Railroad Crossing Safety Technologies

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Part 3: Evaluation of LED Signal Systems
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EXECUTIVE SUMMARY

The use of light emitting diode (LED) warning signals in the railroad industry has increased due to recent technological improvements. LED signals have many potential benefits over traditional incandescent signals, including longer life, increased durability, and lower power consumption. Traditional incandescent signals consist of a single incandescent bulb, and therefore, experience total failure when the bulb is out. However, since an LED signal consists of an array of individual LEDs, partial failure may occur when only a portion of the LEDs fail. Partial failure may be caused by vandalism, defective LED elements, or individual LEDs burning out. Safety concerns arise if an LED signal is not visible to an approaching train crew or vehicle driver. Therefore, it is necessary to determine the effects of an LED signal partial failure on the ability of an approaching train crew or vehicle driver to accurately see the warning signal.

The 12 inch LED crossing signals tested in this project can be categorized as being with or without a power supply or regulator to control the voltage and current supplied to the LED circuit. In the lab tests, the two signals that do not use power supplies exhibited maximum light intensities (in candela) that were a strong function of both the supply voltage and the number of active LED elements. The four LED crossing signals and the three LED wayside signals exhibited maximum light intensities that were much less sensitive to either the supply voltage or the number of active LED elements. Consequently, there is no overall conclusion that can be drawn about the light intensity output of an LED signal without knowledge of the way the signal is constructed.

A field test procedure was developed to determine how an individual perceives the partial failure of an LED signal light. A manually operated switch system was designed and built to select different patterns of non-illuminated LEDs. In addition, signal housings and test stands were designed and built to display LED signals during field tests. Two field tests were conducted using volunteers, who evaluated four 12 inch, red, LED railroad crossing signals at distances between 100 and 1500 ft. The volunteers evaluated the lights in different combinations of partial failures during each test. The field test indicated that the on/off status of an LED signal was usually determined correctly if 50% or more of the LED elements were active.

ACKNOWLEDGEMENTS

The research conducted as during this project could not have been accomplished without the assistance of several graduate and undergraduate students at The University of Alabama. Matthew Chatham designed and built the computer-controlled goniometer used in the lab tests as his Master's degree project. Matthew also conducted the initial tests on the first LED signal. He has written most of the background section and the description of the lab test equipment included in this report. Anitha Gupta conducted the remaining lab tests on the LED signals and formatted the plots included in the Appendix. Scott Beams, Heather Hendrix, and Mark Nichols planned and conducted the field tests of the LED signals as their senior design project during the Spring 2003 semester. They have written most of the section describing the field test setup and results included in this report. The efforts and contributions of these students to this project is greatly appreciated.

The author of this report also had the privilege of serving on the Transport Canada *Steering Committee on LED Technology for Improved Conspicuity of Signal Lights at Grade Crossings* from August 2001 through April 2002. The interaction with the members of this committee while participating in the Canadian efforts to develop a standard for LED crossing signals was invaluable. The assistance of Dr. David Green of Carmanah Technologies and Anthony Napoli of the Transportation Development Center was particularly beneficial.

INTRODUCTION

LEDs (light-emitting diodes) are becoming more common in safety signals for railroad, highway, automotive, and many other applications. In addition to having a longer life and greater durability than incandescent bulbs, LEDs are much more energy efficient than their incandescent counterparts. LED signals are comprised of an array of individual LEDs, as opposed to the single bulb that illuminates incandescent railroad signals. This characteristic introduces a new failure mode not experienced with incandescent signals. With an incandescent bulb, any failure is a total failure of the signal. LED signals can however have partial failures where only some of the LEDs are lit. These partial failure could be due to vandalism, defective LED elements in the array, or by one or more LED elements simply burning out. This new failure mode raises many questions about the behavior of LED signals. What happens to the light output of the signals during partial failure? What percentage of LEDs must remain lit for the signal to be perceptible? Will the color of the signal remain the same during partial failure? What happens to current consumption and voltage requirements of LED signals in partial failure? Could this change in electrical characteristics be used to detect a level of failure of a signal?

The use of LED signals in railroad applications, specifically wayside signals and highway/railway crossing signals, is the focus of this study. Crossing signals occur in several flashing pairs. This redundancy makes the failure of an individual signal less catastrophic. Wayside signals indicate track conditions to the train engineer. Safety concerns arise if a wayside signal fails, or if a less restrictive color or aspect (such as flashing) is shown. Proper operation of these signals is critical to the safe and efficient operation of trains.

A brief literature review describes the photometric requirements for effective signaling of train engineers and automobile drivers. In the next section, the design of a computer-controlled goniometer (a device used to change the angular position of a test signal) is presented along with instrumentation used in the laboratory tests. Data gathered includes light intensity (measured in candela), signal voltage and current. A limited amount of chromaticity/color data will also be presented. Nine different LED signals (six 12 inch red crossing signals and three 8 inch wayside signals) have been tested over a range of voltages and with and different partial failures. Results from a single incandescent signal will also be given. Detailed light intensity maps from each of these lab tests are shown in the voluminous appendix.

Results from field tests conducted with four of the 12 inch red LED crossing signals are presented along with a description of the field test hardware and setup. This report ends with conclusions from the project.

BACKGROUND

Literature Review

LEDs are commonly used as indicator lights in electronic devices such as televisions and computers. They can efficiently produce light with low current and voltage, have a nearly instantaneous rise and fall time, have a much longer life than incandescent bulbs, and are more robust than incandescent filaments in terms of withstanding shock and vibration. Photons are emitted from an LED when current flows through a p-n junction. Doping materials such as aluminum, gallium, indium, nitrogen, phosphorus, arsenic, and antimony form this p-n junction. The wavelength of the photon emitted from the p-n junction is dependent on the materials used to make the LED. For example, aluminum indium gallium phosphate (AlInGaP) is used to produce red light at a wavelength of 622 nm (Christiansen, 1997).

A driver's proper response to a traffic signal requires seeing that the signal is lit and then reacting to its color. The conspicuity of the signal, or its ability to attract the attention of the driver, depends greatly on the brightness, or luminous intensity, of the signal. Other factors, such as the flash rate used with railway crossing signals, also contribute to the conspicuity of a signal. These other factors are not considered in this report. The luminous intensity and chromaticity of LED signals are the focus of this work.

Luminous intensity, a measure of the brightness of visible light, is measured in candela. By definition, a candela is a lumen per steradian. A lumen is a measure of the power of visible light, weighted to match the response of the human eye. A steradian is solid angle that covers the surface area of a sphere that is equal to the square of the radius of the sphere. A sphere of radius "r" has a surface area of $4\pi r^2$. Therefore, a sphere has 4π steradians of solid angle. The luminous intensity of a theoretical point light source is independent of distance. For example, if a light bulb produces one candela of light, then that means that one lumen per steradian is emitted by the bulb. So at one foot away from the bulb, one lumen passes through an area of one square foot. Similarly, one lumen passes through a hundred square foot area at a distance of ten feet. A steradian is a dimensionless number, independent of distance. Therefore, the luminous intensity of a theoretical point light source is the same, regardless of distance from the source (Ryer, 1997).

A hypothetical average normal observer, as defined by the International Commission on Illumination in 1931, is used to define the color of light. A standard hypothetical observer is required because different people's eyes perceive color differently. The chromaticity of a color, expressed in terms of this standard observer, is given by the numbers x, y, z (called trichromatic coefficients or trilinear coordinates), which may be considered as roughly expressing the respective red, green, and blue contents of the color. Since the sum of x, y, and z always equals one, the chromaticity is adequately specified by giving only x and y (ITE, Chapter 2, 1998).

Green and Milanovic produced a report entitled "LED Technology for Improved Conspicuity of Signal Lights at Road/Railway Grade Crossings" for Transport Canada (TC). This comprehensive study covered many aspects of highway/railway grade crossings, such as the history of crossing signal specifications, the history of LED technology, and human factors involved in signal perception. The purpose of their study was to produce a standard for highway/railway crossing signals in Canada. Green and Milanovic have presented an excellent background history of signal specifications in this report. The following is a synopsis of that history.

Light intensity requirements for traffic signals and highway/railway grade crossing signals have been stated in terms of viewing distance and luminous intensity at various viewing angles. In 1966, the American Association of Railroads (AAR) specified that crossing signals be clearly visible to a normal viewer in bright sunlight conditions. Viewing distance, not luminous intensity, was the criterion by which the signal was measured. With a 30-15 lens, the specification called for a range of 1,500 feet from on-axis to 10° left and right. The range was 500 feet for 15° off-axis. Ranges for vertical displacement were not specified (Green and Milanovic, 2001).

In 1968, a study was conducted on signals that met the 1966 AAR standard. This led to a luminous intensity-based standard for crossing signals. The vertical axis remained unspecified, but the horizontal axes at 0°, 5°, 10°, and 15° had luminous intensity requirements of 1,100, 350, 200, and 100 candela for a 30-15 lens (Green and Milanovic, 2001).

The next change occurred in 1991. This time, the vertical axis was specified, and the luminous intensity values increased across the horizontal axis. Table 1 shows the 1991 AAR specification for the 30-15 lens (Green and Milanovic, 2001).

Table 1. AAR 1991, Luminous Intensity Requirements for a 30-15 Lens.

Luminous Intensity (candela)		Horizontal Axis			
		0°L/R	5° L/R	10° L/R	15° L/R
Vertical Axis	0°D	1,600	1,000	500	200
	5°D	35			
	10°D	25			
	15°D	15			

In 1996, the AAR included a standard for LED crossing signals. The requirements were significantly lowered to accommodate the limitations of LED technology of the time. The 1996 AAR LED crossing signal standard is shown in Table 2 (Green and Milanovic, 2001).

Table 2. AAR 1996, Luminous Intensity Requirements for 30-15 Lens.

Luminous Intensity (candela)		Horizontal Axis						
		0°D	5°L/R	10°L/R	15°L/R	20°L/R	25°L/R	30°L/R
Vertical Axis	0°D	160	128	51	13	5	3	3
	5°D	128						
	10°D	51						
	15°D	13						
	20°D	5						
	30°D	3						

In 1999, the American Railway Engineering and Maintenance-of-Way Association (AREMA) became responsible for setting standards for railway signals. Visibility requirements were given in distance, and the same standard applied to both LED and incandescent signals. The viewing distance requirements were the same as the 1966 AAR standard for the 30-15 lens. However, the 1999 AREMA standard also specified a beam pattern in terms of percentage of on-axis luminous intensity. The beam pattern for an incandescent signal with a 30-15 lens is shown in Table 3 (Green and Milanovic, 2001).

Table 3. Percentage of On-Axis Luminous Intensity for 30-15 Lens.

Percentage of On-Axis Luminous Intensity		Horizontal Axis 0°L/R	5°L/R	10°L/R	15°L/R
Vertical Axis	0°D	100%	63%	31%	13%
	5°D	2%			
	10°D	2%			
	15°D	1%			

Current AREMA standards do have lumen requirements for incandescent bulbs, and chromaticity and transmittance requirements for lenses. The lumen requirements for an incandescent lamp operating at voltages of 10, 11, and 12 volts are 234, 129, and 96 lumens, as given by section 14.2.1 of the standard. Section 7.1.10 requires a minimum transmittance of 0.127 for a red highway/railway grade crossing lens (AREMA, 2001).

The most recent draft of the AREMA standard also includes vertical axis requirements for beam pattern. Section 3.2.35 of the manual describes an intensity profile for highway/railway grade crossing signals. This profile is described on the horizontal and vertical axes of the signal, without giving requirements for deflections from both axes. Requirements for different lens types are specified. Because luminous intensity is not specified in this standard, the profile requirements shown in Tables 4 and 5 are given in terms of percentage of maximum intensity (AREMA, 2001).

Table 4. AREMA's Required Percentage of Maximum Intensity on the Horizontal Axis.

	Horizontal Axis Deflection							
Roundel-Type	0° L/R	5° L/R	10° L/R	15° L/R	20° L/R	25° L/R	30° L/R	35° L/R
30-15	100	63	31	13				
20-32	100	63	31	13				
70	100	67	33	21	13	2	1	1
LED	100	80	33	8	3	2	2	2

Table 5. AREMA's Required Percentage of Maximum Intensity on the Vertical Axis.

	Vertical Axis Deflection				
Roundel-Type	5°D	10°D	15°D	20°D	30°D
30-15	2	2	1		
20-32	3	2	1	1	0.3
LED	80	33	8	3	2

For laboratory testing of an LED signal, luminous intensity and chromaticity, rather than viewing range, are the desired measurements. Two standards are used for comparison in this research. Chapter 2a of the *Equipment and Material Standards of the Institute of Transportation Engineers (ITE)*, “Vehicle Traffic Control Signal Heads (VTCSH),” is a standard for road traffic signals. This standard specifies mechanical, electrical, color, luminous intensity, and other requirements for traffic signals (ITE, Chapter 2, 1998).

Section 11 of the VTCSH gives the luminance requirements of a traffic signal. Section 11.02 describes the apparatus needed for testing a signal. A goniometer positions the signal to various viewing angles encountered in traffic situations. A photometer, calibrated to the human eye response curve of the CIE standard observer, measures luminous intensity. A regulated power supply and test lamps are also called for in this section. Section 11.03 describes the alignment of the test signal. The specifications require that the center of the signal be aligned with the horizontal and vertical axes of the goniometer, and that the light sensor be perpendicular to the aiming axis of the goniometer. The fourth rule in this section specifies a tolerance of ±0.25°. Section 11.04 specifies the intensity requirements of a signal at 44 separate test points. The standard states that all measurements at the test points be at least 80% of the desired intensity value. Further, no more than eight test points are allowed to drop below 90% of the desired intensity value. The luminous intensity values, in candela, for a red 12-inch signal are given in Table 6 (ITE, Chapter 2, 1998).

Table 6. ITE Incandescent Signal Luminous Intensity Requirements.

Luminous Intensity (candela)		Horizontal Angle (Left and Right)					
		2.5°	7.5°	12.5°	17.5°	22.5°	27.5°
Vertical Angle (Down)	2.5°	399	295	166	90	-	-
	7.5°	266	238	171	105	45	19
	12.5°	59	57	52	40	26	19
	17.5°	26	26	26	26	24	19

For LED signals, the luminous intensity requirements are reduced from the requirements stated above. The LED signal requirements, which are about 85% of the incandescent signal requirements, are shown in Table 7 (ITE, Chapter 2a, 1998).

Table 7. ITE LED Signal Luminous Intensity Requirements.

Candlepower Values (candela)		Horizontal Angle (Left and Right)					
		2.5°	7.5°	12.5°	17.5°	22.5°	27.5°
Vertical Angle (Down)	2.5°	339	251	141	77	-	-
	7.5°	226	202	145	89	38	16
	12.5°	50	48	44	34	22	16
	17.5°	22	22	22	22	20	16

The color requirements of a traffic signal are given in section 8 of chapter 2. The chromaticity requirements are the same for both incandescent and LED signals. The standard states that color shall be expressed in terms of a CIE normal average observer. The ITE standard specifies that the lens color for red, yellow, and green fall within certain color coordinates. For a red lens, the y value (green component) should be less than 0.308, but greater than 0.998-x. For a yellow lens, the y value should be less than 0.452, but greater than 0.411 and greater than 0.995-x. These locations are shown in Figure 1 (ITE, Chapter 2, 1998).

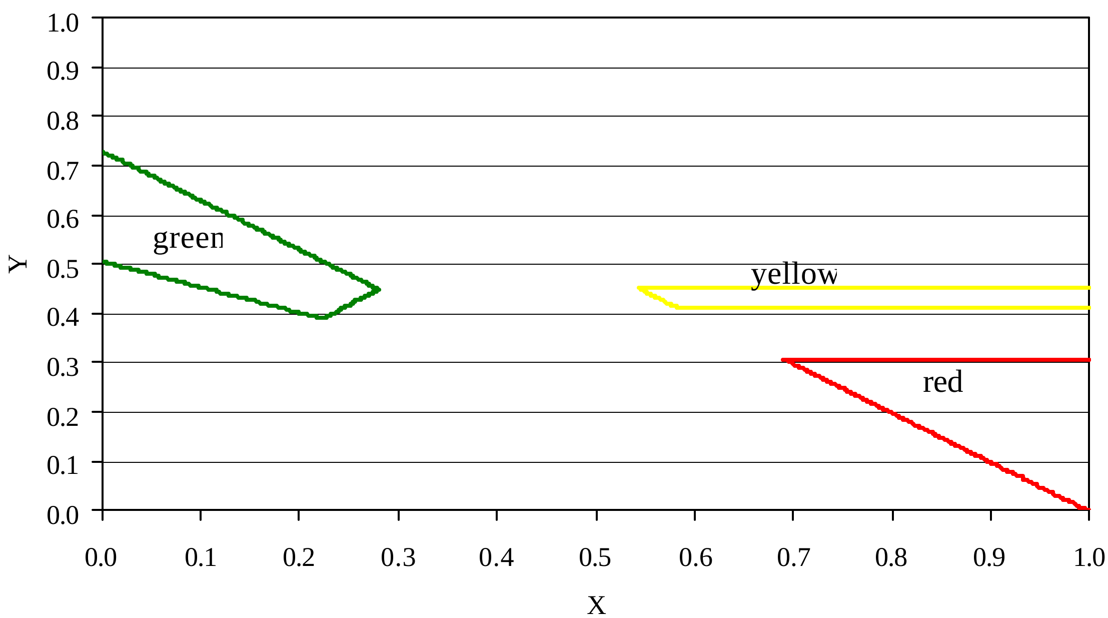

Figure 1. ITE Chromaticity Requirements.

Another standard used for comparison purposes in this research is the proposed "Transport Canada Standard for LED Signal Modules at Highway/Railway Grade Crossings." Many aspects of the TC standard were based on the ITE standard, because having a crossing signal with the same characteristics as a traffic signal should help automobile drivers recognize and respond to the signal. The chromaticity requirement section of the proposed TC standard refers to the ITE standard. The luminous intensity requirements for different viewing angles are given in a format similar to the ITE standard. These values are shown in Table 8 (TC, 2002).

Table 8. TC LED Luminous Intensity Requirements.

Luminous Intensity (candela)		Horizontal Angle (Left and Right)						
		0°	5°	10°	15°	20°	25°	30°
Vertical Angle (Down)	0°	400	375	300	200	100	50	15
	5°	350	325	250	150	75	40	15
	10°	130	125	110	85	60	35	15
	15°	45	40	35	30	25	20	15
	20°	15	15	15	15	15	15	10

These requirements differ from the ITE requirements in several ways. First, this standard has an on-axis measurement, while the ITE standard does not. Both standards require measurements in five-degree increments with respect to the horizontal and vertical axes. Also, the TC requirements are absolute minimums, whereas the ITE standard allows a certain number of measurements to fall slightly below requirements. The profiles for the TC and ITE specifications for LED signals are compared in Figure 2. The TC requirements exceed the ITE requirements across the range. The profiles are very similar, with the TC profile being slightly wider and deeper.

Many LED signal manufacturers are able to meet or exceed these standards. Some provide information about the dominant wavelength and peak luminous intensity (Dialight, n.d.). Others provide beam profiles for different LED signal products in addition to luminous intensity and chromaticity (Gelcore, 2001).

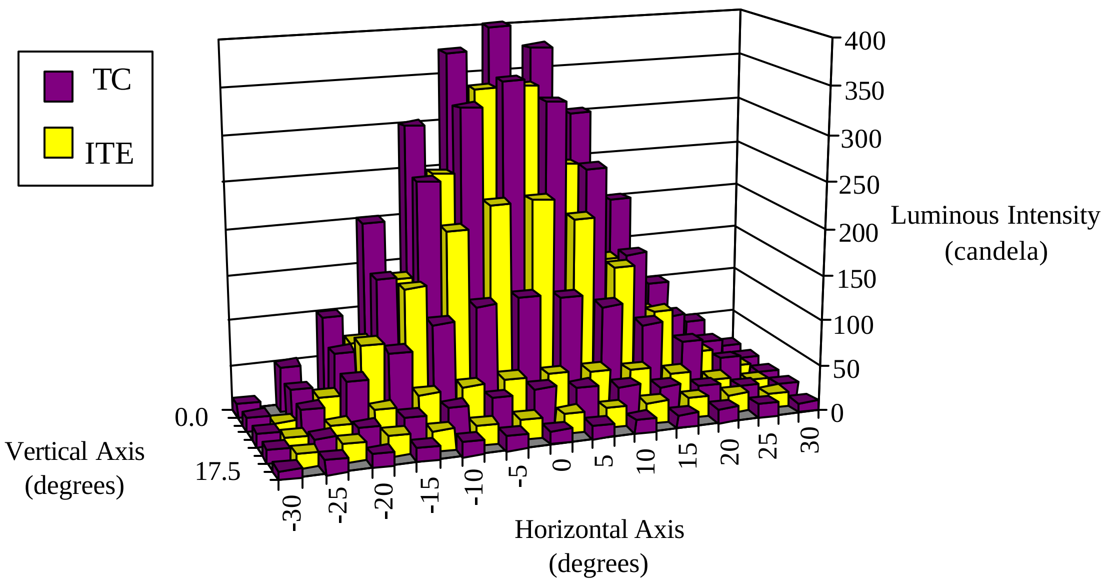

Figure 1. Comparison of ITE and TC Specifications for LED Signals.

The two main differences between traffic signals and crossing signals are operating power and alignment. Traffic signals operate off of a 120V AC line from the electrical grid. A 150-watt bulb is used in standard incandescent traffic signals. However, due to the dangerous potential of train accidents, grade crossings and wayside signals need to be able to run off of batteries in case of a power outage. Standard bulbs for railway applications are 18-watt bulbs, which require a much smaller battery bank than a 150-watt bulb would require. Because of the reduced amount of operating power, the light produced by these bulbs must be precisely focused to be effective. In the case of wayside signals, the path of a train is well-defined by the tracks, and proper alignment is a straightforward process. For grade crossings, there can be many angles of approach for cars, thus requiring more effort in alignment. Rigid mounting of the signal is required to maintain alignment (Green and Milanovic, 2001).

LED technology has improved exponentially over the years. Red LEDs commercially available today have efficiencies of 15-20 lumens/watt, as compared to the most efficient LED of 1970, which had an efficiency of 1 lumen/watt. Incandescent lamps also produce about 15-20 lumens/watt of white light. However, a red filter reduces the light output by about two-thirds. Therefore, an LED is about three times more efficient at producing red light as an incandescent lamp with a red filter. Furthermore, the LED efficiencies continue to improve, approaching efficiencies of 45 lumens/watt in laboratories in 2001 (Green and Milanovic, 2001).

LEDs also perform well under shock and vibration, since they are a solid-state technology. Light degradation over time is also excellent, with LEDs producing over 90% relative light output after 10,000 hours. The report notes that the reliability of drive circuitry is more likely to be the cause of failure of an LED signal. The drive circuitry has a reliability of about 90% after five years of operation (Green and Milanovic, 2001).

The California Department of Transportation conducted a study to determine the functional equivalence of LED signals to incandescent signals for traffic applications. This study employed a “usability factor” to make a relative comparison of different light sources. Tests were conducted by setting an incandescent reference signal at a set luminance. The brightness of the test signal was adjustable. The images of the signals were superimposed, and the images appeared alternately to the human test subject at a rate of 16 Hz. The test subject adjusted the brightness of the test lamp until the perceptible difference in signal brightness was at a minimum. This brightness setting was recorded seven times each for six subjects. The luminance of the reference signal was divided by the average of the medians of each test set. This ratio was the “usability factor.” Tests were conducted with subjects looking directly at the signal, viewing it, and looking at it with a +1 diopter lens to simulate 20/40 vision. This study concluded that a red LED round signal is not significantly different than a red incandescent round signal. The “usability factor” was close to unity, meaning the perceived brightness and measured brightness were essentially the same (Caltrans, n.d.).

Manufacturer Contacts

Several LED manufacturers and/or distributors have been contacted during the course of this project. A total of six 12 inch red LED crossing signals were obtained and tested. Three 8 inch LED wayside signals (red, green, yellow) have also been obtained and tested. Table 9 lists the companies and types of signals that were tested during this project. Contact has been made with these manufacturers and others to obtain additional LED wayside signals, without success. ALSTOM Transport Information Solutions expressed initial interest in supporting the project. Dialight was in the final stages of field testing a new design for their wayside signals during 2002-2003. Unfortunately, no additional LED wayside signals were obtained from either manufacturer.

Table 9. Manufacturers and Distributors of LED Railway Signals Used in Project.

Company	Manufacturer or Distributor	Type of LED Signal	Purchased or Donated
Dialight	Manufacturer	12 inch red crossing	Donated
Electro-Techs	Manufacturer	12 inch red crossing	Purchased
GELcore	Manufacturer	8 inch wayside (red, green, yellow)	Donated
General Signals	Manufacturer	12 inch red crossing	Purchased
Ledtronics	Manufacturer	12 inch red crossing	Purchased
Safetran	Distributor	12 inch red crossing	Donated
Western-Cullen Hayes	Distributor	12 inch red crossing	Purchased

Transport Canada

Both Dr. Parker and one of his graduate students (Matthew Chatham) were members of the Transport Canada *Steering Committee on LED Technology for Improved Conspicuity of Signal Lights at Grade Crossings* from August 2001 through April 2002. The committee met with several telephone conference calls as well as two meetings in Victoria, British Columbia. These meeting were conducted at the facilities of Carmanah Technologies, the contractor for the Transport Canada study. Both daytime and nighttime field tests of five different rail crossing safety lights (four LED, one incandescent) were conducted during the September 2001 meeting. The field test procedure used by the Transport Canada committee will be discussed more thoroughly in the Field Testing section of this report. Two of the most significant findings from the TC field tests were:

1. All of the LED signals were significantly more "conspicuous" than the single incandescent signal when viewed from any angle except on-axis, and
2. The TC committee lowered their minimum on-axis rating from 600 to 400 candela.

The draft Canadian standard for the use of LED lights for railway/highway crossings is available on the WWW at http://www.railwaycrossings.com/. This document has a great deal of information and materials relevant to LED signal development. The reference section in particular would be useful to anyone wishing to become more knowledgeable in this field.

Dr. Parker also presented a talk entitled “LED Signal Performance with Non-Illuminated Elements” for the Fourth Annual Workshop on Highway-Railway Grade Crossing Research sponsored by Transport Canada on November 26, 2002.

AREMA

Contact was also made with two AREMA (American Railway Engineers and Maintenance-of-Way Association) committees that have an interest in LED signal technology. Two committee meetings (#36 - Highway-Rail Grade Crossing Warning Systems and #37 - Signal Systems) on February 25-27, 2001 in Jacksonville, FL. A brief presentation on the status of the LED project was made to each committee.

Several issues were discussed at the AREMA meeting that relate to this LED project:

- Chromaticity / color of the wayside signal is an important issue.
- Environmental issues (particularly sunlight reflecting from the lens) are important as they affect how lights appear.
- An on-axis measurement should be added to the ITE-style test used by Transport Canada and in our preliminary results
- Many members thought the ITE-style test numbers from the sides were also important, since they simulate the approach to a signal along a curve.
- A suggestion was made that both styles of wayside signals should be tested: “searchlight” and “traffic,” possibly with a lunar white signal added to the bottom.
- There were many comments made about the different types of LED signals, those with power supplies (abbreviated as WPS in this report) and the older style that has no power supply (abbreviated as NPS in this report).

The issue of using LED signals for wayside signals was the topic of discussion at one session of the AREMA 37.2 Sub-committee. Two items of interest to our project were discussed.

- Wayside signals have an 8-16 volt operating range (which we should duplicate in our testing).

- The LED signal must hold enough current at the lowest voltage to maintain the lights-out relay (LOR) -- 0.68 amps is the lowest rating for standard relays by Alstom / Safetran / Union Switch.

The sub-committee spent a great deal of time discussing the effect that losing LED elements would have on the signal operation. The "FRA requirement for 50% output" was mentioned several times. During these discussions three positions became clear:

1. Railways do not want to guarantee that 50% of the original light intensity is maintained (due to the difficulty in measuring light output in the field),
2. Manufacturers do not want to signal the lights-out condition when 50% of the individual LED elements are non-functional (no low-cost way to determine how many LED elements are operational), and
3. Most members of the committee wanted to rely on a current setting to activate the lights-out relay. This was discussed at great length with no definite resolution.

LABORATORY TEST EQUIPMENT

Goniometer

Testing of crossing signals and wayside signals requires that measurements of light intensity and chromaticity be taken at various angles likely to be encountered by train crews and drivers. The ITE specification has 44 required test points, ranging from 27.5° left and right of the vertical axis, and from 2.5° to 17.5° down from the horizontal axis, as shown in Figure 3. The proposed TC specification has test points that range from 30° left and right of the vertical axis, and 0° to 20° down from the horizontal axis. Both specifications use 5-degree intervals between test points. As discussed at the AREMA committee meetings, an on-axis measurement of light output was added to the TC test pattern.

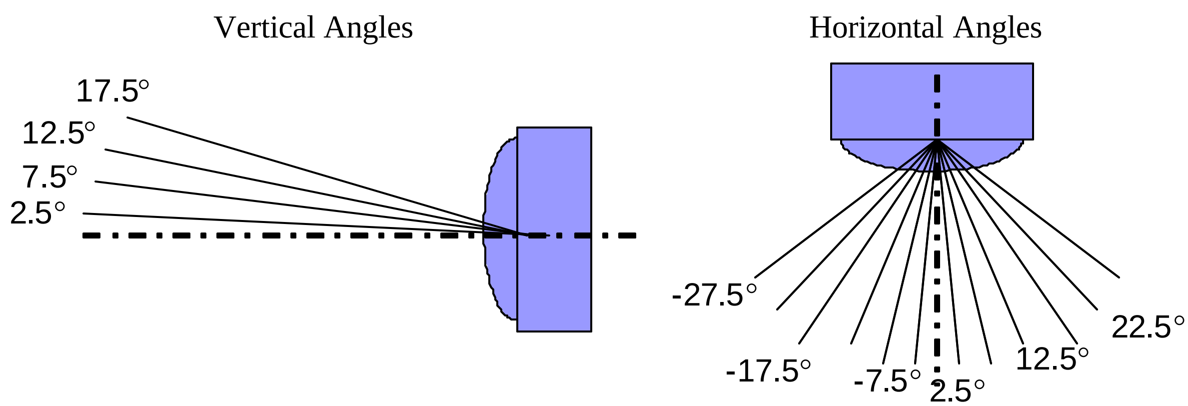

Figure 3. ITE-style test angles.

The number of test points per test, the number of signals to test, and the number of possible failure modes of each signal were all reasons to design and build an automated goniometer that could quickly and repeatedly orient the signals to specified angles. A goniometer is a device used to adjust the angular orientation of a test item. The goniometer used in this research can adjust the angle of a signal about both the horizontal and vertical axes.

The goniometer designed and built for this research is shown in Figure 4. It has an aluminum base and frame. A stepper motor and a 30:1 Tsubakimoto Emerson gearbox, model TM10E, are bolted to the middle of the base plate. This stepper motor controls the movement about the vertical axis of the goniometer. The power supply and drivers for the stepper motors are also located on the base plate.

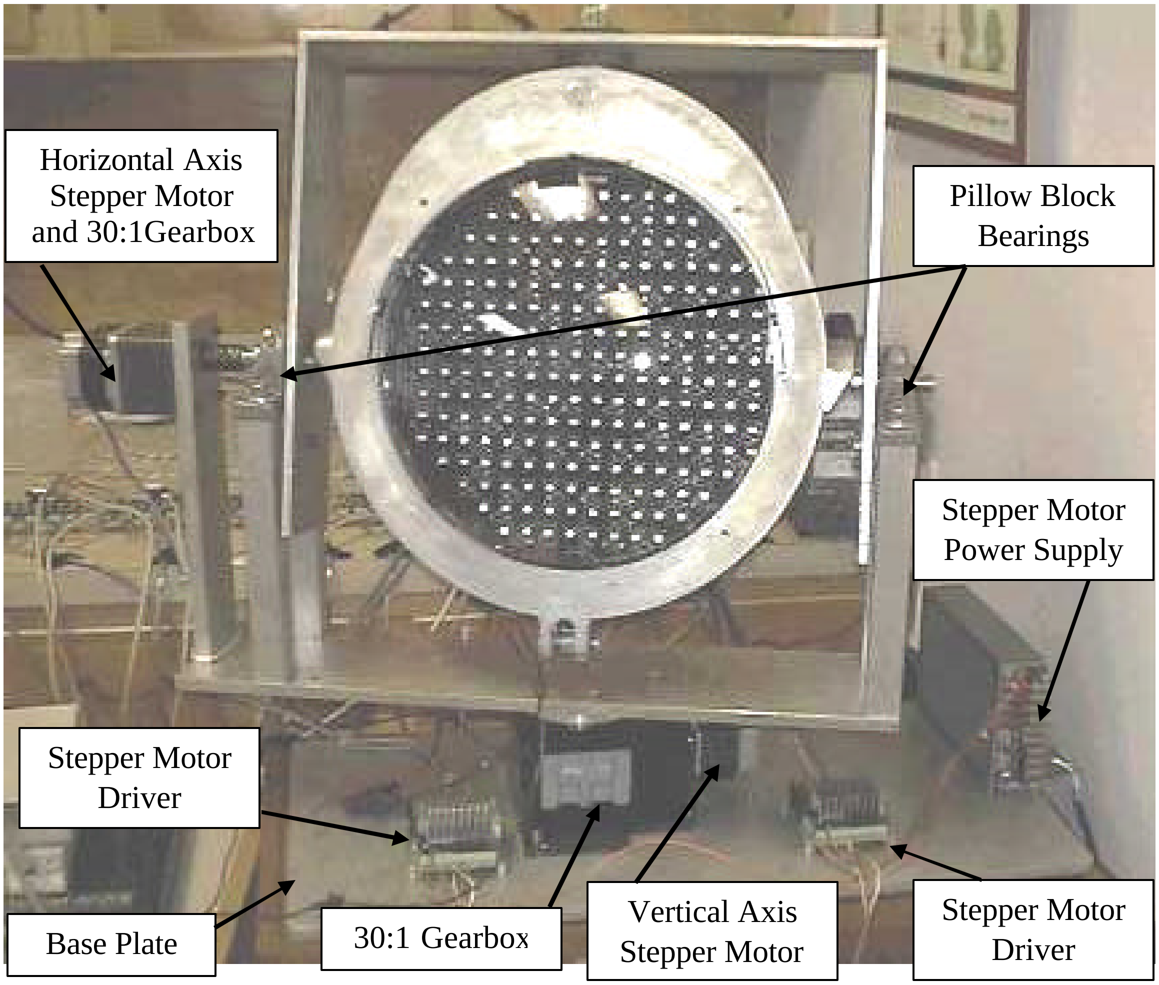

Figure 4. Goniometer.

Attached to the output shaft of the vertical axis gearbox is a hub and another horizontal plate, which supports the horizontal axis components of the goniometer. Two sets of aluminum posts are located near the ends of the horizontal plate. Pillow block bearings bolted on the top of these posts support the horizontal axis of the goniometer. The mounting plate for the horizontal axis stepper motor and gearbox is bolted on the end of the horizontal plate near one set of support posts. The horizontal axis stepper motor/gearbox combination is bolted at the top of this mounting plate, in line with horizontal axis. Two shafts are secured in the pillow block bearings with setscrews. The output shaft of the 30:1 gearbox is coupled to one of these shafts. A three-sided frame for holding the signal is attached to these shafts. Two parts of the frame extend up from the shafts, and the top part of the frame is bolted to the ends of the other two parts. A standard signal head is attached to the frame.

The Vexta Stepper Motor model PK566NAWA was selected for moving the goniometer in the vertical axis, and a Vexta Model PK564NAWA-T30 was selected for moving the goniometer in the horizontal axis. These stepper motors have a step size of 0.72 °/step, or 500 steps per revolution. A finer resolution of 0.024 °/step, or 15,000 steps per revolution, is achieved by running each motor through a 30:1 gearbox. Gearboxes improve accuracy in positioning the goniometer to the desired orientation and allow the stepper motors to easily move the goniometer. This ensures that no steps will be skipped, which is important for precision placement in an open loop system. The calculated minimum amount of time for the stepper motor to move the goniometer/signal combination 5° is 0.105 seconds, or about one-tenth of a second. To minimize the strain on the motor, and better ensure precision in moving the goniometer, the stepper motors are operated at a maximum acceleration of 1.68 rad/sec^2 (4000 steps/sec^2), and a maximum velocity of 4.19 rad/sec (10,000 steps/sec), which results in a five degree move time of 0.50 seconds. These restrictions are applied by the National Instruments motion control board PCI-7344 used to control the stepper motors.

The stepper motors each require 1.4 amps at 24 volts DC. The power supply is a Nemic Lambda model HR-10-24, which can provide an output current of 3 amps at 24 volts to the stepper motors.

Colorimeter

A colorimeter is used to measure the light intensity and color coordinates of the safety signal. A Minolta Chroma Meter, model CS-100A, was selected for this task. This colorimeter has a one-degree acceptance angle, which allows accurate measurement of the safety signal without including ambient light from the test area. The colorimeter can be controlled by a computer via an RS-232 link. The computer can receive measurements from the colorimeter. The luminance data sent by the colorimeter is in units of candela per square meter, and the “x” and “y” color coordinates are sent as unitless, decimal values. The Minolta CS-100A colorimeter uses three silicon photocells to match the spectral response of the CIE Standard Observer. For the “Fast” response setting used in this research, the colorimeter has a range from 0.01 to 299,000 cd/m^2, with an accuracy of ±2% of reading, ±1 of the third significant digit. Chromaticity values are accurate to within ±0.004 (Minolta, Instruction Manual, n.d.). The Minolta CS-100A is shown in Figure 5.

Figure 5. Minolta CS-100A Colorimeter.

Programmable Power Supply

The LED signals were powered by a Hewlett-Packard 6038A power supply. This programmable power supply can control the voltage supplied to the signal and can communicate with a computer via general purpose interface board (GPIB). The computer sets the desired voltage and current limit to be supplied to the signal. The programmable power supply can also tell the computer the actual voltage output and the actual current draw. The supplied voltage remains at the specified setting, even if the load is changed by enabling or disabling LED elements in the signal. A National Instruments PCI-GPIB card was installed in the computer to communicate with the power supply.

Data Acquisition

The National Instruments DAQPad 6020E, seen in ***Figure*** , has analog and digital IO capabilities. One of its digital lines is used to switch the signal relay, turning the signal on and off, as needed. This allows the testing programs to mimic the partial duty cycle experienced by crossing signals in the field. The analog channels could be used to measure voltage and current supplied to the signal. However, the programmable power supply is used to measure this data, so the analog channels were not used during testing (National Instruments, DAQPad 6020E, 1998).

Figure 6. DAQPad 6020E.

Motion Control Board

A National Instruments Motion Control Board PCI-7344 was used for stepper motor control. This board enables National Instruments software, such as LabView and Measurement and Automation Explorer, to set operational limits, such as maximum velocity and maximum acceleration. For signal tests, a trapezoidal motion profile is sent to the motion control board. The trapezoidal profile enables smooth, fast movement of the goniometer. The board outputs step and direction signals to the stepper motor drivers according to this profile (National Instruments, Motion Control, 2001).

Testing Procedure

Tests on the signals were run by placing the signal in the goniometer, aligning the signal with the colorimeter, setting the parameters, running the LabView testing program, saving the data, and resetting parameters for additional tests. LED signal retrofit kits allow for easy replacement of incandescent signals. The hardware used to hold the lens and parabolic reflector of the incandescent signal secures the LED signal in the housing. Installation procedures for an LED retrofit kit vary from brand to brand, so the manufacturer-provided installation instructions were followed for each kit.

Power wires were run through a hole near the bottom of the signal, and the LED relay switch wires were run through the top of the signal, as indicated in ***Figure*** 7. The nuts holding the signal head to the frame were checked and tightened to prevent the signal head from shifting around during a test.

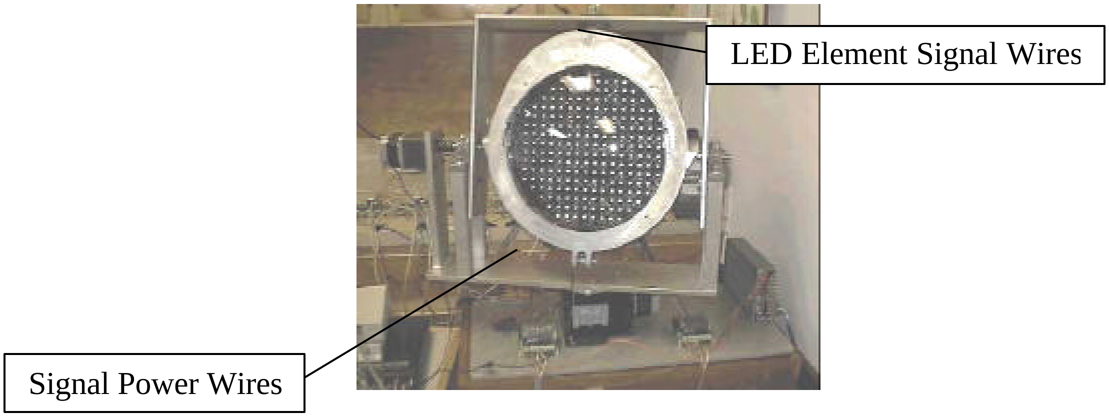

Figure 7. Layout of Signal and Power Wires for Test Signal.

The signal must be properly aligned with the colorimeter. The colorimeter is placed approximately 57.3 feet away from the signal. As shown in Figure 8 this allows the one-degree acceptance angle of the colorimeter to measure the entire 12-inch diameter signal. The colorimeter is positioned on the tripod such that the entire signal is inside the viewing circle.

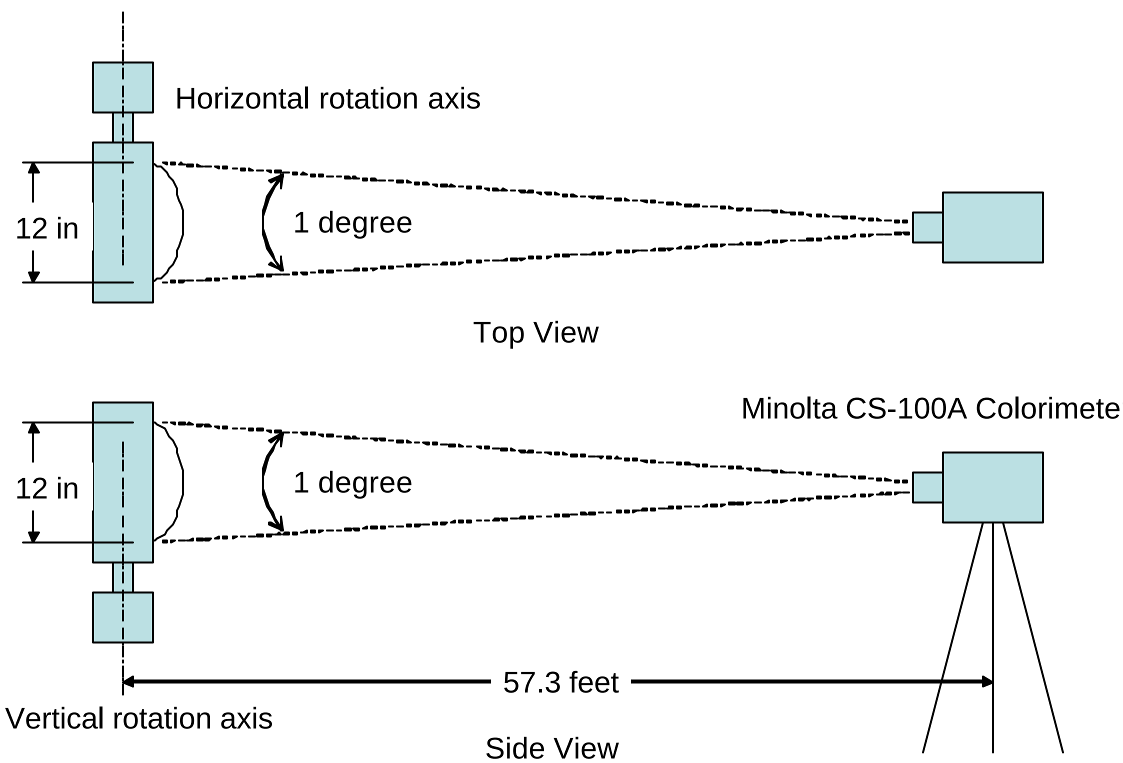

Figure 8. Layout of Test Setup for 12 Inch Signals.

A torpedo laser level was used to align the goniometer with the signal. The laser level bracket was screwed onto the lower right bolt on the face of the signal, as seen in Figure 9. The bracket was twisted until it fit tightly against the face of the signal to ensure it was orthogonal to the signal. The torpedo level was placed in the notch of the bracket, with the laser end pointing toward the colorimeter. A ¼-20 x 1-inch bolt secures the level to the bracket. The laser is turned on by pressing the push button at the end of the level opposite the laser.

A “Jog Motors” program is used to align the signal with the colorimeter. The goniometer is positioned such that the laser points at a cardboard target attached to the colorimeter. This target, seen in ***Figure*** 10, is in the same location with respect to the

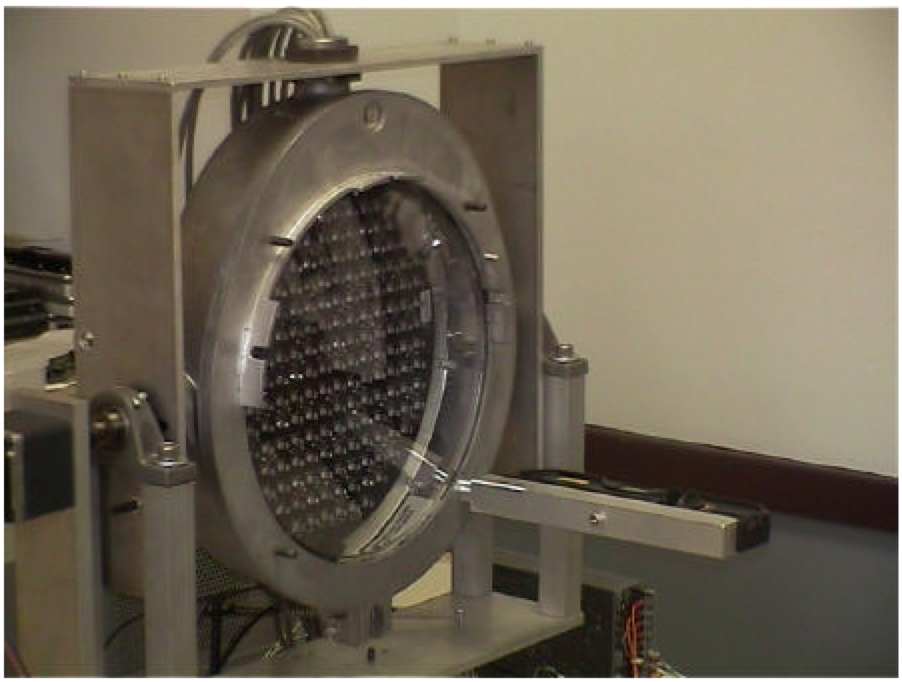

Figure 9. Positioning the Laser Torpedo Level on the Goniometer

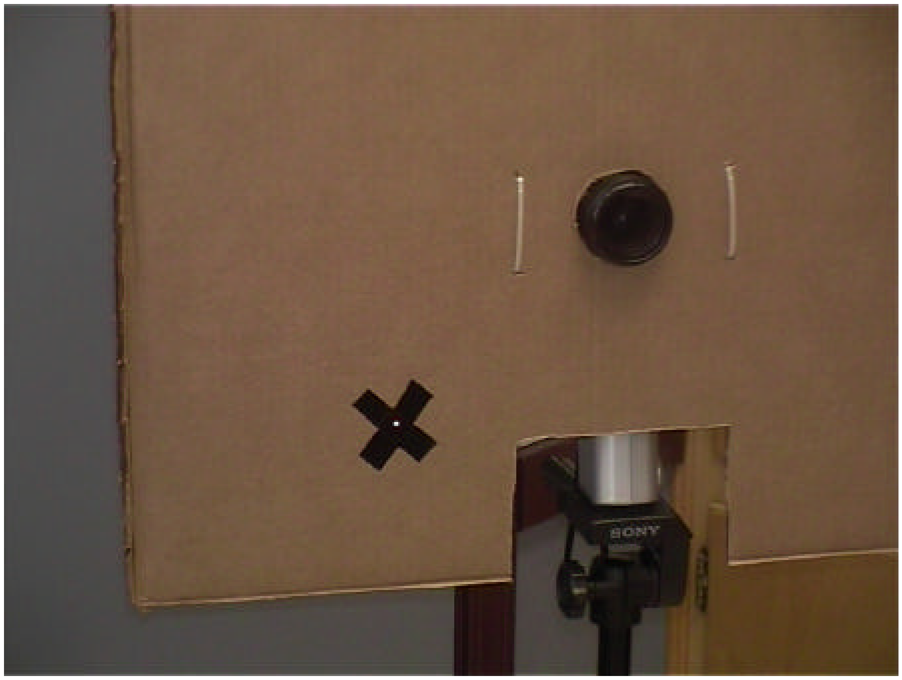

Figure 10. Aiming the Goniometer at the Colorimeter.

center of the colorimeter lens as the torpedo level is to the center of the signal. Now the signal is pointed directly at the colorimeter. The torpedo level and bracket are then carefully removed from the signal face.

Rule four of section 11.03 of the ITE standard specifies an alignment tolerance of ±0.25°. Over a distance of about 57.3 feet, the laser must point to a six-inch diameter circle centered at the target to meet this tolerance requirement. The accuracy of the IntelliPoint Plus Laser Torpedo Level is ¼-inch at 100 feet (Stanley, 1998).

<u>Determining the Distance Between Goniometer and Colorimeter</u>

LED signals are comprised of an array of LEDs, so a virtual point source must be determined to accurately calculate luminous intensity. The location of a virtual point source can be found with two irradiance (cd/m^2) measurements taken at known distances from an intermediate reference point (Ryer, 1997). These distances (d_1 and d_2) and irradiance measurements (E_1 and E_2) can be used with the equation below to find the offset of the reference point to the virtual point source.

$$X = \frac{d_1\sqrt{\frac{E_1}{E_2}} - d_2}{1 - \sqrt{\frac{E_1}{E_2}}}$$

For example, the irradiance at 57 feet away from the signal was measured at 6405 cd/m^2, and the irradiance at 59 feet was 5840 cd/m^2. With the reference point located at the signal, calculation of Equation 9 results in an offset of –14.7 feet. Therefore, if measurements are taken at a distance of 57 feet away from the signal, the virtual point source is 42.3 feet away from the colorimeter. <u>This virtual point source correction factor was used for all data taken from the 12 inch red LED crossing signals.</u>

RESULTS OF LABORATORY TESTING

The results from hundreds of lab tests of the nine LED signals are presented in this section of the report. These results will be summarized in two parts, based on the basic construction of the signals and operating similarities,

1. summary of results for the two 12 inch red crossing signals that did not have a power supply (NPS#1 and NPS#4),
2. summary of results for the four 12 inch red crossing signals that did have a power supply (WPS#2, WPS#3, WPS#5, and WPS#6),

Immediately following these two summaries are detailed results from each of the nine LED signals, as well as results from a small number of tests of a single 12 inch, red, incandescent crossing signal. Plots for the data collected in the lab are attached in the Appendix.

<u>Summary of Results for 12 Inch Red Crossing Signals without Power Supplies</u>

Two of the 12 inch red crossing signals that were tested did not use a power supply, NPS#1 and NPS#4. These signals are intended to be connected directly to the nominally 10 to 12 volt battery pack commonly found at crossings. Figure 11 summarizes the results from tests of these signals with 100% of the elements active at supply voltages ranging from 9 to 13 volts or more. Figure 12 summarizes the results from tests of these signals with different percentages of the elements active at a supply voltage of 10.5 volts. Three important observations about <u>LED signals that do not use power supplies</u> can be drawn from these two figures:

- there is a threshold supply voltage below which the signals have no light output,
- above this threshold voltage the maximum light intensity is a strong, fairly linear function of the supply voltage, and
- the maximum light intensity is essentially proportional to the number of active LED elements across the wide range tested (20% to 100% active).

As will be shown in later results, both of these signals exhibited a fairly constant relationship between the maximum light intensity and the <u>current draw</u> during all tests. For the NPS#1 signal (which uses fairly old technology), this constant is approximately 125 to 150 candela/amp. The NPS#4 signal had a much better light efficiency at roughly 700 to 900 candela/amp.

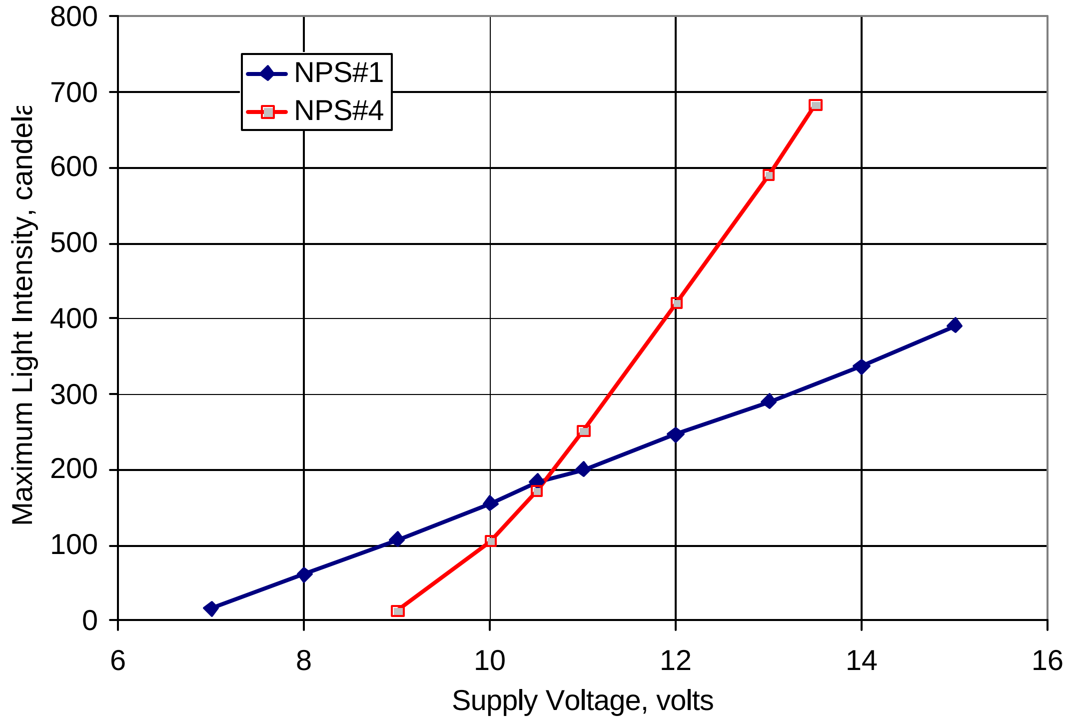

Figure 11. Maximum Light Intensity from NPS#1 and NPS#4 Signals with Different Supply Voltages.

