Critical Design Review (CDR)
Of
ULTRA VIOLET IMAGING TELESCOPE (UVIT)

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Detectors' Distortion

UVIT-CDR-00-04.2

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CRITICAL DESIGN REVIEW

ULTRAVIOLET IMAGING TELESCOPE (UVIT)

Calibration of UVIT Detector's distortion

UVIT-CDR-00-04.2: V0.1

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DERIVATION OF UVIT DETECTOR'S DISTORTION: EXPERIMENTAL & ANALYSIS PROCEDURES AND RESULTS

1. Introduction:

The distortion correction in the UVIT optics is a necessity for good astrometry. The distortions in UVIT can be divided into two parts, the first part due to the optics and the second part due to the distortions in the CPU (Camera Proximity Unit containing the Detector Module and some electronics mounted on the focal plane of the detector). The latter distortions are mainly believed to be due to the imperfections in the Fiber-taper construction.

In principle it is best to calibrate the distortions of the full optical chain in the orbit. However, it is difficult to find a dense astrometric field for ultraviolet, and only low frequency distortions might be measured in the orbit. Therefore we plan to derive distortions in three steps:

i) The Cass optics is simulated in Zemax to find geometrical-optics distortion – it is low frequencies.
ii) Distortion in each CPU is measured by imaging a simple geometrical pattern, e.g. a set of parallel lines or a grind of pin holes etc.
iii) An astrometric field is exposed in the orbit to confirm the distortions estimated on ground.

Here we discuss the experimental procedure and analysis of observations used for estimating distortions in the CPUs.

2. Observations

Two sets of data have been collected for detector's distortion estimation.

a) At Calgary two sets of parallel lines were imaged : one set was nearly parallel to the X-axis and the other nearly parallel to the Y-axis, and each of the sets has about 40 lines across the field. Figure-1 shows one such image. To obtain this image, a mask with nine pin holes arranged in a square grid is rotated and the exposure is taken by moving this mask to and fro over the CPU in horizantal direction to get a set of nine nearly parallel lines. The experiment is then repeated by rotating the mask and moving in the vertical direction. In these data, the two sets of lines are expected to be orthogonal. But the deviations from the orthogonality is found to be 0.75 degree (20 pixel) and hence, these sets of parallel lines are not used for estimating distortions at present.

b) At IIA, a mask with nearly regular grid of pin-holes has been imaged. Images are made by keeping the mask at a distance of ~ 2 mm from window of the CPU, and illuminating it by a diverging beam from a pin-hole of ~ 0.1 mm diameter kept at a distance of 1254 mm. The pin hole is within 10 mm of the axis (normal through the centre of the window) of the CPU, and planes of the mask and the window are parallel to < 0. 5 mm over 40 mm. A schematic of the experimental setup is shown in Figure 2. Multiple exposures are taken for each CPU by rotating/shifting the mask with reference to the CPU. In each exposures greater than close to 1000 photons are collected in the image of each pin-hole. The images have rms size of < 1 pixel (25 μm) of Star-250, and hence centre of each image can be found to < 1/30 of a pixel. The holes are nearly on a square grid of 2 X 2 mm.

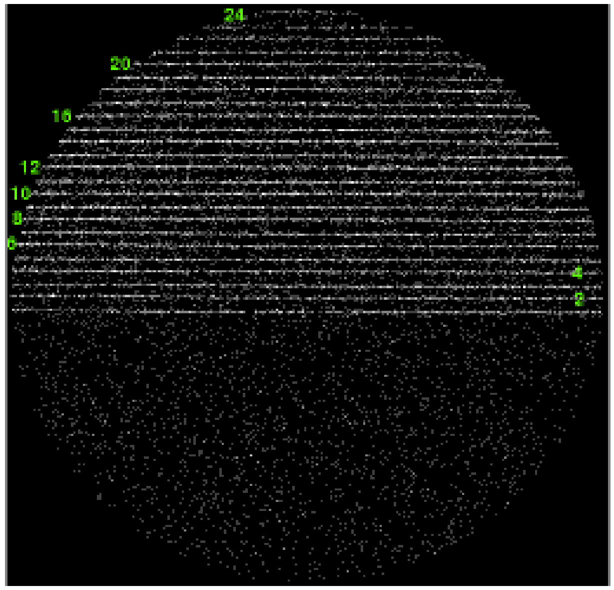

Figure 1: NUV exposure along the horizantal axis taken at Calgary. A mask of 9 holes on a rectangular grid is rotated at an angle and illuminated while moving the mask pattern to and fro along the X-axis to obtain a pattern of horizantal lines.

