Investigating Contrast, Resolution and Field-of-View of the Questar QM-1 SZ Tele-Microscope

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1 Abstract

The purpose of this report is to highlight the optical properties that the QM-1 SZ system possesses. Current methods of imaging and target alignment in high power laser systems require complex placement of lenses and cameras within the target chambers themselves.

The QM-1 SZ Tele-Micropscope was tested to find out various characteristics of the system such as the contrast, resolution and field-of-view (FoV) in order to determine its usability within an experimental environment, such as that in the Central Laser Facility of Rutherford Appleton Laboratory. These characteristics were tested for 5 different, increasing, focal lengths at two distances. For a distance of 65 cm, the highest focal length had the highest resolution at 6.96 um but also the smallest FoV at 1 mm, whereas the lowest focal length has the lowest resolution of 39.3 um and the widest FoV of 13.5 mm. As for a distance of 1.4 m, only focal lengths 2 through 5 were available. The highest resolution was 13.9 um with a 2 mm FoV and the second lowest resolution was 31.3 um with a FoV of 10 mm, due to the fact focal length 1 could not be used.

2 Motivation

Imaging itself is a form of diagnostics that has to be performed for a majority of experiments, especially when users are not able to be in the room when the experiment is running. Evidently the use of this system has many advantages over other imaging techniques used frequently, which usually require space inside the chamber itself. The target chambers are usually very tight for space and hence by taking up a lot of room just for alignment, the experiment itself becomes quite limited. The QM-1 SZ system is a combination of a large working distance but with a microscopic level of magnification, and hence can be located outside of the target area and can be used to image the target without taking up room in the chamber itself. The purpose of this investigation was to test its optical qualities such as contrast, resolution and field-of-view (FoV). This report will ensure future users of the QM-1 SZ will have a clear understanding of the strengths of this system, and will be able to use the appropriate method of imaging for the experiment they need to run.

3 Manufacture

The QM-1 SZ system is a microscopic system with a working distance of between 560 mm to 1520 mm [1], however when testing the range was more like 580 mm to 1400 mm. The system has a keypad control to enable remote control along with the ability of manual or automatic focusing, known as parfocalization. This is a programmable feature of the system which will correct the focus automatically for changes in focal length. This feature means that the user does not have to be in/near the target area in order to adjust the systems focus. The back of the microscope has a C-mount which allows digital imaging of the viewfinder for more automated control. The QM-1 SZ consists of a fully motorized, microprocessor controlled Multi-Power Lens (MFL). It is a small aperture lens (89 mm) providing five focal lengths and five neutral density filter selections, as seen in Table 1. These focal lengths and ND filters are selected through the keypad with preset values, although there is the ability to vary focal lengths to the users choice [1]. An image of the system itself is shown in Fig. 1. It should be noted that 2 of the systems have been sent off for re-modification to work at distances over 3 m, and will be tested similarly once returned.

Keypad No.	Focal Length	ND Filter
1	100mm	0
2	130mm	0.3
3	172mm	0.8
4	1.5x Zoom	1.5
5	2x Zoom	2.5

Table 1: Focal length and ND for each keypad number.

Figure 1: Image of the back of the QM-1 SZ system.

4 Method

A diagram of the experimental setup is shown in Fig. 2. The QM-1 SZ was mounted onto a stable base and clamped to the table. The microscope was then directed towards a target at the same height as the imaging optic, at a distance of 65 cm from the front of the lens. It was also tested at the maximum range of 1.4 m, the results of which will be tabled towards the end of the report and but with not as much discussion. On the rear of the system was mounted an Allied Vision Stingray FireWire.b Camera, model F-033B. This camera had an 8-bit to 14-bit sensor, and for the test 8-bit was used. This put a maximum input of 255 counts onto the sensor, and then was connected to a laptop where a live image could be seen. The camera was set to a shutter of 50 ms throughout the testing.

