Alignment Mask Design and Image Processing for the Advanced Radiographic Capability (ARC) at the National Ignition Facility

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ABSTRACT

The Advance Radiographic Capability (ARC) at the National Ignition Facility (NIF) is a laser system that employs up to four petawatt (PW) lasers to produce a sequence of short pulses that generate X-rays which backlight high-density inertial confinement fusion (ICF) targets. ARC is designed to produce multiple, sequential X-ray images by using up to eight back lighters. The images will be used to examine the compression and ignition of a cryogenic deuterium-tritium target with tens-of-picosecond temporal resolution during the critical phases of an ICF shot. Multi-frame, hard-X-ray radiography of imploding NIF capsules is a capability which is critical to the success of NIF's missions. As in the NIF system, ARC requires an optical alignment mask that can be inserted and removed as needed for precise positioning of the beam. Due to ARC's split beam design, inserting the nominal NIF main laser alignment mask in ARC produced a partial blockage of the mask pattern. Requirements for a new mask design were needed. In this paper we describe the ARC mask requirements, the resulting mask design pattern, and the image analysis algorithms used to detect and identify the beam and reference centers required for ARC alignment.

Key words: Advanced Radiographic Capability (ARC), Optical alignment, mask design, image processing, image analysis, National Ignition Facility (NIF), back lighters, Crosshairs, fiducials

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1. INTRODUCTION

The National Ignition Facility at the Lawrence Livermore National Laboratory has been operational since 2009 for the study of high-energy density and fusion science. Three of the main goals in NIF are to study new regimes in astrophysics and basic science, to ensure the United States stockpile stewardship is and will remain reliable, safe, and secure, and to achieving ignition and produce a net energy gain for the first time in a laboratory setting [1-3].

Experiments and operation of the National Ignition Facility (NIF) will soon utilize high-energy x-ray back lighters. In March 2014, NIF began deployment of a vital diagnostic named ARC (Advanced Radiographic Capability) which is designed to generate precise, high-energy short-pulses [4-7]. ARC is a petawatt-class laser with peak power exceeding a quadrillion (10^{15}) watts. ARC is designed to produce brighter, more penetrating, higher-energy x rays well beyond what can be obtained using conventional radiographic techniques. ARC is the world's highest-energy short-pulse laser, capable of creating picosecond-duration laser pulses to produce energetic x rays in the range of 50,000 to 100,000 electron volts for backlighting NIF experiments [8-9]. ARC currently uses two of NIF's 192 beamlines where each beam provides two

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'beamlets'. Using this split-beam configuration, two short-pulse beams are created for each NIF aperture configuration as depicted in figure 1.0.

