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Evaluation of Proposed Cab Glass Coating for FAA Control Towers

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14. ABSTRACT AFRL assessed the effects of an "after-market" coating that could possibly be applied to FAA air traffic control tower (ATCT) windows intended to improve visibility out of the towers. Based on the results of the study, there is no reason to believe the coating would degrade vision through the glass for recently coated glass for the room temperature and humidity under which the samples were measured. However, the coating can degrade the view with haze at certain times of the day based on the angle of the sun. With the unexpected result that the coated side of the glazing increased observed haze effects, it is recommended that this phenomenon be investigated further. Additionally, the coating effects the distribution of water droplets from rain in such a way that one would expect improved visibility through the coated windows.

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SUMMARY

AFRL assessed the effects of an "after-market" coating that could possibly be applied to FAA air traffic control tower (ATCT) windows intended to improve visibility out of the towers. Based on the results of the study, there is no reason to believe the coating would degrade vision through the glass for recently coated glass for the room temperature and humidity under which the samples were measured. However, the coating can degrade the view with haze at certain times of the day based on the angle of the sun. With the unexpected result that the coated side of the glazing increased observed haze effects, it is recommended that this phenomenon be investigated further. Additionally, the coating effects the distribution of water droplets from rain in such a way that one would expect improved visibility through the coated windows.

1.0 Introduction

In mid-2011, the Federal Aviation Administration (FAA) contacted personnel at the Air Force Research Laboratory (AFRL) for help in assessing the effects of an "after-market" coating that could possibly be applied to FAA air traffic control tower (ATCT) windows intended to improve visibility out of the towers. At that time, FAA had a cooperative research and development agreement (CRDA) with a company to evaluate a coating product that could possibly provide improved visibility through ATCT glazing under adverse weather conditions. AFRL personnel, having had significant past experience with evaluating the optical-visual characteristics of aerospace transparencies, suggested that there were several questions that should be addressed regarding this proposed ATCT coating product with respect to possible *adverse* effects on visibility, especially as the product ages and wears over time. AFRL proposed a joint effort to evaluate the coating (see Appendix A) by specifically addressing three questions:

Questions to be answered:

1) Does the coating degrade the view through the glass?

2) Does the coating effect (if any) degrade over time?

3) Does the coating improve visibility in "problem" weather conditions (precipitation, condensation, other)?

The first two questions are directed at insuring the coating does not cause any adverse effects and the third question was directed at determining the potential benefits of the coating product.

A test plan was coordinated between AFRL and FAA to address these questions (see Appendix B).

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2.0 Approach

2.1 Addressing Questions 1 and 2

The American Society for Testing and Materials (ASTM) subcommittee F7.08 is tasked with the area of Aerospace Transparencies testing. The test plan proposed to the FAA by AFRL included optical testing of a collection of FAA-provided ATCT glazing samples with the goal of determining whether or not any of the parameters tested were affected by the application of the proposed ATCT coating. Several basic optical-visual variables can have an effect on the ability of ATCT controllers to see through the glass. These include light transmission, reflectivity, and haze. Table 1 is a summary of the ASTM Test Methods that were used to measure these variables. There were two test methods that addressed light transmission (D 1003 and F 1316-90). An additional test method (F 1863-98) was added to the proposed test matrix to provide information on ATCT glazing with respect to the possible use of night vision goggles (NVGs) in the control towers. Currently, there is no requirement for NVGs in control towers.

Table 1. Summary of ASTM Test Methods used to characterize glass samples.

ASTM Test Designator	Description of ASTM Test Method
F1252-89	Test method for measuring optical reflectivity of transparent materials
F1316-90	Test method for measuring the transmissivity of transparent parts
F1863-98	Test method for measuring transparency night vision goggle weighted light transmission
D 1003	Test method for measuring haze in a transparent part
D 1003	Test method for measuring light transmission of a transparent part

The approach to answering question 1 ("Does the coating degrade the view through the glass?") was to simply measure the three basic "visibility" parameters (transmission, reflection, haze) for both coated and uncoated glass samples and see if there was any significant change in any of these variables. FAA supplied ATCT glazing samples for measurement by AFRL (Table 2).

Table 2. FAA-Supplied Glass Samples.

Line #	Sample	Descriptor	Comments - IF ANY
N/A	A	24"x24"x1 1/2"; AFGO; Laminated; 2x2 with air gap	Label unreadable; 4 sheets (BIG and HEAVY)
N/A	B	24"x24"x1 1/2"; AFGO; 4 Thin Laminated Sheets; 2x2 with air gap; 1/2 CLEAR ANN IG; 1-1/2" 0-A; 1/2" CLEAR; 1/2" CLEAR	Lite 1: 12CL; Spacer: 12SV; Lite 2: 12CL
N/A	**C**	12"x12"x1 1/2"; **Insulated;** 1/2" STARPHIRE; .060 CLEAR PVB; 1/2" STARPHIRE	Bubble Pack Sheet Stuck to Surface
N/A	**D**	12"x12"x1 1/2"; Cristavurva.com; 1/2" Clear **1/2" Air** +1/2"Clear; Insulated	3/4"Foam Pad Stuck to Surface/Finger Prints; Quote # 110/00/200
N/A	**E**	12”x12”x1 ½”; **Insulated**	Strike Face
N/A	**F**	**Insulated**; 12”x12”x1 ½”	Unknown Sample; Chipped/Scratches/Tape on Surface; NO LABEL

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N/A	**G**	12"x12"x1 3/8"; Insulated; Laminated; 1" 3/8 O/A DUAL SEAL SILICONE; 1/4" SOLEXIA SB 60VT TEMP C-2; **1/2" MILL SPACER**; 9/16" CLEAR TEMP LAMI; LAMI: 1/4" CLEAR TEMP; .090 CLEAR PVB; 1/4" CLEAR TEMP	Chipped Sample; VLT .59; SC .39; SHGC .31; U-VAL .29
N/A	**H**	12"x12"x1 ½"; **Insulated**	SC 0.57; SHGC 0.5; % Visible Light Trans 64; LSG Ratio 1.28; U-Value Summer 0.31; U-Value Winter 0.32; RHG 119
N/A	**I**	12"x12"x1 ½"; 1-1/2" clear insulating glass units for the control cab windows; 1-1/2" STARPHIRE ANNEALED; 1/2" STARPHIRE ANNEALED; 1/2" AIRSPACER W/ BREATHER TUBE; 1/2" STARPHIRE ANNEALED	**CRACKED SAMPLE**
N/A	**J**	12"x12"x11/16"; 11/16" Custom Lami; 1/4 Solarban 60.060 Clear 3/8 Clear); 7513 S SUN GLASS	
N/A	**K**	14"x14"x15/16"; 1" Overall; 1/4" BRZ ANLD; 1/2" AS; 1/4" CLR ANLD	**CRACKED SAMPLE**
#1	**L**	1" VE1-2M INSULATED GLASS - 1/4" (6 mm) Clear AN VE-2M #2; **1/2" (13.2 mm) airspace** - mill finish black silicone; 1/4" (6 mm) Clear AN	
#1	**M**	1" VE1-2M Insulated Glass; 1/4" (6 mm) Clear AN VE-2M #2; **1/2" (13.2 mm) airspace** - mill finish black silicone; 1/4" (6 mm) Clear AN	
#2	**N**	1" VE1-2M/ Pryolytic Insulated Glass; 1/4" (6 mm) Clear AN VE-2M #2; **1/2" (13.2 mm) airspace** - mill finish black silicone; 1/2" (13.2 mm) sightline; 1/4" (6 mm) Clear Pyrolytic Low E #3 HS	
#2	**O**	1" VE1-2M/Pryolytic Insulated glass; 1/4" (6 mm) Clear AN VE-2M #2; **1/2" (13.2 mm) airspace** - mill finish black silicone; 1/2" (13.2 mm) sightline; 1/4" (6 mm) Clear Pyrolytic Low E #3 HS	
#3	**P**	1" Clear Insulated Glass; FT/FT; 1/4" (6 mm) Clear FT; **1/2" (13.2 mm) airspace** - mill finish black silicone; 1/4" (6 mm) Clear FT	
#4	**Q**	1" Clear Insulated Glass; HS/HS; 1/4" (6 mm) Clear HS; **1/2" (13.2 mm) airspace** - mill finish black silicone; 1/4" (6 mm) Clear HS	
#5	**R**	1" Clear Insulated Glass; HS/FT; 1/4" (6 mm) Clear HS; **1/2" (13.2 mm) airspace** - mill finish black silicone; 1/4" (6 mm) Clear FT	
#6	**S**	1 5/16" Clear Insulated Laminated Glass; 1/4" (6 mm) Clear HS; 1/2" (13.2 mm) airspace - mill finish black silicone; 1/4" (6 mm) Clear HS; .060 (1.52 mm) clear PVB; 1/4" (6 mm) Clear HS	**CRACKED SAMPLE**
#7	**T**	1 5/16" VE1-2M Insulated Laminated Glass; 1/4" (6 mm) Clear HS VE-2M #2; **1/2" (13.2 mm) airspace** - mill finish black silicone; 1/4" (6 mm) Clear HS; .060 (1.52 mm) clear PVB; 1/4" (6 mm) Clear HS	

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#8	**U**	1 5/16" Clear/Pyrolytic Laminated Insulated Glass; 1/4" (6 mm) Clear HS; .060 (1.52 mm) clear PVB; 1/4" (6 mm) Clear HS; 1/2" (13.2 mm) airspace - mill finish black silicone; 1/4" (6 mm) Clear Pyrolytic Low E #5 HS	**CRACKED SAMPLE**
#9	**V**	1 5/16" Clear/Pyrolytic Laminated Insulated Glass; 1/4" (6 mm) Clear HS; .060 (1.52 mm) clear PVB; 1/4" (6 mm) Clear Pyrolytic Low E #4 HS; **1/2" (13.2 mm) airspace** - mill finish black silicone; 1/4" (6 mm) Clear HS	
#10	**W**	1-5/16" VLE1-70 Laminated Insulated Glass - 1/4" (6 mm) clear HS VLE-70 #2; 0.060 (1.52 mm) clear PVB; 1/4" (6 mm) Clear HS; **1/2" (13.2 mm) airspace** - mill finish black silicone; 1/4" (6 mm) Clear HS	

All samples received from the FAA were given a unique letter designator (second column in Table 2), which was applied to the sample so that the samples could be tracked throughout this evaluation process. Each sample was divided into six areas so that there would be three separate measurements for each sample and condition. For example, Figure 1 is a picture of sample "W," which was measured in six locations (upper W1, W2, W3 for the uncoated section and lower W1, W2, W3 for the coated section) providing three coated and three uncoated measurements for comparison.

Table 3. Measurement locations on each glass sample - 3 coated and 3 uncoated.

ASTM Test	**Parameter**	**Top - Uncoated**			**Bottom - Coated**		
F1252	Reflection	Left	Mid	Right	Left	Mid	Right
F1316	Visible transmission	Left	Mid	Right	Left	Mid	Right
F1863	NVG Transmission	Left	Mid	Right	Left	Mid	Right
D 1003	Haze	Left	Mid	Right	Left	Mid	Right
D 1003	Visible transmission	Left	Mid	Right	Left	Mid	Right

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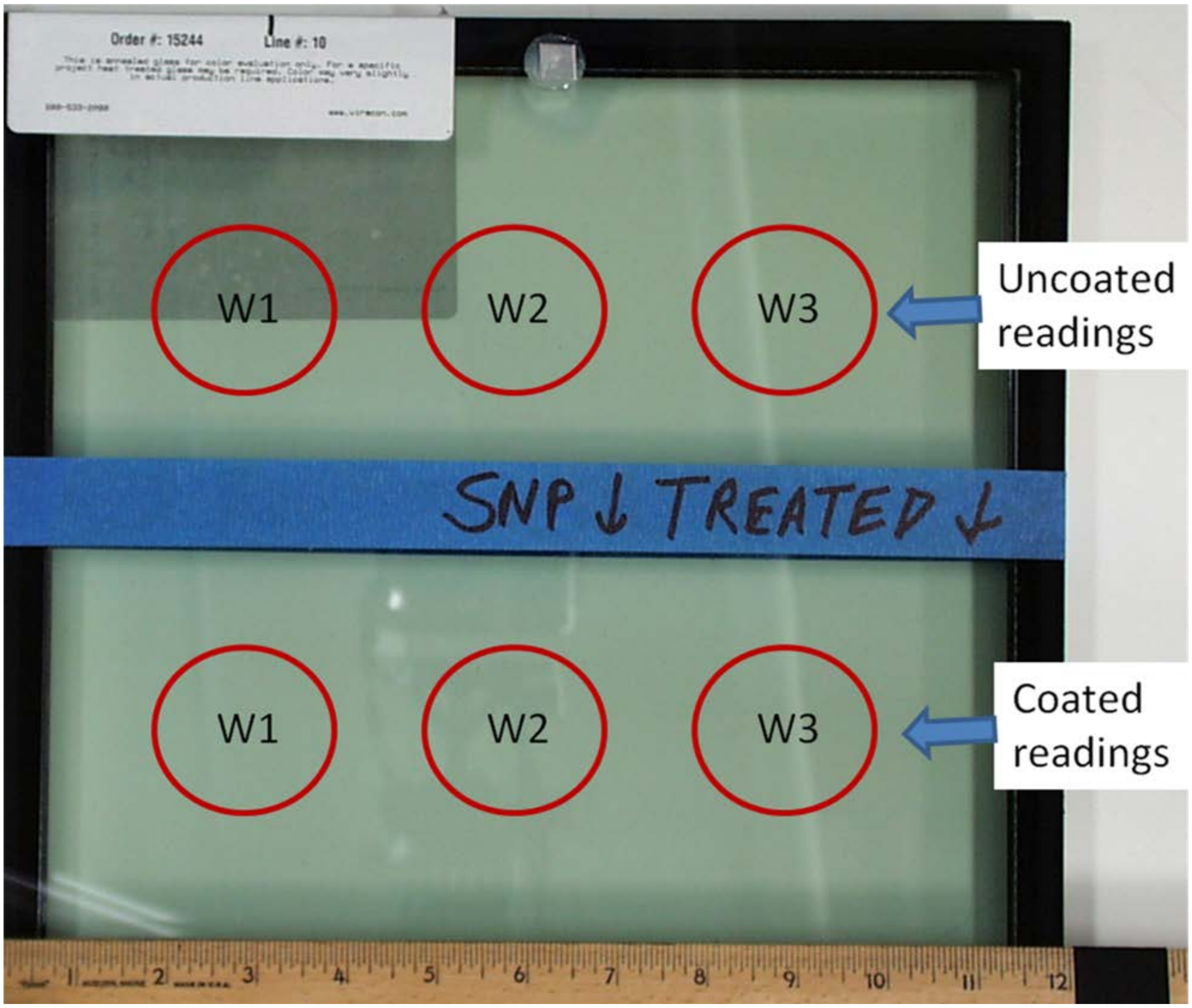

Figure 1. Picture of Sample "W" showing approximately where measurements were made for the various parameters.

