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# **Airport Traffic Control Tower Lighting and Viewing Measurements**

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May 2007

Technical Report

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<b>16. Abstract</b> The Federal Aviation Administration (FAA) conducted the Airport Traffic Control Tower (ATCT) lighting and viewing measurement field survey to determine and record illumination in the ATCT environment and to document display viewing data. Researchers took lighting measurements at 21 ATCTs. They took viewing measures from primary, secondary, and auxiliary users of various types of displays that are used at these towers. Researchers used a photometer to take ambient and incident illumination measurements from various locations inside and outside of the ATCTs. In addition, they used a compass/clinometer to take tilt and viewing angle measurements, and they used a carpenter's square and string to measure the lateral viewing angle from the user to the display. This report includes maximum illumination readings for each facility. The range of viewing distances and angles are reported according to type of display and type of user. Incorporating the operational data collected in this survey will enable FAA to provide display specifications and minimum viewing distances and angles under the maximum lighting levels for optimum performance.					
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1. Baltimore/Washington International (BWI)
2. Charlottesville-Albermarle (CHO)
3. Dallas/Fort Worth International (DFW - East, West, & Center)
4. Daytona Beach International (DAB)
5. St. Louis Downtown (CPS)
6. Long Beach (Daugherty Field), (LGB)
7. Los Angeles International (LAX)
8. Manassas Regional/Harry P. Davis Field (HEF)
9. Melbourne International (MLB)
10. Miami International (MIA - old & new)
11. North Perry (HWO)
12. Ontario International (ONT)
13. Orlando International (MCO)
14. Phoenix Sky Harbor International (PHX)
15. Deer Valley (DVT)
16. Phoenix Goodyear (GYR)
17. Spirit of St. Louis (SUS)
18. Lambert-St Louis International (STL)



## Executive Summary

The purpose of the Airport Traffic Control Tower (ATCT) lighting and viewing measurement field survey was to determine and record the operational conditions in the ATCTs' unique environment. The objective of this project was to support development of a proposed Human Factors ATCT Display Specification. This report documents the results of the measurements taken and describes the equipment and procedures used to collect the data. Also included is a discussion of the results with recommendations for the resulting Human Factors ATCT Display Specification.

In addition, this report describes some of the operational conditions existing in ATCTs, such as lighting levels and viewing measurements. Researchers surveyed 21 ATCTs across the country, from early January 2003 to mid March 2003, and collected relevant operational and engineering data. We collected viewing data at all 21 ATCTs; however, we collected lighting data at only 15 ATCTs. The remaining six ATCTs were Grade 10 or higher (i.e., facilities with high traffic volumes). At these six ATCTs, the data collection effort occurred only at night to minimize any inconvenience to the tower operations.

The maximum amount of light measured falling directly onto (incident to) a tower display was 6,040 foot-candles (fc), which occurred at the Dallas/Fort Worth International ATCT. The second highest incident illumination reading was 5,130 fc, which occurred at the North Perry ATCT.

The maximum incident illumination found during a mixed shade position (partially deployed shades) set according to controller preference was 2,780 fc, which occurred at the Deer Valley ATCT in Phoenix, Arizona.

We divided the viewing angle and distance results into categories and subcategories, as dictated by the Federal Aviation Administration Terminal Business Service Unit (ATO-T) *Terminal Display Integration Plan*, which was published in June of 2003. It specifies four high-level display categories:

1. Tactical Displays (Primary Situation Displays, Surface Surveillance Displays, Communications Display System, and Flight Data Management Display)
2. Information Displays (including Weather Information Displays)
3. Miscellaneous and Administrative Displays
4. Maintenance Displays and Monitor and Control Displays

We further broke down these display categories on the basis of personnel who use the displays:

1. Primary users (i.e., Local Controllers)
2. Secondary users (i.e., Ground Controllers and Cab Coordinator)
3. Auxiliary users (i.e., Supervisor, Flight Data/Clearance Delivery, and Traffic Management Coordinator)

Researchers report the results according to whether the users read or viewed the displays from a particular location. In addition, we report whether the locations are current locations where the controllers could read the display or the positions where they need to read the display (but could only view it due to various conditions).

## 1. INTRODUCTION

### 1.1 Statement of Problem

Personnel in Airport Traffic Control Towers (ATCTs) are responsible for monitoring and directing the takeoff of outgoing aircraft, the landing of incoming aircraft, and movement of all aircraft and vehicles on the ground. The typical crew positions that are present in the ATCT are Local Controller, Assistant Local Controller, Ground Controller, Assistant Ground Controller, Flight Data and Clearance Delivery, and Supervisor. The Traffic Management Specialist may also be present in some ATCTs to control the aircraft en route between airports.

Although the primary source of information for the Local Controller, Assistant Local or Assistant Ground Controller, and the Ground Controller is the view out the windows of the ATCT, they use electronic displays within the tower cab to augment that view and to enhance situational awareness. Due to the criticality of the work being performed by the controllers and the rather unique environment of the ATCT, designers have developed display hardware standards that are not directly applicable for general use. Hence, there is a gap in tower display hardware standards.

### 1.2 Background

There have been a few surveys that attempted to define the operational conditions in the tower cab. As stated in one of the previous surveys performed by Crown Communications, Inc., these studies were limited in nature (Spunich, Krois, Lenorovitz, Mogford, & Masterson, 1999). There are only a few studies that provide data on ATCT ambient illumination levels. Unfortunately, these studies do not provide sufficient information on either the lighting conditions present or the methods used to measure the conditions so that there is confidence in extrapolating their results to upcoming Tower Display Workstation evaluations. For example, Hannon (1995) reported an ambient light reading of 6,325 foot-candles (fc) at the Boston International ATCT, and Federal Aviation Administration (FAA) (1997) reported an ambient light reading of 5,230 fc at the Las Vegas International (LAS) ATCT. It is unclear whether these levels represented the brightest possible illumination, the average reading in the tower cab, or the amount of illumination falling directly on the Digital Bright Radar Indicator Tower Equipment (D-BRITE) screen (the display of interest during measurement). Furthermore, initial indications were that controllers typically viewed the D-BRITE from a distance of 4 ft to 8 ft and, in some instances, from 12 ft and beyond. It was unclear how these distances might vary between console- and ceiling-mounted D-BRITE screens (Spunich et al., 1999).

The Spunich et al. (1999) tower study determined that the highest incident illumination levels measured were found under engineering test conditions, that is, conditions in which all shades were temporarily moved to the “up” position, regardless of normal controller preference settings. The maximum incident illumination level on the D-BRITE under these engineering test conditions was 765 fc, which occurred at the St. Petersburg Clearwater ATCT in Florida. The associated tower ambient lighting level was 3,350 fc. Generally, when researchers took the operational light readings for this study, they classified the sky coverage situations as being either “overcast” or “clear-to-broken.” Due to meteorological conditions, the data collected were a subset and did not represent the upper (highest) range of illumination levels present in ATCTs throughout the National Airspace System (NAS).

For the viewing distances and angles, Spunich et al. (1999) found that the viewing distances for the local controllers using ceiling-mounted D-BRITEs ranged from 3 to 6 ft, whereas distances for those using console-mounted D-BRITEs ranged from 2 to 3 ft. Irrespective of the D-BRITE mounting mode, the observed viewing angles typically fell within an arc of 15° left or right perpendicular to the center of the D-BRITE.

The Spunich et al. (1999) survey did not include the full range of all types of tower cab configurations, nor did it include a representative range of tower sizes. It contained a small sample size and limited scope. The study did record the weather conditions outside while the measurements were taken (i.e., clear with 10 miles of visibility), but it did not specify the actual light measurements outside. Therefore, it did not allow a comparison between the amount of light present outside and the amount of light reaching the displays inside.

### 1.3 Purpose and Rationale

The purpose of the ATCT lighting and viewing measurement field survey was to determine and record operational illumination and display viewing distances in the tower's unique environment. The objective of this project was to supply data to populate the Human Factors ATCT Display Specifications that are currently under development. The final specifications will present design and performance criteria for tower displays. The specifications will then be made available for use in the acquisition, design, development, and selection of tower displays.

This document reports the results of lighting data collected and viewing measurements taken and describes the equipment and procedures used to collect these data. Researchers measured the amount of light (illumination) falling directly on (incident to) the display screen and the general ambient lighting levels with procedures adopted from The Illuminating Engineering Society of North America Lighting Handbook (Rea, 2002). We associated these measurements with specific times of the day, existing weather conditions, light measurements outside, and the position of the tower shades. We recorded controller viewing distances (i.e., the distance from which controllers viewed or detected targets on the screen and the distance from which they actually read data tags). We also measured and recorded the horizontal (i.e., lateral) and vertical-viewing angles of the monitor to the controller.

## 2. METHOD

Researchers collected relevant operational and engineering data at 21 ATCTs across the country. We spent 2 days on data collection activity. On the first day, Human Factors Engineers recorded lighting measurements from sunrise to sunset and collected viewing measurements. Viewing measurements determine the distances and angles from displays. When necessary, we used the second day to fill in any missing or confounded data caused by overcast skies, rainy afternoons, or equipment errors or malfunctions (see Appendix A for the schedule).

## 2.1 Airport Traffic Control Towers

### 2.1.1 Selection

We systematically selected the towers based on their location, cab configuration, cab size, and radar display monitor mounting technique. We surveyed the 21 ATCTs from early January to mid March 2003. As some of the towers visited were Grade 10 or higher (i.e., facilities with high traffic volumes), to prevent interference, we did not collect lighting measurements at these towers. We collected both lighting and viewing measurements from the following 15 ATCTs:

1. Charlottesville-Albermarle (CHO)
2. Dallas/Fort Worth International Center (DFWC)
3. Daytona Beach International (DAB)
4. St. Louis Downtown (CPS)
5. Long Beach (Daugherty Field), (LGB)
6. Manassas Regional/Harry P. Davis Field (HEF)
7. Melbourne International (MLB)
8. Miami International (MIA - Old)
9. Miami International (MIA - New)
10. North Perry (HWO)
11. Ontario International (ONT)
12. Orlando International (MCO)
13. Deer Valley (DVT)
14. Phoenix Goodyear (GYR)
15. Spirit of St. Louis (SUS)

We collected only viewing measurements (we could not collect lighting measurements) at the following six ATCTs:

1. Los Angeles International (LAX)
2. Phoenix Sky Harbor International (PHX)
3. Baltimore/Washington International (BWI)
4. Lambert-St Louis International (STL)
5. Dallas/Fort Worth International (DFW East)
6. Dallas/Fort Worth International (DFW West)

### 2.1.2 Variables

This study attempts to address the most important characteristics relevant to lighting and viewing angle and distance data. The study addressed these variables in many ways, one being through the use of a systematic selection of towers. There were four main criteria for selection: meteorological conditions, tower location (geographic latitude), shape and size of cab, and display mounting technique.

The largest and least controllable variables that had an effect on the amount of light reaching inside the tower cab were weather or meteorological conditions. Rain, fog, smog, snow, or overcast clouds in some instances restricted the amount of sunlight illuminating the tower. We also hypothesized the shape of the tower cab to have an effect on the level of light. Moreover, we thought tower cab configuration, such as the display mounting technique (e.g., in console, on console, and ceiling mounting) and quality and use of the shades changed the amount of sunlight entering the tower and hitting the displays. Additionally, the sun is closest to the earth at the equator and, therefore, varies in distance and angle to the earth across the United States. This also had an effect on how the light entered the various towers at different times of the day.

The variable that we hypothesized to have the largest effect on the viewing angle and distance measurements was the display technology used in the towers and how controllers implemented it. Controllers may limit where they stand to access the information on the existing displays. If incident lighting or a change in viewing angle degraded the displays, then controllers might be free to move to a more advantageous location for their primary task. We collected data about where controllers would like to be able to view displays to determine this location.

In addition, the amount of light entering the tower was a potentially confounding variable. At towers that experienced prolonged times of high ambient and incident light, we hypothesized the viewing angles and distances to shrink due to the limitations of the displays. To help to control this variable and allow the researchers to observe and record the extreme conditions, we observed where the controllers stood during times of low lighting conditions (e.g., overcast skies, at night).

## 2.2 Equipment

### 2.2.1 Lighting Measurement

Researchers took lighting measurements using a Photo Research LiteMate III (PR-504) Photometer with the following specifications:

- Range: 0.00929 fc to 18,579.907 fc within a 180° cone, and
- Calibrated within 1 month of initial use.

### 2.2.2 Viewing Measurement

A SUUNTO Tandem Compass/Clinometer took vertical angle measurements. It measured the tilt angle and viewing angles. The clinometer scale reads in degrees: 0°, 90°, 0° (in 1° increments). A carpenter's square and a string measured the controllers' horizontal (i.e., lateral) angle to the display.

We took distance measurements using a measuring tape, and these measurements determined the viewing distance from the center of the display to the appropriate eye height. We cut a string corresponding to 5<sup>th</sup> percentile female and 95<sup>th</sup> percentile male eye height data and used it for measurement purposes. While taking the measurements, a digital camera recorded the tower layout. We excluded controllers from the photos.

## 2.3 Procedure

### 2.3.1 Lighting Level

We spent 2 days at each site to increase the chances that we could record a complete data set of a sunrise to sunset cycle with maximum lighting conditions present. We collected and recorded hourly measurements on a data collection sheet (see Appendix B).

We took illumination measurements every hour in conditions created by controller preference with regard to the position of tower window shades. During engineering test conditions, we removed all the shades. Each morning, before measurements began, we checked and calibrated the photometer. Then, we either sketched a diagram of the tower's layout or obtained it from a supervisor. The diagram depicted the location of the displays and control positions. Next, we measured and recorded the displays' tilt angles. We took new measurements if a controller changed the tilt angles during the course of the day. We also recorded the following items:

1. Location of the displays in the tower: North, South, East, or West; the direction the display was facing (e.g., South = 180°) or whether they are ceiling or console mounted. We divided console mounting into *on the console* or *recessed into the console*.
2. Type and condition of artificial light source.
3. Visibility and sky condition data from the Automated Surface Observing System (ASOS).
4. Position of the tower shades: up, down, or mixed across the full set of tower windows.
5. Height of the tower cab ceiling and window height.