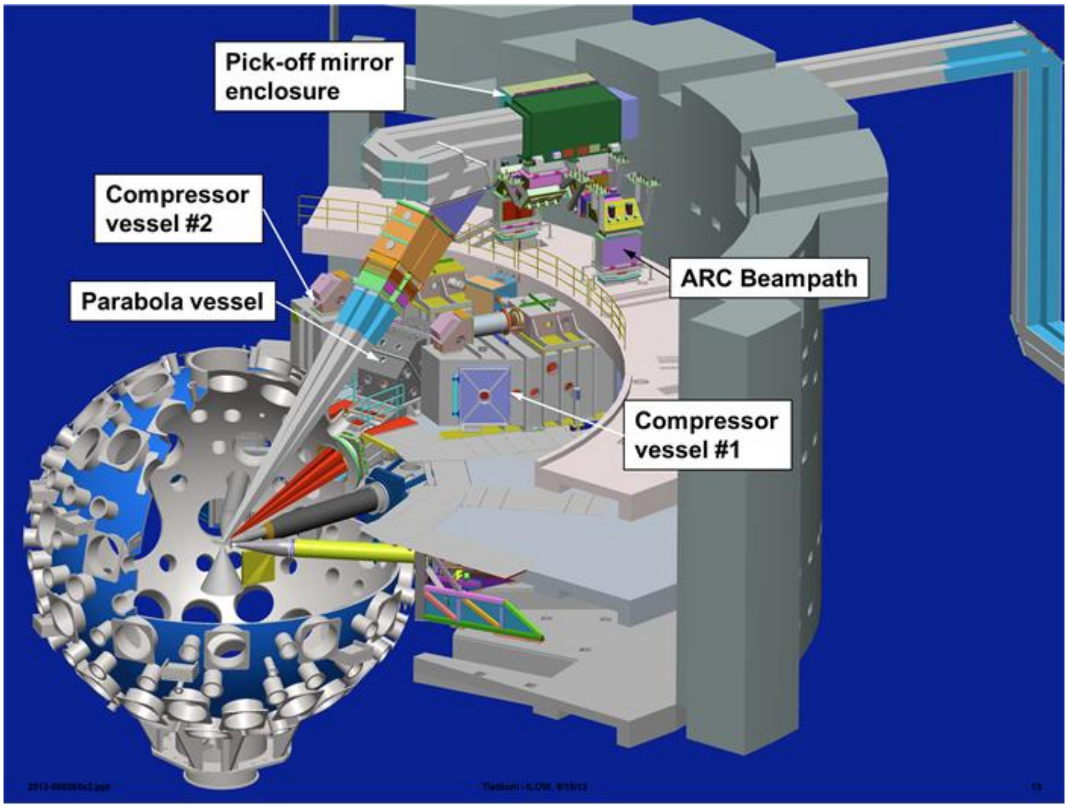

Figure 1.0 Schematic view of some of the elements in the National Ignition Facility, where ARC beams, after amplification in the NIF laser, are compressed in the target bay and focused to target chamber center (TCC). For a sense of scale in this figure, the round TCC in the lower left is 10 meters in diameter.

Staggering the arrival of the ARC beamlets onto backlighted targets will produce an x-ray "movie" (Figure 1.1) for diagnosis of the fuel compression and ignition phases of a cryogenic deuterium-tritium (DT) target. This allows for viewing the most critical phases of an inertial confinement fusion (ICF) shot at tens-of-picoseconds temporal resolution that enables experimentation in frontier science and high-energy-density (HED) stewardship science

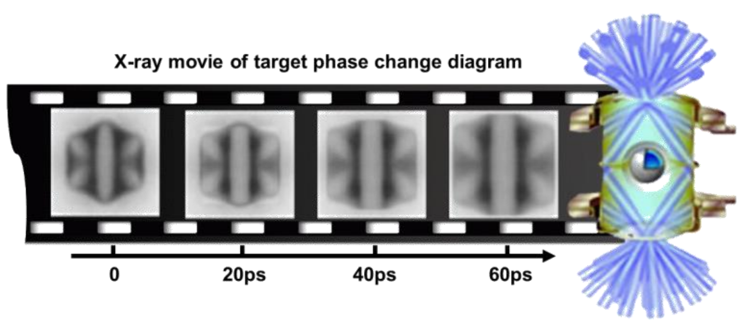

Figure 1.1 ARC will conduct multi-frame, hard-x-ray radiography of NIF capsules during compression and ignition phases. Using ARC, NIF researchers will be able to record target firings at the rate of 50 billion frames per second.

2. ARC ALIGNMENT MASK

Laser alignment precision is a vital element in the successful operation of the NIF and the ARC systems [10-12]. During alignment, the NIF Input Sensor Package (ISP) alignment mask is inserted and imaged. Careful processing of the image provides measures the pointing and centering position of the laser beam. The NIF mask contains an etched chrome on-glass 'GAMMA' pattern that is seen in figure 2.0.

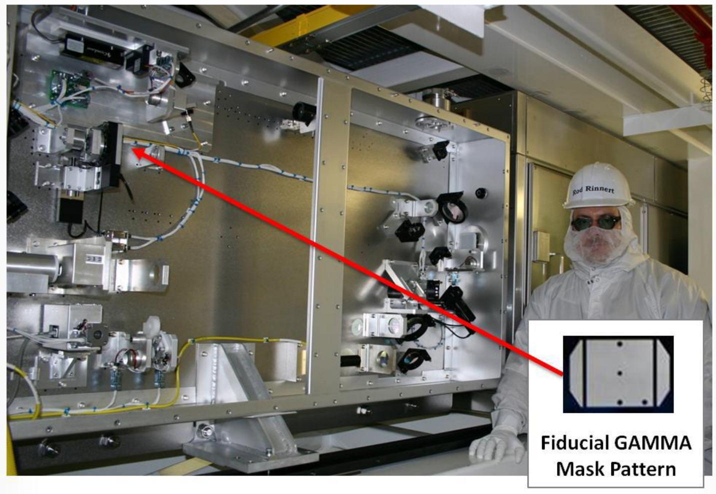

Figure 2.0 Four circles in 'L' or GAMMA pattern comprise the current ISP fiducial pattern used in NIF for alignment. Wings may or may not be present in some images.