In the original test plan (Appendix B), the FAA had assumed that there would be 3 different kinds of ATCT glazing and therefore each "set" of samples to be used to answer the second question ("Does the coating effect (if any) degrade over time?") would consist of three different kinds of glazing, with half of each glazing sample coated and the other half uncoated. It became apparent from the samples that were received by AFRL that most of the samples were the same type of glazing, which consisted of two panes of glass with a 1/2 inch air gap in between the panes. Therefore, for the aging/weathering test a total of 12 samples were selected, with relatively similar characteristics, and divided into six sets of 2 samples each. Table 4 is a summary of the sample set numbers and the corresponding glass sample letter identifiers included in each set. Two of these sets (Sets #1 and #6) were retained by AFRL and the other four were shipped back to FAA for distribution to various ATCT around the country to capture possible weathering effects from different extreme climates. Set #1 was installed in the AFRL mock tower and Set #6 was placed in storage at AFRL to act as a control set. After about eleven months, all sample sets are to be shipped back to AFRL for re-measurement to see if any of the variables have changed differently for the coated versus uncoated portions of the samples. This is currently scheduled for about August 2014.

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Table 4. Glass sample sets selected for answering question 2.

Set Number	Sample ID
Set #1	H, W
Set #2	N, T
Set #3	O, D
Set #4	V, R
Set #5	L, P
Set #6	M, Q

2.2 Addressing Question 3: Does the coating improve visibility through the glazing?

As part of the proposed test plan submitted to the FAA it was noted that there was a "mock" air traffic control tower located at Wright-Patterson AFB which is under the control of AFRL that could be made available for an efficacy and longevity study of the subject window coating. Although the tower was in need of general cleaning and did not have heating, cooling, or water available, it did have glazing similar to a real ATCT (installation angles were similar although the glass was non-insulated) and a catwalk around the outside making the exterior of the windows easily available for coating the exterior of the glass (Figure 2). The tower's lighting and electricity were in operating condition.

The coating was applied to half of the center pane of glass on each of three sides of the tower; North, South, and West. Figure 3 shows the central pane of tower glazing viewing toward the South. The blue tape down the center of the pane divides the uncoated left half from the coated right half of the window. A representative from the company did the actual cleaning and coating of the windows in the June, 2012 time-frame.

A quantitative, subjective study was devised based on what was proposed in Appendix B to compare the coated and uncoated sides of the ATCT glazing for a period of about a year. Details of the study and the results are the subject of a separate report.

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Figure 2. The mock air traffic control tower at Wright-Patterson AFB.

Figure 3. The AFRL mock ATCT tower view to the South - the blue tape divides the coated (right side) from the uncoated (left side) sections of the window.

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3.0 Results

This section provides the results for primarily the first question listed in the Introduction section with some results associated with the third question. As of the time of this report the 12 samples that were selected for aging/weathering are still in the field at locations selected by the FAA and are not yet available to conduct the "after" tests, which means that question 2 cannot be answered until after the weathered samples are returned to AFRL. Once the samples are returned to AFRL they will again be measured and the measurements compared to the "before" weathering condition to answer question 2.

3.1 Results of FAA-provided coated glass samples: ASTM tests

Table 5 is a summary of the results of the ASTM Test Methods applied to the samples. Each value listed in the cells under the "Unctd" (uncoated) and "Ctd" (coated) columns is the average of three measurements (the left, mid, and right areas of the sample as shown in Figure 1).

Table 5. Summary of the three main optical parameters measured plus the NVG transmission.

	All values for are in percent									ASTM F1863	
	ASTM F1252			ASTM D1003			ASTM D1003			Spectral Scans	
	Reflection			Trans (visible)			HAZE			Unctd glass samples	
Glass sample	**Unctd**	**Ctd**	**Diff**	**Unctd**	**Ctd**	**Diff**	**Unctd**	**Ctd**	**Diff**	**NVG Trans**	**Visible Trans**
A	13.1	13.1	0.0	74.4	74.5	0.1	0.2	0.1	-0.1	45.6	74.8
B	12.4	12.6	0.2	71.6	71.4	-0.2	1.0	0.8	-0.2	38.8	71.5
C	8.0	8.0	0.0	88.5	88.6	0.1	0.3	0.3	0.0	81.3	88.7
D	13.5	13.6	0.1	72.4	72.5	0.1	0.2	0.1	-0.1	45.0	72.6
E	13.0	13.0	0.0	80.0	80.0	0.0	1.8	2.0	0.2	74.1	80.4
F	14.7	14.7	0.0	81.7	82.2	0.5	0.9	0.3	-0.6	75.6	82.5
G	10.1	10.1	0.0	52.6	52.6	0.0	0.1	0.2	0.1	16.4	52.5
H	16.0	16.0	-0.1	64.3	64.3	0.0	1.3	0.8	-0.5	39.9	64.2
I		11.8		77.2	77.4	0.2	5.7	5.8	0.1	71.6	76.5
J	9.1	8.9	-0.2	68.4	68.5	0.0	0.4	0.5	0.2	31.6	67.7
K		12.5		46.9	47.1	0.2	0.1	0.1	0.0	41.3	47.1
L	11.1	10.9	-0.1	70.3	70.4	0.1	0.1	0.2	0.1	39.8	70.5
M	11.2	11.0	-0.1	70.9	70.8	-0.1	0.1	0.2	0.1	40.4	70.9
N	12.8	12.8	-0.1	64.3	64.4	0.1	0.4	0.2	-0.1	35.8	64.4
O	12.4	12.3	-0.1	64.9	64.6	-0.2	0.3	0.3	0.0	37.2	64.9
P	13.8	13.8	0.0	78.6	78.6	0.0	0.2	0.3	0.1	62.0	78.3
Q	13.8	13.7	-0.1	78.6	78.7	0.1	0.2	0.3	0.1	62.0	78.4
R	13.8	13.8	0.0	78.6	78.6	0.1	0.4	0.2	-0.1	62.1	78.5
S	13.3	13.2	-0.1	75.1	75.1	0.0	0.3	0.7	0.4	52.5	75.1
T	10.6	10.7	0.0	67.6	67.5	0.0	0.2	0.3	0.1	34.0	67.6
U	15.3	15.2	-0.1	69.1	69.1	0.0	0.7	0.8	0.1	48.6	68.8
V	15.9	16.0	0.1	69.4	69.4	0.0	0.5	0.5	0.0	48.7	69.3
W	17.5	17.2	-0.2	60.5	60.8	0.3	0.2	0.4	0.2	29.1	60.4
		AVG:	-0.032		AVG:	0.070		AVG:	0.0029		

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It is apparent from Table 5 that, in general, there is no measureable difference in reflection, transmission, or haze between the coated and uncoated glass samples measured soon after coating. The uncoated reflection values for samples "I" and "K" could not be measured because of the location of cracks in these samples. All measurements are in percent so the typical difference between the coated and uncoated sections are on the order of a couple tenths of a percent, which is within the estimated accuracy of measurement for these ASTM test methods. Two samples had at least one parameter that changed by 1/2 percent or more (lightly shaded cells in Table 5). For sample "F", the coating may have improved (increased) the light transmission by about 1/2 percent and improved (decreased) the level of haze by a bit more than 1/2 percent. This suggests that sample "F" may have had some type of surface "roughness" that caused the light-scattering haze, which was smoothed over by the coating thereby improving the sample. This was a small effect and close to the limits of the accuracy of the test method but the changes in transmission and haze due to the coating are in the desirable direction. Sample "H" also showed an improvement in haze with the coated versus the uncoated side although there was no similar change in transmission.

If one looks at the "Diff" (difference) columns in Table 5 one can see that sometimes the coated and uncoated values are the same but a non-zero "Diff" value shows up. This is because the numbers are the average of three readings and the values presented in the table were rounded to the nearest single decimal point. For example, the sample "H" in the table has a 16.0 percent reflection value for both the coated and uncoated areas but it shows a -0.1 percent difference between the uncoated and coated values. The actual average uncoated value is 16.02 and the coated value is 15.95 (both of which round to 16.0) with a difference of -0.07, which rounds to -0.1 percent. As noted earlier, the accuracy of this test method is on the order of a couple of tenths of a percent so differences on this order are definitely not significant.

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Table 6. Summary of the aging/weathering sample sets and their baseline optical values.

Destination	Set #/ID	Sample	ASTM F1252 Reflection Unctd	ASTM F1252 Reflection Coated	ASTM D1003 Transmsn (visible) Unctd	ASTM D1003 Transmsn (visible) Coated	ASTM D1003 HAZE Unctd	ASTM D1003 HAZE Coated	NVG Trans Unctd
W-P Tower	**1a**	**H**	16.0	16.0	64.3	64.3	**1.3**	**0.8**	39.9
	1b	**W**	17.5	17.2	60.5	60.8	0.2	0.4	29.1
FAA	**2a**	**N**	12.8	12.8	64.3	64.4	0.4	0.2	35.8
	2b	**T**	10.6	10.7	67.6	67.5	0.2	0.3	34.0
FAA	**3a**	**O**	12.4	12.3	64.9	64.6	0.3	0.3	37.2
	3b	**D**	13.5	13.6	72.4	72.5	0.2	0.1	45.0
FAA	**4a**	**V**	15.9	16.0	69.4	69.4	0.5	0.5	48.7
	4b	**R**	13.8	13.8	78.6	78.6	0.4	0.2	62.1
FAA	**5a**	**L**	11.1	10.9	70.3	70.4	0.1	0.2	39.8
	5b	**P**	13.8	13.8	78.6	78.6	0.2	0.3	62.0
W-P Storage	**6a**	**M**	11.2	11.0	70.9	70.8	0.1	0.2	40.4
	6b	**Q**	13.8	13.7	78.6	78.7	0.2	0.3	62.0

Table 6 is a summary of the glass samples that were selected to be sent out for the aging/weathering test. Originally, the FAA was going to place five sample sets (sets 1 through 5) at various FAA sites (towers) for weathering. However, only four sample sets were sent out by the FAA and the 5th set was sent back to Wright-Patterson AFB (AFRL) to be placed on the catwalk around their mock tower for the aging/weathering test. The sixth set retained by AFRL was placed in storage (in a box in Room 122), not subjected to weathering, as a control set.

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Table 7. Location of samples distributed for weathering.

Point of Contact	Address	Samples	Code
Alan Pinkus	711HPW/RHCV 2255 H St. Area B, Bldg. 248, Rm 300 Wright-Patterson AFB, OH 45433-7022	2	1 a/h 1 b/w
Jon Holman	699 Wright Brothers Lane Las Vegas NV 89119	2	2 a/n 2 b/t
Jon Ikeda	Snohomish County Airport Paine Field 3220 100th Street SW, Ste A Everett, WA 98204	2	3 a/o 3 b/d
Mike Zubricky	FAA/PBI SSC 3550 Belvedere Road West Palm Beach, Florida 33406	2	4 a/v 4 b/r
Nick Dooda	Phoenix ATCT/FAA Attn: PHX ENV 3500 E. Sky Harbor Blvd Phoenix. AZ 85034	2	5 a/c 5 b/p

Figure 4 is a graph of the spectral transmission for all 23 FAA glazing samples. The data that produced these curves are what was used to calculate the night vision goggle-weighted transmission values shown in the "NVG Trans" columns of Tables 5 and 6. All NVG transmission values were calculated using "NVG A" spectral sensitivity curves. If the "B" type of coating is used on the NVGs, then the transmission values will be somewhat lower than shown.