#### 2.3.1.1 Operational Test Condition

Researchers first collected ambient light data from outside the tower (i.e., either on the catwalk or the roof). We collected the data while in direct sunlight on the side of the tower that was closest to the sun's location. We did not collect data in a shaded area. In the morning, we collected the outside lighting data on the east side of the tower's catwalk, slowly moving south during the day and ending in the west. We took readings 4 ft above the surface with the photometer in the horizontal plane consistent with the international lighting standard method of light measurement (Rea, 2002). Then, we took readings again in the vertical plane facing north, south, east, and west. We took an additional reading with the photometer facing directly into the sun. This direct reading resulted in the highest possible reading outside. We could compare it directly to the readings inside to gain an accurate ratio of outside light versus light reaching the inside of the tower cab. This also offers a gauge as to the effectiveness of windows and shades.

Immediately upon returning to the tower cab, we collected light levels incident to the displays (i.e., light falling directly onto the displays) by holding the photometer directly in front of the display's face, parallel to the display's tilt. The measurement only took a few seconds, and we always requested permission for momentarily obscuring the display from the controller(s) using that display. It should be noted that in the operational testing conditions, the shades were deployed, partially deployed, or not deployed depending on the controllers' preference.

We then took ambient light measurements in a similar fashion to the outside measurements. First, we took measurements from the center of the tower by holding the photometer 4 ft above the floor in the horizontal plane, per the international lighting standard method of light measurement, and in the four cardinal directions of the vertical plane. We then divided the tower into four equal sections and took readings from the center of each section. We recorded additional readings in front of each window. If the tower was large, we took two readings at each window by dividing the window in half and taking the readings from the center of each (see Figure 1). We then took readings in the horizontal plane, four cardinal directions in the vertical plane, and with the photometer directly facing the sun from the point judged to be the brightest area in the tower. We repeated the procedures at the top of each hour. Depending on the size of the ATCT and the amount of displays present, the measurements sometimes took the full hour to complete. In this case, the last measurement for the hour of data collection also counted as the first measurement of the next hour of data collection.

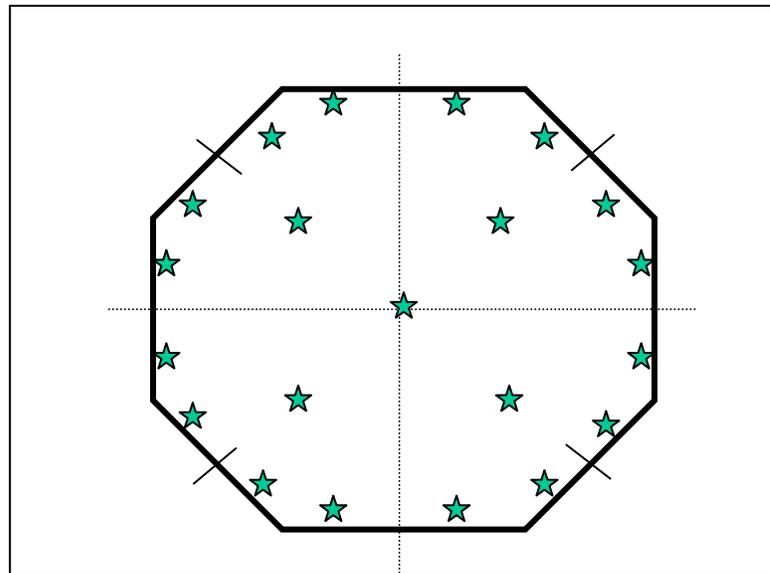


Figure 1. Example of light measurement locations.

In smaller towers, data collection had a tendency to take less than an hour, so we took additional outside measurements at the top of the hour as well as at the end of that set of data collection. In either case, we collected the outside lighting data before and after we collected the data inside the tower cab. This provided a comparison between how much light was present outside and how much light was reaching the inside.

Figure 2 represents a schematic layout of the HEF Tower. Figure 2 illustrates various controller-working positions, displays and their placement, and the points where we recorded the ambient light measurements.

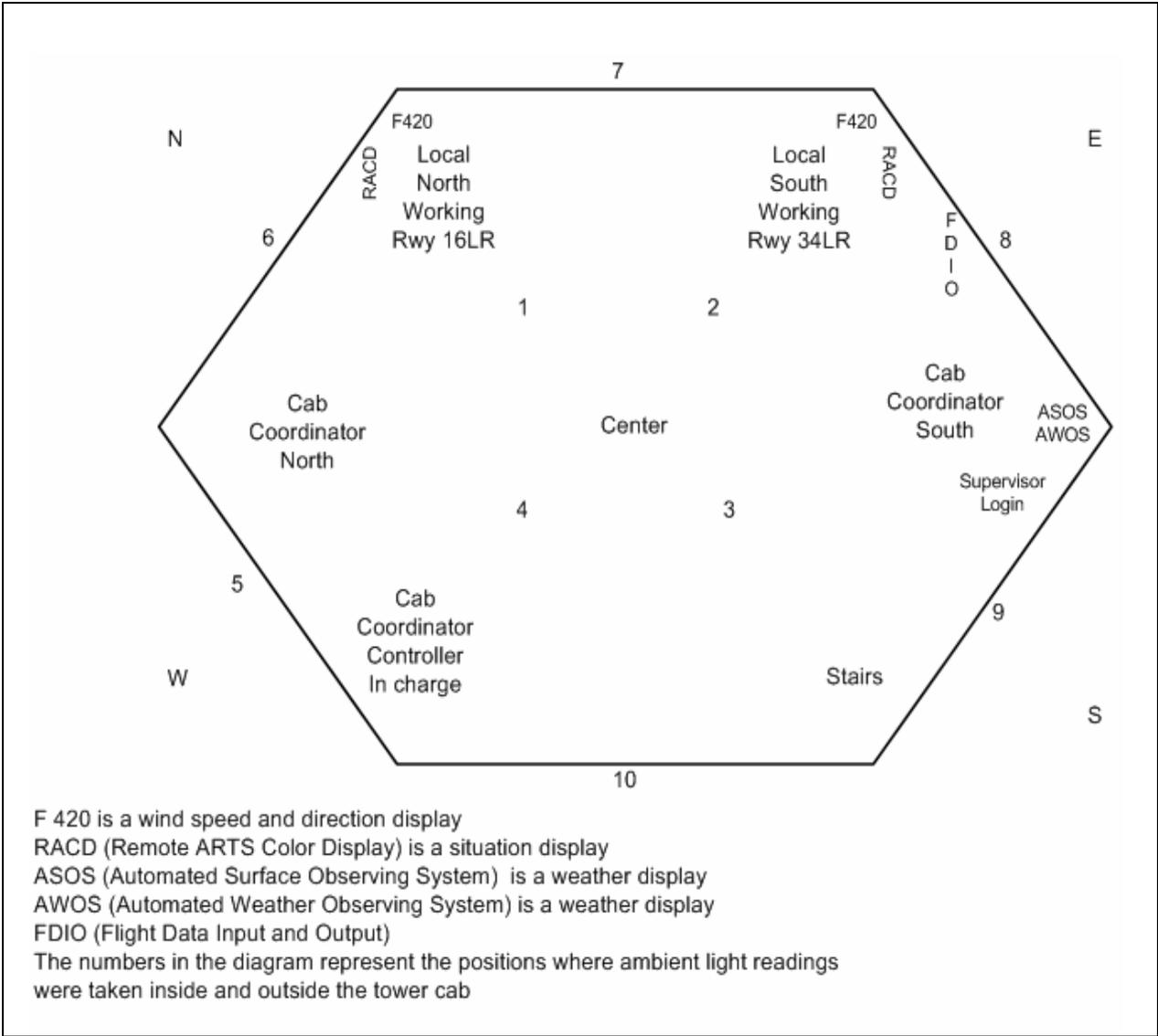


Figure 2. Schematic layout of the Manassas Tower Cab.

2.3.1.2 Engineering Test Condition

There were two times in the day when we temporarily raised any window shades present in order to collect extreme lighting measurements. We coordinated with and received the approval of the tower supervisor and all controllers working their respective positions at that time for the execution, timing, and duration of this engineering test. When lighting and traffic conditions permitted, we performed this test around sunrise and sunset when the sunlight fell below the roof of the tower. The procedures mirrored the operational test, with the exception of the ambient

tower measurements. First, we took lighting measurements outside. We took the inside incident light readings at each display with the shades not deployed. We took the ambient readings (horizontal and vertical, North, South, East, West, and direct) from the brightest area in the tower. We then deployed the shades to the original controller-preferred positions. Finally, we took lighting measurements outside, again, to conclude the data collection for this condition.

### 2.3.2 Viewing Measurement

Mobility is an essential aspect of a controller's job (Bruce, 1996). Controllers sit and stand (usually one or the other) depending on the airport layout, the tower layout, and the customs of the tower staff. Even in towers where it is common practice to sit while controlling traffic, movement about the cab still occurs. The tower displays must, therefore, be designed to support the varying viewing angles and distances. The goal of this portion of the survey was to find the maximum viewing angles and distances controllers need to both read and view the displays. These data will then be integrated into design specifications and testing parameters.

There were two types of viewing angle and distance data collected. The first type was the areas where the controller reads (i.e., identifies) the information on the monitor, and the second type was the locations where the controller views (i.e., detects) the information. For example, a controller may read the data blocks on the D-BRITE for the purpose of separating traffic at a certain distance from a display or simply detect the targets to maintain situational awareness from another distance. These data reflect actual viewing measurement data.

Collecting only these types of data would have limited the specification to just characterizing the current technology with its limitations. Therefore, researchers took measurements from places where the supervisor and controllers indicated that they needed to read and detect the information on the display, even if not currently possible. These needed viewing positions are critical because the controllers' primary focus is out the tower cab windows, and they use the displays within the tower to augment that information. Due to controllers' primary source of information coming from their view out the tower windows, they are often forced to change their physical position within the tower to obtain a better view of the traffic outside and the displays inside. These data reflect needed viewing measurement data. We took the following measurements for each display:

- Tilt angle. The angle (vertical) declined away from or inclined toward the operator.
- Swivel angle. The compass heading (horizontal), towards which the display's face is pointing.
- Display measurements. Length of all four sides and distance from the center of the display to the floor.
- Vertical visual angle. Angle measured from the "normal" visual angle (i.e., perpendicular to the center of the display - 0°) and the vertical angle from the center of the display to the user's line of sight for reading or viewing the display.

It should be noted that with the tools available, it proved faster to physically measure and record the angle from the user's eye to the center of the display and calculate the resulting vertical angle from the display. We used both the standing and sitting eye height for the 5<sup>th</sup> percentile female or the 95<sup>th</sup> percentile male depending on the display's configuration.

- Horizontal visual angle. Angle from the normal visual angle at the center of the display to the users' line of sight for reading or viewing the display. We used both the standing and sitting eye height for the 5<sup>th</sup> percentile female or the 95<sup>th</sup> percentile male.
- Viewing distance. Length from the center of the display to the standing and sitting eye heights of the 5<sup>th</sup> percentile female or the 95<sup>th</sup> percentile male at a reading or viewing location depending on the display's configuration (i.e., hanging, recessed into the console, or on the console).

We used the following 5<sup>th</sup> percentile female and 95<sup>th</sup> percentile male data:

- 5<sup>th</sup> percentile female - standing: 55.72 in., sitting: 26.97 in. (United States Army, 1988). Used if the display was mounted on the ceiling.
- 95<sup>th</sup> percentile male - standing: 68.62 in., sitting: 33.4 in. (United States Army, 1988). Used if the display was mounted on or recessed in the console.

Researchers took these measurements only at times of low operations (in the evening or at night) to prevent any intrusion. We blocked the displays temporarily while we took the measurements. The measurements required two people: one to hold the tool to the center of the display and the other to stand at the appropriate locations to read and record the measurements at the appropriate eye height.

Upon initial entry into the tower cab, the researchers took a period of time to observe and record where the controllers stood and sat to view the different displays. Then, they spent time with the tower supervisor or an assigned controller to go over the positions of the tower, the operating procedures, and the users of the various displays. These personnel provided additional information that included whether the controllers sat or stood (generally both), and whether the controller actually read the information on the particular display or viewed it from a particular position. We then asked the guide to point out the different positions where the controllers needed to view or read the displays, but currently could not. The researchers marked and labeled all the indicated locations with masking tape and began their measurements.

#### 2.3.2.1 Viewing Angle Measurements

To ensure that we measured the extreme angles, we determined appropriate eye height first by the display's configuration. If the display was hanging from the ceiling, we used the eye-height for the 5<sup>th</sup> percentile female; if the display was either mounted on or in the console, we used the eye-height for the 95<sup>th</sup> percentile male. To take the readings, we then read the SUUNTO Tandem Compass/Clinometer to determine the vertical angles from the different locations to the display. We calculated the resulting vertical angle from the display after we collected the data from all of the sites.

We measured the horizontal angles using the carpenter's square and a string because, in the majority of the towers, the equipment and metal consoles threw off the compass. One researcher held the carpenter's square and one end of the string to the center of the display; the other

researcher unwound the string to the different positions. They read the resulting angle directly from the carpenter's square; Figure 3 shows an example of a horizontal angle of approximately 45°. They repeated this method for each position in the tower.

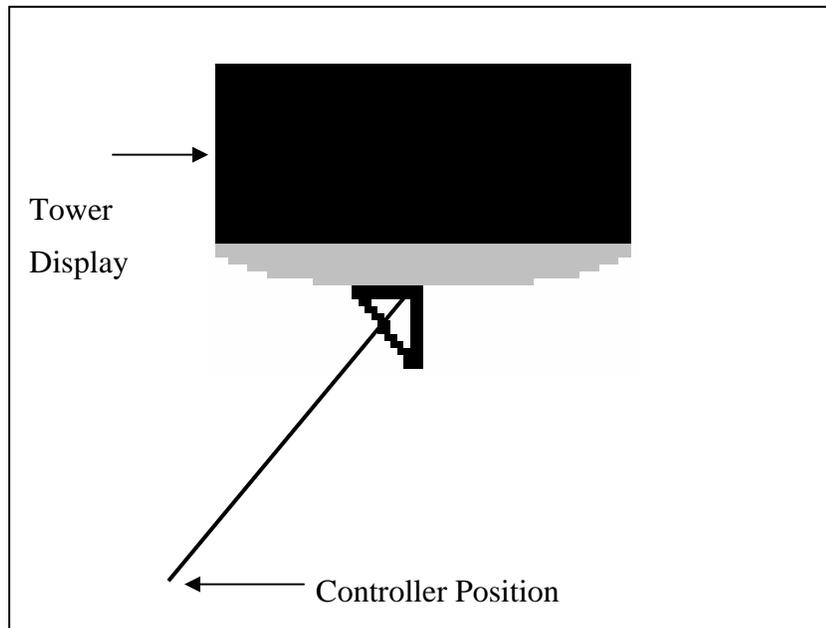


Figure 3. Example using a carpenter's square and string to determine horizontal angle.

