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**The Variability of Spatial Resolution
Estimates Obtained Using a CCD Camera**

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THE VARIABILITY OF SPATIAL RESOLUTION ESTIMATES OBTAINED USING A CCD CAMERA

SUMMARY

We have previously developed techniques for measuring the spatial resolution of flight simulator displays. In the present experiment, we estimate the relative variability of the measurement technique and the display projectors they were designed to assess. We use the ratio of the standard deviation and mean of the resolution estimates as a measure of variability. Variability was found to be about 1.3% for grating transparencies illuminated by a stable light source. This value may be taken as the inherent variability of our measurement hardware and analysis procedures. Analogous measurements made on cathode ray tube (CRT) projectors resulted in a mean variability of about 4.3%. The difference between the two estimates, 3.0%, may be taken as a measure of the variability of the CRT projectors alone.

BACKGROUND / INTRODUCTION

In many flight-simulator applications, spatial resolution is the major determinant of the fidelity and effectiveness of displayed imagery. Operational visual display systems are often difficult to calibrate for both practical reasons, such as limited working room and limited access time, as well as technical reasons, such as the lack of standardized tests and a general lack of consensus as to which tests are required, and what the results of those tests mean. Further, it is well known that projector resolution decreases with age. In addition, variations in routine setup procedures, such as focusing and color convergence, can alter display resolution. For these reasons, it is good practice to objectively measure display resolution on a regular basis.

We have previously developed a technique for measuring, specifying, and conceptualizing the spatial resolution of visual displays (Geri, Winterbottom, & Pierce, 2004). That technique is based on a well-established measurement standard (VESA, 1998). However, the precision of that technique is limited by the variability of both the light measurement device and the procedures used to estimate spatial resolution. Since very little data are available concerning either of these sources of variability, we have attempted to assess them here.

We performed three related evaluations of spatial resolution variability: two on CRT-projectors, and one using grating transparencies illuminated by a stable light source. The first projector evaluation examined the variability of the display's spatial resolution across a six-hour test-period and over four days. The second projector evaluation measured spatial resolution variability within each test-period. Finally, the grating transparency evaluation used a stable light source and a set of grayscale gratings to distinguish what percentage of the variation was due to the CRT monitor, as compared to the measurement hardware, and measurement and analysis procedures.

METHOD

Stimuli and Apparatus.

For both the grating-transparency and projector evaluations, luminance measurements were obtained using a CCD camera (Model ST7, Santa Barbara Instrument Group, Santa Barbara, CA). Additional measurements were obtained using a calibrated Minolta LS-100 photometer.

Spatial resolution was estimated from the luminance distributions obtained with the CCD camera using techniques developed for this purpose (see Geri *et al.*, 2004).

Projector Evaluations. The stimuli used to estimate projector resolution were generated using special-purpose software and hardware (Geri *et al.*, 2004). The test images were horizontal and vertical grille patterns composed of on-off lines consisting of one, two, or three pixels in width. The lines of each grille pattern were modeled as either full-black (grayscale = 0) or full white (grayscale = 255). The test images were displayed using a Barco Model 808 CRT projector (Barco Inc., Kennesaw, GA) and a Proscreen Model 1.2 rear-projection screen (Proscreen Inc., Medford Oregon). To match the Mobile Modular Display for Advanced Research and Training (M2DART) settings used in the operational simulators at the Air Force Research Laboratory, Warfighter Readiness Research Division (AFRL/HEA), Mesa AZ, the dimensions of the rear-projected image were set to 52 in. (H) $\times$ 43 in. (V). The distance from the projector to screen was 97 inches. The test images were generated at 1600 $\times$ 1200 pixels using a PC-based test system that included an AGP NVIDIA GeForce 4 video card.

Grating-Transparency Evaluation. Three transparencies, consisting of the same grating frequency at three different contrasts were created using Illustrator 10 (Adobe, San Jose, CA), and were printed at 600 dpi. The gratings consisted of alternating dark and light lines at a frequency of 51 lines/in. The resulting line widths (0.5 mm) approximated those of the 1 on/1 off grille pattern used in the projector evaluations. The nominal contrast values (low, medium, and high) were chosen to approximate those typically encountered when spatial resolution measurements are obtained from CRT projectors. The grating transparencies were illuminated by a stable incandescent light source. A 1.6 neutral density filter was used to reduce the mean luminance of the grating to about 16 fL, to approximately match the mean luminance of the imagery used in the projector evaluations. In addition, a heat-absorbing filter was used to remove near-IR radiation to which the CCD camera was sensitive but the Minolta photometer was not.