It is apparent from Figure 4 that there is a fairly wide range of spectral transmission curves for the various types of glass samples provided by the FAA. If the FAA ever considers using NVGs in their ATC towers, the NVG transmission values would need to be considered.

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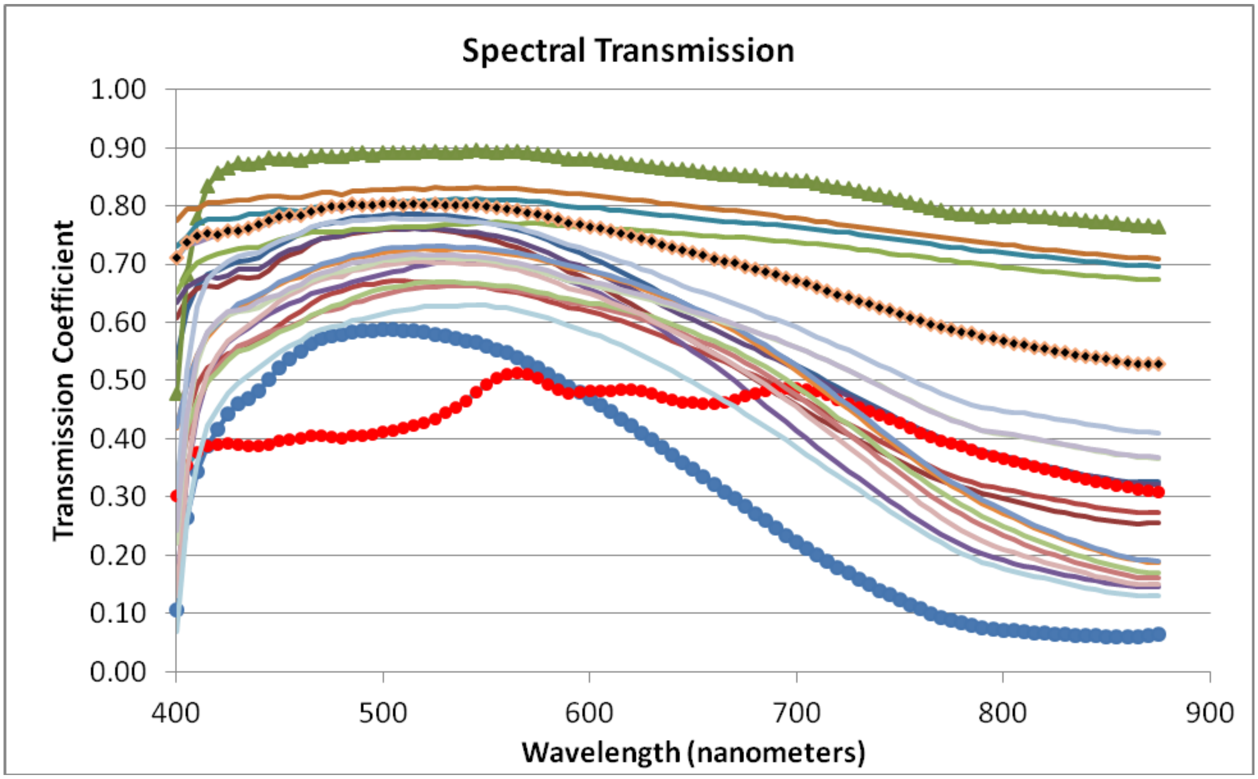

Figure 4. Spectral transmission curves for the 23 FAA glazing samples.

3.2 Results of W-P mock ATCT observer evaluations

Anecdotal observations from the AFRL mock ATCT study resulted in the documentation of some coating effects. There were two separate phenomena that were observed during the mock tower study: one was the effect of the coating on water droplet distribution from rain and the second was an observed haze effect due to the coating after about a year of weathering.

Figure 5. Effect of coating on distribution of water droplets from rain (left is uncoated, right is coated).

Figure 5 shows how the coating changed the surface effects of the glazing such that raid droplets could not "stick" as easily to the surface of the glass, thereby allowing less obstructed viewing through the window. Pictures taken for the South and West ATCT windows show similar effects.

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After weathering for about a year it was noticed that the coated sides of the windows appeared to have a haze effect if the sun angle was in a certain area. Figure 8 shows the contrast-reducing haze effect for the south facing window. Note the exterior of the window had not been cleaned during the entire year-long-plus testing period.

The haze pattern seen on the coated side of the window in Figure 8 appeared to have structure the looked like the pattern one might expect from the wiping action associated with the cleaning/coating process. The pattern consisted of long streaks**. It is not known if this haze effect can be removed by cleaning or not.** But it is interesting to note that the coated side suffers from this problem and the uncoated side does not even though both sides have not been cleaned for the same period of time.

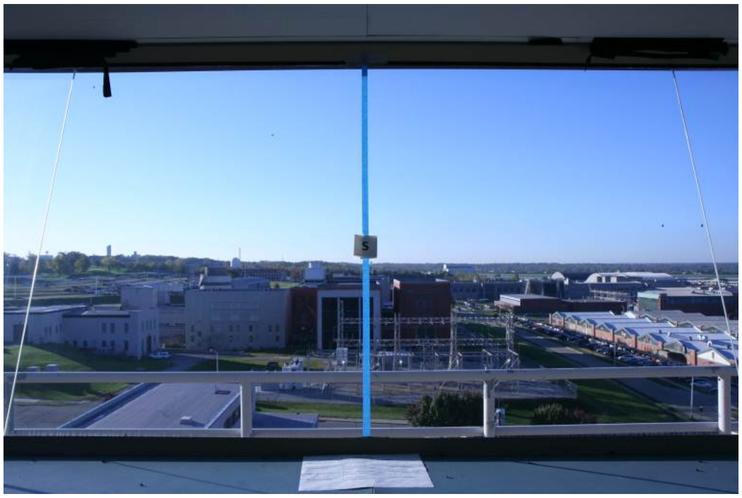

Figure 6. South view (normal), left side is uncoated and right side is coated.

Figure 7. South view (45 degrees), left side is uncoated and right side is coated.

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Figure 8. Contrast loss on coated side (right of blue tape) due to light scatter from rising sun.

The human observer-based study conducted in the AFRL mock ATCT required subjects to provide subjective ratings of various aspects of glass quality on a response scale (from one to six). These ratings include glass cleanliness, near detail (a predetermined relatively near object), far detail (a predetermined relatively far object), near dynamic target (a moving target in the same "near" area), far dynamic target (a moving target in the same "far" area), haziness, cloudiness, and distortion. Subjects also indicated which panel (treated or untreated) they thought had the better viewing quality by marking a spot along a continuous line (Appendix C). Quantitative data was extracted by measuring the mark with a ruler with the midpoint being zero, to the left being negative and to the right being positive. The independent variables of the study were panel type (treated or untreated), direction (the panel was facing north, south, or west), and observation type (naked eye or binocular). A 3x2x2 Repeated Measures ANOVA and appropriate post-hoc tests were conducted. A summation of the most interesting significant effects follows. A more detailed review of the analysis can be found in Appendix D.

Overall, regarding the subjective measures of glass cleanliness, near and far detail, and near and far dynamic detail, the treated panels were usually observed as having higher viewing quality than the untreated panels. However, even when statistically significant, the differences were very small. These small differences were due to an interaction with the direction the panels were facing. South facing treated panels had consistently worse viewing quality than the south facing untreated panels while the opposite was true for west and north. This result is most likely due to the previously stated sun angle issue (see Figure 8). Additionally, using binoculars tended to result in higher cleanliness ratings. Therefore, binoculars tended to reduce or eliminate any observed cleanliness differences between the panels.

Analysis of subjective measures of haziness, blurriness, cloudiness and distortion in the panels found an effect for cloudiness and haziness. Overall, more subjects found the treated panel to be cloudy and hazy than the untreated panel. However, there was an interaction with direction for cloudiness. When looking with the naked eye, more subjects found the south facing treated panel to be cloudy than the untreated panel. Furthermore, there was a significant difference between directions for treated panels viewed with the naked eye for both cloudiness

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and haziness. More subjects described the south treated panel as cloudy and hazy than both the west panel and the north panel. The use of binoculars eliminated the effect.

Finally, subjects were asked to estimate the comparative quality of one panel type over the other. Overall, there was no difference between panel types. However, as we have seen before, there was an interaction with direction. Subjects rated the untreated south facing panel as having a higher viewing quality than the treated south facing panel. The opposite was true for west and north. The use of binoculars reduced or eliminated this effect.

4.0 Conclusions of Phase I

4.1 Does the coating degrade the view through the glass?

Based on the results shown in Table 5 there is no reason to believe the coating would degrade vision through the glass for recently coated glass for the room temperature and humidity under which the samples were measured. However, some haze effects have been observed anecdotally under certain conditions with the AFRL mock tower coated glass (see section on mock tower results).

The statistical analysis of the data collected from the human observer-based study conducted in the AFRL mock ATCT confirms the anecdotal observations. The coating can degrade the view through the glass at certain times of the day based on the angle of the sun. However, when the sun was not a factor, treated panels had the same or higher subjective ratings of viewing quality than untreated panels. Furthermore, any effects on viewing quality were reduced or eliminated with the use of binoculars.

4.2 Does the coating effect (if any) degrade over time?

The answer to this question will come after the test samples have been recovered from the field and been re-measured, which is expected to occur sometime in late summer of 2014.

4.3 Does the coating improve visibility in "problem" weather conditions (precipitation, condensation, other)?

The results of the human-observer-based study are available in Appendix D. Observations during this study suggest that the coating does, indeed, affect the distribution of water droplets from rain in such a way that one would expect improved visibility through the coated windows. However, after about a year it is also apparent (and documented in Figure 8) that there is some effect of the coating that causes increased haze (and therefore contrast loss) for certain sun angles when viewing through the window. This effect is in the direction of reducing visual capability through the window. It is unknown at this writing as to whether or not this haze phenomenon can be reduced by cleaning. It is somewhat disturbing that the uncoated side exhibited less of a haze effect over the year-plus time period than the coated side suggesting that either there is a change in the coating or that the coating somehow results in increased dirt/debris attracted to the surface.

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5.0 Recommendations

With the unexpected result that the coated side of the glazing increased observed haze effects, it is recommended that this phenomenon be investigated further. Once the viewing/lighting conditions under which the haze effect is observed (low sun angle off to one side of the view angle) is fully documented, it is suggested the tower windows be cleaned (both coated and uncoated side) and the photographic and subjective assessment be repeated to see if the effect can be "cleaned away" or if it is some structural effect with the coating.

It will be interesting to see what the weathered samples look like once they are returned to AFRL. It is recommended that in addition to the standard ASTM test methods being applied to these samples to answer question 2 of the Introduction section, that a glare test be devised along the lines of the geometry under which the mock tower haze/contrast loss was observed. This should give us more insight into the haze effect that was observed on the AFRL mock tower

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Acronyms

AFRL – Air Force Research Laboratory
FAA – Federal Aviation Administration
ATCT – air traffic control tower
CRDA – cooperative research and development agreement
ASTM – American Society for Testing and Materials
NVG – night vision goggles
ANOVA –analysis of variance

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APPENDIX A: Recommendations for Cab glass coatings tests

H.L.Task - 6-21-2011

Questions to be answered:

1) Does the coating degrade the view through the glass?

2) Does the coating effect (if any) degrade over time?

3) Does the coating improve visibility in "problem" weather conditions (precipitation, condensation, other)?

The ASTM tests listed in part "A" below can be used to help answer the first two questions. These are fairly basic tests and one would not expect a reasonable coating to cause a degradation in any of these parameters (transmission, reflection, haze). However, these standard ASTM tests do not cover all possible optical/visual degradations that may be caused by the coating. It is possible that the coating could cause slight blurring, especially for large aperture viewing (such as with binoculars), due to non-uniform thickness of the coating. It may be possible to try to capture this effect (and perhaps provide a partial answer to question 3 above) using photographic techniques discussed later.

A. Standardized ASTM Test Procedures that could be conducted at Wright-Patterson AFB

ASTM test procedures that could be used to measure: 1) baseline Cab glass sample (uncoated), 2) coated Cab glass sample - newly coated, and 3) coated Cab glass sample that has been "weathered" for X amount of time. Compare test values for all three conditions.

F1252-89	Test method for measuring optical reflectivity of transparent materials
F1316-90	Test method for measuring the transmissivity of transparent parts
F1863-98	Test method for measuring transparency night vision goggle weighted light transmission
D 1003	Test method for measuring haze in a transparent part
D 1003	Test method for measuring light transmission of a transparent part

B. Other possible assessments that could be done cooperatively with FAA data collection

Photographic data collection in the field with coated/uncoated glass under "problem" weather conditions such as rain and condensation conditions might help answer question 3 above. Multiple photographs over time of a specific external scene could be obtained to compare degradation of coating (if any) and possible improvements under "problem" weather conditions. This needs to be done with both small aperture (eyeball simulation) and larger aperture (binocular use) photo capture techniques. If possible, the FAA could coat part of a window in their test control tower and take pictures using a digital camera using at least two different lenses or lens settings. We can discuss this further and, if the FAA is interested in pursuing this, discuss what would be required and how we could proceed.