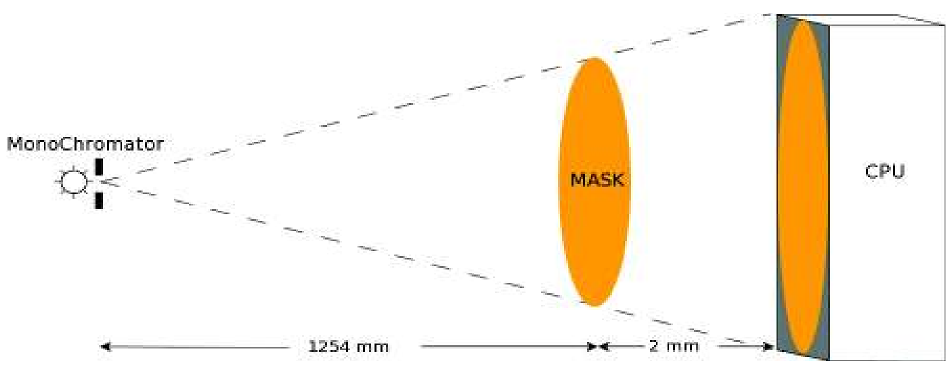

Figure 2: Schematic of the experimental setup for distortion estimation using mask pattern

3. Analysis of the data:

i) In an ideal situation the mask is projected on the photo-cathode with a small magnification, and it is imaged on the Star-250 with a reduction given by the fibre taper.

ii) In this ideal situation, the only parameter to be obtained from the data is the "scale" on photo-cathode per pixel of Star-250. To get this we need to estimate magnification of the mask during its projection by the diverging beam on the photo-cathode. A*ny error in the estimation of the "scale" will be corrected during the checks in orbit.*

iii) Distortions in the CPU can be of two kinds:

   a. The "scale" varies across the field
   b. A line on the photo-cathode is imaged on Star-250 with a "rotation" which varies across the field. *It may be noted that if this "rotation" is constant it need not be treated as distortion.*

iv) Corrections for distortion in effect involves a linear transformation of the points in Star-250 to points on the photo-cathode. However, as discussed above, in ii) & iii) this transformation could have errors in “scale” and “rotation”, and these errors can be corrected through checks with sparse astrometric fields in the orbit.

v) The required steps thus can be listed:
   a) The middle 256 X 256 pixels are used in estimating the scale and rotation to minimize the effects of distortions at the edges.
   b) The centres of the images of all the holes using 2d Gaussian fits are determined.
   c) With the parameters, scale and rotation fixed in `a' above, expected centres of all the images of the holes are calculated.
   d) Differences in the coordinates obtained in “(b)” and “(c)” gives X/Y coordinates of the distortion for locations of each point.

vi) Each image of the mask can be analysed as above to get the distortion across the field, e.g. a 20 X 20 matrix of errors in X and Y across the 512 X 512 field, and an optimal combination can be made of all the matrices.

1. **Finding centres of the images :**
   The images are taken in Photon Counting mode and are reduced as files with 4 k X 4k sub-pixels, i.e. pixels of Star-250 are magnified by 8. As rms size of the images is > 0.5 & < 1 pixel of Stra-250, a fit is made with a suitable (fixed rms size) 2-D Gaussian, and centre of the Gaussian gives location of the image. In case the images have variations in their shapes, centroid can be used as measure of the centre. Only parts of the image devoid of ghosts and hot spots etc. are used for finding the centres. Figure 2 shows the central part of the image used for measuring the centers of the holes and a plot of corresponding centers of the holes obtained by Gaussian fitting.