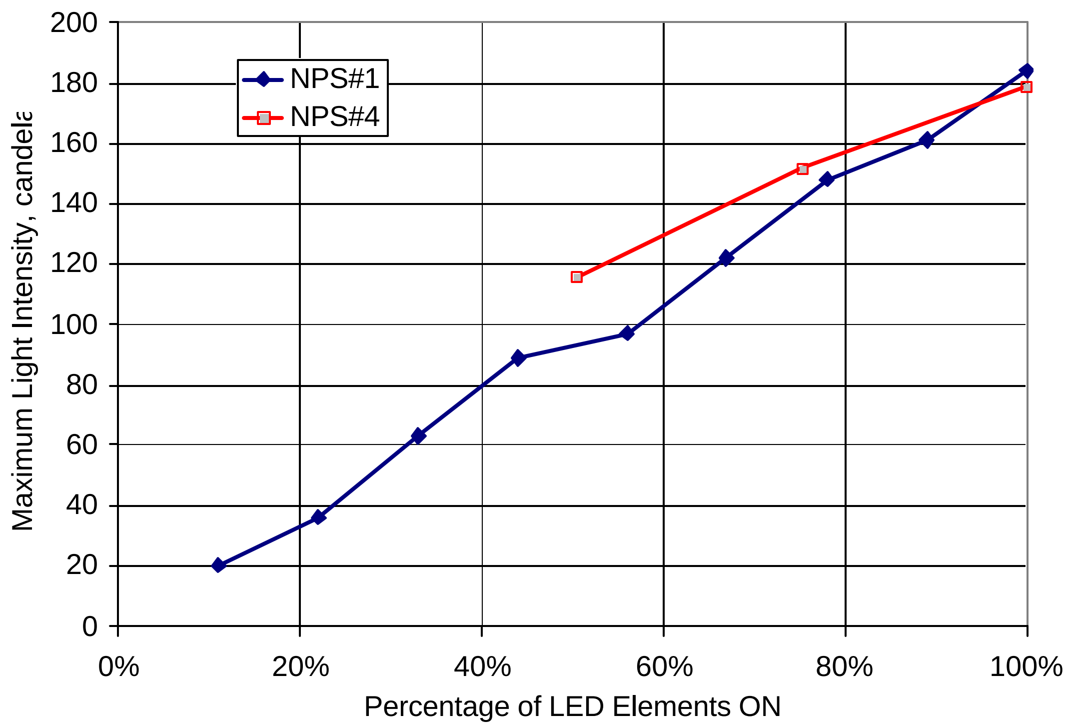

Figure 12. Maximum Light Intensity from NPS#1 and NPS#4 Signals with Different Percentages of Active Elements.

Summary of Results for 12 Inch Red Crossing Signals with Power Supplies

Four of the 12 inch red crossing signals that were tested used a power supply to regulate the current supplied to the LEDs (WPS#2, WPS#3, WPS#5 and WPS#6). These signals are clearly intended maintain a relatively constant light output over a fairly wide range of battery supply voltages. Figure 13 summarizes the results from tests of these signals with 100% of the elements active at supply voltages ranging from 7.5 to 13 volts or more. Figure 14 summarizes the results from tests of two of these signals (WPS#2 and WPS#3) with different percentages of the elements open-circuited at a supply voltage of 10.5 volts. Two important observations about LED signals that use power supplies or regulators can be drawn from these two figures:

1. above a threshold voltage (typically 9 volts), the maximum light intensity is not a strong function of the supply voltage, and
2. the maximum light intensity is not a strong function of the number of open-circuited LED elements.

As will be shown in later results, all four of these signals exhibited a fairly constant relationship between the maximum light intensity and the power consumption during all tests. These ratios ranged from 12 to 15 candela/watt for the WPS#5 signal up to about 60 to 70 candela/watt for the WPS#2 signal.

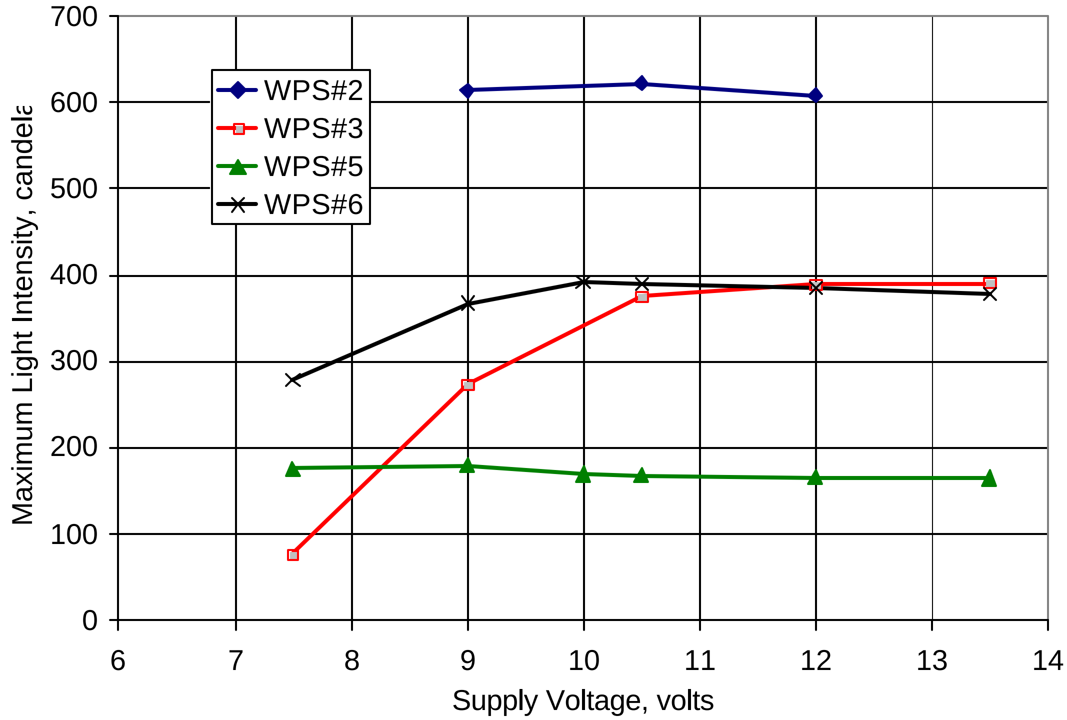

Figure 13. Maximum Light Intensity from WPS#2, WPS#3, WPS#5 and WPS#6 Signals with Different Supply Voltages.

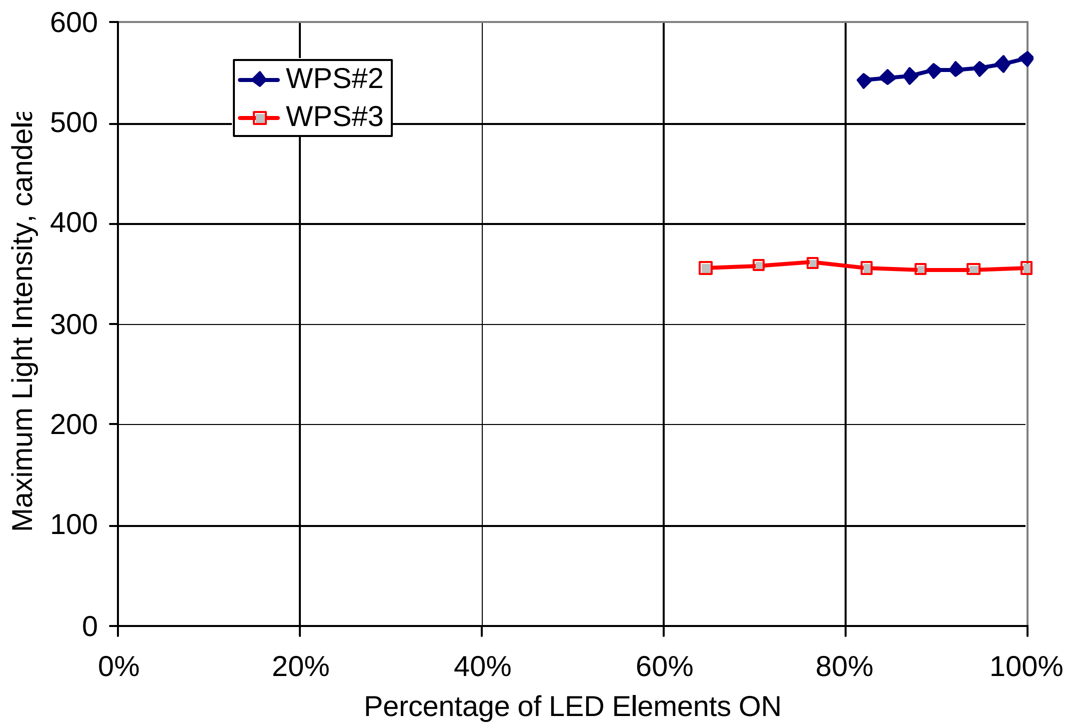

Figure 14. Maximum Light Intensity from WPS#2 and WPS#3 Signals with Different Percentages of Active Elements.

Data from Incandescent signal

A limited amount of data was collected from the incandescent signal purchased from Western Cullen-Hayes along with the aluminum signal housing. This unit was supplied with a 25 watt incandescent bulb and a 30/15 red lens. Figures A0.1 through A0.4 of the appendix show the effects of varying voltage in the range of 9.0 volts to 13.5 volts with the incandescent signal. Table 11 summarizes the maximum light intensity responses, which are significantly larger than any of the responses from the 12 inch red LED signals. The incandescent crossing signal has a distinct, very bright "hot spot" in the 0 degree, on-axis position. However, as the data in the appendix show, the light intensity drops rapidly as the signal is viewed in anything other than the horizontal plane. This observation was corroborated in the field tests conducted during the Transport Canada study. The incandescent signal is easily visible from large distances when viewed directly on-axis, but was significantly less visibly when viewed off-axis.

Table 11. Results from incandescent signal with varying voltage input.

Voltage	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)
9.0	1166	2.30	20.7
10.5	1889	2.50	26.3
12.0	2802	2.69	32.3
13.5	3923	2.88	38.8

Figure 15 shows the chromaticity results from the same tests shown in Table 11. The results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. There is a small, but definite trend towards a more red (larger x value), and less green (lower y value) color as the voltage is increased. Most of the LED signals did not exhibit this color shift trend as a function of supply voltage.

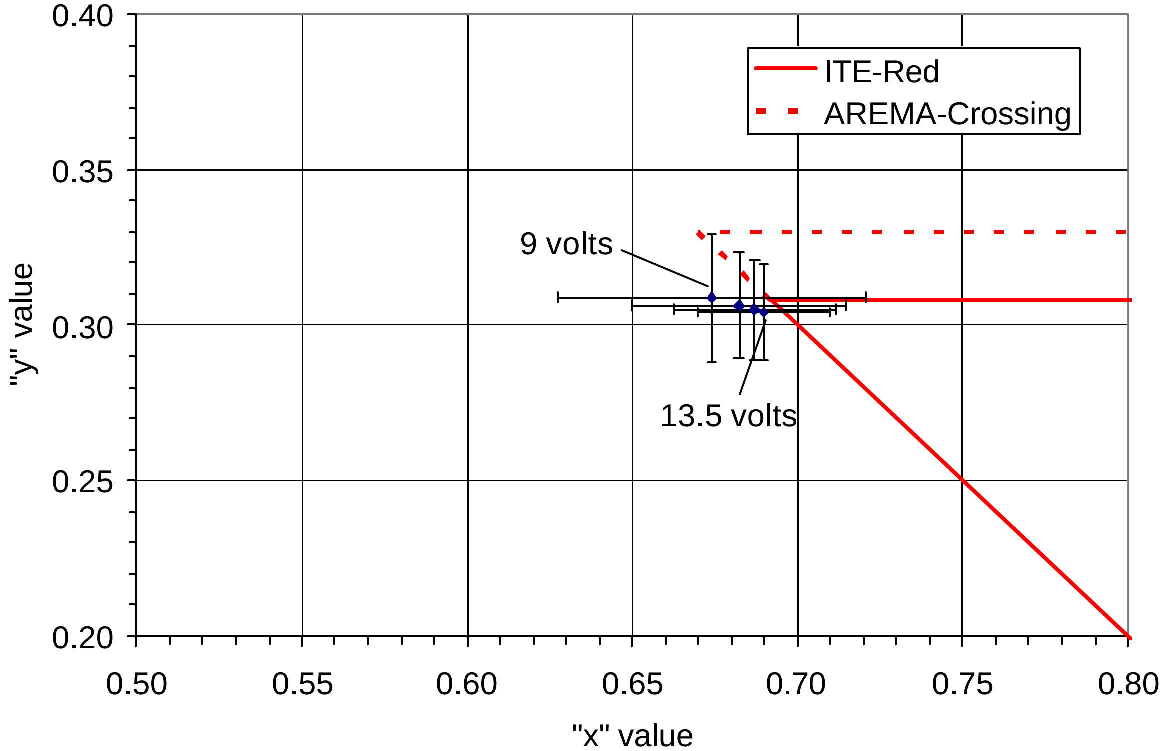

Figure 15. Chromaticity results from incandescent signal with varying voltage input.

<u>Data from Aurora signal (NPS#1)</u>

The first twelve inch rail crossing signal tested is the Aurora unit purchased from Western Cullen-Hayes. No power supply (NPS) is used with this signal - the LEDs are directly connected to AC or DC power. The circuit configuration for this signal is shown in Figure 16. This signal (referred to as NPS#1 in this report) has 72 sets of three LEDs arranged in a series circuit, for a total of 216 visible elements.

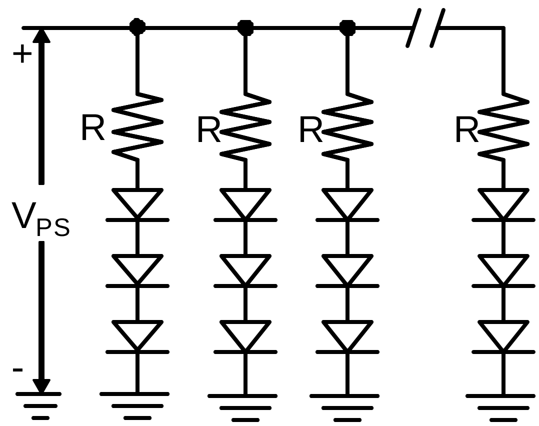

Figure 16. LED circuit configuration for NPS#1 signal.

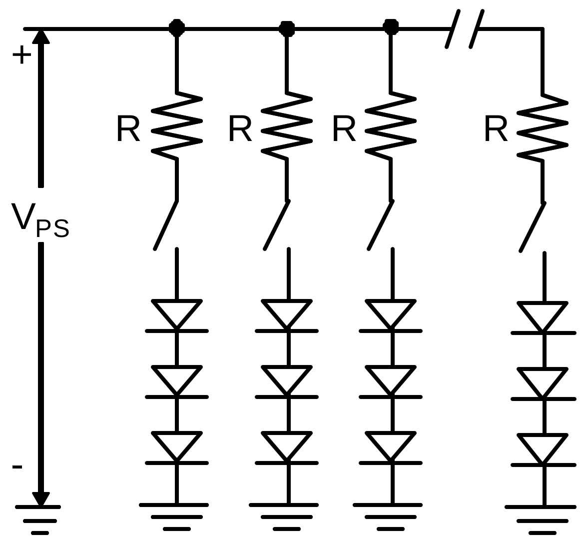

Figure 17. NPS#1 signal configured for open-circuiting.

Figures A1.1.1 through A1.1.10 of the appendix show the effects of varying voltage in the range of 7.0 volts to 15.0 volts with 100% of the LED elements active. Data from these figures is summarized in Table 12 and Figure 18. The light output from this signal is a strong function of the voltage, with maximum outputs ranging from 390 candela at 15.0 volts to 16 candela at 7.0 volts. The maximum output at the nominal 10.5 volts is approximately 184 candela. This value is fairly close to the nominal 160 candela rating of this light. As shown in Table 12, supply currents ranged from 0.13 amps at 7.0 volts to 2.52 amps at 15 volts with 1.11 amps at the nominal 10.5 volt input. Power consumption ranged from 0.9 watts at 7.0 volts to 21.8 watts at 15 volts with 13.2 watts at the nominal 10.5 volt input. The light-current efficiency is relatively constant at 133 to 146 candela/amp at all but the lowest supply voltage.

Table 12. Results from NPS#1 with varying voltage input.

Supply Voltage	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Current Efficiency (candela/amp)
7.0	16	0.13	0.9	126
8.0	60	0.42	3.4	142
9.0	107	0.76	6.8	141
10.0	155	1.11	11.1	139
10.5	184	1.26	13.2	146
11.0	200	1.46	16.1	137
12.0	245	1.82	21.8	135
13.0	290	2.17	28.2	134
14.0	336	2.52	35.3	133
15.0	390	2.87	43.1	136

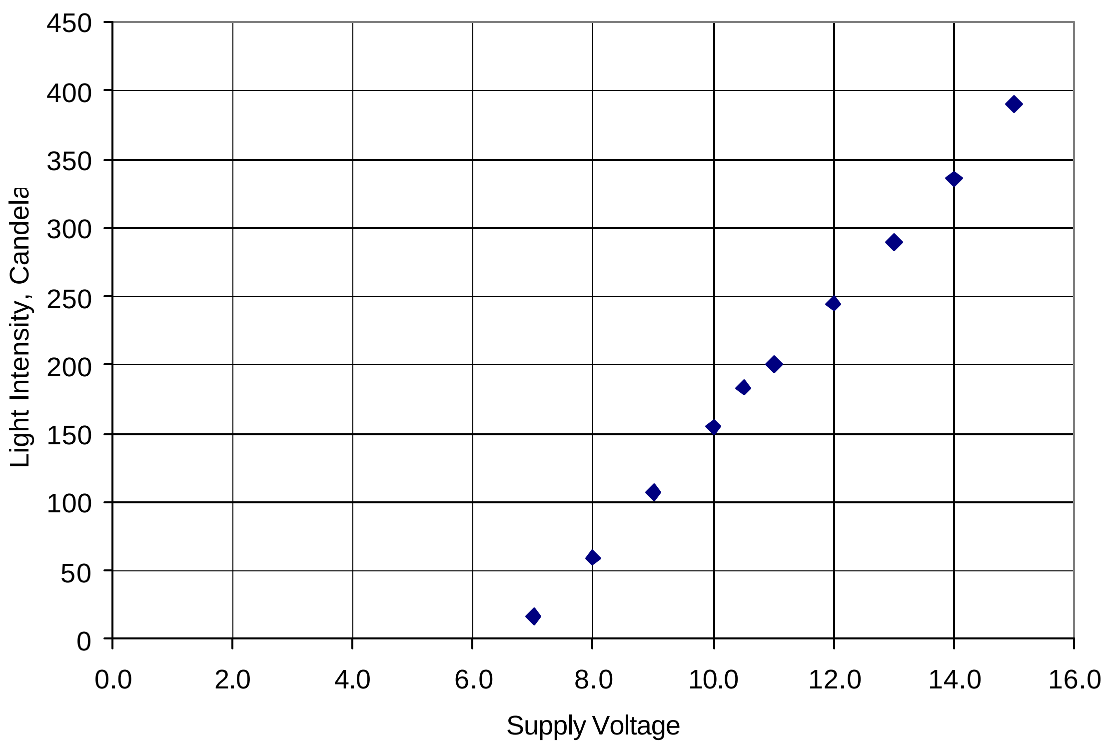

Figure 18. Maximum light intensity from NPS#1 with varying voltage input.

Figure 19 shows the chromaticity results from the same tests shown in Figure 18. All of the results (except for those at 7.0 volts) show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. The color shift at 7.0 volts is closely related to the low level of light intensity (only 16 candela). There is no apparent color shift with input voltage with the NPS#1 signal.

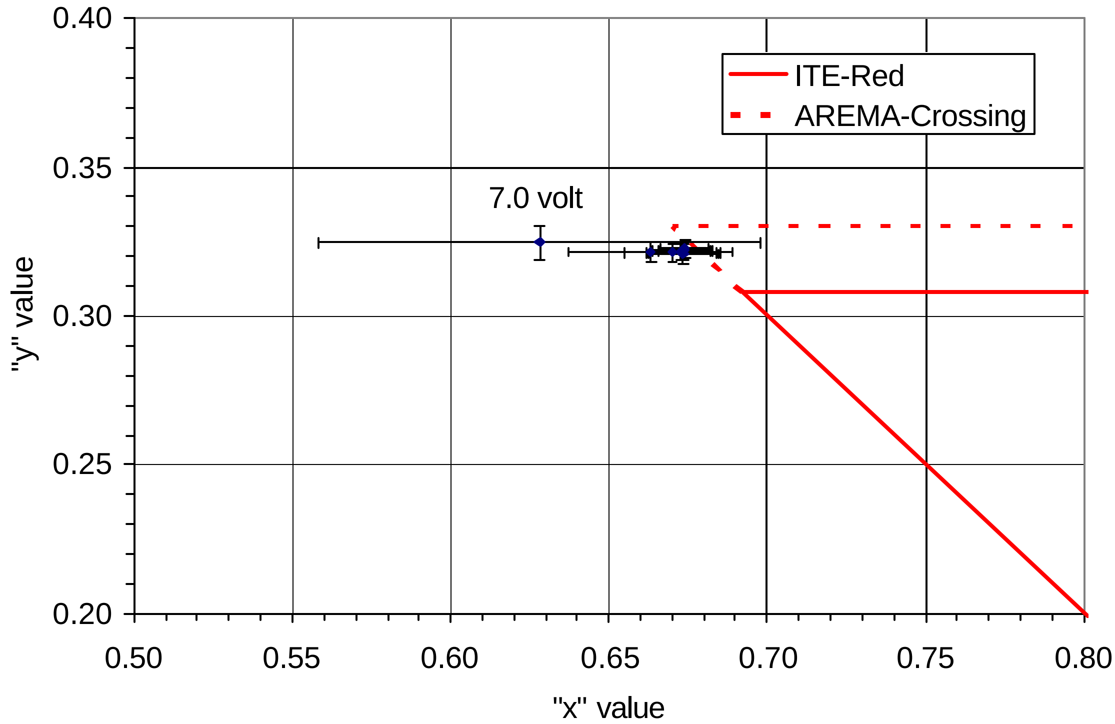

Figure 19. Chromaticity results from NPS#1 with varying voltage input.

Figures A1.2.1 through A.1.2.9 of the appendix show the effects of varying the number of active LED elements from 100% to 11% at a constant 10.5 volts. Table 13 and Figure 20 summarize these results. The light output from the NPS#1 signal is a strong function of the number of active elements, with maximum outputs ranging from 184 candela at 100% (216 elements) to 20 candela at 11% (24 elements). Supply currents ranged from 1.26 amps at 100% (216 elements) to 0.15 amps at 11% (24 elements). Power consumption ranged from 13.2 watts at 100% (216 elements) to 1.6 watts at 11% (24 elements). These results show a fairly linear relationship between the number of active LED elements and the maximum light intensity output. There is also a fairly constant relationship between the supply current and the maximum light intensity output of between 125 and 146 candela/amp.

Table 13. Results from NPS#1 at 10.5 volts.

Percentage of LEDs ON	Portion of Signal ON/OFF	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Current Efficiency (candela/amp)
100%	FFF	184	1.26	13.2	146
89%	FBF	161	1.13	11.9	143
78%	D7F	148	1.00	10.5	148
67%	FEC	122	0.86	9.0	141
56%	F93	97	0.72	7.6	135
44%	D6C	89	0.58	6.1	153
33%	D13	63	0.44	4.6	144
22%	F80	36	0.29	3.0	125
11%	D02	20	0.15	1.6	136

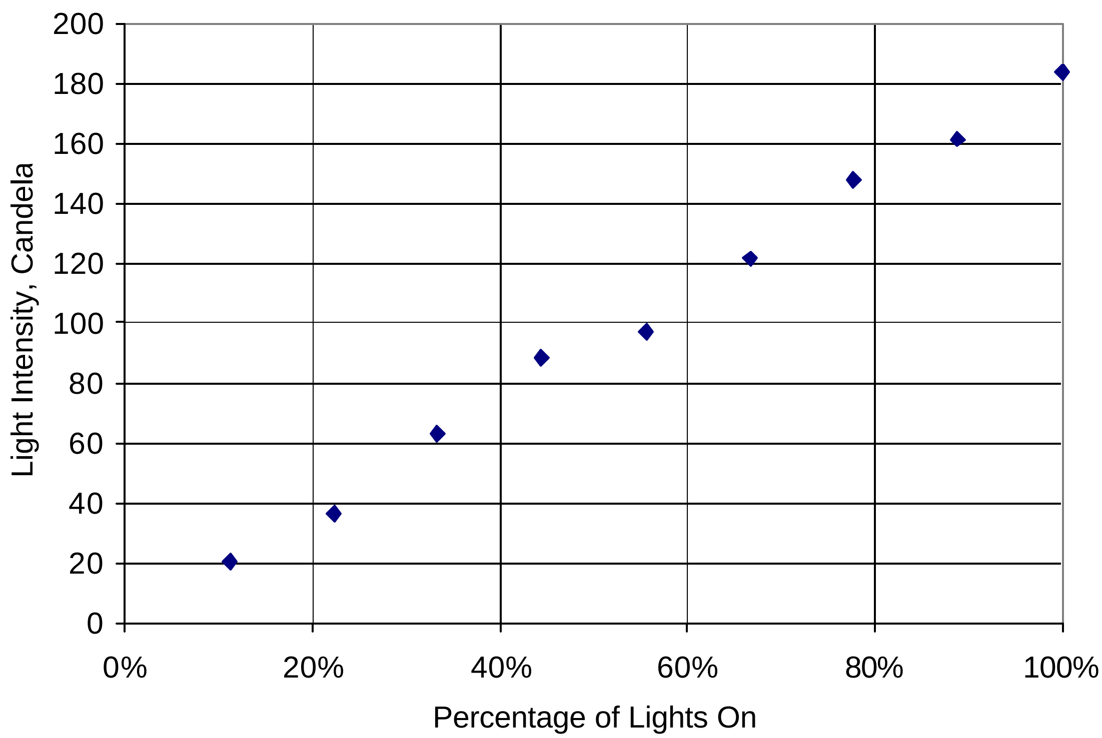

Figure 20. Maximum light intensity from NPS#1 at 10.5 volts.

Figure 21 shows the chromaticity results from the same tests shown in Figure 20. There is more scatter in the color measurements shown in this figure than in any other results of this report. However, there is no correlation to the color values and the percentage of lights on. The data are essentially randomly distributed. Since this data was taken during one of the earliest tests conducted during the project, there may have been a testing error.

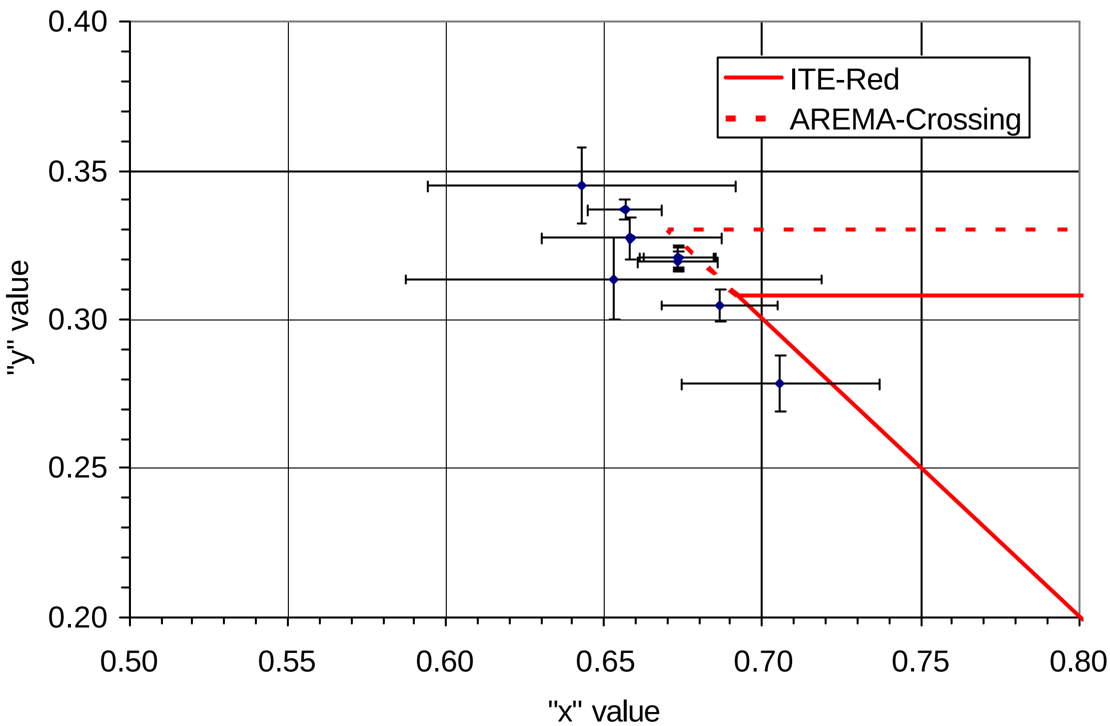

Figure 21. Chromaticity results from NPS#1 at 10.5 volts.

Figures A1.3.1 through A.1.5.10 of the appendix show the effects of varying the voltage in the range of 7.0 volts to 15.0 volts with 67% (144) of the LED elements active. Three different patterns of ON/OFF elements (FD3, FEC, and D3F) are shown in Figure 22.

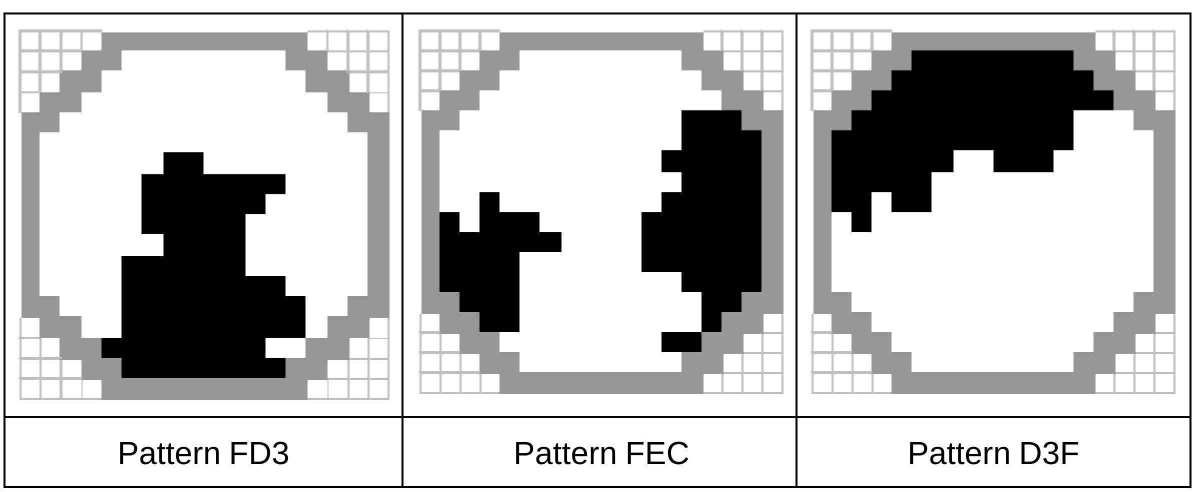

Figure 22. Patterns FD3, FEC, and D3F.

Data from these figures is summarized in Figure 23. The maximum light output from this signal remains fairly constant regardless of the particular sections of the signal that are open-circuited to the OFF state. The maximum difference of 23 candela (266 – 243) occurs at 15 volts. The maximum difference at the nominal voltage of 10.5 volts is only 12 candela (129-117). There is also a fairly constant relationship between the supply current and the maximum light intensity output of between 125 and 151 candela/amp.

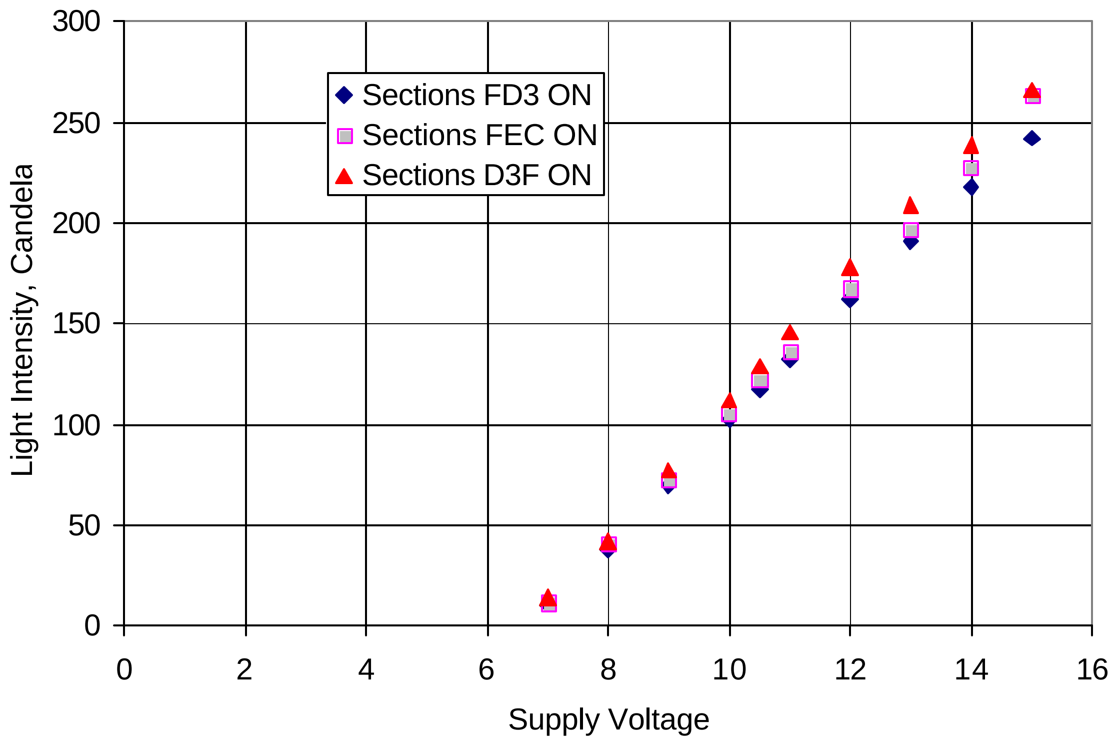

Figure 23. Maximum light intensity from NPS#1 with varying voltage input and 67% (144) LED elements ON.

Data from Safetran signal (WPS#2)

Figure 24 shows the configuration of the elements in a twelve inch signal supplied by Safetran that uses a power supply to regulate the voltage and current applied to the LEDs. This signal will be referred to as WPS#2 ("with power supply") in this report. The WPS#2 signal uses 192 elements in 49 sets of four LEDs. Note that the LEDs are arranged in both series and parallel to minimize the effect of losing a single element. Figure 25 shows the modification to the WPS#2 signal that allows a single LED in a set of four elements to be open-circuited. The voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used.

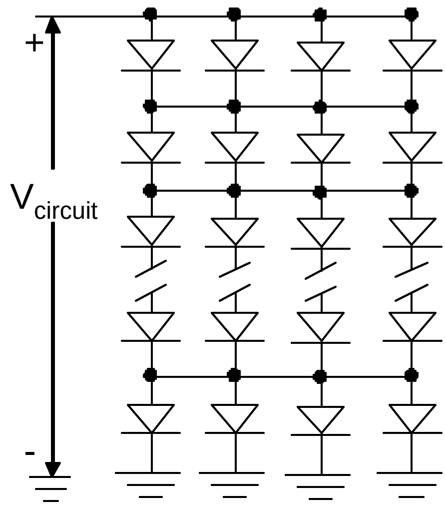

Figure 24. LED circuit configuration for WPS#2 signal

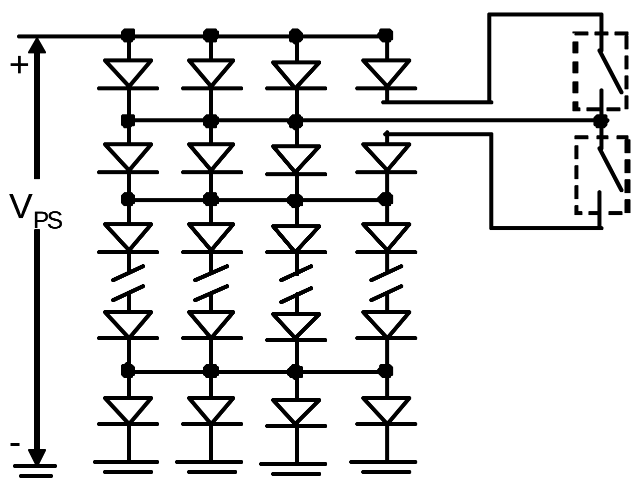

Figure 25. WPS#2 signal configured for open-circuiting

Figures A2.1.1 through A2.1.3 of the appendix show the effects of varying voltage in the range of 9.0 volts to 12.0 volts with 100% of the LED elements active. Data from these figures is summarized in Table 14. The light output from this signal is not a strong function of the supply voltage, with maximum outputs ranging from 622 candela at 10.5 volts to 614 candela at 9.0 volts. Supply currents ranged from 0.72 amps at 12.0 volts to 1.07 amps at 12 volts. Power consumption was essentially constant in the range from 8.7 to 9.6 watts. The light-power efficiency is relatively constant, ranging from 64.0 candela/watt at 9.0 volts to 69.9 candela/watt at 12.0 volts.

Table 14. Results from WPS#2 with varying voltage input.

Supply Voltage	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light - Power Efficiency (candela/watt)
9	614	1.07	9.6	64.0
10.5	622	0.86	9.1	68.4
12	608	0.72	8.7	69.9

Figure 26 shows the chromaticity results from the same tests shown in Table 14. All of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift with input voltage with the WPS#2 signal.

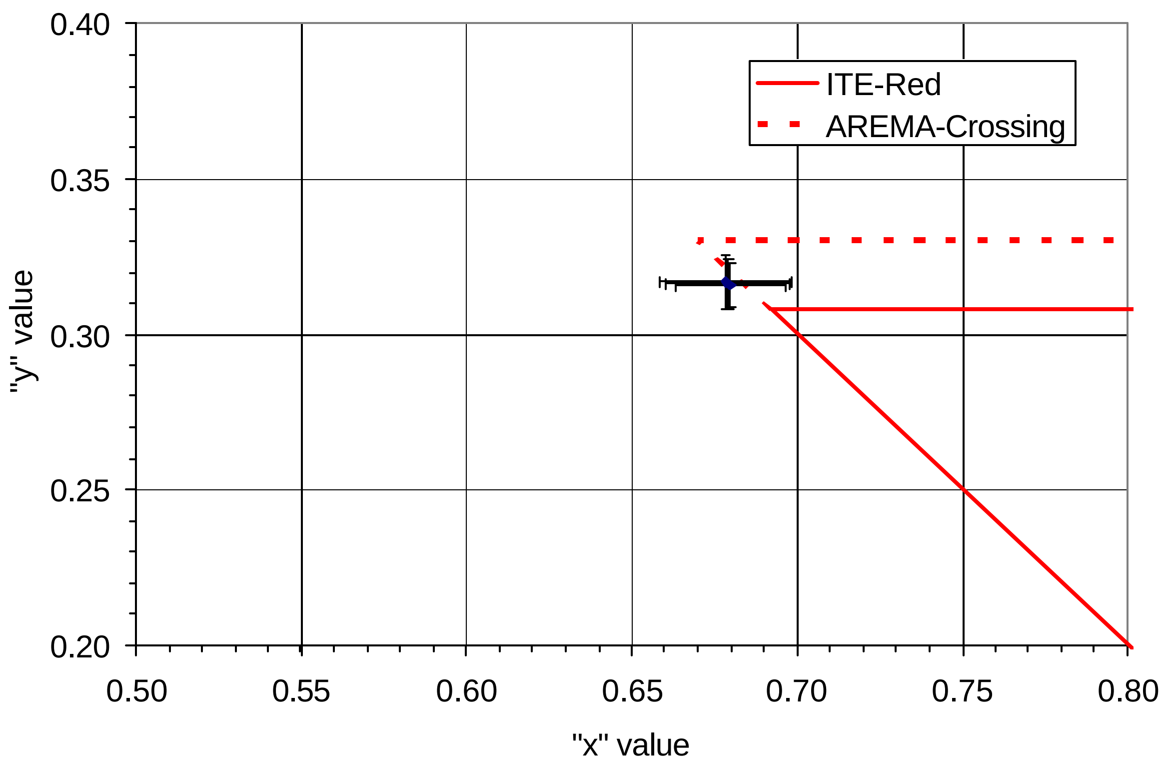

Figure 26. Chromaticity of WPS#2 with varying voltage input.

Figures A2.2.1 through A.2.2.8 of the appendix show the effects of varying the number of active LED elements from 100% to 82% via open-circuiting at a constant 10.5 volts. Table 15 summarizes these results. The light output from the WPS#2 signal is not a function of the number of active elements, with maximum outputs ranging from 564 candela at 100% (196 elements) to 548 candela at 82% (161 elements). Supply current and power consumption are essentially constant at 0.88 amps and 9.2 watts, respectively. The number of open-circuited elements has a negligible effect on the power requirements for the WPS#2 signal. The relative insensitivity of the WPS#2 signal to the number of open-circuited elements is due to two factors:

1. the use of a power supply to regulate voltage and current, and
2. the combined series and parallel arrangement of LEDs (shown in Figure 24).

There is also a fairly constant relationship between the maximum light intensity output and the power consumption of between 58.9 and 61.9 candela/watt.

Table 15. Results from WPS#2 at 10.5 volts (open-circuits)

Supply Voltage	Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
10.5	100%	196	564	0.87	9.1	61.9
10.5	97.4%	191	559	0.87	9.1	61.4
10.5	94.9%	186	554	0.87	9.1	60.9
10.5	92.3%	181	553	0.87	9.1	60.8
10.5	89.8%	176	552	0.87	9.2	60.0
10.5	87.2%	171	547	0.87	9.2	59.5
10.5	84.7%	166	545	0.88	9.2	59.2
10.5	82.1%	161	542	0.88	9.2	58.9
9.0	89.8%	176	551	1.08	9.8	56.2
10.5	89.8%	176	552	0.87	9.2	60.0
12.0	89.8%	176	548	0.87	10.5	52.2

Figure 27 shows the chromaticity results from the same tests shown in Table 15. All of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift due to varying the percentage of ON elements via open circuiting with the WPS#2 signal.

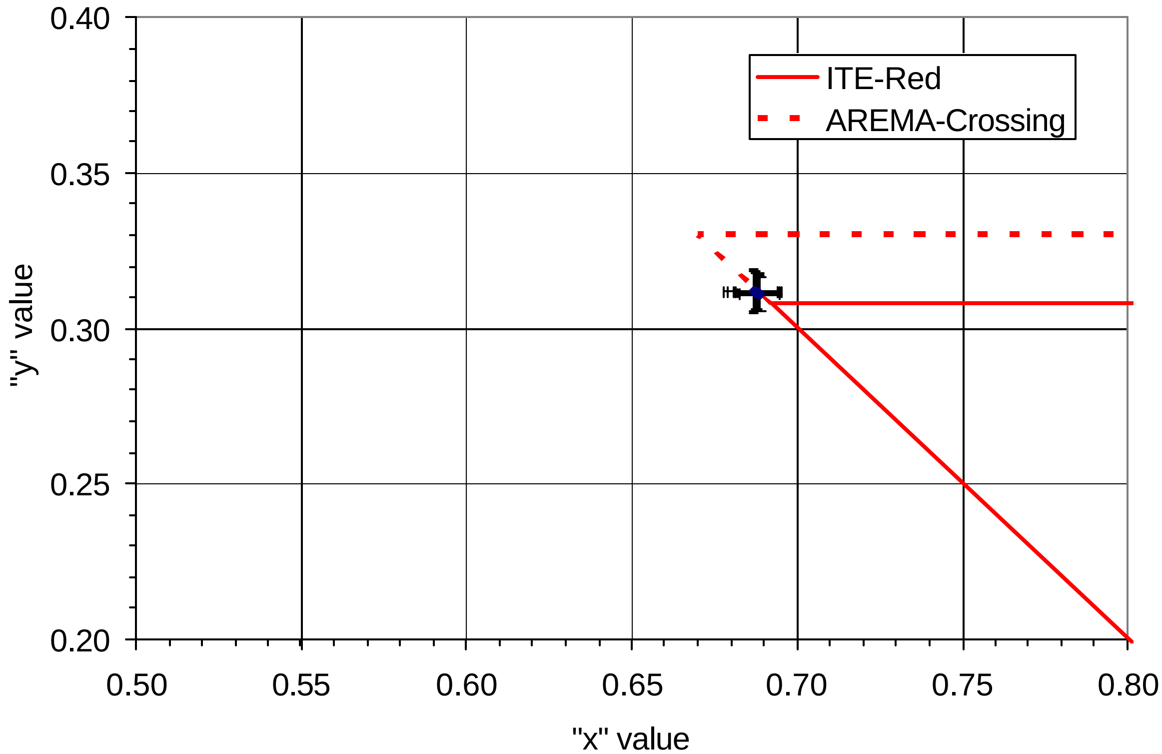

Figure 27. Chromaticity of WPS#2 at 10.5 volts (open circuits).

Figures A2.2.9 through A2.2.11 of the appendix show the effects of varying voltage in the range of 9.0 volts to 12.0 volts with 89% of the LED elements active. Data from these figures is summarized in the last three rows of Table 15. These data show again that the light output from the WPS#2 signal is not a strong function of the supply voltage, with maximum outputs ranging from 552 candela at 10.5 volts to 548 candela at 9.0 volts.

Figures A2.3.1 through A.2.3.8 of the appendix again show the effects of varying the number of active LED elements from 100% to 82% via open-circuiting at a constant 10.5 volts. Table 16 summarize these results. This is a duplicate set of data to that shown in Table 15. This second set of data was taken more than 12 months after the first set of data. As shown in Table 16, the maximum outputs have dropped to 483 candela at 100% (196 elements) to 457 candela at 85% (166 elements). Supply current and power consumption are similar to the earlier data at 0.84 amps and 9.0 watts, respectively. The fairly constant relationship between the power consumption and the maximum light intensity output has dropped to between 50.7 and 54.9 candela/watt. There are three possible reasons for the differences in these two sets of data:

1. aging effects in the WPS#2 signal have reduced the available output,
2. the calibration of the Minolta colorimeter has shifted, and
3. small differences in the test setup have occurred.

In any event, the differences seen between these two sets of data are relatively small and are not a source of concern.

Table 16. Results from WPS#2 at 10.5 volts (open-circuits), second test

Supply Voltage	Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
10.5	100.0%	196	483	0.84	8.8	54.9
10.5	97.4%	191	477	0.84	8.9	53.6
10.5	94.9%	186	473	0.84	8.9	53.1
10.5	92.3%	181	472	0.85	8.9	53.1
10.5	89.8%	176	469	0.85	8.9	52.7
10.5	87.2%	171	464	0.85	9	51.6
10.5	84.7%	166	457	0.85	9	50.7
10.5	82.1%	161	465	0.86	9	51.7
9	89.8%	176	466	1.05	9.4	49.6
10.5	89.8%	176	469	0.85	8.9	52.7
12	89.8%	176	466	0.85	10.3	45.3

Similarly, Figures A2.3.9 through A2.3.11 of the appendix show the effects of varying voltage in the range of 9.0 volts to 12.0 volts with 89% of the LED elements active. Data from these figures is summarized in the last three rows of Table 16. These data can be compared to the last three rows of Table 15.

Figure 28 shows the modification to the WPS#2 signal that allows short-circuiting of individual elements. Figures A2.4.1 through A.2.4.6 of the appendix show the effects of varying the number of active LED elements from 100% to 59.2% <u>via short-circuiting</u> at a constant 10.5 volts. Table 17 and Figure 29 summarize these results. The light output from the WPS#2 signal is a strong function of the number of active elements, with maximum outputs ranging from 542 candela at 100% (196 elements) to

316 candela at 59.2% (116 elements) on. Supply currents ranged from 0.85 amps at 100% to 0.49 amps at 59.2% on. Power consumption ranged from 9.0 watts at 100% to 5.1 watts at 59.2% on. These results show that the maximum light output by the WPS#2 light was proportional to the number of illuminated LEDs in the short-circuiting tests. There is also a very constant relationship between the power consumption and the maximum light intensity output of between 60.2 and 63.8 candela/watt. One interesting phenomena observed with the WPS#2 signal is that it began to blink off and on when less than 59% (116 elements) of the 196 LED elements were on.

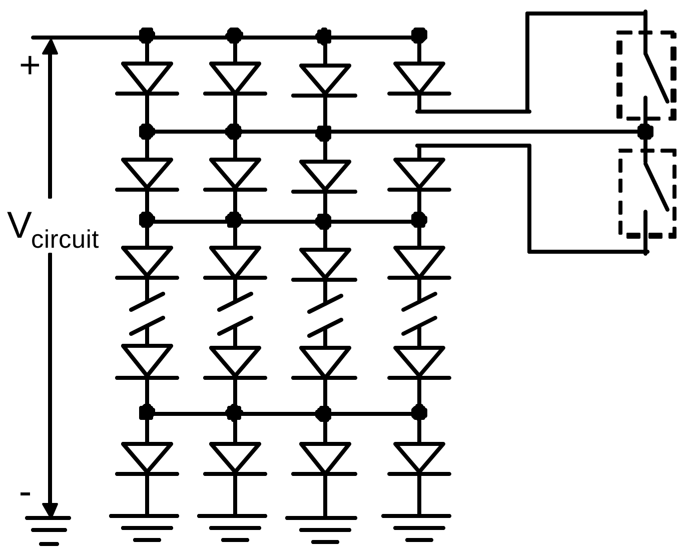

Figure 28. WPS#2 signal configured for short-circuiting

Table 17. Results from WPS#2 at 10.5 volts (short-circuits)

Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
100%	196	542	0.85	9.0	60.2
91.8%	180	507	0.78	8.2	61.8
83.7%	164	453	0.70	7.4	61.2
75.5%	148	405	0.63	6.6	61.4
67.3%	132	370	0.55	5.8	63.8
59.2%	116	316	0.49	5.1	61.9

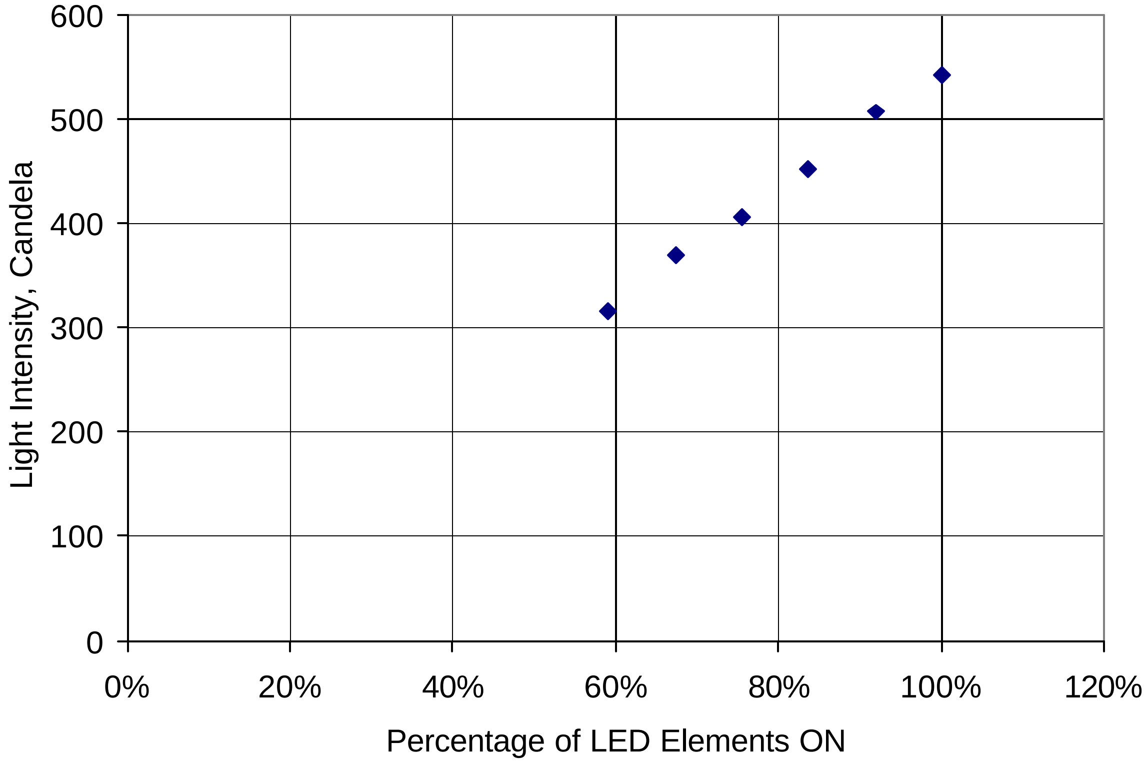

Figure 29. Maximum light intensity from WPS#2 at 10.5 volts (short-circuits)

Figure 30 shows the chromaticity results from the same tests shown in Figure 29. There is a small trend of color shift due to varying the percentage of ON elements via short circuiting with the WPS#2 signal. As the percentage of ON elements is decreased the color shifts to slightly lower "x" (red) values and slightly higher "y" (green) values. All of the results show remain clustered near the edge of the AREMA limits for red crossing signals.

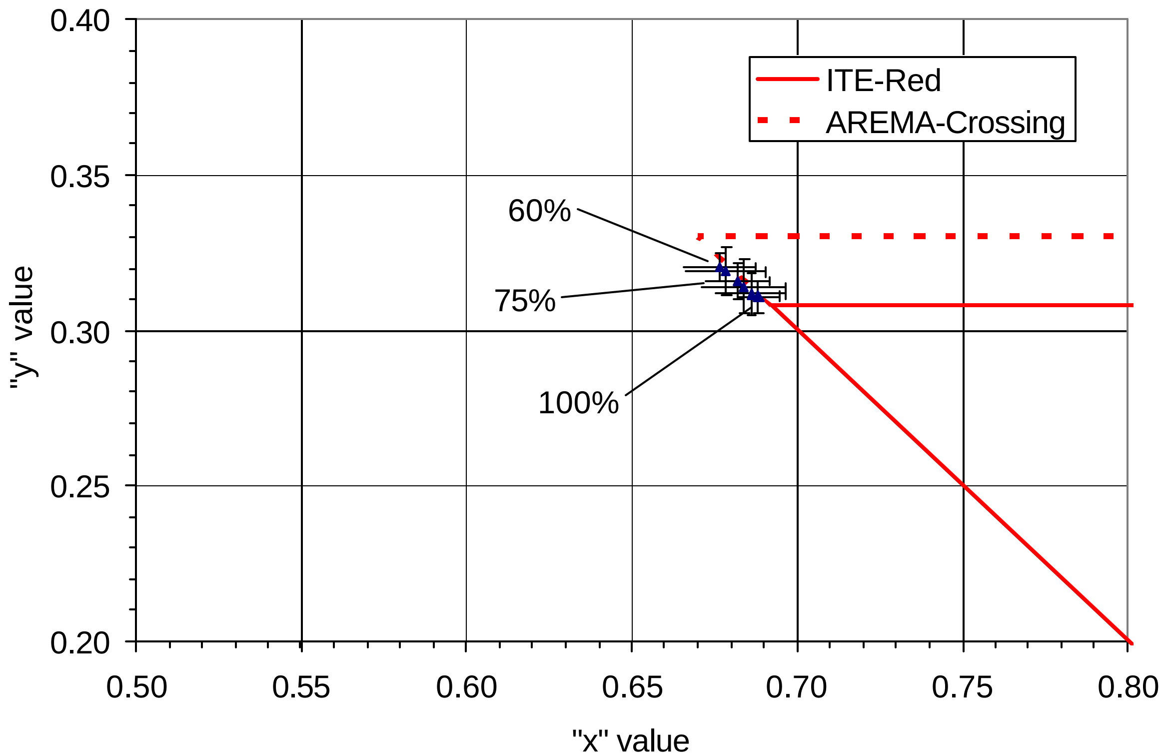

Figure 30. Chromaticity of WPS#2 at 10.5 volts (short-circuits)

Data from General Signal signal (WPS#3)

Figure 31 shows the configuration of the elements in a twelve inch signal supplied by General Signal that uses a power supply to regulate the voltage and current applied to the LEDs. This signal will be referred to as WPS#3 ("with power supply") in this report. The WPS#3 signal uses 254 visible elements in sets of three LEDs in a series circuit. Several other white LEDs are used as sidelight indicators. Due to the configuration of this signal, only open-circuit testing is possible. Figure 32 shows the modification to the WPS#3 signal that allows a set of three LED elements to be open-circuited. Note that the voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used.