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For "A" above: the FAA would provide coated and uncoated samples and perhaps "aged" samples, if available. Wright-Patterson would conduct the listed ASTM tests on the samples and analyze for differences between the sample conditions.

For "B" above: the FAA would iterate with Wright-Patterson to develop a standardized photographic set-up (digital camera, specific lens(es), F/no., selected external target, time of day, etc.) and photograph test patches (uncoated glass, coated glass, coated and uncoated glass under problematic weather conditions, "aged" coated glass, "aged" coated glass under problematic weather conditions) and provide the digital photographs to Wright-Patterson. Wright-Patterson would analyze the photographs and try to quantify differences in contrast and spatial frequency content between photographic conditions. Wright-Patterson has a "poor man's" control tower with windows that could be coated with product IF the FAA provides the material and coating procedures. Wright-Patterson then could also conduct photographic data collection of the different conditions and compare results with the FAA-provided photographs. This area obviously open for further discussion.

Added 6/23/2011:

C. Conduct subjective assessment tests at the FAA test ACT or at Wright-Patterson using coating (by the company), glass, and providing "rain" or "mist" conditions and getting subjective ratings from subjects looking through glass at specific target scenes both with unaided eye and with binoculars.

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APPENDIX B: DRAFT Test Plan for ATCT Cab Glass Coating for FAA

H. L. Task 6-23-2011 UPDATED 6-30-2011

Introduction

The FAA currently has a CRDA with a company to evaluate a coating product that could provide improved visibility through air traffic control tower (ATCT) glazing under adverse weather conditions. There are several questions that need to be addressed regarding this coating product with respect to possible adverse affects on visibility, especially as the product ages and wears over time. There are several basic American Society for Testing and Materials (ASTM) standard test methods that can be applied to verify that the fundamental optical/visual properties of the glass have not been adversely affected by the coating (no adverse effects are expected). This test plan outlines these tests and a suggested procedure to determine the effects of this coating over time and under different adverse weather conditions.

The Standardized ASTM Tests

Below are the proposed ASTM test methods. Note that both ASTM D1003 and F1316 both measure transmission, although the D1003 method can result in measurements that are slightly contaminated by haze effects IF haze is present. Also, F1863 is suggested in the event that image intensifier technology is used in the ATCT environment. Each sample section will be measured in three locations on the sample for each of the tests below in case there are variations across the samples.

F1252	Test method for measuring optical reflectivity of transparent materials
F1316	Test method for measuring the transmissivity of transparent parts
F1863	Test method for measuring transparency night vision goggle weighted light transmission
D 1003	Test method for measuring haze in a transparent part
D 1003	Test method for measuring light transmission of a transparent part

The Glazing Samples

Discussions with the FAA indicate that there are three primary glazing types. The FAA will acquire five samples each of the three types for a total of 15 glazing samples that are nominally about a foot square. Each sample will be clearly marked as to which glass surface is the "exterior" surface that will be coated. Also, each sample exterior surface will be divided into two equal halves - one half that will be coated with the product and the other half that will remain uncoated. Each half (coated and uncoated) will be clearly marked. Each sample will be measured at Wright-Patterson AFB at six locations on the sample as indicated by the measurement matrix below:

Test matrix for **each** of the 15 samples.

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ASTM Test	Parameter	Coated			Uncoated		
F1252	Reflection	Top	Mid	Bottom	Top	Mid	Bottom
F1316	Visible transmission	Top	Mid	Bottom	Top	Mid	Bottom
F1863	NVG Transmission	Top	Mid	Bottom	Top	Mid	Bottom
D 1003	Haze	Top	Mid	Bottom	Top	Mid	Bottom
D 1003	Visible transmission	Top	Mid	Bottom	Top	Mid	Bottom

The Overall Test Procedure

1. The FAA will acquire the 15 samples (5 each of 3 different glazing types) and mark them appropriately.

2. The FAA will have half of each sample coated with product and clearly marked accordingly.

3. All 15 glazing samples will be provided to Wright-Patterson AFB for measurement (15 samples, two sides [coated and uncoated], three replications [top, middle, bottom], five test procedures - a total of 15x2x3x5 = 450 measurements)

4. Wright-Patterson AFB will return 12 of the samples to the FAA for distribution to four operating locations nominally representing four different environmental conditions: cold, salt, hot humid, hot dry (e.g., Fairbanks, Miami, Atlanta, Phoenix). The 5th set of three glazing types would be retained in protected storage at Wright-Patterson AFB to serve as a control.

5. Wright-Patterson AFB would perform analysis and provide interim report to the FAA regarding all 15 non-"aged" samples to see if there was any statistically significant difference between coated and uncoated sections, between glazing types, or between samples of the same glazing type.

6. After a specific period of time (one to three months?), the 12 samples distributed by the FAA to the different environmental locations would be returned to Wright-Patterson AFB for post-weathering testing.

7. Wright-Patterson AFB would repeat previous measurements on all 15 samples to compare the effects of time and weathering on the coated and uncoated surfaces and provide a report to the FAA regarding the results.

NOTE: It has been suggested that the "interior" side of all samples be covered during weathering as this surface is not part of the test.

Other General Comments/Discussion

Wright-Patterson AFB does have available, a test ATCT that could be used for both subjective and objective assessments of the coating product. Notional approach would be to coat

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part of the exterior glazing of this tower with the product and conduct visibility assessment tests using both photographic and human vision techniques. Parameters that could be addressed include direct eye viewing, binocular aided viewing, and night vision goggle-aided viewing. Rain effects via controlled spraying of the windows could also possibly be performed. External to the tower are a variety of viewable scenes including the possibility of providing a controlled object, chart, or target for quantitative viewing performance. A Likert scale could be developed to quantitatively (but subjectively) evaluate observer's viewing capability through the coated and uncoated portions of the glass for different lighting and weather (rain v sunny v cloudy) conditions. This area is open for further discussion and consideration.

The Wright-Patterson "Tower Study" option addendum

As noted above, there is a "poor-man's" ATCT tower located at Wright-Patterson AFB which is under the control of the Air Force Research Laboratory (AFRL) and, as recently determined, could be made available for an efficacy and longevity study of the subject window coating. Although the tower is in need of general cleaning and does not have heating, cooling, or water currently available, it does have appropriate glazing similar to a real ATCT and a catwalk around the outside making the exterior of the windows easily available for coating the exterior of the glass. The tower's lighting and electricity are functioning. The following is a draft outline of a suggested efficacy and longevity study that could be performed at Wright-Patterson with internal personnel and/or with FAA-provided participants as appropriate.

Objective of the "tower study" option: quantify the effectiveness of the exterior/interior window coating with respect to improving visual capability under adverse weather conditions and determine if this improvement (if any) degrades over time.

Participants: In-house Wright-Patterson personnel and/or FAA-provided "guest" evaluators, as appropriate.

Approach 1 - photography and photographic analysis: A digital camera will be used to photograph selected external scenes through both the coated and uncoated glass sections. Photography will be done with both a telephoto lens (to simulate effects of a binocular-sized aperture) and a relatively wide angle lens (simulating un-aided eye viewing). External scenes will, in general, be buildings and structures in the near-field area as well as distant objects/buildings. The near-field objects are intended to simulate ATCT controllers observing aircraft in the immediate area (taxi-way traffic and runways) and the distant objects are intended to provide clarity information regarding the potential effect on controllers looking at airborne aircraft. If practical, a spatial frequency analysis of the images will be conducted to determine if the coating has reduced the effective MTF (modulation transfer function) of the glazing (this should be able to pick up any contrast loss/blurring that may occur).

Approach 2 - direct visual observation: Observers will be instructed to view through the coated and uncoated parts of the glazing and answer a few questions using a Likert scale. These questions will be developed if this option is selected but the questions would be on the order of "On a scale of 1 to 7 in which 1 means the view through the window is as clear as if no window was present and 7 means the view through the window is extremely degraded." Participants would be able to view through an open doorway at the external scene to "set" their

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basis for visual comparison using this approach. Analysis would then involve comparing the scores on the coated glass with the uncoated glass. An alternative to this type of question development would be to simply have the participants do a direct comparison between the coated and the uncoated glazing and provide a scaled answer. A question of this type would be something like: "Compare the view through the two sections of glazing and circle the most appropriate answer: 1) the coated side is much clearer than the uncoated side, 2) coated side is slightly clearer than the uncoated side, 3) the coated and uncoated sides are about equally clear, 4) the coated side is slightly less clear than the uncoated side, 5) the coated side is much less clear than the uncoated side."

Longevity: Either or both approaches could be done for evaluating the coating. For both approaches, an initial evaluation will be done soon after the coating is applied and the dates of both the coating and the first evaluation will be recorded. Over the next six months evaluations will be conducted approximately monthly although if unique weather conditions occur (blowing rain) an "adverse weather" evaluation will be conducted. In each case, the date of the evaluations will be recorded to compare results over time. Periodic cleaning of the coated and uncoated glazing may be done pending outcome of further discussions with the FAA regarding standard practices. If high pressure water is available at the tower then a configuration of "blowing rain" may be possible to simulate that weather condition allowing for better controlled assessment of the coating. One problem (which may actually be an advantage) of using synthetic blowing rain is that only the window area is affected regarding visibility of objects exterior to the tower - one would not be looking the hundreds of feet of rain but only water near the window. NOTE: it would be nice to keep participants uninformed as to which glass is coated and which is not coated except that the expected effect of the coating (reducing water "sticking" to the glass) will most likely make this futile.

Analysis: A comparison of the photographic and subjective assessment scoring for the coated and uncoated glass over time will be done to see if 1) the coating improves visual clarity when initially applied, and 2) how well the coating holds up over time and weather. It is expected a brief initial report would be prepared after the initial coating and evaluation (with sprayed water) and then a final report after the 6 month study period to assess the efficacy over time.

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APPENDIX C: Observer Subjective Questionnaire

ATC Cab Glass Evaluation

Initial Demographics Collection (one time):

Date: ____________

Observer ID	1	2	3	4	5

Observer Name: ___________________________________

Gender	M	F	**Age**__________		
Do you wear vision correction?	None	Contacts	Glasses	Both	
If required, which correction do you use:	Monofocal	Bifocal	Trifocal		
Color perception results	Normal				
Depth perception results	Normal				

ATC Cab Glass Evaluation

Periodic evaluation feedback:

Investigator section:

Observer ID: ____________

Date: __________________

Local Time: ___________AM/PM

Sunrise local: _______________

Sunset local: _______________

Outside Temp: _____________

Weather conditions: Based on KFFO METAR

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Clear   Cloud coverage 1-8:_______   Description: ____

____

____

Wind conditions: Direction: ____________ Velocity:____________
Description:____________________

Precip: N/A   Description: ____

Glass surface contamination: Yes/no

Contamination numbers:	**S(A)**	light/mod/heavy	**S(B)**	light/mod/heavy
	W(A)	light/mod/heavy	**W(B)**	light/mod/heavy
	N(A)	light/mod/heavy	**N(B)**	light/mod/heavy

0) N/A
1) Condensation outside
2) Condensation inside
3) Water droplets
4) Streaming water
5) Frost
6) Sticking snow
7) Ice
8) Spotting
9) Dust
10) Dirt
11) Other (specify):

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Observer Feedback Section

Position S (naked eye)

Panel S(A)

Quality	**Poor**					**Excellent**
Glass Cleanliness	1	2	3	4	5	6
Near Detail	1	2	3	4	5	6
Far Detail	1	2	3	4	5	6
Dynamic Target (Near)	1	2	3	4	5	6
Dynamic Target (Far)	1	2	3	4	5	6

Artifacts (circle all applicable terms):	Haziness	Blurriness	Cloudiness	Distortion	Other: add below
Transition Between Panels		Noticeable		Not Noticeable	

Panel S(B)

Quality	**Poor**					**Excellent**
Glass Cleanliness	1	2	3	4	5	6
Near Detail	1	2	3	4	5	6
Far Detail	1	2	3	4	5	6
Dynamic Target (Near)	1	2	3	4	5	6
Dynamic Target (Far)	1	2	3	4	5	6

Artifacts (circle all applicable terms):	Haziness	Blurriness	Cloudiness	Distortion	Other: add below

Overall Comparison: Mark along the line the relative viewing quality you experienced after viewing objects through both panels.

Panel **A** best___________________________Same___________________________Panel **B** best

Would you prefer to use one of the panels over the other?: Y/N

If yes: circle panel A or B. **Please describe below why you have a preference:**

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Observer Feedback Section

Position S (binoculars)

Panel S(A)

Quality	**Poor**					**Excellent**
Glass Cleanliness	1	2	3	4	5	6
Near Detail	1	2	3	4	5	6
Far Detail	1	2	3	4	5	6
Dynamic Target (Near)	1	2	3	4	5	6
Dynamic Target (Far)	1	2	3	4	5	6

Artifacts (circle all applicable terms):	Haziness	Blurriness	Cloudiness	Distortion	Other: add below
Transition Between Panels		Noticeable		Not Noticeable	

Panel S(B)

Quality	**Poor**					**Excellent**
Glass Cleanliness	1	2	3	4	5	6
Near Detail	1	2	3	4	5	6
Far Detail	1	2	3	4	5	6
Dynamic Target (Near)	1	2	3	4	5	6
Dynamic Target (Far)	1	2	3	4	5	6

Artifacts (circle all applicable terms):	Haziness	Blurriness	Cloudiness	Distortion	Other: add below

Overall Comparison: Mark along the line the relative viewing quality you experienced after viewing objects through both panels.

