Testing and Installation of the Reticle Projector on OMEGA's Target Viewing System

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Abstract

A reticle projector is an optical device that forms a calibration test pattern. This paper describes how a reticle projector was designed, built, and installed on the OMEGA Target Viewing System at the University of Rochester's Laboratory for Laser Energetics. In this design, a 780-nm infrared laser shines through a grid to a lens which forms the optical Fourier transform of a grid pattern (reticle) to create a periodic spot pattern. This pattern is re-imaged to a focal plane at the center of the target chamber so that it can be captured by each of five cameras in the Imager assembly on the opposite side of the target chamber. By projecting a common image onto all cameras simultaneously, one can measure relative magnification, image rotation, pattern registration, and distortion. The reticle projector was first tested in a laboratory setting where images were acquired, analyzed using MATLAB, and compared with synthesized images. Preliminary results suggest that this system meets the design objectives. This paper begins with an overview of the Target Viewing System, presents the design and analysis of the reticle projector and concludes with sample data and recommendations for future work.

1. Introduction – Overview of the Target Viewing System

The Target Viewing System (TVS) on the OMEGA laser is not only used for viewing the target; it also plays a large role in the feedback system ensuring correct placement of the target. In order to measure the position of objects in three dimensions, two viewing axes having an angular separation of approximately 90 degrees are required. Each view is composed of an Illuminator and an Imager. The Illuminator side consists of four dichroic mirrors that combine four LED colors and the reticle projector's infrared beam[1] (Fig. 1).

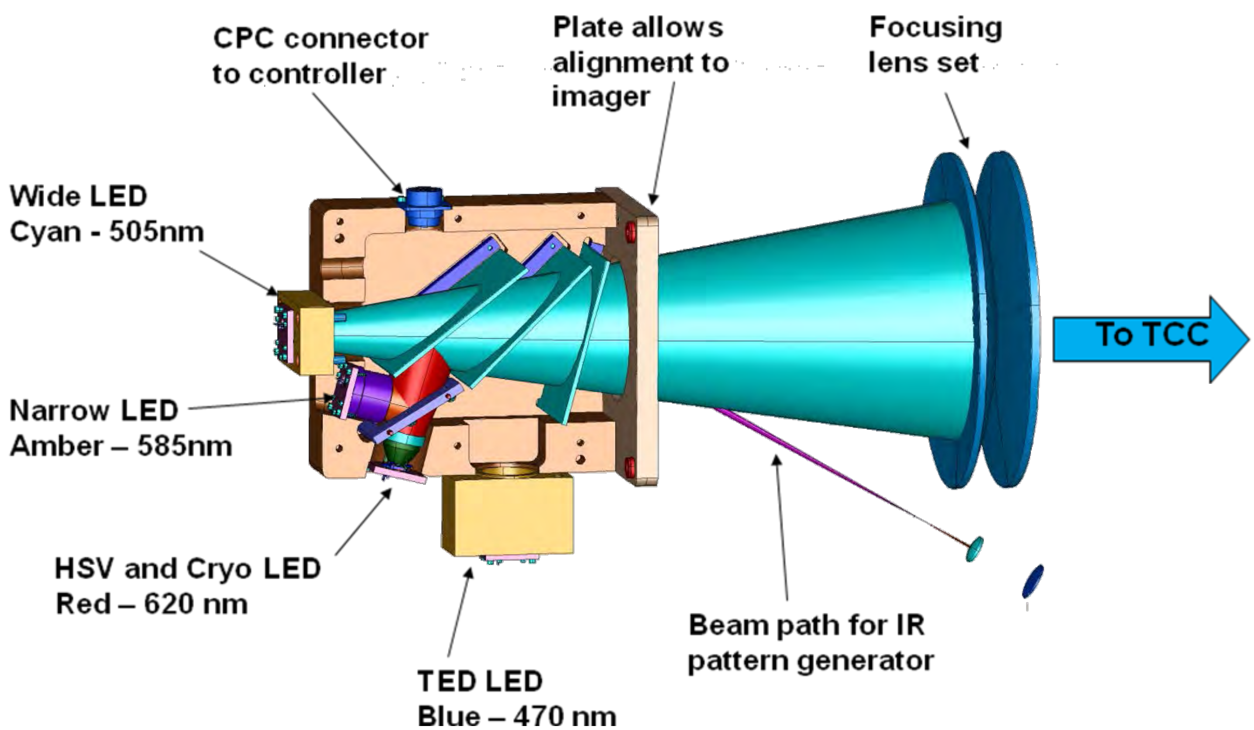

Figure 1: CAD (computer aided design) model of the Illuminator assembly. Four dichroic mirrors combine four LEDs and, with the addition of the reticle projector, a 780 nm infrared laser into a single beam heading towards the center of the target chamber. Each LED color corresponds to a camera on the Imager assembly.