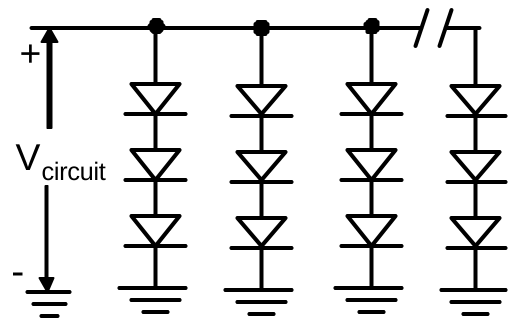

Figure 31. LED circuit configuration for WPS#3 signal

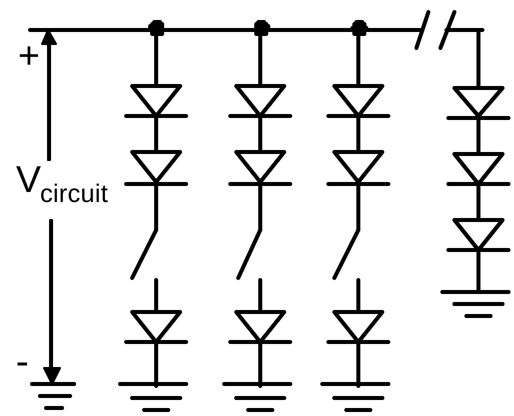

Figure 32. WPS#3 signal configured for open-circuiting

Testing of the WPS#3 signal with open-circuited elements determined that this signal has a relatively strong "heating" effect. Figure 33 shows results from a test where the signal was pointed directly at the colorimeter and not moved during 6 minutes of measurements. The data show that the light output (open triangles and diamonds) increases with time. Figure 33 also shows that the light output closely tracks the current consumption (shown by the closed triangles and diamonds). This "heating effect" was observed when all 254 of the elements were active (shown by triangles) and when 80 of the elements were open-circuited (shown by the diamonds). The amount that the light intensity changes during the test is not large -- about 35 candela out of 325 to 375 candela. However, the heating effect does make it difficult to accurately characterize the light intensity of the WPS#3 signal as a function of the number of active elements while conducting the ITE or TC position tests. Light intensity measurements taken during the ITE or TC tests with this signal are not only a function of the horizontal and vertical angle, but are also a function of time. Note that Figure 33 shows the initial light output for 254 LEDs (~325 cd) to be less than the final light output with 164 LEDS (~332 cd).

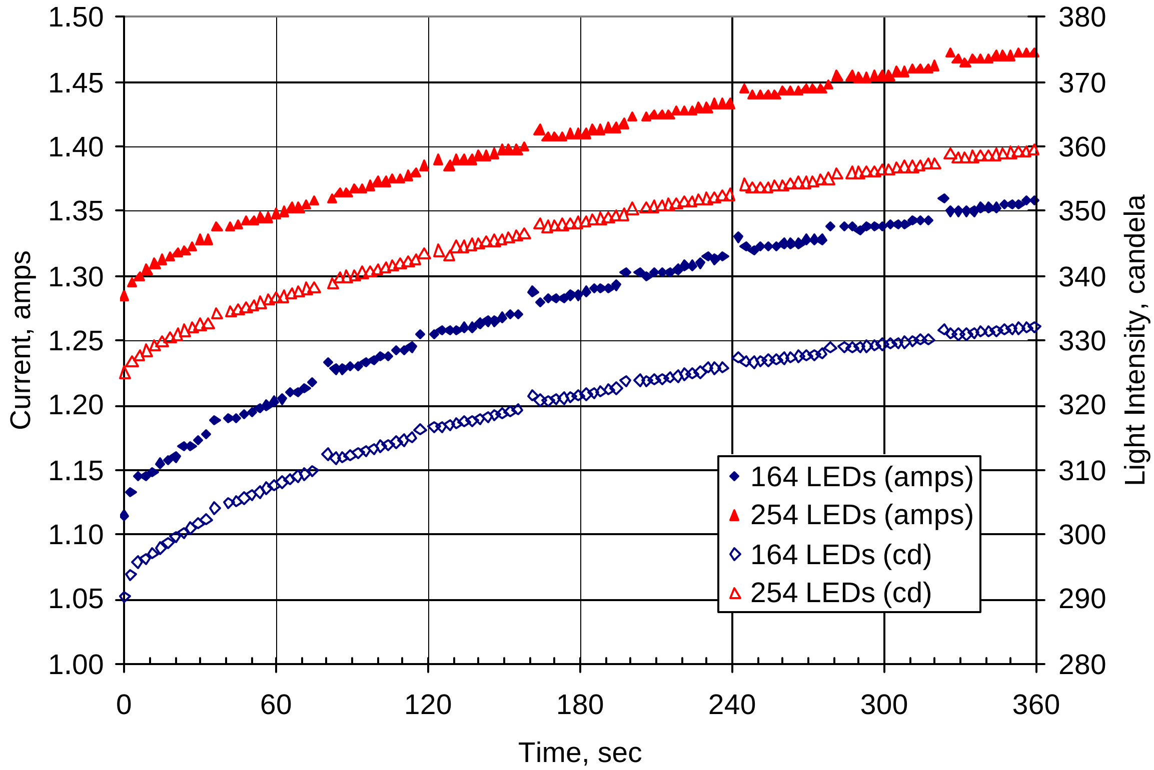

Figure 33. Current and Light Output vs. Time for WPS#3 signal.

Figures A3.1.1 through A.3.1.5 of the appendix show the effects of varying voltage in the range of 7.5 volts to 13.5 volts with 100% of the LED elements active. Data from these figures is summarized in Table 18 and Figure 34. In light of the results shown in Figure 33, these data must be interpreted carefully. The light output from this signal is a function of the voltage, with maximum outputs ranging from 391 candela at 13.5 volts to 76 candela at 7.5 volts. As shown in Table 18, supply currents ranged from 0.41 amps at 7.0 volts to 1.53 amps at 10.5 volts. Power consumption ranged from 3.1 watts at 7.5 volts to 16.2 watts at 12 volts. The maximum light outputs and the power from the nominal 10.5 volts (375 candela, 16.1 watts) up to 13.5 volts (391 candela, 16.1 watt) are essentially the same, which indicates that the power supply is effective at limiting the power once the nominal supply of 10.5 volts is applied. The light-power efficiency is also remarkably constant in the range of 23.4 to 24.6 candela/watt over the entire 7.5 to 13.5 volt range.

Table 18. Results from WPS#3 with varying voltage input.

Supply Voltage	Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
7.5	100%	254	76	0.41	3.1	24.6
9.0	100%	254	273	1.26	11.3	24.1
10.5	100%	254	375	1.53	16.1	23.4
12.0	100%	254	390	1.35	16.2	24.1
13.5	100%	254	391	1.19	16.1	24.3

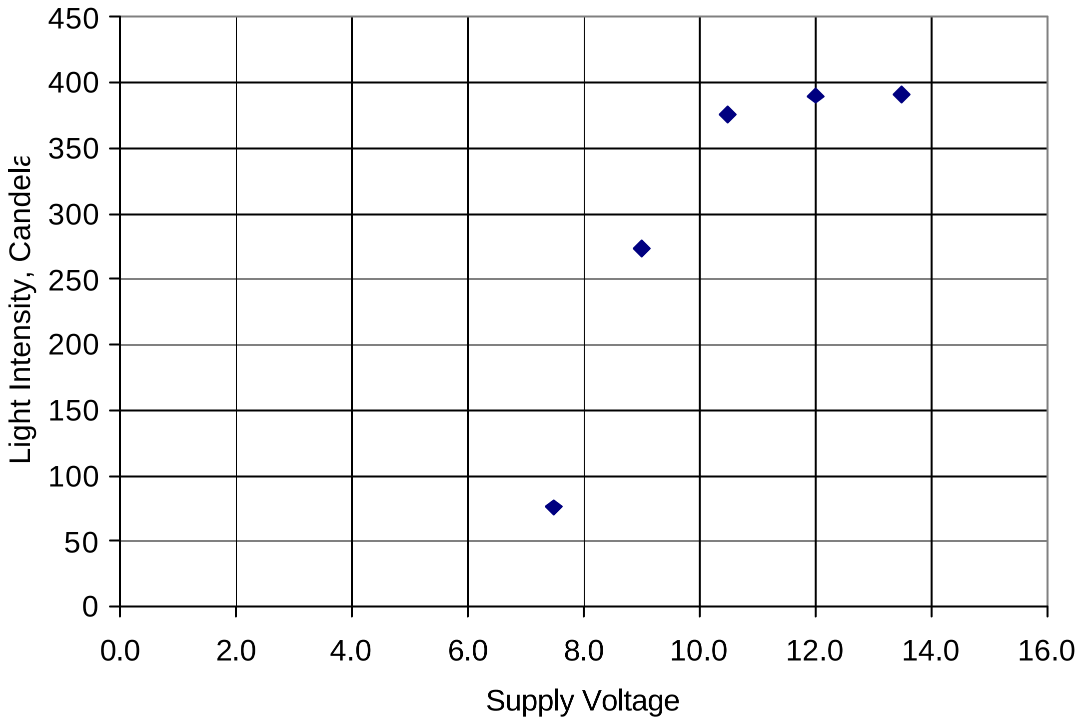

Figure 34. Maximum light intensity from WPS#3 with varying voltage input.

Figure 35 shows the chromaticity results from the same tests shown in Figure 35. Most of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The low level of light intensity (76 candela) associated with the measurements at 7.5 volts is the probable cause of the color shift of this point in Figure 35. In general, the small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. With the exception of very low voltage, there is no apparent color shift with input voltage with the WPS#3 signal.

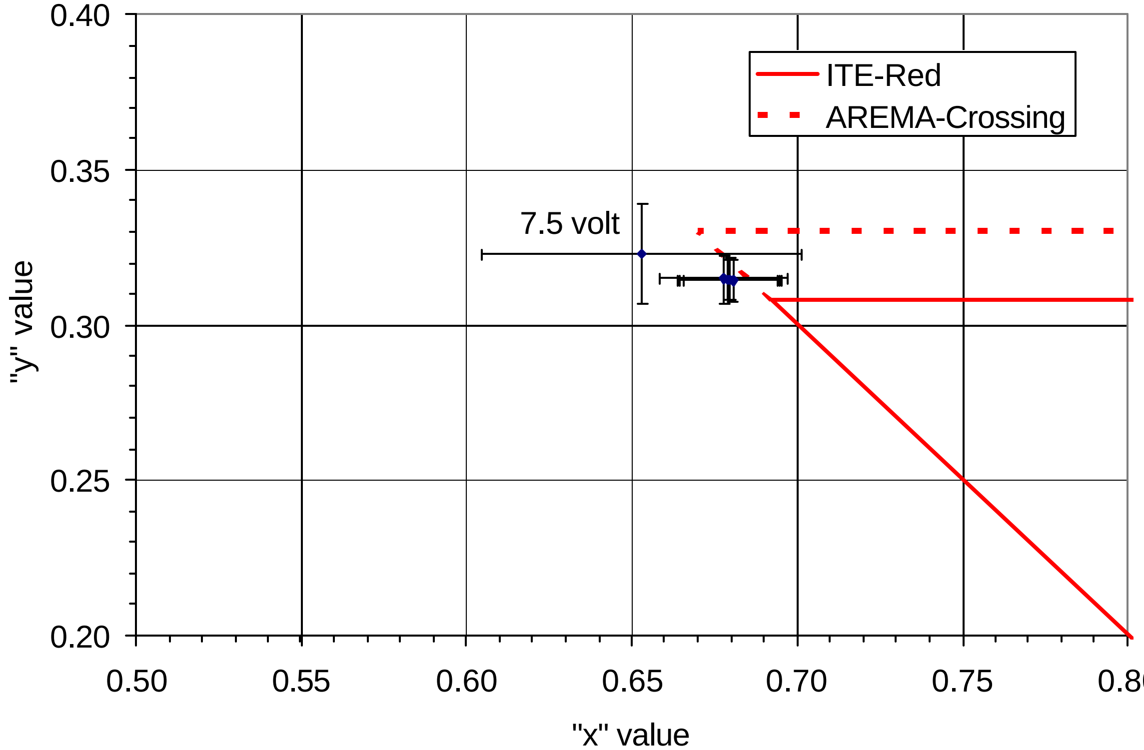

Figure 35. Chromaticity of WPS#3 with varying voltage input.

Figures A3.2.1 through A3.2.7 of the appendix show the effects of varying the number of active LED elements from 100% to 64% at a constant 10.5 volts. Table 19 summarizes these results. In light of the heating effect results shown in Figure 33, these data must be considered at least somewhat suspect, but the general trends should be correct. Note that the order of testing is the same as the order in which the figures are presented in the appendix. The light output from the WPS#3 signal is <u>not a function of the number of active elements</u> when there are 164 (64%) to 254 (100%) active elements. Maximum outputs range from 355 to 361 candela over this range of active elements. Supply currents were also relatively constant in the range of 1.48 to 1.58 amps. Power consumption ranged from 15.5 to 16.6 watts. These results show that the power supply is able to maintain a very constant current, power, and light intensity with up to 36% of the LED elements deactivated. There is also a very constant relationship between the power consumption and the maximum light intensity output of between 21.6 and 22.9 candela/watt.

Table 19. Results from WPS#3 at 10.5 volts.

Supply Voltage	Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
10.5	100.0%	254	356	1.48	15.5	22.9
10.5	94.1%	239	355	1.5	15.8	22.6
10.5	88.2%	224	355	1.5	15.8	22.5
10.5	82.3%	209	356	1.55	16.3	21.9
10.5	76.4%	194	361	1.58	16.6	21.7
10.5	70.5%	179	359	1.58	16.6	21.6
10.5	64.6%	164	356	1.57	16.5	21.6

Figures A3.3.1 through A3.3.52 of the appendix show the effects of varying the number of active LED elements from 100% to 41% at supply voltages of 9.0, 10.0, 12.0, and 13.5 volts. Figure 36 summarizes these results. The maximum light intensity for the WP#3 signal is a function of the supply voltage up to 10 or so volts. Once the supply voltage reaches this nominal level the light output, current, and power consumption tend to remain constant. Also, the maximum light output is not a strong function of the number of active LEDs until the percentage of ON elements is somewhat less than 50%. The small increases in the light intenstity for all four voltages at the 47% level is most likely an anomaly of the testing procedure. These four data points were taken consecutively by varying the voltage with a fixed pattern of active LEDs. A small misalignment of the testing fixture can easily cause a shift of this magnitude (20 to 30 candela).

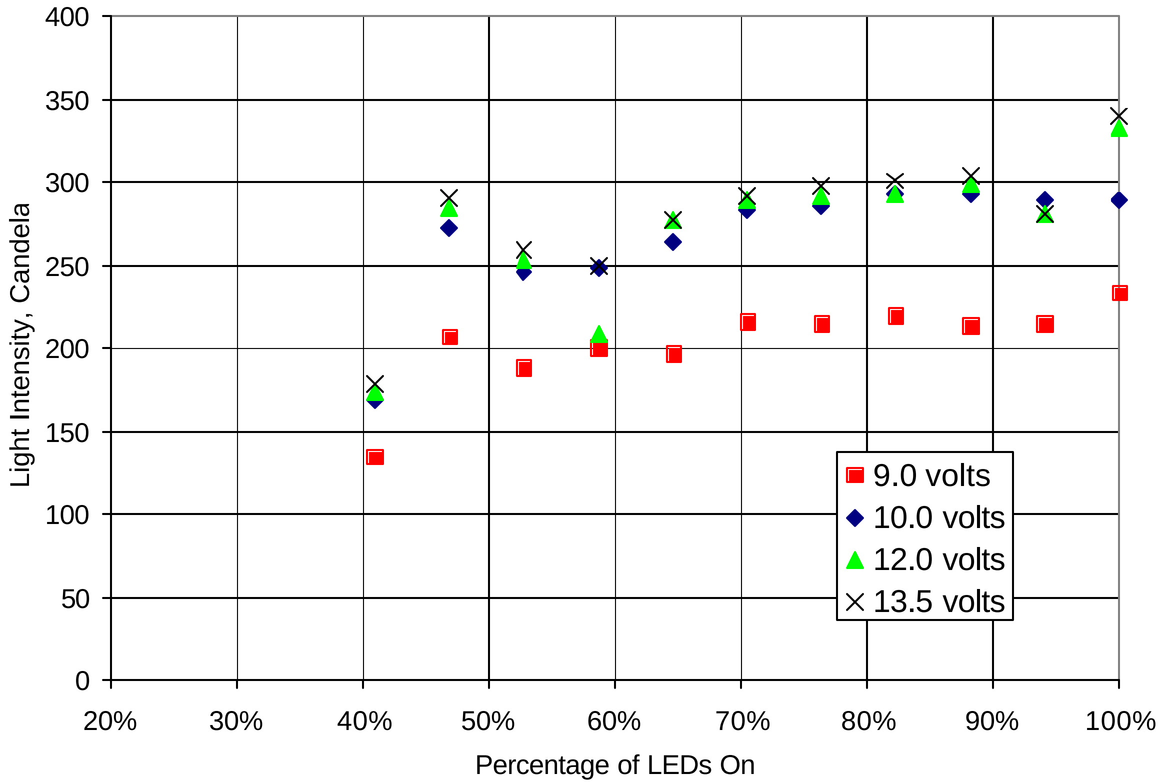

Figure 36. Maximum light intensity from WPS#3 with varying voltage and varying percentage of active LED elements.

Figure 37 shows the chromaticity results from the same tests shown in Figure 36. All of the results show similar color values clustered near the edge of the AREMA limits for red crossing signals. There is a small color shift due to varying the percentage of ON elements via open circuiting at very low levels (less than 40%) with the WPS#3 signal.

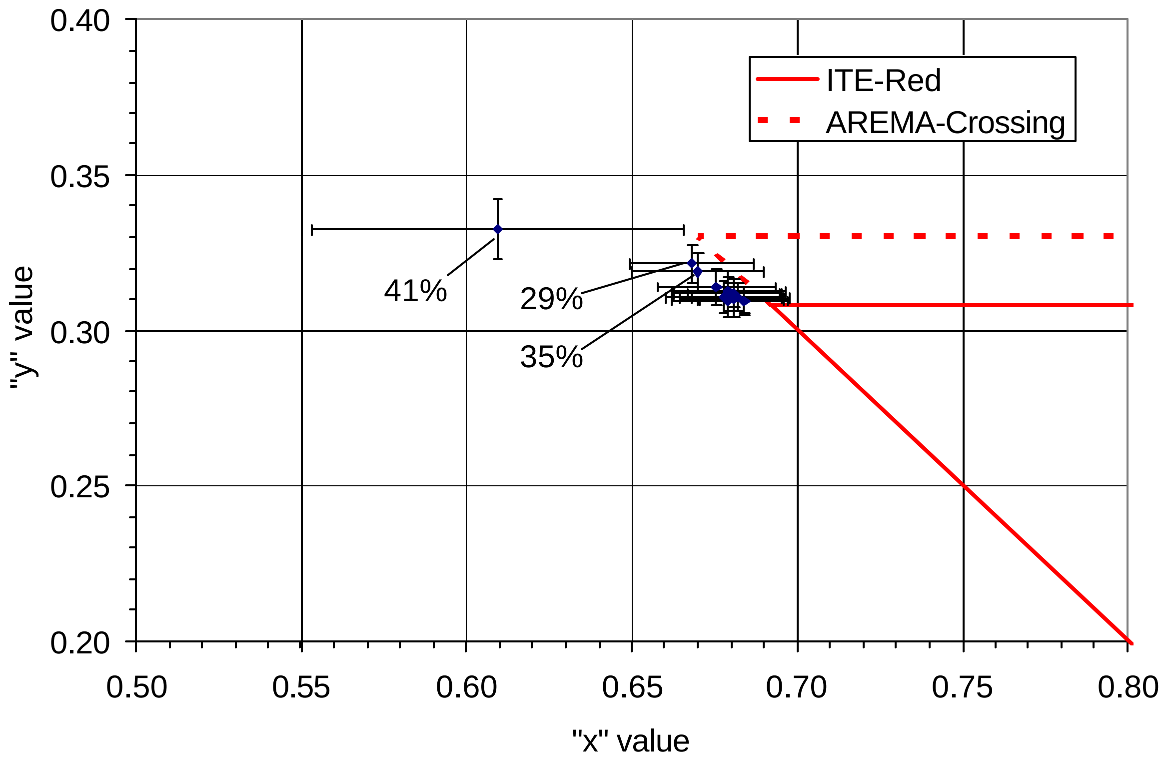

Figure 37. Chromaticity of WPS#3 at 10.5 volts (open circuit).

<u>Data from LEDTRONICS signal (NPS#4)</u>

The fourth twelve inch rail crossing signal tested was the LEDTRONICS unit. No power supply (NPS) is used with this signal, since the LEDs are directly connected to AC or DC power. The circuit configuration for this signal is shown in Figure 38. This signal (referred to as NPS #4 in this report) has 25 sets of five LEDs arranged in a series circuit. Four of the groups use a single diode instead of an LED, so there are a total of 121 visible elements. Due to the configuration of this signal, only open-circuit testing is possible.

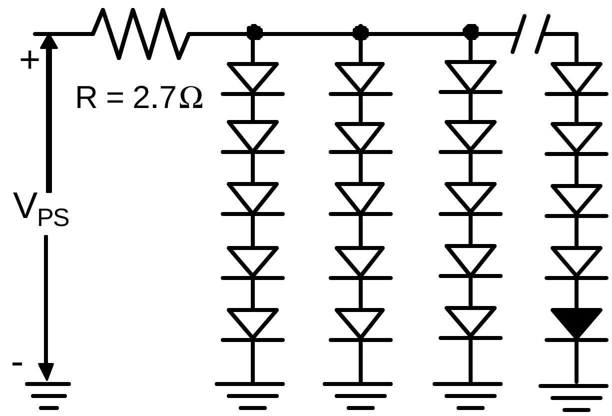

Figure 38. LED circuit configuration for NPS#4 signal.

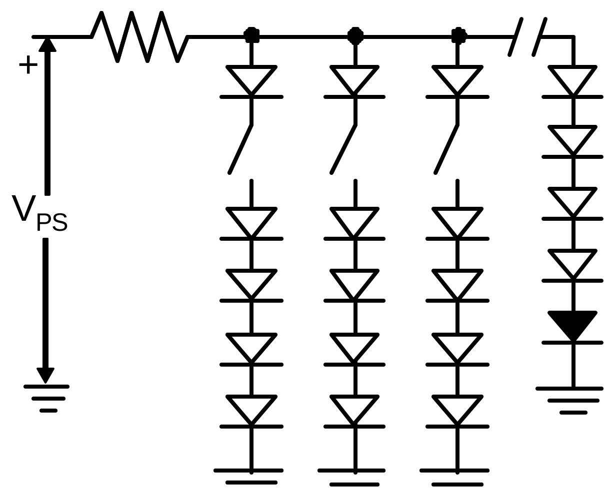

Figure 39. NPS#4 signal configured for open-circuiting.

Figures A4.1.1 through A4.1.8 of the appendix show the effects of varying voltage in the range of 9.0 volts to 15.0 volts with 100% of the LED elements active. Data from these figures is summarized in Table 20 and Figure 40. The light output from this signal is a strong function of the voltage, with maximum outputs ranging from 684 candela at 13.5 volts to 13 candela at 9.0 volts. The maximum output at the nominal 10.5 volts is approximately 173 candela. As shown in Table 20, supply currents ranged from 0.02 amps at 9.0 volts to 0.74 amps at 13.5 volts with 0.19 amps at the nominal 10.5 volt input. Power consumption ranged from 0.2 watts at 9.0 volts to 10.0 watts at 13.5 volts with 2.0 watts at the nominal 10.5 volt input. The light efficiency for the NPS#4 signal is very interesting since it remains relatively constant at a high value of about 900 candela/amp when the supply voltage is 10 volts or more.

Table 20. Results from NPS#4 with varying voltage input.

Supply Voltage	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Current Efficiency (candela/amp)
9.0	13	0.02	0.2	628
10.0	105	0.12	1.2	871
10.5	173	0.19	2.0	911
11.0	252	0.28	3.1	899
12.0	420	0.45	5.4	934
13.0	592	0.65	8.5	911
13.5	684	0.74	10.0	924

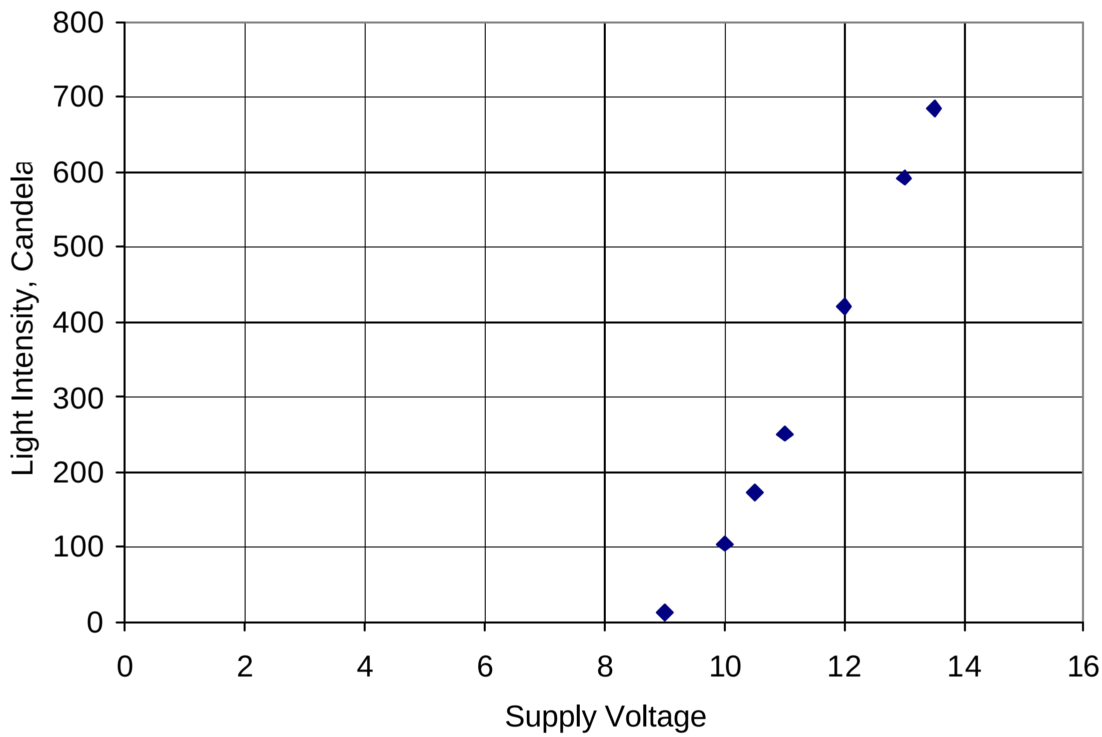

Figure 40. Maximum light intensity from NPS#4 with varying voltage input.

Figure 41 shows the chromaticity results from the same tests shown in Figure 40. With one exception, all of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The dissimilar value taken at 9.0 volts is also accompanied by a barely visible light intensity of only 13 candela. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. Except at low voltages (less than 10 volts), there is no apparent color shift with input voltage with the NPS#4 signal.

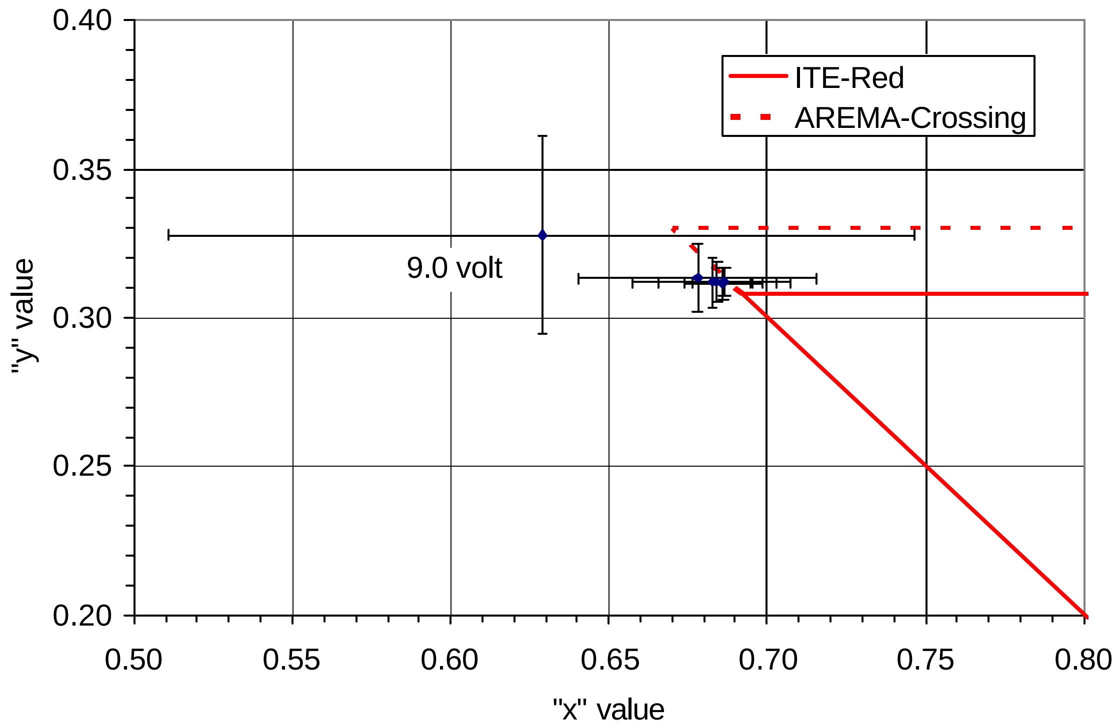

Figure 41. Chromaticity of NPS#4 with varying voltage input.

Figures A4.2.1 through A4.2.3 of the appendix show the effects of varying the number of active LED elements from 100% to 50% at a constant 12.0 volts. Table 21 summarizes these results. The light output from the NPS#4 signal is a strong function of the number of active elements, with maximum outputs ranging from 389 candela at 100% (121 elements) to 238 candela at 50% (61 elements). Supply currents ranged from 0.45 amps at 100% to 0.33 amps at 50%. Power consumption ranged from 5.4 watts at 100% to 4.0 watts at 50%. These results show a somewhat linear relationship between the number of active LED elements and the maximum light intensity output.

Table 21. Results from NPS#4 at 12.0 volts.

Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light Efficiency (candela/amp)
100%	121	389	0.45	5.4	864
75%	91	328	0.40	4.8	819
50%	61	238	0.33	4.0	722

Figure 42 shows the chromaticity results from the same tests shown in Table 21. All of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There appears to be a small color shift due to varying the percentage of ON elements via open circuiting with the NPS#4 signal, but all of the variations were well with the limits for the AREMA red crossing signal.

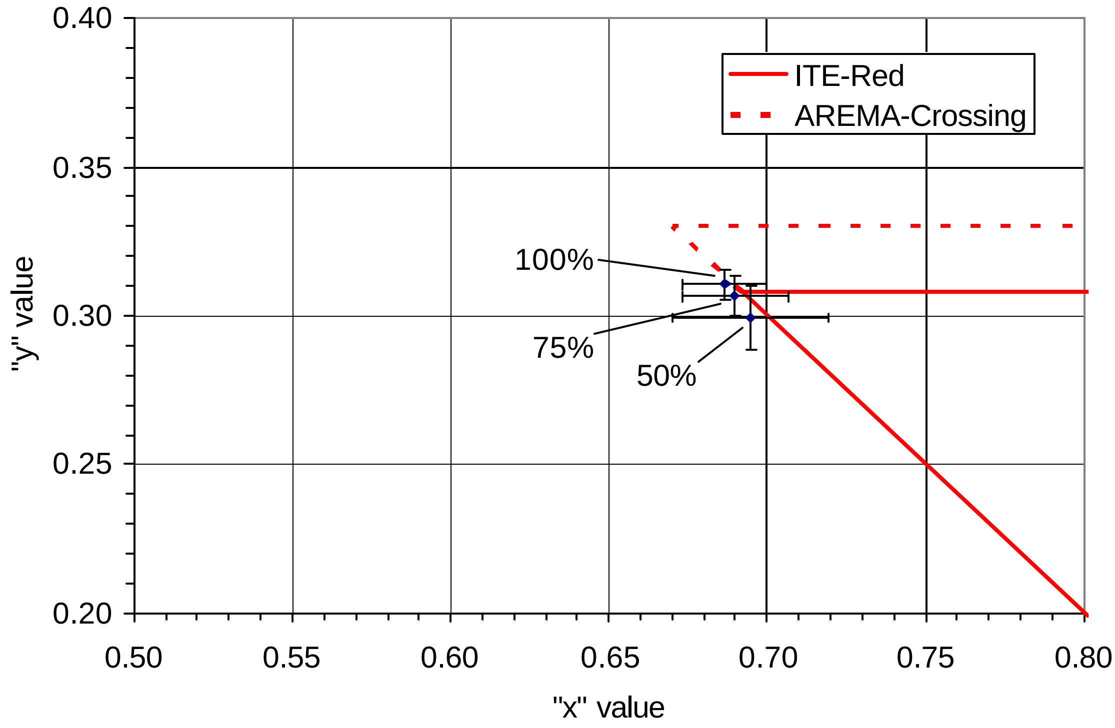

Figure 42. Chromaticity of NPS#4 with varying percentages of active LEDs.

Figure 43 summarizes maximum light intensities for the WPS#4 signal as a function of power supply voltage and percentage of active LED elements. This figure shows an essentially linear relationship between the maximum light intensity and power supply voltage above 10 volts. Figures 44 and 45 show the power supply current and the power consumption for the same data shown in Figure 43.

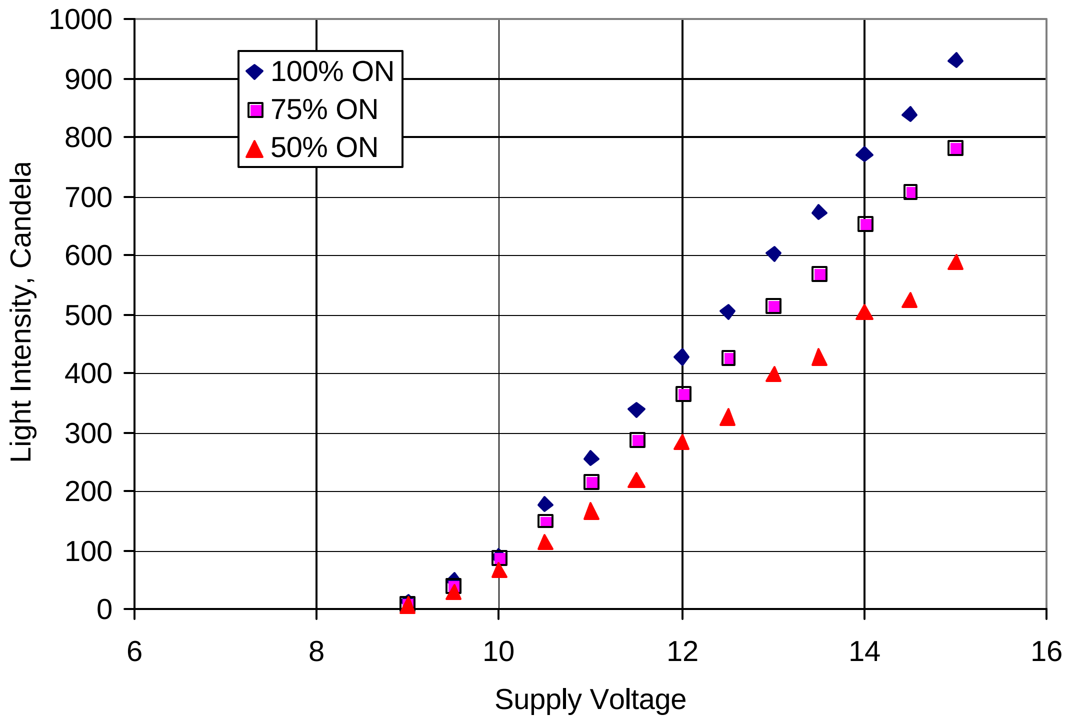

Figure 43. Maximum light intensity from NPS#4 at varying voltages and varying percentages of active LEDs.

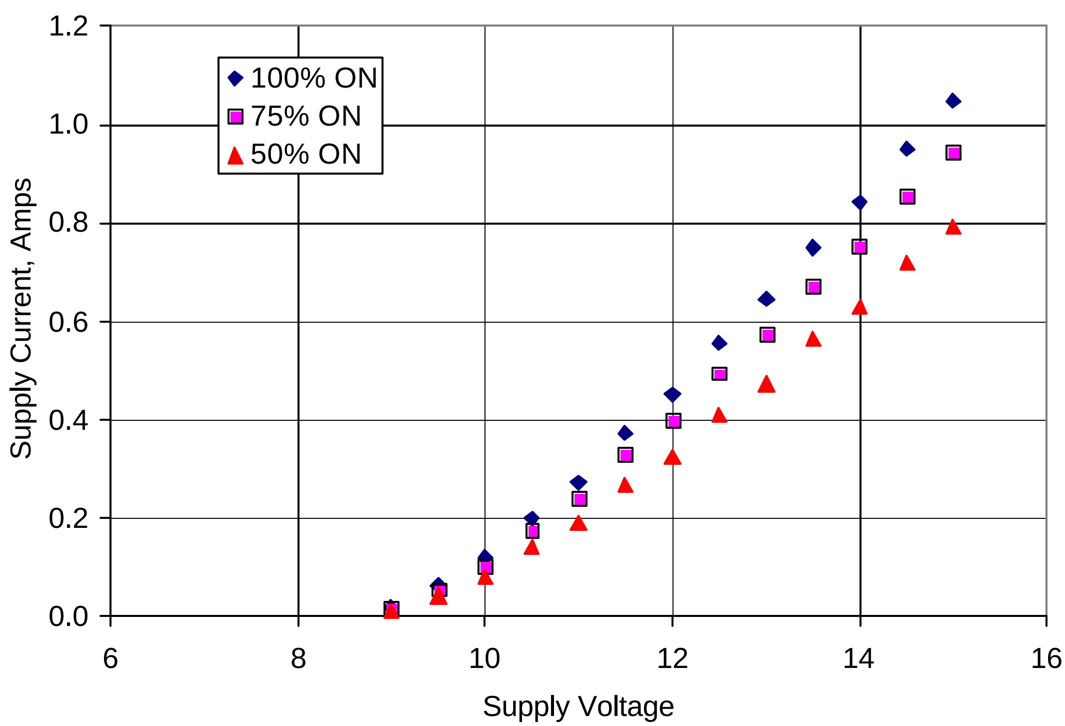

Figure 44. Power supply current for NPS#4 at varying voltages and varying percentages of active LEDs.

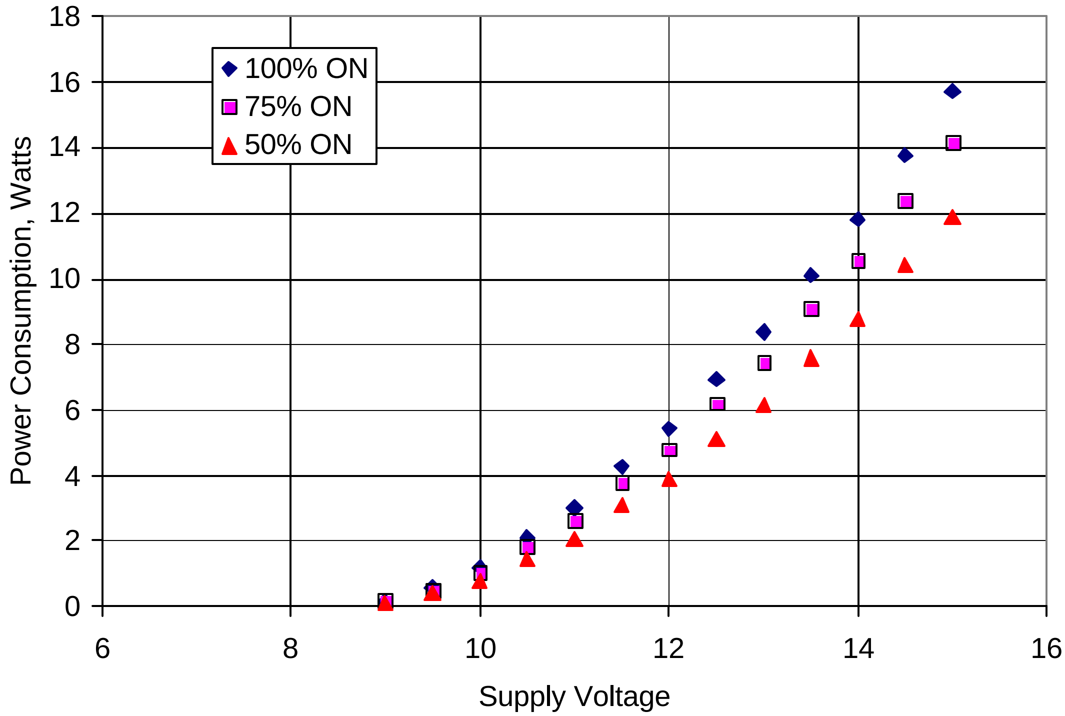

Figure 45. Power consumption for NPS#4 at varying voltages and varying percentages of active LEDs.

Data from Electrotech signal (WPS#5)

Figure 46 shows the configuration of the elements in a twelve inch signal purchased from Electrotech that uses a power supply to regulate the voltage and current applied to the LEDs. This signal (referred to as WPS#5 in this report) has 42 sets of ten LEDs arranged in a series circuit, for a total of 420 visible elements. Due to the configuration of this signal, only open-circuit testing is possible. Figure 47 shows the modification to the WPS#5 signal that allows a set of ten LED elements to be open-circuited. Note that the voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used.

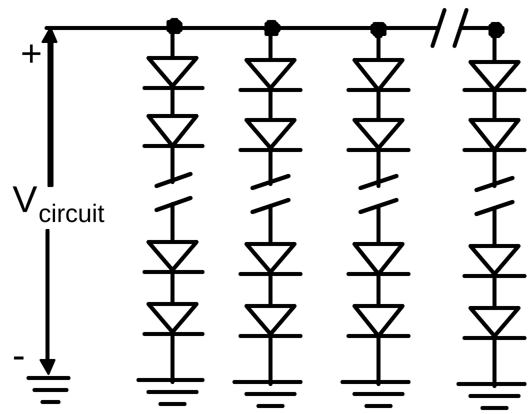

Figure 46. LED circuit configuration for WPS#5 signal

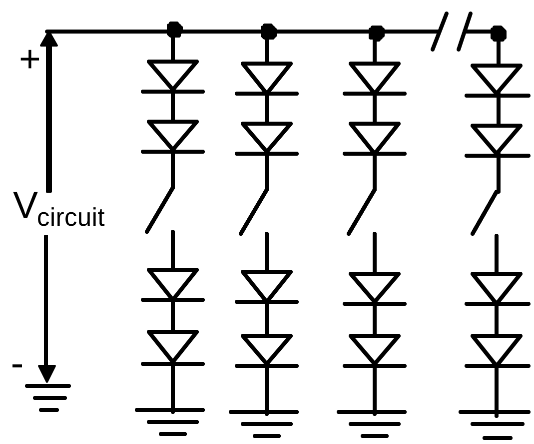

Figure 47. WPS#5 signal configured for open-circuiting

Figures A5.1 through A5.6 of the appendix show the effects of varying voltage in the range of 7.5 volts to 13.5 volts with 100% of the LED elements active. Data from these figures are summarized in Table 22. The maximum light output for the WPS#5 signal is not a function of the supply voltage. Maximum outputs range from 180 candela at 9.0 volts to 165 candela at 13.5 volts. As shown in Table 22, supply currents ranged from 1.91 amps at 7.5 volts to 0.84 amps at 13.5 volts. Power consumption ranged from 14.3 watts at 7.5 volts to 11.3 watts at 13.5 volts. The maximum light outputs and the power from the nominal 10.5 volts (168 candela, 12.1 watts) up to 13.5 volts (165 candela, 11.3 watt) are essentially the same, which indicates that the power supply is effective at limiting the power once the nominal supply of 10.5 volts is applied. The light-power efficiency is also relatively constant in the range of 12.3 to 14.6 candela/watt.

Table 22. Results from WPS#5 with varying voltage input.

Supply Voltage	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
7.5	176	1.91	14.3	12.3
9.0	180	1.44	13.0	13.9
10.0	169	1.23	12.3	13.7
10.5	168	1.15	12.1	13.9
12.0	166	0.97	11.6	14.3
13.5	165	0.84	11.3	14.6

Figure 48 shows the chromaticity results from the same tests shown in Table 22. All of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift with input voltage with the WPS#5 signal.

The signal was modified according to the schematic shown in Figure 47. Unfortunately, the WPS#5 signal did not work correctly after the open-circuit modifications. As shown in Figure 49 the 420 LED elements are very closely spaced in this signal. Some type of inadvertent modification -- most likely cutting the wrong circuit board trace -- caused the modified signal to not work properly. Since the WPS#5 signal had such a low intensity output (160 candela) even with all 420 elements operating, there was no justification for continuing the investigation of this signal with non-illuminated elements.

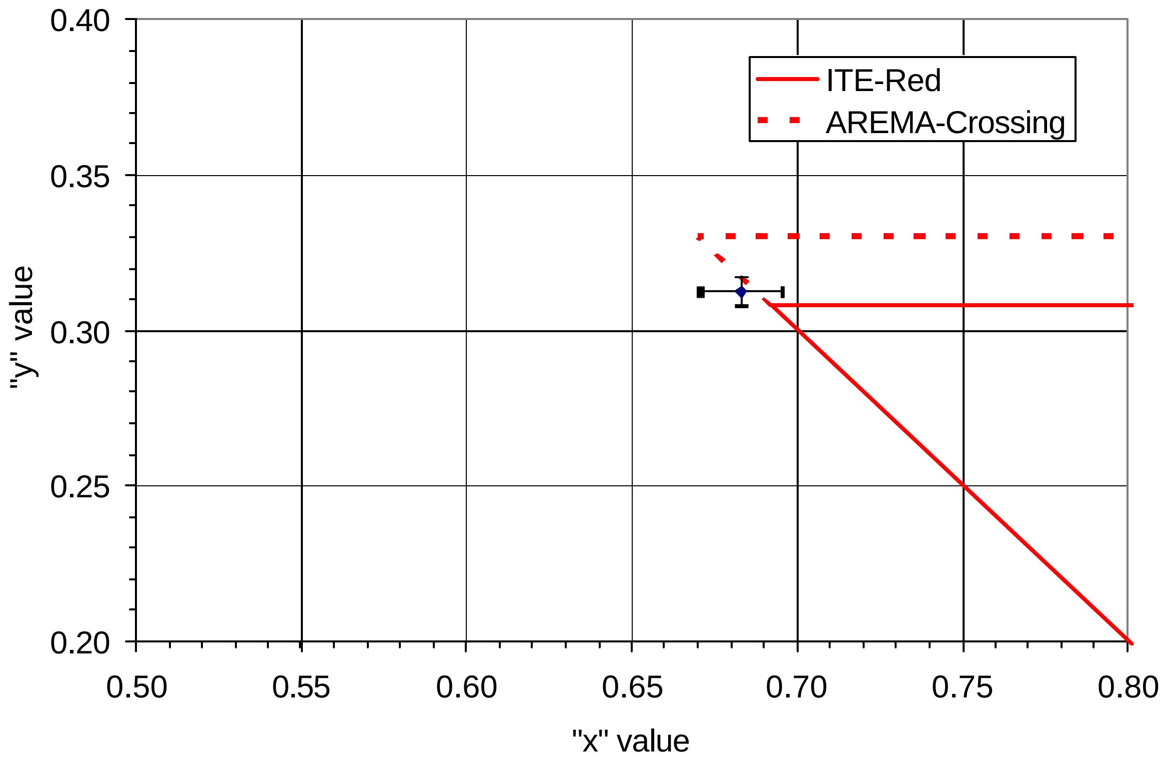

Figure 48. Chromaticity of the WPS#5 signal at varying voltages.

Figure 49. Interior of the WPS#5 signal.

Data from Dialight signal (WPS#6)

Figure 50 shows the configuration of the elements in a twelve inch signal supplied by Dialight that uses a power supply to regulate the voltage and current applied to the LEDs. This signal (referred to as WPS#6 in this report) has only 18 high-intensity LED elements. Note that the voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used.

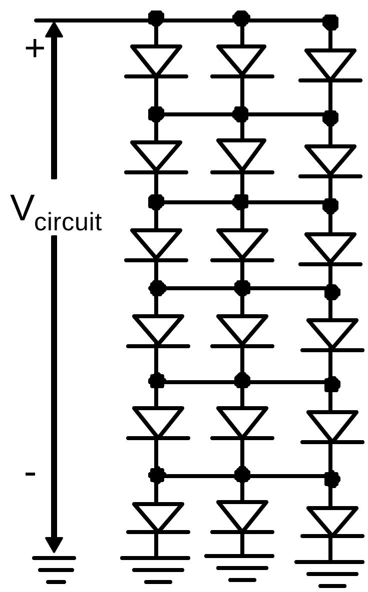

Figure 50. LED circuit configuration for WPS#6 signal

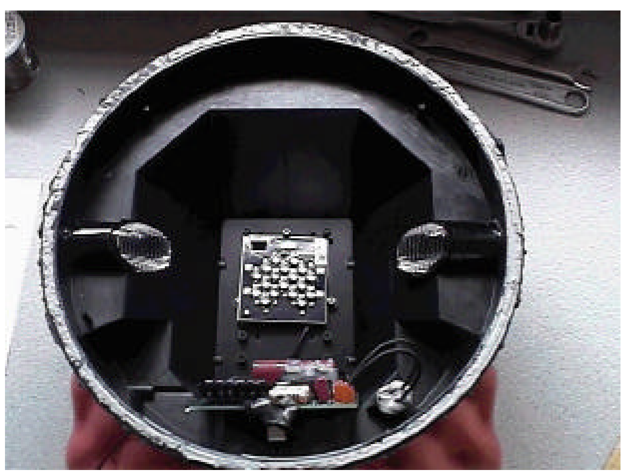

Figure 51. Interior of the WPS#6 signal.

Figures A6.1.1 through A6.1.6 of the appendix show the effects of varying voltage in the range of 7.5 volts to 13.5 volts with 100% of the LED elements active. Data from these figures are summarized in Table 23. The maximum light output for the WPS#6 signal is not a function of the supply voltage. Maximum outputs range from 393 candela at 10.0 volts to 279 candela at 7.5 volts. As shown in Table 23, supply currents ranged from 2.05 amps at 9.0 volts to 1.11 amps at 13.5 volts. Power consumption ranged from 13.7 watts at 7.5 volts to 15.0 watts at 13.5 volts. The maximum light outputs and the power from 10.5 volts and up are essentially the same, which indicates that the power supply is effective at limiting the power once the nominal supply of 10.5 volts is applied. The light-power efficiency remained relatively constant at 22.6 to 25.3 candela/watt in this range as well.

Table 23. Results from WPS#6 with varying voltage input.

Supply Voltage	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light - Power Efficiency (candela/watt)
7.5	279	1.82	13.7	20.4
9.0	368	2.05	18.5	19.9
10.0	393	1.74	17.4	22.6
10.5	390	1.59	16.7	23.4
12.0	385	1.30	15.6	24.7
13.5	379	1.11	15.0	25.3

Figures A6.2.1 through A6.5.6 of the appendix show the results of four additional sets of tests of varying voltage in the range of 7.5 volts to 13.5 volts with 100% of the LED elements active. Data from these figures are summarized in Figure 52. These results also show the typical variation between tests of identical signals. Variations on the order of ±50 candela for any given test point are not uncommon.

Figure 53 shows the chromaticity results from the same tests shown in Figure 52. All of the results show very similar color values clustered near the edge of the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift with input voltage with the WPS#6 signal.

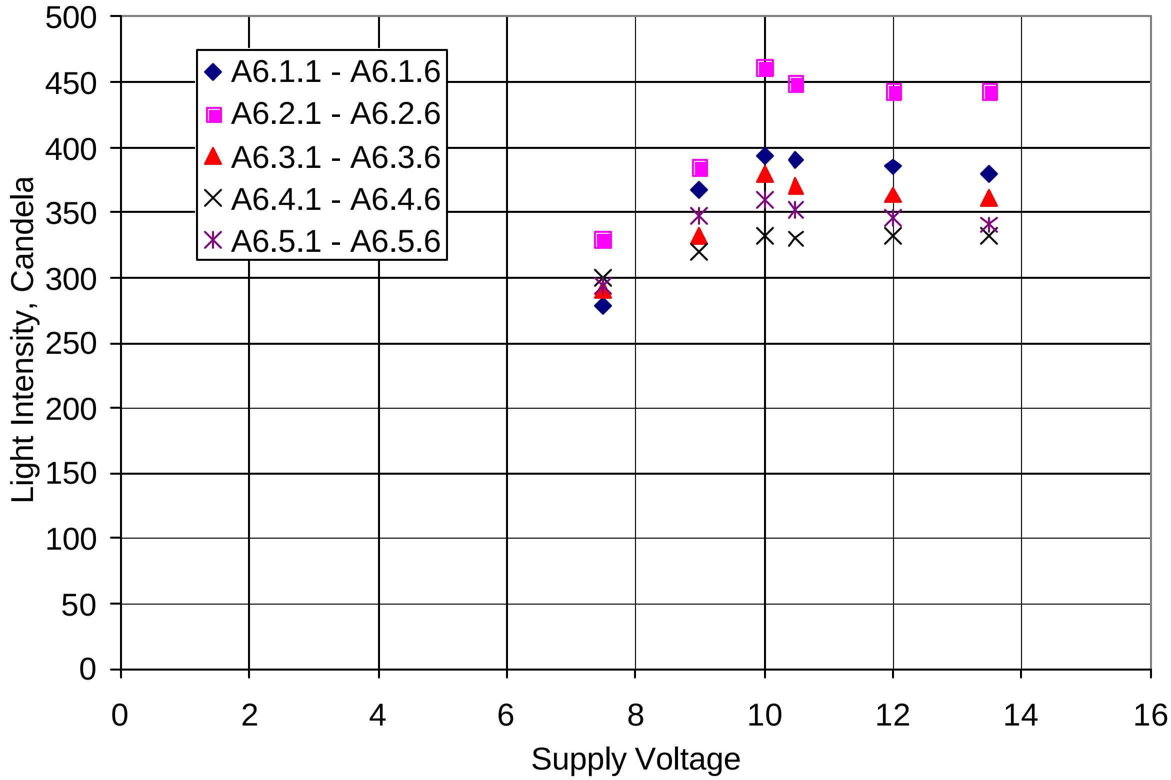

Figure 52. Maximum light intensity from WPS#6 with varying voltage input.

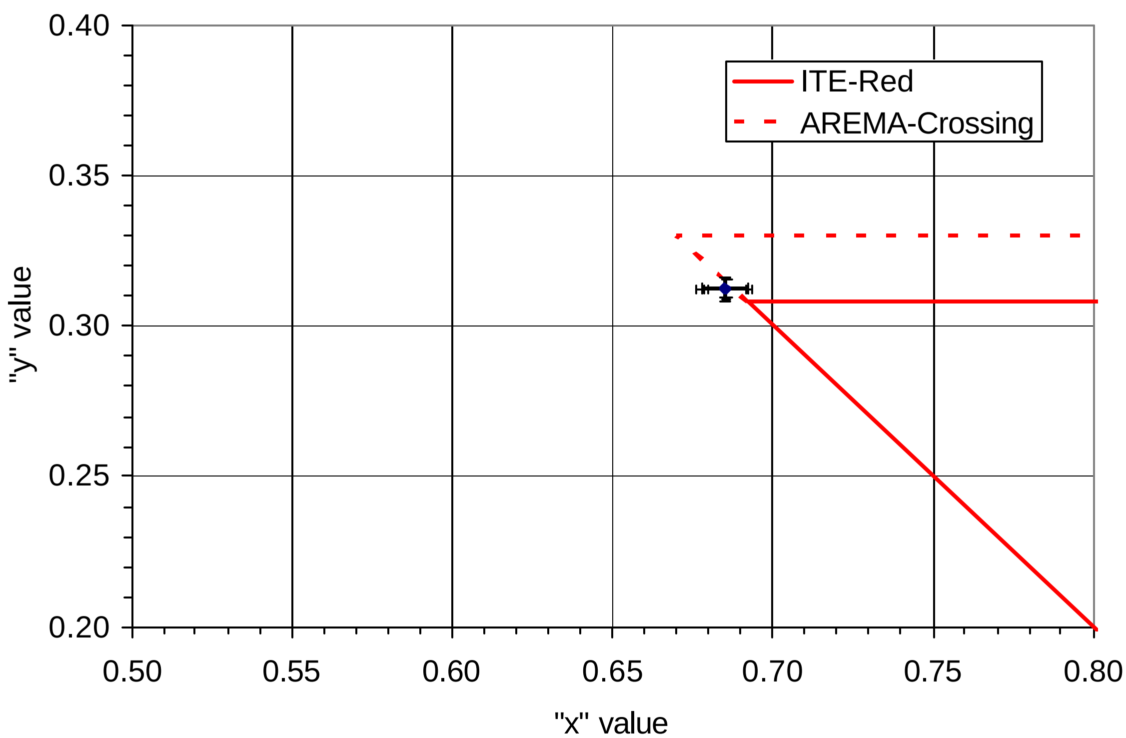

Figure 53. Chromaticity of the WPS#6 signal with varying voltage.