Panel **A** best___________________________Same___________________________Panel **B** best

Would you prefer to use one of the panels over the other?: Y/N

If yes: circle panel A or B. **Please describe below why you have a preference:**

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Observer Feedback Section

Position W (naked eye)

Panel W(A)

Quality	**Poor**					**Excellent**
Glass Cleanliness	1	2	3	4	5	6
Near Detail	1	2	3	4	5	6
Far Detail	1	2	3	4	5	6
Dynamic Target (Near)	1	2	3	4	5	6
Dynamic Target (Far)	1	2	3	4	5	6

Artifacts (circle all applicable terms):	Haziness	Blurriness	Cloudiness	Distortion	Other: add below
Transition Between Panels	Noticeable		Not Noticeable		

Panel W(B)

Quality	**Poor**					**Excellent**
Glass Cleanliness	1	2	3	4	5	6
Near Detail	1	2	3	4	5	6
Far Detail	1	2	3	4	5	6
Dynamic Target (Near)	1	2	3	4	5	6
Dynamic Target (Far)	1	2	3	4	5	6

Artifacts (circle all applicable terms):	Haziness	Blurriness	Cloudiness	Distortion	Other: add below

Overall Comparison: Mark along the line the relative viewing quality you experienced after viewing objects through both panels.

Panel **A** best___________________________Same___________________________Panel **B** best

Would you prefer to use one of the panels over the other?: Y/N

If yes: circle panel A or B. **Please describe below why you have a preference:**

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Observer Feedback Section

Position W (binoculars)

Panel W(A)						
Quality	**Poor**					**Excellent**
Glass Cleanliness	1	2	3	4	5	6
Near Detail	1	2	3	4	5	6
Far Detail	1	2	3	4	5	6
Dynamic Target (Near)	1	2	3	4	5	6
Dynamic Target (Far)	1	2	3	4	5	6

Artifacts (circle all applicable terms):	Haziness	Blurriness	Cloudiness	Distortion	Other: add below
Transition Between Panels	Noticeable		Not Noticeable		

Panel W(B)						
Quality	**Poor**					**Excellent**
Glass Cleanliness	1	2	3	4	5	6
Near Detail	1	2	3	4	5	6
Far Detail	1	2	3	4	5	6
Dynamic Target (Near)	1	2	3	4	5	6
Dynamic Target (Far)	1	2	3	4	5	6

Artifacts (circle all applicable terms):	Haziness	Blurriness	Cloudiness	Distortion	Other: add below

Overall Comparison: Mark along the line the relative viewing quality you experienced after viewing objects through both panels.

Panel **A** best___________________________Same___________________________Panel **B** best

Would you prefer to use one of the panels over the other?: Y/N

If yes: circle panel A or B. **Please describe below why you have a preference:**

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Observer Feedback Section

Position N (naked eye)

Panel N(A)						
Quality	**Poor**					**Excellent**
Glass Cleanliness	1	2	3	4	5	6
Near Detail	1	2	3	4	5	6
Far Detail	1	2	3	4	5	6
Dynamic Target (Near)	1	2	3	4	5	6
Dynamic Target (Far)	1	2	3	4	5	6

Artifacts (circle all applicable terms):	Haziness	Blurriness	Cloudiness	Distortion	Other: add below
Transition Between Panels		Noticeable		Not Noticeable	

Panel N(B)						
Quality	**Poor**					**Excellent**
Glass Cleanliness	1	2	3	4	5	6
Near Detail	1	2	3	4	5	6
Far Detail	1	2	3	4	5	6
Dynamic Target (Near)	1	2	3	4	5	6
Dynamic Target (Far)	1	2	3	4	5	6

Artifacts (circle all applicable terms):	Haziness	Blurriness	Cloudiness	Distortion	Other: add below

Overall Comparison: Mark along the line the relative viewing quality you experienced after viewing objects through both panels.

Panel **A** best___________________________Same___________________________Panel **B** best

Would you prefer to use one of the panels over the other?: Y/N

If yes: circle panel A or B. **Please describe below why you have a preference:**

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Observer Feedback Section

Position N (binoculars)

Panel N(A)

Quality	**Poor**					**Excellent**
Glass Cleanliness	1	2	3	4	5	6
Near Detail	1	2	3	4	5	6
Far Detail	1	2	3	4	5	6
Dynamic Target (Near)	1	2	3	4	5	6
Dynamic Target (Far)	1	2	3	4	5	6

Artifacts (circle all applicable terms):	Haziness	Blurriness	Cloudiness	Distortion	Other: add below
Transition Between Panels		Noticeable		Not Noticeable	

Panel N(B)

Quality	**Poor**					**Excellent**
Glass Cleanliness	1	2	3	4	5	6
Near Detail	1	2	3	4	5	6
Far Detail	1	2	3	4	5	6
Dynamic Target (Near)	1	2	3	4	5	6
Dynamic Target (Far)	1	2	3	4	5	6

Artifacts (circle all applicable terms):	Haziness	Blurriness	Cloudiness	Distortion	Other: add below

Overall Comparison: Mark along the line the relative viewing quality you experienced after viewing objects through both panels.

Panel **A** best___________________________Same___________________________Panel **B** best

Would you prefer to use one of the panels over the other?: Y/N

If yes: circle panel A or B. **Please describe below why you have a preference:**

Notes:

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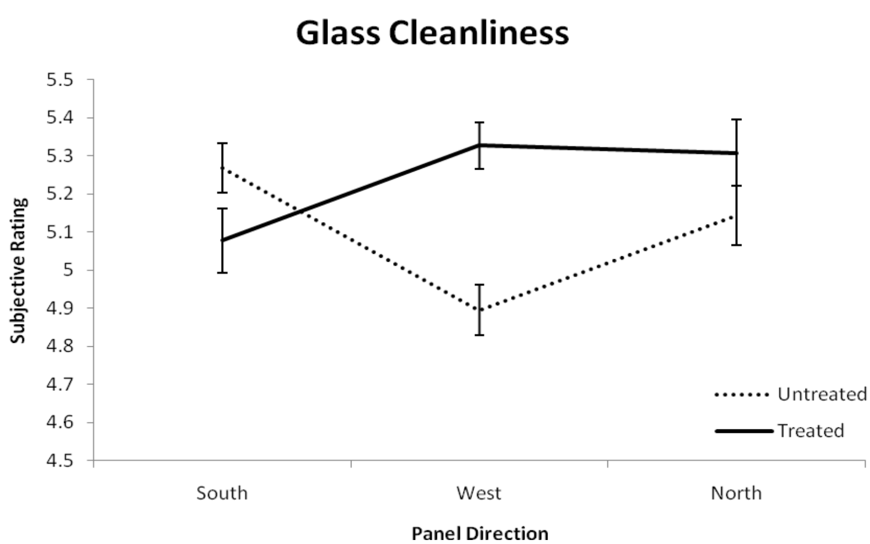
APPENDIX D: Statistical Analyses

Glass Cleanliness

Subjective observations (Appendix C) of glass cleanliness were rated from one (poor) to six (excellent). There were no differences in ratings of glass cleanliness between the south (M = 5.173, SE = 0.066), west (M = 5.111, SE = 0.057), and north (M = 5.226, SE = 0.076) directions, $F(2, 102) = 1.436$, $p = 0.243$. There was a main effect of panel type, $F(1, 51) = 8.734$, $p = 0.005$, with the untreated panel (M = 5.103, SE = 0.049) being rated as less clean than the treated panel (M = 5.237, SE = 0.067). There was also a main effect of observation type, $F(1, 51) = 108.367$, $p < 0.001$. Subjects rated the panels as being cleaner when viewed through binoculars (M = 5.426, SE = 0.061) than when viewed with the naked eye (M = 4.913, SE = 0.057).

There was a significant interaction between direction and panel type, $F(2, 102) = 31.697$, $p < 0.001$. Pairwise comparisons between directions within the untreated panel condition show a significant difference between south and west ($p < 0.001$), and west and north ($p = 0.007$). Within the treated panel condition, significant differences were found between south and west ($p < 0.001$), and south and north ($p = 0.004$). Significant differences were also found between panel types for south facing panels ($p = 0.008$), west facing panels ($p < 0.001$), and north facing panels ($p = 0.014$).



	Untreated		Treated	
	M	SE	M	SE

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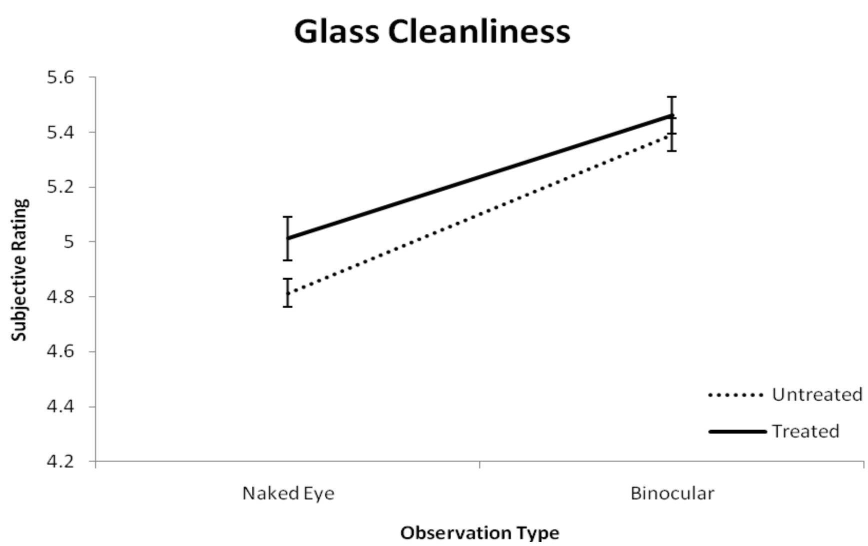
South	5.269	0.065	5.077	0.084
West	4.894	0.066	5.327	0.061
North	5.144	0.078	5.308	0.087

There was no significant interaction between direction and observation type, $F(2, 102) = 0.908$, $p = 0.406$.

	Naked Eye		Binoculars	
	M	SE	M	SE
South	4.904	.081	4.904	.081
West	4.837	.071	4.837	.071
North	5.000	.087	5.000	.087

There was a significant interaction between panel type and observation type, $F(1, 51) = 4.250$, $p = 0.044$. Within the naked eye condition, there was a significant difference between the untreated panel and the treated panel, $p = 0.006$. There was also a significant difference between naked eye observations and binocular observations within both the treated ($p < 0.001$) and untreated panel ($p < 0.001$) conditions.



	Untreated		Treated	
	M	SE	M	SE
Naked Eye	4.814	0.052	5.013	0.079
Binocular	5.391	0.060	5.462	0.068

There was a significant three-way interaction between direction, panel type, and observation type, $F(2, 102) = 34.392$, $p < 0.001$. There was a significant difference in glass cleanliness between treated and untreated panels within the naked eye condition for south

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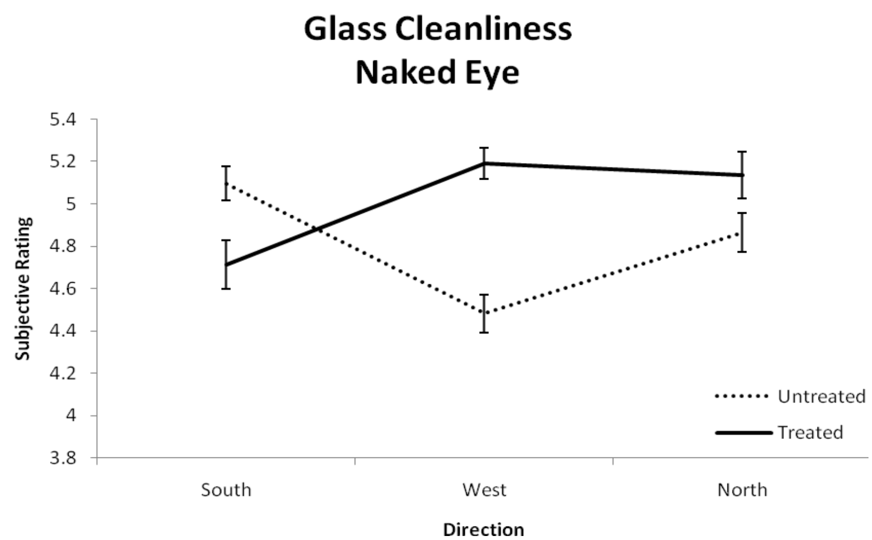
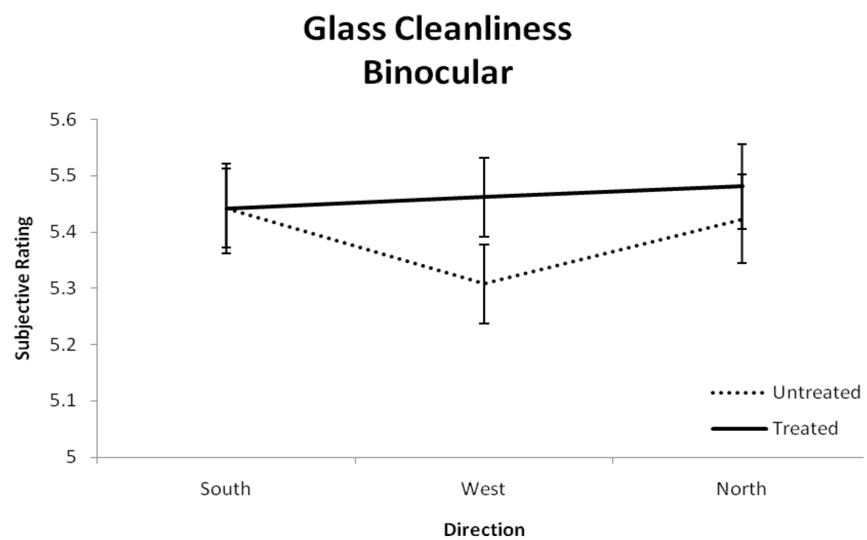
(p = 0.001), west (p < 0.001), and north (p = 0.012). The same was true for the binocular condition for west facing panels only (p = 0.01). Furthermore, for untreated panels viewed with the naked eye, there was a cleanliness difference between west and south facing panels (p < 0.001) and west and north facing panels (p = 0.002). For treated panels viewed with the naked eye, there was a difference between south and north facing panels (p = 0.001) and south and west facing panels (p < 0.001).