An issue arose when it was observed that ARC's split beam design resulted in a dark vertical bar in alignment images that partially blocked the GAMMA pattern. The blockage resulted in a higher alignment measurement uncertainty. In addition, issues previously seen in NIF such as fiducial clipping, the introduction of corner-blockers, glints from stray reflected light, and intensity gradients motivated the need for a better alignment mask pattern design for ARC. Examples are illustrated in figure 2.1.

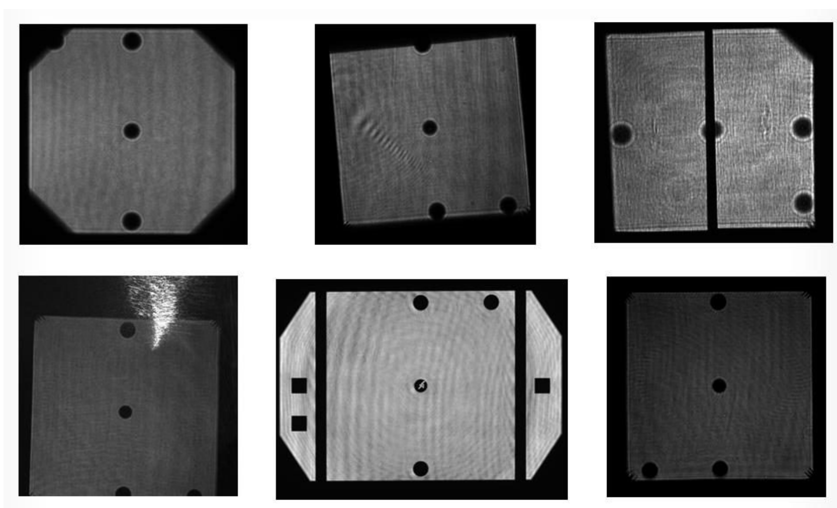

Figure 2.1 Beamlets in ARC introduce blockage that covered and distorted the center spot (top right). Clipping may also occur in some images (top left, middle). Images may contain glints due to stray reflected light (bottom left, center) or contain intensity gradients (bottom right).

3. ARC FIDUCIAL MASK DESIGN

Requirements for a beam alignment pattern design include separate measurement estimates of horizontal and vertical image magnification, horizontal and vertical image center, rotation, and asymmetry (image may be flipped, rotated, or transposed). The new mask design was not restricted to circular or spot fiducials. As seen in figure 3.0, there are many fiducial types that have been used successfully throughout science and industry. In high precision optics, reticles are often used. To meet ARC requirements, high contrast fiducials with low footprint and high 'pixels per feature' were desirable properties which could provide precise measurement estimates with low uncertainty.

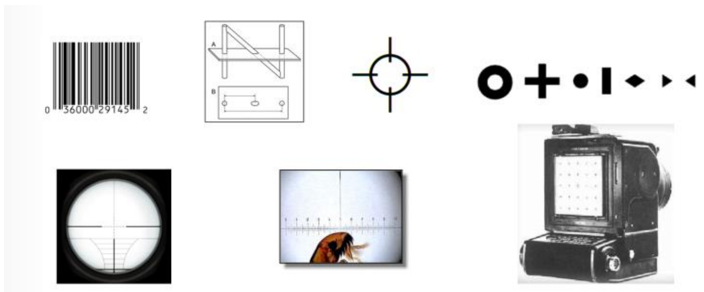

Figure 3.1 A wide variety of fiducial types are used in science and industry. For example UPC bar codes (a), N-localizer used in 3d medical applications, registration marks used in printing, fiducial markers for printed circuit board manufacturing (d). In optics, crosshairs are commonly used as seen in sniper rifle scopes (e), microscopes (f) and in the NASA Hasselblad Lunar Surface Camera fitted with a Reseu plate (g).

A total of four measurement reference points on the ARC mask were required to meet alignment requirements. To meet this need, ARC reference points were carefully designed using strategically placed reticles or lines whose intersection provided three of the four reference points. The advantage of using reticle lines that stretched across the mask image is that obscured line intersections can be reliably found by extrapolating the lines through the blocked area. The fourth reference point was a circle or spot in the image. The spot allowed for unique registration of the orientation of the pattern within the image.