### 2.3.2.2 Viewing Distance Measurements

Researchers measured the distances at the same locations measured for the angles. While one researcher held the end of the measuring tape to the center of the display, the other researcher extended the measuring tape to the standing or sitting location at the appropriate eye height.

## 3. RESULTS

### 3.1 Lighting Measurement

The amount of sunlight illuminating a tower during normal daytime operations can approach and surpass the luminance produced by a display. When this occurs, it leaves the information on the display unreadable. By providing the actual lighting conditions present in a variety of tower cab configurations, luminance specifications can be written for the display to reduce or eliminate this loss in visual performance and ensure operational effectiveness.

We took three types of lighting measurements. The first measurement was the amount of light striking the face of the display (called incident illumination). The second measurement was the amount of light present at predetermined locations in the tower cab to give the general ambient illumination (as shown in Figure 1). The third measurement was the amount of light present outside before and after we took the light measurements inside. We took this outdoor measurement to correlate the outside lighting conditions with the indoor lighting conditions. We also recorded meteorological conditions at the time that we took these measurements.

Inside the tower cab, there were two types of conditions present: operational test conditions and engineering test conditions. Operational test conditions represent the controllers' preferred shade position. The shades were either not deployed (i.e., no shades present on the windows), deployed (i.e., shades present on the windows), or partially deployed (i.e., some shades present on some windows, but not all). In the engineering test conditions, controllers did not deploy the shades on the windows.

### 3.1.1 Incident Readings

Researchers collected the amount of light hitting the face of the display by momentarily placing the photometer parallel to the face of the display and recording the results. We collected outside lighting data before and after we collected data inside the tower cab to show the comparison between how much light was present outside the cab and how much light was reaching the inside. We reported incident data adjacent to data that we collected outside from the same cardinal direction to illustrate the difference between the light present outside and the light hitting the display inside.

The researchers found that, generally, the highest incident reading corresponded to the position of the sun in the sky (i.e., the displays facing directly into the sun had the highest readings). For example, when the sun was rising, the displays facing east had the highest incident readings, and when the sun was setting, the displays facing west had the highest readings. Therefore, Figure 4, Figure 5, and Figure 6 show the readings for the corresponding outside lighting measurement with the photometer facing directly into the sun.

We report the highest incident reading at each ATCT first, regardless of the condition (engineering or operational) from which we collected them. Subsequently, we present the highest incident reading recorded for operational and engineering conditions. We expanded upon the three highest readings in each category; these readings can be seen along with the rest of the top 20 in Appendix C, Tables C1 through C3.

#### 3.1.1.1 Highest Incident Readings at ATCTs

Figure 4 displays the highest incident readings along with its corresponding reading outside (photometer on the vertical plane facing directly into the sun) at the end of measurement. The maximum amount of light measured falling directly onto (i.e., incident to) a tower display was 6,040 fc at DFWC. Researchers obtained this reading during sunset between 4:20 p.m. and 4:58 p.m., with 10 miles of visibility and clear sky conditions (an ambient outside illumination of 3,610 fc in the horizontal plane and 9,720 fc facing directly into the sun); the window shades were not deployed. We mounted the display on the counter, facing west (about 270°) and tilted back about 5°, leaving the display facing directly into the setting sun. Please refer to Appendix C, Table C1, for additional information. We recorded this reading during the engineering test condition.

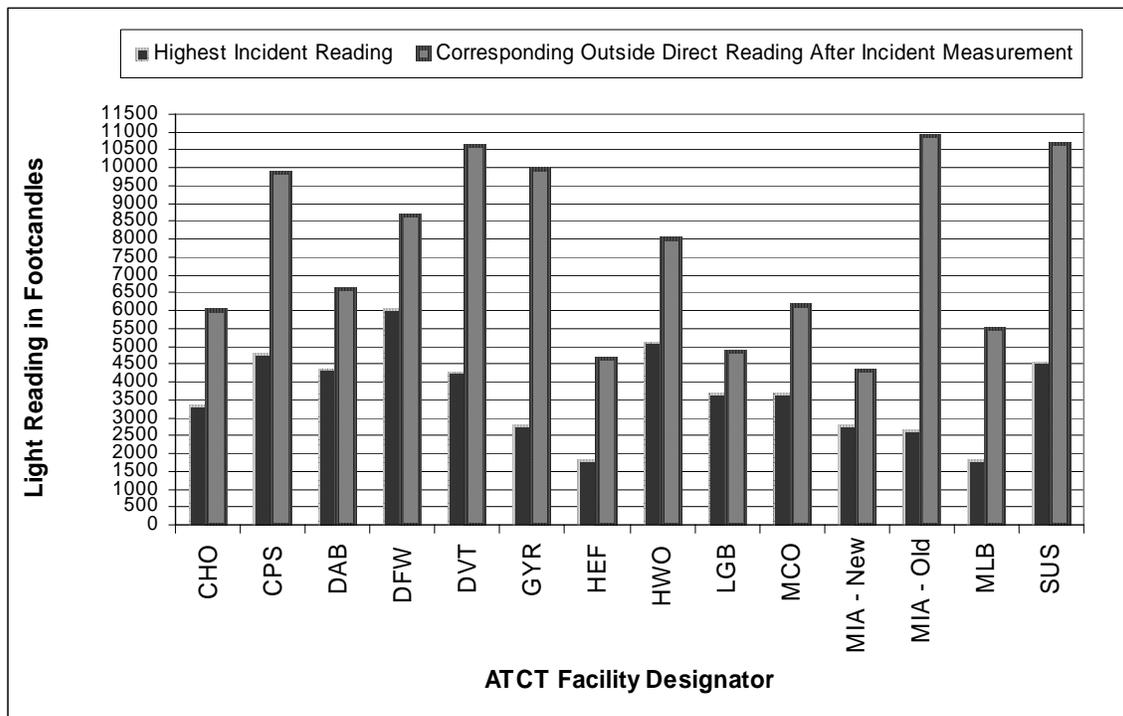


Figure 4. Highest incident readings at ATCTs.

The second highest incident illumination reading was 5,130 fc at HWO Tower. We measured this reading during sunrise between 8:25 a.m. and 9:10 a.m., with 10 miles of visibility and a clear sky condition (an ambient outside illumination of 2,600 fc in the horizontal plane and 7,000 fc in the vertical plane facing east); the window shades were not deployed. We mounted the display on the counter, facing southeast (about 165°) and tilted back about 17°, leaving the display facing almost directly into the rising sun. Although all the shades were not deployed, we took this reading in actual operational conditions (i.e., windows set according to controller preference).

The maximum incident illumination found during a mixed shade position in an operational condition was 2,780 fc at DVT Tower in Phoenix, Arizona. Specifically, a controller deployed the shade on the window facing east into the sun but did not deploy the rest of the shades. We took the measurement during sunrise between 9:00 a.m. and 9:30 a.m., with 10 miles of visibility and clear sky conditions (an ambient outside illumination of 4,670 fc in the horizontal plane and 9,140 fc in the vertical plane facing east). We recessed the display in the console tilted back about 41° and facing south (about 180°).

### 3.1.1.1.1 Highest Incident Readings in Operational Test Condition

Researchers recorded these readings during operational test conditions when controllers chose how to position the shades. Figure 5 displays the highest operational readings recorded during the operational test conditions (to see a corresponding table, refer to Appendix C, Table C3). Under this condition, the highest incident reading was 5,130 fc found at HWO Tower. This reading was also the second highest overall incident reading. We measured the reading during sunrise between 8:25 a.m. and 9:10 a.m., with 10 miles of visibility and clear sky conditions (an ambient outside illumination of 2,600 fc in the horizontal plane and 7,000 fc in the vertical plane facing east); the window shades were not deployed. We mounted the display on the counter facing southeast (about 165°) and tilted back about 17°, leaving the display facing almost directly into the rising sun.

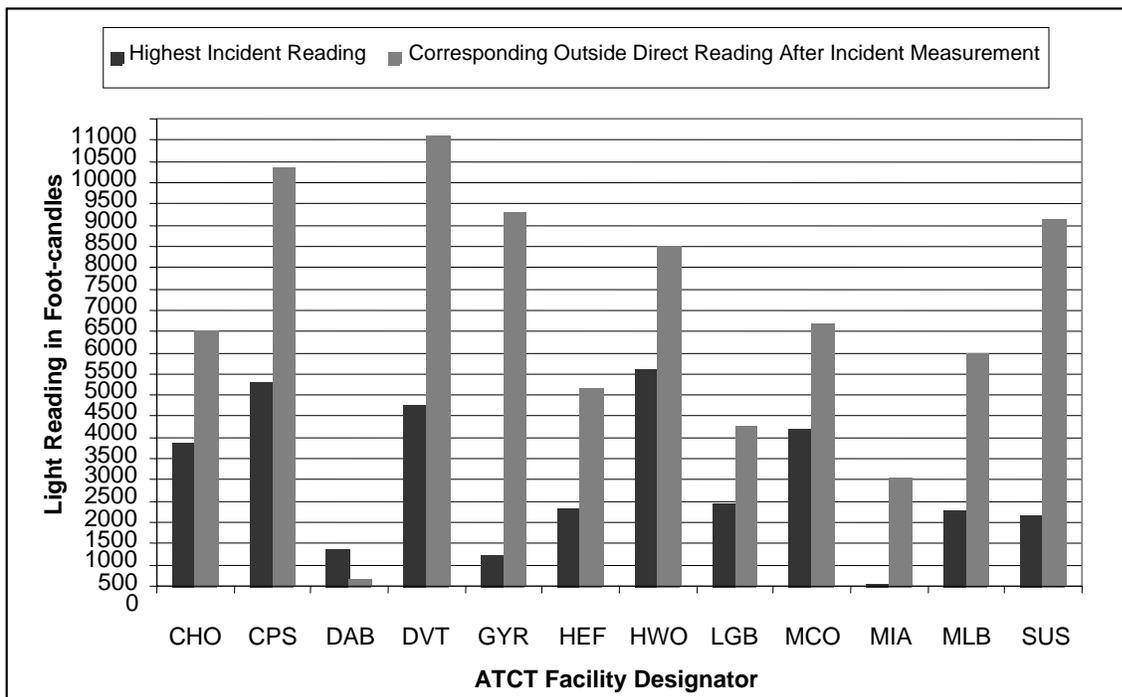


Figure 5. Highest incident readings at ATCTs in operational conditions.

### 3.1.1.1.2 Highest Incident Readings in Engineering Test Condition

Researchers recorded these readings during engineering test conditions when all the window shades were temporarily not deployed. Figure 6 displays the highest incident readings at various ATCTs recorded during the engineering test conditions; a corresponding table is available in Appendix C, Table C2. The highest incident reading was 6,040 fc (at DFWC), which is also the highest overall incident reading (see Section 3.1.1.1). The lowest recorded reading was 376 fc (at MLB Tower).

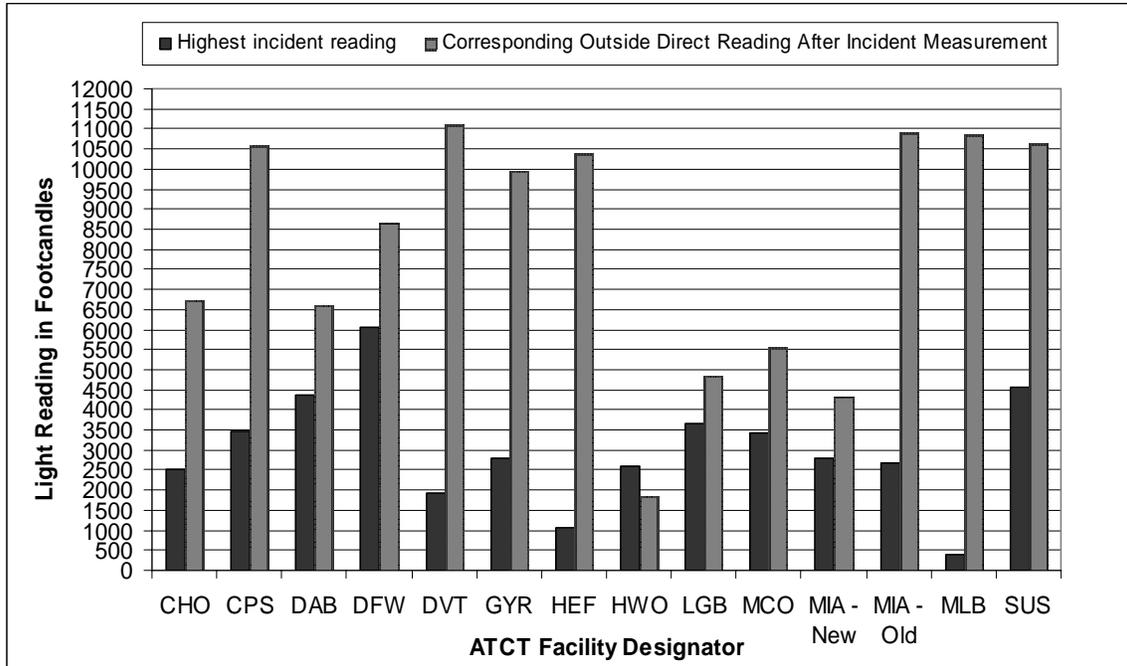


Figure 6. Highest incident readings at ATCTs in engineering conditions.

### 3.1.2 Ambient Readings

We took ambient light levels starting from the center of the tower and working outward in the predetermined pattern as Figure 7 shows. We then took readings in the horizontal plane, four cardinal directions in the vertical plane, and with the photometer directly facing the sun from the point judged to be the brightest area in the tower. The researchers then immediately returned outside to collect the ambient light readings in the same fashion as the top of the hour. Again, we collected outside lighting data before and after we collected data inside the tower cab to show the comparison between how much light was present outside the cab and how much light was reaching the inside. We reported ambient data along side data that we collected outside from the same cardinal direction to illustrate the difference between the light present outside and the light present inside. For example, the ambient readings in the horizontal plane inside have the corresponding horizontal readings outside reported, and the ambient readings in the vertical plane facing directly into the sun have the corresponding direct readings outside reported.