Modification of this signal to deactivate individual LED elements was difficult and ultimately not successful. The high-intensity LED “chips” use surface mount technology which is less amenable to modification since the entire circuit appears on only one side of the circuit board. This particular signal uses a pre-packaged circuit board which contains the 18 high-intensity LED chips. Two additional circuit boards were purchased from LumiLeds and were modified as shown in Figure 54. Unfortunately, the WPS#6 signal did not work correctly after the open-circuit modifications. A component on the power supply for the circuit board (most likely a capacitor) failed and rendered the entire unit inoperable. Due to the very small number of LED elements (18), successful testing with non-operable elements would have been difficult at best. No further testing with the WPS#6 signal was conducted.

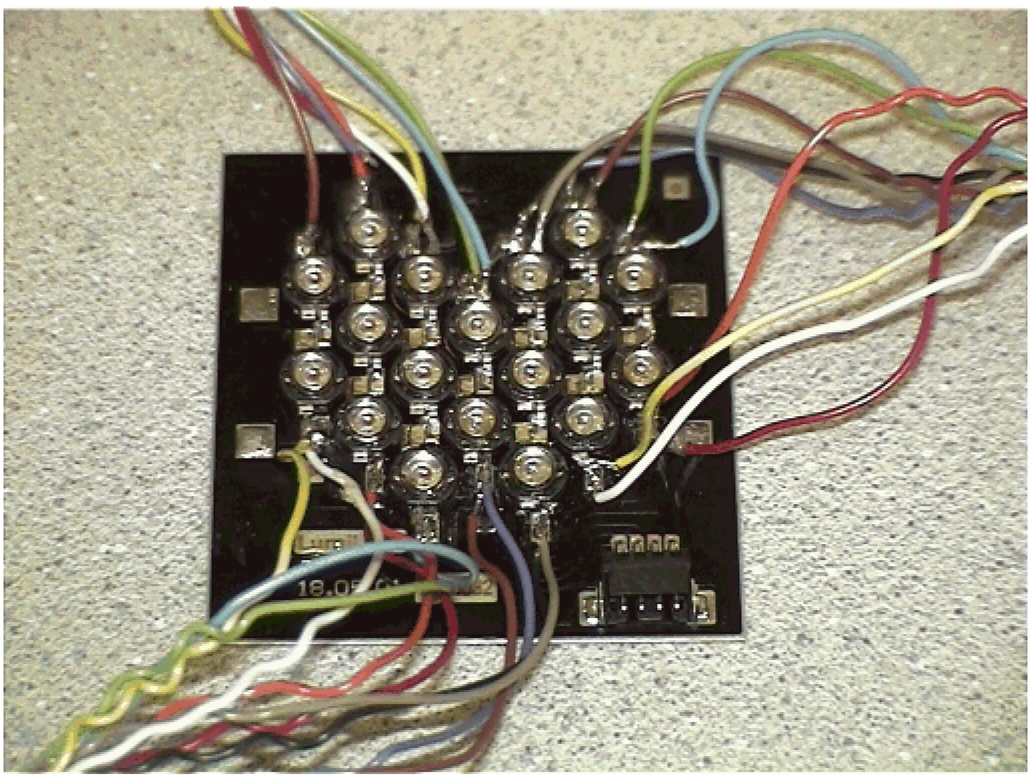

Figure 54. Modification to WPS#6 signal circuit board.

<u>Data from Gelcore signal (WPS#7)</u>

Figure 55 shows the configuration of the elements in a eight inch, red, wayside signal (#RM4 RC 75) supplied by Gelcore. This signal (referred to as WPS#7 in this report) has 88 LED elements arranged in 22 groups of 4 in a series/parallel circuit as shown in Figure 55. The WPS#7 signal uses a power supply to regulate the voltage and current applied to the LEDs. Note that the voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used.

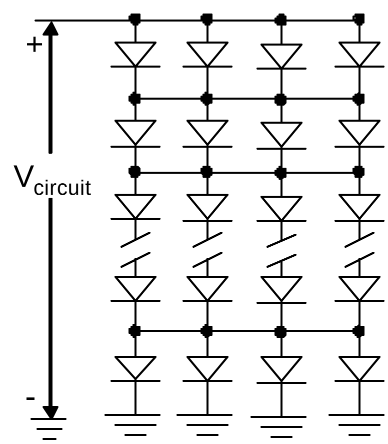

Figure 55. LED circuit configuration for WPS#7 signal

This eight inch wayside signal was equipped with a lens that gives a narrower (13 degree) field of view than the twelve inch crossing signals. The six twelve inch signals tested earlier (NPS#1, WPS#7, WPS#3, NPS#4, WPS#5, WPS#6) all used the same point source correction factor to convert the candela measurement made at 57 feet. An eight inch signal would ideally be measured at a distance of 38.2 feet as shown in Figure 56.

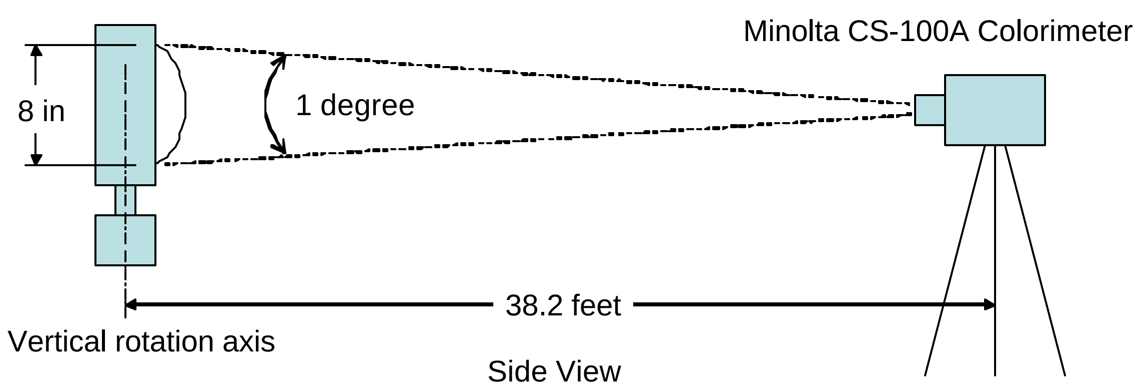

Figure 56. Camera setting distance for 8 inch signals.

Figures A7.1.1 through A7.3.8 show the results of a series of tests that were conducted to determine the point source correction factor for the red signal. Figure 57 summarizes the results from this series of tests, which were very inconsistent. Under ideal circumstances the output of this signal should have somewhat approximated the inverse square law shown in Figure 57. In several cases moving the signal further from the measuring colorimeter caused the maximum light intensity to increase – which should not have happened. The exact reason for the erratic behavior of this signal is unknown, but is most likely due to the narrow beam angle (13 degrees) of the WPS#7 signal making the initial alignment more critical than with the twelve inch crossing signals. Due to the erratic measurements of the WPS#7 signal at different distances, <u>the point source correction was not applied to any of the readings for the eight inch signals</u> (WPS#7, WPS#8, and WPS#9).

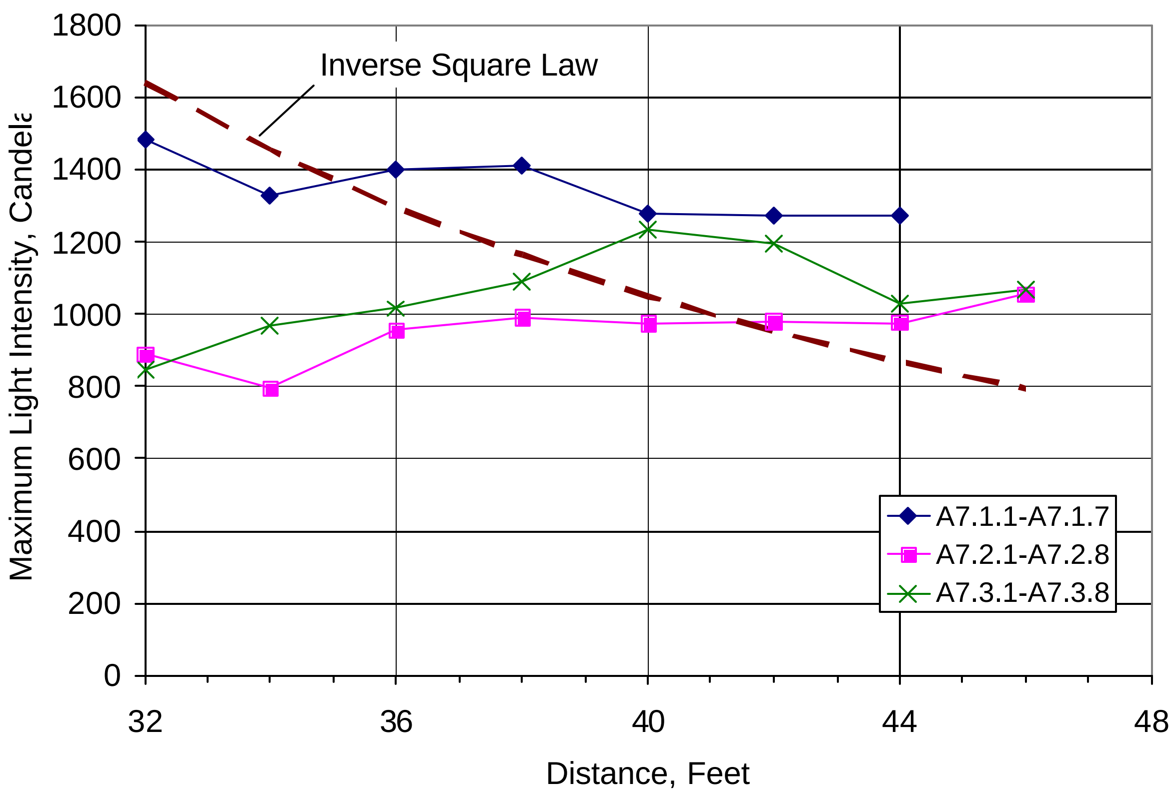

Figure 57. Maximum light intensity vs. distance for WPS#7

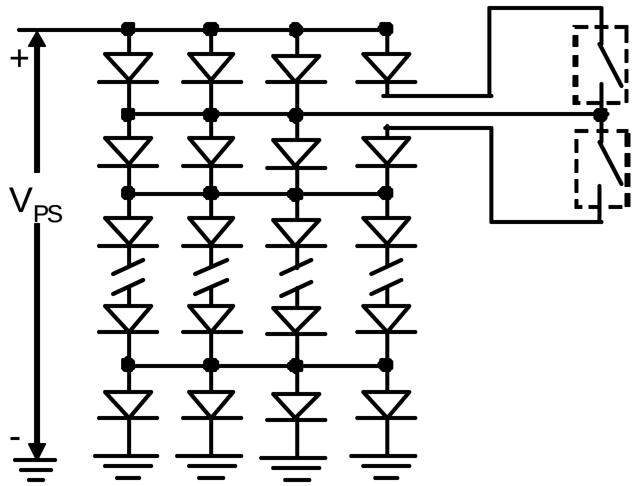

Figure 58. WPS#7 signal configured for open-circuiting

Figures A7.6.1 through A.7.6.16 of the appendix show the effects of varying the number of active LED elements from 95% (84 active elements) to 77% (68 active elements) via open-circuiting at a constant 10.0 volts. Table 24 and Figure 59 summarize these results. The light output from the WPS#7 signal is not a function of the number of active elements, with maximum outputs ranging from 1163 to 1205 candela. Supply current and power consumption are essentially constant at 1.46-1.50 amps and 14.6-15.0 watts, respectively. The number of open-circuited elements has a negligible effect on the power requirements for the WPS#7 signal. The relative insensitivity of the WPS#7 signal to the number of open-circuited elements is due to two factors:

3. the use of a power supply to regulate voltage and current, and
4. the combined series and parallel arrangement of LEDs (shown in Figure 55).

There is also a constant relationship between the maximum light intensity output and the power consumption of between 79.2 and 81.5 candela/watt.

Table 24. Results from WPS#7 at 10.0 volts (open-circuits)

Figure	Percentage of LEDs ON	Number of LEDs ON	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
A7.6.1	95.5%	84	1170	1.46	14.6	80.1
A7.6.2	95.5%	84	1165	1.46	14.6	79.7
A7.6.3	95.5%	84	1177	1.46	14.6	80.5
A7.6.4	95.5%	84	1191	1.46	14.6	81.5
A7.6.5	95.5%	84	1163	1.46	14.6	79.6
A7.6.6	95.5%	84	1186	1.46	14.6	81.1
A7.6.7	90.9%	80	1169	1.47	14.7	79.4
A7.6.8	90.9%	80	1194	1.47	14.7	81.2
A7.6.9	90.9%	80	1165	1.47	14.7	79.2
A7.6.10	90.9%	80	1175	1.47	14.7	79.9
A7.6.11	86.4%	76	1200	1.48	14.8	81.0
A7.6.12	86.4%	76	1198	1.48	14.8	80.9
A7.6.13	86.4%	76	1205	1.48	14.8	81.3
A7.6.14	81.8%	72	1211	1.49	14.9	81.2
A7.6.15	81.8%	72	1190	1.49	14.9	79.8
A7.6.16	77.3%	68	1190	1.5	15.0	79.2

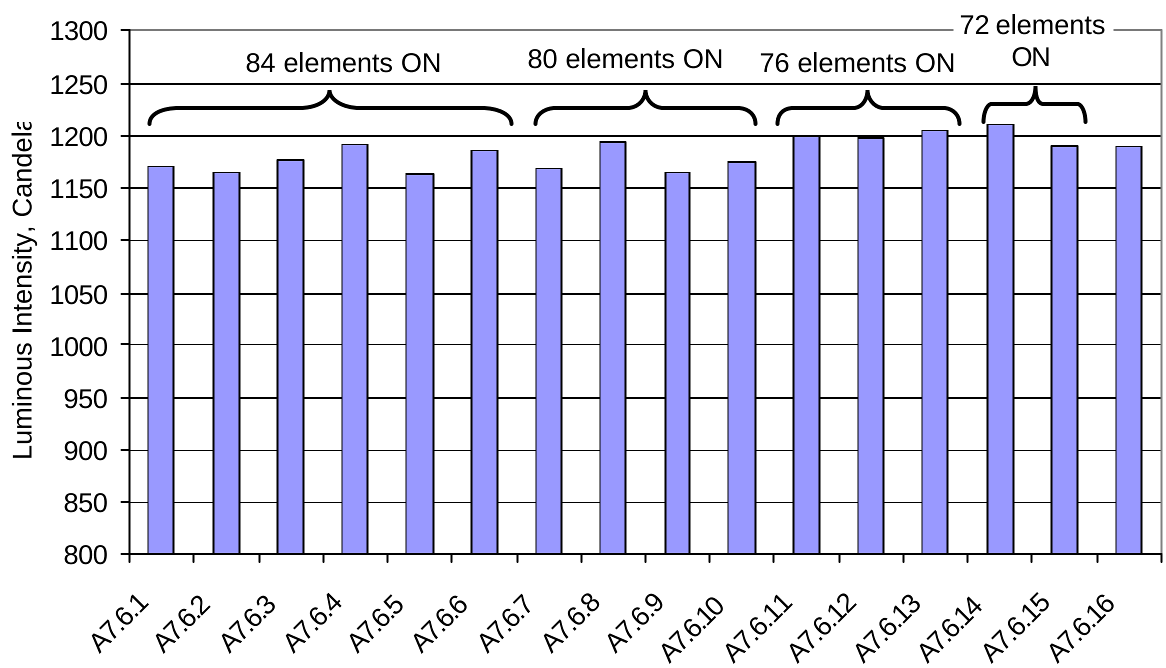

Figure 59. On-axis luminous intensity for the WPS#7 signal with different combinations of LEDs illuminated (open-circuited)

Figure 60 shows the chromaticity results from the same tests shown in Figure 59. All of the results show very similar color values clustered fairly close to the edge of the AREMA limits for red wayside signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift due to varying the percentage of ON elements via open circuiting with the WPS#7 signal.

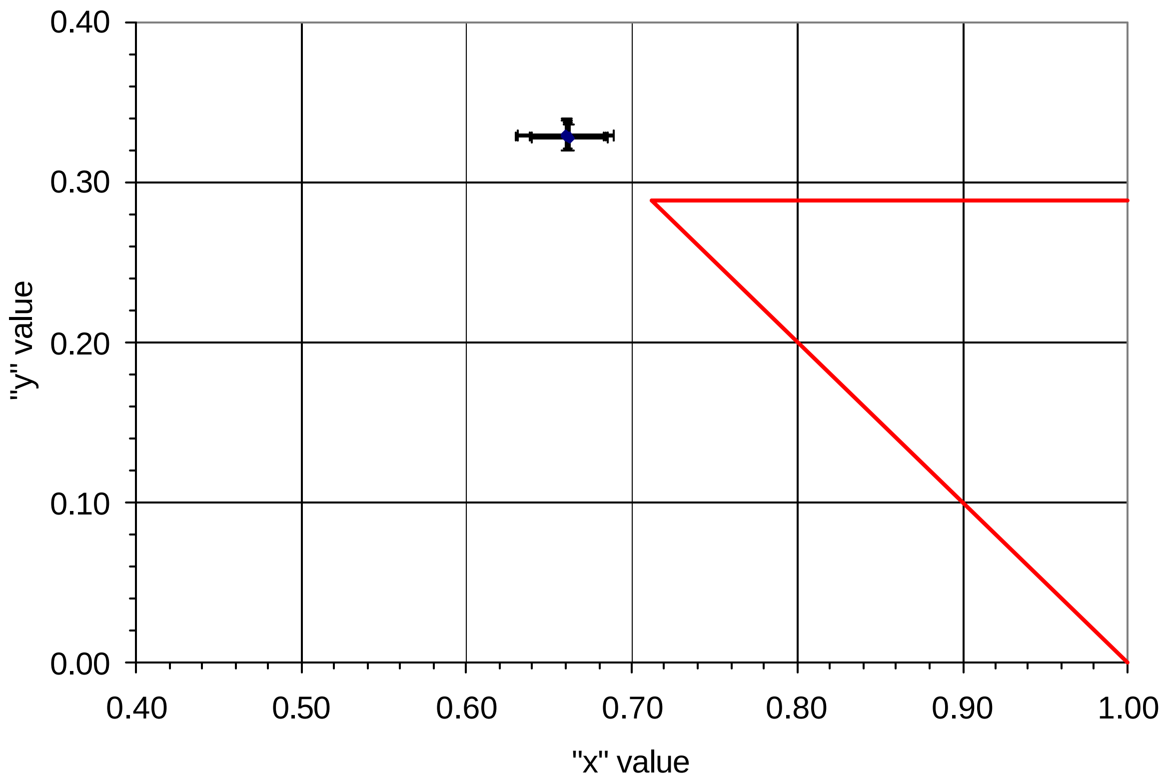

Figure 60. Chromaticity of the WPS#7 signal with different combinations of LEDs illuminated (open-circuited)

Figure 61 shows the modification to the WPS#7 signal that allows short-circuiting of individual elements. Figures A7.5.1 through A.7.5.18 of the appendix show the effects of disabling 8 of the 88 LED elements in different parts of the signal via short-circuiting at a constant 10.0 volts. Figure 62 summarize these results. The light output from the WPS#7 signal is not a function of the particular pattern of active elements, with maximum outputs ranging over a narrow range from 1215 to 1260 candela. Supply current and power consumption remained constant at 1.37 amps and 13.7 watts, respectively.

Figures A7.6.1 through A.7.6.17 of the appendix show the effects of disabling 24 of the 88 LED elements in different parts of the signal via short-circuiting at a constant 10.0 volts. Figure 63 summarize these results. With the exception of one anomalous data point (A7.6.8 at 832 candela), the light output from the WPS#7 signal is not a function of the particular pattern of active elements, with maximum outputs ranging over a narrow range from 970 to 1070 candela. Supply current and power consumption remained constant at 1.20 amps and 12.0 watts, respectively.

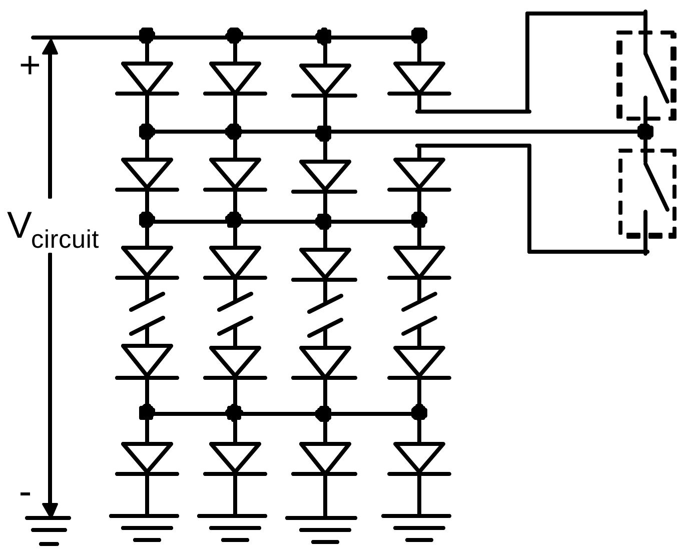

Figure 61. WPS#7 signal configured for short-circuiting

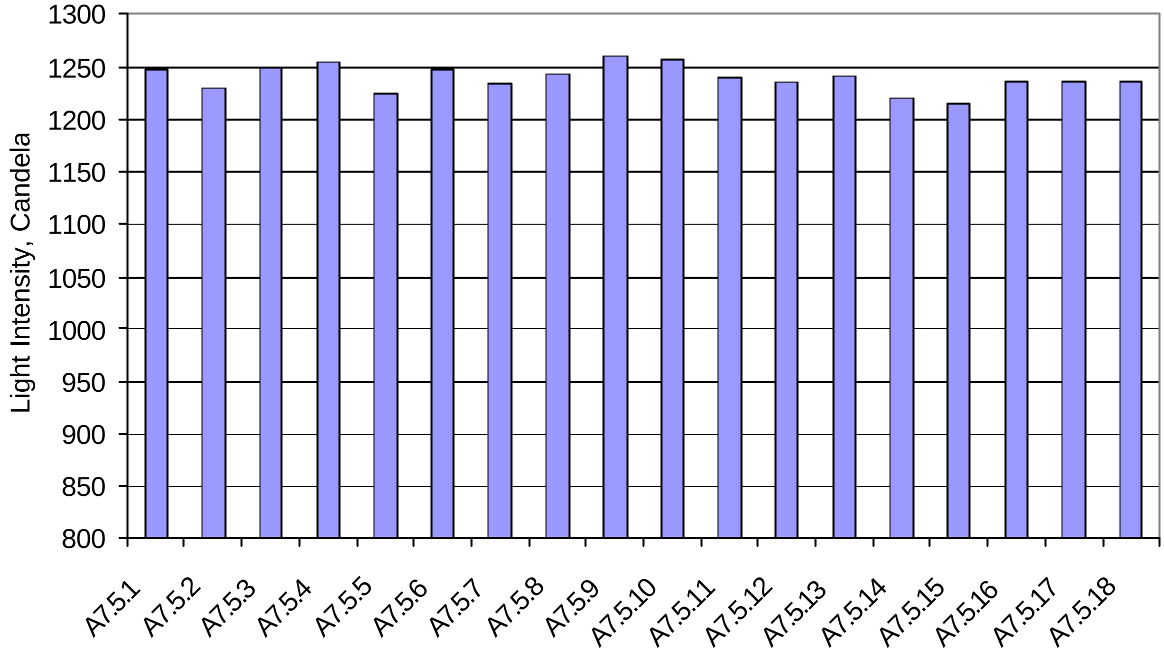

Figure 62. Maximum light intensity from WPS#7 with 80 active elements at 10.0 volts (short-circuits)

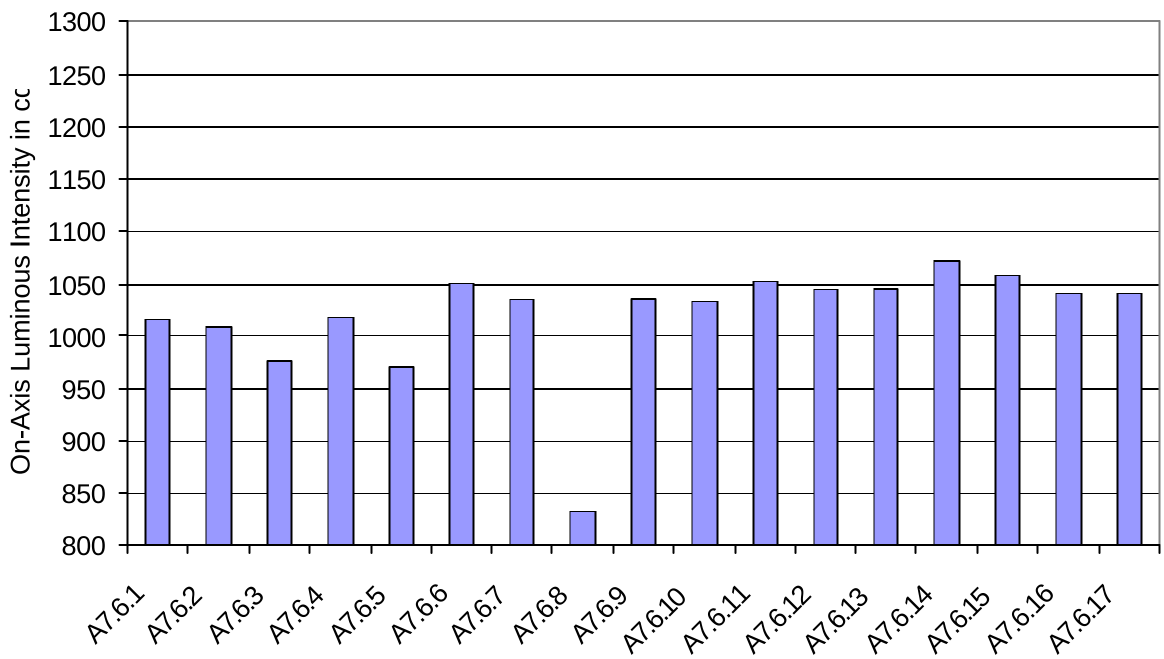

Figure 63. Maximum light intensity from WPS#7 with 64 active elements at 10.0 volts (short-circuits)

Figure 64 shows the chromaticity results from the same tests shown in Figure 62. All of the results show very similar color values clustered fairly close to the edge of the AREMA limits for red wayside signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift due to varying the percentage of ON elements via short circuiting with the WPS#7 signal.

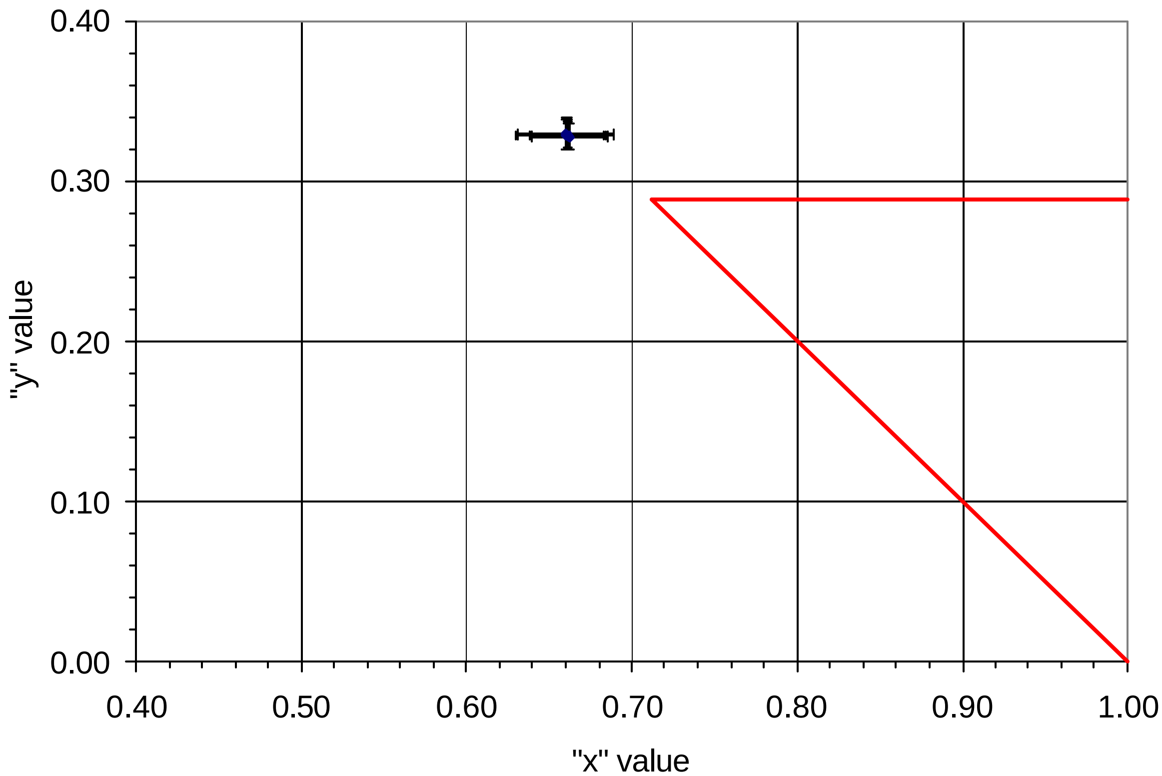

Figure 64. Chromaticity of the WPS#7 signal with different combinations of LEDs illuminated (short-circuited)

Data from Gelcore signal (WPS#8)

Figure 65 shows the configuration of the elements in a eight inch, yellow, wayside signal (#RM4 YC 85) supplied by Gelcore. This signal (referred to as WPS#8 in this report) has 88 LED elements arranged in 22 groups of 4 in a series/parallel circuit as shown in Figure 65. The WPS#8 signal uses a power supply to regulate the voltage and current applied to the LEDs. Note that the voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used. This eight inch wayside signal was equipped with a lens that gives a very narrow (~3 degree) field of view, with a claimed visible distance of 7500 feet.

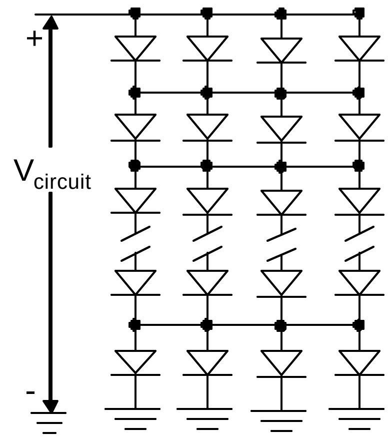

Figure 65. LED circuit configuration for WPS#8 signal

Preliminary lab testing of the three eight inch wayside signals indicated that there was a fairly strong reduction in the signal light intensity with time. WPS8b shows the uncorrected maximum luminous intensity of the three signals as a function of time. The yellow light (WPS#8) showed an almost 50% reduction from nearly 6000 candela to a steady-state value of about 3000 candela. The red light (Gelcore #RM4 RC 75) and the green light (Gelcore #RM4 GC 75) were equipped with a lens that gives a much broader (13 degree) field of view with a claimed visible distance of 4000 feet. The red light also shows a reduction in the uncorrected maximum luminous intensity, although the effect is not nearly as severe. The green light showed an almost negligible reduction in the uncorrected maximum luminous intensity as a function of time. All subsequent testing of the 8 inch wayside lights was done after "conditioning" the signal by leaving it in the ON state for 120 minute prior to testing.

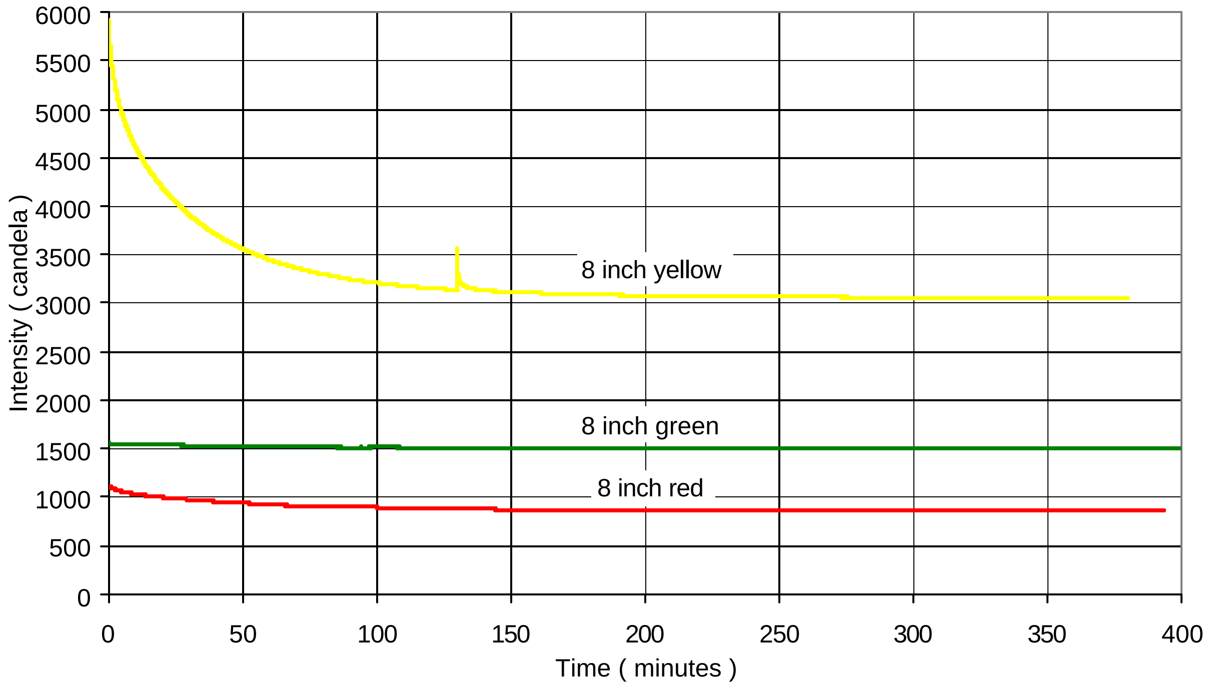

Figure 66. Uncorrected maximum luminous intensity vs. time for 8 inch wayside signals.

Figures A8.1.1 through A8.3.8 show the results of a series of tests that were conducted (unsuccessfully) to determine the point source correction factor for the yellow signal. Figure 67 summarizes the results from this series of tests, which were very inconsistent. Under ideal circumstances the output of this signal should have somewhat approximated an inverse square law. In several cases moving the signal further from the measuring colorimeter caused the maximum light intensity to increase – which should not have happened. The exact reason for the erratic behavior of this signal is unknown, but is most likely due to the narrow beam angle (~3 degrees) of the WPS#8 signal making the initial alignment much more critical than with the twelve inch crossing signals. Due to the erratic measurements of the WPS#8 signal at different distances, <u>the point source correction was not applied to any of the readings for the eight inch signals</u> (WPS#7, WPS#8, and WPS#9).

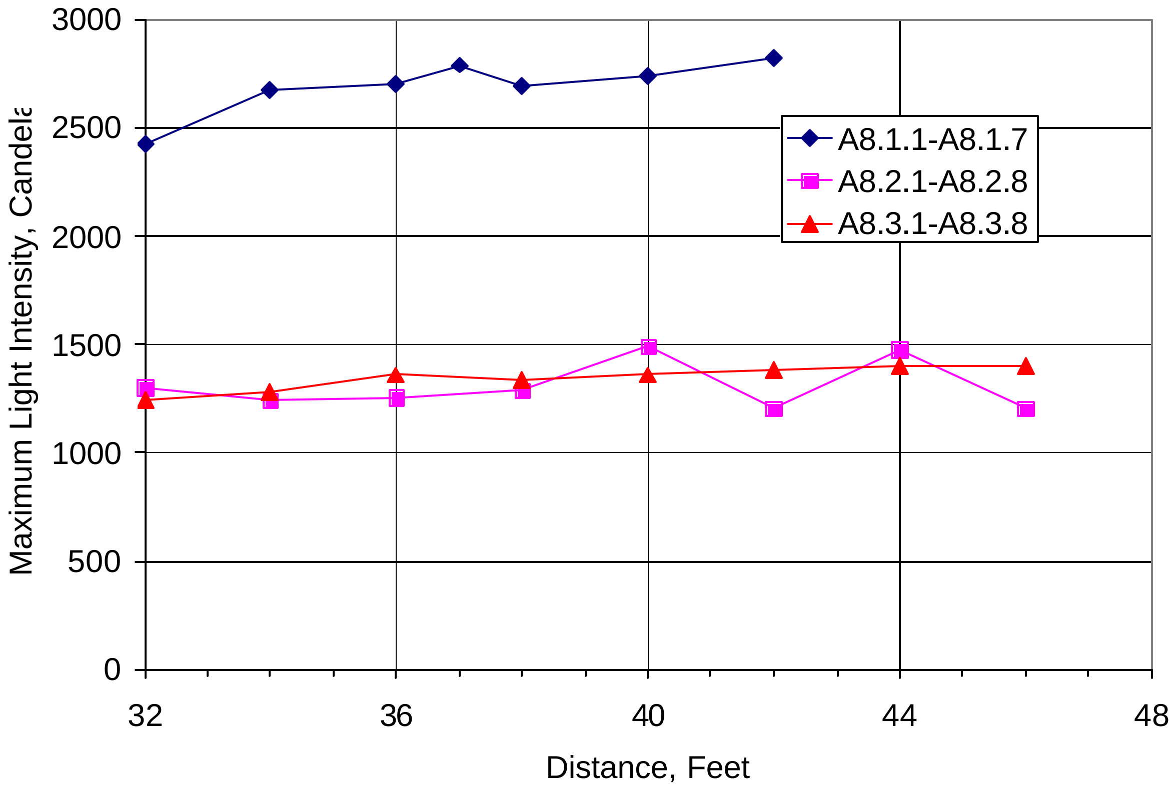

Figure 67. Maximum light intensity vs. distance for WPS#8

Figure 68 shows the circuit configuration for disabling individual LED elements via open-circuiting. Figures A8.4.1 through A.8.4.16 of the appendix show the effects of varying the number of active LED elements from 95% (84 active elements) to 77% (68 active elements) via open-circuiting at a constant 10.0 volts. Figure 69 summarizes these results. The WPS#8 signal was focused 1.1 degrees below on-axis to get the highest intensity possible. The light output from the WPS#8 signal is not a strong function of the number of active elements, with maximum outputs ranging from 1660 to 2300 candela with no apparent pattern to the results. Supply current and power consumption are essentially constant at 1.39-1.41 amps and 13.9-14.1 watts, respectively. The light-power efficiency remained relatively constant in the range of 120 to 165 candela/watt. The number of open-circuited elements has a negligible effect on the power requirements for the WPS#8 signal. The relative insensitivity of the WPS#8 signal to the number of open-circuited elements is due to two factors:

1. the use of a power supply to regulate voltage and current, and
2. the combined series and parallel arrangement of LEDs (shown in Figure 65).

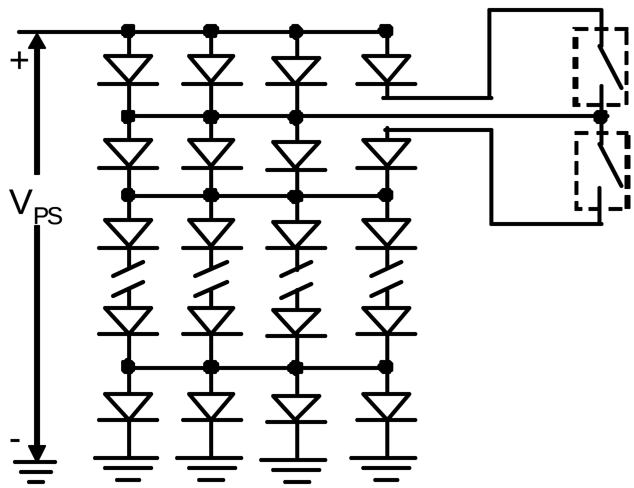

Figure 68. WPS#8 signal configured for open-circuiting

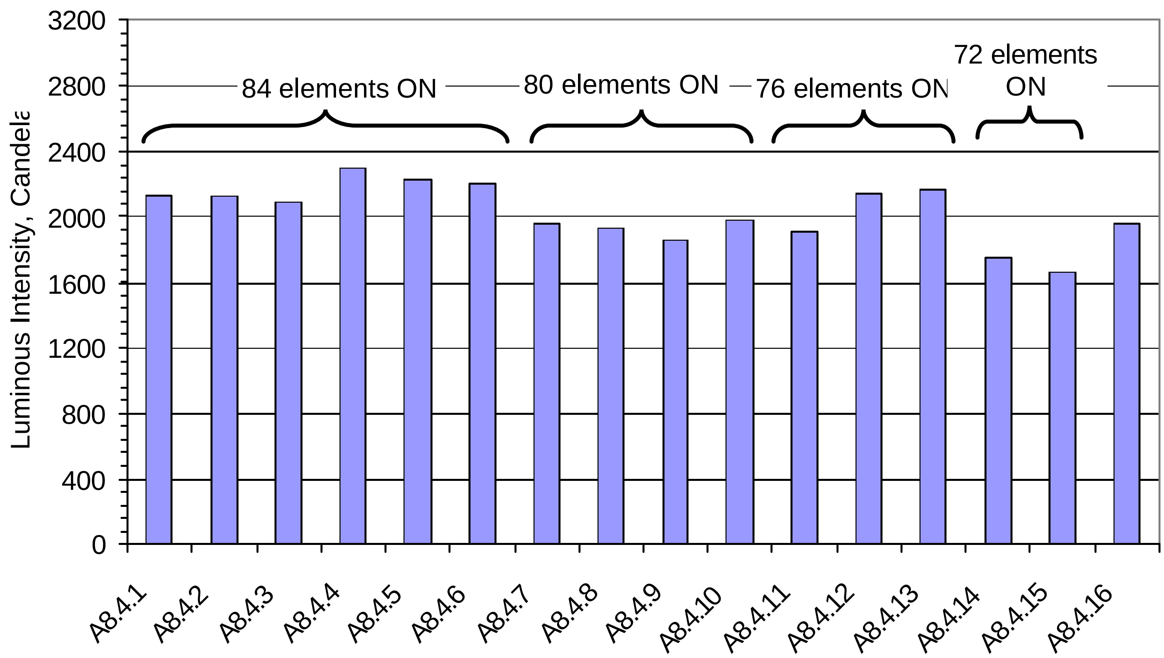

Figure 69. On-axis luminous intensity for the WPS#8 signal with different combinations of LEDs illuminated (open-circuited)

Figure 70 shows the chromaticity results from the same tests shown in Figure 69. All of the results show very similar color values clustered fairly close to the edge of the AREMA limits for yellow wayside signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift due to varying the percentage of ON elements via open circuiting with the WPS#8 signal.

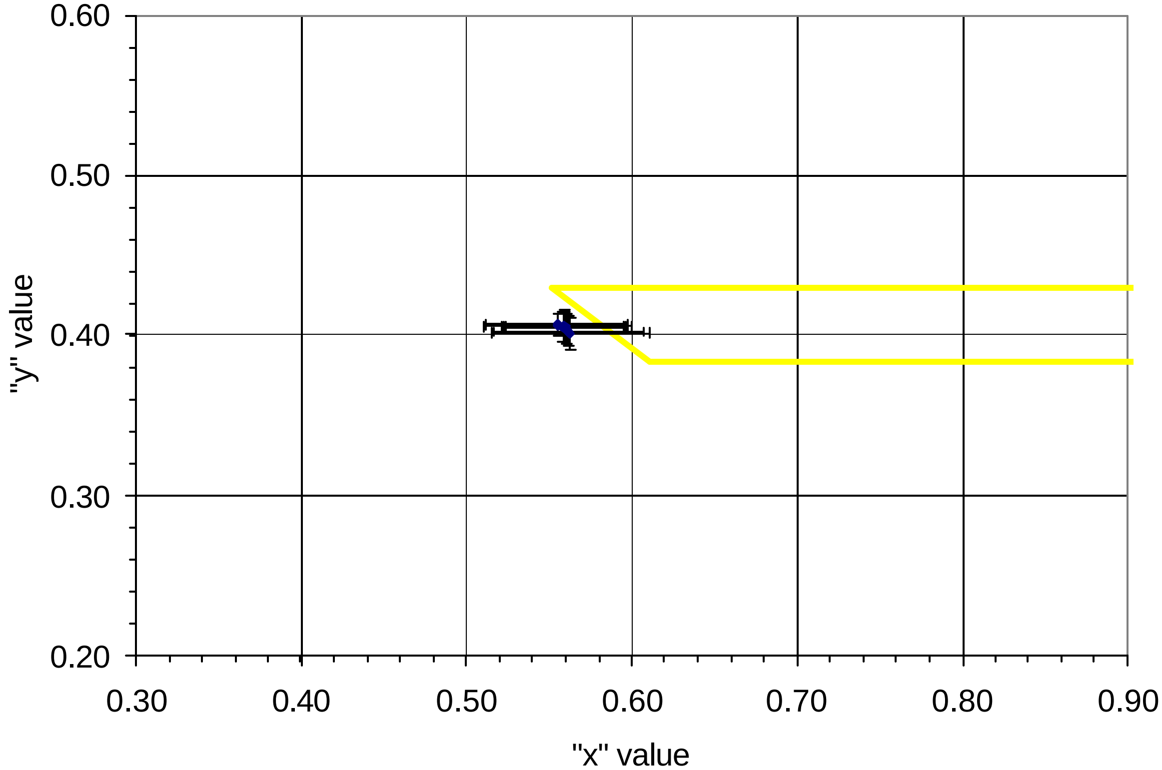

Figure 70. Chromaticity of the WPS#8 signal with different combinations of LEDs illuminated (open-circuited)

Figure 71 shows the modification to the WPS#8 signal that allows short-circuiting of individual elements. Figures A8.5.1 through A8.5.21 of the appendix show the effects of disabling 8 of the 88 LED elements in different parts of the signal via short-circuiting at a constant 10.0 volts. Figure 72 summarize these results. The light output from the WPS#8 signal is not a function of the particular pattern of active elements, with maximum outputs ranging over a narrow range from 2685 to 2856 candela. Supply current and power consumption remained constant at 1.31 amps and 13.1 watts, respectively. The light-power efficiency remained relatively constant in the range of 205 to 218 candela/watt.

Figures A8.6.1 through A8.6.21 of the appendix show the effects of disabling 24 of the 88 LED elements in different parts of the signal via short-circuiting at a constant 10.0 volts. Figure 73 summarize these results. With the exception of one anomalous data point (A8.6.8 at 2856 candela), the light output from the WPS#8 signal is not a function of the particular pattern of active elements, with maximum outputs ranging over a range from 1800 to 2290 candela. Supply current and power consumption remained constant at 1.16 amps and 11.6 watts, respectively. The light-power efficiency remained relatively constant in the range of 155 to 197 candela/watt.

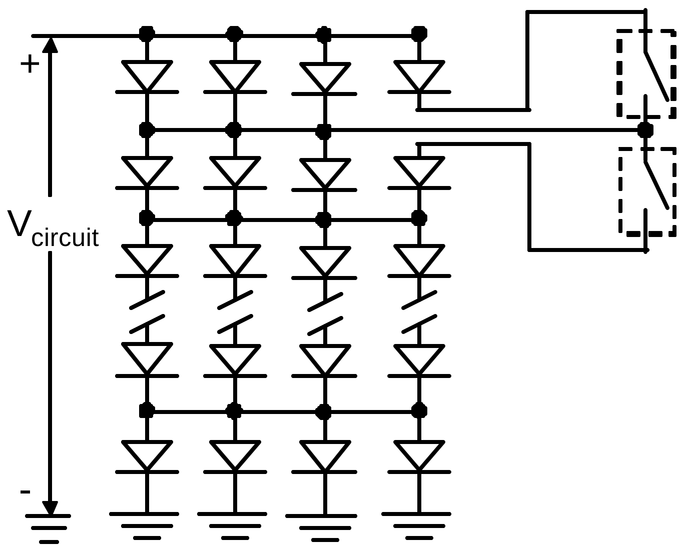

Figure 71. WPS#8 signal configured for short-circuiting

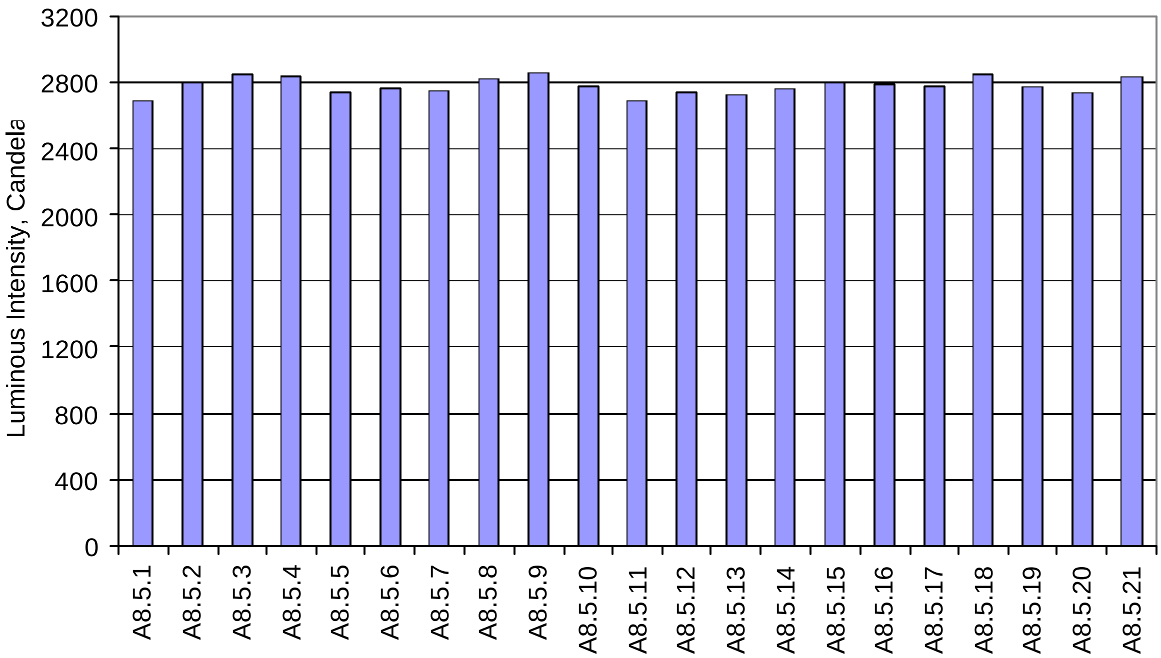

Figure 72. Maximum light intensity from WPS#8 with 80 active elements at 10.0 volts (short-circuits)

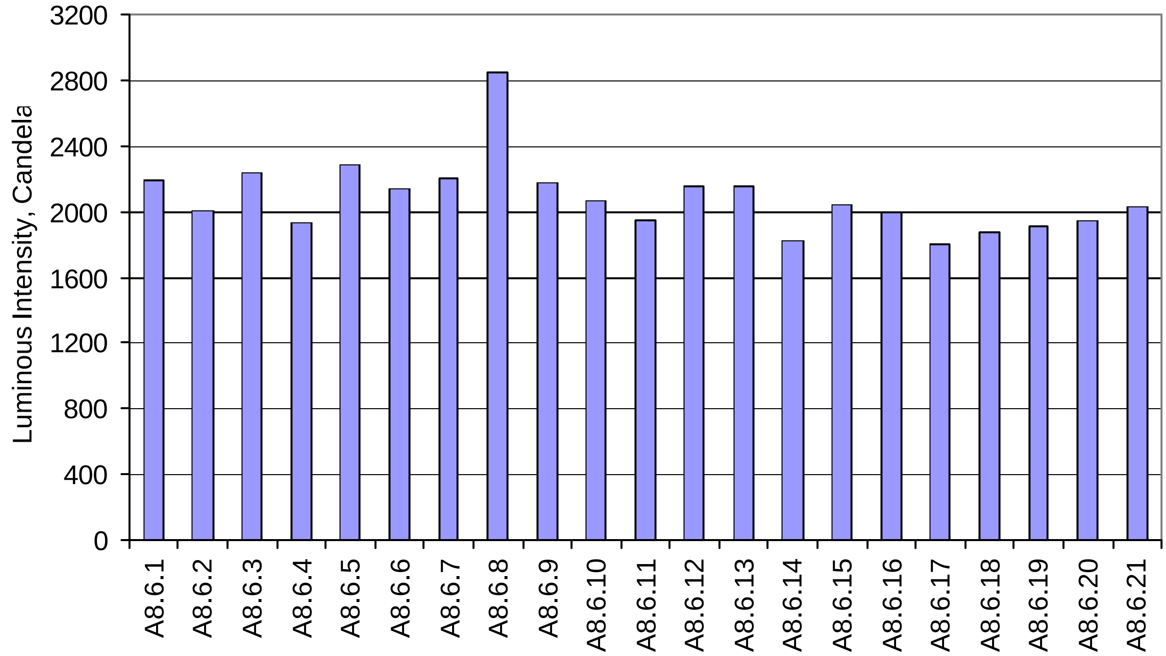

Figure 73. Maximum light intensity from WPS#8 with 64 active elements at 10.0 volts (short-circuits)

Figure 74 shows the chromaticity results from the same tests shown in Figure 73. All of the results show very similar color values clustered fairly close to the edge of the AREMA limits for yellow wayside signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift due to varying the percentage of ON elements via short circuiting with the WPS#8 signal.