The Imager side, on the other hand, consists of five cameras which each correspond to one of the LED colors in the Illuminator assembly (Fig. 2). The Narrow camera, used as the "master" camera, captures only amber light, for instance. Each camera has a different purpose.

[1] Source wavelengths: 470nm (blue), 505nm (cyan), 585nm (amber), 620nm (red), 780nm (infrared)

A problem can arise if these five cameras are not calibrated to each other. In the system before the reticle projector was installed, camera recalibration was very difficult.

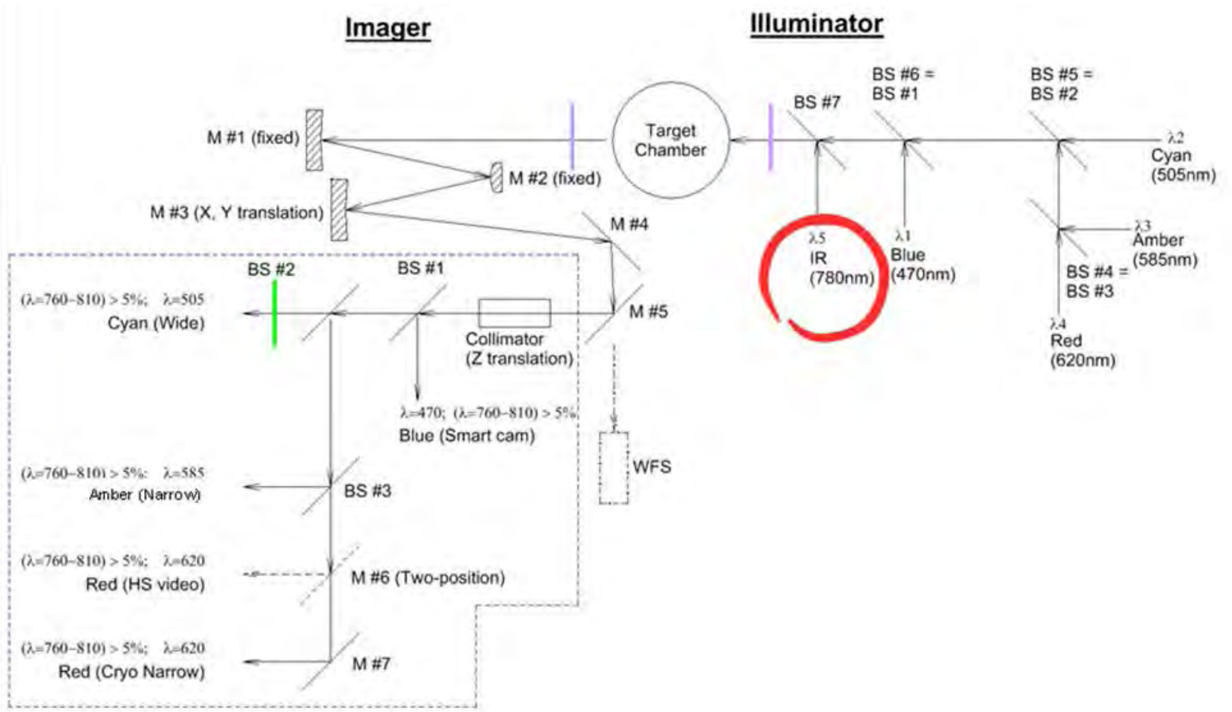

Figure 2: Schematic of the TVS. The circled IR source is the pattern generator, located in the Illuminator assembly. The combined beam propagates through TCC to the other side of the target chamber and the Imager assembly, where certain wavelengths of light are directed into each camera (the green line represents a Tiffen green filter that keeps the blue wavelength out of the wide-field camera). The purple lines are UV filters on either side of the target chamber.

2. Motivations and Design

The idea for the reticle projector was for it to simultaneously project a pattern onto all of the cameras in a single view. The resulting images could be matched to each other and would allow for cross-calibration relative to the Narrow-field camera. One way of accomplishing this would have been to put a grid in the center of the target chamber. This is possible; however, it is time consuming to load and insert the grid inside the vacuum chamber, and it requires special equipment and trained personnel. The reticle projector has the benefit of turning on/off with the flip of a switch (actually controlled by TVSII software), allowing calibration to be done at almost any time without special training.

In this design, a 15 mW, 780 nm continuous wave infrared laser is directed through an exchangeable filter and then through the grid, forming a grid pattern (Fig. 3). This grid pattern continues through a lens which takes the optical Fourier transform of the grid pattern to form a periodic spot pattern, which is re-imaged to a focal plane at the target chamber center (TCC), to be captured by each of the five cameras in the Imager assembly.