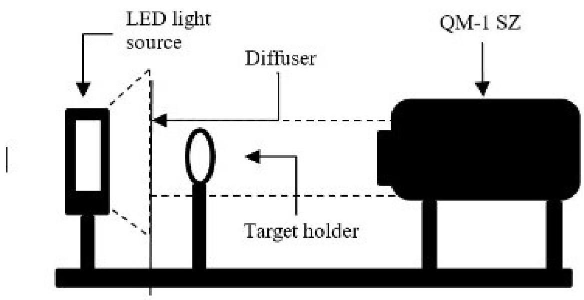

Figure 2: Setup used to determine experimental results. LED light source is positioned behind the diffuser, which is then behind the target holder. This produced a fairly uniform and diffuse beam to back light the target

Behind the target post a uniform light source made by a green LED screen was placed so that the target could be easily seen by the sensor. This is because of the how the QM-1 SZ has a small aperture, at 89 mm, and hence a large amount of light must enter the optic in order for an image to be seen. This light source was also sent through a diffuser to limit any bright spots that may appear from the LED source. The main method to find contrast and resolution was to use Modulated Transfer Function (MTF) alongside a 1951 USAF resolution test target, as shown in Fig. 3. This was the target for the system throughout the characterisation. As the optic had an adjustable focal length, each one was tested for its resolution, contrast and FoV. At each of these focal lengths, the focusing was changed via the keypad which may have changed the distance between the tele-microscope and the target.

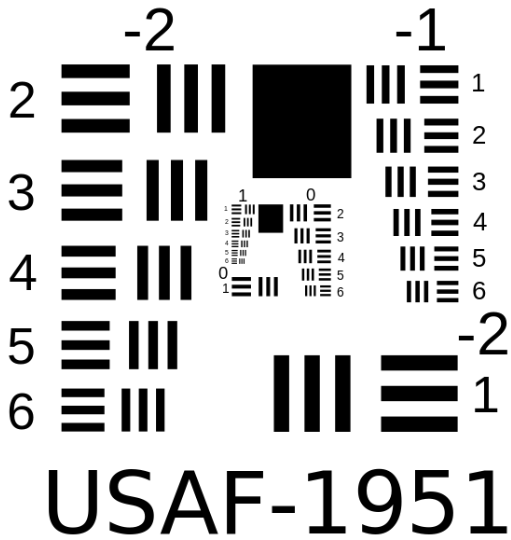

Figure 3: USAF Test Target [2].

At each focal length, an image was captured of the resolution chart in focus. From this image, a line out could be determined across each individual Group and Element and produce a plot of relative light intensity across the sensor. This graph contained 3 peaks and 2 troughs, in which the Modulated Transfer Function could be used. Before the calculation the count rate (intensity) was determined from the reference point, which in this case was the largest square visible on the image. This was done in order to better scale the intensity, as the count rate at the square was likely to be the largest. When scaled, the count rate determined from the line outs was between 0 and 1.

4.1 *Modulated Transfer Function*

To use the MTF method, the line outs produced at each Element had the data extracted and used in the following equation

$$M = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

where I_{max} was the maximum intensity, and I_{min} was the minimum intensity as measured between two separate peak intensities. This equation resulted in the Modulation, which was plotted against its respective line pairs per mm (spatial frequency) found from the already pre-calculated table, as seen in Table 2. Referring to Fig. 3, each Group contains 6 Elements which are each numbered. This is the format to determine the number of line pairs per mm as per Table 2. This plot was then be used to determine the contrast at various resolutions for each focal length. The line outs were performed using the software ImageJ [3], and completed with a wide line as to produce an average value for the intensities across the patterns. This reduced error in results, but as a precaution the standard deviation was also taken to show variation in the intensity.

4.2 Field of View

As for the FoV measurement, a ruler which had increments as small as 1/2 mm was replaced for the grid and again became the target image. From this, the widest distance each focal length could image was recorded.