Naked Eye	Binocular

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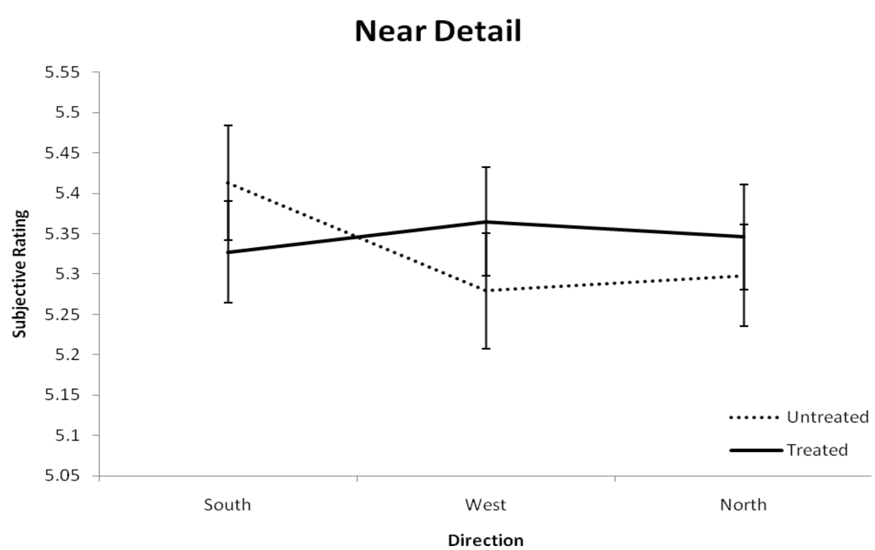
		M	SE	M	SE
South	Untreated	5.096	.079	5.442	.070
	Treated	4.712	.114	5.442	.080
West	Untreated	4.481	.089	5.308	.070
	Treated	5.192	.073	5.462	.070
North	Untreated	4.865	.091	5.423	.079
	Treated	5.135	.110	5.481	.075

Near Detail

There were no differences in ratings of near detail between the south (M = 5.370, SE = 0.064), west (M = 5.322, SE = 0.068), and north (M = 5.322, SE = 0.063) directions, $F(2, 102) = 0.721$, $p = 0.489$. Overall, there was no significant difference between untreated (M = 5.330, SE = 0.061) and treated (M = 5.346, SE = 0.059) panels, $F(1, 51) = 0.860$, $p = 0.358$. There was a significant difference between observation type with naked eye ratings (M = 5.205, SE = 0.067) being lower than binocular ratings (M = 5.471, SE = 0.064), $F(1, 51) = 22.483$, $p < 0.001$.

The interaction between direction and panel type violated sphericity, $\chi^2(2) = 0.829$, $p = 0.009$. Degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = 0.881$). The interaction was significant, $F(1.762, 89.859) = 6.766$, $p = 0.003$. Pairwise comparisons were corrected using a Bonferroni adjustment. For untreated panels, there was a significant differences between south and north ($p = 0.045$). For south facing panels, treated panels had lower ratings than untreated panels ($p = 0.038$). For west facing panels, treated panels had higher ratings than untreated panels ($p = 0.005$).



Untreated	Treated

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	M	SE	M	SE
South	5.413	0.071	5.327	0.063
West	5.279	0.072	5.365	0.067
North	5.298	0.063	5.346	0.065

There was no interaction between direction and observation type, *F*(2, 102) = 0.777, *p* = 0.462.

	Naked Eye		Binoculars	
	M	SE	M	SE
South	5.250	0.078	5.490	0.068
West	5.202	0.079	5.442	0.071
North	5.163	0.076	5.481	0.069

There was no interaction between panel type and observation type, *F*(1, 51) = 0.034, *p* = 0.855.

	Untreated		Treated	
	M	SE	M	SE
Naked Eye	5.199	0.069	5.212	0.067
Binocular	5.462	0.066	5.481	0.064

There was no three-way interaction, *F*(2, 102) = 2.040, *p* = 0.135.

		Naked Eye		Binocular	
		M	SE	M	SE
South	Untreated	5.308	0.093	5.519	0.070
	Treated	5.192	0.078	5.462	0.070
West	Untreated	5.173	0.081	5.385	0.078
	Treated	5.231	0.081	5.500	0.070
North	Untreated	5.115	0.081	5.481	0.070
	Treated	5.212	0.079	5.481	0.070

Far Detail

There were no differences in ratings of far detail between south (M = 5.144, SE = 0.062), west (M = 5.005, 0.074), and north (M = 5.038, 0.074), *F*(2, 102) = 2.822, *p* = 0.064. There was a significant difference between untreated (M = 5.022, SE = 0.058) and treated (M = 5.103, SE = 0.065), *F*(1, 51) = 10.758, *p* = 0.002. There was a significant difference between naked eye

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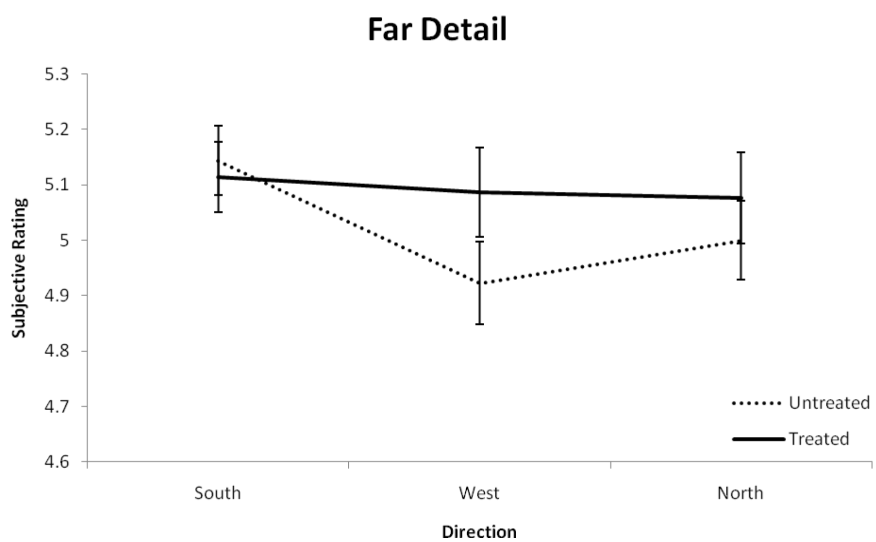
(M = 4.878, SE = 0.079) and binocular (M = 5.247, SE = 0.062) ratings of quality, $F(1, 51) = 23.554$, $p < 0.001$.

There was a significant interaction between direction and panel type, $F(2, 102) = 4.856$, $p = 0.010$. For untreated panels, there was a significant difference between ratings for south and west ($p = 0.001$). For west facing panels, there was a significant difference between treated and untreated panels ($p < 0.001$).



	Untreated		Treated	
	M	SE	M	SE
South	5.144	0.063	5.114	0.063
West	4.923	0.074	5.087	0.080
North	5.000	0.071	5.077	0.082

There was an interaction between direction and observation type, $F(2, 102) = 4.597$, $p = 0.012$. For binocular observations, there was a significant difference between west and south facing panels ($p = 0.006$) and west and north facing panels ($p = 0.010$). There was a significant difference between naked eye and binocular observations for south ($p < 0.001$), west ($p = 0.006$), and north facing panels ($p < 0.001$).

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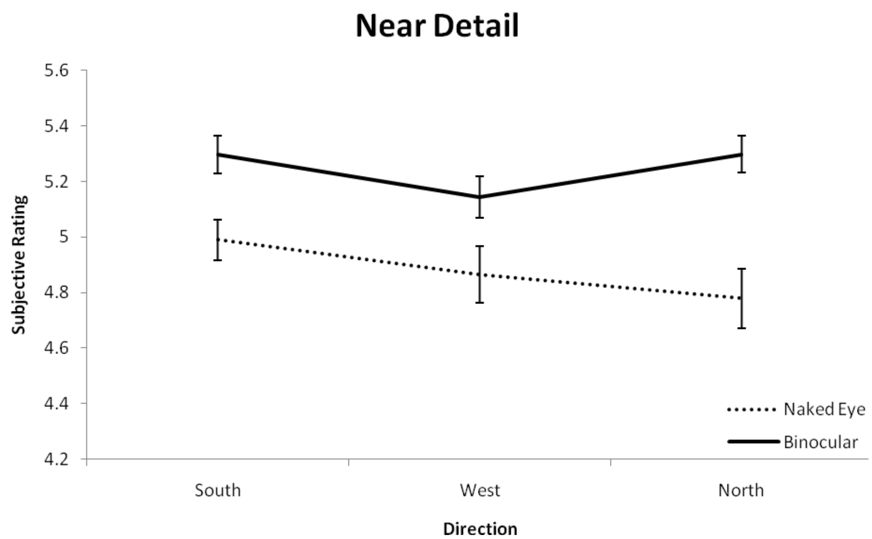

	Naked Eye		Binoculars	
	M	SE	M	SE
South	4.990	0.073	5.298	0.068
West	4.865	0.101	5.144	0.074
North	4.779	0.108	5.298	0.066

There was no interaction between panel type and observation type, $F(1, 51) = 0.754$, $p = 0.389$.

	Untreated		Treated	
	M	SE	M	SE
Naked Eye	4.846	0.079	4.199	0.060
Binocular	4.910	0.083	5.295	0.068

There was no three-way interaction between direction, panel type, and observation type, $F(2, 102) = 1.239$, $p = 0.294$.

		Naked Eye		Binocular	
		M	SE	M	SE
South	Untreated	5.000	0.078	5.288	0.069
	Treated	4.981	0.075	5.308	0.070

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West	Untreated	4.808	0.103	5.038	0.077
	Treated	4.923	0.106	5.250	0.082
North	Untreated	4.731	0.107	5.269	0.068
	Treated	4.827	0.119	5.327	0.071

Near Dynamic Target

There was no significant difference between ratings of near dymaic target quality between south (M = 5.341, SE = 0.061), west (M = 5.226, SE = 0.068), and north (M = 5.337, SE = 0.064), $F(2, 102) = 2.926$, $p = 0.058$. There was no difference between untreated panels (M = 5.295, SE = 0.056) and treated panels (M = 5.308, SE = 0.058), $F(1 , 51) = 0.887$, $p = 0.351$. There was a significant difference between naked eye observations (M = 5.186, SE = 0.063) and binocular observations (M = 5.417, SE = 0.061), $F(1, 51) = 21.335$, $p < 0.001$.

There was no significant interaction between direction and panel type, $F(2, 102) = 1.747$, $p = 0.179$.

	Untreated		Treated	
	M	SE	M	SE
South	5.346	0.062	5.337	0.063
West	5.202	0.068	5.250	0.072
North	5.337	0.064	5.337	0.065

There was no significant interaction between direction and observation type, $F(2, 102) = 1.588$, $p = 0.209$.

	Naked Eye		Binoculars	
	M	SE	M	SE
South	5.269	0.068	5.413	0.068
West	5.077	0.093	5.375	0.068
North	5.212	0.073	5.462	0.070

There was no significant difference between panel type and observation type, $F(1, 51) = 0.000$, $p = 1.000$.

	Untreated		Treated	
	M	SE	M	SE
Naked Eye	5.179	0.064	5.192	0.064
Binocular	5.410	0.060	5.423	0.062

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There was no significant three-way interaction between direction, panel type, and observation type, $F(2 , 102) = 2.793$, $p = 0.066$.