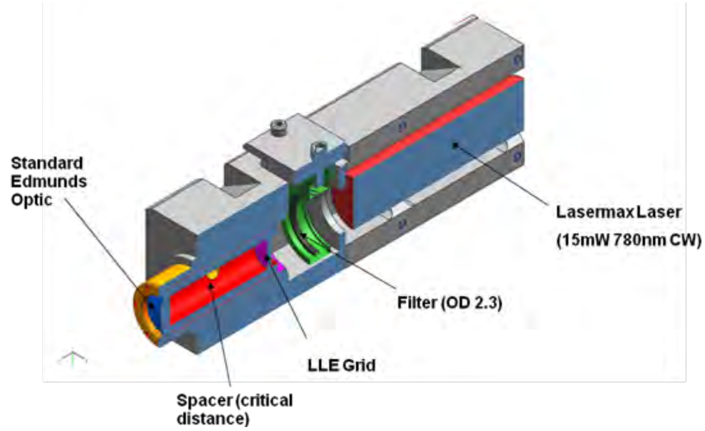

Figure 3: Cross-section of the reticle projector. Key components include a 15 mW 780 nm continuous wave (CW) infrared laser, a filter, an LLE grid (the reticle), a lens barrel, and a plano-convex lens. The filter is used to reduce the optical output power to match camera sensitivity; currently both axes include filters of optical density 2.3.

2.1 The Optical Fourier Transform

The Fourier transform, used in the formation of the pattern projected to target chamber center from the reticle projector, is a mathematical operation often used in digital image processing that breaks a signal up into its fundamental frequencies.

According to Fourier's theorem, any continuous function defined over some distance L can be synthesized by a sum of harmonic functions whose wavelengths are integral submultiples of L, (such as L/2, L/3, ...); essentially, every curve can be exactly reproduced by superimposing simple harmonic curves on top of one another[1].

Figure 4 is an example of a very basic optical Fourier transform setup. In this setup, parallel light is scattered into plane waves by a transparency in the front focal plane of a converging lens; these scattered waves are collected by the lens, and parallel bundles of rays converge at the back focal plane (the transform plane, marked by Σ_t in the schematic). If a screen were to be placed there, the far-field diffraction pattern of the transparency would be imaged there[2].

In the case of the reticle projector, a Fourier transform was taken of a reticle, or grid. Each individual grid section was 200 μm (vertical) by 100 μm (horizontal); the opaque section was 190 μm by 90 μm, leaving 10 μm transparent on each side. The two sides were made unequal so that cross-calibration later would be easier. MATLAB simulations were run and, using the repmat() function, were able to replicate the reticle. The Fourier transform was taken of this image in MATLAB to provide comparison for future experimental results (Fig. 5). The difference in side lengths manifest themselves in the Fourier transformation in that the higher spatial frequency of the 200 μm sides lead to closer dot spacing in the transform plane than that of the 100 μm sides.

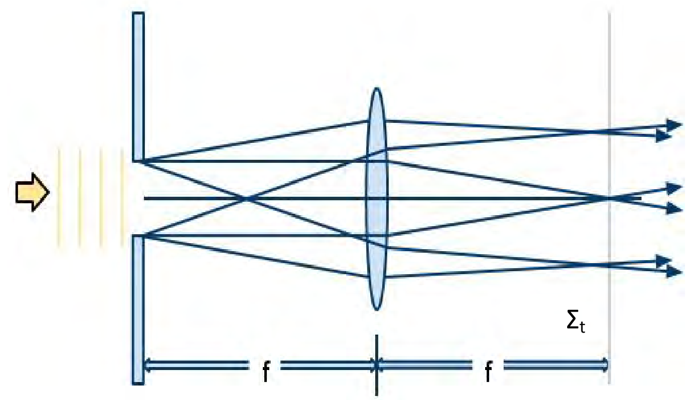

Figure 4: Schematic depicting a basic optical Fourier transform setup. Light diffracted by the transparency at the object focal point of a lens converges to form the far-field diffraction pattern at the image focal point of the lens.