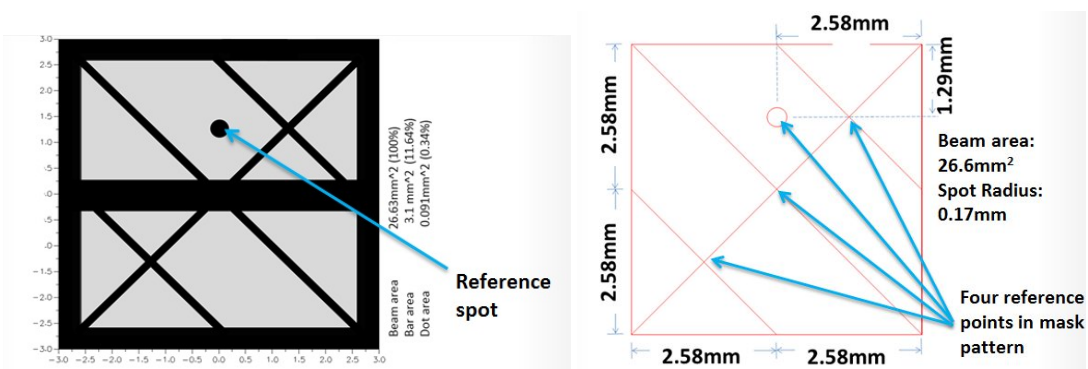

Figure 3.2 Diagonal crosshair reticles and a single spot were selected to meet the design requirements for ARC. The spot center and the three reticle intersections are used to estimate horizontal and vertical magnification, image center, rotation, and symmetry as image may be flipped, rotated, or transposed.

The new design also provided an opportunity for simple iterative image processing. By separating the ARC mask image into quadrants, each quadrant can be processed with the same image processing algorithm. Figure 3.3 illustrates the design requirements and how the image is segmented into quadrants for analysis.

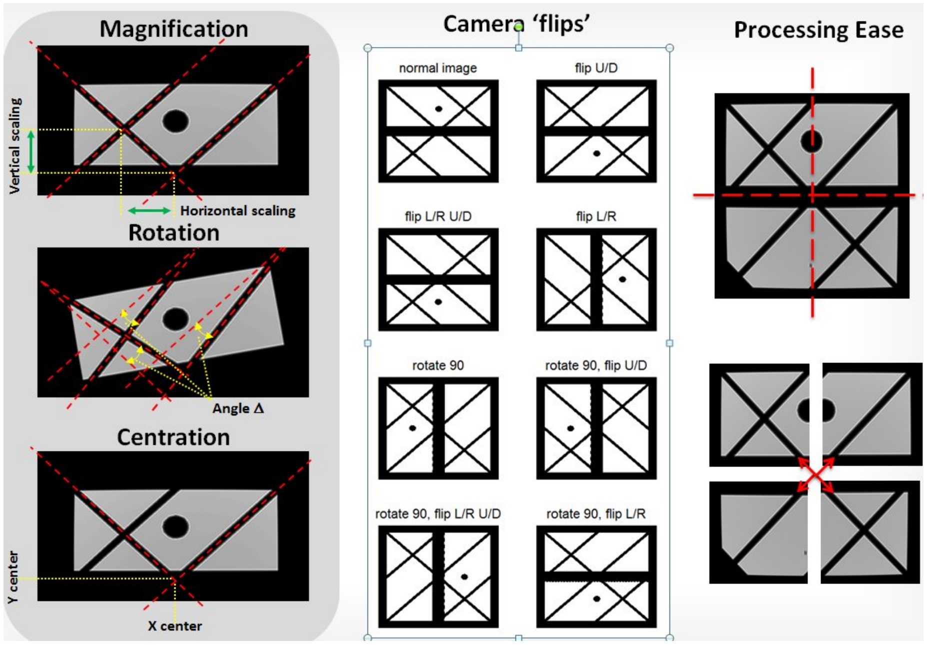

Figure 3.3 The ARC fiducial mask design meets the requirements and provides horizontal scale, vertical scale, image center, image rotation, and symmetry. Image is separated into quadrants for ease of processing (lower right).

Normally, significant changes to the current NIF mask hardware in the ISP would incur prohibitive costs and delays. However, a simple repositioning of the mask patters as well as the addition of the new mask pattern on the chrome-on-glass etched plate enabled the change for the new ARC alignment fiducial mask. Figure 3.4 shows the final, upgraded mask containing the original NIF GAMMA mask, two beam masks, and the new ARC fiducial mask in the upper left corner of the plate. Light through the mask is imaged by the ISP camera and the resulting image is processed for final alignment measurements.