		Naked Eye		Binocular	
		M	SE	M	SE
South	Untreated	5.288	0.069	5.404	0.069
	Treated	5.250	0.072	5.423	0.069
West	Untreated	5.038	0.095	5.365	0.067
	Treated	5.115	0.094	5.385	0.073
North	Untreated	5.212	0.074	5.462	0.070
	Treated	5.212	0.074	5.462	0.070

Far Dynamic Target

There was no significant difference in ratings of far dynamic target quality between south (M = 5.072, SE = 0.058), west (M = 4.952, SE = 0.075), and north (M = 5.067, SE = 0.079), $F(2, 102) = 2.615$, $p = 0.078$. There was no significant difference between untreated panels (M = 5.016, SE = 0.060) and treated panels (M = 5.045, SE = 0.065), $F(1, 51) = 3.389$, $p = 0.071$. There was a significant difference between naked eye observations (M = 4.840, SE = 0.079) and binocular observations (M = 5.221, SE = 0.061), $F(1, 51) = 32.100$, $p < 0.001$.

The interaction between direction and panel type violated sphericity, $\chi^2(2) = 13.309$, $p = 0.001$. Degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = 0.833$). The interaction was significant, $F(2, 102) = 6.052$, $p = 0.003$. Pairwise comparisons were corrected using a Bonferroni adjustment. For untreated panels, there was a significant difference between south and west ($p = 0.009$). For west facing panels, there was a significant difference between treated and untreated panels ($p = 0.006$).

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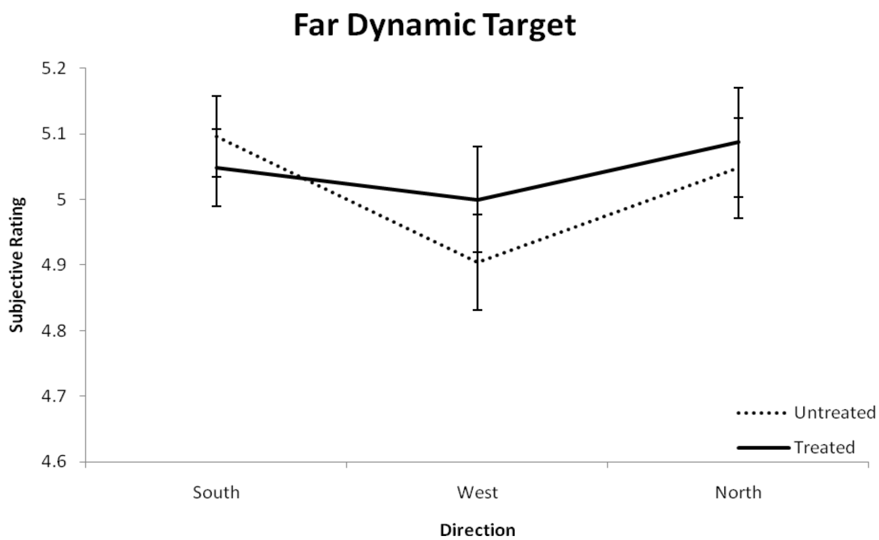

	Untreated		Treated	
	M	SE	M	SE
South	5.096	0.061	5.048	0.059
West	4.904	0.073	5.000	0.08
North	5.048	0.076	5.087	0.083

There was no interaction between direction and observation type, $F(2, 102) = 0.329$, $p = 0.720$.

	Naked Eye		Binoculars	
	M	SE	M	SE
South	4.894	0.074	5.250	0.067
West	4.740	0.096	5.163	0.077
North	4.885	0.104	5.250	0.072

There was no interaction between panel type and observation type, $F(1, 51) = 0.424$, $p = 0.518$.

	Untreated		Treated	
	M	SE	M	SE
Naked Eye	4.821	0.076	4.859	0.084
Binocular	5.212	0.062	5.231	0.061

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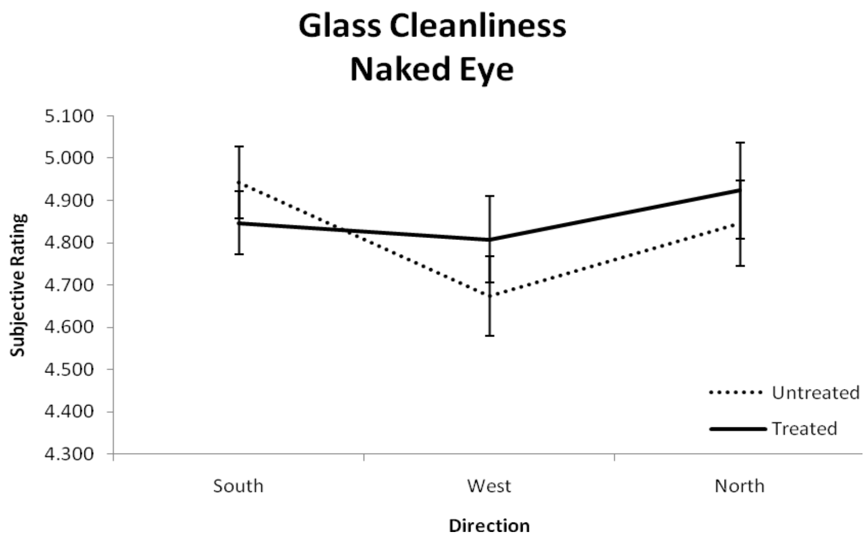
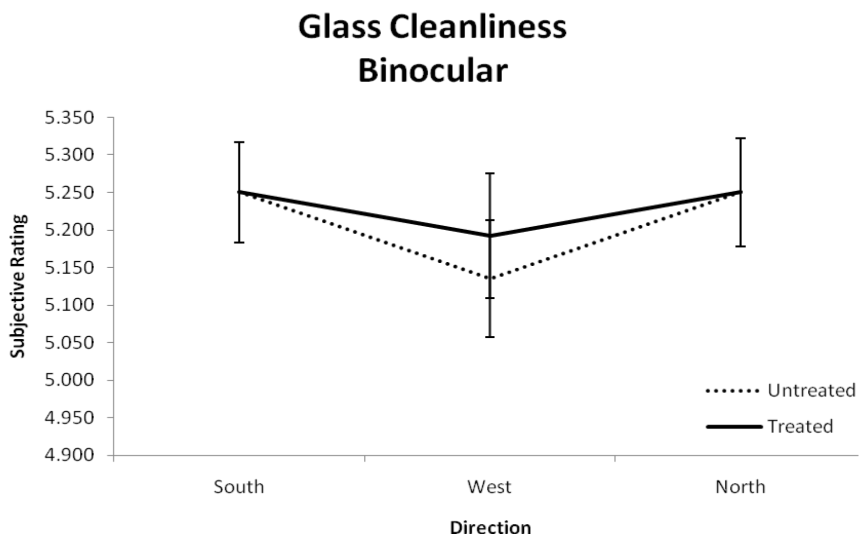
There was a three-way interaction between direction, panel type, and observation type, $F(2, 102) = 3.122$, $p = 0.048$. For untreated panels viewed with the naked eye, there was a significant difference between south and west ($p = 0.007$) and west and north ($p = 0.049$). For west facing panels viewed with the naked eye, there was a difference between treated and untreated panels ($p = 0.007$).





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		Naked Eye		Binocular	
		M	SE	M	SE
South	Untreated	4.942	0.084	5.250	0.067
	Treated	4.846	0.094	5.250	0.067
West	Untreated	4.673	0.094	5.135	0.078
	Treated	4.808	0.103	5.192	0.083
North	Untreated	4.846	0.100	5.250	0.072
	Treated	4.923	0.113	5.250	0.072

Haziness

Subjects were asked whether or not the panel seemed “hazy.” Subjects responded with a yes or a no. The data was converted into a proportion (i.e., proportion of subjects who described the panel as hazy). This proportion data was transformed using an arcsine square root transformation to reduce normality and sphericity issues before being analyzed using a 3x2x2 Repeated Measures ANOVA. This approach was utilized for the haziness, blurriness, cloudiness, and distortion dependent variables.

There was a difference between south (M = 0.394, SE = 0.081), west (M = 0.177, SE = 0.054), north (M = 0.250, SE = 0.086), $F(2, 6) = 18.902$, $p = 0.003$. Tukey post-hoc shows more subjects described the south facing panels as hazy than both the west ($p = 0.016$) and north ($p = 0.009$) facing panels. There was no difference between untreated panels (M = 0.268, SE = 0.060) and treated panels (M = 0.279, SE = 0.090), $F(1, 3) = 0.043$, $p = 0.849$. There was no difference between naked eye observations (M = 0.385, SE = 0.125) and binocular observations (M = 0.162, SE = 0.078), $F(1, 3) = 2.228$, $p = 0.232$.

There was no interaction between direction and panel type, $F(2, 6) = 1.711$, $p = 0.258$.

	Untreated		Treated	
	M	SE	M	SE
South	0.325	0.044	0.463	0.160
West	0.270	0.098	0.085	0.038
North	0.210	0.081	0.290	0.098

There was no significant interaction between direction and observation type, $F(2, 6) = 0.762$, $p = 0.507$.

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	Naked Eye		Binoculars	
	M	SE	M	SE
South	0.569	0.186	0.218	0.116
West	0.264	0.095	0.090	0.071
North	0.322	0.113	0.178	0.094

There was a significant difference between panel type and observation type, $F(1, 3) = 11.917$, $p = 0.041$. Pairwise comparisons showed a significant difference (at a 0.10 criterion) between untreated and treated panels for naked eye observations ($p = 0.094$) and between naked eye and binocular observations for treated panels ($p = 0.087$).

	Untreated		Treated	
	M	SE	M	SE
Naked Eye	0.316	0.101	0.455	0.150
Binocular	0.221	0.105	0.103	0.058

There was a significant three-way interaction between direction, panel type, and observation type, $F(2, 6) = 9.876$, $p = 0.013$. Pairwise comparisons reveal a difference between (at a 0.10 criterion) west and north for untreated panels viewed with the naked eye ($p = 0.091$). For treated panels viewed with the naked eye, there was a difference between both south and west ($p = 0.066$) and south and north ($p = 0.090$).

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		Naked Eye		Binocular	
		M	SE	M	SE
South	Untreated	0.353	0.120	0.297	0.175
	Treated	0.785	0.125	0.140	0.120
West	Untreated	0.378	0.125	0.161	0.142
	Treated	0.150	0.076	0.019	0.000
North	Untreated	0.216	0.065	0.205	0.116
	Treated	0.429	0.170	0.150	0.076

Blurriness

There was no difference between south (M = 0.148, SE = 0.090), west (M = 0.052, SE = 0.019), north (M = 0.060, SE = 0.040), $F(2, 6) = 1.744$, $p = 0.253$. There was no difference between untreated panels (M = 0.087, SE = 0.043) and treated panels (M = 0.086, SE = 0.054), $F(1, 3) < 0.001$, $p = 0.988$. There was no difference between naked eye observations (M = 0.132, SE = 0.099) and binocular observations (M = 0.041, SE = 0.022), $F(1, 3) = 0.736$, $p = 0.454$.

There was no interaction between direction and panel type, $F(2, 6) = 2.194$, $p = 0.193$.

	Untreated		Treated	
	M	SE	M	SE
South	0.123	0.068	0.172	0.114
West	0.085	0.038	0.019	0.000
North	0.052	0.033	0.067	0.048

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There was no significant interaction between direction and observation type, $F(2, 6) = 0.084$, $p = 0.921$.

	Naked Eye		Binoculars	
	M	SE	M	SE
South	0.211	0.192	0.085	0.065
West	0.085	0.038	0.019	0.000
North	0.100	0.081	0.019	0.000

There was no significant difference between panel type and observation type, $F(1, 3) < 0.001$, $p = 0.988$.

	Untreated		Treated	
	M	SE	M	SE
Naked Eye	0.132	0.086	0.132	0.112
Binocular	0.041	0.022	0.041	0.022

There was no significant three-way interaction between direction, panel type, and observation type, $F(2 , 6) = 2.194$, $p = 0.193$.

		Naked Eye		Binocular	
		M	SE	M	SE
South	Untreated	0.161	0.142	0.085	0.065
	Treated	0.260	0.241	0.085	0.065
West	Untreated	0.150	0.076	0.019	0.000
	Treated	0.019	0.000	0.019	0.000
North	Untreated	0.085	0.065	0.019	0.000
	Treated	0.115	0.096	0.019	0.000

Cloudiness

There was a significant effect of direction, $F(2, 6) = 7.841$, $p = 0.021$. A Tukey post hoc showed that more subjects described the south facing panels (M = 0.240, SE = 0.065) as cloudy than the west facing panels (M = 0.098, SE = 0.047), $p = 0.042$. There was also a significant main effect of panel type with fewer subjects describing the untreated panels (M = 0.123, SE = 0.050) as being cloudy compared to treated panels (M = 0.123, SE = 0.047), $F(1, 3) = 17.397$, $p = 0.025$. There was no significant main effect of observatoin type, $F(1, 3) = 5.883$, $p = 0.094$.