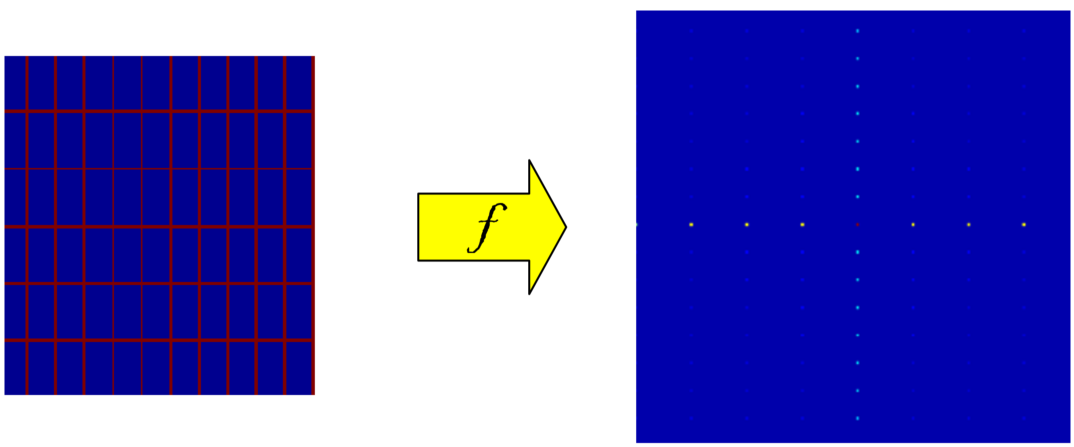

Figure 5: Simulation of reticle and Fourier transform of reticle taken in MATLAB. When the Fourier transform of the grid is taken, it forms a cross-shaped dot pattern; the spaces between dots are wider in the horizontal direction. The center dot is red because of its higher peak intensity; likewise, yellow is greater in intensity than blue.

Since the same pattern is to be projected onto each of the five cameras, images taken from each of them can be compared for magnification, image rotation, pattern registration, and possibly distortion. This comparison is made with respect to the Narrow-field camera because it has the finest optical resolution (5 µm/pixel) and no moving optics in the beam path (i.e. no focus adjustment). Calibration of the Narrow-field cameras must be done rigorously with certified calibration objects.

In this way the reticle projector will allow for individual calibration of the camera systems. Should a camera need to be replaced, it can be calibrated according to its own pattern of dots as well as the patterns displayed on the other cameras (particularly the narrow-field one, our designated control). The images can be compared and cross-calibrated and corrections can be made to camera placement so that all five images correspond to each other.

Also theoretically possible will be calibration of focus stage walk-off on future cameras. Because the optical axis has now been aligned to the current mechanical axis and the projection does not move, any further misalignment of the mechanical axis relative to the optical axis (perhaps due to the installation of a new camera) will be apparent and therefore adjustable.

Figure 6: Drawing of the pattern generator assembly. The reticle projector fits within the housing and is adjusted by the set screws located around the sides.

There are a number of notable features in the design of both the projector and the pattern generator assembly in which it is housed. The lens barrel in the reticle projector adjusts independently within the lens assembly with relationship to the fixed laser and has a lock nut to keep it in place once the focus is found.

The projector itself is also adjustable via 8 set screws in the pattern generator assembly: two sets of three fine-pitch set screws are set 120° apart, which can tip and tilt, and two longitudinally mounted set screws help the system focus to TCC (Fig. 6). Altogether, this allows for ±1.6° of travel.

There are additional ways to adjust the image projection once the pattern generator assembly is mounted. A mirror mount is adjustable for tip, tilt, and translation (and includes locking screws). This entire assembly mounts to the Extension Tube Weldment on the Illuminator assembly with spherical washers (Fig. 7).

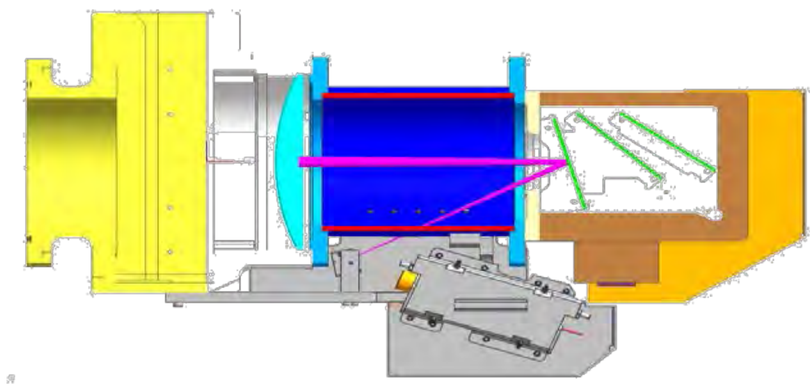

Figure 7: Cross-section of the Illuminator assembly. The pattern generator assembly, in shades of grey, is mounted to the Illuminator. The beam emitted from the reticle projector is directed towards a dichroic beam splitter by a mirror mount.