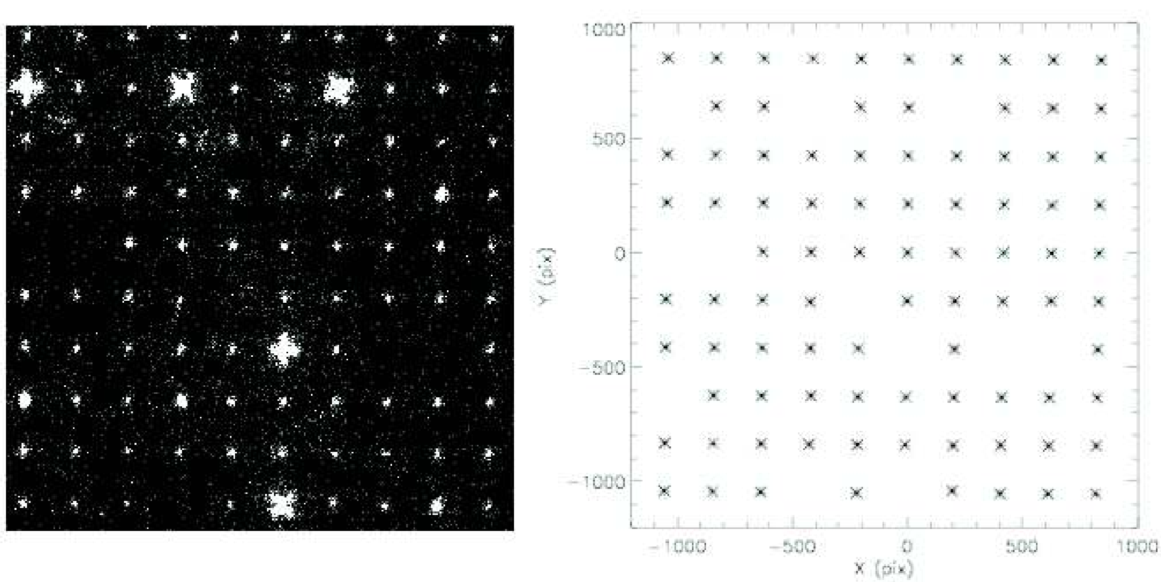

Figure 3: Central positions 2k x 2k subpixel region of the NUV exposure and corresponding positions of the holes obtained by 2d-Gaussian fits

2. Scale and Rotation calculation:

If we assume that there is no warping in the image, then the transformation will be linear and involves only rotation and zooming. In this case of linear transformation, for a gain/scale of `g' and rotation 'θ', the translated positions can be written as,

$$(X_i, Y_i) = (g[x_i \cos\theta - y_i \sin\theta], g[x_i \sin\theta + y_i \cos\theta])$$

Then to determine the angle and scale, we have to minimize the distances between the two points given by,

$$f(g,\theta) = \sum [X_i - g(x_i \cos\theta - y_i \sin\theta)]^2 + \sum [Y_i - g(y_i \sin\theta + y_i \cos\theta)]^2$$

The two partial derivatives are,

$$\frac{\partial f}{\partial g} = -2 f(x)[x_i \cos\theta - y_i \sin\theta] - 2 f(y)[x_i \sin\theta + y_i \cos\theta]$$

$$\frac{\partial f}{\partial \theta} = -2 g f(x)[x_i \sin\theta - y_i \cos\theta] - 2 g f(y)[x_i \cos\theta - y_i \sin\theta]$$

where, $f(x) = X_i - g[x_i \cos\theta - y_i \sin\theta]$ and $f(y) = Y_i - g[x_i \sin\theta + y_i \cos\theta]$

We used the positions obtained by the 2d Gaussian fits for the holes (X_i, Y_i). For the mask, we assumed a uniformly separated holes on a square grid of size 2 mm which corresponds to 80 subpixels. The function is then minimized using the tools available in IDL (interactive data language). In this minimization, the centers of the two images are fixed at the (6,6) hole and hence, we do not apply any shift in the center. For the image shown in Figure 1, we obtained a rotation angle of -0.51315 degree and a scale/magnification of 2.6205. With the help of these two values, we calculated the translated positions and the difference of these translated positions with the centers of holes gives us an estimation of the detector distortions. Figure 4 shows a vector plot of these derived distortions. Here it should be noted that the assumption of uniform separated holes for mask pattern is used only for establishing the procedure. We will be using measured hole positions of the mask for estimating the actual distortions later.