We divided the results into two sections. The first section reports the highest ambient readings in the horizontal plane recorded at each ATCT, regardless of the test condition in which we collected them. The second section reports the highest ambient readings at each ATCT in operational and engineering conditions. We took these readings with the photometer facing directly into the sun.

### 3.1.2.1 Highest Horizontal Ambient Reading at ATCTs

The brightest area in the horizontal plane found in a tower was 5,340 fc at DFWC. Researchers obtained this reading at 2:50 p.m., with 10 miles of visibility and a few clouds at 3,000 ft (an ambient outside illumination taken directly after the inside ambient readings of 7,440 fc in the horizontal plane) and with the window shades not deployed on the windows. We took the reading during an engineering test condition at the southwest side of the tower, which corresponds to the outside location. Please refer to Appendix C, Table C5, for additional information.

The next brightest reading in the horizontal plane was 4,910 fc found at CPS Tower. We recorded this reading at 1:20 p.m., with 10 miles of visibility and a clear sky condition (an ambient outside illumination taken directly after the inside ambient readings of 5,110 fc in the horizontal plane) and with the window shades deployed on the windows. We took this reading from a strip of bright light that stretched from one side of the tower to the other. It originated from the space between two shades and traveled across the tower as the sun traveled across the sky. We took this particular reading at the southeast side of the tower, which corresponds to the outside location. These bright strips of light were common in almost all of the towers and often fell across the displays making them very difficult, if not impossible, to read. We took the reading during an operational test condition.

The lowest recorded reading was 2,860 fc at DAB Tower. Figure 7 shows the highest direct ambient readings recorded at various ATCTs. Please refer to Appendix C, Table C6, for additional information.

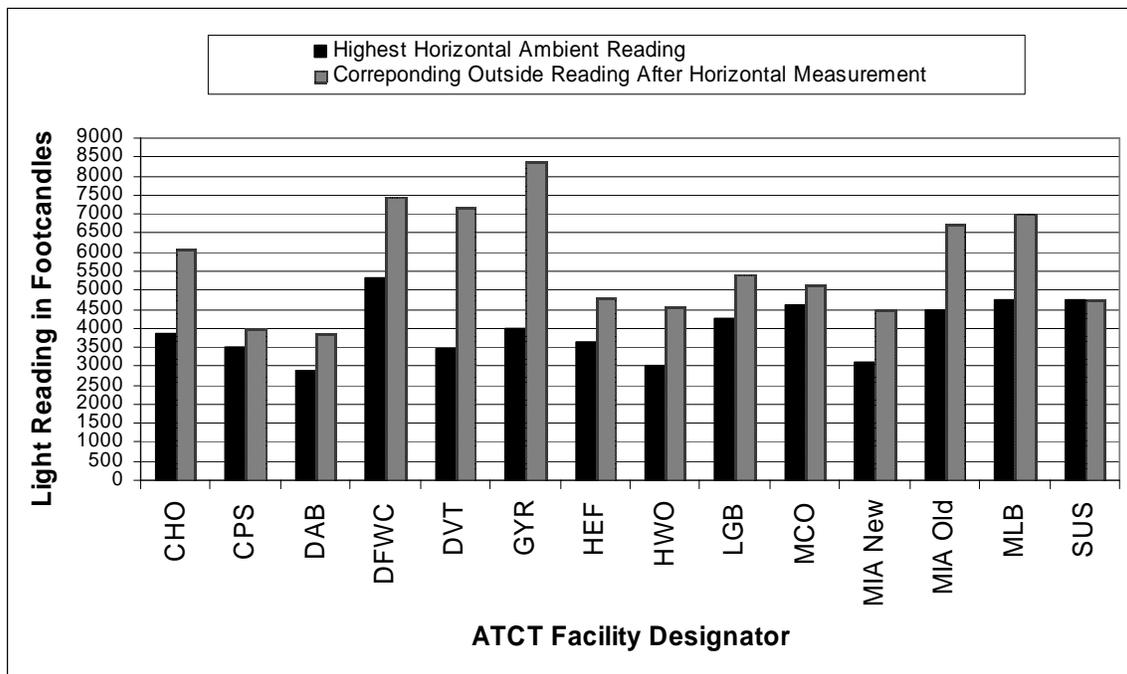


Figure 7. Highest horizontal ambient readings at ATCTs.

### 3.1.2.1.1 Highest Horizontal Ambient Readings in Operational Condition

The brightest area in the horizontal plane found during an operational test condition was 4,910 fc at CPS Tower.

The next brightest reading during an operational condition was 4,760 fc at MLB Tower in Melbourne, FL. We recorded this reading at 12:55 p.m., with 10 miles of visibility and a clear sky condition (an ambient outside illumination taken directly after the inside ambient readings of 7,000 fc in the horizontal plane) and with the shades deployed on the windows. We also took this reading from a strip of bright light that stretched from one side of the tower to the other.

The lowest recorded reading was 40 fc at DAB Tower. Figure 8 shows the highest direct ambient readings recorded at various ATCTs. Please refer to Appendix C, Table C6, for additional information.

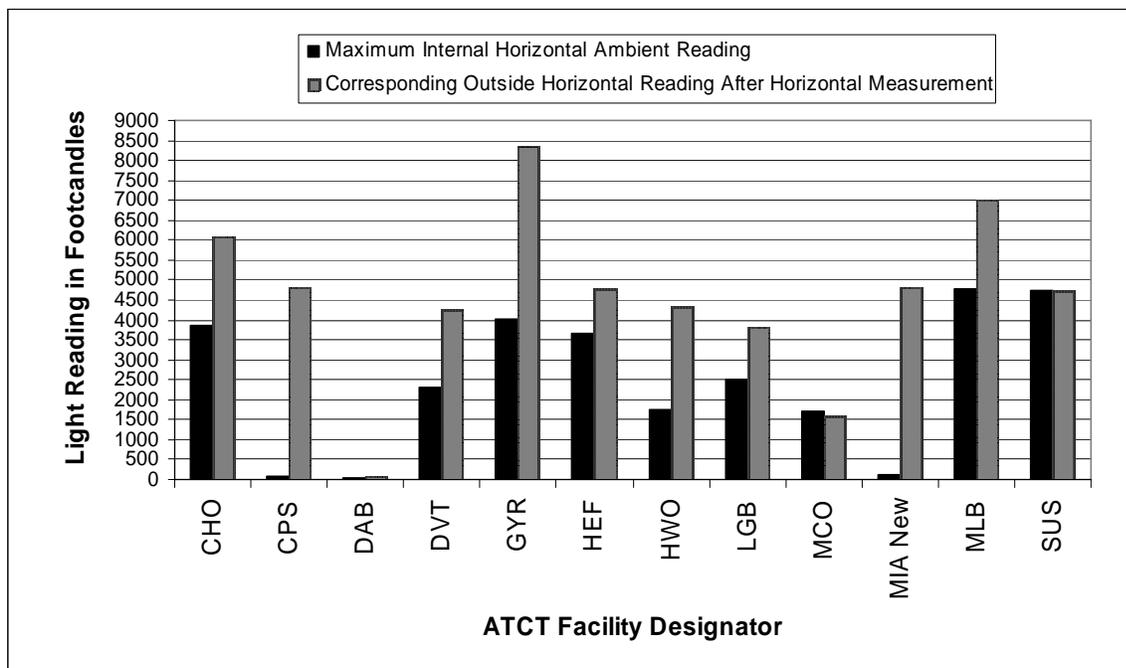


Figure 8. Highest horizontal ambient readings at ATCTs in operational conditions.

### 3.1.2.1.2 Highest Horizontal Ambient Readings in Engineering Condition

Researchers recorded the brightest reading in the horizontal plane in the engineering test conditions at DFWC (see Figure 9). The recorded reading was 5,340 fc; the shades were not deployed on the window. The lowest recorded reading was 1,077 fc at MLB Tower. Please refer to Appendix C, Table C7, for additional information.

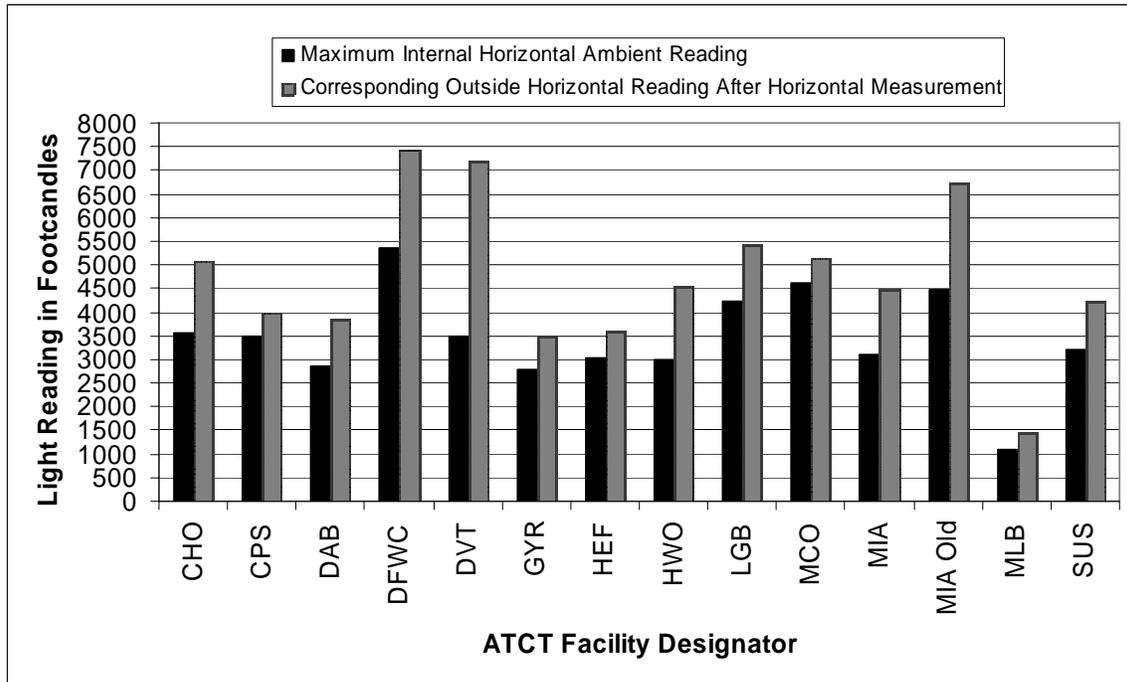


Figure 9. Highest horizontal ambient readings at ATCTs in engineering conditions.

### 3.1.2.2 Highest Direct Ambient Readings at ATCTs

The brightest area in the vertical plane with the photometer facing directly into the sun was 9,160 fc at MCO Tower in Orlando, FL. Researchers recorded this reading at 10:15 a.m., with 10 miles of visibility and a clear sky condition (an ambient outside illumination taken directly after the inside ambient readings of 10,850 fc in the vertical plane, facing the sun); the shades were not deployed at the windows. We took this reading during an engineering test condition at the east side of the tower, which corresponded to the outside readings. Please refer to Appendix C, Table C8, for additional information.

The second brightest area found was 8,730 fc at CPS Tower. We obtained this reading at 1:20 p.m., with 10 miles of visibility and clear sky conditions (an ambient outside illumination taken directly after the inside ambient readings of 10,920 fc in the vertical plane, facing the sun) and with the window shades deployed at the windows. We took this reading from a strip of bright light that stretched from one side of the tower to the other. We took the reading at the south/southeast side of the tower, corresponding to the location of the outside lighting measurements during an operational test condition.

The lowest recorded reading was 6,360 fc at HWO Tower. Figure 10 shows the highest direct ambient readings recorded at various ATCTs. Please refer to Appendix C, Table C8, for additional information.

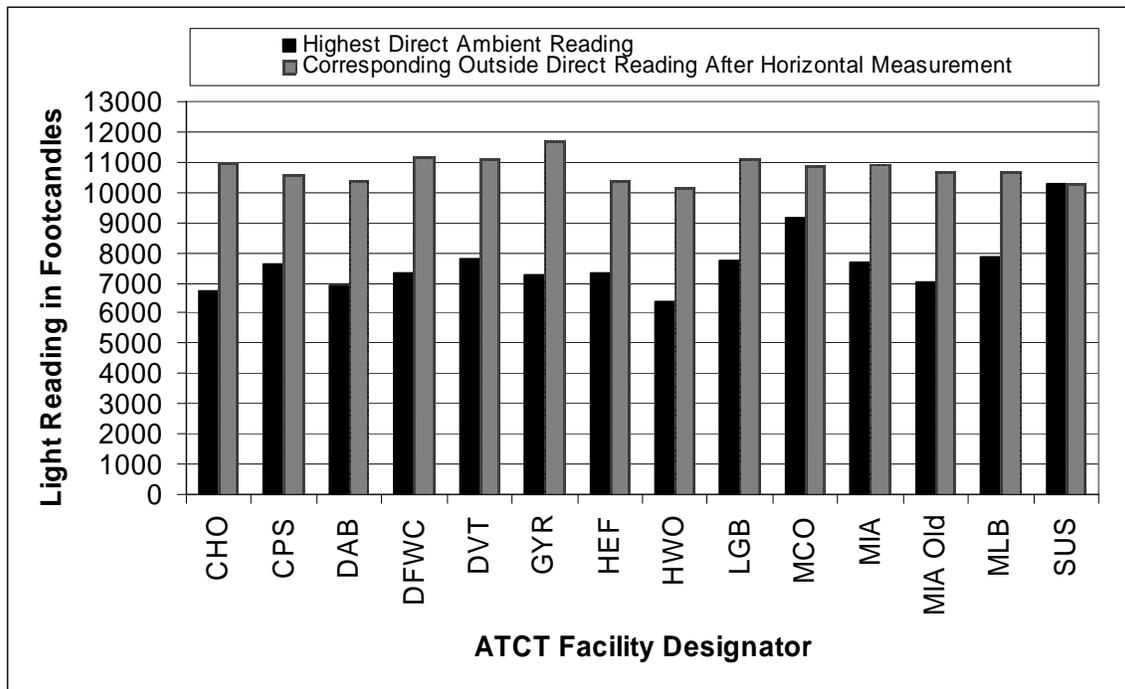


Figure 10. Highest direct ambient readings at ATCTs.