Safety concerns in regards to the laser were addressed as well. The projector housing has no openings, so stray laser light cannot escape. An exchangeable filter in the reticle projector as well as a partially transmissive reticle ensures that optical output power is set to the minimum practical level. Actual measurements show that the output of the laser with no filtration is 14.6 mW, the transmitted power through the reticle and lens is 2.65 mW (showing that the reticle is approximately 18% transmissive), and the output is 1.27 μW with the additional filtration (of OD 2.3). While the laser may be turned on and off using a button control on the TVS Illumination dialog, a keyed power switch may be used to disable the laser when necessary to protect anyone working in the target chamber; a sheet metal cover was provided for this keyed on/off control for the laser to prevent accidental operation. Further safety measures include procedural measures (when the laser must be turned off, for instance) and the fact that all operators of the reticle projector must wear the proper laser safety eyewear.

The pattern generator is housed in the Illuminator assembly. The infrared light given off by the laser is directed towards a dichroic beam splitter that combines it with the LED beams (as shown in Figure 2). Unlike these colored beams, a fraction of the infrared (IR) laser beam reaches all five cameras. This is clearly shown when the beam splitter coatings are graphed in terms of what wavelengths they allow through. The same beam splitter coatings are used to combine the colors as to separate them (Fig. 8).

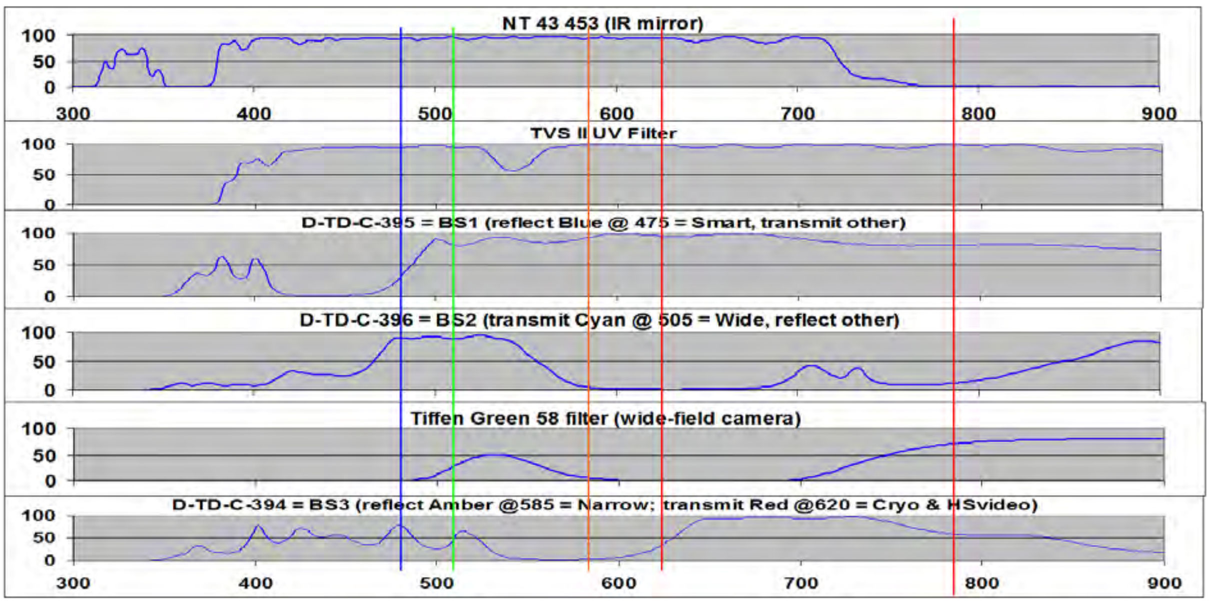

Figure 8: Transmission as a function of wavelength for the beam splitter coatings. The five vertical lines from left to right represent the four LEDs (blue, cyan, amber, and red) and the infrared source. The infrared source is completely reflected by the IR mirror and completely transmitted by the UV filter; once it reaches the beam splitters, however, some of it is transmitted and some is reflected each time.

We can use the graphs in Figure 8 and the schematic in Figure 2 to estimate the total amount of infrared light that reaches any of the cameras. For example, Figure 2 shows that to reach the Narrow-field camera, the infrared beam must be transmitted through the UV filter and BS1, reflected off BS2, and finally reflected off BS3 into the Narrow-field camera. Using Figure 8, then, we can estimate the actual percentage of light transmitted or reflected in each case; all of the infrared light is transmitted through the UV filter, but close to 20% is reflected off BS1, leaving 80% of the initial infrared beam. Then around 90% of the remaining light is reflected off BS2, leaving 72% of the initial beam. Finally, close to 45% of this light is reflected off BS3 into the Narrow-field camera, meaning that approximately 32.4% of the original infrared beam is directed to the Narrow-field camera.