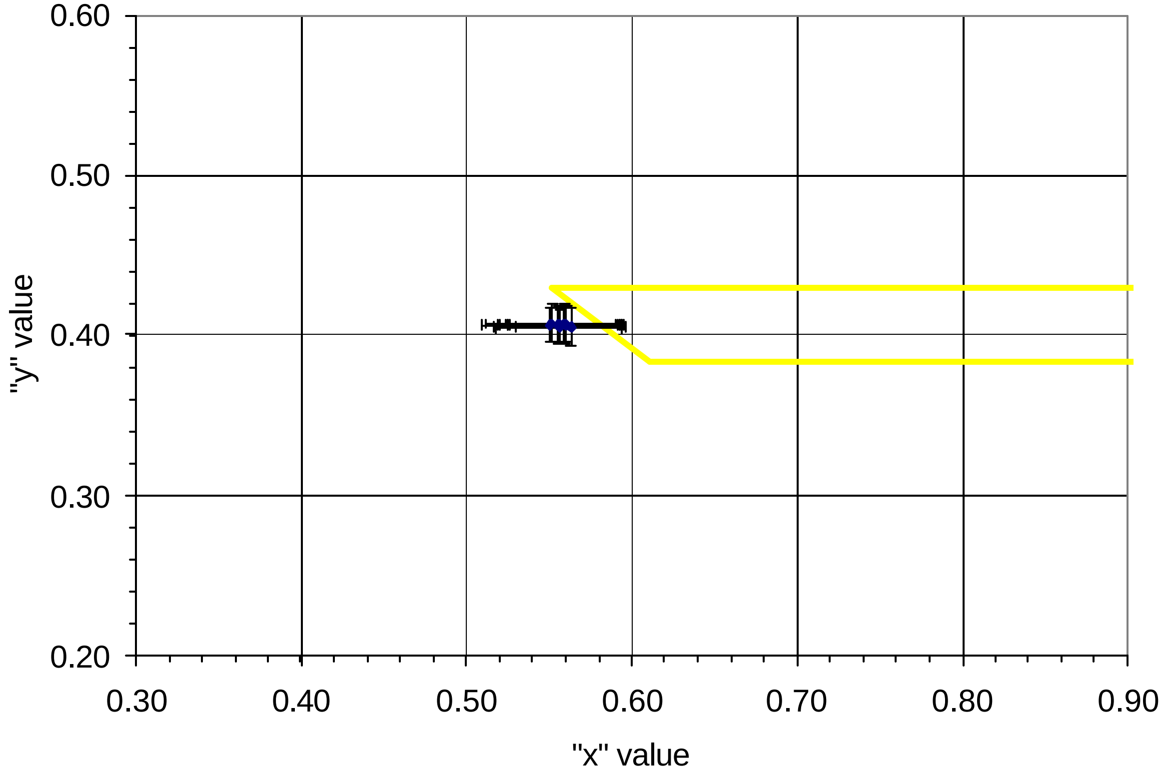

Figure 74. Chromaticity of the WPS#8 signal with different combinations of LEDs illuminated (short-circuited)

Data from Gelcore signal (WPS#9)

Figure 75 shows the configuration of the elements in a eight inch, green, wayside signal (#RM4 GC 75) supplied by Gelcore. This signal (referred to as WPS#9 in this report) has 90 LED elements arranged in 15 groups of 6 in a series/parallel circuit as shown in Figure 75. This eight inch wayside signal was equipped with a lens that gives a narrow (13 degree) field of view, with a claimed visible distance of 4000 feet. The WPS#9 signal uses a power supply to regulate the voltage and current applied to the LEDs. Note that the voltage applied to the LED circuit ($V_{circuit}$) is not equal to the voltage supplied to the signal when a power supply is used.

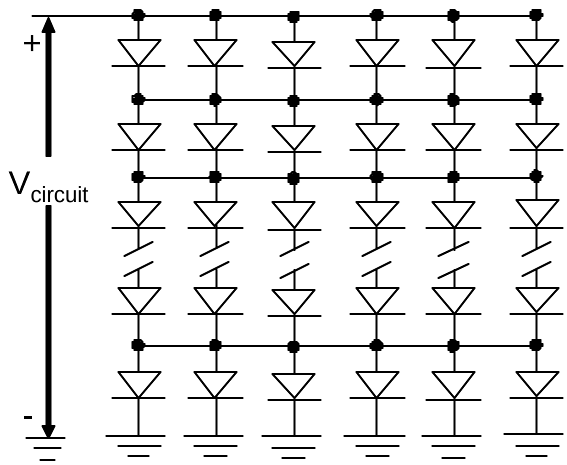

Figure 75. LED circuit configuration for WPS#9 signal

Figures A9.1.1 through A9.2.8 show the results of a series of tests that were conducted (unsuccessfully) to determine the point source correction factor for the green signal. Figure 76 summarizes the results from this series of tests, which were very inconsistent. Under ideal circumstances the output of this signal should have somewhat approximated an inverse square law. In several cases moving the signal further from the measuring colorimeter caused the maximum light intensity to remain the same or even increase, which should not have happened. The exact reason for the erratic behavior of this signal is unknown, but is most likely due to the narrow beam angle (13 degrees) of the WPS#9 signal making the initial alignment much more critical than with the twelve inch crossing signals. Due to the erratic measurements of the WPS#9 signal at different distances, <u>the point source correction was not applied to any of the readings for the WPS#9 eight inch signal.</u>

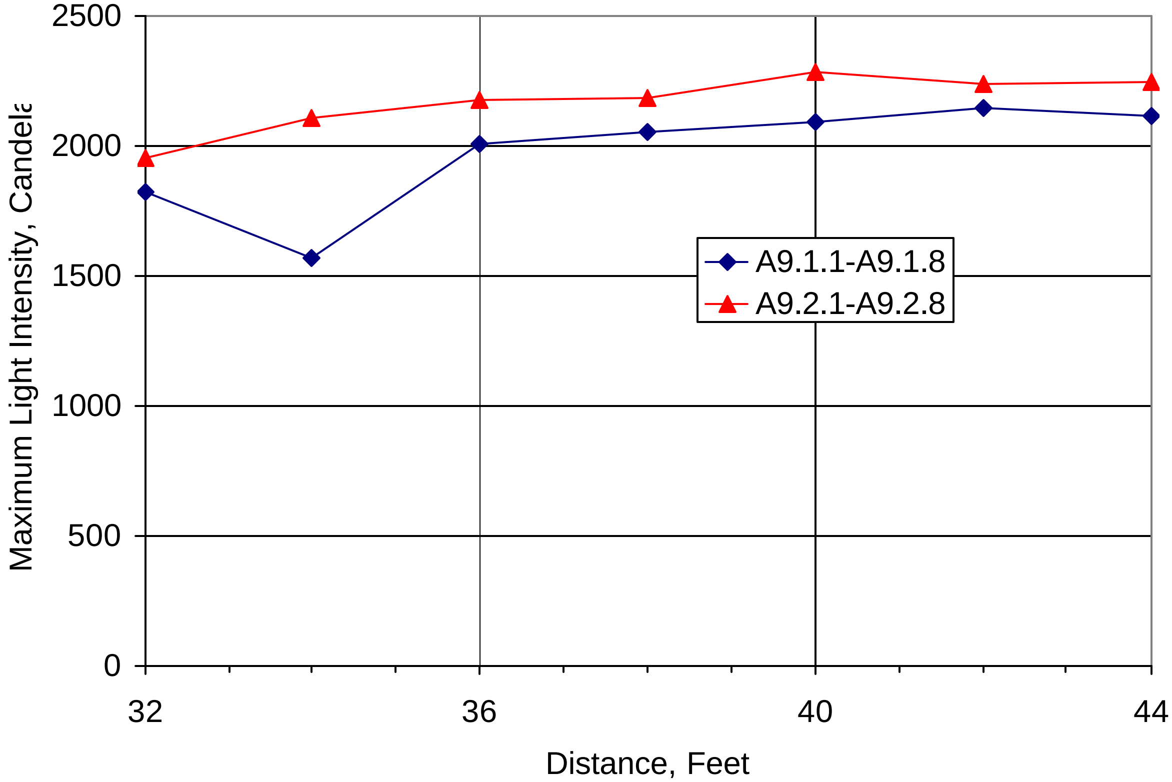

Figure 76. Maximum light intensity vs. distance for WPS#9

Figures A9.1.1, A9.1.2, and A9.1.9 through A9.1.12 of the appendix show the effects of varying voltage in the range of 8.0 volts to 13.5 volts with 100% of the LED elements active. Data from these figures is summarized in Table 25. With the exception of one anomalous reading (12.0 volts, 1505 candela), the light output from this signal is not a function of the supply voltage, with maximum outputs ranging from 2075 candela at 13.5 volts to 2055 candela at 10.0 volts. Supply currents ranged from 1.27 amps at 9.0 volts to 1.40 amps at 12 volts. Power consumption varied widely from 10.3 to 18.8 watts. The light-power efficiency was not constant, ranging from less than 100 to slightly more than 200 candela/watt.

Table 25. Results from WPS#9 with varying voltage input.

Case	Supply Voltage	Distance (feet)	Maximum Light Intensity (candela)	Supply Current (amps)	Power Consumption (watts)	Light-Power Efficiency (candela/watt)
9	8.0	38	2070	1.29	10.3	201
10	9.0	38	2072	1.27	11.4	182
1	10.0	38	2055	1.28	12.8	161
11	10.5	38	2073	1.28	13.4	154
2	12.0	38	1505	1.40	16.7	90
12	13.5	38	2075	1.39	18.8	110

Figure 77 shows the chromaticity results from the same tests shown in Table 25. All of the results show very similar color values clustered well within the AREMA limits for green wayside signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift with input voltage with the WPS#9 signal.

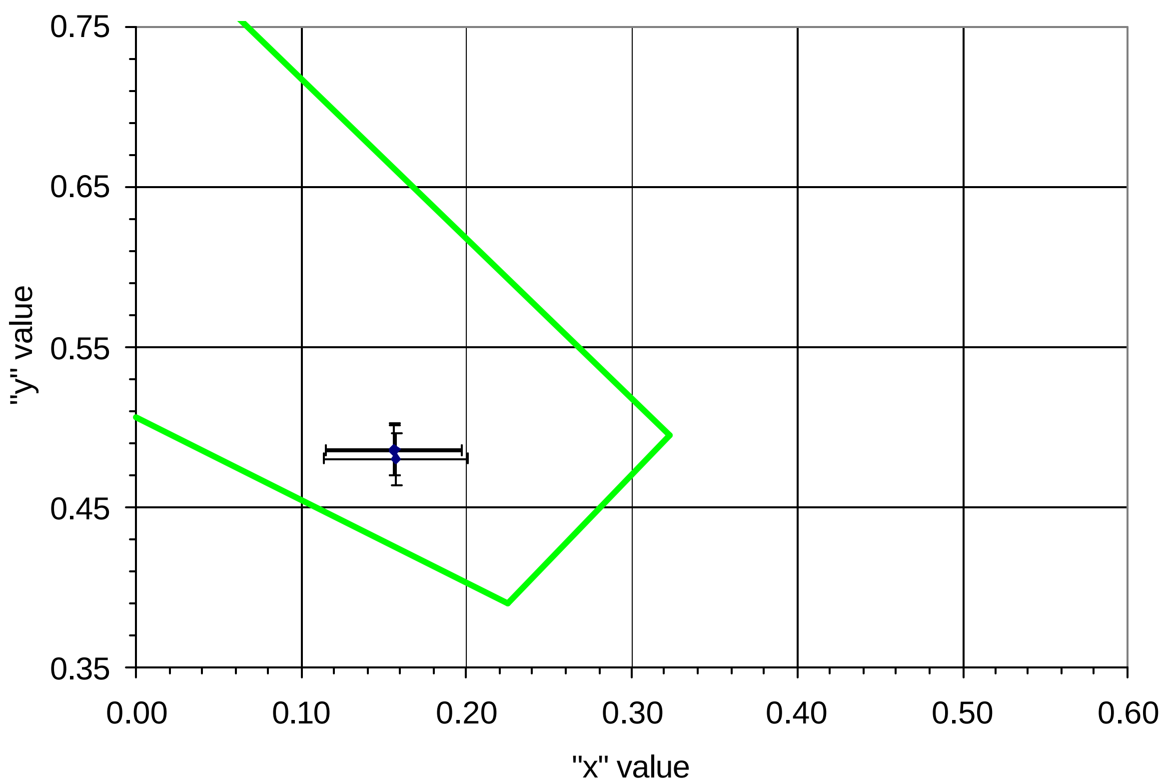

Figure 77. Chromaticity of WPS#9 with varying voltage input.

Figure 78 shows the circuit configuration for disabling individual LED elements via open-circuiting. Figures A9.3.1 through A9.3.13 of the appendix show the effects of varying the number of active LED elements from 95.6% (86 active elements) to 83.3% (75 active elements) via open-circuiting at a constant 10.0 volts. Figure 79 summarizes these results. The light output from the WPS#9 signal is not a strong function of the number of active elements, with maximum outputs ranging from 1958 to 2094 candela with no apparent pattern to the results. Supply current and power consumption are essentially constant at 1.26-1.27 amps and 12.6-12.7 watts, respectively. The light-power efficiency remained relatively constant in the range of 155 to 166 candela/watt. The number of open-circuited elements has a negligible effect on the power requirements for the WPS#9 signal. The relative insensitivity of the WPS#9 signal to the number of open-circuited elements is due to two factors:

1. the use of a power supply to regulate voltage and current, and
2. the combined series and parallel arrangement of LEDs (shown in Figure 75).

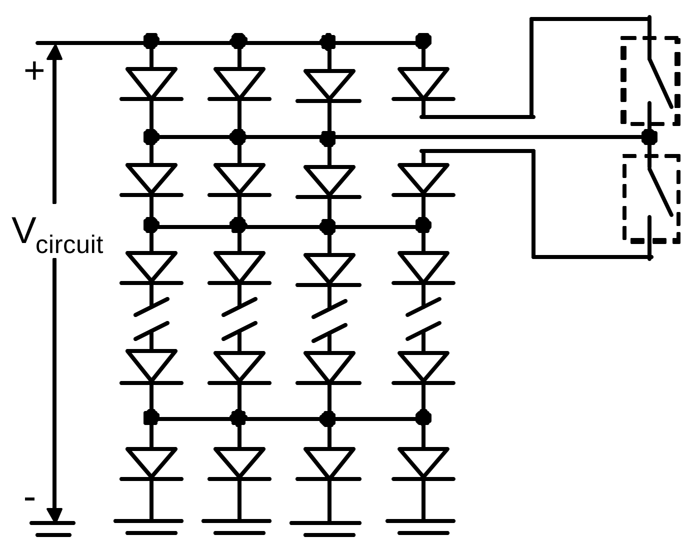

Figure 78. WPS#9 signal configured for open-circuiting

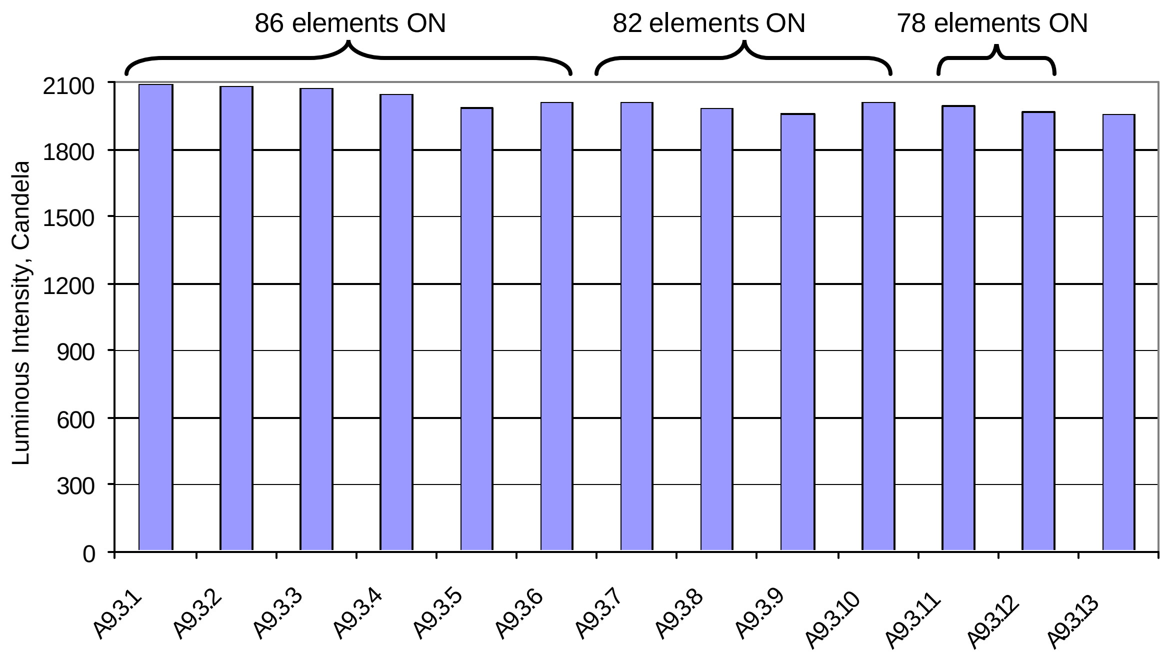

Figure 79. On-axis luminous intensity for the WPS#9 signal with different combinations of LEDs illuminated (open-circuited)

Figure 80 shows the chromaticity results from the same tests shown in Figure 79. All of the results show very similar color values clustered well within the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift due to varying the percentage of ON elements via open circuiting with the WPS#9 signal.

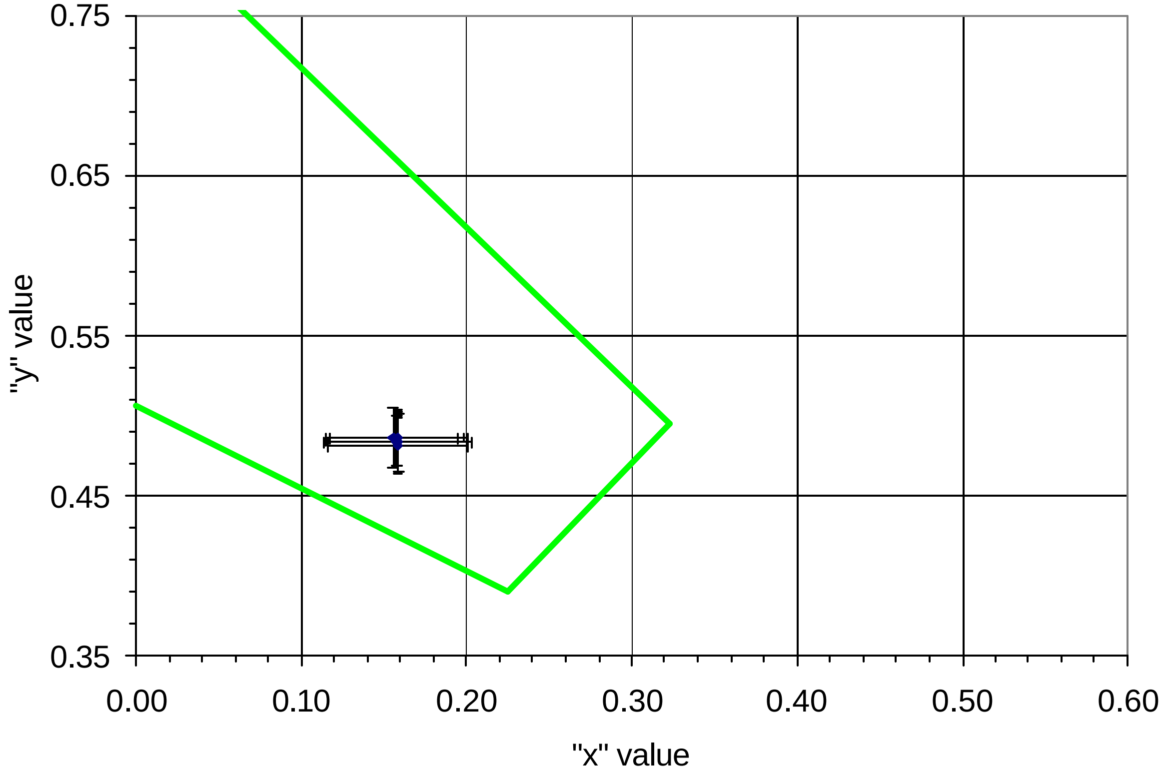

Figure 80. Chromaticity of the WPS#9 signal with different combinations of LEDs illuminated (open-circuited)

Figure 81 shows the modification to the WPS#9 signal that allows short-circuiting of individual elements. Figures A9.4.1 through A9.4.20 of the appendix show the effects of disabling 8 of the 90 LED elements in different parts of the signal via short-circuiting at a constant 10.0 volts. Figure 82 summarize these results. The light output from the WPS#9 signal is not a function of the particular pattern of active elements, with maximum outputs ranging over a narrow range from 1614 to 1905 candela. Supply current and power consumption remained constant at 1.19 amps and 11.9 watts, respectively. The light-power efficiency remained relatively constant in the range of 135 to 160 candela/watt.

Figures A9.5.1 through A9.5.21 of the appendix show the effects of disabling 24 of the 88 LED elements in different parts of the signal via short-circuiting at a constant 10.0 volts. Figure 83 summarize these results. The light output from the WPS#9 signal is not a function of the particular pattern of active elements, with maximum outputs ranging over a range from 1445 to 1629 candela. Supply current and power consumption remained constant at 1.12 amps and 11.2 watts, respectively. The light-power efficiency remained relatively constant in the range of 129 to 145 candela/watt.

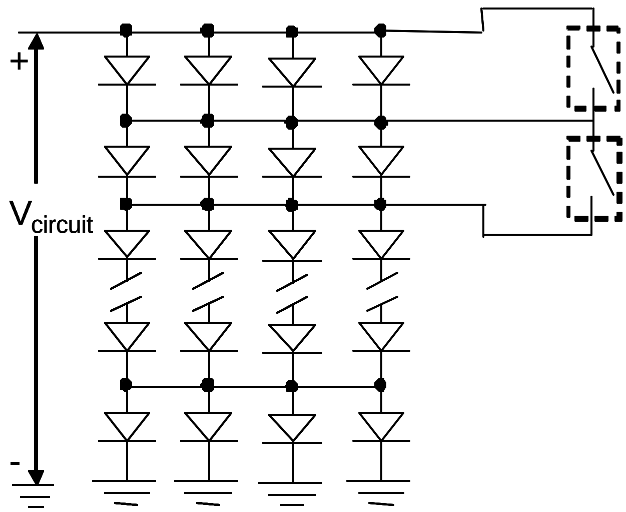

Figure 81. WPS#9 signal configured for short-circuiting

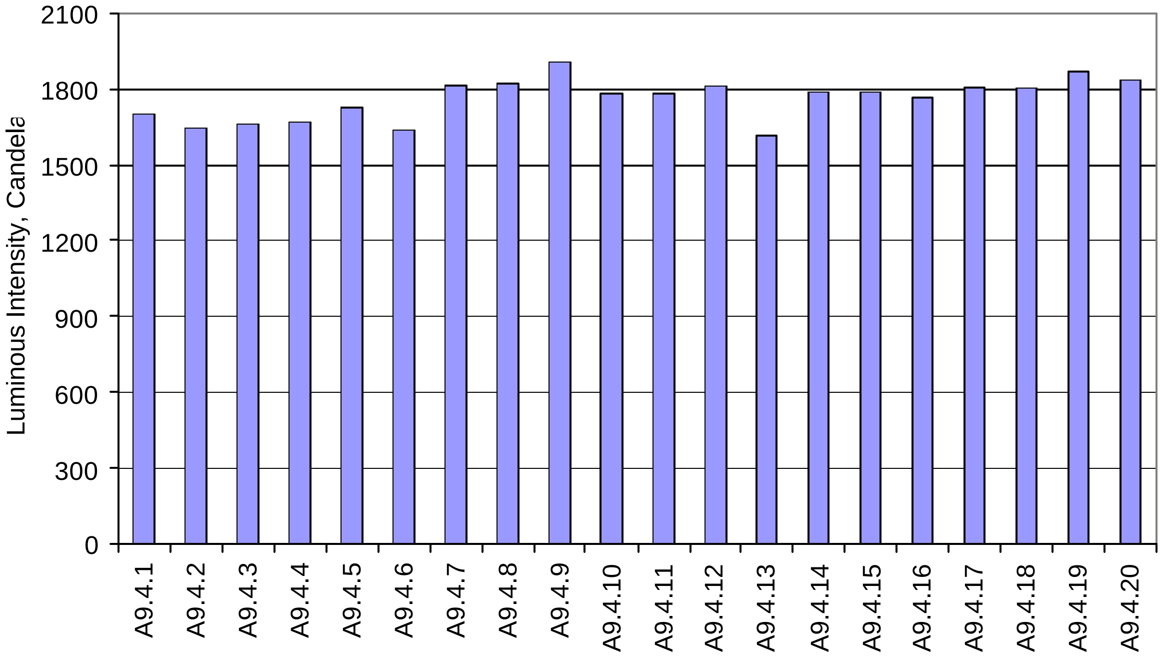

Figure 82. Maximum light intensity from WPS#9 with 80 active elements at 10.0 volts (short-circuits)

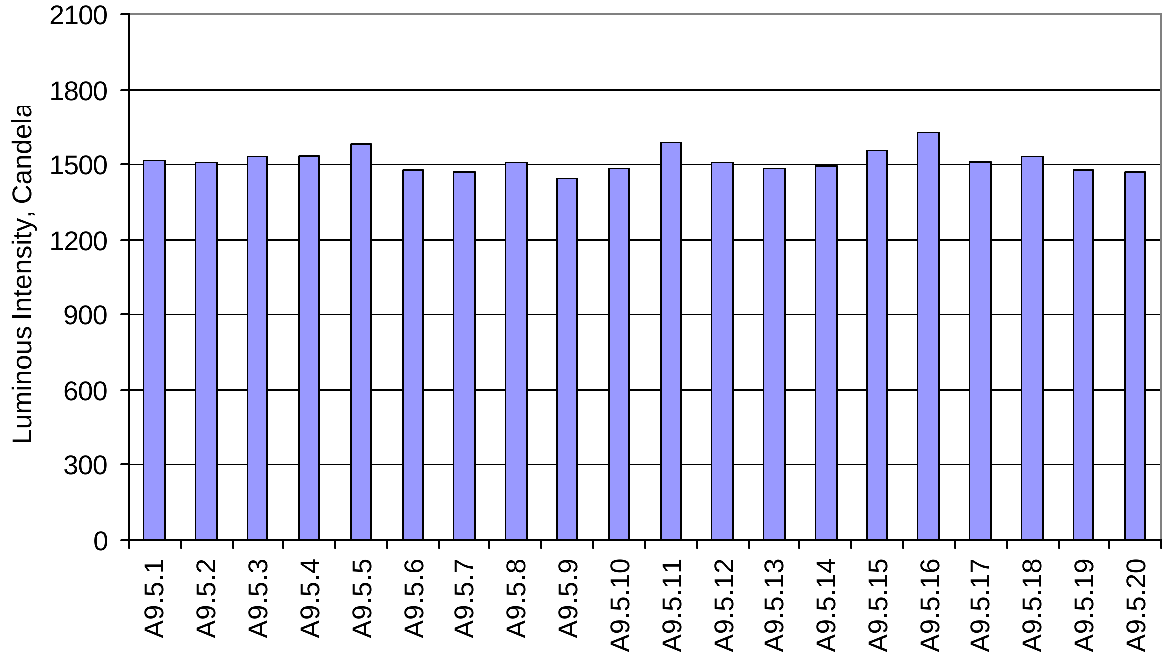

Figure 83. Maximum light intensity from WPS#9 with 64 active elements at 10.0 volts (short-circuits)

Figure 84 shows the chromaticity results from the same tests shown in Figure 82. All of the results show very similar color values clustered well within the AREMA limits for red crossing signals. The small differences in the mean color values are much less than the differences measured during the test, as shown by the error bars. There is no apparent color shift due to varying the percentage of ON elements via short circuiting with the WPS#9 signal.

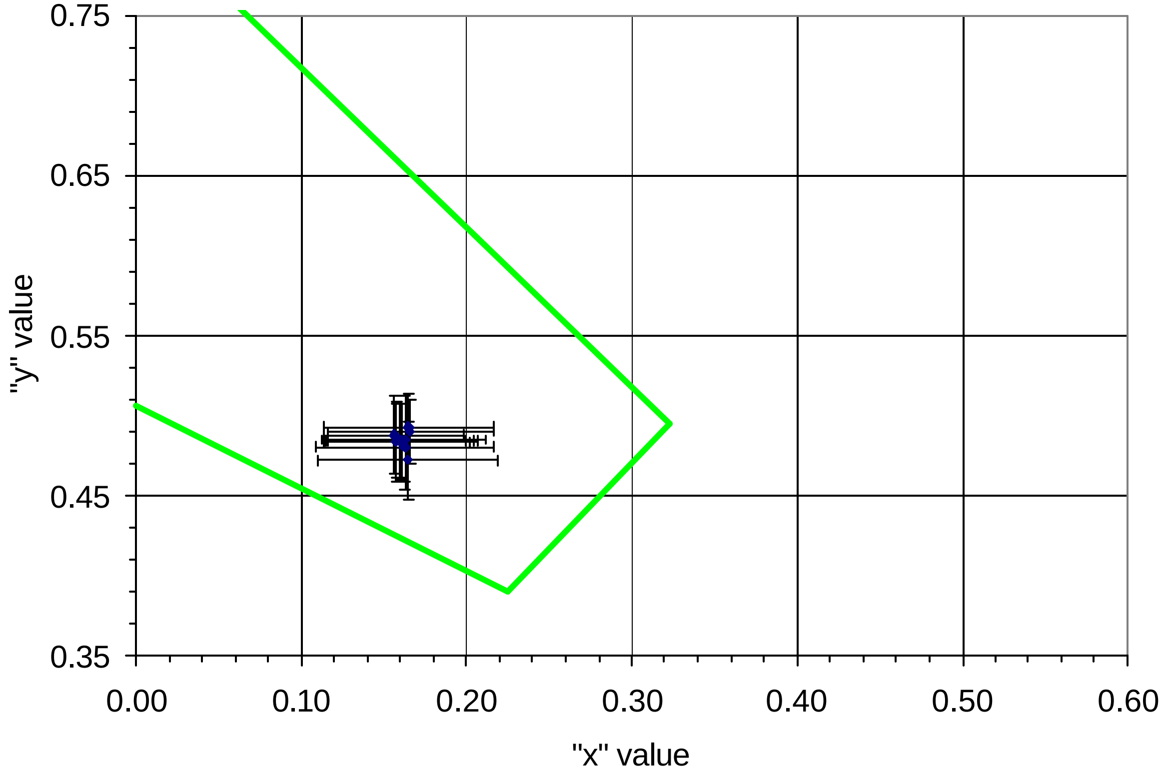

Figure 84. Chromaticity of the WPS#9 signal with different combinations of LEDs illuminated (short-circuited)

FIELD TESTING OF LED SIGNALS

Introduction

In the laboratory environment, the light output of a signal is determined by measuring the luminous intensity and chromaticity; however, the visible range of a signal should ultimately be measured in a field testing environment. Green and Milanovic (2002) helped to develop the Transport Canada standard for highway/railway crossing signals in Canada. As a part of this study, field testing was done to compare the visibility of four pairs of LED signals and traditional incandescent signals. The intensities and beam patterns of the LED signals were first characterized in a laboratory environment. The luminous intensity of the four signals ranged from 300 to 800 candela. The field test was conducted at a former military firing range in Victoria, British Columbia. The signals were mounted to five sawhorses in front of the targets. The field testing set-up is shown in Figure 85. LED signals were placed in Lanes 1, 2, 4, and 5 and traditional incandescent signals were located in Lane 3. A focus group of eleven individuals evaluated the five pairs of signals simultaneously on a clear day. The signals were ranked on a scale of 0 to 10. A 10 was given to the most conspicuous signal, and the remaining signals were ranked in comparison to this signal. The group evaluated the signals at several observation points located between 50 yards and 1000 yards away from the signals. The test was repeated at night with only six evaluators. All four LED signals performed better than the traditional incandescent signals; however, the improved performance was less evident at night. Two more field tests were conducted using newer incandescent lamps and improved test stands. These tests also showed that LED signals performed better than traditional incandescent signals.

Figure 85. Field testing set-up of signal lights (Green and Milanovic, 2002).

The field testing conducted for Transport Canada compared fully-illuminated LED warning signals to traditional incandescent signals. At the University of Alabama, laboratory testing has been conducted to measure the luminosity and chromaticity of LED signals experiencing partial failures; however, no field testing has been conducted to determine the how partially-illuminated signals are interpreted by automotive drivers or train crews. The objective of this project was to develop a field test procedure that can be used to describe how individuals perceive warning signals in partial failure. This included the design and construction of two test stands, a manual switch system to select patterns of non-illuminated LEDs, and the test procedure. Four field tests were conducted with volunteers to determine the efficacy of the field test procedure.

<u>System Design</u>

The procedure for testing individuals' perception of the LED lights was approved by the Institutional Review Board (IRB) at the University of Alabama. The field trial procedure consisted of two tests, a simple eye exam and the LED perception test. Volunteers were recruited from the faculty, staff, students and friends of students in the Department of Mechanical Engineering at The University of Alabama. After the volunteers gave their informed consent, they were given a simple eye chart vision test called "The E-game", which gives approximate visual acuity.

The volunteers were tested “as is” in that they were not prepared in any way, to better reflect their normal vision. They were also asked to wear their usual eyeglasses or contacts as recorded on their driver’s license. The field test must be conducted in a large flat open area with an unobstructed line of sight of 1600 feet. Palmore Park, a Tuscaloosa Parks and Recreation Association (PARA) facility was used for this experiment. The equipment for the test includes two test stands, which each housed two LED warning signals. A description of the test is provided following a description of the test equipment.

Two stands, shown in Figure 86, were constructed to encase two LED signals eight feet high. A manually operated switch system was designed and built to create different failure patterns. The stands also used their own power source (12 volt battery) to operate the lights.

Figure 86. Signal housing with stand.

The manually operated switch system was laid out on aluminum plates, as shown in Figure 87. Double-pole single-throw switches were placed through the holes. A total of sixty-two switches were used to operate the failure patterns. Each light used a different number amount of switches to activate different failure patterns. The signals NPS #4, WPS #2, WPS #3, and NPS #1 were used in field testing, as shown in Figure 88.

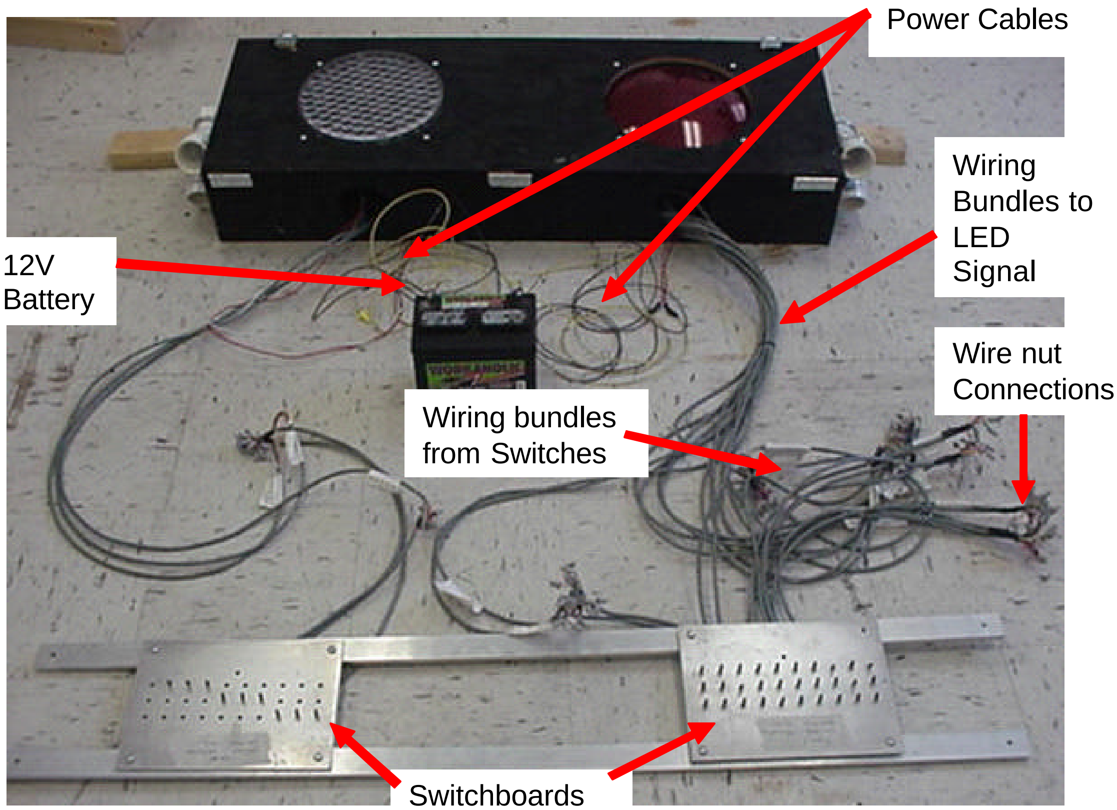

Figure 87. Complete Signal Wiring.

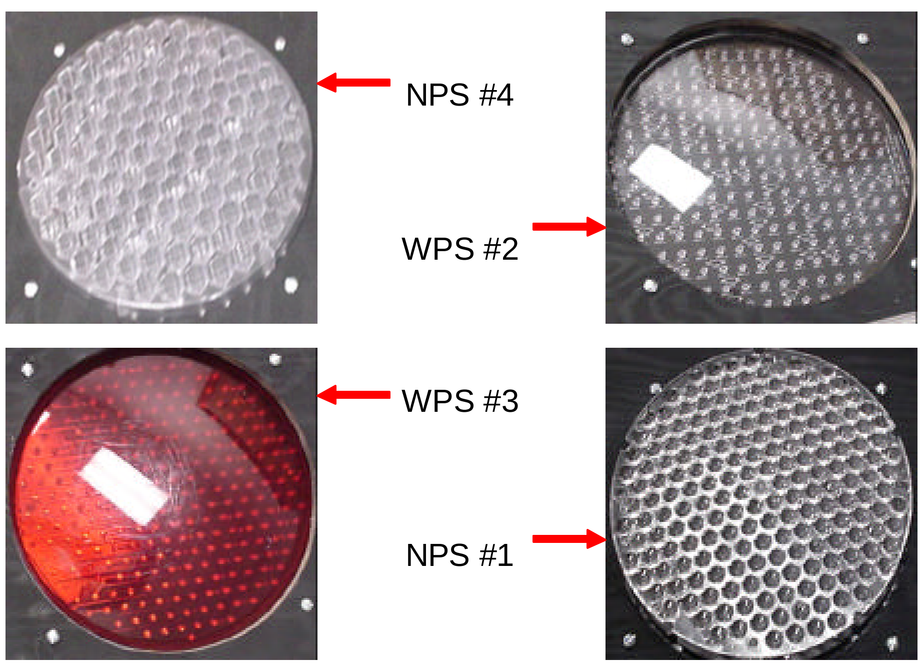

Figure 88. LED warning signals used in field testing.

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All equipment was set up at the field test site well before the testing began, and the stations were pre-marked for the volunteers. Stations were located at distances of 100, 450, 800, 1150 and 1500 feet as shown in Figure 89. Also, for each different test group a pre-arranged test was devised which had specific LED failure patterns for each individual signal to be shown at each observation station. These failure patterns are illustrated in Appendix #. Two pairs of LED signals were located approximately 1600 feet apart facing each other. Each signal was designated by a number to aid the volunteers in differentiating between the signal lights.

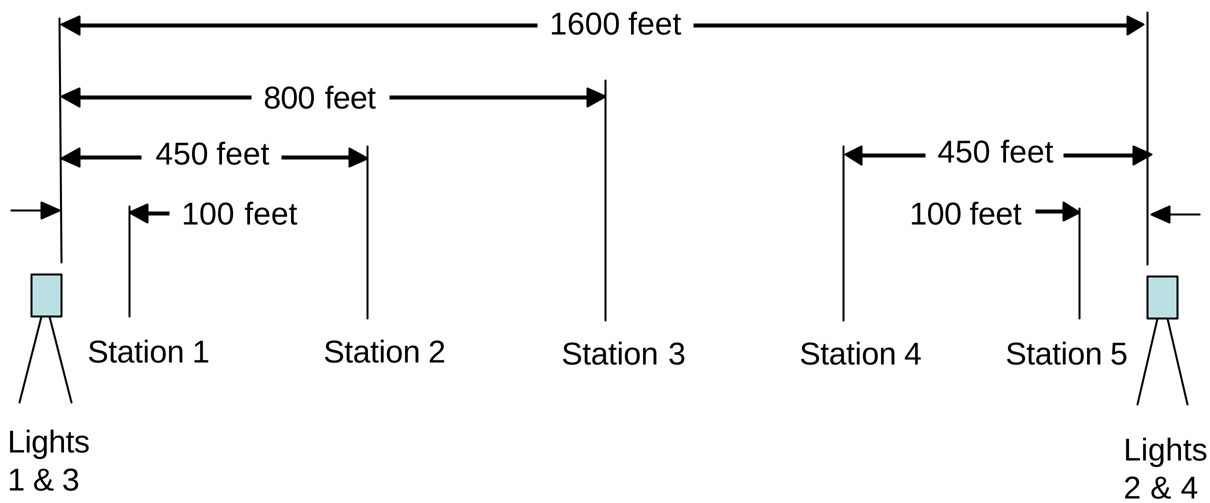

Figure 89. Field Test Layout.

Depending on which station the volunteers were at, each signal group operator set the signals to display the correct test pattern according to the test layout they were given. The following list shows some of the steps taken to administer the field test:

1. The volunteers are given an informed consent form to read and sign.
2. Each volunteer is given the simple eye exam.
3. Response forms were then handed out to the volunteers.
4. The volunteers were taken to station 1, located 100 feet from Signals 1 (NPS#4) and 3 (WPS#3) and 1500 feet from Signals 2 (WPS#2) and 4 (NPS#1).
5. Once the volunteers reached station 1 they were turned to face signals 2 and 4 while the signal 1/3 operator illuminated signal 1.
6. The volunteers were turned around and asked to look at Signal 1 and mark on the test form if the signal appeared to be on, off, or if it was not clearly perceivable.

7. While the volunteers were evaluating Signal 1, the operator of Signals 2 and 4 illuminated Signal 2.
8. After the volunteers evaluated Signal 1, they turned and faced Signals 2 and 4 where they evaluated if Signal 2 appeared to be on, off, or unclear.
9. While the evaluation of Signal 2 was underway, the Signal 1/3 operator turned off Signal 1 and illuminated Signal 3.
10. When ready the volunteers were instructed to turn and face Signals 1 and 3 again and evaluate Signal 3.
11. Similarly, the Signal 2/4 operator turned off Signal 2 and illuminated Signal 4. The volunteers then turned one last time and faced Signal 4 and evaluated it.
12. After evaluating all four signals, the volunteers were escorted to the next station.

The volunteers and signal operators repeated this procedure at each station between the signal pairs. The volunteers were routinely reminded not to compare signals but to evaluate how each signal appeared. Also, the failure patterns were varied at each station per the test layouts to discourage comparison. The distances for the 5 stations the volunteers were asked to observe the signals from is given in Figure 89.

After the volunteers had finished with the test, they were given new forms and repeated the procedure with one of the other pre-arranged LED pattern tests. Since the volunteers were already located at station 5 they were faced toward Signals 1 and 3, and the Signal 2/4 operator prepped Signal 2 for viewing. The volunteers then turned and evaluated Signal 2. The Signal 1/3 operator meanwhile set up and illuminated Signal 3. The previous test procedure was repeated with a few changes. The volunteers were moving through the stations backwards and because of this they viewed the signals in a different order: Signal 2, then 3, then 4 and finally Signal 1.

Throughout the field test the signal operators and the field-test conductor maintained a line of communication through the use of two-way radios. The radios were used so that the operators could inform the test conductor that signals were ready for viewing. Also the test conductor would inform the signal operators what signal the volunteers were observing and when the volunteers were in transit to the different stations.

Students and faculty members within the College of Engineering were recruited as volunteers. Volunteers were used because the nature of this test depends on how people perceive the LED signals. Every person is different and so perception is likewise particular to each individual. Seventeen volunteers participated in four separate field tests. Twelve of the seventeen volunteers were between the ages of 19 and 24. The remaining five volunteers were over thirty years in age. A wide age range was desired to include the effects of aging on vision. Also, the older volunteers are a better representation of a typical train crew. Of the volunteers tested, 8 were females and 9 were males. Figure 90 shows one of the volunteer groups that participated in the field test.

Figure 90. Volunteers during field test.

Palmore Park was chosen as the test site for a number of reasons. First, it met the distance constraints for the test – a total distance of 1600 feet with room to set up the test stands. Secondly, it could be reserved through the Tuscaloosa Parks and Recreation Association. Finally, it was a low traffic location with large flat open spaces that provided the fewest number of hazards for the volunteers and the least amount of distraction for road traffic.

Upon reaching the test site each volunteer was given a consent form to read and fill out. The purpose of informed consent is to protect the rights of the volunteers while providing them with information about the test. Before the field test, volunteers were given a simple vision test. The results of the vision tests were used to screen the experiment results. For instance, if someone’s vision was 20/200 or worse then they would not be expected to see any of the signals. The volunteers were not prepped for the vision test, so their “normal vision” could be tested, since this is the vision they would be using while driving.

Failure patterns were chosen arbitrarily and by the LED signals' limitations. Some of the LEDs could not be completely controlled due to the way the signals were constructed. Signal WPS#2 had a structural member on the back of the integrated circuit that could not be removed and so the three middle rows of LED lights could not be turned off except by disconnecting the signal's power source. Signal WPS#3 had a built in feature in that it began to flash when a certain number of the LEDs were turned out. Each light had its LEDs grouped in sets. Thus, to simulate failures, LEDs were activated or deactivated in bundles created by the manufacturer. Failure patterns were chosen based on percentages of the LEDs. The patterns that were used were roughly 0%, 25%, 50%, 75% and 100%. This was done to simplify the tests for the volunteers and to minimize the number of electrical modifications needed for each light.

For each field test, two pre-planned sets of patterns were chosen for each signal depending on the observation station. The observation stations were arbitrarily chosen at varying distances between the sets of signal lights. The patterns to be shown at each station were decided upon by following a design matrix. By utilizing a design matrix, it was not necessary to test each pattern at each station. This made the test easier for volunteers to follow and took less time to complete.

The results from the volunteer response forms are summarized below. Volunteer responses marked as "off" or "unclear" were both counted as signal failures. In addition, volunteer responses marked "on" with comments such as "barely" or "maybe" were counted as signal failures. The results discussed below also include volunteer responses for signals that were completely off and fully illuminated. The test provides the opportunity for subjects to report misinterpretation of the signal without being influenced by what happened at greater distances. It also provides for subjects to report lights being "on" when no LEDs were illuminated.

<u>Results for NPS#1</u>

The NPS#1signal was recognized as “on” at all distances when 75% or 100% of the LEDs were illuminated and at distances near to the signal when 50% of the LEDs were illuminated. The signal was misinterpreted at each distance by at least one volunteer when 25% of the LEDs were illuminated. At 100 ft, almost 60% of volunteers misinterpreted the signal. In addition, the signal was unclear at close distances when only 50% of the LEDs were illuminated. A bar graph of volunteer responses is in Figure 91.

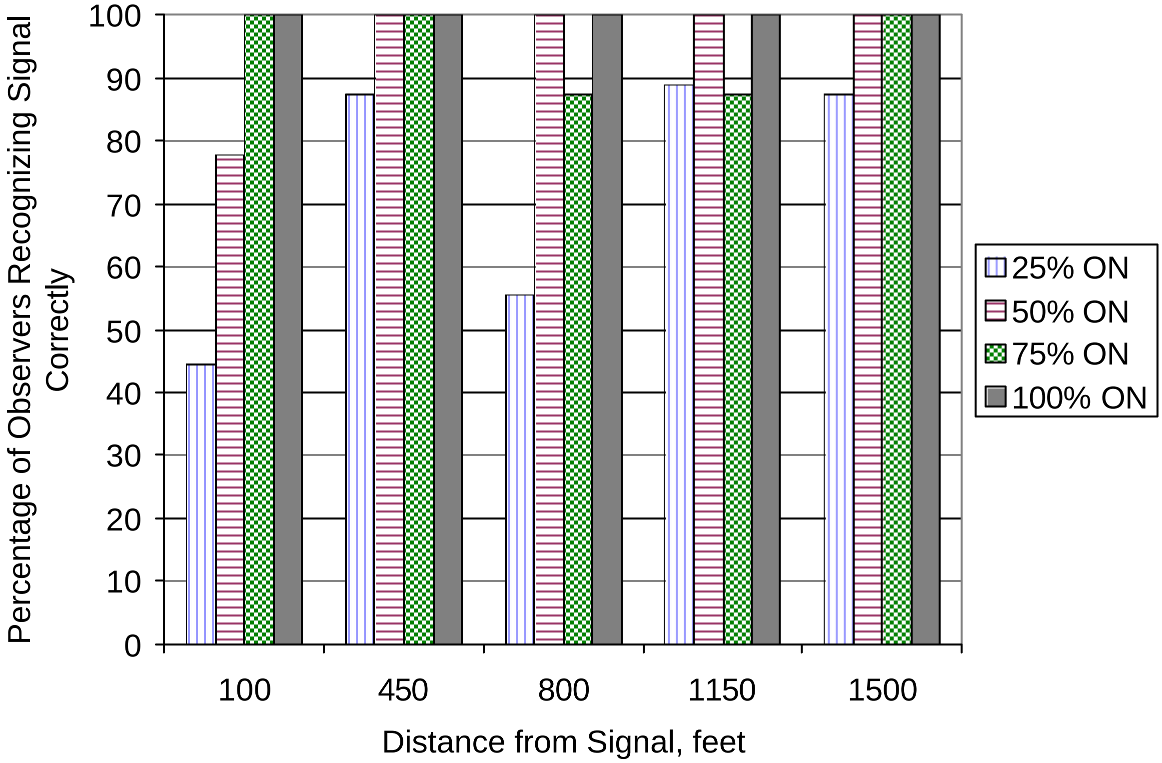

Figure 91. Volunteer responses for NPS#1.

Results for WPS#2

The WPS#2 signal was recognized as "on" at all distances when 75% or 100% of the LEDs were illuminated and at close distances when 50% of the LEDs were illuminated. The signal was misinterpreted at all distances when only 25% of the LEDs were illuminated and at greater distances when 50% of the lights were illuminated. A bar graph of volunteer responses is shown in Figure 92.

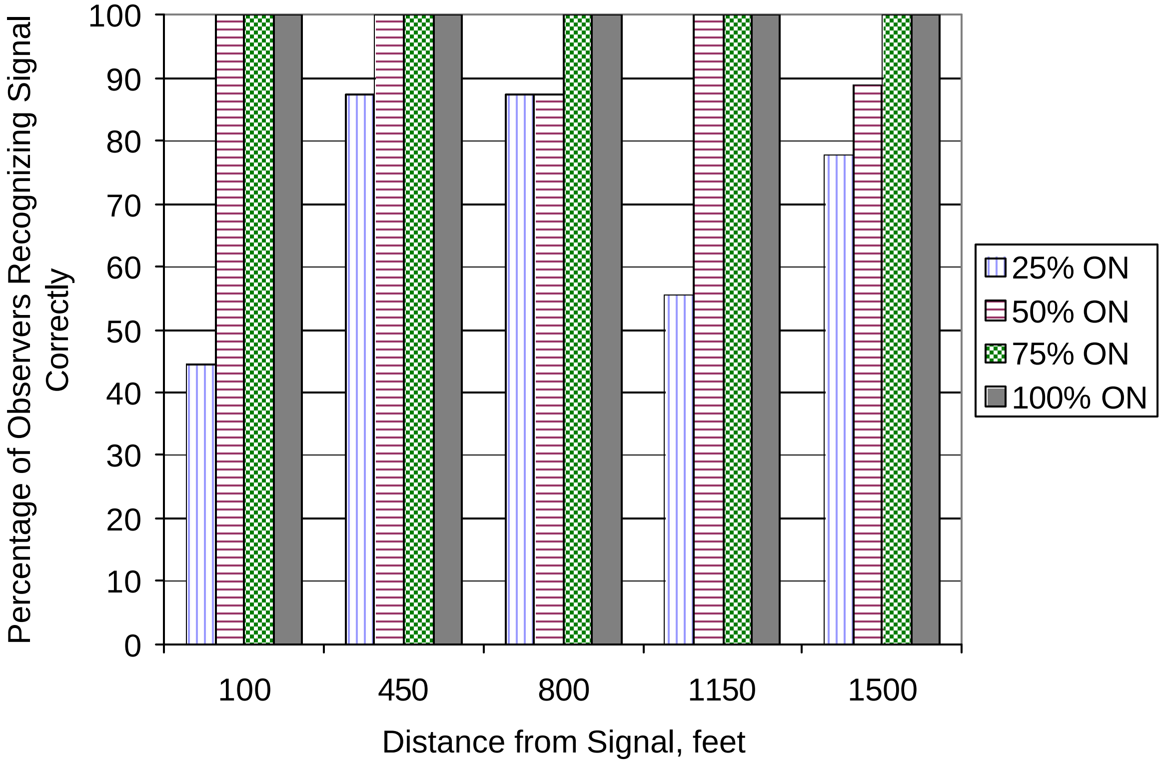

Figure 92. Volunteer responses for WPS#2.

Results for WPS#3

All volunteers recognized signal WPS#3, as "on" at all distances when any portion of LEDs was illuminated with only two exceptions. The signal appeared unclear at 100 ft when 25% of the LEDs were illuminated. As discussed previously, this is due to the ability to distinguish between non-illuminated and illuminated portions of the signal at close distances. Also, the signal appeared unclear to one volunteer at 1500 ft when 75% of the LEDs were illuminated. A bar graph of volunteer responses is in Figure 93.

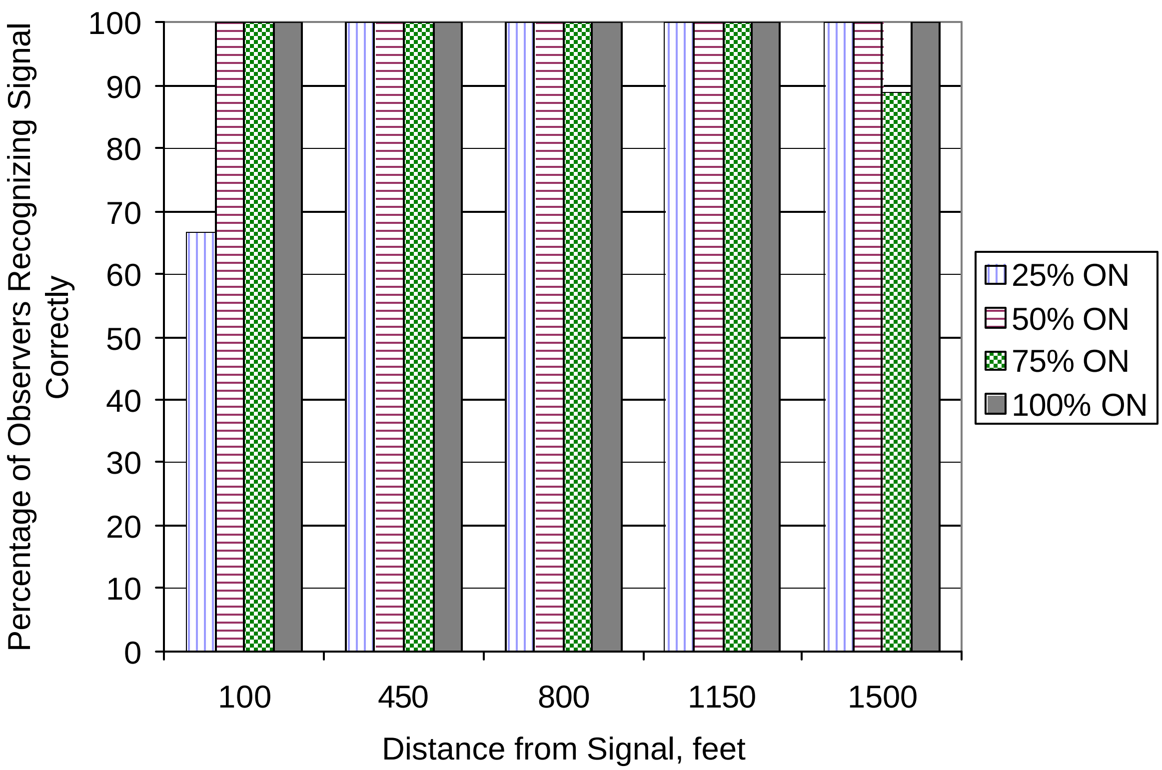

Figure 93. Volunteer responses for WPS#3.

<u>Results for NPS#4</u>

The NPS#4 signal was recognized as "on" by all volunteers at all but one distance when any portion of LEDs was illuminated. The only exception is one volunteer who responded that the signal was unclear at 100 ft when 25 % of the lights were illuminated. This signal might appear unclear to an observer at close distances because it is possible to distinguish between the illuminated and non-illuminated LEDs. At distances farther from the signal, an observer cannot distinguish individual LED sections. The volunteer responses are shown in Figure 94. In addition, one volunteer incorrectly responded that the signal appeared to be ON at a distance 1500 ft away from the signal. This test was conducted on a sunny day and glare from the sun may have caused the signal to appear on when no LEDs were illuminated.