### 3.1.2.2.1 Highest Direct Ambient Readings in Operational Condition

The brightest area in the vertical plane with the photometer facing directly into the sun during an operational condition was 8,730 fc at CPS Tower. The second brightest area found in this condition was 7,400 fc at MLB Tower. We obtained this reading at 12:55 p.m., with 10 miles of visibility and a clear sky condition (an ambient outside illumination taken directly after the inside ambient readings of 11,000 fc in the vertical plane, facing the sun) and with the window shades covering the windows (see Figure 11). We took this reading from a strip of bright light that stretched from one side of the tower to the other at the south side of the tower, corresponding to the location of the outside lighting measurements.

The lowest recorded reading was 5,600 fc at DVT Tower. Figure 11 shows the highest direct ambient readings recorded at various ATCTs. Please refer to Appendix C, Table C9, for additional information.

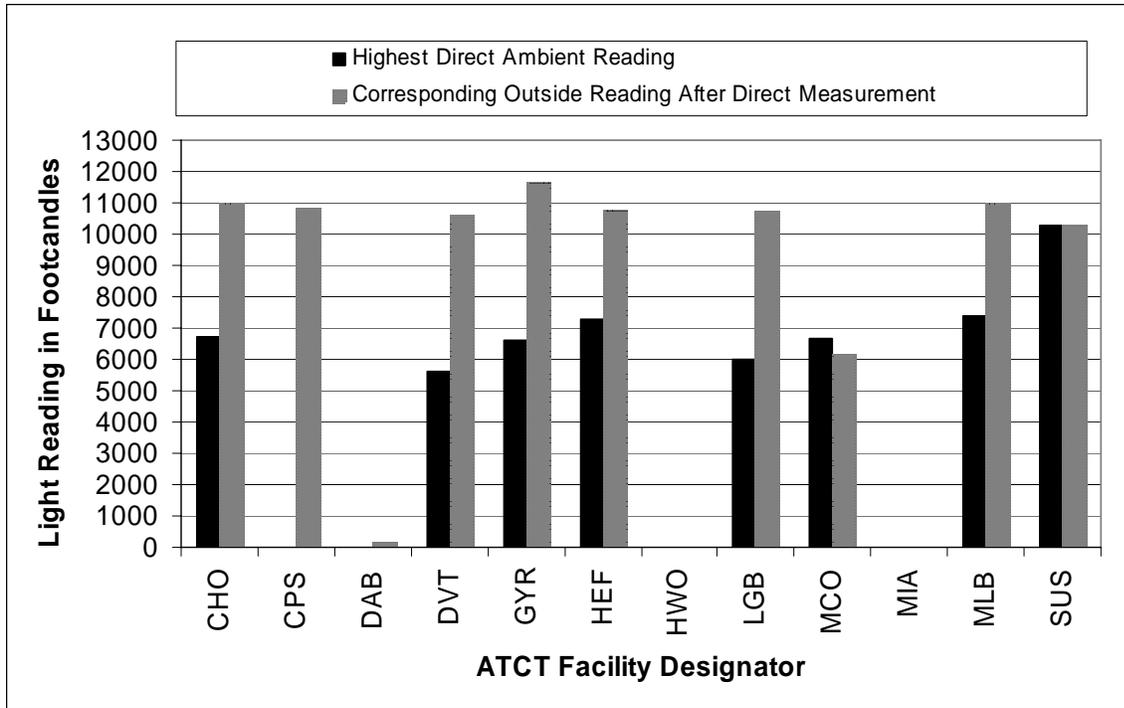


Figure 11. Highest direct ambient readings at ATCTs in operational conditions.

### 3.1.2.2.2 Highest Direct Ambient Readings in Engineering Condition

The brightest area in the engineering condition was 9,160 fc at MCO Tower. Researchers obtained this reading at 10:15 a.m., with 10 miles of visibility and clear sky conditions (an ambient outside illumination taken directly after the inside ambient readings of 10,850 fc in the vertical plane, facing the sun); the window shades were not deployed at the windows. We took this reading at the east side of the tower, which corresponded to the reading taken outside.

The next brightest reading taken was 7,880 fc at MLB Tower. We recorded this reading at 10:25 a.m., with 10 miles of visibility and clear sky conditions (an ambient outside illumination taken directly after the inside ambient readings of 10,720 fc in the vertical plane); the window shades were not deployed at the windows. We took this reading at the southeast side of the tower, which corresponded to the reading taken outside.

The lowest recorded reading was 6,570 fc at CHO Tower. Figure 12 shows the highest direct ambient readings recorded at various ATCTs. Please refer to Appendix C, Table C9, for additional information.

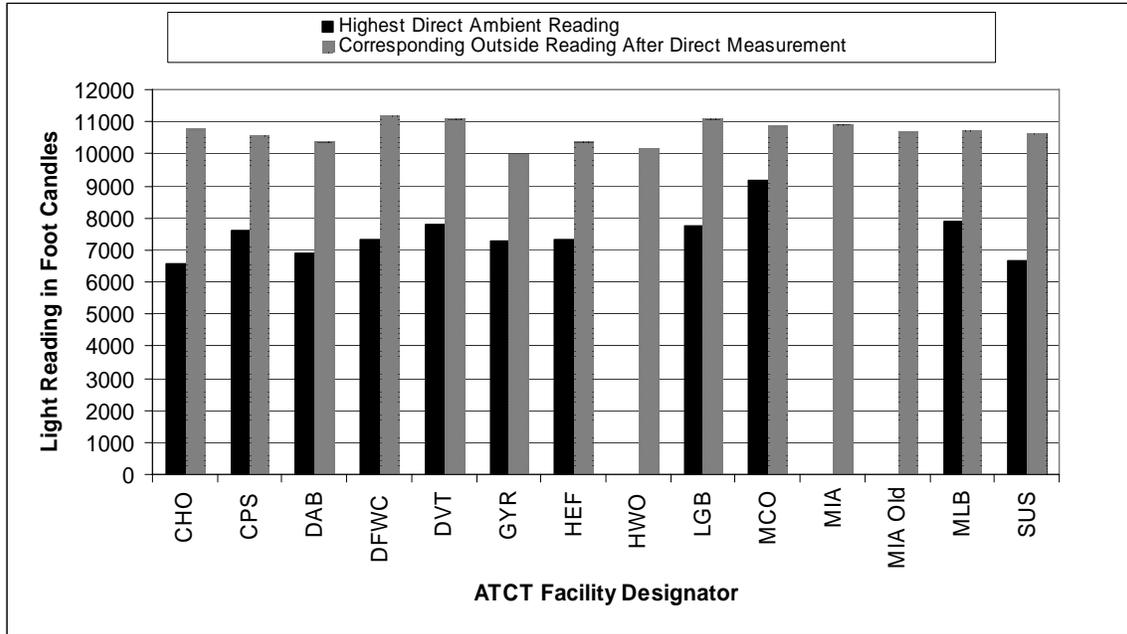


Figure 12. Highest direct ambient readings at ATCTs in engineering conditions.

### 3.2 Viewing Angle and Distance

The viewing angle and distance results are divided into categories and subcategories based on recommendations found in the Terminal Display Integration Plan (FAA, 2003). It specifies five high-level categories: Tactical Displays, Information Displays, Miscellaneous and Administrative Displays, Maintenance Displays, and Monitor and Control Displays. According to the Terminal Display Integration Plan, “tactical display systems are those used in direct connection with any controller interface with an aircraft or vehicle on the airport movement area, runway, airborne in the airport traffic area or terminal radar coverage area as necessary” (FAA, 2003, p. 20). We have broken down the tactical displays into four subcategories: primary situation displays, airport surface management displays, communication displays, and flight data management displays. Information displays pull information from a vast number of sources and consist of two subcategories: weather displays and traffic flow management displays. Miscellaneous and administrative displays fill a variety of purposes and consist of all of the displays that do not fit into any of the other categories. Examples of these displays range from controller’s log and duty hour tracker to security displays. Airway Facilities personnel primarily use maintenance displays for the monitoring and maintenance of equipment. They use these displays mainly in the maintenance rooms and are therefore not covered in this report. The monitor and control displays provide the controller the means to monitor the status of and control airfield equipment like the Navigational Aids or Visual Aids.

We break the categories further into primary, secondary, and auxiliary displays. We describe the primary displays as those displays that controllers use to control traffic and to convey information to pilots. Information content on a primary display is critical in terms of its information content and timing. The D-BRITE and Wind Direction and Speed Display (F-420) are both considered primary displays even though they fit into different categories. The secondary displays contain

important information used primarily to increase situation awareness but not to control traffic. Auxiliary displays contain information that is not time critical and controllers and/or supervisors use it on an as needed basis.

Another consideration in categorizing the systems includes the personnel who use them. For example, a D-BRITE is a primary display for the Local Controller but an auxiliary display for the Supervisor. Therefore, we categorize the D-BRITE as a Tactical, Primary Situation Display that has distance and angle ranges for its primary users (i.e., Local Controllers), secondary users (i.e., Ground Controllers), and auxiliary users (i.e., Supervisors).

We also report the results according to whether the users read or viewed the display from a particular location. We define reading as being able to decipher (i.e., identify) the alphanumeric characters on the screen, and we define viewing as being able to detect changes in the information or perceive objects in relation to one another. If required, the data also show when there were locations in addition to the current locations from which the controllers needed to read or view the displays; we referred to these as “needed” in the appropriate sections. We excluded any data outside of two standard deviations from the results, with the exception of Primary Situation Displays.

### 3.2.1 Tactical Displays

#### 3.2.1.1 Primary Situation Displays

The primary situation displays provide an automated view of controller critical information. Currently, the primary situation displays consist of D-BRITES, Remote Automated Radar Terminal System Color Displays, and Standard Terminal Automation Replacement System Tower Displays. Although all the other results report only the data falling inside two standard deviations, this particular category contained a very large amount of data ( $n = 119$ ) that formed a tight distribution; therefore, we used three standard deviations to exclude the outliers.

Local Controllers and the combined position, which includes the duties of both the Local and Ground Controllers, were the tactical primary situation displays’ *primary* users (controllers identified all locations as either read or view and did not identify any as view under these conditions). The *secondary* users consisted mainly of the Ground Controllers and Cab Coordinator. The *auxiliary* users consisted mainly of the Supervisors, Flight Data/Clearance Delivery, and the Traffic Management Coordinators. Table 1 displays the recorded ranges.

Table 1. Viewing Measurement Data for Tactical Primary Situation Displays by Type of Users

Type of Display/ Type of User	Reading				Viewing		
	Actual Reading Distance (feet)	Needed Reading Distance (feet)	Horizontal Viewing Angle (degrees)	Vertical Viewing Angle (degrees)	Viewing Distance (feet)	Horizontal Viewing Angle (degrees)	Vertical Viewing Angle (degrees)
<i>Primary</i>	2.5 to 9.0	9.2 to 15.9	0° to 58°	-17° to 43°	10 to 12.8	4° to 46°	3° to 6°
<i>Secondary</i>	3.3 to 9.0	9.4 to 12.5	2° to 69°	-21° to 52°	N/A	N/A	N/A
<i>Auxiliary</i>	4.3 to 8.0	10.0 to 16.7	10° to 63°	-2° to 8.5°	9.3 to 16.7	5° to 55°	-18° to 23°

### 3.2.1.2 Surface Surveillance Displays

The surface surveillance displays provide an automated view of the airport movement area. Currently, they consist mainly of the family of Airport Surface Detection Equipment displays. Ground Controllers are the primary users; Local Controllers and Ground Assistants are the secondary users; and Supervisors and Traffic Management Coordinators are the auxiliary users. Table 2 displays the recorded ranges.

Table 2. Viewing Measurement Data for Tactical Surface Surveillance Displays by Type of Users

Type of Display/ Type of User	Reading				Viewing		
	Actual Reading Distance (feet)	Needed Reading Distance (feet)	Horizontal Viewing Angle (degrees)	Vertical Viewing Angle (degrees)	Viewing Distance (feet)	Horizontal Viewing Angle (degrees)	Vertical Viewing Angle (degrees)
<i>Primary</i>	3.9 to 9.4	<i>N/A</i>	10.5° to 57°	0° to 41°	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>
<i>Secondary</i>	2.6 to 10.7	<i>N/A</i>	19° to 50°	48° to 59°	3.3 to 5.5	0° to 30°	-48° to -13°
<i>Auxiliary</i>	6.3 to 14.6	<i>N/A</i>	15° to 65°	-38° to 5°	6.2 to 16.7	15° to 26°	0° to 16°

### 3.2.1.3 Communications Display Systems

The communication display systems provide the controllers with an automated interface to the communication switches. They allow the controllers to communicate from ground to air (and vice versa), from ground to ground, and within and between facilities. They currently consist mainly of Enhanced Terminal Voice Switch, Rapid Deployment Voice Switch, and Small Tower Voice Switch.

The tactical-communication display systems' primary users include all the positions in the tower cab. Because these systems must be physically interacted with on a regular basis in order to be utilized, they were within an arms length. Therefore, we collected only two data points in this category. Table 3 displays the recorded ranges.

### 3.2.1.4 Flight Data Management Displays

The flight data management displays are personal computer-based tactical information processors. They currently consist mainly of Flight Data Input Output and Tower Data Link Service.

The primary users of the tactical flight-data management displays consisted exclusively of the flight data and clearance positions. Because controllers do not use these displays to control traffic, they are classified as auxiliary; Table 3 provides the ranges.

Table 3. Viewing Measurement Data for Tactical Communications and Flight Data Management Displays by Type of Users

Type of Display/ Type of User	Reading				Viewing		
	Actual Reading Distance (feet)	Needed Reading Distance (feet)	Horizontal Viewing Angle (degrees)	Vertical Viewing Angle (degrees)	Viewing Distance (Feet)	Horizontal Viewing Angle (degrees)	Vertical Viewing Angle (degrees)
<i>Primary</i>	3.6 to 3.9	N/A	0°	-5° to 13°	N/A	N/A	N/A
<b>Flight Data Management Display</b>							
<i>Auxiliary</i>	4.6 to 10.5	N/A	21° to 65°	-11° to 20.5°	N/A	N/A	N/A

### 3.2.2 Information Displays

The information displays pull information from a vast number of sources to provide non-tactical information to the controllers. Examples of information displays are Systems Atlanta, Informational Display System (IDS), and ASOS Controllers Equipment-Information Display System (ACE-IDS), which contains two subcategories: weather displays and traffic flow management displays. We collected data for the information displays (IDS family) and weather displays.