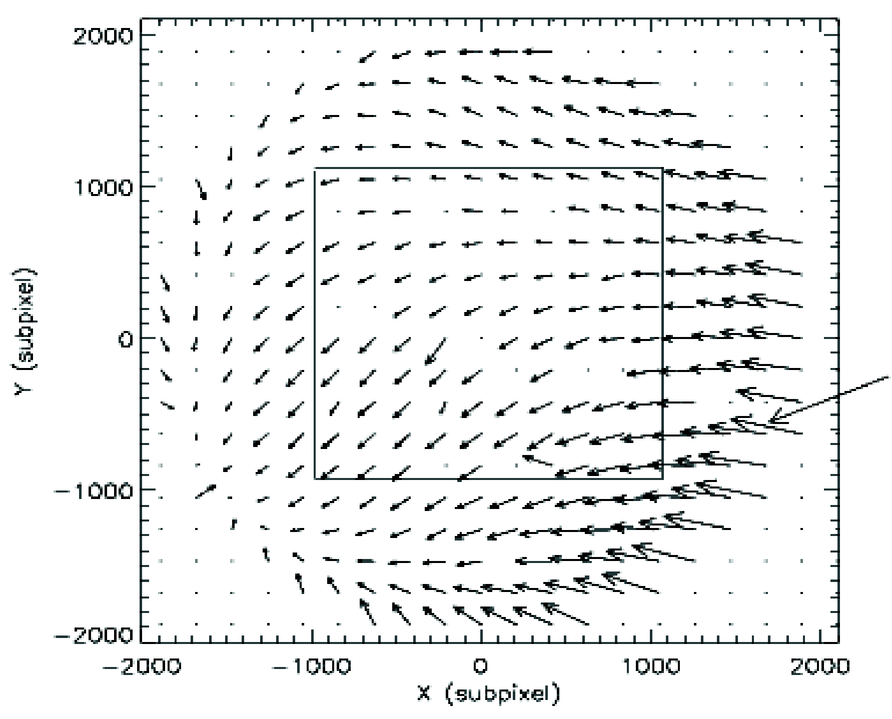

Figure 4: Vector plot of UVIT detector's distortion. The length of the vectors correspond to the magnitude of distortion and the vectors represent the direction. The maximum distortion (shown by arrow) corresponds to 34 subpixels or 4.25 pixels. Other vector magnitudes are normalized to this value. The middle portion of the positions used for deriving the scale and rotation are also marked.

In estimating the distortions here, the shift or the image with respect to reference is assumed to be zero. This assumption introduces a bias in the distortion values. The procedure will be refined later to remove the bias by including the shifts into consideration.

3. Further Analysis:

As mentioned before, we used a regular hole pattern for the reference mask just to establish the procedure only. For actual distortions estimation, we will be using the measured mask positions. With the help of the derived distortion values using the actual mask as the reference, the individual distortions at each subpixel positions will be estimated by interpolation and a look-up table will be created. This lookup table will be refined/corrected for errors with the observations in orbit. The probable candidate UV fields for such kind of observations are globular clusters. One such probable candidate for the in orbit observations, Omega Centauri is shown in Figure 5. The image shown in the figure is a false colour image taken in far UV (1300-1800 Ang) with UIT onboard Astro-1 mission and covers a field of 1 deg x 1 deg. The astrometry of this kind of globular clusters are known to very high accuracy and hence can be used a reference for estimating distortions. Using the correction values obtained by observing analysing the globular cluter fields, the lookup table will be refined and is used for correcting the detector distortions of UVIT later on.

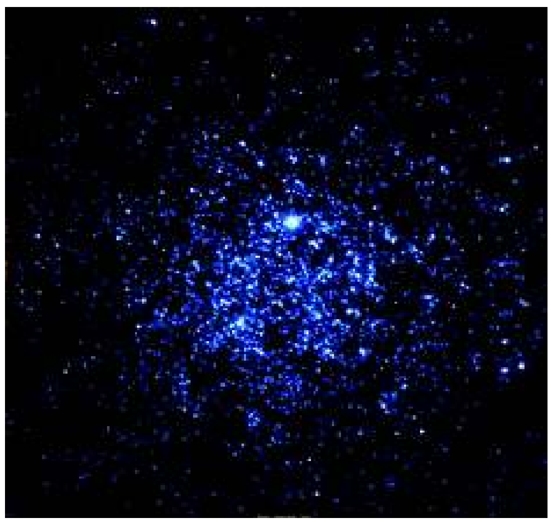

Figure 5: Far UV (1300 – 1800 Ang) image of globular cluster Omega Centauri obtained with UIT onboard Astro-1.