Procedure

Resolution measurements were obtained with the CCD camera placed 16 cm from the projected image under test. This resulted in the CCD-camera field-of-view covering a rectangular area of about 7 mm (H) $\times$ 5mm on the displayed image.

For all evaluations, spatial resolution estimates were calculated using an MS-Excel spreadsheet that implemented the techniques described in Geri *et al.* (2004). The spreadsheet routines located the maximum and minimum values from each of the measured grill-pattern luminance distributions, calculated their averages, and then computed a Michelson contrast. Horizontal and vertical resolutions were obtained using a contrast criterion of 25%.

Grating Transparency Evaluation. The light source that illuminated the gratings was first allowed to warm up for 15 min. The contrast of each of the three contrast gratings was then measured three times for each of three grating contrast levels, with the measurement order randomized. This procedure was then repeated twice, with the camera moved and set up again between each repetition, resulting in 3 measurement-sets within the daily test-period. The three sets of measurements were then repeated on each of four test-days. Spatial resolution estimates were obtained from each set of measurements made on the three (low, medium, high) contrast gratings.

Projector Evaluation 1. The projector was left on stand-by overnight. At the beginning of each test day, the projector was turned on. For the first 30 min, the projector was allowed to stabilize using Barco's built-in White-Pattern Warm-Up Screen and then remained on for the remainder of the test-day. After this initial warm up period, spatial resolution measurements were obtained, and then repeated at three hour and six hour intervals, for a total of three test-periods. Each of the test-periods lasted approximately 15 min, and all were repeated on each of four days.

The projector was fully on, i.e., imagery was projected, for the entire test-day. Before each test-period, the projector's color convergence was checked and adjusted if necessary. For both the spatial-resolution and gamma measurements (see below), the camera and photometer were moved and then set up again between each of the three test-periods.

Spatial resolution estimates were obtained using horizontal and vertical, 1-on/1-off, 2-on/2-off and 3-on/3-off grille-patterns. The order in which the grille-patterns were tested was randomized. A gamma function was also obtained within each test-period (see below). The order in which the grayscale levels, used to obtain the gamma functions, were tested was also randomized.

Projector Evaluation 2. A second projector evaluation was performed to assess the variability of the spatial resolution estimates within each test-period. Methods and procedures were identical to Projector Evaluation 1 except that three measurements were obtained for each grille pattern within each test-period. Each test-period lasted approximately 30 min.

CCD Luminance Calibration. In order to calibrate the data obtained from the CCD camera, gamma functions were obtained by relating the CCD output to luminance measurements obtained using the calibrated Minolta photometer. The order in which the gamma function and spatial-resolution data were collected was randomized. For the projector evaluation, the gamma functions were obtained using a series of full-screen images whose luminances corresponded to DAC values ranging from 0 to 255 in steps of 30. The luminance of the series of images was measured with both the Minolta photometer and the CCD camera. The output of the latter varied between 0 and 65536 (i.e., 16-bits). For the gamma measurements, the CCD-camera and the Minolta photometer were placed 16 cm and 91 cm, respectively, from the image being measured. For the grating transparency evaluation, image luminance was varied using nine neutral density filters ranging from 1.6 to 4.1 ND. Each filter or filter combination was placed in front of the heat-absorbing filter and light source. For each filter, the measured luminance was plotted as a function of the CCD output, and a power function was fit to the data using SigmaPlot (v. 8.0, SPSS Inc., Chicago, IL).

RESULTS AND DISCUSSION

Grating-Transparency Evaluation. Shown in Figure 1 are mean contrast measures obtained for the grating transparencies. The results of an Analysis of Variance (ANOVA) showed a significant main effect of Test-Day ($F_{3,24}=94$, $p<0.001$) but not Measurement-Set ($F_{2,24} = 23.1$, $p = 0.062$). Based on the ANOVA results, it was decided to estimate CCD-measurement variability by collapsing the data across measurement-sets, and finding the ratio of the standard deviation to the mean of the resolution measures for each test-day. The ratios found were 0.0192, 0.0127, 0.00984, and 0.00828. The mean of these four ratios is 0.0125 (1.25%), which we take as the variability of our CCD measurements and spatial-resolution analysis procedure.