#### 3.2.2.1 Auxiliary Users of Information Displays

The information displays' users consisted of all positions in the tower. The displays in this category are Systems Atlanta, IDS, ACE-IDS, and so on. We classify these as auxiliary because controllers do not use these displays to control traffic. Table 4 displays the recorded ranges.

Table 4. Viewing Measurement Data for Information Displays by Type of Users

Type of Display/ Type of User	Reading				Viewing		
	Actual Reading Distance (feet)	Needed Reading Distance (feet)	Horizontal Viewing Angle (degrees)	Vertical Viewing Angle (degrees)	Viewing Distance (Feet)	Horizontal Viewing Angle (degrees)	Vertical Viewing Angle (degrees)
<b>Information Display</b>							
<i>Auxiliary</i>	2.5 to 11.6	N/A	0° to 47°	-43.5° to 45°	N/A	N/A	N/A

#### 3.2.2.2 Weather Displays

The weather display category consists of a multitude of weather systems that provide weather information to support the controller's air traffic mission. They range from F-420s and Low Level Wind Shear Alert System (LLWAS) alerts to Integrated Terminal Weather Center and ASOS displays.

### 3.2.2.2.1 Primary Users of Weather Displays

The information-weather displays' primary users consisted of Local and Ground Controllers. The weather displays in this category are the F-420 and LLWAS ribbon displays. Table 5 displays the recorded ranges.

Table 5. Viewing Measurement Data for Weather Displays by Type of Users

Type of Display/ Type of User	Reading				Viewing		
	Actual Reading Distance (feet)	Needed Reading Distance (feet)	Horizontal Viewing Angle (degrees)	Vertical Viewing Angle (degrees)	Viewing Distance (Feet)	Horizontal Viewing Angle (degrees)	Vertical Viewing Angle (degrees)
<b>Weather Displays</b>							
<i>Primary</i>	3.0 to 8.0	N/A	0° to 59°	-45° to 27°	3.9 to 5.8	48° to 50°	-37° to -18°
<i>Secondary</i>	4.3 to 9.0	N/A	0° to 40°	-36.5° to -5°	N/A	N/A	N/A
<i>Auxiliary</i>	2.6 to 13.3	N/A	0° to 70°	-46° to 27°	12.8	0°	6°

### 3.2.2.2.2 Secondary Users of Weather Displays

The information-weather displays' secondary users consisted of Cab Coordinators using F-420s or Local and Ground Controllers using displays other than the displays at their workstation. For example, if Local Controllers are looking for an aircraft out the window on the other side of the tower, they will look at an F-420 in their field of vision or scan path, instead of turning around to look at the one in their workstation. The weather displays in this category are the F-420 and LLWAS ribbon displays. Table 5 displays the recorded ranges.

### 3.2.2.2.3 Auxiliary Users of Weather Displays

The information-weather displays' auxiliary users consisted of Supervisors using F-420s or Local and Ground Controllers using auxiliary weather displays. The weather displays in this category are the ASOS, Automated Weather Observing System, and National Weather Display. Table 5 displays the recorded ranges.

### 3.2.3 Miscellaneous and Administrative Displays

The miscellaneous and administrative displays fill a variety of purposes and consist of all of the displays that do not fit into any of the other categories. Examples of these displays range from controller's log and duty hour tracker to security displays. Auxiliary users consisted mainly of the supervisors, and controllers. Table 6 displays the recorded ranges.

Table 6. Viewing Measurement Data for Miscellaneous and Administrative Displays by Type of Users

Type of Display/ Type of User	Reading				Viewing		
	Actual Reading Distance (feet)	Needed Reading Distance (feet)	Horizontal Viewing Angle (degrees)	Vertical Viewing Angle (degrees)	Viewing Distance (Feet)	Horizontal Viewing Angle (degrees)	Vertical Viewing Angle (degrees)
<b>Miscellaneous and Administrative Display</b>							
<i>Auxiliary</i>	2.1 to 3.1	N/A	0° to 12°	7° to 35°	N/A	N/A	N/A

## 4. DISCUSSION

### 4.1 Lighting Level

In this study, researchers collected data at a given site over multiple days, which allowed them to generally collect data under clear cloud conditions with 10+ miles of visibility and yielded more operationally accurate incident light readings than previous studies.

We collected light levels to quantify the extreme amount of light falling onto displays in an ATCT. In both the engineering and operational conditions, the incident light reached levels that resulted in items on a display or the display in its entirety being unreadable. Such was the case for many of the touch-screen communication displays observed in this study.

In conditions with high ambient readings outside, shade deployment was the single highest variable that effected light levels. Controllers influenced the ambient light level by deploying the ATCT shades. However, the controllers indicated that the shades made it more difficult to detect aircraft, especially aircraft at a distance. Therefore, controllers delayed deploying them; they deployed the shades only when absolutely necessary. Depending on the quality and cleanliness of the shades, the controllers also indicated that the shades could distort the image of aircraft, or that a spot on the shades could be misinterpreted as the aircraft for which they were searching. There were many times when controllers were forced to use a shade in order to read the information on their displays.

On the other hand, some controllers preferred to deploy shades based on a daylight usage pattern. As soon as the sun started to peak over the horizon, they deployed all of the shades and they remained present until sunset. These controllers specified that the benefits of the shades outweighed their detractions. The shades allowed them to read the items on the display with more ease, and controllers reported fewer headaches due to eyestrain. The shades also allowed better control of the climate, with noticeable changes in temperature varying with the position of the shades. In either case, shade usage should not determine display quality.

Even in the towers that implemented shades on a continuous basis, a persistent problem occurred with a beam of light that came from the space between the shades or a shade and the window's edge. This space resulted in a strip of light that fell across the entire tower cab, increasing in width and moving parallel with the sun. The strip of light was often the brightest spot in the cab and fell across various displays making items on those displays difficult, if not impossible, to read (see Figure 13). This beam of light was most problematic on the displays opposite the entry point of light. The unobstructed beam of light would travel across the face of the displays, as the sun moved across the horizon, making those displays partially or entirely unreadable.

As depicted in the results section, the highest incident light measurements corresponded to the sun's position (i.e., time of day) and the equipment that was facing the direction of the sun. Sunrise and sunset always produced the highest incident ratings because the sun's rays, originating from lower on the horizon and unobstructed by the roof, directly entered the cab.



Figure 13. Beam of light caused by space between shades.

During sunrise, the displays facing east produced the highest incident readings; conversely, the displays facing west had the highest readings during sunset. The lower incident light readings usually resulted during midday because the sun was positioned above the tower allowing the roof to shade the displays inside. Local and Ground Controllers work close to the windows because that is where their primary source of information is coming from, so equipment/displays also have a tendency to be close to the windows. The only tower in which this was not the case was MIA New. The MIA New Tower has the operator's workstations placed farther away from the windows than other towers to account for surface traffic viewing problems discovered after completing construction. This also partially accounts for the lower incident light readings in Miami, because the displays farthest from the windows also had a tendency to have lower incident readings.

In addition to using the tower shades to combat high incident and ambient light levels and the slow moving beam of light that traveled across the tower, we observed controllers at virtually every tower implementing a range of additional ad hoc measures to view the various tower displays. These measures ranged from makeshift barriers using other pieces of equipment to soda can cardboard barriers, and even to draping a jacket over an auxiliary Commercial-off-the-Shelf display, such as a crew log, to make it readable. Even in towers with the newest adjustable displays and mounting methods, some controllers were forced to move their own tactical primary situation display to a sub-optimal position to remove it from direct sunlight, which highlights the need for display design improvement. Other improvisations included utilizing alternative supplementary sources of information they would not normally use to substitute for the information provided by the obscured display.

Due to variability among the controllers with respect to shade use and various other reasons cited previously, we strongly recommended that designers use lighting levels corresponding to the engineering test condition (6,040 fc) to develop a proposed Human Factors ATCT Display Specification.

#### 4.2 Viewing Angle and Distance

The most significant determining factor in the magnitude of viewing angles and distances turned out to be tower layout and display placement. In general, the displays were placed near the primary users of a particular display. However, there were many instances where displays were simply placed where there was room to fit them, regardless of who needed to use them. Instead of being optimized, equipment was placed where space was available; and one piece of equipment on top of another was not uncommon.

Most often, researchers took measurements at various places for one operator, due to the different pieces of information a controller must gather and assimilate by moving around to different locations within the tower. These locations consisted of the operators' normal working areas and places in the tower consistently visited by the operator. The common tasks of flight strip retrieval and visually tracking aircraft are examples. Both tasks occur on a regular basis and often require movement of the controller from the workstation to another location in the tower. The controllers still need to read or view the information on their displays when visiting these different locations. Therefore, we took measurements of viewing distances and angles from those locations to their displays. In instances such as these, we would ask the controller if they read the information off of the display from those locations or if they viewed the display to obtain general information such as the relative position of aircraft. The results indicated, as expected, that the controllers' viewing distances were generally greater than their reading distances.

To account for differences in technology, we also asked the controllers to identify working locations where they needed to read or view the displays but were currently unable. These results also indicated that the controllers needed to read and view the displays from places farther than currently available. This approach allowed us to collect and record data that are more representative of operational conditions and needs than previous studies. The large resulting angles and distances are an outcome of both the qualities intrinsic to the design of the displays (character height, contrast ratio, etc.) and to the display placement.

In this study, we experienced that larger towers often have shorter viewing distances and smaller viewing angles; perhaps because they are equipped with more displays. Having more displays may compensate for the sub-optimal display placement, configuration, and layout that many of the smaller towers endured. For instance, smaller towers regularly produced greater reading/viewing distances and angles than the larger towers. These results may have occurred because the smaller towers had a tendency to have fewer displays and equipment with which to work, forcing multiple controllers to share one sub-optimally placed display. The smaller towers also had a tendency to have less sophisticated ceiling mounting techniques (i.e., stationary pole mounting or tethered track mounting versus an articulating arm). Therefore, improving both the design of the display itself and the layout of the tower will result in a design that will ultimately increase human performance.

All tower displays are not equally critical and one should not expect them to meet the same requirements. For example, designers should create the tactical primary situation displays with the most stringent requirements due to the number of users and the critical nature of the information presented. They should determine display specifications by the data collected from the primary users of the displays and use the secondary and auxiliary data to specify procedures for display placement, configuration, and layout.

Due to the limitations of the human visual system, only a person with 20/20 vision can discern a character or object on a display up to a defined distance. For example, as the size of a character on a display increases or decreases, so does the maximum distance from which a controller can discern it. From a design perspective this means that, given the specified characters or information that controllers can discern under the maximum operational lighting conditions and from the maximum operational viewing angles, they can only optimize the technology up to a defined viewing distance. If a controller needs to view a display beyond that distance or if the viewing distances identified as “needed” fall beyond those parameters, this would warrant other alternative solutions such as additional displays or reconfiguration of existing displays or workstations. This also indicates that during display configuration and analysis (i.e., when determining the number and placement of displays for a given tower), the maximum viewing distance directly corresponds to information presentation and display characteristics such as character size and contrast ratio. For instance, if a tactical primary situation display is purchased for a tower with a maximum reading distance of the information/characters being presented at less than nine feet, and a maximum horizontal angle of 50 degrees, the specification should stipulate the procedure for determining how many displays belong in the tower and the relative placement of those displays. Based on the data in this report and the size of the information or characters being presented on the tactical primary situation display, a reading distance of less than nine feet will not meet the operational needs of the controllers. Therefore, a reconfiguration to achieve the optimal tower layout is needed.

By plotting the current operational workstations and outside viewing-vantage points with the other associated equipment stations that controllers must regularly visit (i.e., performing a linkage analysis), we can determine the number and placement of equipment. Figure 14 and Figure 15 provide a simplified diagram of the concept. Figure 14a shows two displays with small viewing distances and angles. In this case, another display could be placed within the visual range of the Ground Controller (perhaps a smaller slaved display) (see Figure 14b). Figure 15 shows two displays that we designed with greater viewing distances. In this case, the Ground Controller does not necessarily need an additional display because the two other displays are within the controller’s visual range.

Incorporating the operational data collected in this survey will enable the display specification to set minimum viewing distances and angles under the maximum lighting levels to which all candidate tower displays must comply. This will not only facilitate the standardization of tower display design, but it will also increase the operational effectiveness and efficiency of the technology being placed in ATCTs. Specifying and designing to maximum viewing distances and angles will also allow tower designers to create an optimal tower layout by performing informational needs analyses and linkage analyses to determine the overall placement of equipment and displays to maximize human performance.

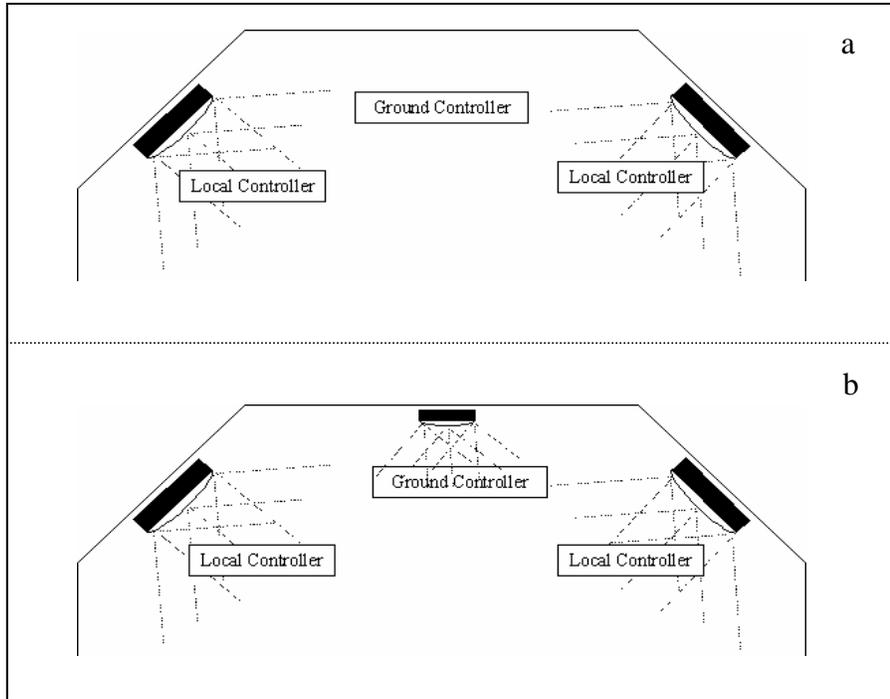


Figure 14. Tower design layout with and without the addition of a display.