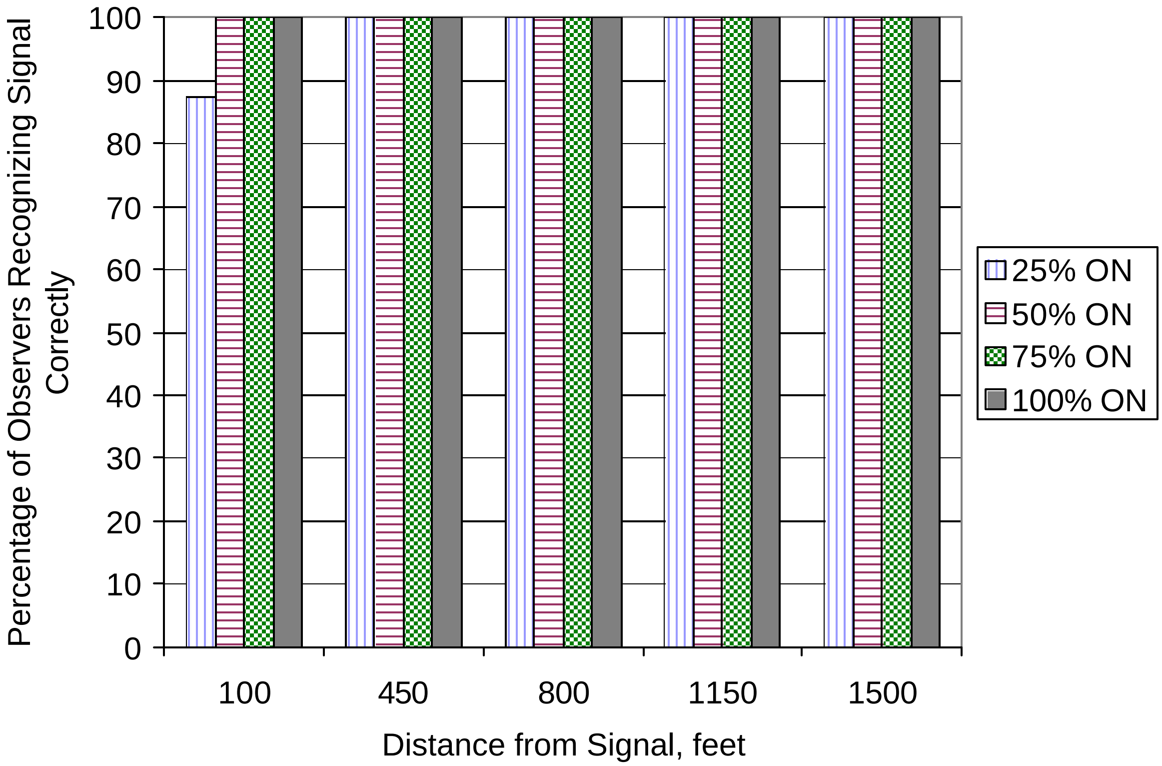

Figure 94. Volunteer responses for NPS#4.

No field tests were conducted with the other five LED signals – WPS#5 through WPS #9. As shown in the lab results, there are relatively small differences in the light intensity output for these six signals as a function of the percentage of LEDs that are on. Results from the initial four 12 inch red crossing signals indicated that it is difficult to quantify relatively small differences in light intensity with field tests. This is believed to be partially due to the logarithmic response of the human eye. Another factor is the field test procedure itself, where test subjects know the location of the LED signal and are able to see it in almost all conditions. The highly focused beams used in the 8 inch crossing signals would almost certainly always be seen while on-axis regardless of the percentage of non-illuminated LEDs. The off-axis response would also not be a function of the percentage of non-illuminated LEDs.

CONCLUSIONS

A computer-controlled goniometer was designed, constructed, and used to test LED signals used in rail applications. Six 12 inch red LED crossing signals, and three 8 inch (red, yellow, green) LED wayside signals were tested. All lab tests were conducted using both the ITE and proposed Transport Canada evaluation patterns.

Two the 12 inch red LED signals tested do not use any type of power supply or regulator to control the voltage and current supplied to the LED circuit. Important observations about LED signals that do not use power supplies can be drawn from the lab tests:

- there is a threshold supply voltage below which the signals have no light output,
- above this threshold voltage the maximum light intensity is a strong, fairly linear function of the supply voltage, and
- the maximum light intensity is essentially proportional to the number of active LED elements across the wide range tested (20% to 100% active).

The remaining four 12 inch red LED signals used a power supply to regulate the voltage and current supplied to the LED circuit. Two important observations about LED signals that use power supplies or regulators can be drawn from the lab tests:

- above a threshold voltage, the maximum light intensity is not a strong function of the supply voltage, and
- the maximum light intensity is not a strong function of the percentage of active LED elements – for the open-circuit tests – in the ranges tested (60% to 100%).

In general, the light intensity responses (in terms of peak light output in candela) of units that do not use power supplies are very sensitive to both the supply voltage and the number of active LED elements. The LED signals that use power supplies have, in general, light intensity responses that are much less sensitive (in many cases insensitive) to power supply variations and the number of active LED elements. The primary conclusion that can be drawn from these observations is that <u>there is no consistency in the performance of all types of LED crossing signals with respect to power supply variations or the number of active LED elements.</u> Consequently, there is no overall conclusion that can be drawn about the light intensity output of an LED signal without knowledge of the way the signal is constructed, i.e. does it have a power supply or regulator?

The light intensity response of the three 8 inch wayside signals was similar to that of the four 12 inch crossing signals that used power supplies. The maximum light intensity was significantly different for each color, but for each signal there was little variation in light intensity with changes in supply voltage or the number of open-circuited elements.

All of the lab tests were conducted with a colorimeter that was capable of measuring the color of the signal as well as the light intensity. With a few exceptions, there were no significant changes or shifts in the color output from any of the LED signals tested during any of the tests. The few color shifts that were observed occurred primarily at very low supply voltages and low signal light intensity,

A field test procedure was developed that was used to determine how individuals perceive LED signals experiencing partial failure. Two test stands were designed and built to support four railroad warning signals during field tests. A manually operated switch system was designed to allow two operators to select patterns of non-illuminated LEDs during field tests. Two field tests were conducted with volunteers using the field test procedure. The field test was designed to allow volunteers to report misinterpretations of a signal at a short distances (100feet) as well as greater distances up to 1500 feet.

In general, all of the 12 inch red signals were correctly interpreted when 50% or more of the LED elements were active. Interestingly, the signals with approximately 25% of the LED elements active were often misinterpreted at the closest distance of 100 feet. Some of the volunteers were apparently confused by the discrete appearance of the “on” and “off” portions of the LED signal. Unfortunately, this type of field testing appears to be greatly affected by the volunteer’s experiences during the test, since the signals were fixed in the same location during all tests.

Also note that field test results for the WPS#3 and NPS#4 signals, which were located on the same test stand, were nearly identical. The results for the WPS#2 and NPS#1 signals were also similar. Therefore, there may be an undetermined factor related to the orientation of the signals with respect to the sun that may influence how an individual perceives each signal.

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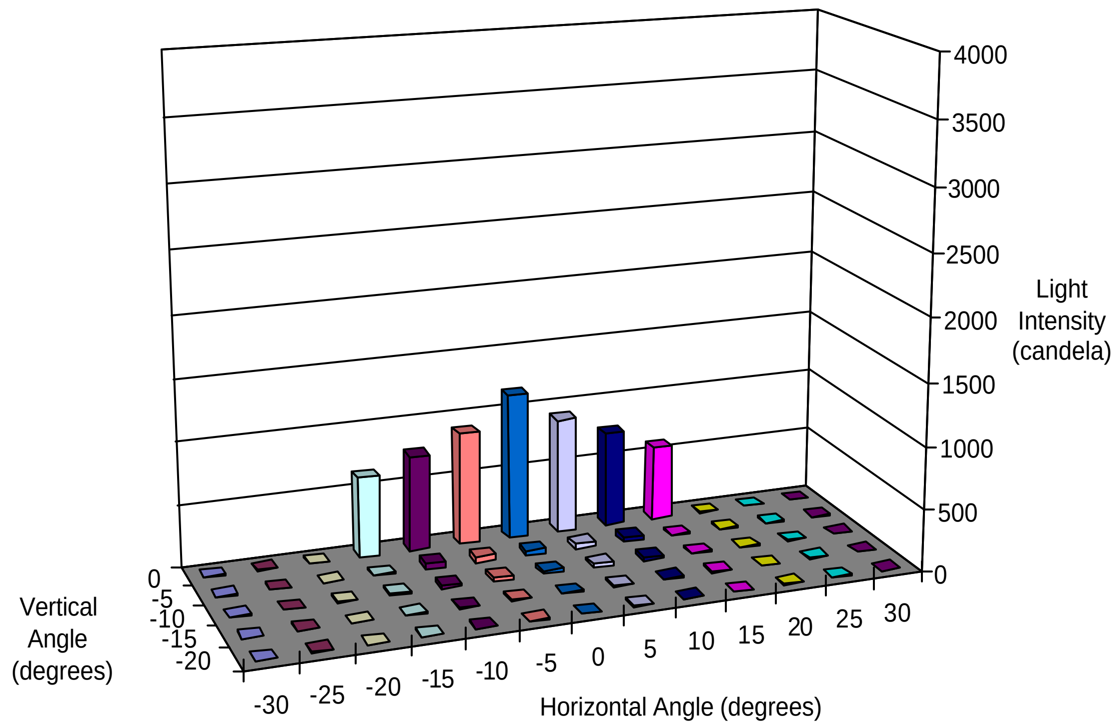

Figure A0.1a Output from Incandescent (Red) signal, 9.0 volts, TC test.

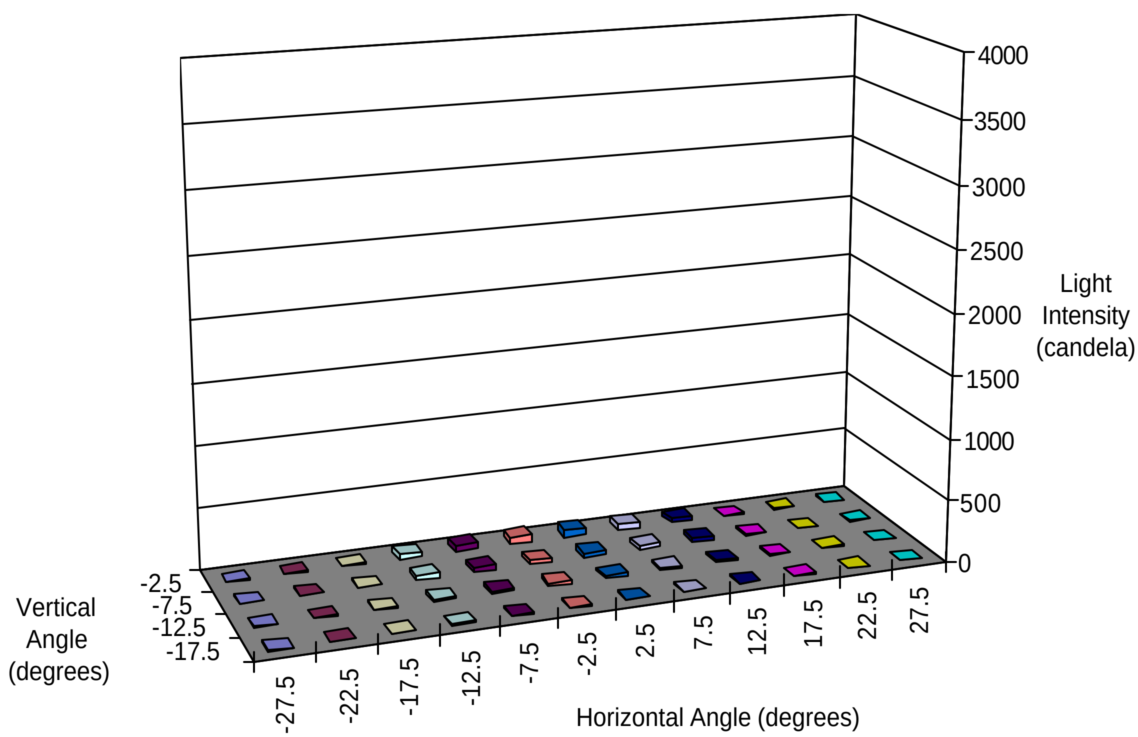

Figure A0.1b Output from Incandescent (Red) signal, 9.0 volts, ITE test.

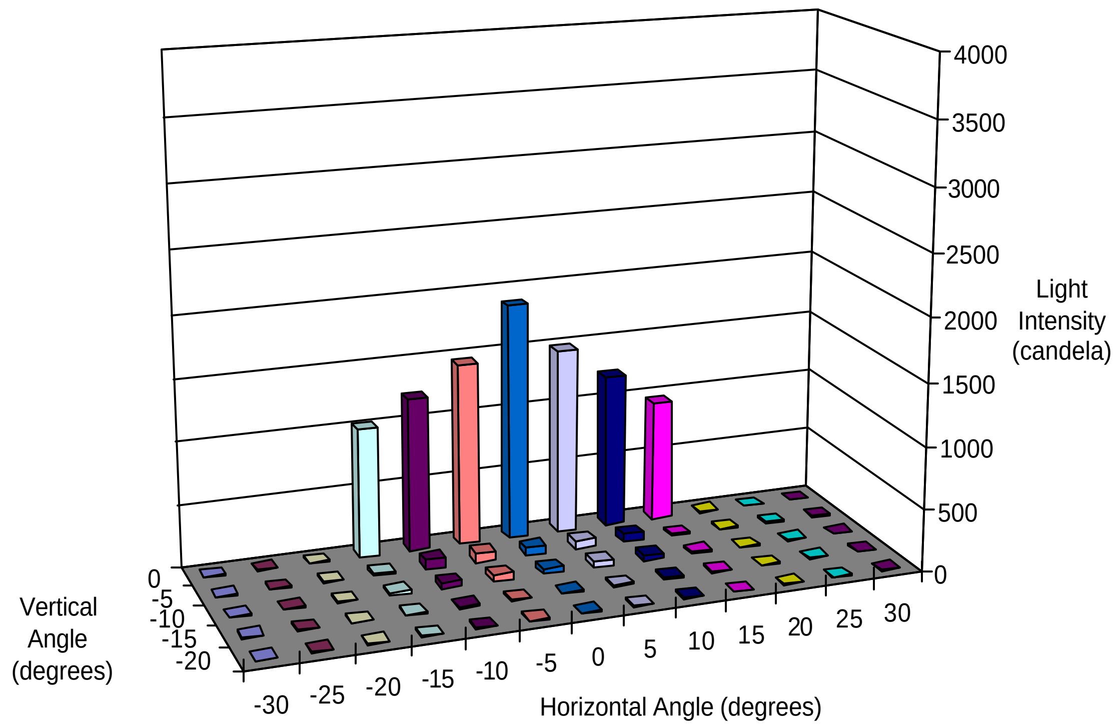

Figure A0.2a Output from Incandescent (Red) signal, 10.5 volts, TC test.

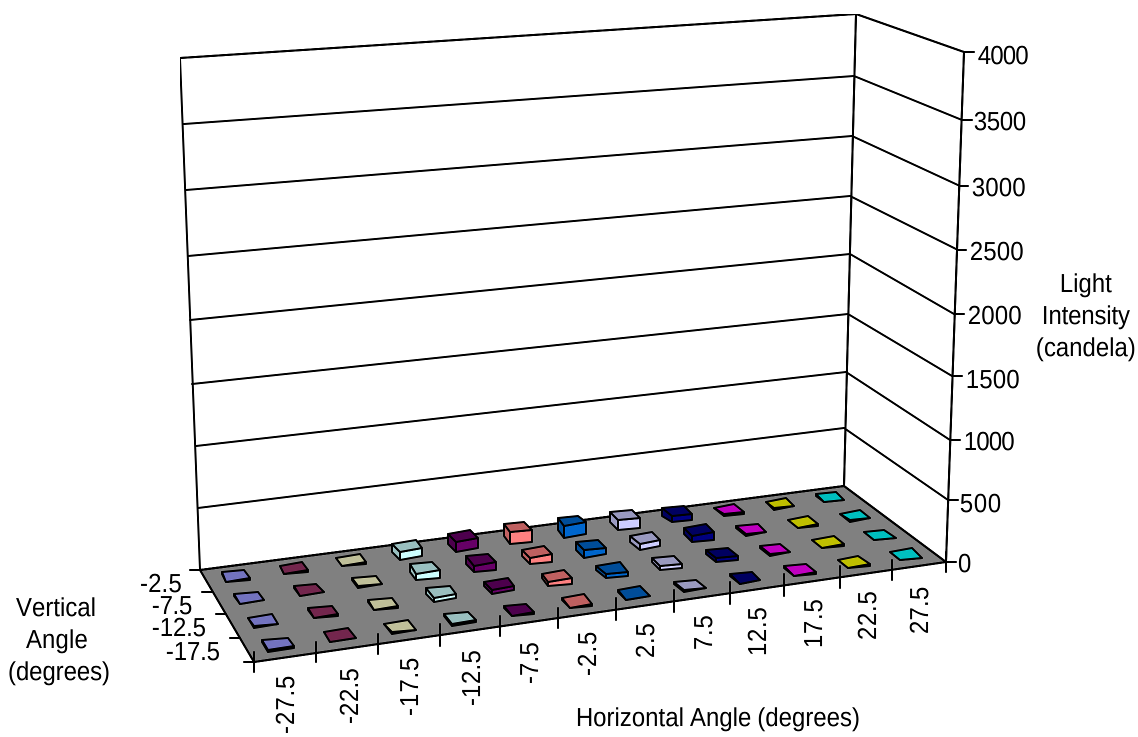

Figure A0.2b Output from Incandescent (Red) signal, 10.5 volts, ITE test.

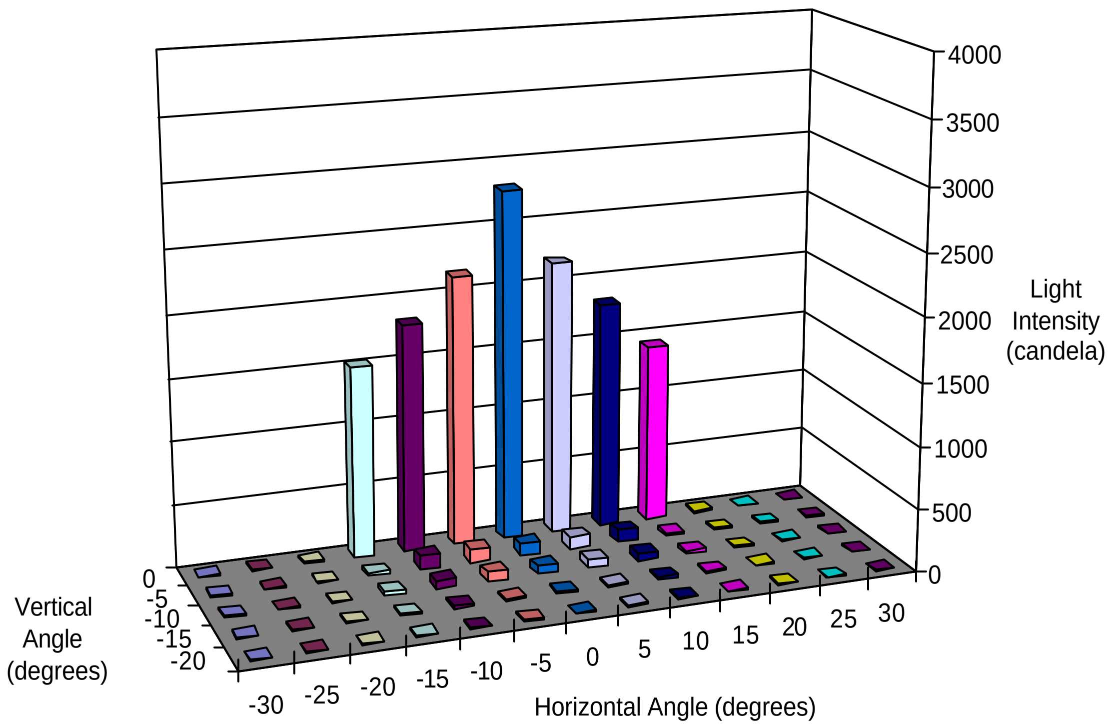

Figure A0.3a Output from Incandescent (Red) signal, 12.0 volts, TC test.

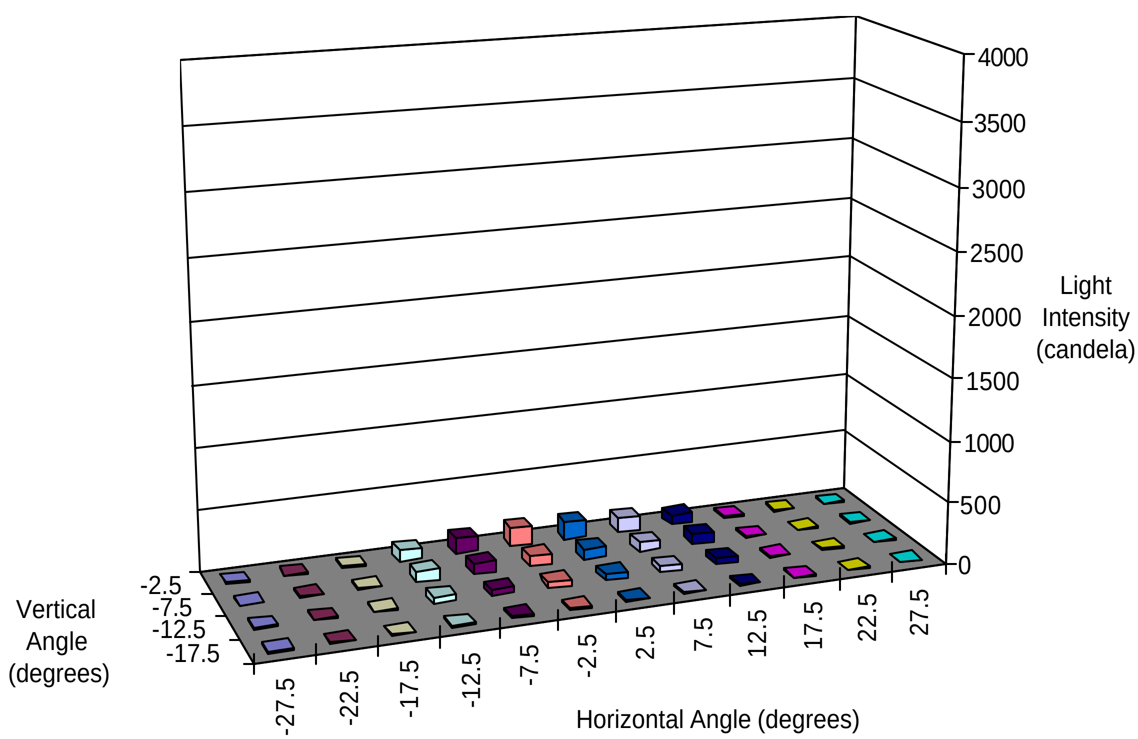

Figure A0.3b Output from Incandescent (Red) signal, 12.0 volts, ITE test.

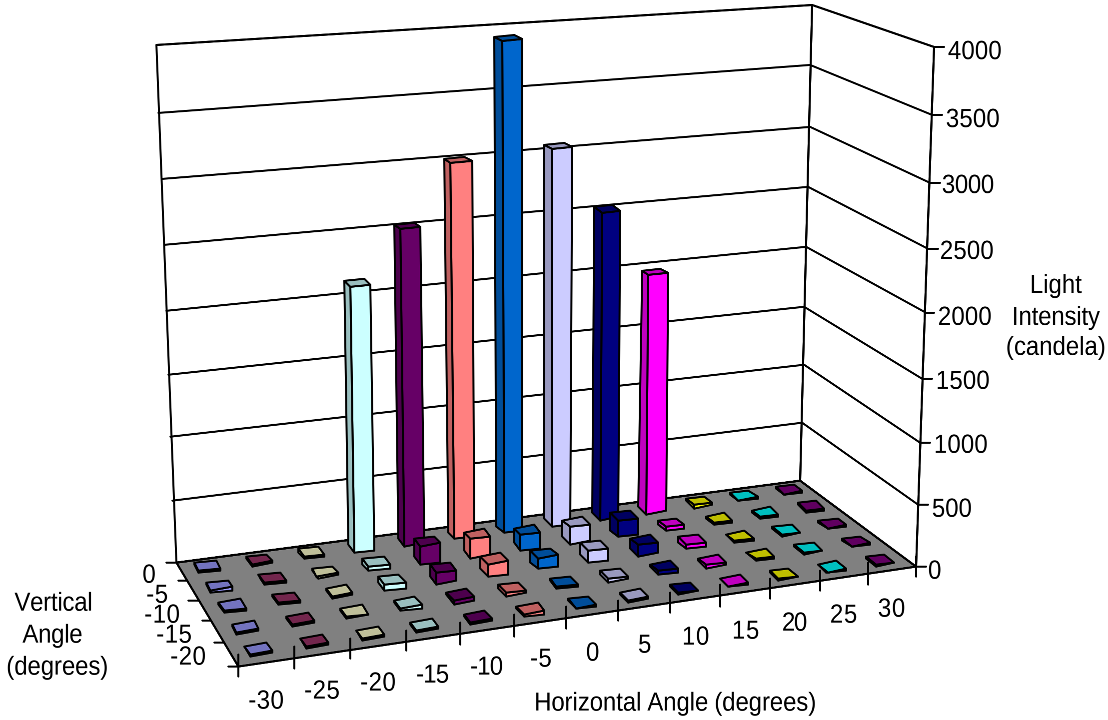

Figure A0.4a Output from Incandescent (Red) signal, 13.5 volts, TC test.

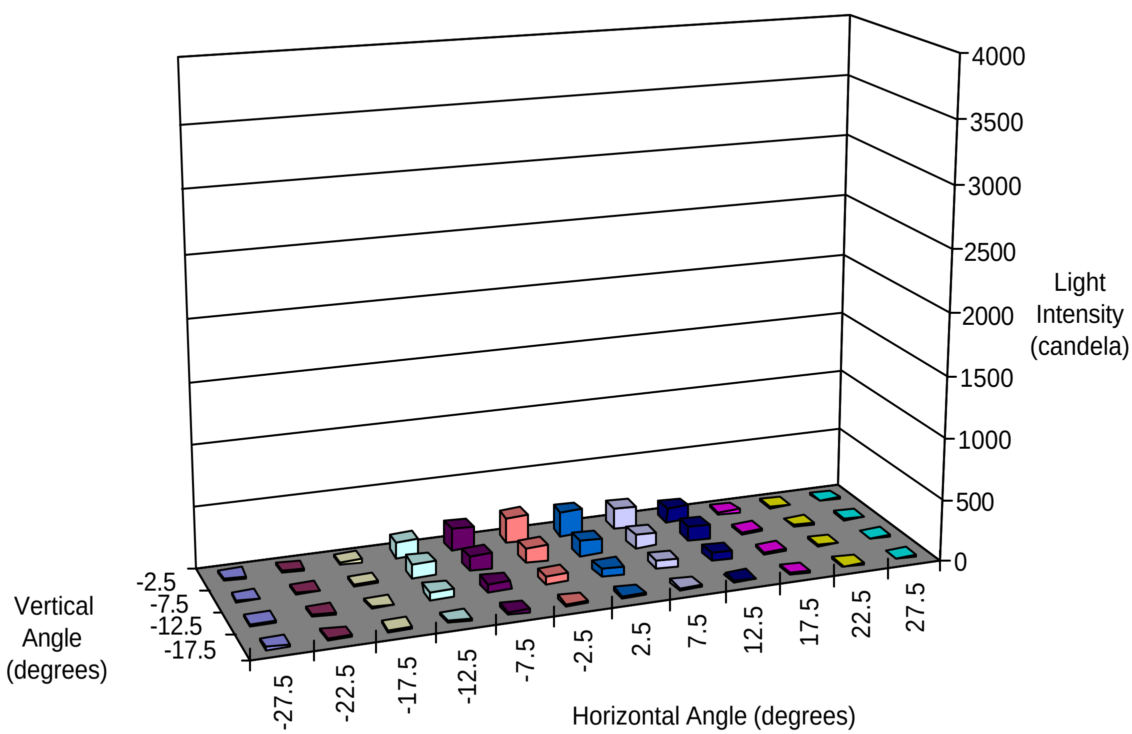

Figure A0.4b Output from Incandescent (Red) signal, 13.5 volts, ITE test.

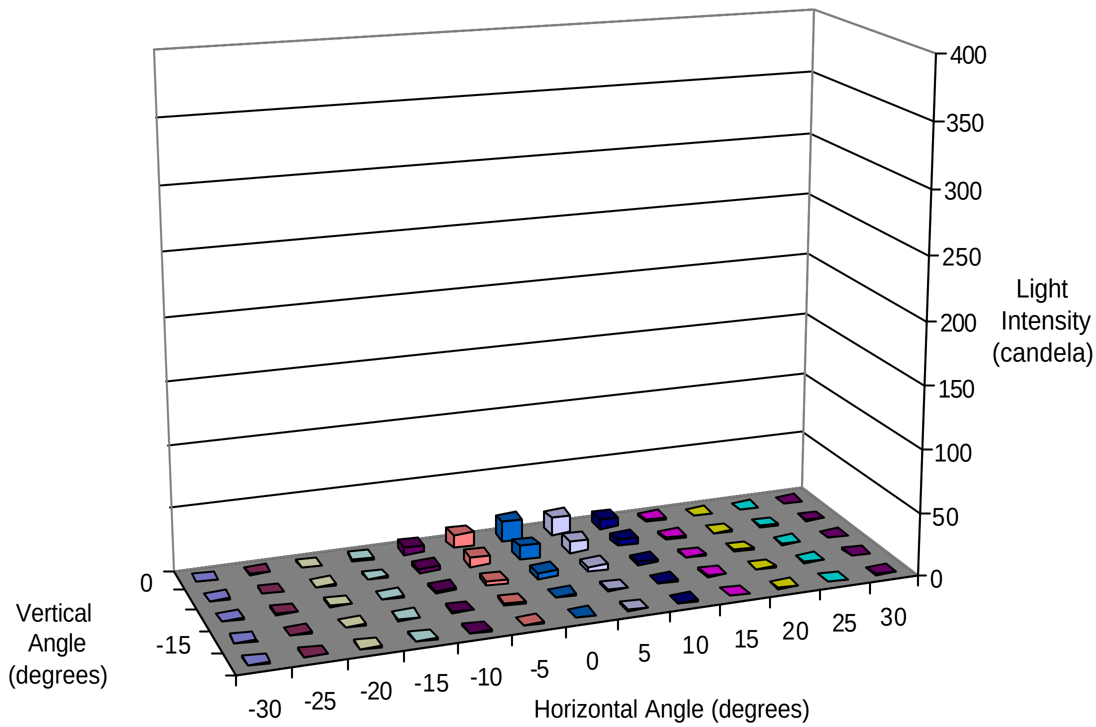

Figure A1.1.1a Output from NPS#1 (Red) signal, 7.0 volts, portion-FFF of signal on/off, TC test.

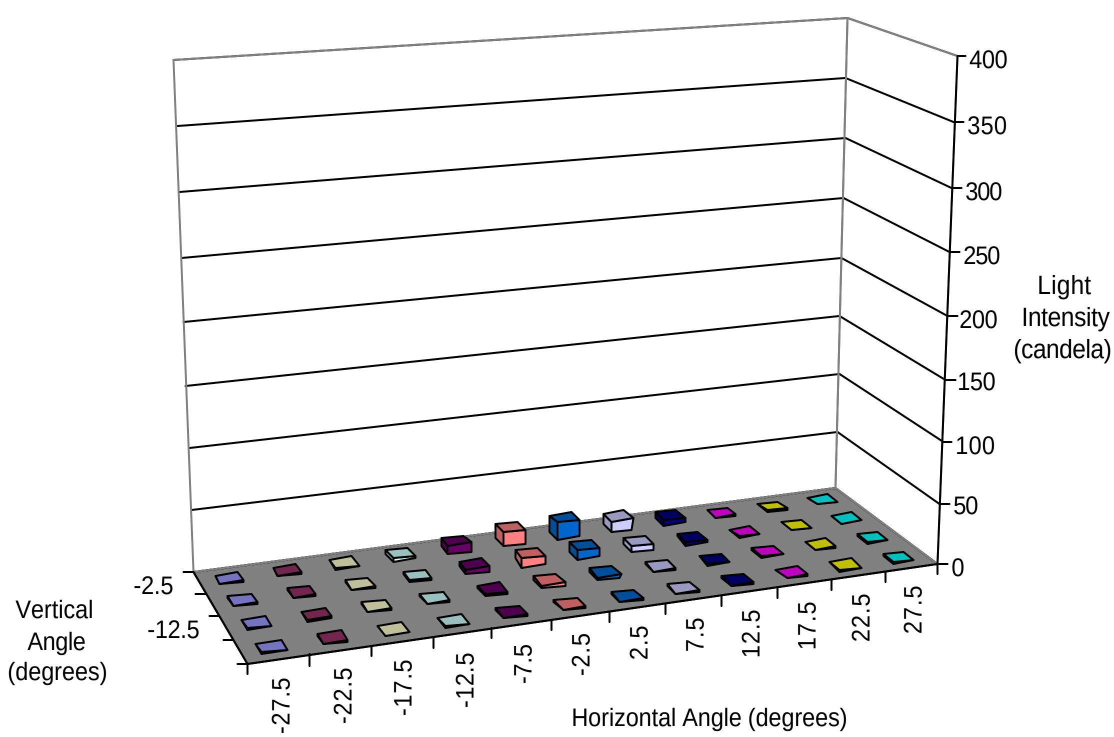

Figure A1.1.1b Output from NPS#1 (Red) signal, 7.0 volts, portion-FFF of signal on/off, ITE test.

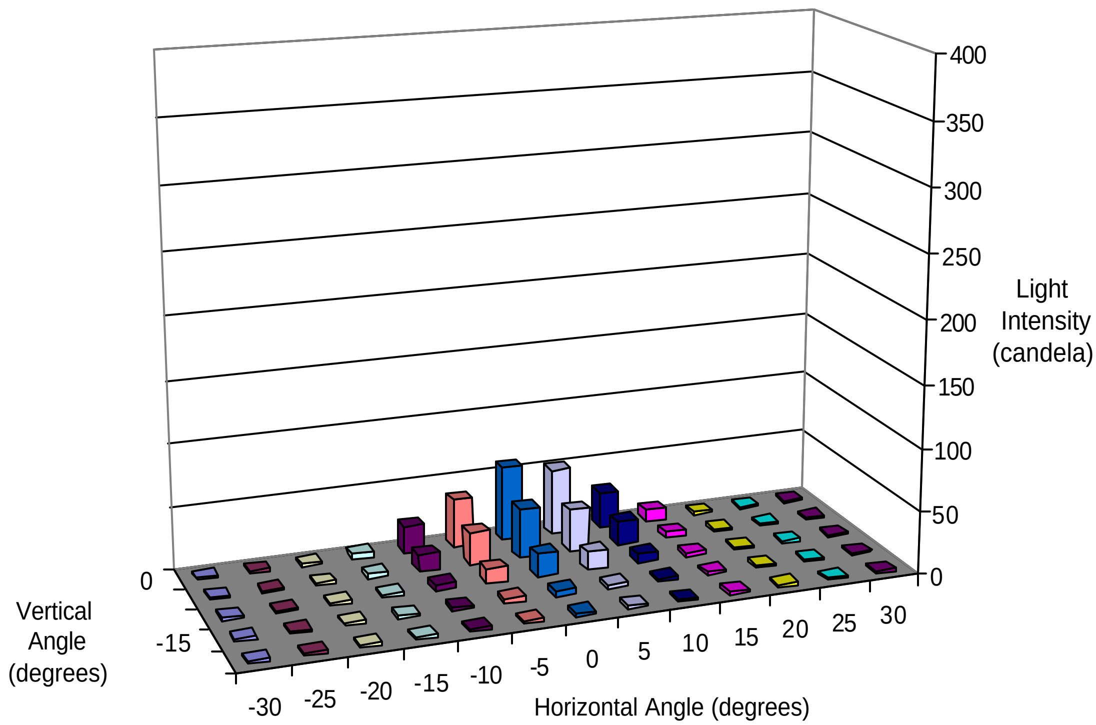

Figure A1.1.2a Output from NPS#1 (Red) signal, 8.0 volts, portion-FFF of signal on/off, TC test.

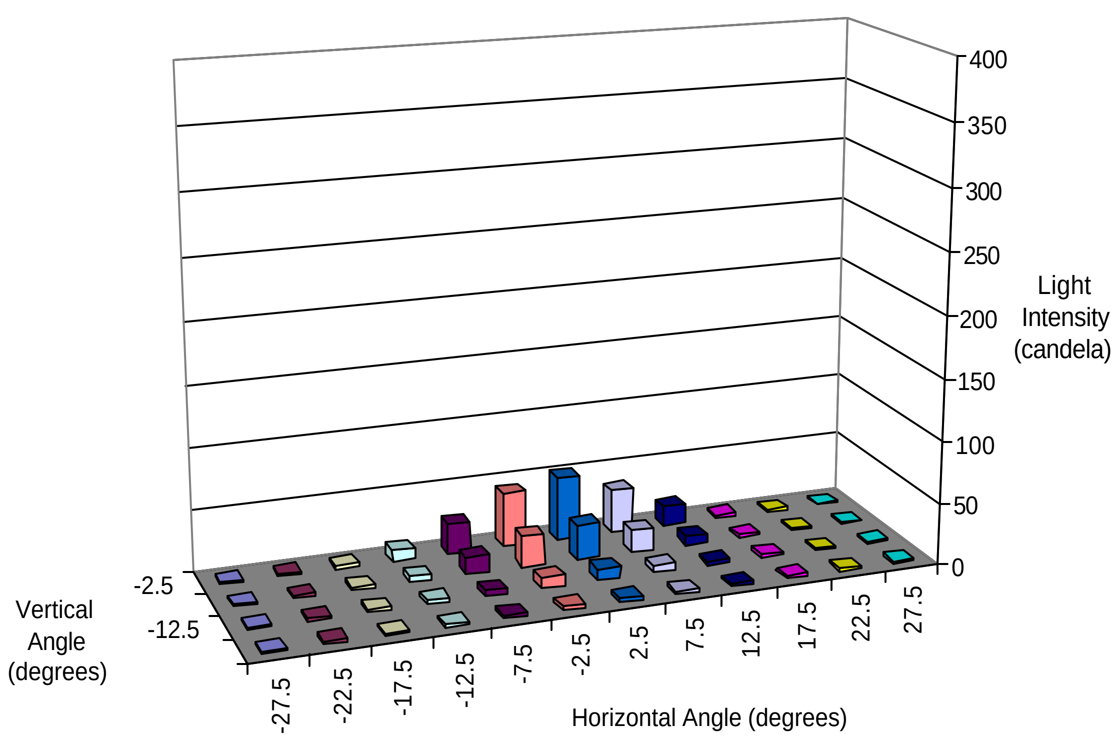

Figure A1.1.2b Output from NPS#1 (Red) signal, 8.0 volts, portion-FFF of signal on/off, ITE test.

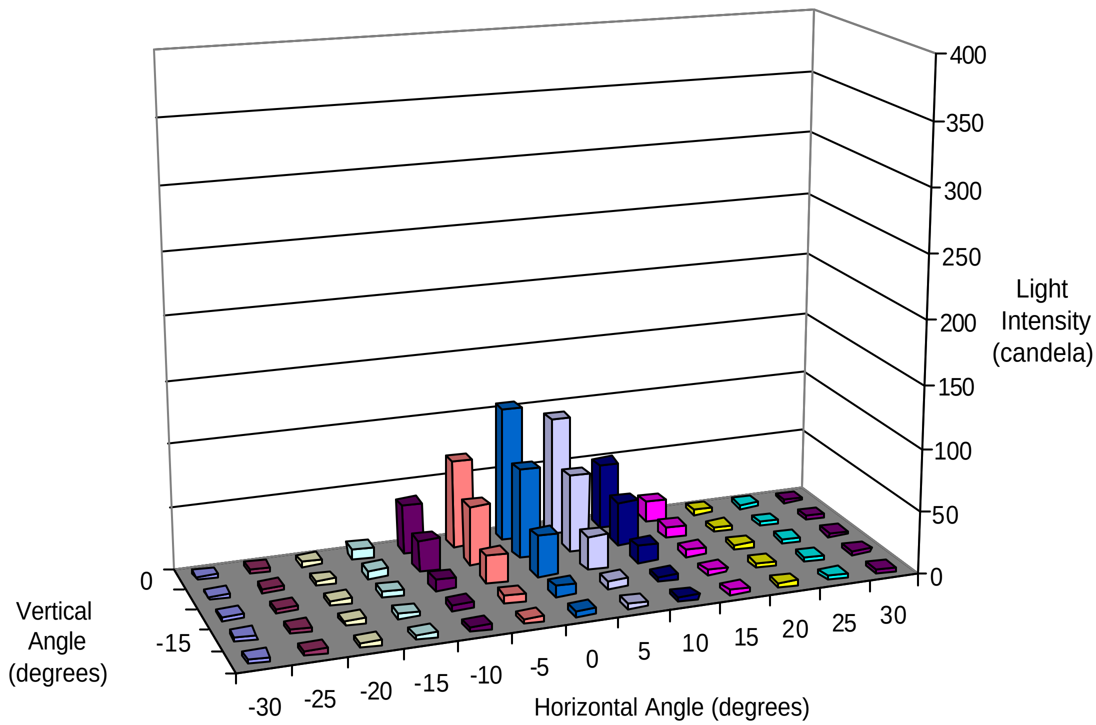

Figure A1.1.3a Output from NPS#1 (Red) signal, 9.0 volts, portion-FFF of signal on/off, TC test.

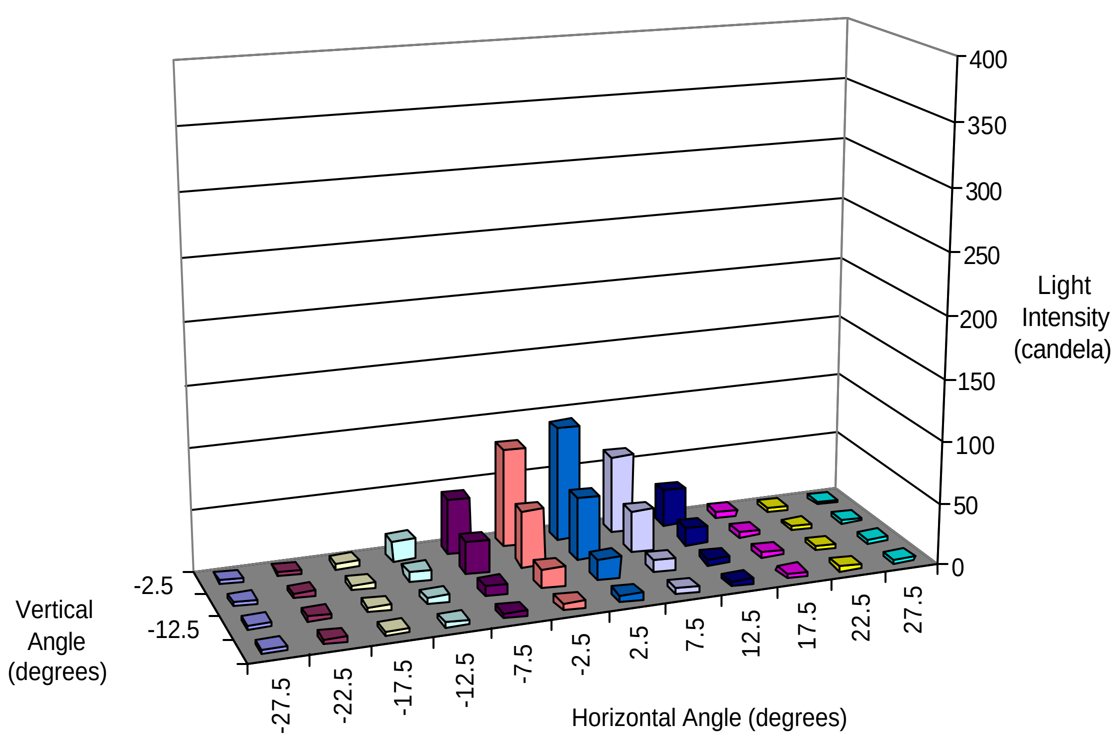

Figure A1.1.3b Output from NPS#1 (Red) signal, 9.0 volts, portion-FFF of signal on/off, ITE test.

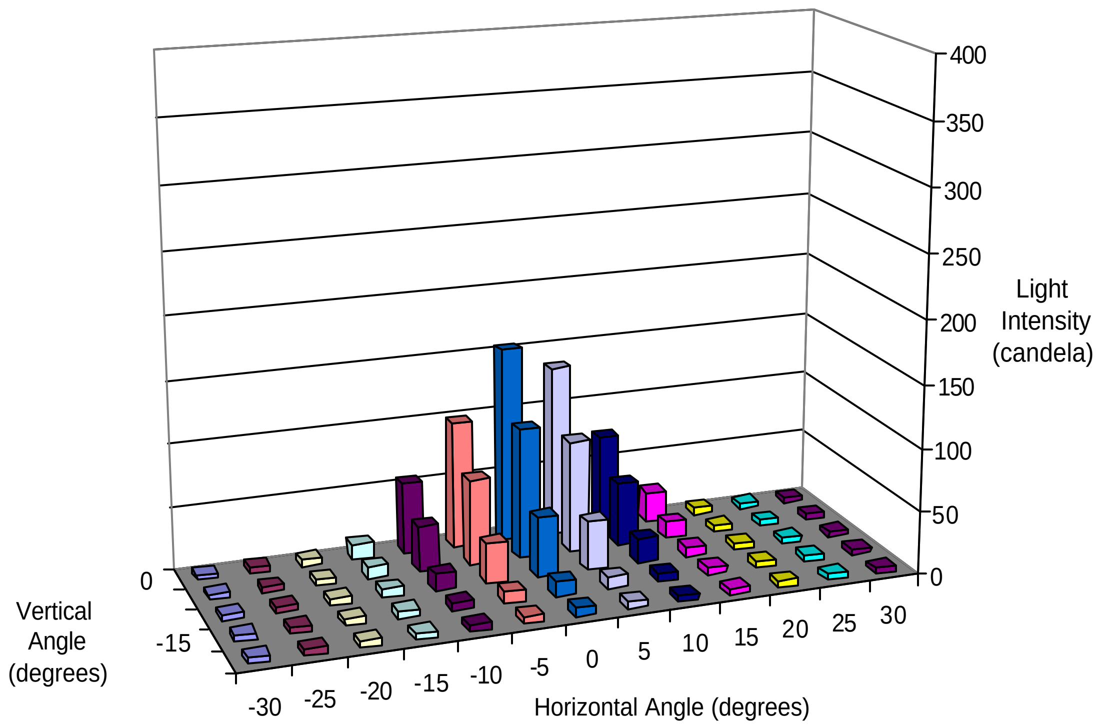

Figure A1.1.4a Output from NPS#1 (Red) signal, 10.0 volts, portion-FFF of signal on/off, TC test.

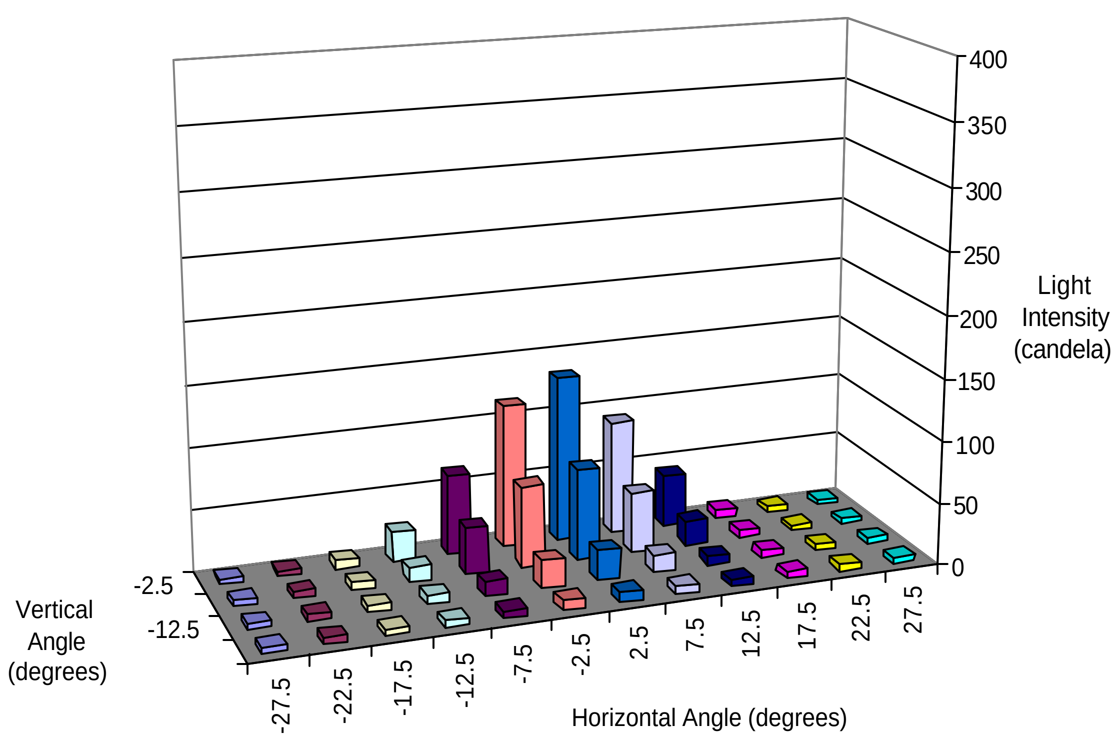

Figure A1.1.4b Output from NPS#1 (Red) signal, 10.0 volts, portion-FFF of signal on/off, ITE test.

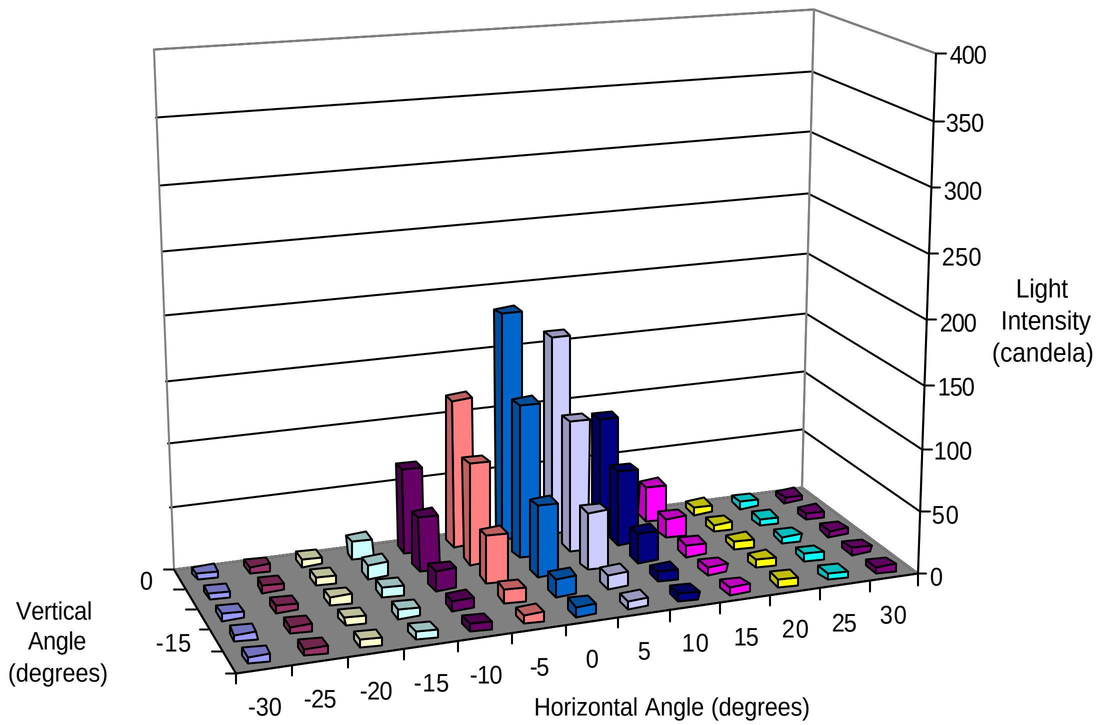

Figure A1.1.5a Output from NPS#1 (Red) signal, 10.5 volts, portion-FFF of signal on/off, TC test.

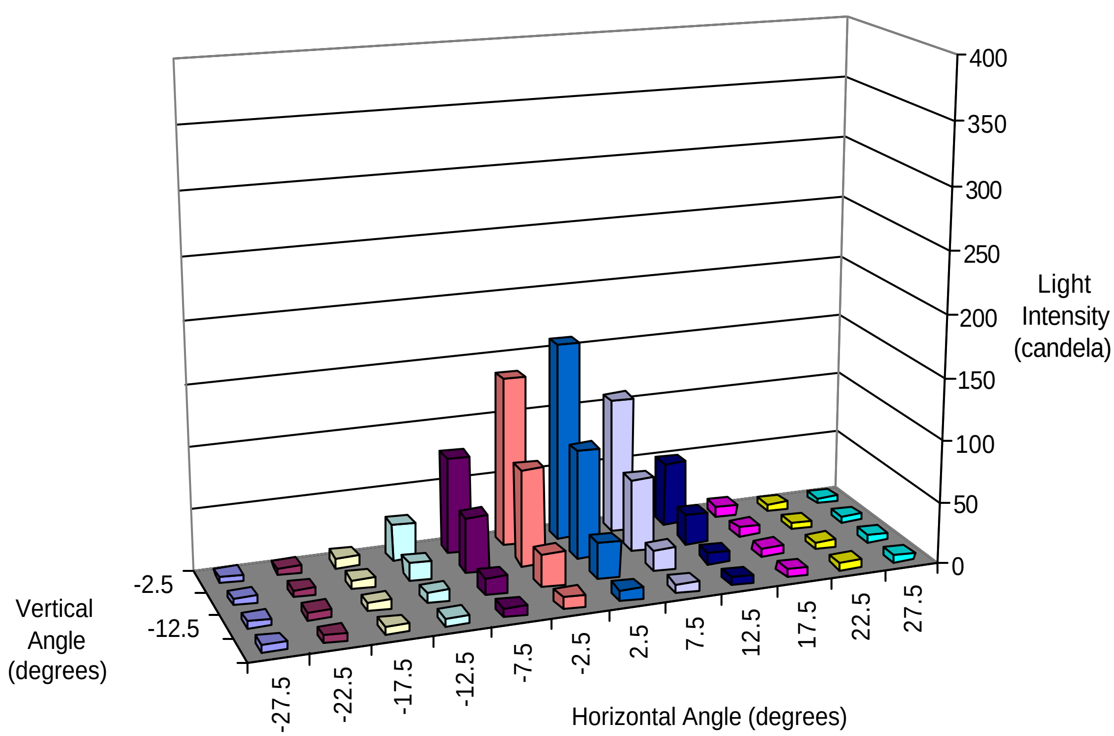

Figure A1.1.5b Output from NPS#1 (Red) signal, 10.5 volts, portion-FFF of signal on/off, ITE test.