5 Results and Analysis for 65 cm

5.1 Focal Length 1 Performance

Fig. 4 shows the plotted results for all five focal lengths used, with the modulation calculated on each Group and Element against their respective line pairs per mm. The standard deviations for each of these focal lengths are also shown together in Fig. 5. Also shown in Fig. 6 is the image captured for Focal Length 1. This image is only shown for reference and will not be shown for every focal length.

From Fig. 4 it can clearly be seen that for Focal Length 1, the modulation decreases as the line pairs per mm increases. This was expected for all the focal lengths due to the smaller grid patterns becoming harder to distinguish due to the diffraction limit of the system. The amount of light able to pass though the smaller grids also decreased significantly, which meant that the QM-1 SZ was not able to image them due to its small aperture size.

It can also be seen that the modulation decreases rapidly over only a slight increase in line pairs per mm compared to the other focal lengths. This is due to the fact that this focal length is much more zoomed out compared to the others, and therefore much less of the smaller Elements are visible to the camera sensor. From this test, the limit to which lines could be distinguished by the human eye was towards a modulation of 0.2. This value was then used to determine the maximum line pairs per mm that each focal length was able to observe reliably. In this case, the maximum resolution of this focal length was 25.4 line pairs per mm, or a resolution of 39.3 um.

The standard deviation in Fig. 5 decreases overall as the resolution became smaller, although clearly over a much smaller range compared to the other focal lengths. Again this is due to the fact the smaller Elements are much harder to image for this focal length. The standard deviation represents how the image was being seen by the software as at the larger, more distinguishable grids, there is a larger deviation from the mean intensity. This shows that the bright and darker areas are being more easily separated. This was not the case for the smaller spaced grids, as the bright areas tended to merge into a single bright area, and hence there is not as much deviation. This idea will be used to represent the uncertainty of the program ImageJ.

5.2 Focal Length 2 Performance

This focal length had a drastic improvement on the resolution capabilities. Compared to the first focal length, the modulation was much larger at 25.4 line pairs per mm and was be clearly visible on the camera. The modulation begins to drop still, but not at such a rapid rate. The rate it begins to drop is exponential, and shows how the modulation decreases at a faster rate as the line pairs per mm increases. The resolution of this focal length limits at 50.8 line pairs per mm, or 19.6 m; double of that at focal length 1. It is also much easier to see how the plot levels off at the smaller resolutions compared to the previous focal length.

As for the standard deviation, again as seen in Fig. 5, the general trend was that the deviation decreased as the line pairs per mm increased. This was expected and shows that the error in results became larger with less deviation in the intensity.

5.3 Focal Length 3 Performance

Looking at Fig. 4 again, it could be seen how the modulation decreased exponentially over the resolution, and for this focal length the minimum resolution observable was 71.8 line pairs per mm which equated to 13.9 m. This was still an improvement on the resolution of Focal Length 2. As for the standard deviation, it shows a near identical line to Focal Length 2 but with a little less deviation on the larger spaced Elements.

5.4 Focal Length 4 Performance

The general trend seen in the previous modulation plots seems to alter slightly when compared to the fourth focal length. Although it follows the same exponential curve at the start, a small section rises again at 100 line pairs per mm. This effect is sometimes, but rarely seen, in some optics. However, by observing the standard deviation plot it can be seen that the deviation decreases very slightly at 100 line pairs per mm. Hence, this observation may be due to ImageJ not being able to resolve the lines very accurately, and not the characteristics of the optic. Compensating for this error, the resolution at this focal length was said to be 90.5 line pairs per mm, or 11.05 m.

						Group						
Element	2	1	0	1	2	3	4	5	6	7	8	9
1	0.250	0.500	1.00	2.00	4.00	8.00	16.00	32.0	64.0	128.0	256.0	512.0
2	0.281	0.561	1.12	2.24	4.49	8.98	17.96	35.9	71.8	143.7	287.4	574.7
3	0.315	0.630	1.26	2.52	5.04	10.08	20.16	40.3	80.6	161.3	322.5	645.1
4	0.354	0.707	1.41	2.83	5.66	11.31	22.63	45.3	90.5	181.0	362.0	724.1
5	0.397	0.794	1.59	3.17	6.35	12.70	25.40	50.8	101.6	203.2	406.4	812.7
6	0.445	0.891	1.78	3.56	7.13	14.25	28.51	57.0	114.0	228.1	456.1	912.3

Table 2: Table of the line pairs per mm for the USAF target [2].

