combined multiple distortions because it does not require consideration of specific distortion causes; it only needs to compare the distorted image with the standard image to obtain a positional coordinate relationship for correction.

First, we establish a spatial geometric model to obtain a set of control points with known positions. Then, by imaging this spatial geometric model, we obtain the positions of distorted control points and establish a mapping relationship between the two sets of control points. This yields polynomials representing the correct control point positions:

$$Z_x(x, y) = \sum_{i=0}^{n_x} \sum_{j=0}^{m_x} a_{ij} x^i y^j \quad (1)$$

$$Z_y(x, y) = \sum_{i=0}^{n_y} \sum_{j=0}^{m_y} b_{ij} x^i y^j \quad (2)$$

where (Z_x, Z_y) represents the pixel coordinates of correct points and (x, y) represents the pixel coordinates of corresponding distorted points. The correct point' s horizontal or vertical coordinate has a certain relationship with both the horizontal and vertical coordinates of the distorted point. Here, n_x and m_x denote the highest orders of x and y in the correct point's horizontal coordinate, respectively, while n_y and m_y denote the highest orders of x and y in the correct point' s vertical coordinate.

With the formula model established, the next step is solving for polynomial coefficients using control point coordinates—a challenging task due to the large number of coefficients. However, the relationships between Z_x, Z_y and x, y

can be abstracted as surface equations, enabling convenient coefficient solving using MATLAB’ s Surface Fitting Toolbox. This toolbox also provides accuracy assessment metrics including Sum of Squared Errors (SSE) and R-square coefficient of determination.

3. Image Correction Implementation

Control and display software for wedge-strip anode detectors is typically developed using LabVIEW [13,14]. However, LabVIEW is extremely slow when processing complex image pixel position calculations. Therefore, pixel position calculations and processing must be implemented in C++ and called by LabVIEW as a dll module. The dll module schematic is shown in Figure 2 [Figure 2: see original paper]. The output image height and width are set slightly larger than the input image to prevent corrected images from exceeding boundaries and causing errors.

Distorted image grayscale data is stored in a 1024×1024 two-dimensional array. The correction process reads each pixel’ s grayscale value from this array, calculates the correct position coordinates using formula (1), assigns the grayscale value to a new two-dimensional array, and finally displays the image based on the new array.

4. Wedge-Strip Anode Detector Imaging Distortion Correction

To verify the feasibility of the polynomial model and image correction algorithm, correction experiments were conducted using a wedge-strip anode UV detector available in our laboratory. The detector has an effective area of 25mm, spectral range of 20-280 nm, MCP gain 10 , and operating voltage of 3100V.

Figure 3 [Figure 3: see original paper] shows a photograph of a 36-hole mask template with hole diameter of 2mm and center-to-center spacing of 6mm. This mask was placed at the detector’ s entrance window, with a xenon lamp and collimator providing parallel light that passed through the mask and entered the detector’ s optical input window. After processing by the detector, the image was uploaded to the computer for display.

The detector image displayed on the computer is shown in Figure 5 [Figure 5: see original paper]. The image exhibits obvious tilt due to compression along the y=x direction, with vertical hole spacing greater than horizontal spacing. The first and fourth points in the first column were significantly affected by distortion, making coordinate reading impossible, so these were excluded. Coordinates were read for the remaining 12 points, with their horizontal coordinates written as array X and vertical coordinates as array Y. The corresponding correct point coordinates were written as arrays Z_x and Z_y. Since the image distortion did not involve complex nonlinear distortion, third-order polynomial correction was sufficient to achieve ideal results. As shown in Figure 6 [Figure 6: see original paper], the corrected image exhibits consistent hole spacing with no obvious distortion. The horizontal coordinate fitting yielded SSE = 0.9986 and R-square = 1, while vertical coordinate fitting yielded SSE = 0.9807 and R-square = 1. These metrics indicate that the fitting results closely match the target image.

To evaluate correction effectiveness, deviation E between hole positions in the distorted image, corrected image, and constructed standard image was calculated, with the average deviation $\bar{E}$ computed across all holes to characterize image distortion:

$$E = \sqrt{(X - X_{std})^2 + (Y - Y_{std})^2} \quad (2)$$

Calculation using formula (2) shows the distorted image' s average deviation is 17.6 pixels, while the corrected image' s average deviation is 2.7 pixels, demonstrating good correction performance.

A USAF 1951 resolution target was placed at the entrance window for imaging, with results shown in Figure 7 [Figure 7: see original paper]. Applying the polynomial obtained from the mask template correction yielded the result shown in Figure 8 [Figure 8: see original paper], where the resolution target shape is clearly improved.

For even better correction results, smaller hole sizes and spacing with increased hole count are needed to provide more samples for higher-order fitting to eliminate complex nonlinear distortion.

Distortion correction for position-sensitive anode photon imaging detectors has been achieved by establishing a polynomial model combined with MATLAB surface fitting, which greatly simplifies the correction procedure. By designing a dll module, the LabVIEW image correction algorithm was implemented, solving LabVIEW' s slow image coordinate calculation problem. Finally, experiments verified the feasibility of this correction method, meeting design requirements.

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Note: Figure translations are in progress. See original paper for figures.