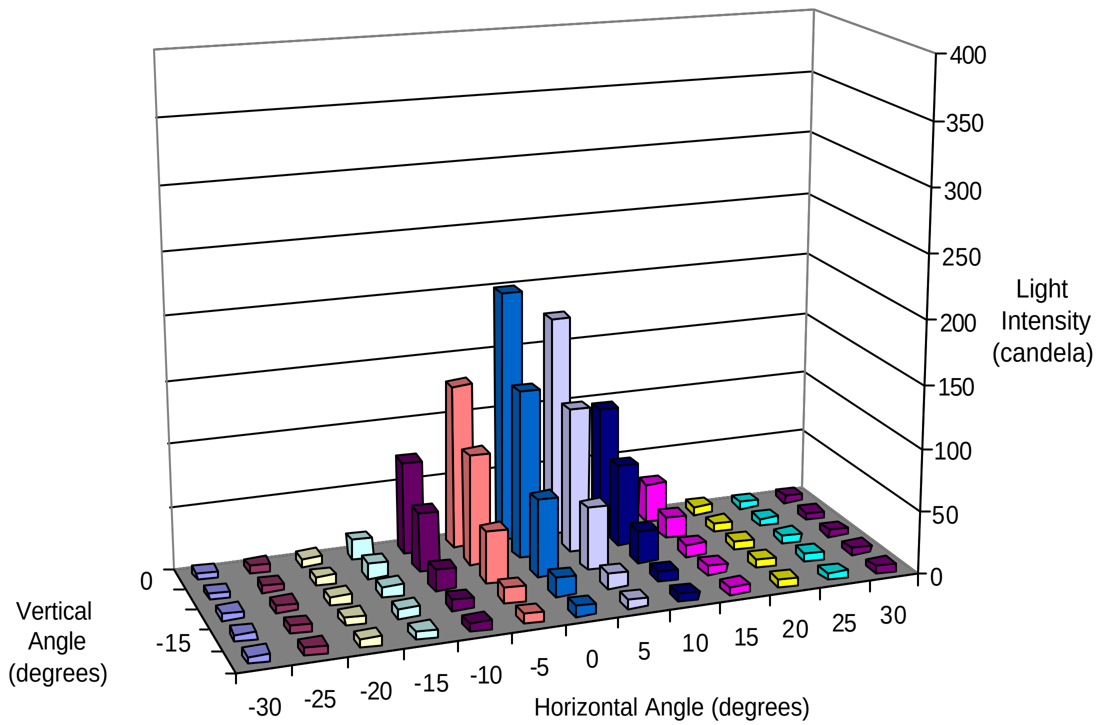

Figure A1.1.6a Output from NPS#1 (Red) signal, 11.0 volts, portion-FFF of signal on/off, TC test.

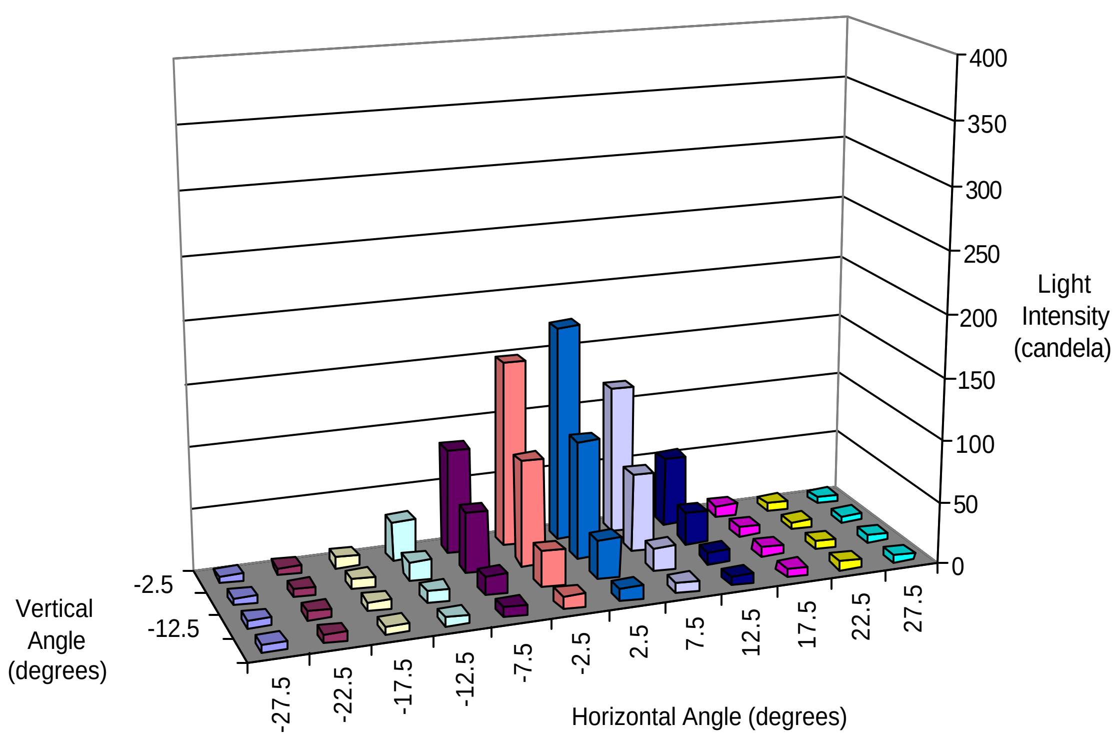

Figure A1.1.6b Output from NPS#1 (Red) signal, 11.0 volts, portion-FFF of signal on/off, ITE test.

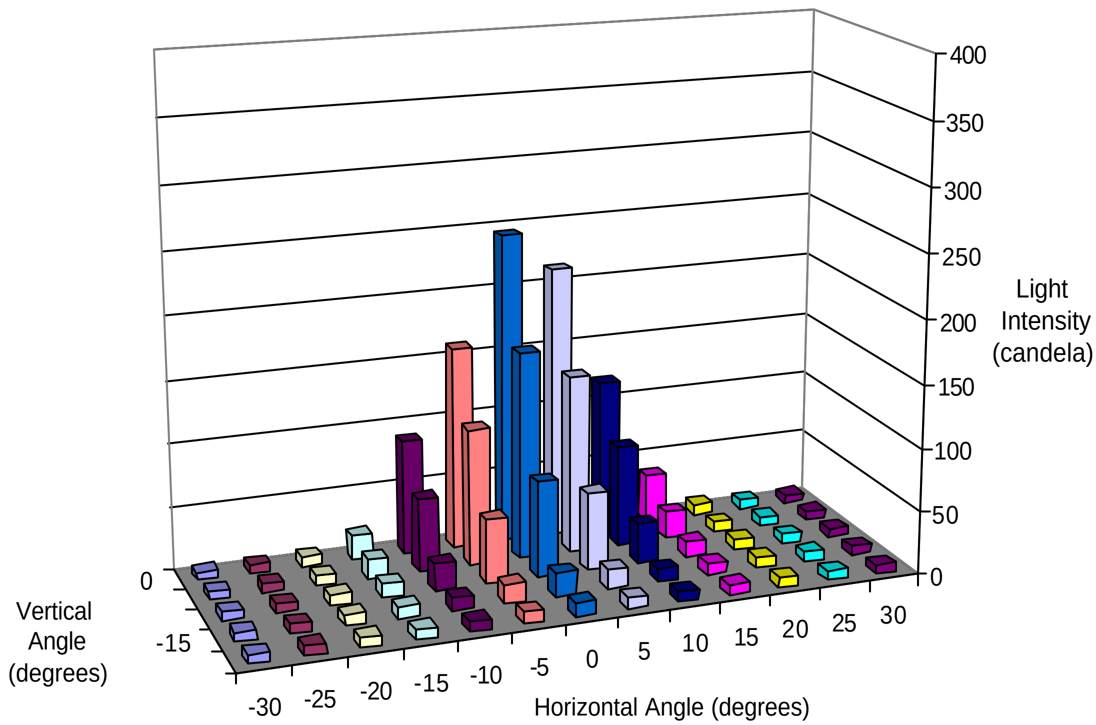

Figure A1.1.7a Output from NPS#1 (Red) signal, 12.0 volts, portion-FFF of signal on/off, TC test.

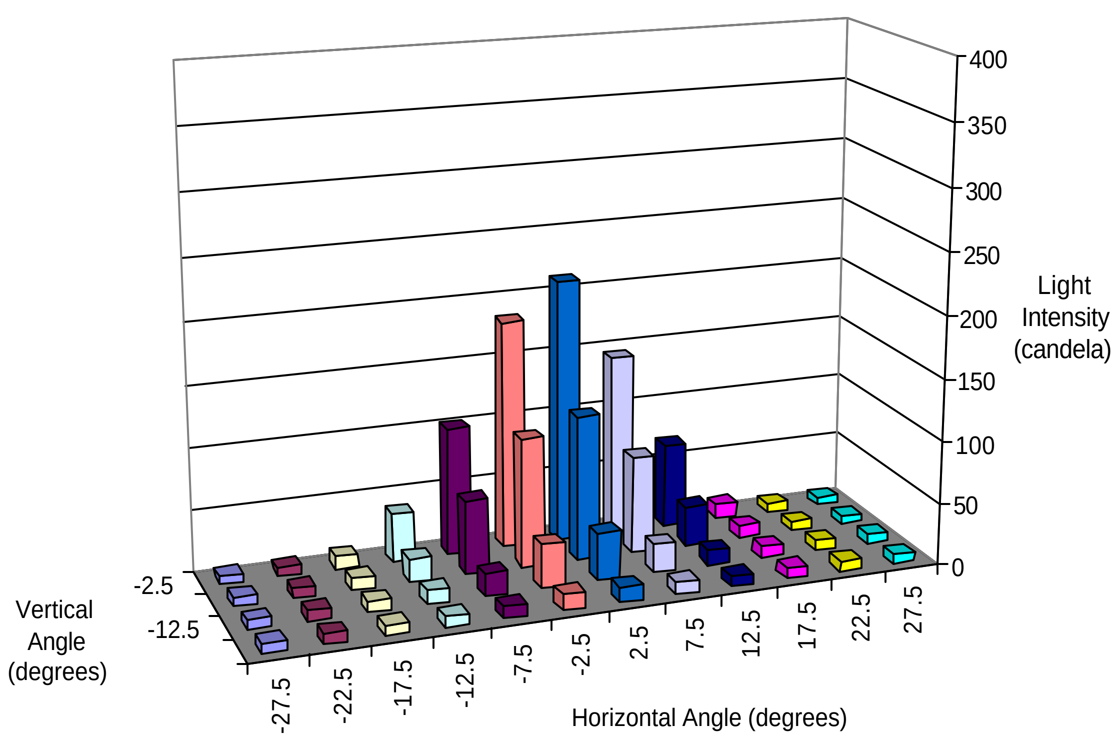

Figure A1.1.7b Output from NPS#1 (Red) signal, 12.0 volts, portion-FFF of signal on/off, ITE test.

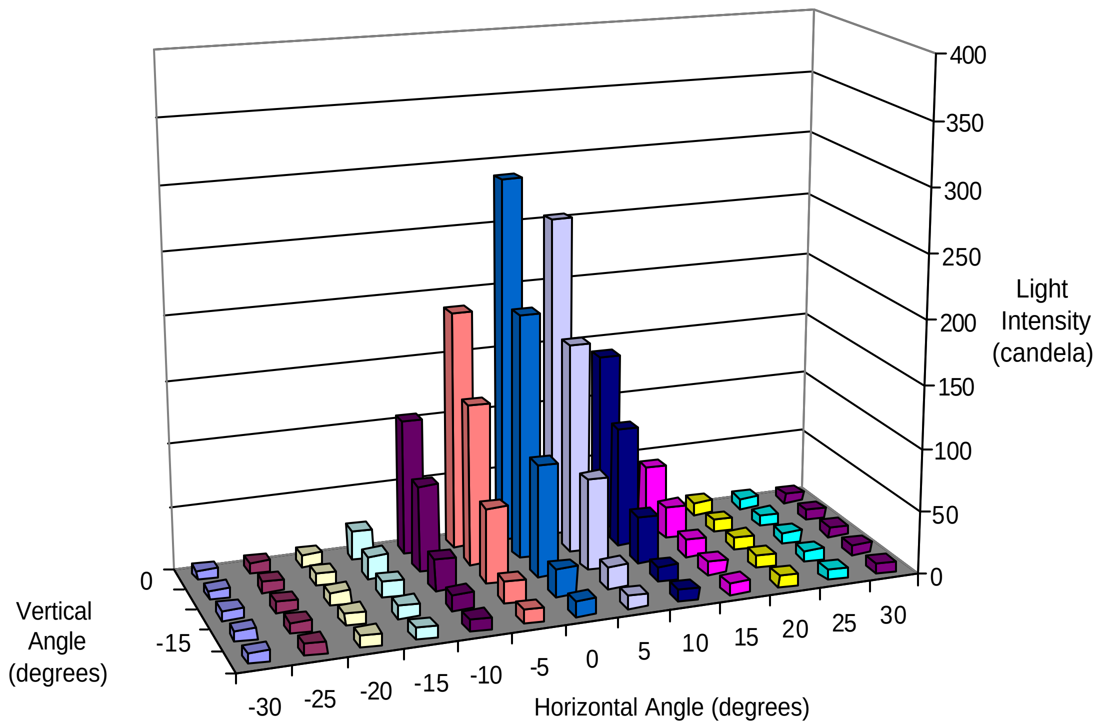

Figure A1.1.8a Output from NPS#1 (Red) signal, 13.0 volts, portion-FFF of signal on/off, TC test.

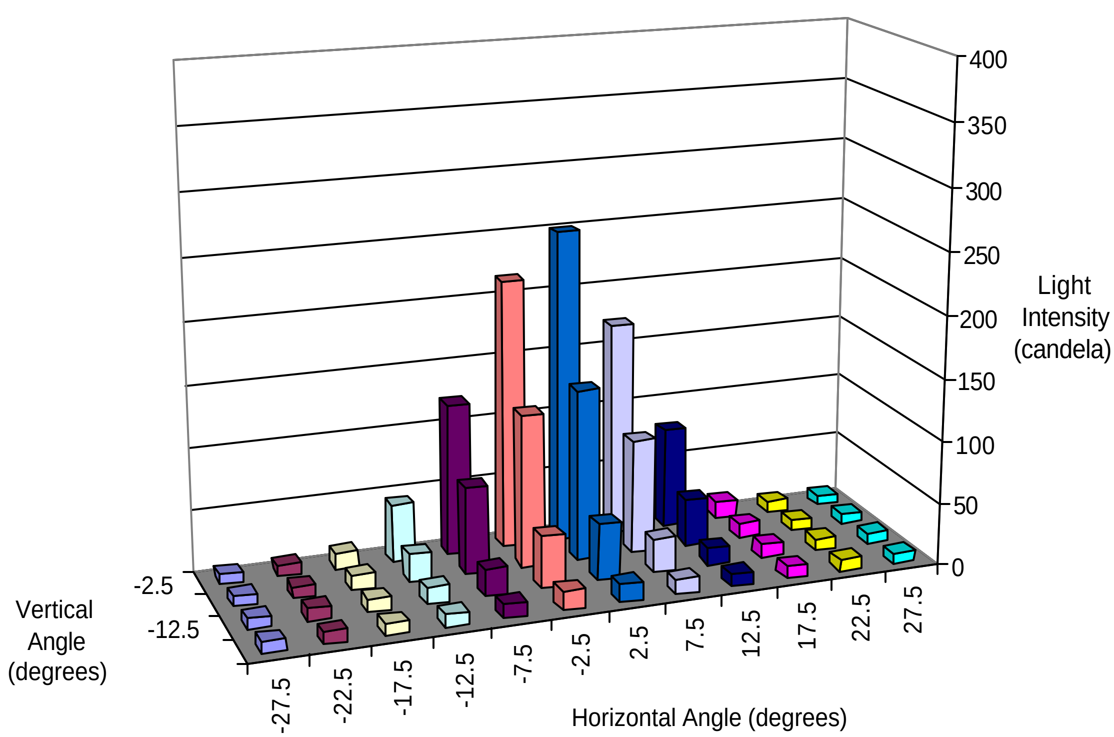

Figure A1.1.8b Output from NPS#1 (Red) signal, 13.0 volts, portion-FFF of signal on/off, ITE test.

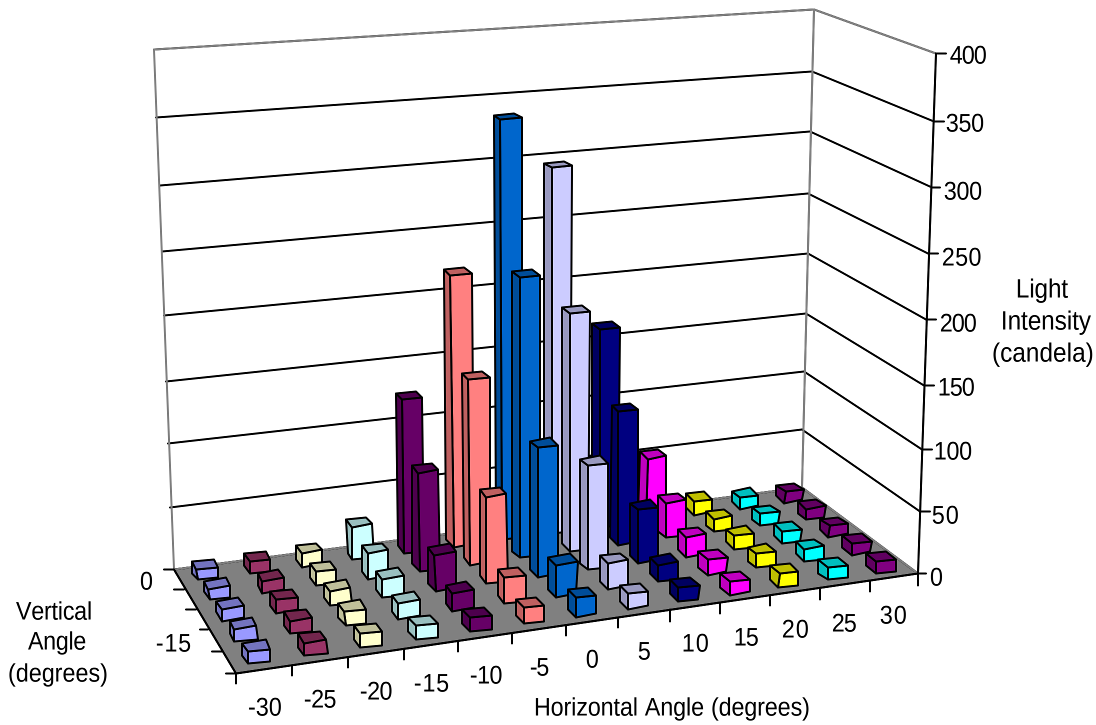

Figure A1.1.9a Output from NPS#1 (Red) signal, 14.0 volts, portion-FFF of signal on/off, TC test.

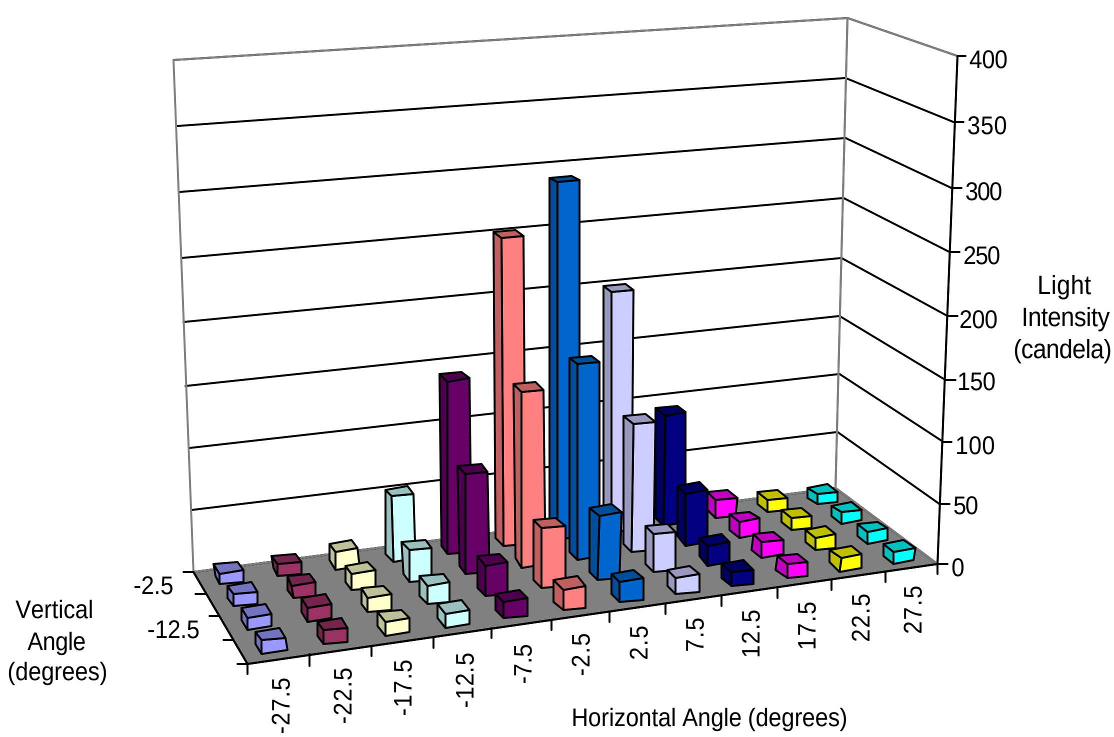

Figure A1.1.9b Output from NPS#1 (Red) signal, 14.0 volts, portion-FFF of signal on/off, ITE test.

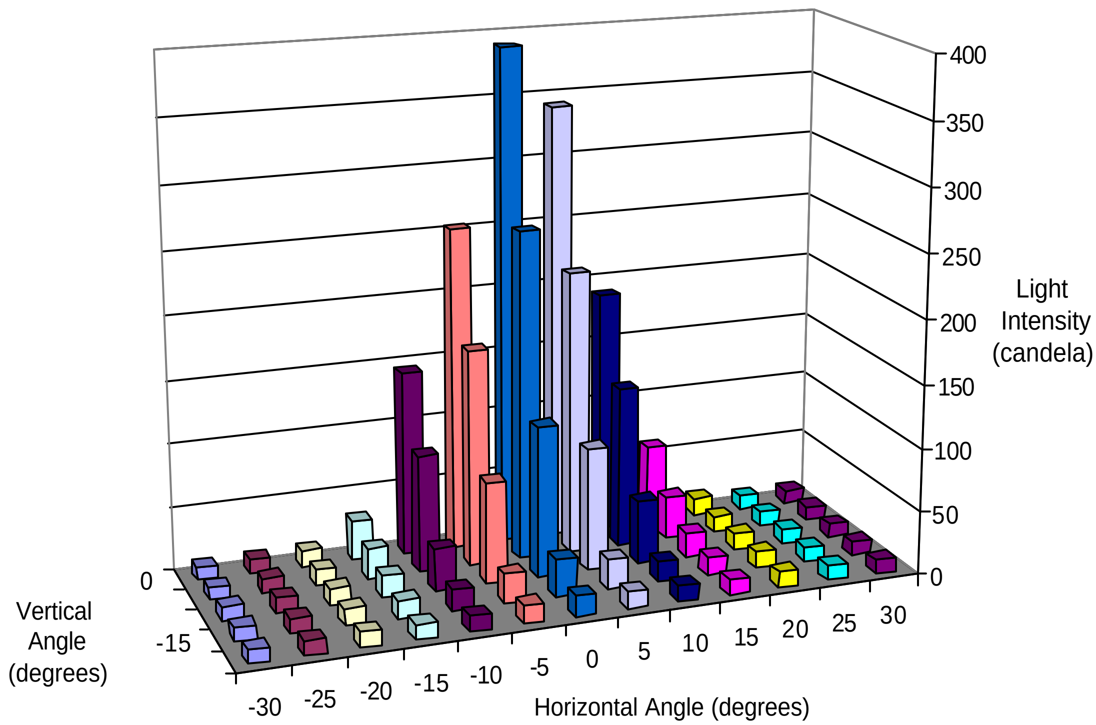

Figure A1.1.10a Output from NPS#1 (Red) signal, 15.0 volts, portion-FFF of signal on/off, TC test.

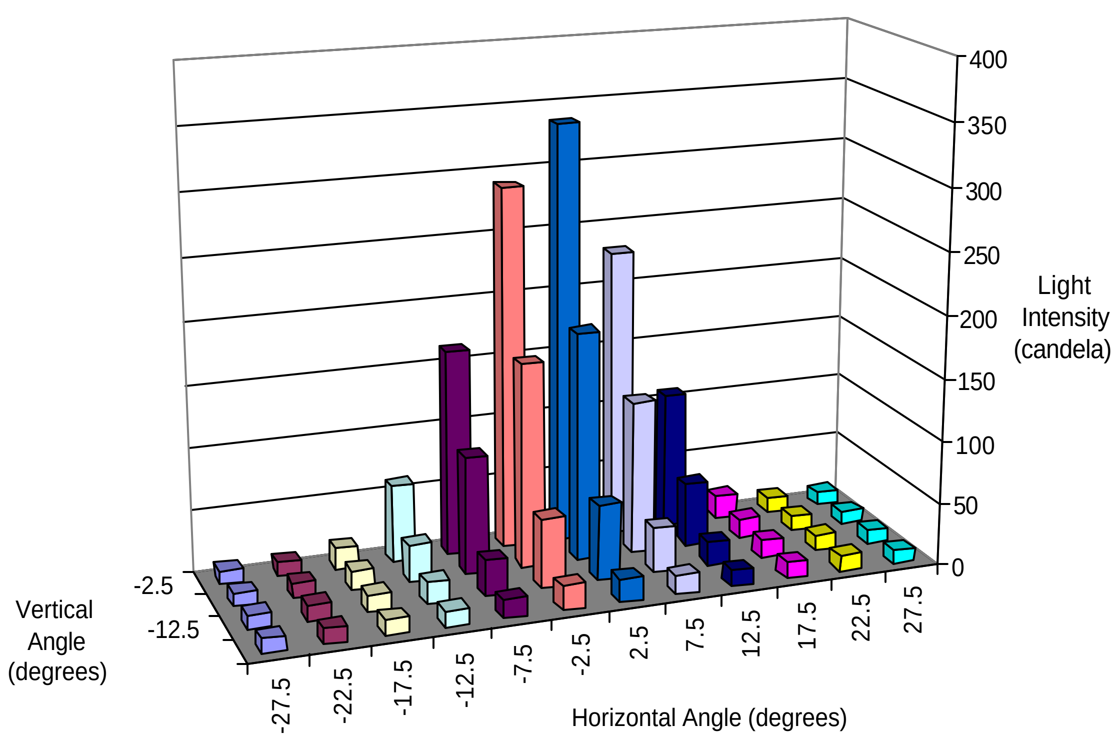

Figure A1.1.10b Output from NPS#1 (Red) signal, 15.0 volts, portion-FFF of signal on/off, ITE test.

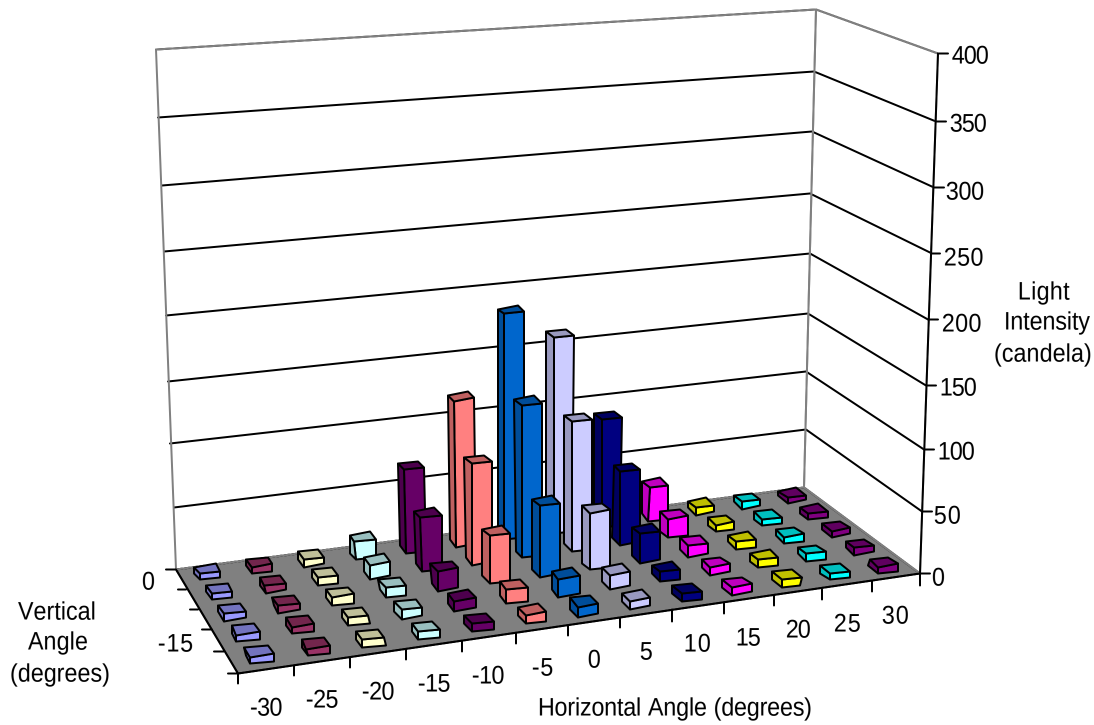

Figure A1.2.1a Output from NPS#1 (Red) signal, 10.5 volts, portion-FFF of signal on/off, TC test.

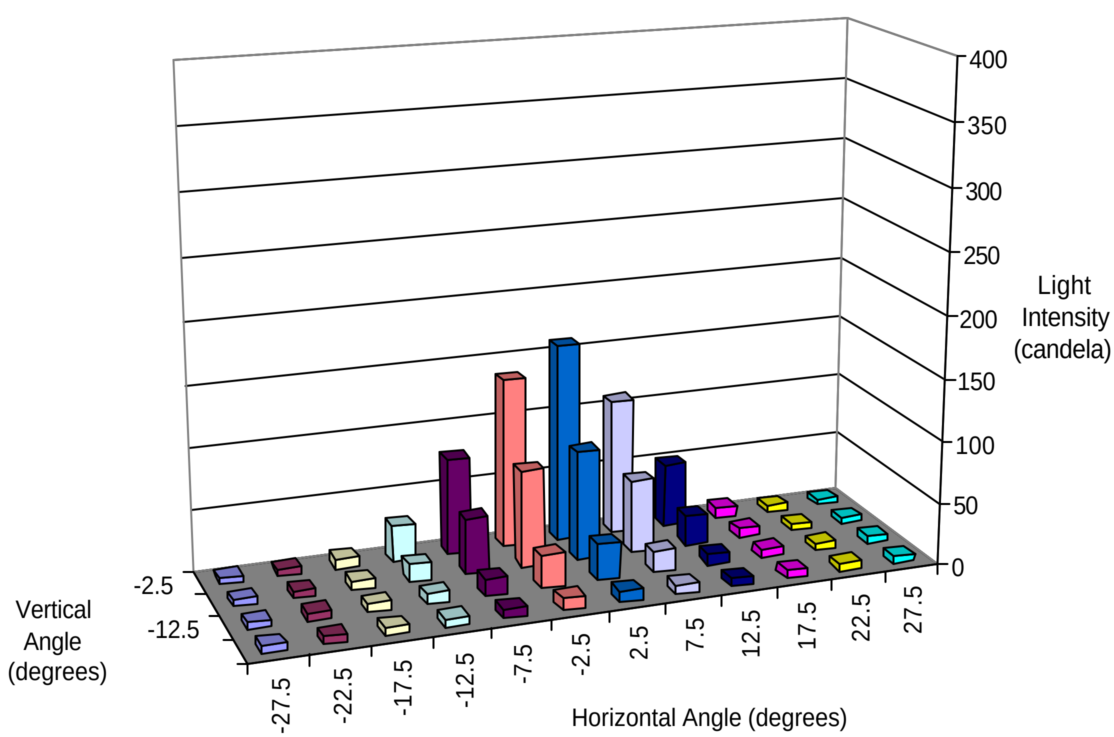

Figure A1.2.1b Output from NPS#1 (Red) signal, 10.5 volts, portion-FFF of signal on/off, ITE test.

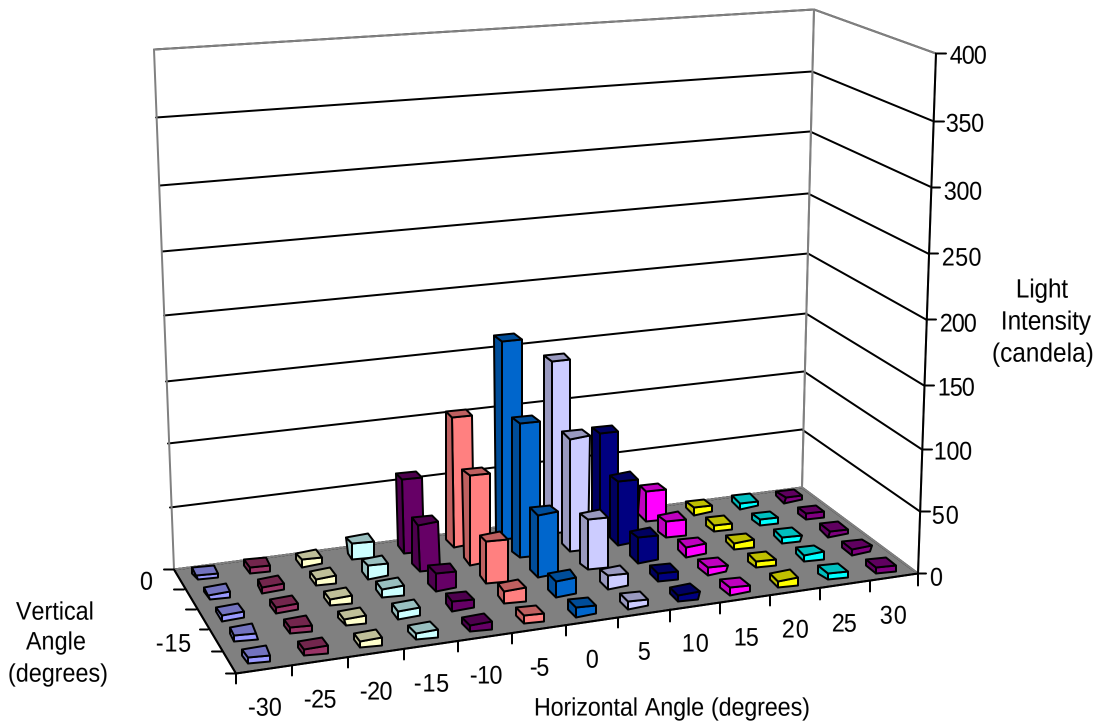

Figure A1.2.2a Output from NPS#1 (Red) signal, 10.5 volts, portion-FBF of signal on/off, TC test.

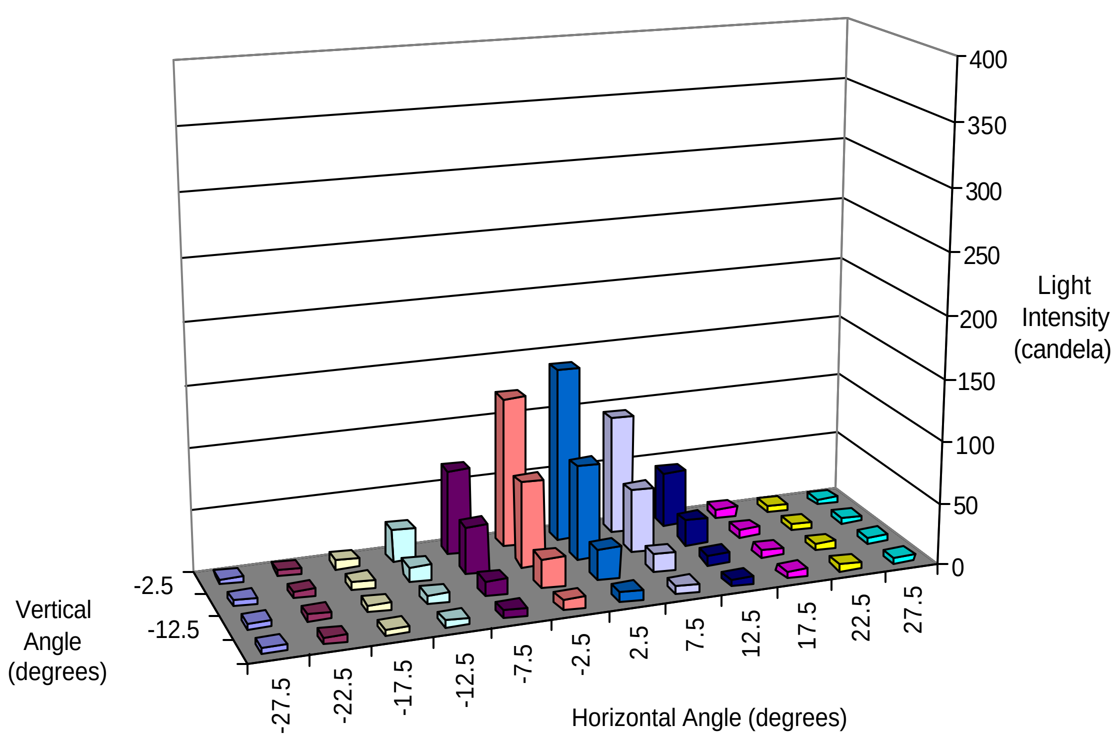

Figure A1.2.2b Output from NPS#1 (Red) signal, 10.5 volts, portion-FBF of signal on/off, ITE test.

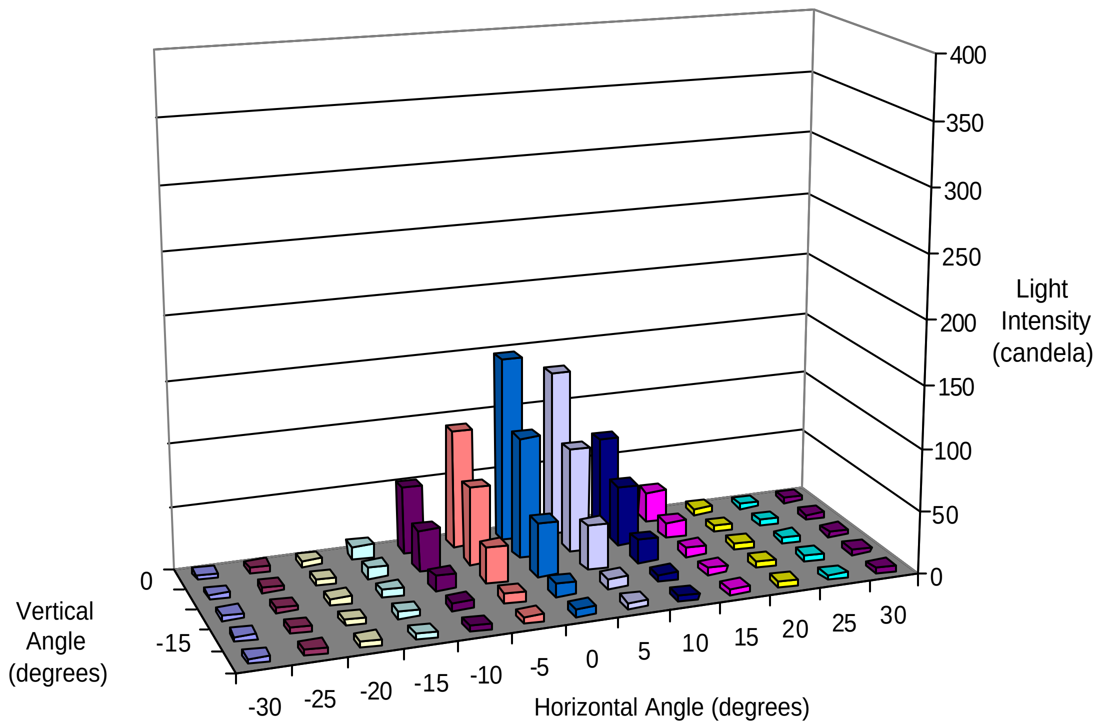

Figure A1.2.3a Output from NPS#1 (Red) signal, 10.5 volts, portion-D7F of signal on/off, TC test.

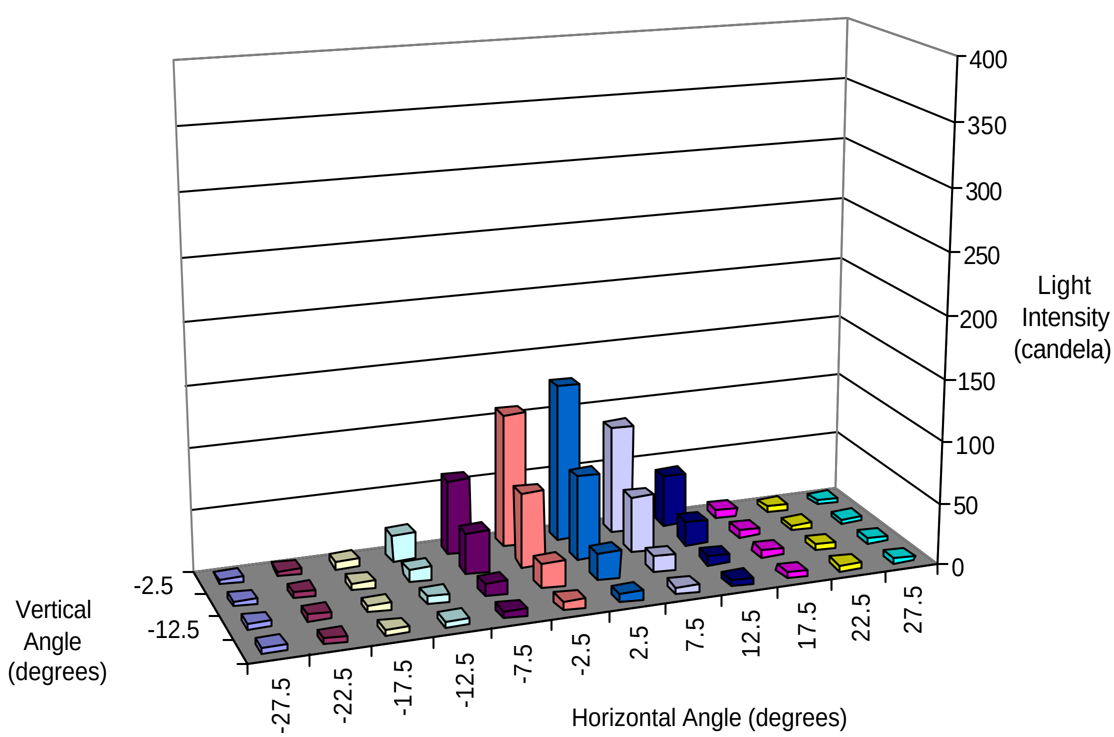

Figure A1.2.3b Output from NPS#1 (Red) signal, 10.5 volts, portion-D7F of signal on/off, ITE test.

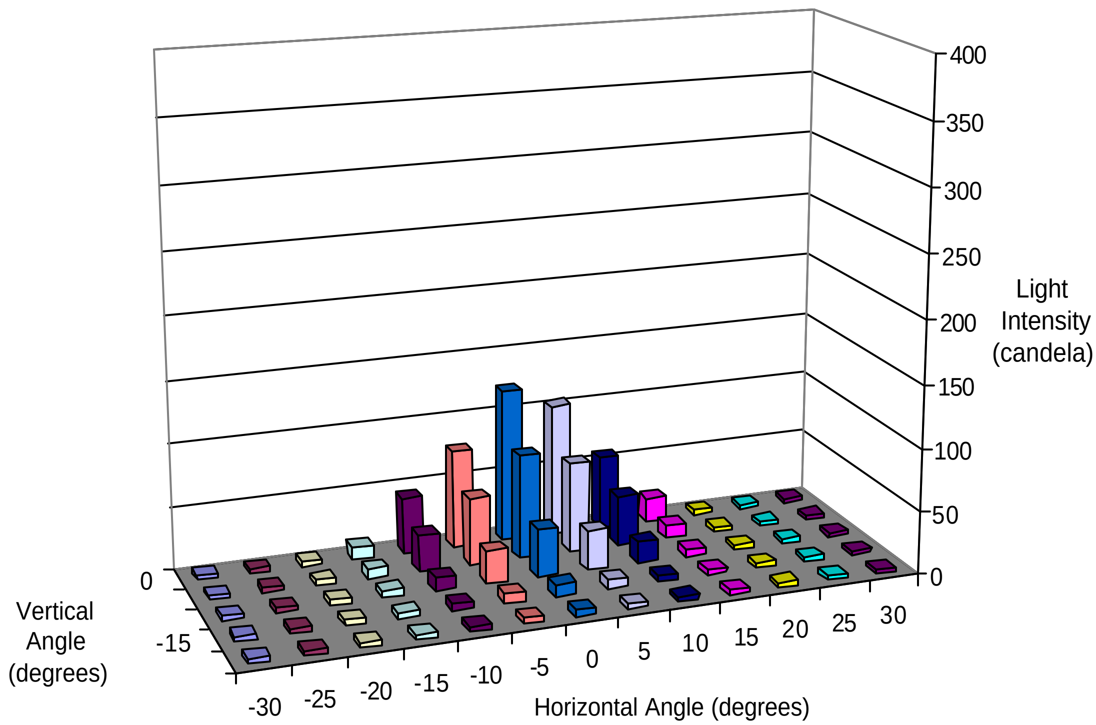

Figure A1.2.4a Output from NPS#1 (Red) signal, 10.5 volts, portion-FEC of signal on/off, TC test.

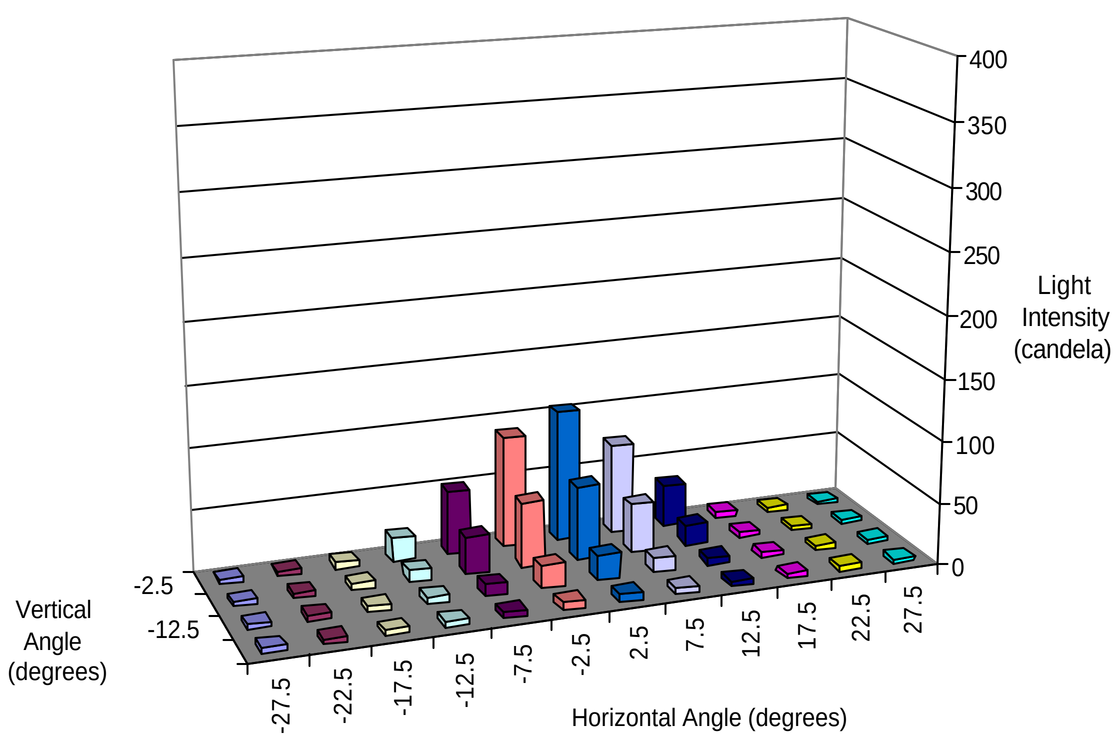

Figure A1.2.4b Output from NPS#1 (Red) signal, 10.5 volts, portion-FEC of signal on/off, ITE test.

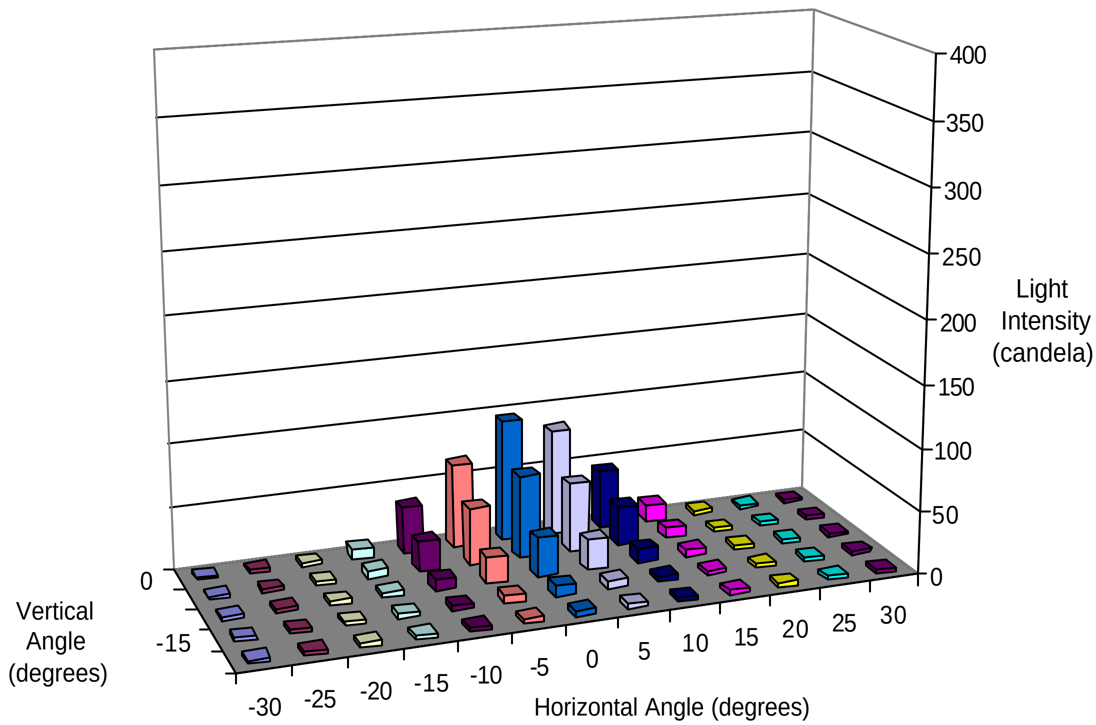

Figure A1.2.5a Output from NPS#1 (Red) signal, 10.5 volts, portion-F93 of signal on/off, TC test.

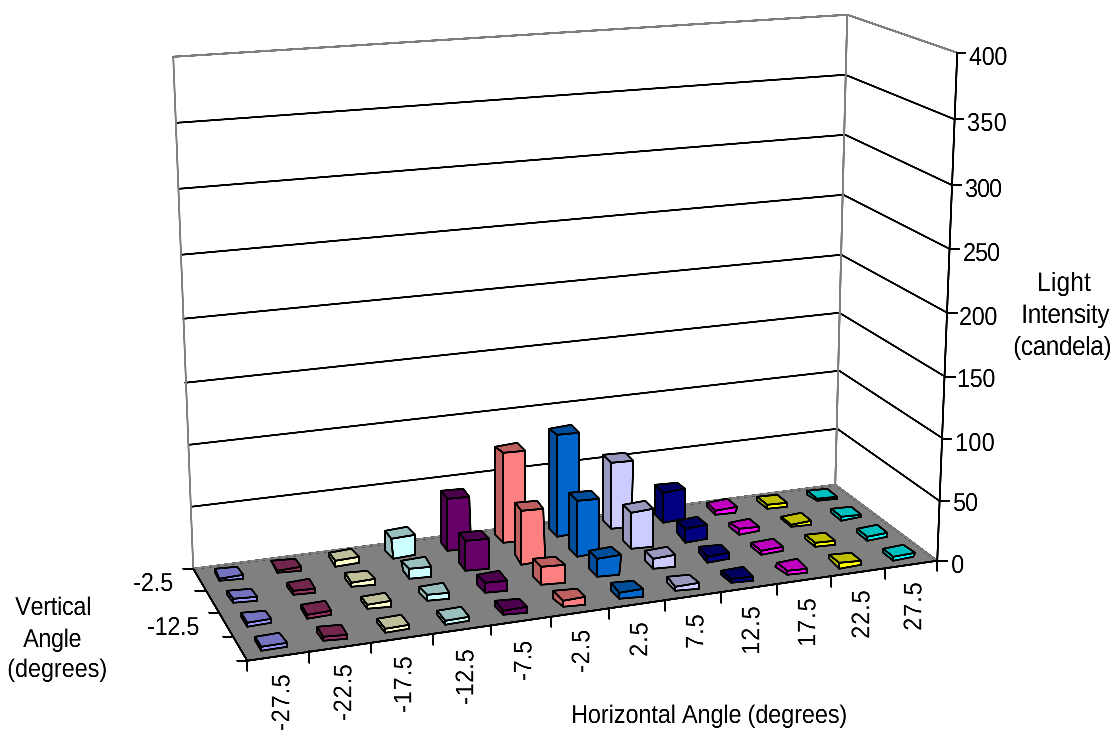

Figure A1.2.5b Output from NPS#1 (Red) signal, 10.5 volts, portion-F93 of signal on/off, ITE test.

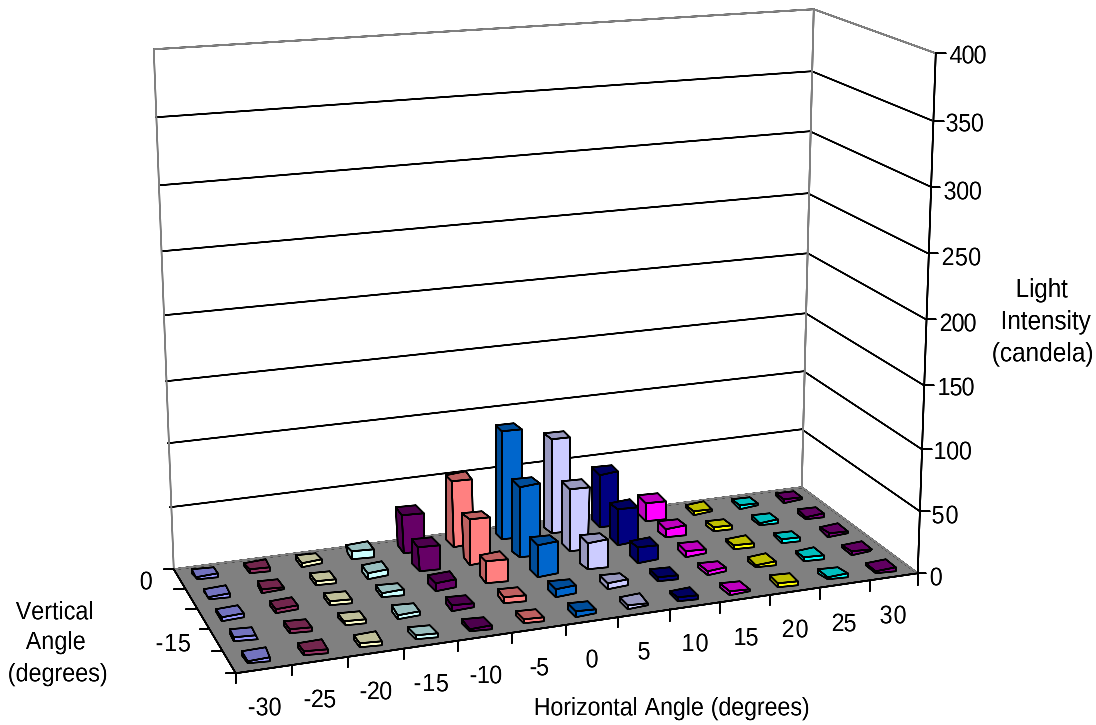

Figure A1.2.6a Output from NPS#1 (Red) signal, 10.5 volts, portion-D6C of signal on/off, TC test.