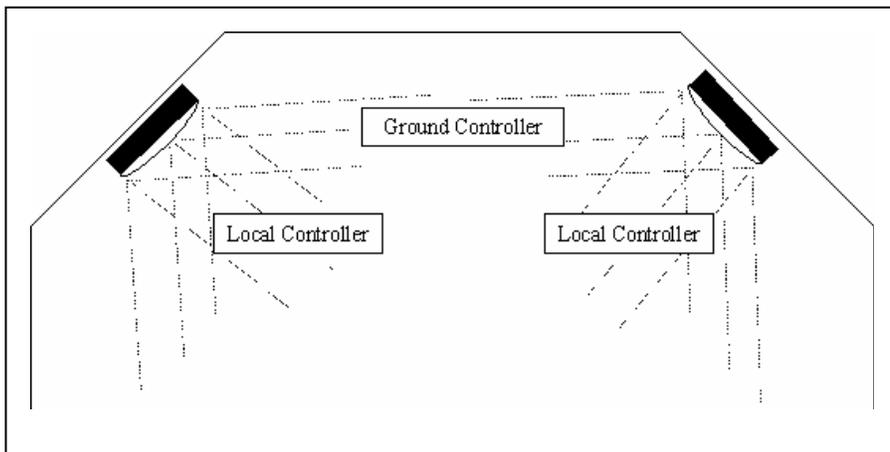


Figure 15. Tower design layout with improved display characteristics.

## 5. SUMMARY AND CONCLUSION

The following is a list of calculations and comparisons that we examined in the data:

1. Incident light exposure/lighting variances
2. Distance and angle variances
3. The effect of shades on lighting levels
4. Light patterns in tower cab according to the time of day
5. Ratio of light present outside to light inside
6. The effect of tower cab shape on lighting levels

This survey found that the most significant determining factor in the magnitude of viewing angles and distances was display quality, tower layout, and display placement. This highlights the need for human factors involvement in configuration and layout of tower cabs and tower display placement in addition to display design. Human factors analyses could optimize display placement and location to maximize performance on a site-by-site basis. The transfer of human factors lessons learned between regions alone could result in substantial cost savings. This is best illustrated by the extensive tower layout fixes made in one region and a different region making similar fixes some time later. Specifically, the consoles at the Regan National Tower were too high for the 5<sup>th</sup> percentile female controller to see over, and they had to be redesigned at a substantial cost. Recently, after construction was completed on the MIA New Tower, the tower cab floor had to be raised 13 in., and the consoles had to be recessed away from the windows in order to allow controllers to see all runways and taxiways. Bulkheads or columns were also originally placed in the direct line of site of critical airspace and ground traffic.

ATCT facility controllers or their union representative(s), supervisors, and system maintainers (i.e., Airway Facilities and/or second level maintenance) usually collaborate on display layout and placement without any analysis by a Human Factors Specialist. They often determine display placement by space availability closest to a workstation. This need for optimization and analysis was present at all levels of facilities and in all the regions researchers visited. Due to the abundance and rate of installation of new equipment and systems throughout each of the regions, as well as the ongoing design of new ATCTs and facilities, designers do not address many operator and maintainer human factors issues. The lack of Human Factors Specialists at the regional level results in sub-optimal installations, layouts, and configurations and, subsequently, does not allow controllers to be maximally efficient and effective. Adding a human factors presence at the regional level would directly benefit the controllers and maintainers as well as the overall operation of the NAS.

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## Acronyms

ACE-IDS	Automated Surface Observing System (ASOS) Controllers Equipment-Information Display System
ASOS	Automated Surface Observing System
ATCT	Airport Traffic Control Tower
BWI	Baltimore/Washington International Airport
CHO	Charlottesville-Albermarle Airport
CPS	St. Louis Downtown Airport
DAB	Daytona Beach International Airport
D-BRITE	Digital Bight Radar Indicator Tower Equipment
DFW East	Dallas/Fort Worth International Airport (Tower - East)
DFW West	Dallas/Fort Worth International Airport (Tower - West)
DFWC	Dallas/Fort Worth International Airport Center
DVT	Deer Valley Airport
F-420	Wind Direction and Speed Display
FAA	Federal Aviation Administration
fc	foot-candles
GYR	Phoenix Goodyear Airport
HEF	Manassas Regional Airport/Harry P. Davis Field
HWO	North Perry Airport
IDS	Informational Display System
LAX	Los Angeles International Airport
LGB	Long Beach Airport (Daugherty Field)
LLWAS	Low Level Wind Shear Alert System
MCO	Orlando International Airport
MIA - New	Miami International Airport (New Tower)
MIA - Old	Miami International Airport (Old Tower)
MLB	Melbourne International Airport
NAS	National Airspace System
ONT	Ontario International Airport
PHX	Phoenix Sky Harbor International Airport
STL	Lambert-St Louis International Airport
SUS	Spirit of St. Louis Airport

Appendix A

Schedule

Trip A  
Two Weeks  
January 2-17, 2003

Florida: (January 2-10)

Thursday (1/2/03): Travel

Friday (1/3/03): Miami (MIA)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Monday (1/6/03): Miami (MIA)

- Lighting and Viewing angle & Distance Measurements
- Missing data

Tuesday (1/7/03): North Perry (HWO)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Wednesday (1/8/03): North Perry (HWO)

- Lighting and Viewing angle & Distance Measurements
- Missing data

Thursday (1/9/03): Melbourne (MLB)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Friday (1/10/03): Melbourne (MLB)

- Lighting and Viewing angle & Distance Measurements
- Missing data

Florida: (January 13-17)

Monday (1/13/03): Daytona Beach (DAB)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Tuesday (1/14/03): Daytona Beach (DAB)

- Lighting and Viewing angle & Distance Measurements
- Missing data

Wednesday (1/15/03): Orlando (MCO)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Thursday (1/16/03): Orlando (MCO)

- Lighting and Viewing angle & Distance Measurements
- Missing data

Friday (1/17/03): Travel

Trip B  
Two Weeks  
February 24 - March 7, 2003

California: (February 24-28)

Monday (2/24/03): Travel

Tuesday (2/25/03): Ontario (ONT)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Wednesday (2/26/03): Ontario (ONT)

- Lighting and Viewing angle & Distance Measurements
- Missing data

Thursday (2/27/03): Long Beach (LGB)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Friday (2/28/03): Long Beach (LGB)

- Lighting and Viewing angle & Distance Measurements
- Missing data

- Night (2/28/03): Los Angeles (LAX): Viewing angle only

Sunday (3/2/03): Fly to Phoenix

Arizona: (March 3-7)

Monday (3/3/03): Phoenix Deer (DVT)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Tuesday (3/4/03): Phoenix Deer (DVT)

- Lighting and Viewing angle & Distance Measurements
- Missing data

Wednesday (3/5/03): Phoenix Goodyear (GYR)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Thursday (3/6/03): Phoenix Goodyear (GYR)

- Lighting and Viewing angle & Distance Measurements
- Missing data

- Night (3/6/03): Phoenix (PHX): Viewing angle only

Friday (3/7/03): Travel

Trip C  
One week  
February 3-7, 2003

Missouri:

Monday (2/3/03): Travel

Tuesday (2/4/03): Spirit of St. Louis (SUS)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset
- Night (2/4/03): St. Louis / Lambert (STL): Viewing angle only

Wednesday (2/5/03): Spirit of St. Louis (SUS)

- Lighting and Viewing angle & Distance Measurements
- Missing data

Thursday (2/6/03): East St. Louis (CPS)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Friday (2/7/03): East St. Louis (CPS)

- Lighting and Viewing angle & Distance Measurements
- Missing data
- Travel

Trip D  
One week  
March 10-14, 2003

Texas:

Monday (3/10/03): Travel

Tuesday (3/11/03): Dallas/Fort Worth International Airport (East or West) (DFW)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Wednesday (3/12/03): Dallas/Fort Worth International Airport (East or West) (DFW)

- Lighting and Viewing angle & Distance Measurements
- Missing data

Thursday (3/13/03): Dallas/Fort Worth International Airport (East or West) (DFW)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Friday (3/14/03): Dallas/Fort Worth International Airport (East or West) (DFW)

- Lighting and Viewing angle & Distance Measurements
- Missing data
- Travel

Trip E  
Local Area – One week  
February 10-13, 2003

Virginia & Maryland:

Monday (2/10/03): Manassas (HEF)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Tuesday (2/11/03): Manassas (HEF)

- Lighting and Viewing angle & Distance Measurements
- Missing data

Wednesday (2/12/03): Charlottesville (CHO)

- Lighting and Viewing angle & Distance Measurements
- Sunrise to Sunset

Thursday (2/13/03): Charlottesville (CHO)

- Lighting and Viewing angle & Distance Measurements
- Missing data
- Night (2/13/03): Baltimore (BWI): Viewing angle only

Appendix B  
Data Collection Sheets

AMBIENT / INCIDENT LIGHTING

**DATA COLLECTION SHEET**

**Date:** \_\_\_\_\_ **Time Started:** \_\_\_\_\_ am/pm

**Facility:** \_\_\_\_\_ **Time Finished:** \_\_\_\_\_ am/pm

**Shades:**

N	NE	E	SE	S	SW	W	NW
Up							
Midway							
Retracted							

**ASOS Weather Data:**

Visibility: \_\_\_\_\_ SM      Sky Conditions: \_\_\_\_\_

**Outside Lighting #1:**

Light Measurement Plane	Location	Light Measurement Plane	Location
Horizontal		Vertical S	
Vertical N		Vertical W	
Vertical E		Direct	

**Monitor Lighting:**

Monitor Location

Floor Layout (check one):

Monitor	Label	Tilt	Mount	Incident	N	NE	E	SE	S	SW	W	NW
Primary Secondary Auxiliary			Ceiling On In	fc								

Primary Secondary Auxiliary			Ceiling On In	fc								
-----------------------------------	--	--	------------------	----	--	--	--	--	--	--	--	--

Primary Secondary Auxiliary			Ceiling On In	fc								
-----------------------------------	--	--	------------------	----	--	--	--	--	--	--	--	--

Primary Secondary Auxiliary			Ceiling On In	fc								
-----------------------------------	--	--	------------------	----	--	--	--	--	--	--	--	--

**General Ambient Lighting in Center of Tower Cab (fc):**

<b>Light Measurement Plane</b>	<b>Location Center</b>	<b>L1</b>	<b>L2</b>	<b>L3</b>	<b>L4</b>	<b>L5</b>	<b>L6</b>	<b>L7</b>	<b>L8</b>	<b>L9</b>	<b>L10</b>
Horizontal											
Vertical N											
Vertical E											
Vertical S											
Vertical W											
<b>Light Measurement Plane</b>		<b>L11</b>	<b>L12</b>	<b>L13</b>	<b>L14</b>	<b>L15</b>	<b>L16</b>	<b>L17</b>	<b>L18</b>	<b>L19</b>	<b>L20</b>
Horizontal											
Vertical N											
Vertical E											
Vertical S											
Vertical W											

**Brightest Area in Tower Cab (fc):**

Vertical N	
Vertical E	
Vertical S	
Vertical W	
Direct	

**Outside Lighting #2 (lux):**

<b>Light Measurement Plane</b>	<b>Location</b>
Horizontal	
Vertical N	
Vertical E	
Vertical S	
Vertical W	
Direct	

Comments

VIEWING ANGLES / VIEWING DISTANCES  
DATA COLLECTION SHEET

**Facility:** \_\_\_\_\_ **Date:** \_\_\_\_\_ **Time:** \_\_\_\_\_

**Display Label:** \_\_\_\_\_ **Primary**      **Secondary**      **Auxiliary**

**Display Tilt:** \_\_\_\_\_

**Display Measurements (inches):** \_\_\_\_\_

**Display Height (inches):** \_\_\_\_\_

**Measurement Type:**    **5<sup>th</sup>% Female**      **95<sup>th</sup>% Male**

	<b>Location</b> (circle one)		<b>Type of Location</b> (circle one)		<b>Activity</b> (circle one)		<b>Distance</b> (inches)	<b>Vertical Angle</b>	<b>Horizontal Angle</b>	
	Standing	Sitting	Actual	Needed	Read	View			N	L
1									_____	_____
	Standing	Sitting	Actual	Needed	Read	View			=	
2									_____	_____
	Standing	Sitting	Actual	Needed	Read	View			=	
3									_____	_____
	Standing	Sitting	Actual	Needed	Read	View			=	
4									_____	_____
	Standing	Sitting	Actual	Needed	Read	View			=	
5									_____	_____
	Standing	Sitting	Actual	Needed	Read	View			=	

Appendix C  
Measurement Data

**Table C1.** Highest Incident Readings at ATCT Measurements are in fc

<b>Tower</b>	<b>Maximum Internal Incident Reading</b>	<b>Test Condition</b>	<b>Shades</b>	<b>Start Time</b>	<b>End Time</b>	<b>Corresponding Outside Direct Reading Before Incident Measurement</b>	<b>Corresponding Outside Direct Reading After Incident Measurement</b>
CHO	<u>3370</u>	Operational	Not Deployed	7:55 am	8:05 am	150	6010
CPS	<u>4800</u>	Operational	Not Deployed	9:00 am	9:30 am	9030	9860
DAB	<u>4360</u>	Engineering	Not Deployed	4:30 pm	4:40 pm	8090	6610
DFW	<u>6040</u>	Engineering	Not Deployed	4:20 pm	4:58 pm	9720	8660
DVT	<u>4280</u>	Operational	Not Deployed	9:00 am	9:30 am	10080	10610
GYR	<u>2790</u>	Engineering	Not Deployed	4:30 pm	5:00 pm	10590	9960
HEF	<u>1820</u>	Operational	Not Deployed	7:40 am	8:00 am	82	4670
HWO	<u>5130</u>	Operational	Not Deployed	8:25 am	9:10 am	7000	8000
LGB	<u>3660</u>	Engineering	Not Deployed	4:30 pm	4:45 pm	7080	4840
MCO	<u>3690</u>	Operational	Not Deployed	3:25 pm	4:30 pm	10340	6160
MIA - New	<u>2780</u>	Engineering	Not Deployed	10:00 am	4:50 pm	5750	4320
MIA - Old	<u>2670</u>	Engineering	Not Deployed	1:45 pm	10:10 am	8840	10910
MLB	1800	Operational	Partially Deployed	7:50 am	8:05 am	8.95	5500
SUS	<u>4560</u>	Engineering	Not Deployed	10:00 am	10:19 am	10250	10640