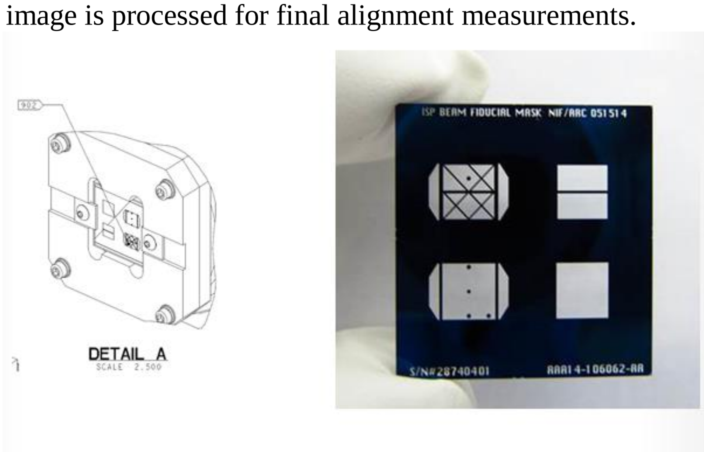

Figure 3.4 Original alignment patterns on the mask were re-positioned and the ARC fiducial pattern was added to the mask. A drawing of the mounting for the glass plate is shown on the left and a photograph of a technician holding the plate is shown on the right. The ARC alignment chrome-on-glass fiducial pattern is the upper left pattern in the photograph of the plate.

4. ARC MASK IMAGE PROCESSING

Image processing of ARC mask images consists of two independent algorithms. The first algorithm provides an estimate of the center of the spot in the image and the second locates the reticle lines in the image. The flow diagram in figure 4.0 illustrates the overall process.

Image processing for the ARC mask image consists of several pre-processing steps. Pre-processing begins with a series of standard off-normal checks that verify the image is not blank, saturated, or overly dim [13]. A beam mask is then created using horizontal and vertical projections coupled with a nominal beam size. The beam area within the mask is processed to identify the dark bar separating and identifying the two beamlets in the image and determine if it is horizontally or vertically oriented. The image and the results of the pre-processing are then used in the application of the spot and reticle algorithms.