3. Testing and Image Analysis

After the reticle projector was built, it had to be tested in a laboratory setting before it could be installed onto the OMEGA laser system. Initial testing of the projector was conducted with a 632.8 nm Helium-Neon laser, though later on an actual 780 nm infrared laser was used. Sets of mirrors and extra lenses, as well as a SMART camera were used to take images in the laboratory.

Once images were taken, they had to be analyzed; in this way the lab testing generated a form of image analysis that was conducted using MATLAB functions and masking in order to evaluate individual spots. Figure 9 demonstrates how a mask was formed using binarization as well as erosion and dilation (noise-minimizing) techniques from the original image. This mask was then superimposed over the original image, allowing the analysis to focus solely on the brightest spots and the cross-shape, with everything else set to zero: this is shown by the lineout taken of the masked image: the blue

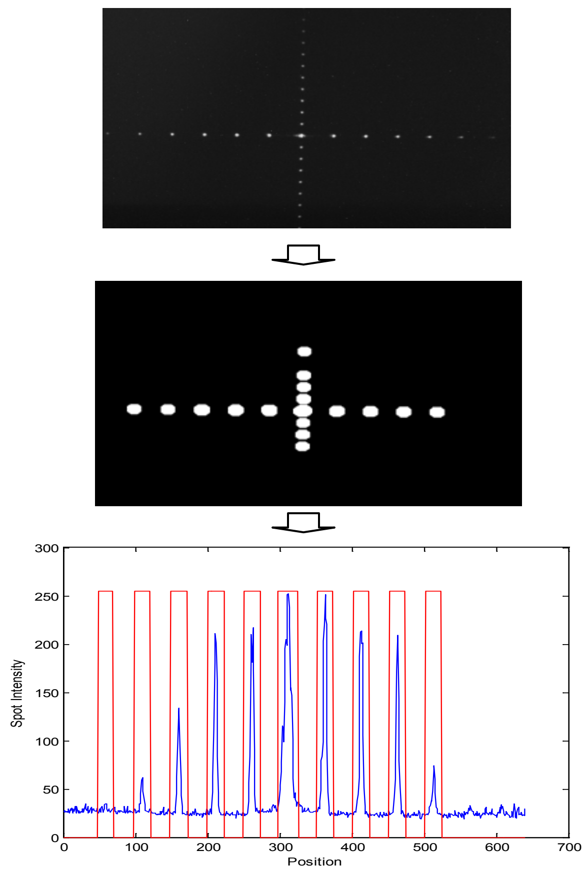

Figure 9: Diagram of the process of image analysis to extract peak intensities. The original image is used to form a mask which is then used to effectively cut out the noise from the original image so that only the brightest spots are analyzed. The graph at the bottom is a horizontal lineout going through the center dot; the blue is from the original image (intensities vary) while the red is from the mask.

represents the variation in intensity of the actual image, whereas the red is the mask; only the parts of the image that fall within the mask (the blue peaks within the red rectangles) are shown in the masked image.

Once the masked image is formed, comparison of radial distance, angular displacement, average distance between adjacent spots, spot area ratios, and peak intensity ratios allow for the examination of images and differences between images from different cameras. Corresponding spots on images taken from different cameras are matched up with each other using spot area ratios and peak intensity ratios; in theory, the ratio of the central spot to any of the other spots will be the same on each camera. A ratio is used so that magnification does not matter. The center spot is determined by its high peak intensity and its centroid is set as the center of the image, correcting for any shift in the image.

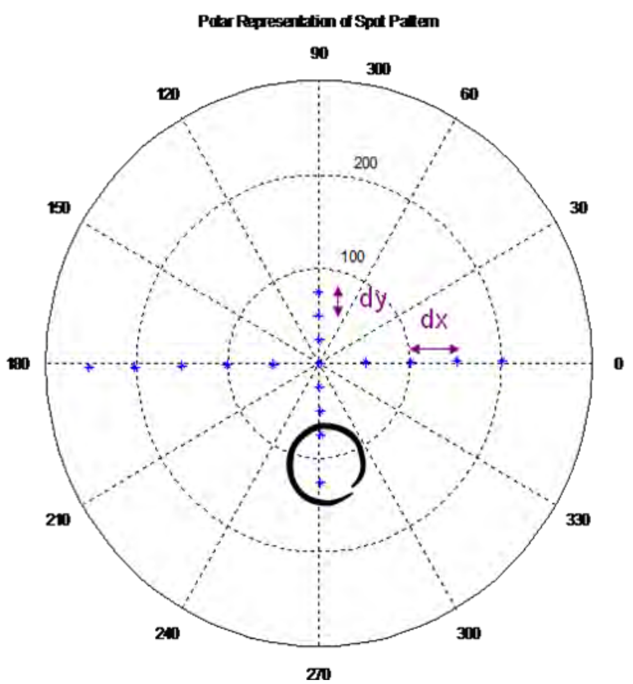

Figure 10: Polar representation of reticle projector spot pattern, as seen at TCC. Average distances are indicated by “dy” and “dx” and are taken because occasionally spots are not captured on the camera, as indicated by the black circle.