Projector Evaluation 1. Shown in Figure 2 are the horizontal and vertical spatial resolution estimates obtained for the first projector evaluation. Separate one-way ANOVAs were performed for the horizontal and vertical resolution estimates for both the Test-Day and Test-Period variables. As there was no significant effect of either Test-Day ($F_{3,8} < 1.0$, $p > 0.44$) or Test-Period ($F_{3,9} < 0.58$, $p > 0.58$), the horizontal and vertical data of Figure 2 were each used to estimate the variability of the spatial resolution measurements by the same technique used for the grating-transparency data. The ratios of the standard deviation to the mean of the 24 horizontal and vertical measurements were found to be 0.035 and 0.016, respectively. The resulting variability estimate for our projector spatial resolution measurements is therefore 0.026 (2.6 %).

It should be noted that the vertical variability estimate obtained for the CRT projector is much smaller than the horizontal estimate. This is the case because the physical properties of most raster projectors allow horizontal lines (used here for the vertical resolution measurements) to be displayed at a greater contrast than the pixels within each line, which form the displayed vertical lines.

Projector Evaluation 2. Projector Evaluation 2 was performed on a second projector to obtain additional data on the variability of our spatial resolution measurements. In addition, in order to assess possible interactions between test-day and test-period, multiple measurements were obtained within each test-period. Shown in Figure 3 are the average horizontal and vertical spatial resolution measurements obtained. The error bars are standard errors of the three resolution estimates obtained for each test-period.

Separate two-way ANOVAs were performed for the horizontal and vertical resolution data. For the horizontal estimates, significant differences were found for both Test-Day ($F_{3,24} = 92$, $p < 0.001$) and Test-Period ($F_{2,24} = 375$, $p < 0.001$), as well as for their interaction ($F_{6,24} < 191$, $p < 0.001$). Likewise, for the vertical estimates, significant differences were found for both Test-Day ($F_{3,24} = 340$, $p < 0.001$) and Test-Period ($F_{2,24} = 430$, $p < 0.001$), and for their interaction ($F_{6,24} < 264$, $p < 0.001$).

Because significant differences in measured resolution were found for different test-days and different test-periods, data were not collapsed across either of these variables in obtaining the measurement variability estimates. The ratios of the standard deviation to the mean of the 36 individual horizontal and vertical measurements were found to be 0.077 and 0.040, respectively. The resulting variability estimate for our projector spatial resolution measurements was the mean of those two estimates, 0.059 (5.9%).

Combining the variability estimates of Projector Evaluations 1 and 2 results in an overall estimate of about 4.3%. However, the variability estimates were much higher for the second evaluation due largely to one data point obtained on the first day of Projector Evaluation 2 (see Figure 3). If that data point is considered an outlier and is removed, the horizontal variability estimate for Projector Evaluation 2 is reduced to 4.4%, and the overall variability is reduced to 3.5%.

CONCLUSIONS / RECOMMENDATIONS

The variability of spatial resolution measurements obtained on CRT projectors used in the M2DART is estimated to be about 4.3%. The analogous variability for test stimuli in the form of transparencies illuminated by a stabilized light source was about 1.3%. The difference

in the two variability estimates, 3.0%, may be taken as an estimate of the variability of the CRT projectors alone.

For the purposes of the present memorandum, the difference in the variability estimates obtained in Projector Evaluations 1 and 2 must be assumed to be due to inherent variability in the output of CRT projectors of the type evaluated here. Given that only two projectors were evaluated, however, it is recommended that additional data be obtained.

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VESA (2001) *VESA flat panel display measurements standard*, Version 2, Video Electronics Standards Association, Milpitas, CA 76-77.