**Table C2.** Highest Incident Readings in Engineering Test Condition Measurements are in fc

<b>Tower</b>	<b>Maximum Internal Incident Reading</b>	<b>Test Condition</b>	<b>Shades</b>	<b>Start Time</b>	<b>End Time</b>	<b>Corresponding Outside Direct Reading Before Incident Measurement</b>	<b>Corresponding Outside Direct Reading After Incident Measurement</b>
CHO	<u>2500</u>	Engineering	Not Deployed	7:30 am	7:40 am	7410	6740
CPS	<u>3450</u>	Engineering	Not Deployed	10:00 am	10:10 am	10520	10580
DAB	<u>4360</u>	Engineering	Not Deployed	4:30 pm	4:40 pm	8090	6610
DFWC	<u>6040</u>	Engineering	Not Deployed	4:20 pm	4:58 pm	9720	8660
DVT	<u>1940</u>	Engineering	Not Deployed	10:00 am	10:05 am	1990	11090
GYR	<u>2790</u>	Engineering	Not Deployed	4:30 pm	5:00 pm	10590	9960
HEF	<u>1065</u>	Engineering	Not Deployed	10:00 am	10:20 am	10340	10400
HWO	<u>2610</u>	Engineering	Not Deployed	4:35 pm	5:20 pm	6000	1860
LGB	<u>3660</u>	Engineering	Not Deployed	4:30 pm	4:45 pm	7080	4840
MCO	<u>3440</u>	Engineering	Not Deployed	4:30 pm	4:45 pm	7600	5540
MIA - New	<u>2780</u>	Engineering	Not Deployed	10:00 am	4:50 pm	5750	4320
MIA - Old	<u>2670</u>	Engineering	Not Deployed	1:45 pm	10:10 am	8840	10910
MLB	<u>376</u>	Engineering	Not Deployed	4:30 pm	1:50 pm	10850	10850
SUS	<u>4560</u>	Engineering	Not Deployed	10:00 am	10:19 am	10250	10640

**Table C3.** Highest Incident Readings in Operational Test Condition Measurements are in fc

<b>Tower</b>	<b>Maximum Internal Incident Reading</b>	<b>Test Condition</b>	<b>Shades</b>	<b>Start Time</b>	<b>End Time</b>	<b>Corresponding Outside Direct Reading Before Incident Measurement</b>	<b>Corresponding Outside Direct Reading After Incident Measurement</b>
CHO	<u>3370</u>	Operational	Not Deployed	7:55 am	8:05 am	150	6010
CPS	<u>4800</u>	Operational	Not Deployed	9:00 am	9:30 am	9030	9860
DAB	<u>837</u>	Operational	Deployed	5:15 pm	5:45pm	6610	176
DVT	<u>4280</u>	Operational	Not Deployed	9:00 am	9:30 am	10080	10610
GYR	<u>712</u>	Operational	Not Deployed	8:00 am	8:35 am	7330	8820
HEF	<u>1820</u>	Operational	Not Deployed	7:40 am	8:00 am	82	4670
HWO	<u>5130</u>	Operational	Not Deployed	8:25 am	9:10 am	7000	8000
LGB	<u>1929</u>	Operational	Not Deployed	6:55 am	7:00 am	110	3790
MCO	<u>3690</u>	Operational	Not Deployed	3:25 pm	4:30 pm	10340	6160
MIA	<u>57.2</u>	Operational	Deployed	4:10 pm	5:30 pm	7276	2566
MLB	<u>1800</u>	Operational	Partially Deployed	7:50am	8:05 am	8.95	5500
SUS	<u>1657</u>	Operational	Deployed	2:28 pm	3:40 pm	10290	8640

**Table C4.** Highest Horizontal Ambient Readings Measurements are in fc

<b>Tower</b>	<b>Maximum Internal Incident Reading</b>	<b>Test Condition</b>	<b>Shades</b>	<b>Start Time</b>	<b>End Time</b>	<b>Corresponding Outside Direct Reading Before Incident Measurement</b>	<b>Corresponding Outside Direct Reading After Incident Measurement</b>
CHO	3870	Operational	Not Deployed	11:00 am	11:45 am	5230	6090
CPS	3500	Engineering	Not Deployed	10:00 am	10:10 am	3570	4000
DAB	2860	Engineering	Not Deployed	10:00 am	10:15 am	4330	3850
DFWC	5340	Engineering	Not Deployed	1:35 pm	2:55 pm	8830	7440
DVT	3480	Engineering	Not Deployed	10:00 am	10:05 am	7070	7190
GYR	4010	Operational	Deployed	8:00 am	8:35 am	6090	8360
HEF	3650	Operational	Partially Deployed	7:40 am	8:00 am	3590	4770
HWO	3000	Engineering	Not Deployed	10:00 am	10:20 am	4530	4560
LGB	4240	Engineering	Not Deployed	10:00 am	10:15 am	5510	5430
MCO	4600	Engineering	Not Deployed	10:00 am	10:20 am	6430	5150
MIA	3100	Engineering	Not Deployed	10:00 am	10:10 am	4810	4480
MIA Old	4490	Engineering	Not Deployed	12:10 pm	12:50 pm	6240	6720
MLB	4760	Operational	Deployed	12:05 am	1:05 pm	7240	7000
SUS	4740	Operational	Deployed	1:33 pm	2:28 pm	5030	4740

**Table C5. Highest Horizontal Ambient Readings in Engineering Test Condition**  
Measurements are in fc

<b>Tower</b>	<b>Maximum Internal Horizontal Ambient Reading</b>	<b>Test Condition</b>	<b>Shades</b>	<b>Start Time</b>	<b>End Time</b>	<b>Corresponding Outside Horizontal Reading Before Horizontal Measurement</b>	<b>Corresponding Outside Horizontal Reading After Horizontal Measurement</b>
CHO	3550	Engineering	Not Deployed	10:00 am	10:45 am	4350	5090
CPS	3500	Engineering	Not Deployed	10:00 am	10:10 am	3570	4000
DAB	2860	Engineering	Not Deployed	10:00 am	10:15 am	4330	3850
DFWC	5340	Engineering	Not Deployed	1:35 pm	2:55 pm	8830	7440
DVT	3480	Engineering	Not Deployed	10:00 am	10:05 am	7070	7190
GYR	2780	Engineering	Not Deployed	4:30 pm	5:00 pm	5220	3490
HEF	3040	Engineering	Not Deployed	10:00 am	10:20 am	4010	3590
HWO	3000	Engineering	Not Deployed	10:00 am	10:20 am	4530	4560
LGB	4240	Engineering	Not Deployed	10:00 am	10:15 am	5510	5430
MCO	4600	Engineering	Not Deployed	10:00 am	10:20 am	6430	5150
MIA	3100	Engineering	Not Deployed	10:00 am	10:10 am	4810	4480
MIA Old	4490	Engineering	Not Deployed	12:10 pm	12:50 pm	6240	6720
MLB	1077	Engineering	Not Deployed	4:30 pm	4:45 pm	1850	1440
SUS	3190	Engineering	Not Deployed	10:00 am	10:19 am	4510	4230

**Table C6. Highest Horizontal Ambient Readings in Operational Test Condition**  
Measurements are in fc

<b>Tower</b>	<b>Maximum Internal Horizontal Ambient Reading</b>	<b>Test Condition</b>	<b>Shades</b>	<b>Start Time</b>	<b>End Time</b>	<b>Corresponding Outside Horizontal Reading Before Horizontal Measurement</b>	<b>Corresponding Outside Horizontal Reading After Horizontal Measurement</b>
CHO	3870	Operational	Not Deployed	11:00 am	11:45 am	5230	6090
CPS	95	Operational	Deployed	1:00 pm	1:25 pm	4000	4810
DAB	40	Operational	Deployed	12:00 pm	1:00 pm	1410	91
DVT	2300	Operational	Not Deployed	9:00 am	9:30 am	4670	4260
GYR	4010	Operational	Deployed	8:00 am	8:35 am	6090	8360
HEF	3650	Operational	Partially Deployed	7:40 am	8:00 am	3590	4770
HWO	1750	Operational	Partially Deployed	11:00 am	11:50 am	2600	4330
LGB	2520	Operational	Deployed	2:00 pm	2:45 pm	1870	3810
MCO	1720	Operational	Deployed	1:50 pm	3:00 pm	4200	1610
MIA	134.4	Operational	Deployed	5:30 pm	5:40 pm	276	4810
MLB	4760	Operational	Deployed	12:05 am	1:05 pm	7240	7000
SUS	4740	Operational	Deployed	1:33 pm	2:28 pm	5030	4740

**Table C7.** Highest Direct Ambient Readings Measurements are in fc

<b>Tower</b>	<b>Maximum Internal Direct Ambient Reading</b>	<b>Test Condition</b>	<b>Shades</b>	<b>Start Time</b>	<b>End Time</b>	<b>Corresponding Outside Direct Reading Before Horizontal Measurement</b>	<b>Corresponding Outside Direct Reading After Horizontal Measurement</b>
CHO	6720	Operational	Not Deployed	11:00 am	11:45 am	10820	10980
CPS	7620	Engineering	Not Deployed	10:00 am	10:10 am	10520	10580
DAB	6900	Engineering	Not Deployed	10:00 am	10:15 am	9900	10400
DFWC	7310	Engineering	Not Deployed	1:35 pm	2:55 pm	11480	11190
DVT	7790	Engineering	Not Deployed	10:00 am	10:05 am	1990	11090
GYR	7290	Engineering	Not Deployed	4:30 pm	5:00 pm	10590	9960
HEF	7310	Engineering	Not Deployed	10:00 am	10:20 am	10340	10400
HWO	6360	Engineering	Not Deployed	10:00 am	10:20 am	9590	10160
LGB	7750	Engineering	Not Deployed	10:00 am	10:15 am	10870	11100
MCO	9160	Engineering	Not Deployed	10:00 am	10:20 am	10720	10850
MIA	7660	Engineering	Not Deployed	10:00 am	10:10 am	none	10910
MIA Old	7040	Engineering	Not Deployed	12:10 pm	12:50 pm	none	10690
MLB	7880	Engineering	Not Deployed	10:15 am	10:35 am	10400	10720
SUS	10290	Operational	Deployed	1:33 pm	2:28 pm	10880	10290

**Table C8.** Highest Direct Ambient Readings in Engineering Test Condition  
Measurements are in fc

<b>Tower</b>	<b>Maximum Internal Direct Ambient Reading</b>	<b>Test Condition</b>	<b>Shades</b>	<b>Start Time</b>	<b>End Time</b>	<b>Corresponding Outside Direct Reading Before Horizontal Measurement</b>	<b>Corresponding Outside Direct Reading After Horizontal Measurement</b>
CHO	6570	Engineering	Not Deployed	10:00 am	10:45 am	10420	10750
CPS	7620	Engineering	Not Deployed	10:00 am	10:10 am	10520	10580
DAB	6900	Engineering	Not Deployed	10:00 am	10:15 am	9900	10400
DFWC	7310	Engineering	Not Deployed	1:35 pm	2:55 pm	11480	11190
DVT	7790	Engineering	Not Deployed	10:00 am	10:05 am	1990	11090
GYR	7290	Engineering	Not Deployed	4:30 pm	5:00 pm	10590	9960
HEF	7310	Engineering	Not Deployed	10:00 am	10:20 am	10340	10400
HWO	6360	Engineering	Not Deployed	10:00 am	10:20 am	9590	10160
LGB	7750	Engineering	Not Deployed	10:00 am	10:15 am	10870	11100
MCO	9160	Engineering	Not Deployed	10:00 am	10:20 am	10720	10850
MIA	7660	Engineering	Not Deployed	10:00 am	10:10 am	none	10910
MIA Old	7040	Engineering	Not Deployed	12:10 pm	12:50 pm	none	10690
MLB	7880	Engineering	Not Deployed	10:15 am	10:35 am	10400	10720
SUS	6650	Engineering	Not Deployed	10:00 am	10:19 am	10250	10640

**Table C9.** Highest Direct Ambient Readings in Operational Test Condition

<b>Tower</b>	<b>Maximum Internal Direct Ambient Reading</b>	<b>Test Condition</b>	<b>Shades</b>	<b>Start Time</b>	<b>End Time</b>	<b>Corresponding Outside Direct Reading Before Horizontal Measurement</b>	<b>Corresponding Outside Direct Reading After Horizontal Measurement</b>
CHO	6720	Operational	Not Deployed	11:00 am	11:45am	10820	10980
CPS	n/a	Operational	Deployed	10:10 am	10:35 am	10580	10810
DAB	none	Operational	Deployed	5:15 pm	5:45 pm	6610	176
DVT	5600	Operational	Not Deployed	9:00 am	9:30 am	10080	10610
GYR	6610	Operational	Deployed	2:25 pm	3:00 pm	13330	11690
HEF	7260	Operational	Partially Deployed	10:20 am	11:00 am	10400	10800
HWO	none	Operational	Partially Deployed	8:25 am	9:10 am	none	none
LGB	6020	Operational	Deployed	8:00 am	9:00 am	8080	10720
MCO	6670	Operational	Deployed	3:25 pm	4:30 pm	10340	6160
MIA		Operational	Deployed	8:44 am	10:00 am	none	none
MLB	7400 (4/45)	Operational	Deployed	12:05am	1:05 pm	10720	11000
SUS	10290	Operational	Deployed	1:33 pm	2:28 pm	10880	10290