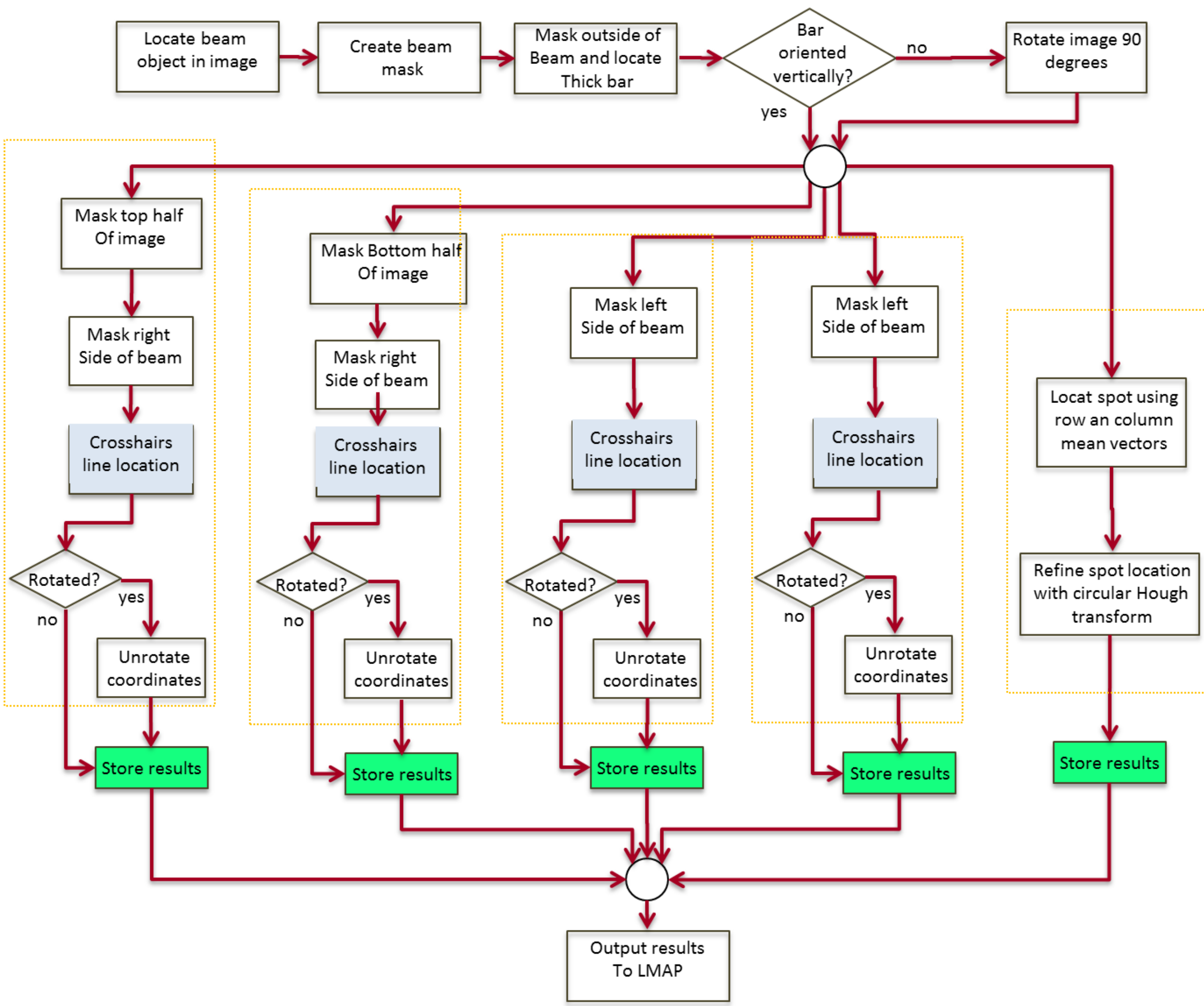

Figure 4.0 Figure 4.0 illustrates the process where each image is processed for reticle lines quadrant by quadrant using the crosshairs algorithm. The spot is located in a separate process using a rough-cut estimate from mean horizontal and vertical projections that is then refined using an iterative, circular Hough transform

4.1 Algorithm for measuring ARC mask spot reference circle

Measurement estimate of the ARC mask spot reference circle begins with creating a mask using the pre-processing measurements and nominal mask size values. After masking the image to isolate and highlight the spot, mean vectors of the horizontal row projections and vertical column projections are created. Location of the horizontal and vertical signal peaks provide the initial estimate of the location of the center of the spot. This process is illustrated in Figure 4.1.

The initial spot center position estimate and the nominal spot radius then used to measure the mean intensity of a small region in the vicinity of the spot center. The mean intensity is then used to threshold and create a binary image from the masked image. A series of circular Hough transforms are then applied to the binarized image, by varying the center around the initial center estimate. The highest peak in the resulting set of accumulator matrices determines the refined spot center estimate.

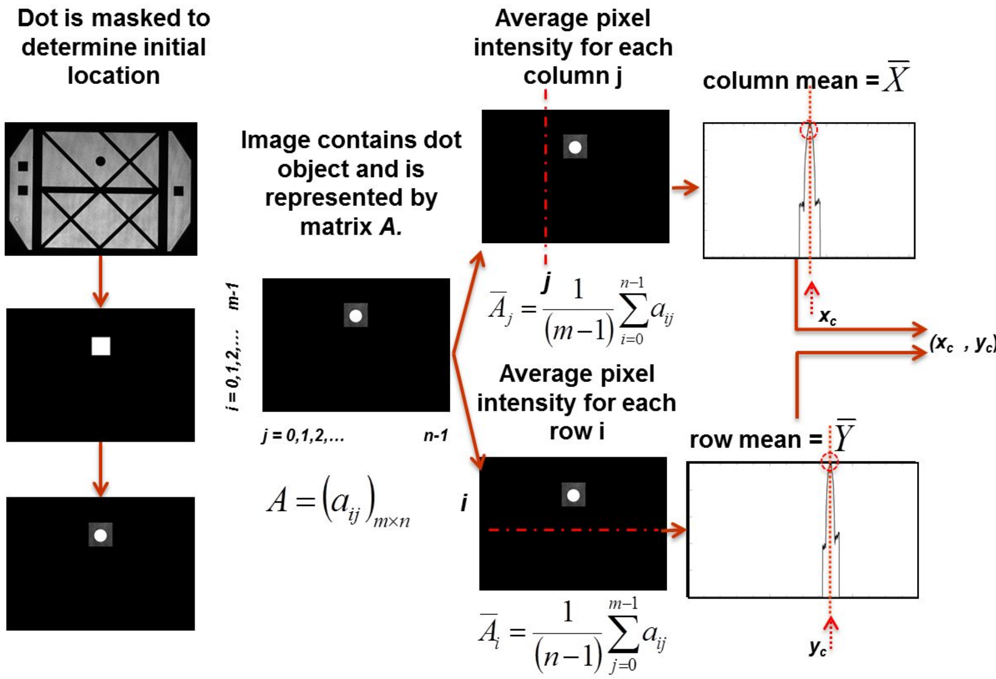

Figure 4.1 The location of the spot reference circle uses a mask to isolate the spot and then generates mean horizontal and vertical projections to isolate the location of the spot. The resulting center location estimate is further refined using an iterative, circular Hough transform.