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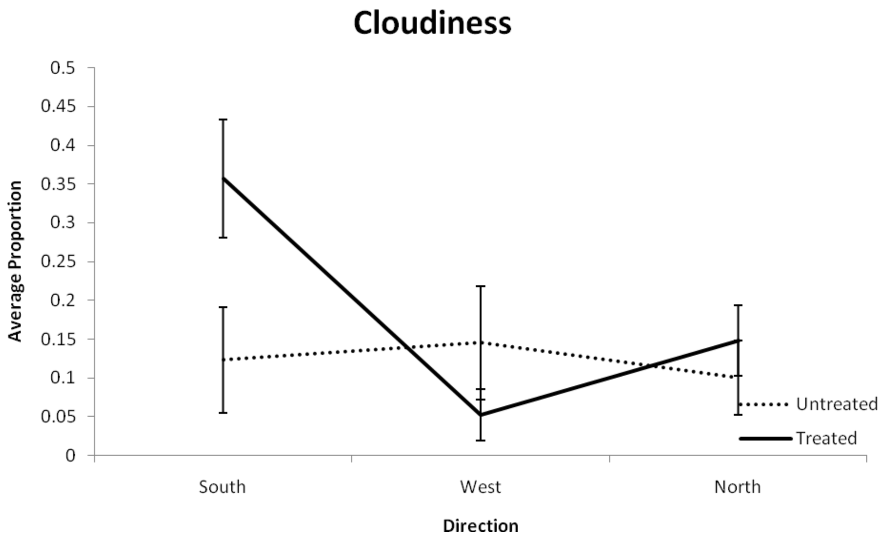
There was a significant interaction between direction and panel type, $F(2, 6) = 6.746$, $p = 0.029$. Pairwise comparisons reveal a significant differences between south and west ($p = 0.015$) and south and north ($p = 0.008$) for treated panels. A significant difference was also found between treated and untreated south facing panels ($p = 0.033$).



	Untreated		Treated	
	M	SE	M	SE
South	0.123	0.068	0.357	0.076
West	0.145	0.073	0.052	0.033
North	0.100	0.048	0.148	0.045

There was no interaction between direction and observation type, $F(2, 6) = 3.214$, $p = 0.113$.

	Naked Eye		Binoculars	
	M	SE	M	SE
South	0.429	0.136	0.052	0.033
West	0.145	0.088	0.052	0.033
North	0.229	0.088	0.019	0.000

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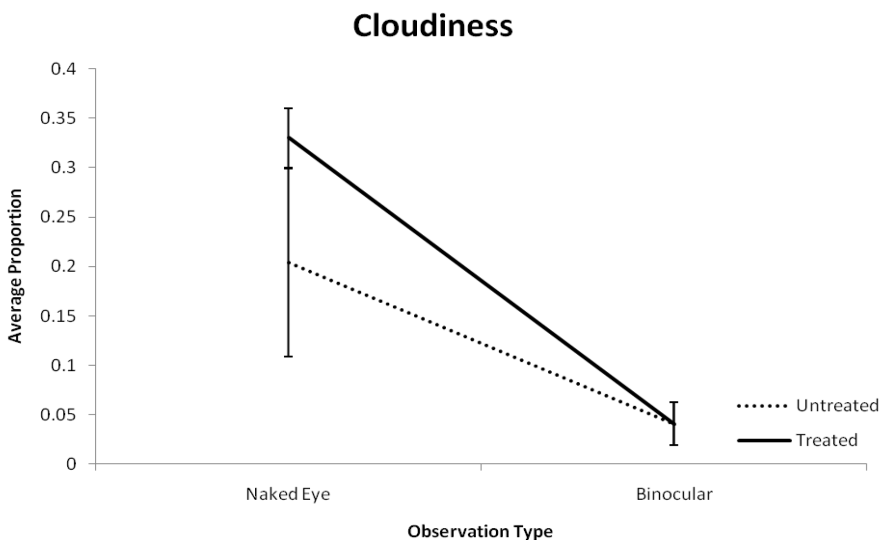
There was a significant interaction between panel type and observation type, $F(1, 3) = 17.397$, $p = 0.025$. There was a significant difference between treated and untreated panels when viewed with the naked eye, $p = 0.025$.



	Untreated		Treated	
	M	SE	M	SE
Naked Eye	0.204	0.095	0.330	0.030
Binocular	0.041	0.022	0.041	0.022

There was a significant three-way interaction between direction, observation type, and panel type, $F(2, 6) = 15.105$, $p = 0.005$. For treated panels viewed with the naked eye, there was a difference between south and west ($p = 0.012$) and south and north ($p = 0.026$). For south facing panels viewed with the naked eye, there was a difference between treated and untreated panels, $p = 0.008$.

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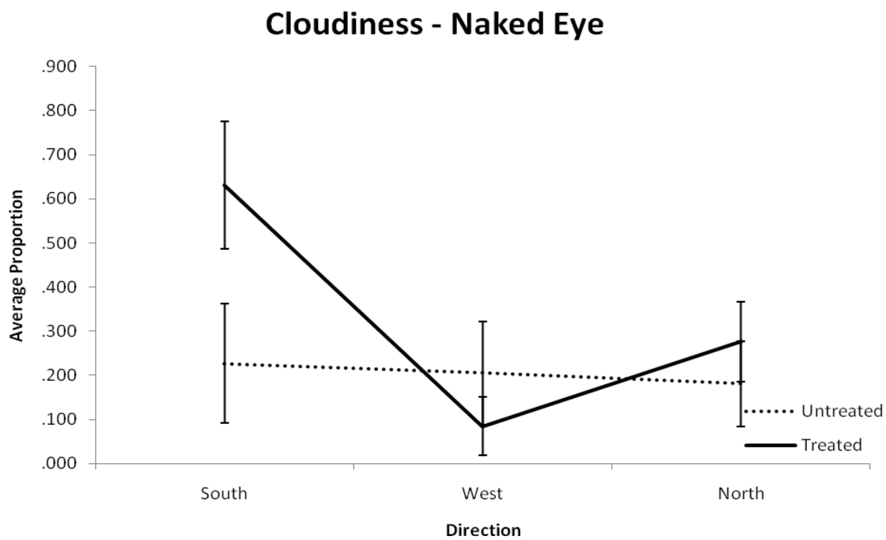

		Naked Eye		Binocular	
		M	SE	M	SE
South	Untreated	0.227	0.135	0.019	0.000
	Treated	0.630	0.144	0.085	0.065
West	Untreated	0.205	0.116	0.085	0.065
	Treated	0.085	0.065	0.019	0.000
North	Untreated	0.181	0.096	0.019	0.000
	Treated	0.277	0.090	0.019	0.000

Distortion

There was no difference between south (M = 0.019, SE = 0.000), west (M = 0.019, SE = 0.000), north (M = 0.036, SE = 0.016), $F(2, 6) = 1.000$, $p = 0.422$. There was no difference between untreated panels (M = 0.019, SE = 0.000) and treated panels (M = 0.030, SE = 0.011), $F(1, 3) = 1.000$, $p = 0.391$. There was no difference between naked eye observations (M = 0.030, SE = 0.011) and binocular observations (M = 0.019, SE = 0.000), $F(1, 3) = 1.000$, $p = 0.391$.

There was no interaction between direction and panel type, $F(2, 6) = 1.000$, $p = 0.422$.

	Untreated		Treated	
	M	SE	M	SE
South	0.019	0.000	0.019	0.000
West	0.019	0.000	0.019	0.000
North	0.019	0.000	0.052	0.033

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There was no significant interaction between direction and observation type, $F(2, 6) = 1.000$, $p = 0.422$.

	Naked Eye		Binoculars	
	M	SE	M	SE
South	0.019	0.000	0.019	0.000
West	0.019	0.000	0.019	0.000
North	0.052	0.033	0.019	0.000

There was no significant difference between panel type and observation type, $F(1, 3) = 1.000$, $p = 0.391$.

	Untreated		Treated	
	M	SE	M	SE
Naked Eye	0.019	0.000	0.041	0.022
Binocular	0.019	0.000	0.019	0.000

There was no significant three-way interaction between direction, panel type, and observation type, $F(2 , 6) = 1.000$, $p = 0.422$.

		Naked Eye		Binocular	
		M	SE	M	SE
South	Untreated	0.019	0.000	0.019	0.000
	Treated	0.019	0.000	0.019	0.000
West	Untreated	0.019	0.000	0.019	0.000
	Treated	0.019	0.000	0.019	0.000
North	Untreated	0.019	0.000	0.019	0.000
	Treated	0.085	0.065	0.019	0.000

Comparison

Subjects indicated which panel (treated or untreated) they thought had the better viewing quality by marking a spot along a continuous line. Quantitative data was extracted by measuring the mark with a ruler with the midpoint being zero, to the left being negative and to the right being positive. A 2x2 Repeated Measures ANOVA was performed direction and observation type.

There was a significant main effect of direction, $F(2, 102) = 35.663$, $p < 0.001$. Subjects tended to prefer the untreated panel when facing south and the treated panels when facing west or north. The preference difference was significant between south (M = -7.901, SE = 1.862) and

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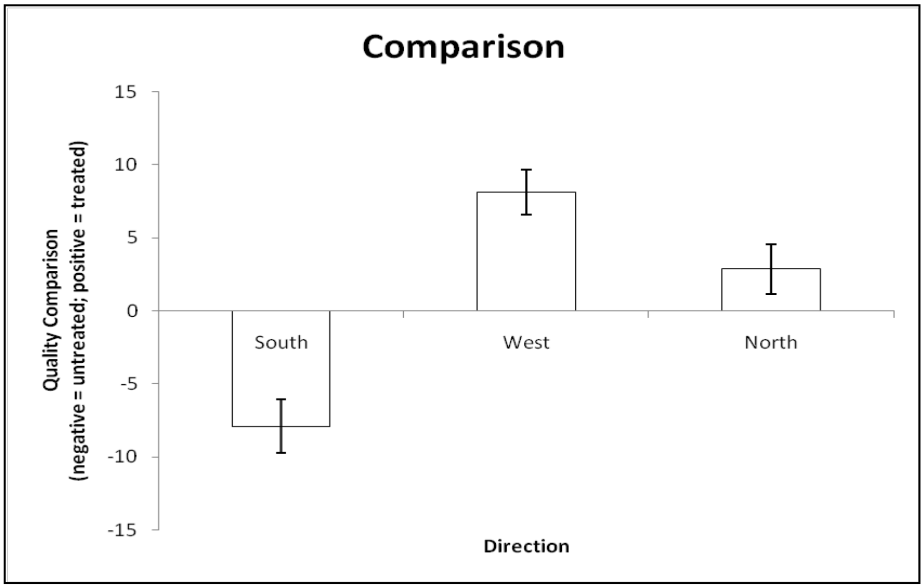
west (M = 8.155, SE = 1.541), $p < .001$, and south and north (M = 2.866, SE = 1.701), $p < 0.001$, and west and north ($p = 0.001$).



There was no significant main effect of observation type, $F(1, 51) = 2.491$, $p = 0.121$. Naked eye observations (M = -0.387, SE = 2.073) had the same quality ratings as binocular observations (M = 2.467, SE = 0.811). Naked eye observations slightly preferred untreated panels while binocular observations slightly preferred treated panels. Given the lack of significance, we conclude that there is no real preference.

There was a significant interaction between direction and observation type, $F(2, 102) = 33.371$, $p < 0.001$. For naked eye observations, south was significantly different than west ($p < 0.001$) and north ($p < 0.001$). Additionally, west was different than north ($p = 0.004$). For binocular observations, south was significantly different than west ($p = 0.005$) and west is different than north ($p = 0.010$). Naked eye observations were significantly different than binocular observations for both south ($p < 0.001$) and west ($p = 0.004$). For naked eye observations, subjects tended to prefer untreated panels when facing south and treated panels when facing west and north.

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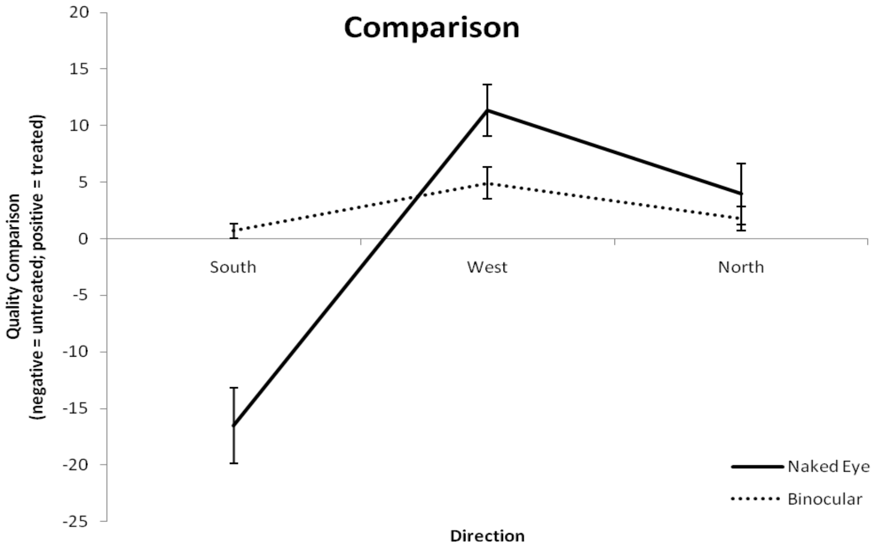

	Naked Eye		Binoculars	
	M	SE	M	SE
South	-16.491	3.350	0.689	0.641
West	11.375	2.278	4.935	1.371
North	3.955	2.695	1.778	1.072

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