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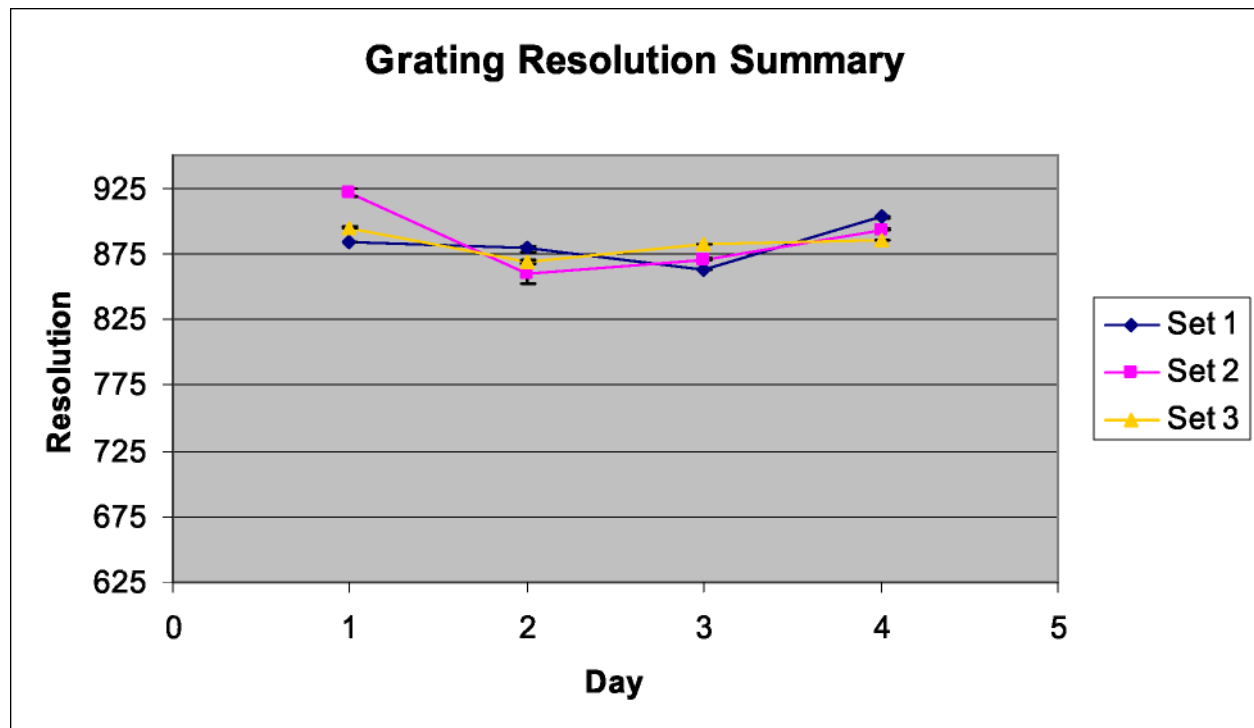


Figure 1. Spatial resolution estimates obtained for the Grating-Transparency Evaluation