4.2 Crosshairs Algorithm for measuring ARC mask reticle lines

The Crosshairs algorithm is commonly used in NIF for line and edge estimation where automatic alignment requires precise location of line objects [14-15].

Images are first rotated so that the target line is vertical in the image. The algorithm then segments the image into horizontal bands which are then compressed to 1D signal by taking a measurement across the band. A measurement is selected such as the mean to form a set of signals, one for each band. The signals are then processed to measure a line or edge detection per band. This provides a set of points that can be evaluated, culled for outliers, and undergo a linear fit to produce the final line estimate. Figure 4.2.1 illustrates the segmentation and signal processing in the algorithm for a NIF target chamber beam alignment image.

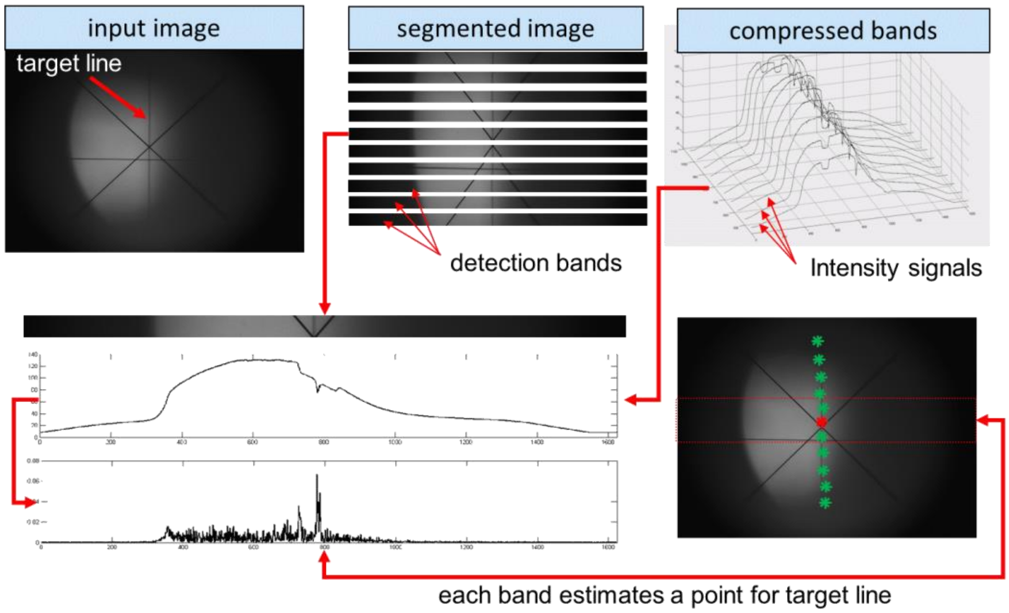

Figure 4.2.1 Crosshairs algorithm segments image into horizontal detection bands which are compressed and processed to provide a set of candidate edge points for each line.

Reducing the image to a 1D signal processing task is computationally efficient and also works well for large images. The segmentation or banding is tolerant to images with noisy, partially hidden, or sparse edges. Figure 4.2.2 illustrates a lower contrast line that is discriminated from nearby higher contrast lines.