After corresponding spots are determined, radial distance from the center, angular displacement from normal, and the average distance between adjacent points are used to find any magnification or image rotation that might have taken place. These measurements can be used to graph the spot centroids onto a polar plot (Fig. 10). This graphing of the spot pattern makes it easier to see angular as well as radial displacement from the center.

4. Installation and Alignment of the projector on OMEGA

After the projectors (one for each axis) were assembled and tested in the lab and cleared for safety features, the next logical step was to mount them onto the OMEGA TVS. The Y-axis reticle projector was installed on August 9, 2010, and the X-axis one was installed a couple of weeks later, on August 20, 2010. Pointing and centering were used to align optics to the wide-field camera over the full travel of its focus stage by first moving it 20 mm towards TCC and aligning it, and then moving it back and aligning it and repeating, so that the end result was an image that does not shift when the camera moves along its focus stage.

Once the optic axis was aligned to the mechanical axis motion, the image itself had to be focused at TCC. This was accomplished using the set screws in the pattern generator as well as the mirror mount in the full assembly. Ultimately, the X-axis reticle projector was pretty much in focus at normal camera position, but the Y-axis reticle projector was focused at a +20 mm focus stage position on the wide-view camera (20 mm away from TCC). It has since been fixed.

Images were then taken of the aligned patterns (Fig. 11).

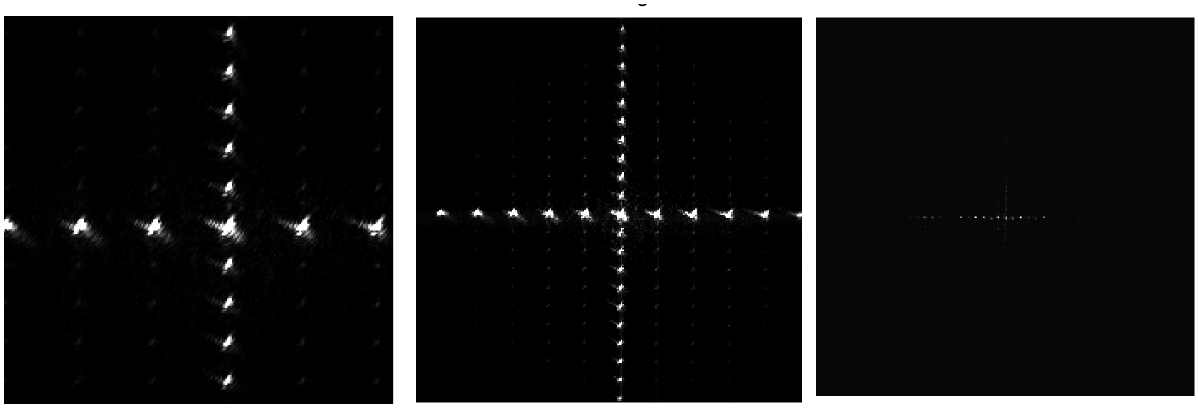

Figure 11: Images taken from the X-axis reticle projector. From left to right, these images were taken from the Cryo Narrow camera, the Narrow-field camera, and the Wide-field camera. The field of view size increases from left to right (Cryo has a field of view of 5 mm x 5 mm, Narrow has 10 mm x 10 mm, and Wide has 50 mm x 50 mm); all are used for different purposes.

These images, taken from the X-axis reticle projector, look much like the MATLAB-simulated one above in the dot pattern and spacing. The pattern seems to be almost perfectly cross-shaped, and the vertical spacing is closer than the horizontal spacing (as it should be). A notable difference is in saturation and spot area; the simulated image is controlled so that each spot takes up one pixel. With the actual images, however, each spot takes up a different area depending on its proximity to the center, brightest spot.

Ghost reflections are seen in these images as well (some of what looks like blurring from afar are actually reflection spots). These occur because there is some internal reflection at each surface which causes superpositioning of the ghost reflection on top of the actual image.

At the same time, these images seem to be experiencing some saturation, evidenced by the blooming of the spots. Less blooming is seen across the vertical spots because they are less intense than the horizontal ones. This image is focused particularly well, as even the dim spots in the quadrants are visible; however, these spots may disappear under further filtration. In order to see these spots, the incident intensity must be quite high (part of what causes the blooming). In any case, they are not included in the current analysis process.