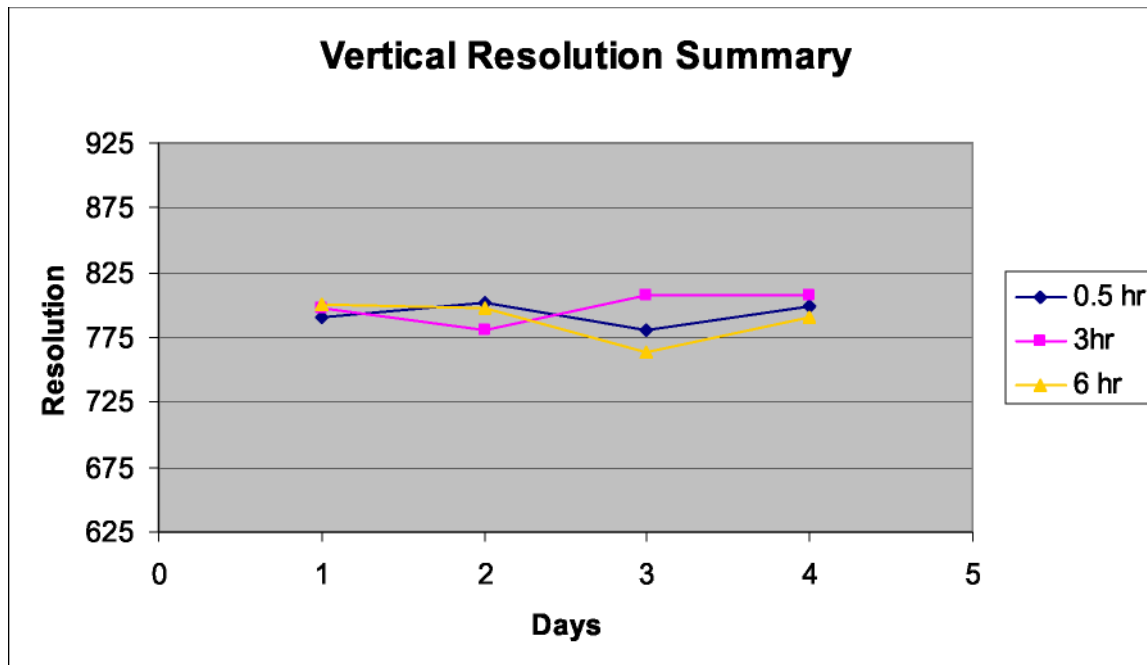
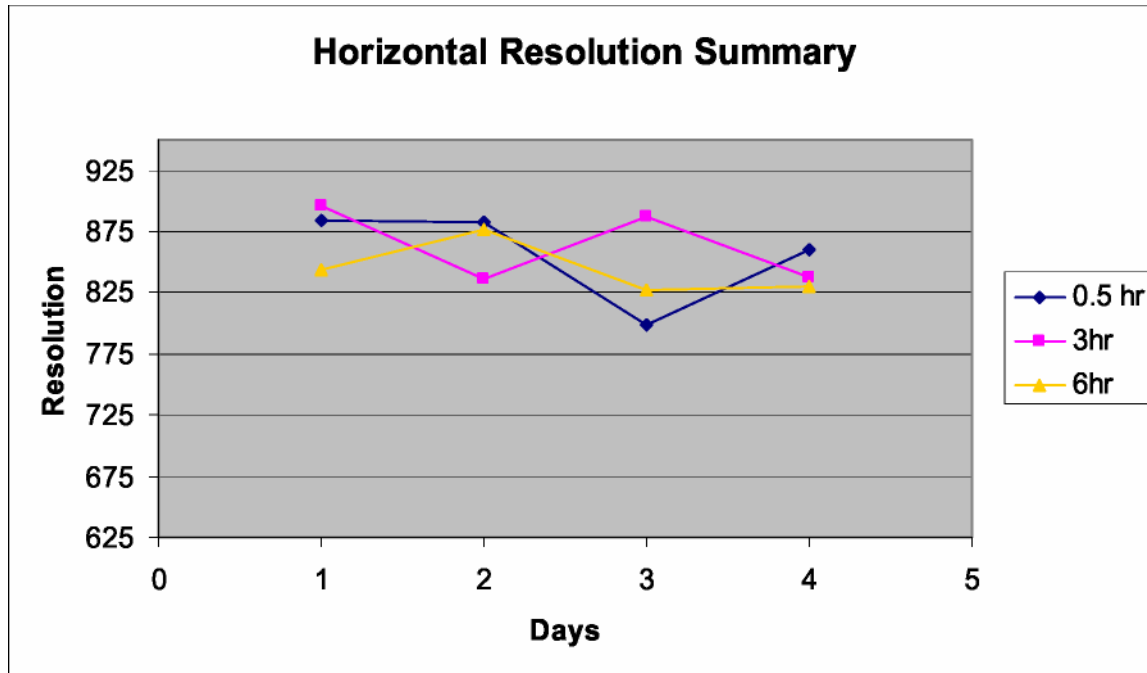


Figure 2. Spatial resolution estimates obtained in Projector Evaluation 1.