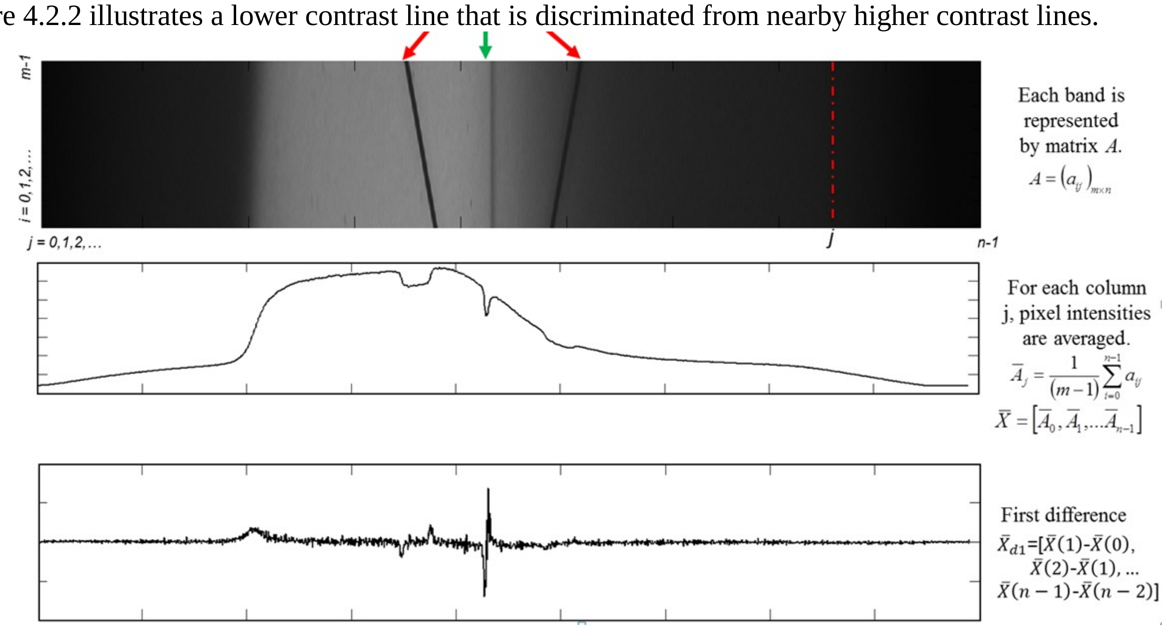

Figure 4.2.2 Example of the crosshairs algorithm locating a lower contrast line in the presence of competing lines. The band (top) is compressed to form a (middle) signal and then processed (below) to emphasize the higher slope of the vertical line. Low-contrast lines (top middle arrow) can be discriminated from high-contrast, off-angle lines (top left/right arrows).

After processing the complete set of bands, outliers are culled using nominal line thickness, mean intensity, deviation from line fit, and nominal spacing parameters. The remaining set of points is used to create a binary image by setting their pixel location of the point in each band in the image to one with zeroes elsewhere. This image is then processed with a linear Hough transform to calculate the line fit.

ARC images are processed using the Crosshairs algorithm in the same manner. The image and the pre-processing values are used to first separate the images into quadrants The Crosshairs Algorithm is then applied to locate one or two diagonal reference reticle lines in each quadrant as shown in Figure 4.2.3

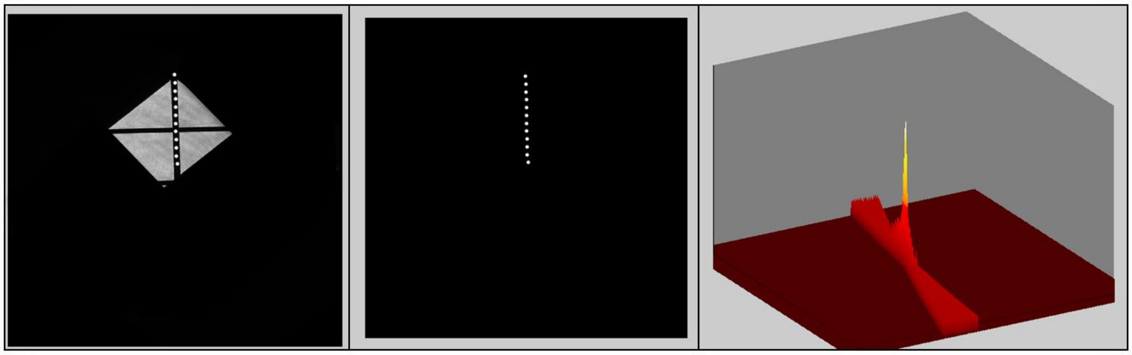

Figure 4.2.3 Rotated ARC image quadrant (left) produces a set of line position estimates seen as white dots. Using the positon of the dots, a binary image is created (center). The resulting accumulator space from the binary image yields a fast and accurate line fit to the data as seen in the high sharp spike (right)

The ARC mask image line measurements and their intersections are then used as reference points, together with the spot center locations to determine the rotation, centration, symmetry, and scale for aligning the ARC beams.

5. SUMMARY

The Image processing for the new ARC mask design provides reference coordinates which are used for estimates of horizontal and vertical magnification, centration in the x and the y direction, rotation, and symmetry. Camera issues or off-normal conditions are also measured. In addition the design is simple (4 lines, 1 spot) with minimal light blockage. It is easy for the human operator to evaluate by eye, but can also be processed autonomously. Uncertainty is generally low due to the high degree of pixels per feature, particularly for the line objects. Finally, the long reticles in the image minimize or lessen corner blocker or other obscurant interference.

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