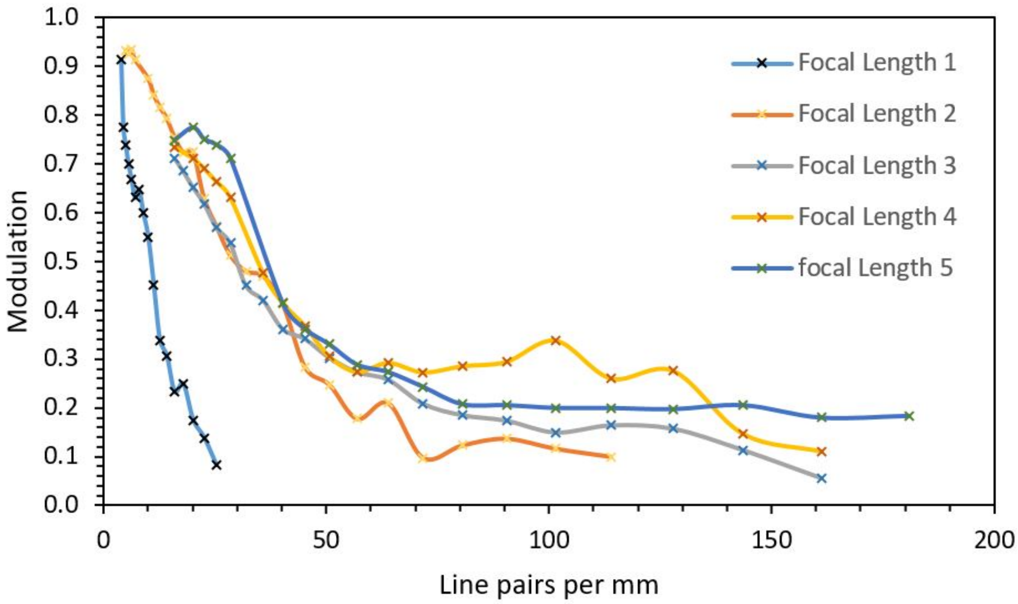

Figure 4: Modulation against the line pairs per mm for 65 cm range. The results were scaled by 255, as per the count rate from the reference square.

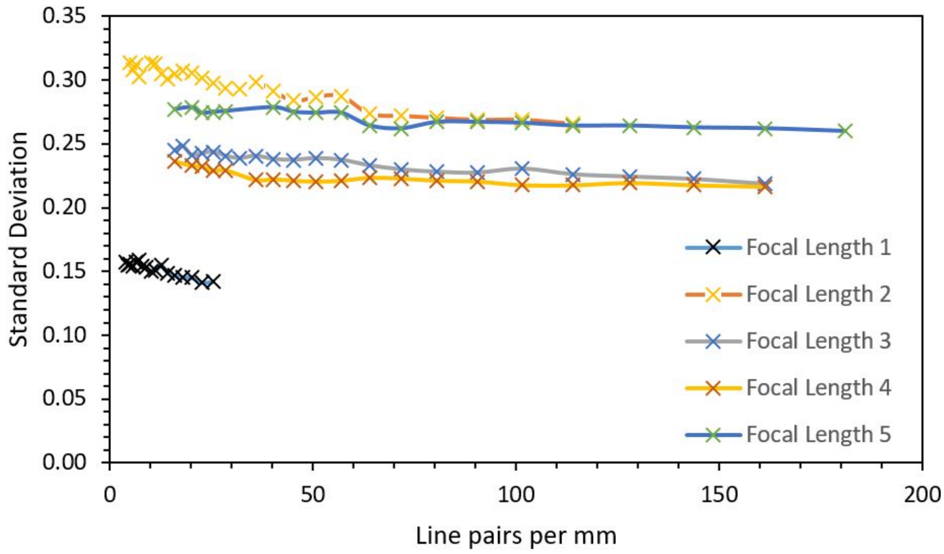

Figure 5: Plot of the standard deviation against the line pairs per mm, scaled by 255 for a range of 65 cm.