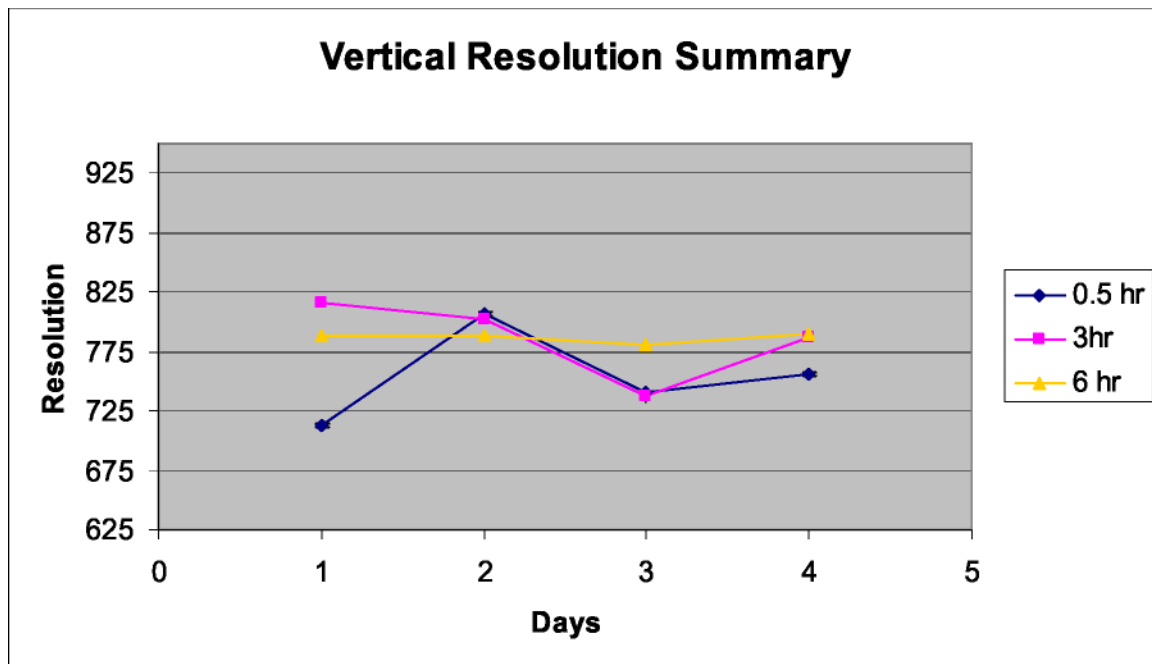
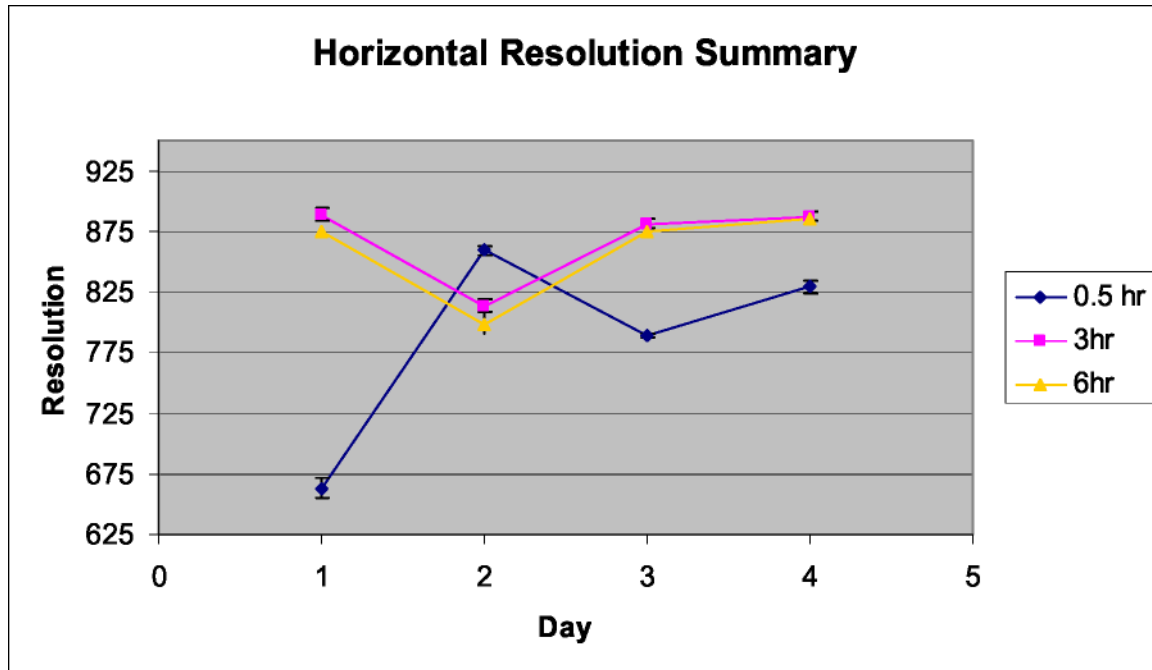


Figure 3. Spatial resolution estimates obtained in Projector Evaluation 2