5. Future

The reticle projector seems to be fine for its current purposes. It is able to project an image onto each of the five cameras, and these images are comparable. In Figure 11 above, it appears that the three cameras used (Cryo Narrow, Narrow, and Wide) are reasonably cross-calibrated; the pattern is imaged at roughly the same location on each of them.

More work needs to be done, however, to make sure this remains a useful tool. As of yet it can be difficult to tell, when something is out of focus, whether it is out of focus because the distance between the camera and image (at TCC) is too large or too small.

Preliminary images suggest that perhaps there is some distortion on the Y-axis cameras (Fig. 12). Each spot appears to be the superposition of multiple spots, possibly caused by surface reflections that were not included in our simulations. Both the MATLAB simulations as well as images taken from the X-axis cameras suggest that the axes should be orthogonal and the spots relatively circular and clearly defined; neither is the case in these Y-axis images. Information from these images is being used to help understand the source of this distortion and determine how to remove or compensate for it.

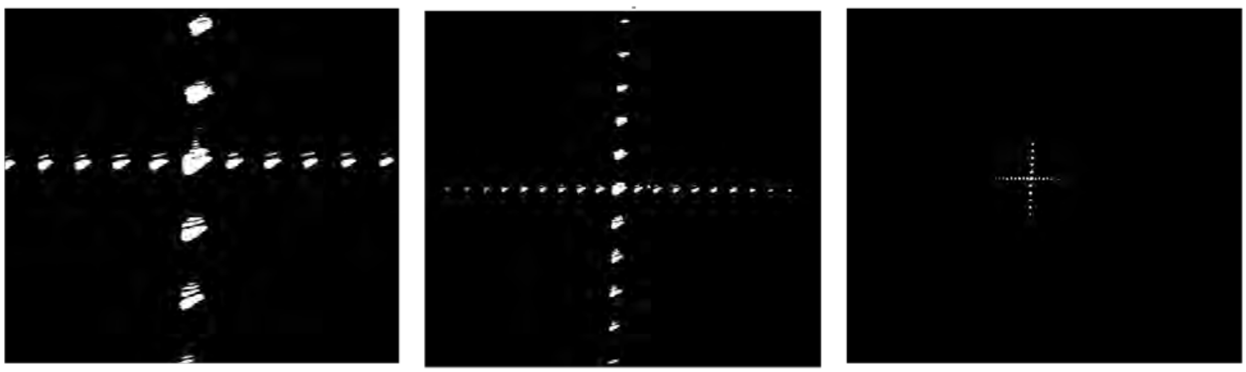

Figure 12: Images taken from the Y-axis reticle projector. These images are taken from the corresponding cameras on the Y-axis as the images of Figure 11 (Cryo Narrow, Narrow, and Wide). On these, however, it is apparent that the images have been rotated 90^{o} relative to the images in Figure 11 (the axes are tilted so that the horizontal spots are closer together), and the axes themselves are not orthogonal. The fact that there are extra reflected spots suggests that something may be wrong with the cameras (and/or other optics in the beam path).

Though these images do not contain enough information to determine the source of the reflections, the overlapping suggests that perhaps they come from a thin plano optic, such as the cover glass used to protect a camera sensor; however, because the reflections are visible on all cameras, they are more likely to be caused by one or more of the beam splitters shared by the cameras. Because the reflections overlap, they most likely do not come from a lens or other curved surface because such reflections would diverge instead. At the same time, these ghosts should not interfere with the intended use of the cameras, as the distortion is displayed in all five of the cameras; they can still be cross-calibrated.

Although currently there are only plans to use the reticle projector as a calibration and diagnostic tool, useful for cross-calibration of the cameras, the projector may also be used to detect distortion. The image analysis conducted in this project focused only on the brightest cross of spots in the pattern; however, the spots within the quadrants may aid in detecting distortion.

Conclusion

The reticle projector was designed, built, and installed onto the Illumination side of the target viewing system of the OMEGA laser system. In it, a 780 nm infrared laser shines through a reticle and then passes through a series of lenses, focusing a Fourier transform image at TCC. This image is then captured by the cameras located on the Imager assembly on the opposite side of the target chamber. Because the pattern will likely have some distortion or defining features, and the projector is not physically in the target chamber, this system is useful in identifying corresponding spot patterns on the different camera images as well as any differences in magnification, rotation, or pattern registration, as well as distortion. This will enable periodic recalibration of the cameras. The reticle projector was first tested in a laboratory setting where images were taken, compared, and analyzed using MATLAB. Preliminary results suggest that this system is capable of detecting discrepancies in camera rotation, magnification, distortion, and misalignment between cameras. Though it is meant to be primarily a calibration and diagnostic tool, other uses for it may be apparent in the future.

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