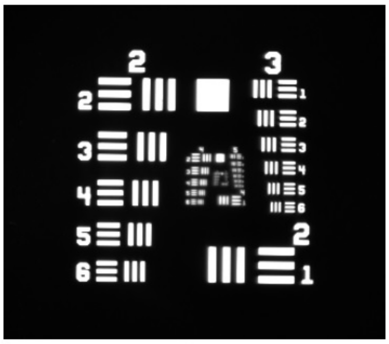

Figure 6: Image captured of the resolution grid using focal length 1. Clearly seen is the reference square and each grid, along with their Group and Element number.

5.5 *Focal Length 5*

Finally, this focal length was the longest focal length achievable on the system and hence the highest magnification. The plot for this modulation followed a much cleaner exponential pattern, smoothing off more than previous results. The resolution from this plot was 143.7 line pairs per mm (6.96 um). The reason for the large increase compared to the previous focal length was due to the shape of the plot, as the line flattened out at a modulation of 0.2. This meant the grids could still be imaged effectively at resolutions much smaller than the previous focal lengths.

As for the standard deviation, the general trend was a decrease as usual but a couple of points lie outside of this trend. In particular, at around 65 line pairs per mm the standard deviation decreases a little. However, this did not seem to affect the results in a negative way, as the modulation plot still had a relatively smooth curve.

6 Field-of-View (FoV) for 65 cm

Shown in the next five figures are the images captured of the ruler for all five focal lengths. However, it should be noted that the results of this test may be limited to the sensor size of the camera and not the system itself. The sensor format is 1/2”, which could be smaller than the image produced by the lens itself. Each image has been adjusted for sharpness and brightness for more visual clarity, with each interval being 1/2 mm apart.

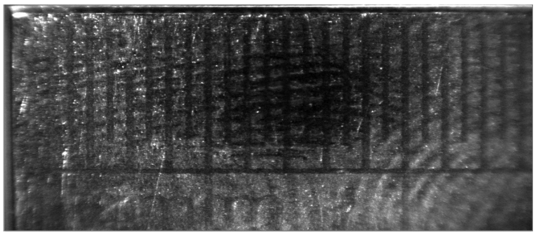

Figure 7: Focal Length 1.

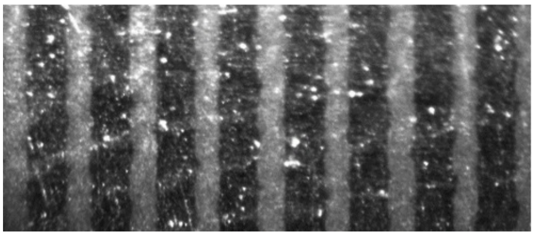

Figure 8: Focal Length 2.

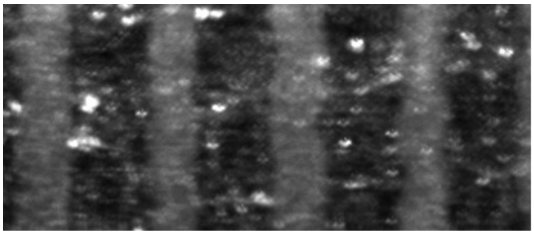

Figure 9: Focal Length 3.

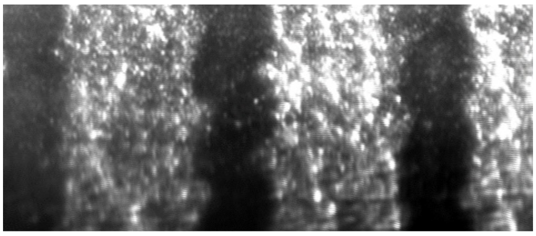

Figure 10: Focal Length 4.

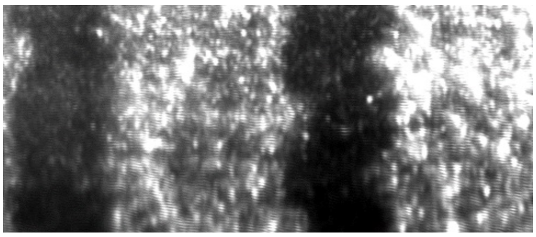

Figure 11: Focal Length 5.

Table 3 shows the measurements of FoV for each focal length. These results may vary in situation, as the working distance of the system may be different.

Focal Length	Field of View
1	13.5 mm
2	4 mm
3	2 mm
4	1.5 mm
5	1 mm

Table 3: Field of View measurements for each focal length, at a working distance of 65 cm.

7 Discussion

By observing these results, it was seen that each focal length can be useful for various tasks. The smallest focal length has a wide field of view and a relatively low magnification and would be best for general positioning of a target, or for just imaging a larger target. If a smaller target was being used, or smaller adjustments were being made, then any of the longer focal lengths would be better. The advantages to these focal lengths all depend on the task at hand.

The longest focal length appeared to have a wide range of applications, due to its high resolution, however this was not always the case as the task may be limited by the field of view. If the target is too large, then the optic will not be able to image it. These factors may depend on the camera used to image the target though.

The depth of field at the longer focal lengths also becomes increasingly smaller and hence can be difficult to focus. This becomes an issue in environments where the optic may be misplaced due to vibrations.

Finally, the spread of standard deviation was similar at all focal lengths. This showed that the program used to do the line outs, ImageJ, was consistent with this method. It showed that the uncertainty in resolution increased as the lines became smaller relative to the focal length.

Focal Length	Resolution	Field of View
1	39.3 um	13.5 mm
2	19.6 um	4 mm
3	13.9 um	2 mm
4	11.05 um	1.5 mm
5	6.96 um	1 mm

Table 4: Results showing resolution and FoV for 65 cm.

8 Results for 1.4 m

Shown in Table 5 are the results for the resolution and FoV for a working distance of 1.4 m. An issue that was prevalent at the longer ranges was that Focal Length 1 never focused beyond the 65cm range, even when the focus was changed on the keypad itself. This may be a problem for some uses of the system, however for this practical Focal Length 2 was suitable in finding the target easily.

As expected, the resolution and FoV at the larger distance was larger than that at the closer distance.

Focal Length	Resolution	Field of View
2	31.3 um	10 mm
3	19.7 um	5 mm
4	17.5 um	3 mm
5	13.9 um	2 mm

Table 5: Results showing resolution and FoV for 1.4 m.

9 Conclusion

Based on the data it can be seen that the QM-1 SZ system has a versatile range of resolutions and magnification which could be used in many different experimental environments. The longest focal length, Focal Length 5, had the highest resolution and also the greatest magnification without sacrificing image quality for both distances. However, this may not be useful for an experiment involving a larger target due to its narrow field of view. This is where Focal Length 1/2, the smallest focal length depending on distance, would be most useful instead due to its wide field of view.

In conclusion, the QM-1 SZ proves to be a very useful piece of optical equipment that offers benefits of high resolutions remote imaging, however is limited by its relatively short working distance.

References

[1] Questar Corporation. SZ M1 Manual. Pennsylvania (2014).
[2] Psyer Optics. Resolution charts and gratings. (2017). Available from: http://www.pyseroptics.com/wp-content/uploads/2017/07/1330_Resolution_Charts_Brochure.pdf
[3] ImageJ Software. Available from: https://imagej.nih.gov/ij/