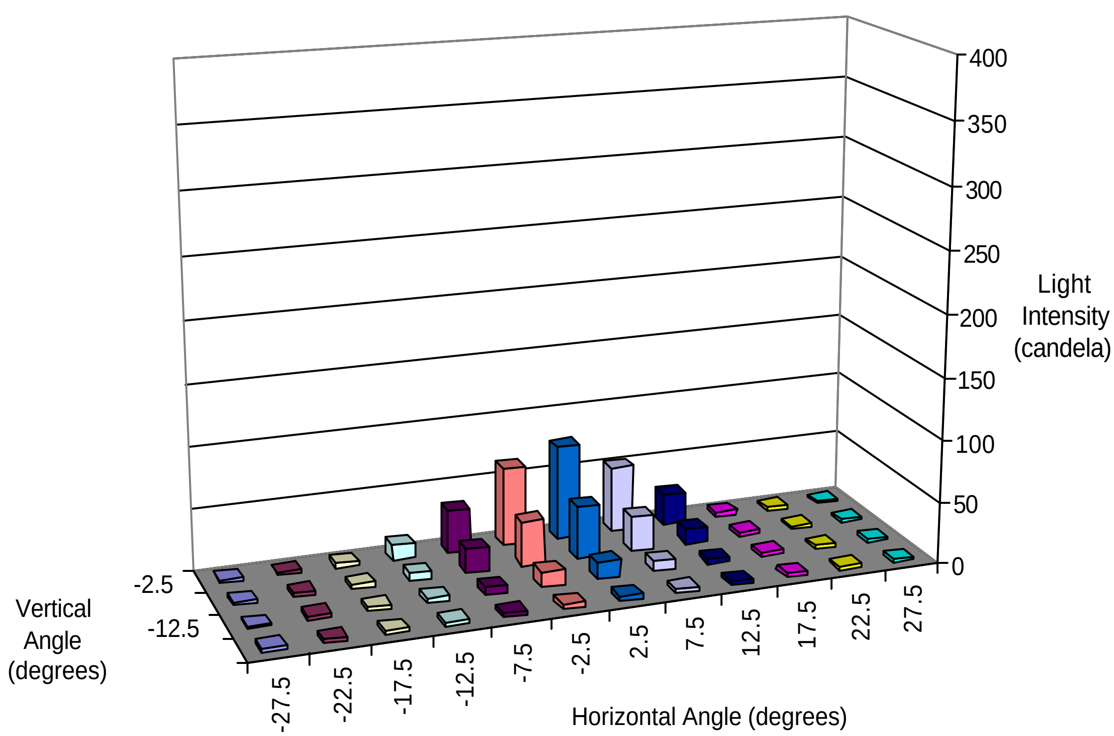

Figure A1.2.6b Output from NPS#1 (Red) signal, 10.5 volts, portion-D6C of signal on/off, ITE test.

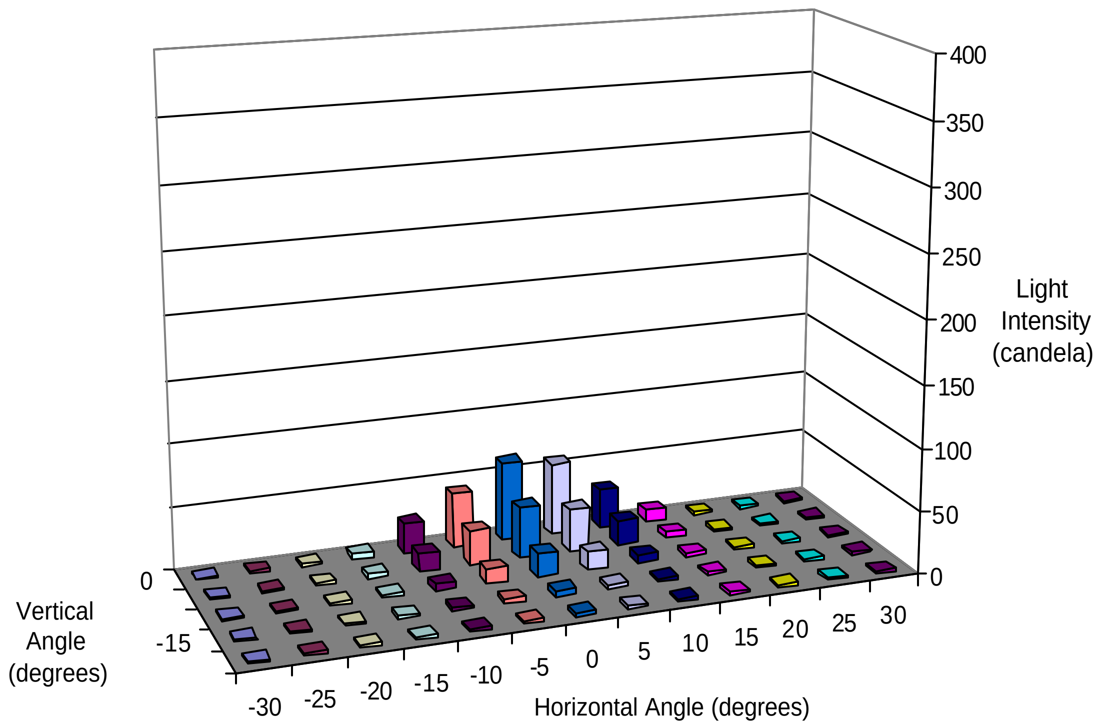

Figure A1.2.7a Output from NPS#1 (Red) signal, 10.5 volts, portion-D13 of signal on/off, TC test.

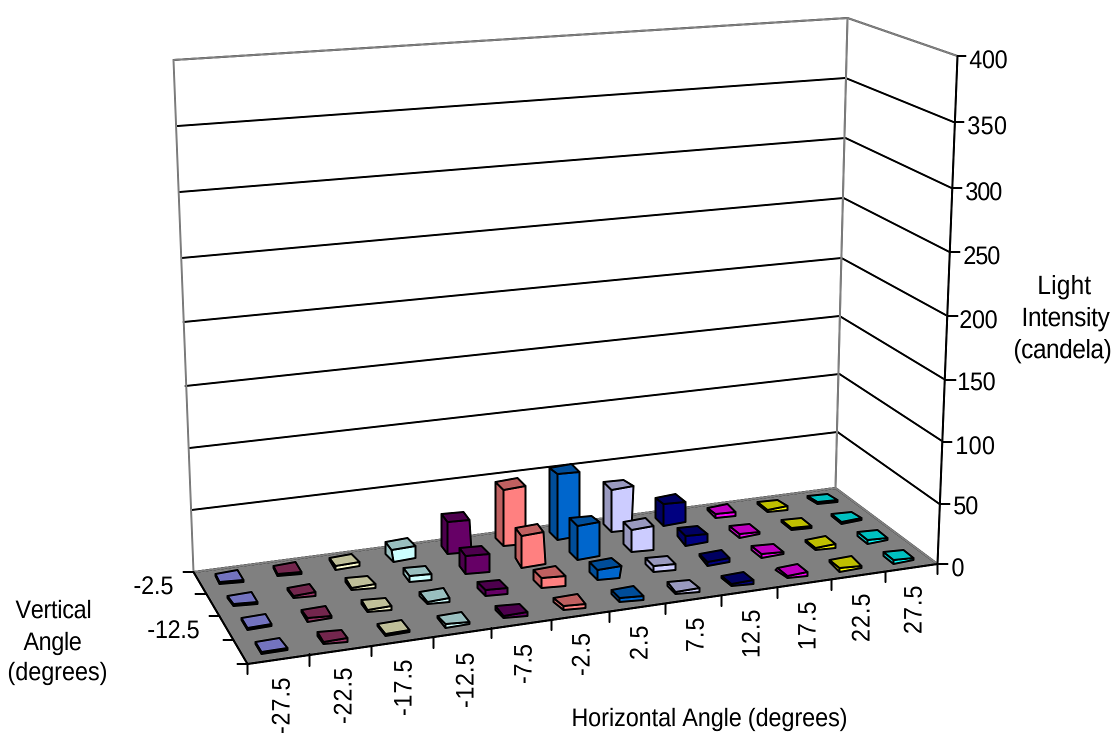

Figure A1.2.7b Output from NPS#1 (Red) signal, 10.5 volts, portion-D13 of signal on/off, ITE test.

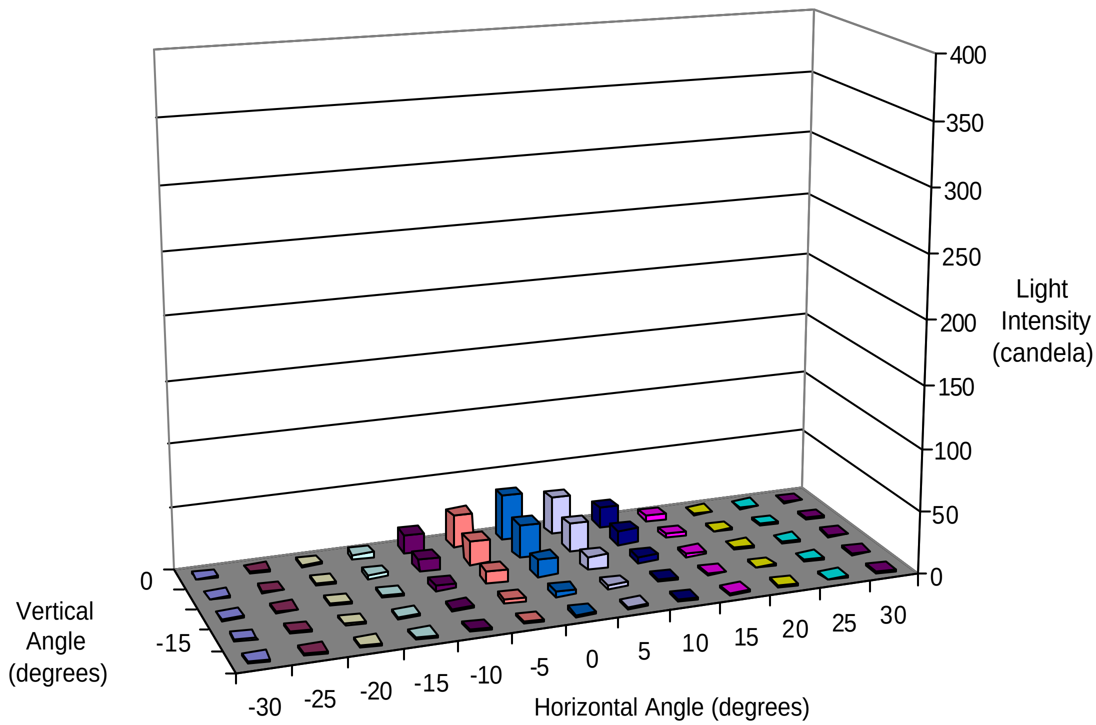

Figure A1.2.8a Output from NPS#1 (Red) signal, 10.5 volts, portion-F80 of signal on/off, TC test.

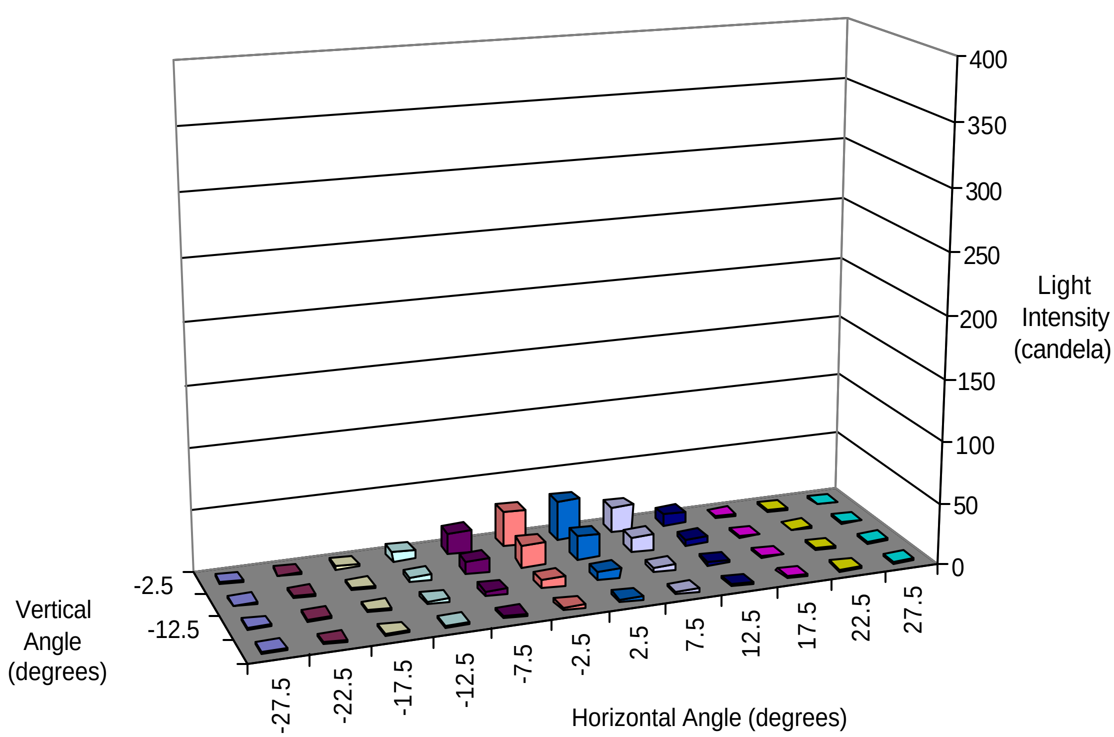

Figure A1.2.8b Output from NPS#1 (Red) signal, 10.5 volts, portion-F80 of signal on/off, ITE test.

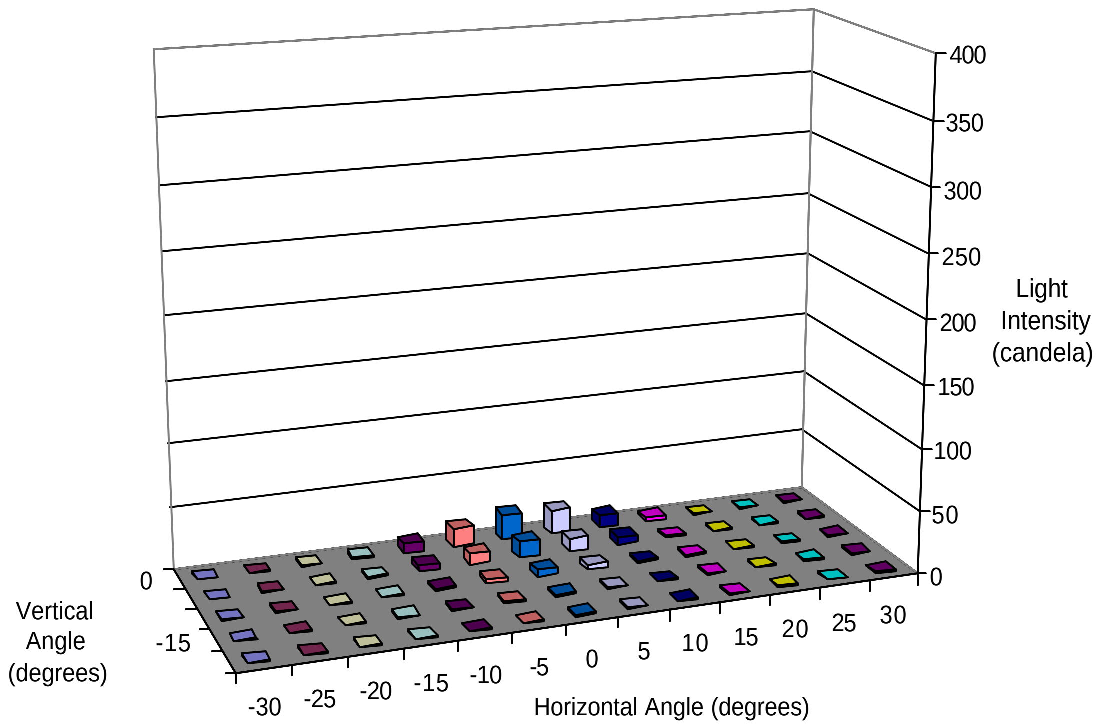

Figure A1.2.9a Output from NPS#1 (Red) signal, 10.5 volts, portion-D02 of signal on/off, TC test.

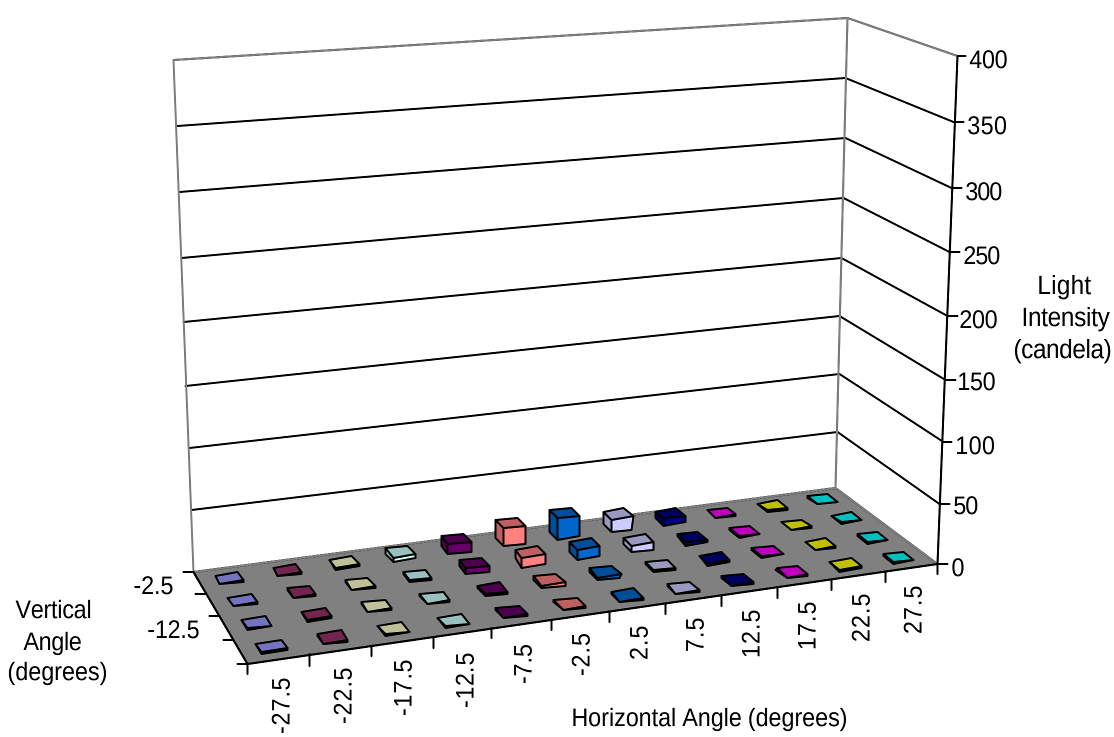

Figure A1.2.9b Output from NPS#1 (Red) signal, 10.5 volts, portion-D02 of signal on/off, ITE test.

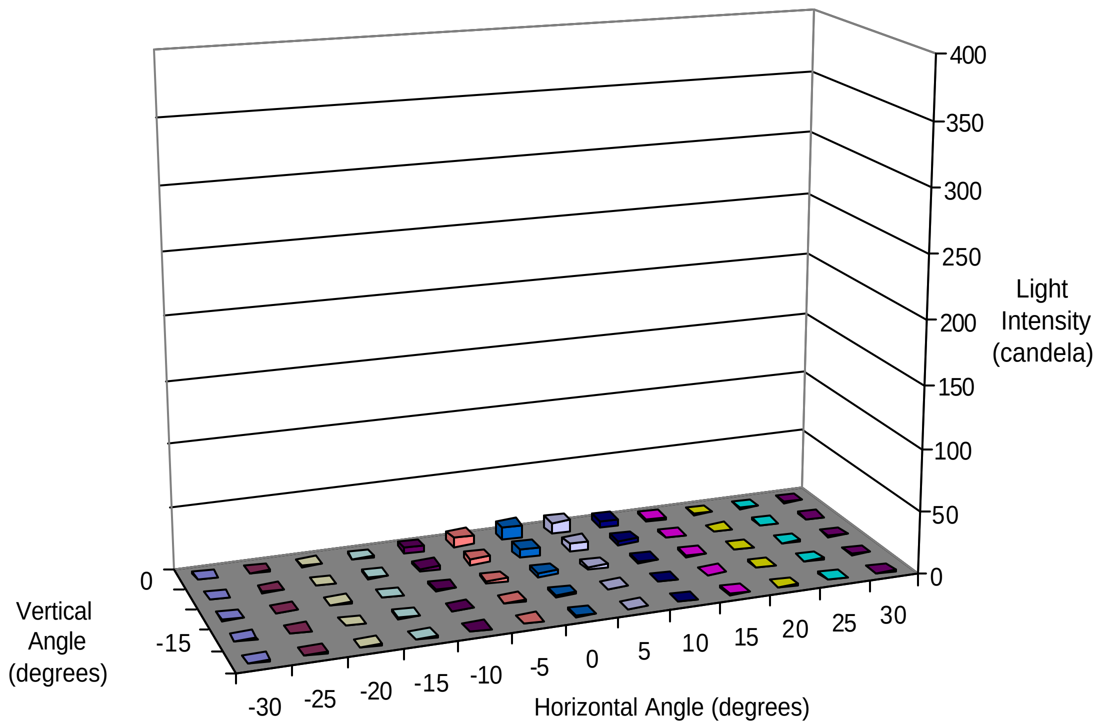

Figure A1.3.1a Output from NPS#1 (Red) signal, 7.0 volts, portion-FD3 of signal on/off, TC test.

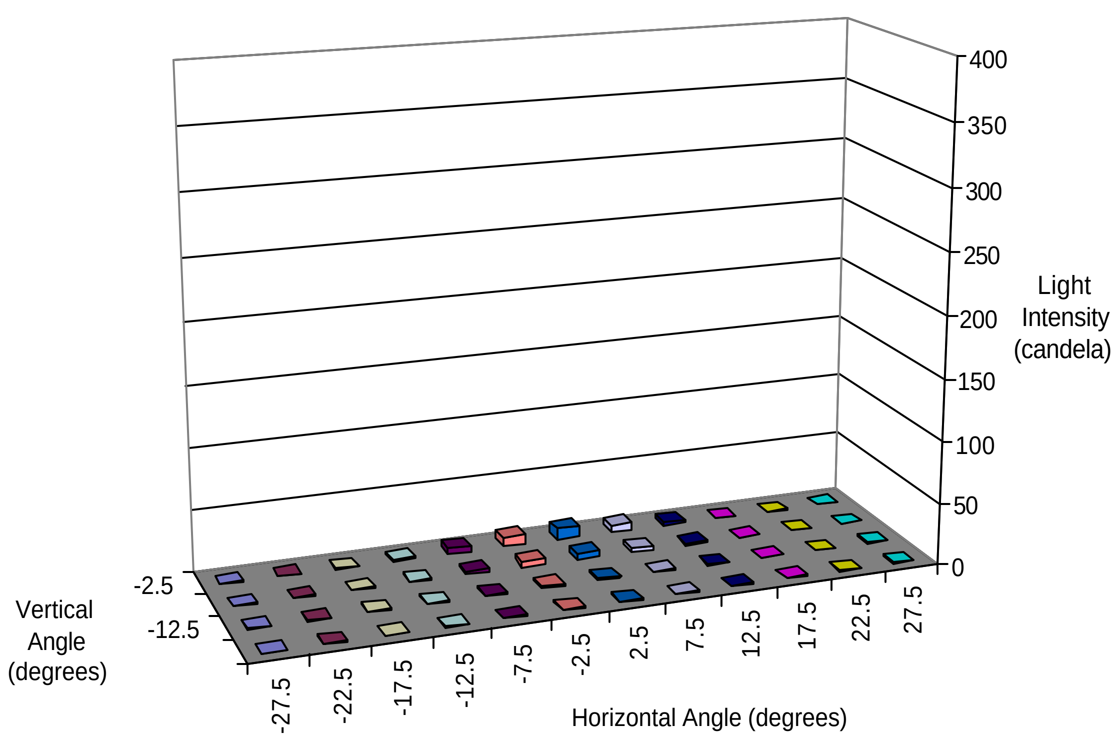

Figure A1.3.1b Output from NPS#1 (Red) signal, 7.0 volts, portion-FD3 of signal on/off, ITE test.

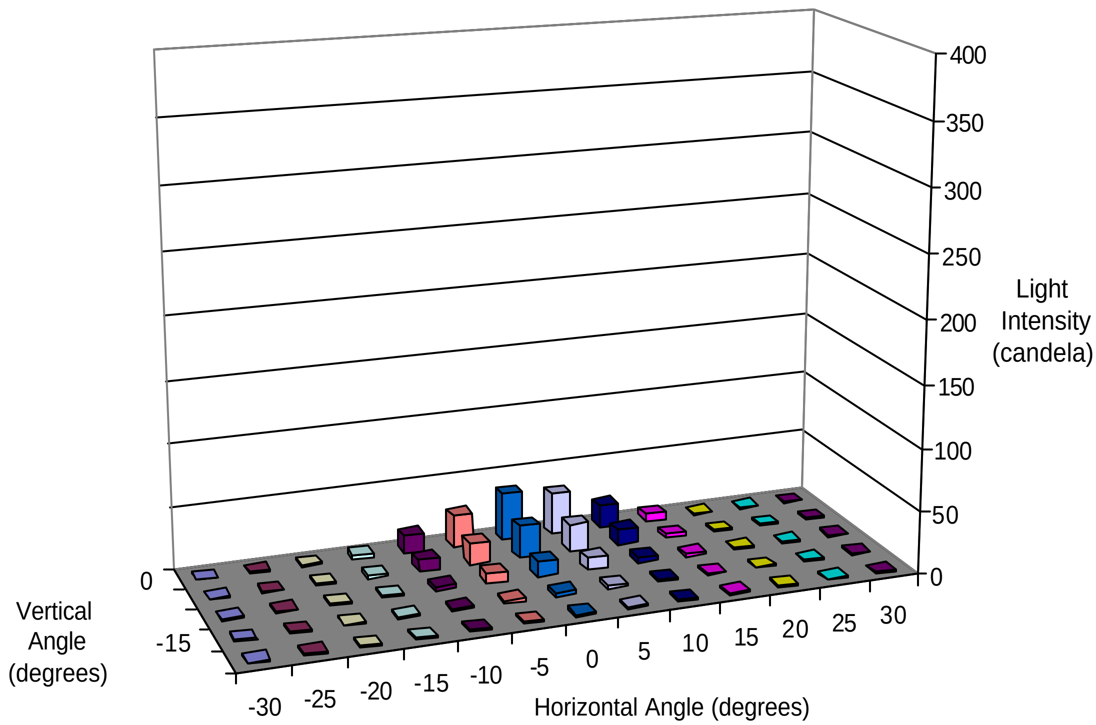

Figure A1.3.2a Output from NPS#1 (Red) signal, 8.0 volts, portion-FD3 of signal on/off, TC test.

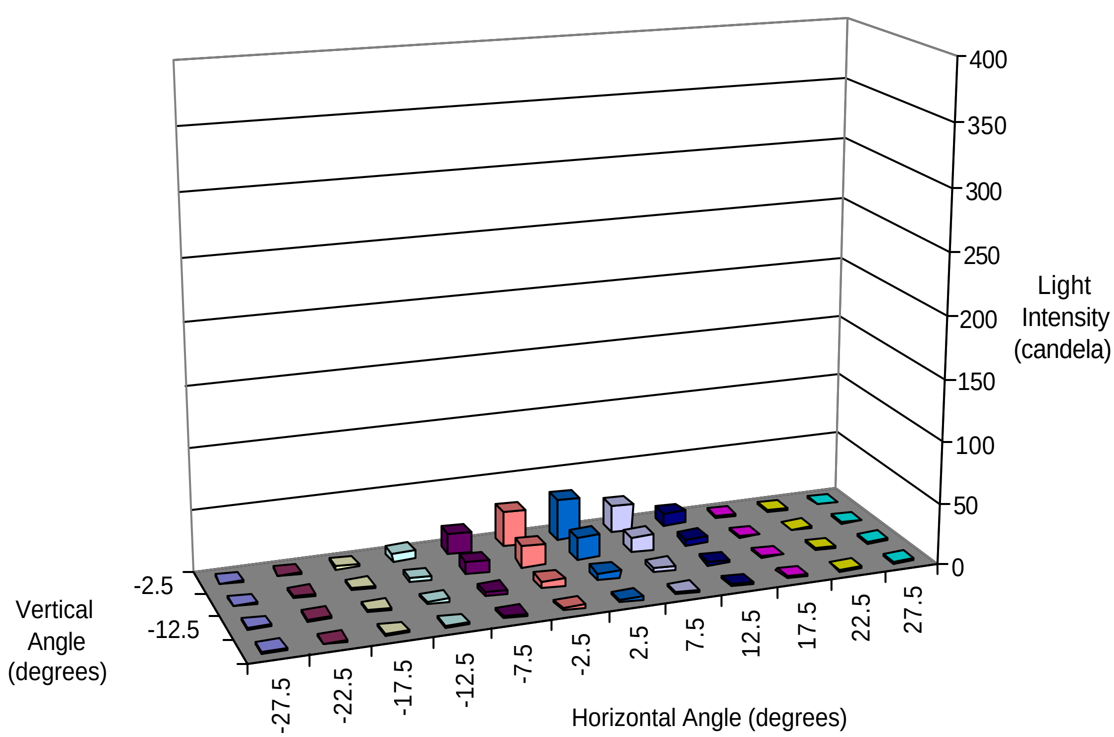

Figure A1.3.2b Output from NPS#1 (Red) signal, 8.0 volts, portion-FD3 of signal on/off, ITE test.

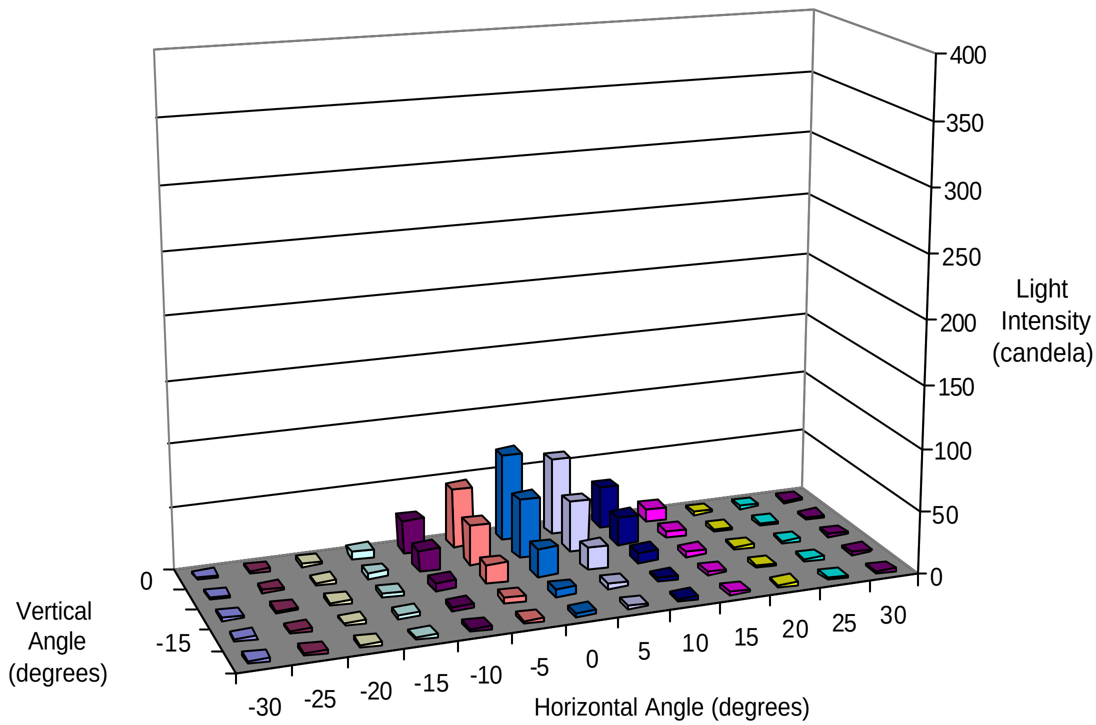

Figure A1.3.3a Output from NPS#1 (Red) signal, 9.0 volts, portion-FD3 of signal on/off, TC test.

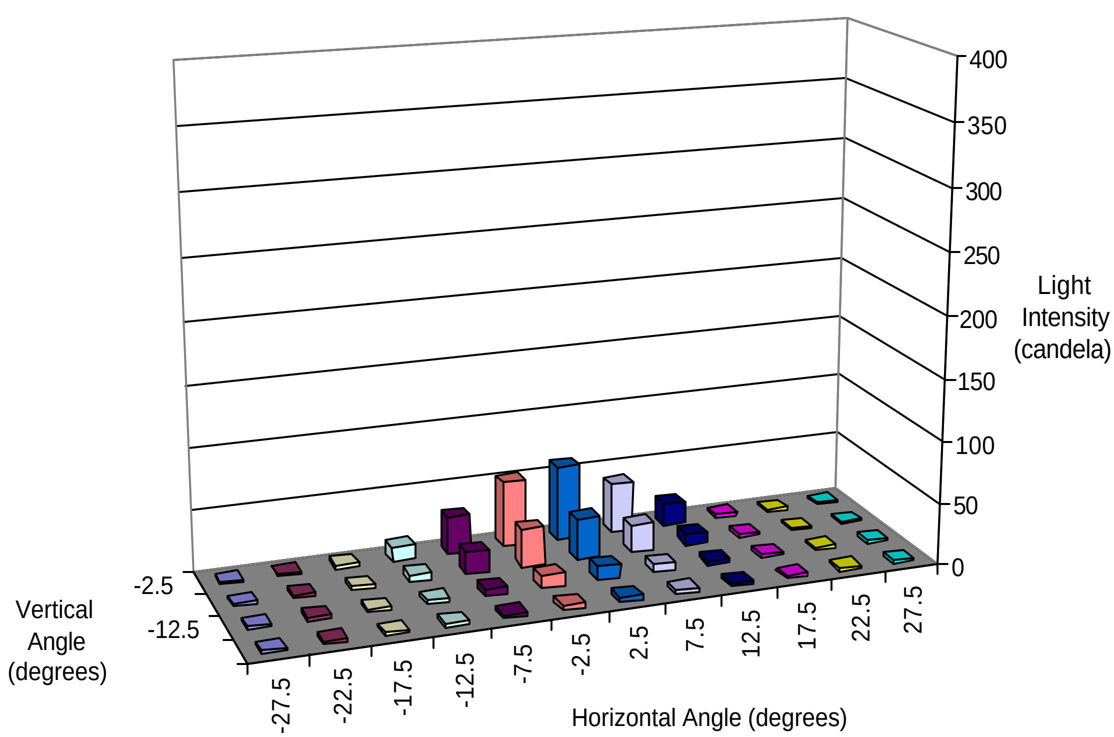

Figure A1.3.3b Output from NPS#1 (Red) signal, 9.0 volts, portion-FD3 of signal on/off, ITE test.

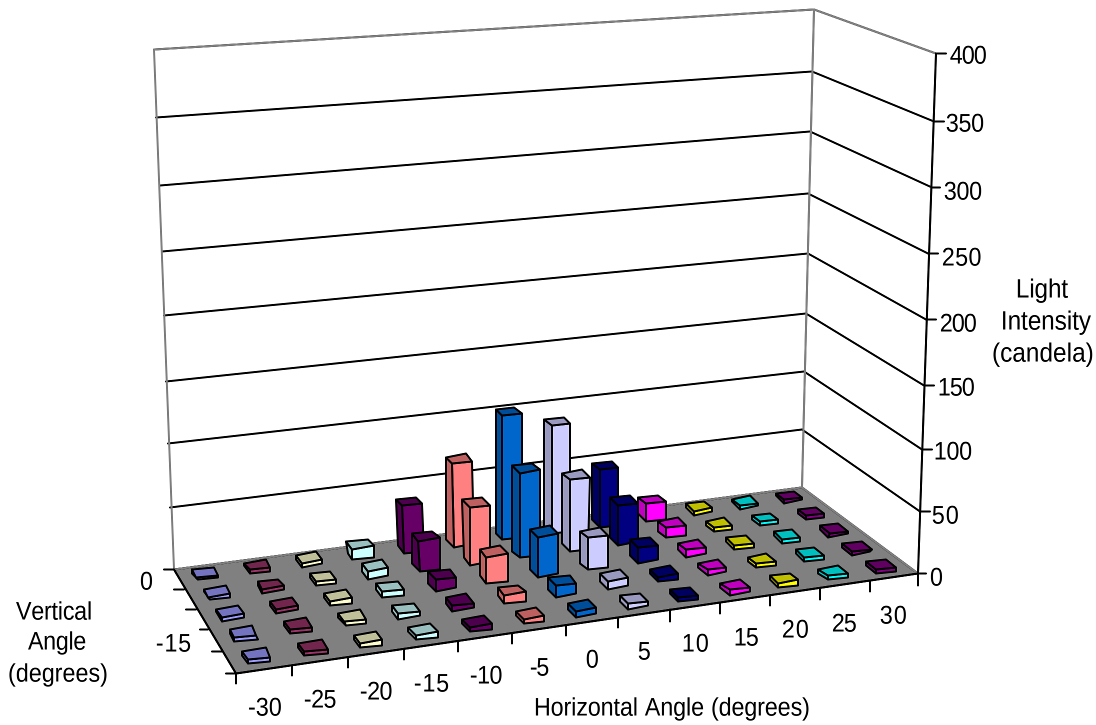

Figure A1.3.4a Output from NPS#1 (Red) signal, 10.0 volts, portion-FD3 of signal on/off, TC test.

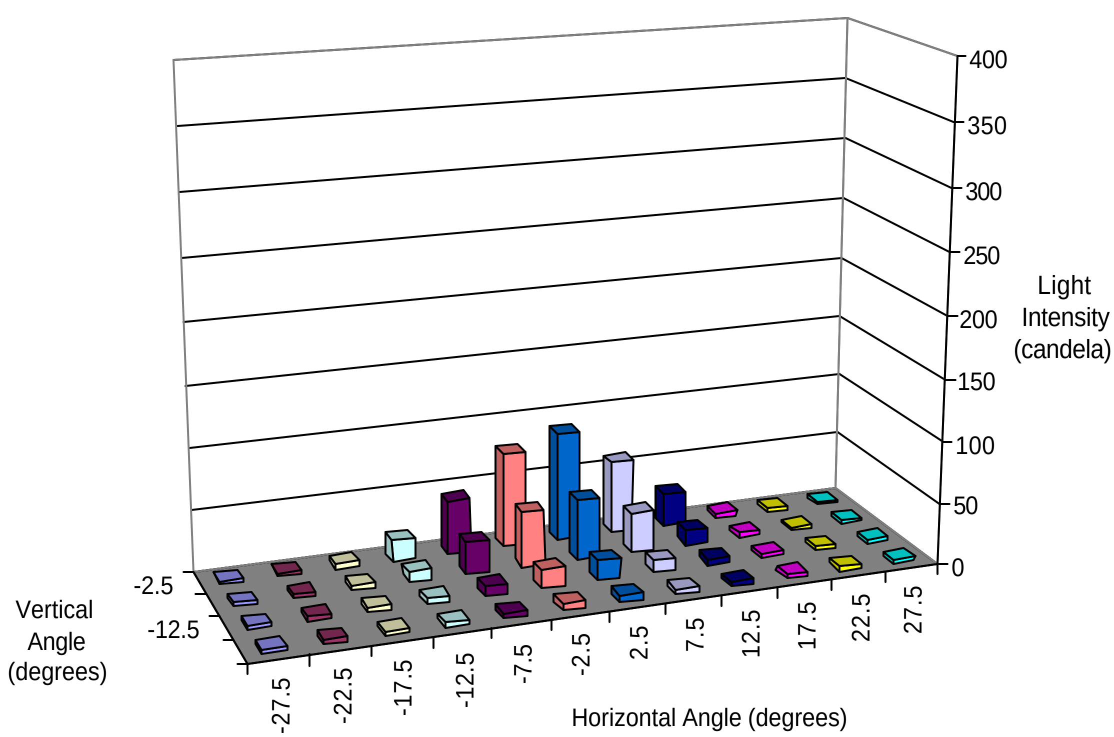

Figure A1.3.4b Output from NPS#1 (Red) signal, 10.0 volts, portion-FD3 of signal on/off, ITE test.

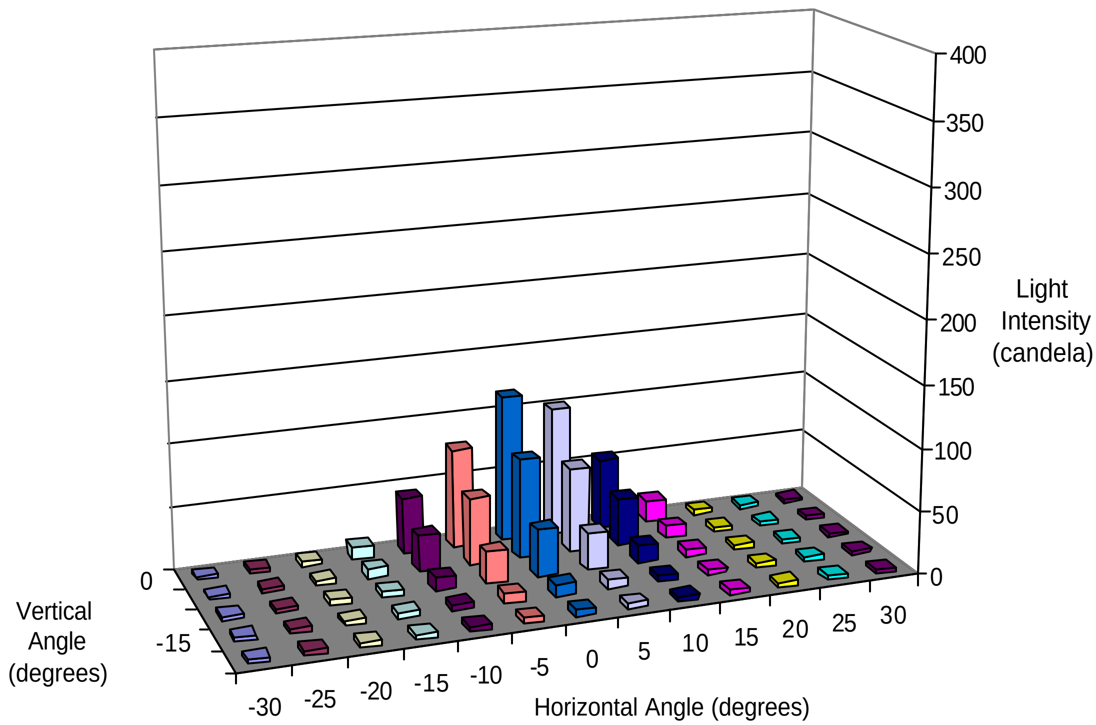

Figure A1.3.5a Output from NPS#1 (Red) signal, 10.5 volts, portion-FD3 of signal on/off, TC test.

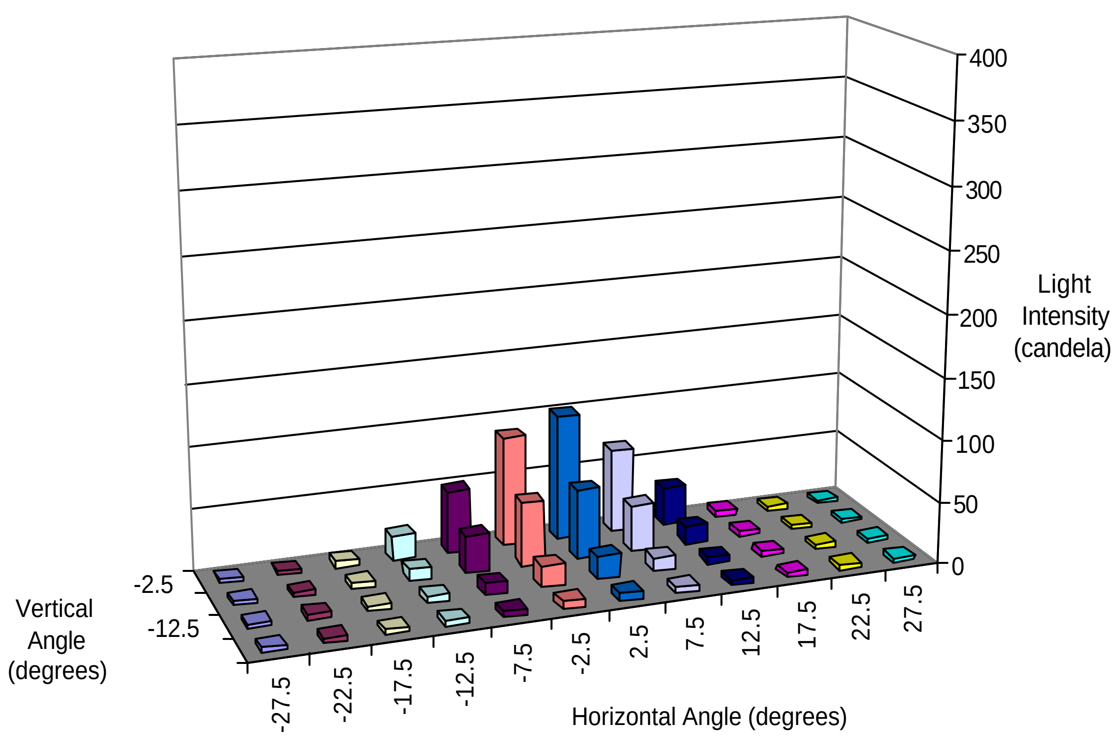

Figure A1.3.5b Output from NPS#1 (Red) signal, 10.5 volts, portion-FD3 of signal on/off, ITE test.

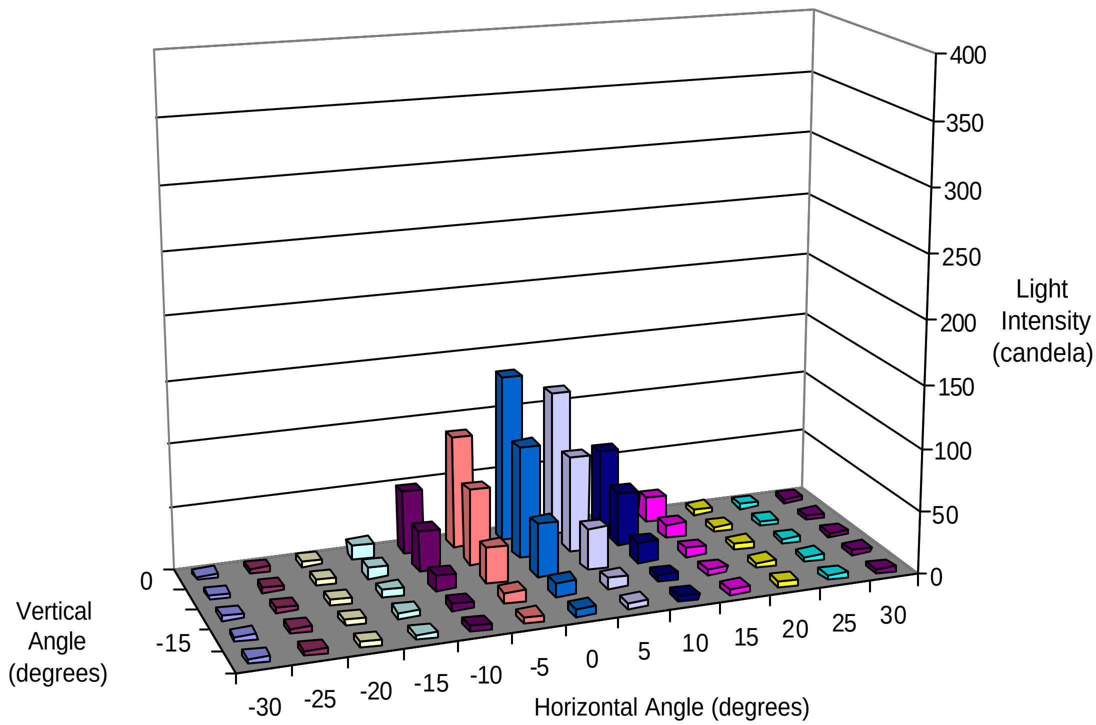

Figure A1.3.6a Output from NPS#1 (Red) signal, 11.0 volts, portion-FD3 of signal on/off, TC test.

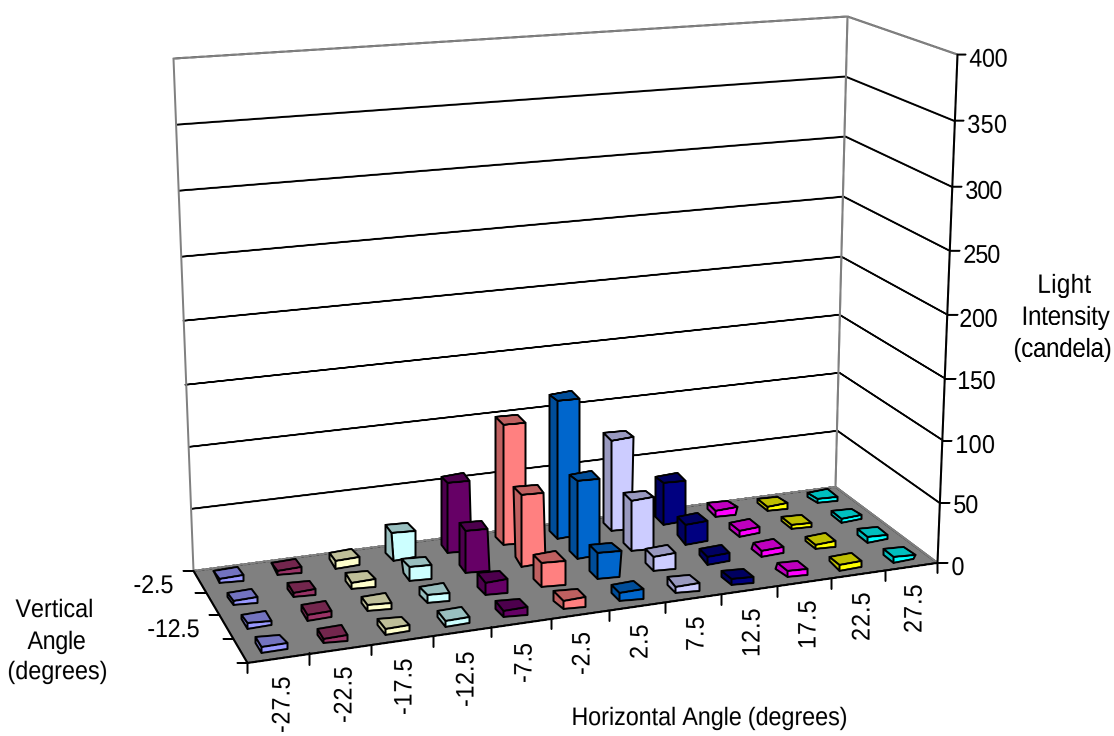

Figure A1.3.6b Output from NPS#1 (Red) signal, 11.0 volts, portion-FD3 of signal on/off, ITE test.

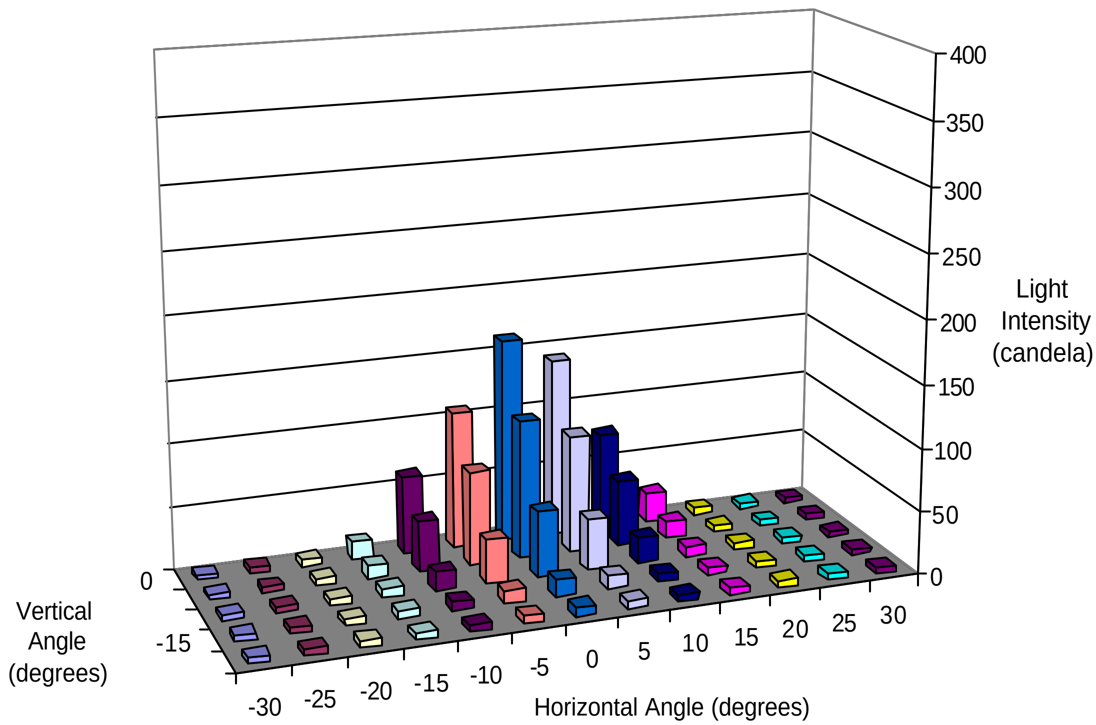

Figure A1.3.7a Output from NPS#1 (Red) signal, 12.0 volts, portion-FD3 of signal on/off, TC test.

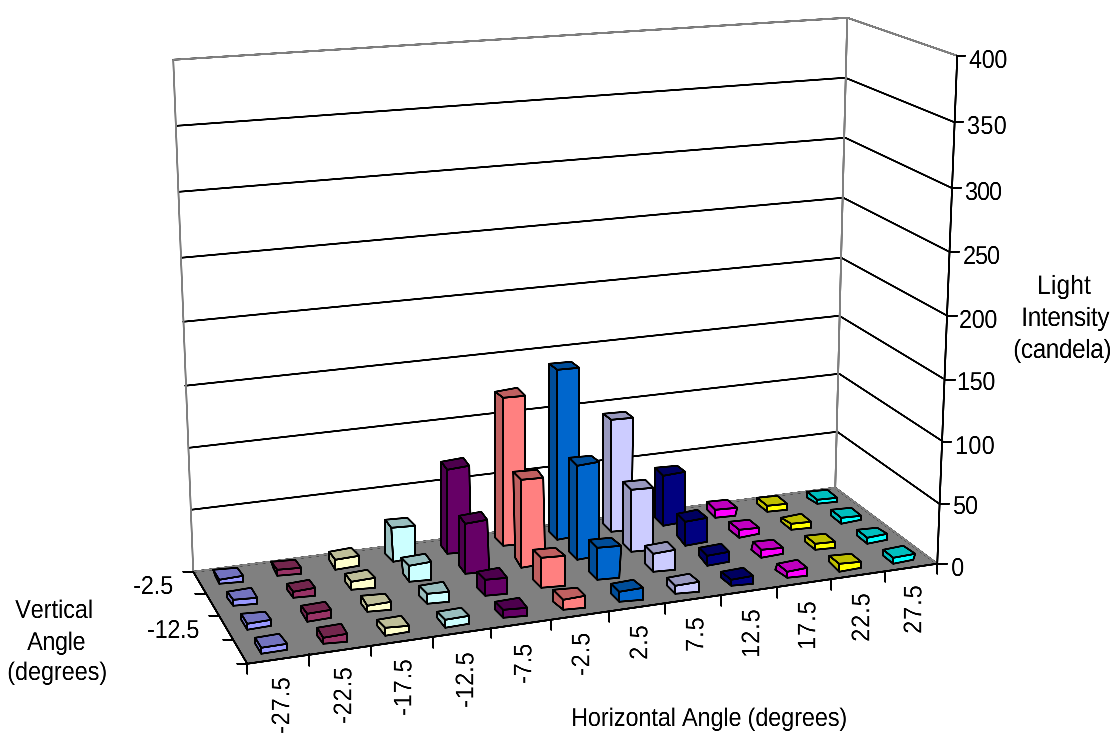

Figure A1.3.7b Output from NPS#1 (Red) signal, 12.0 volts, portion-FD3 of signal on/off, ITE test.

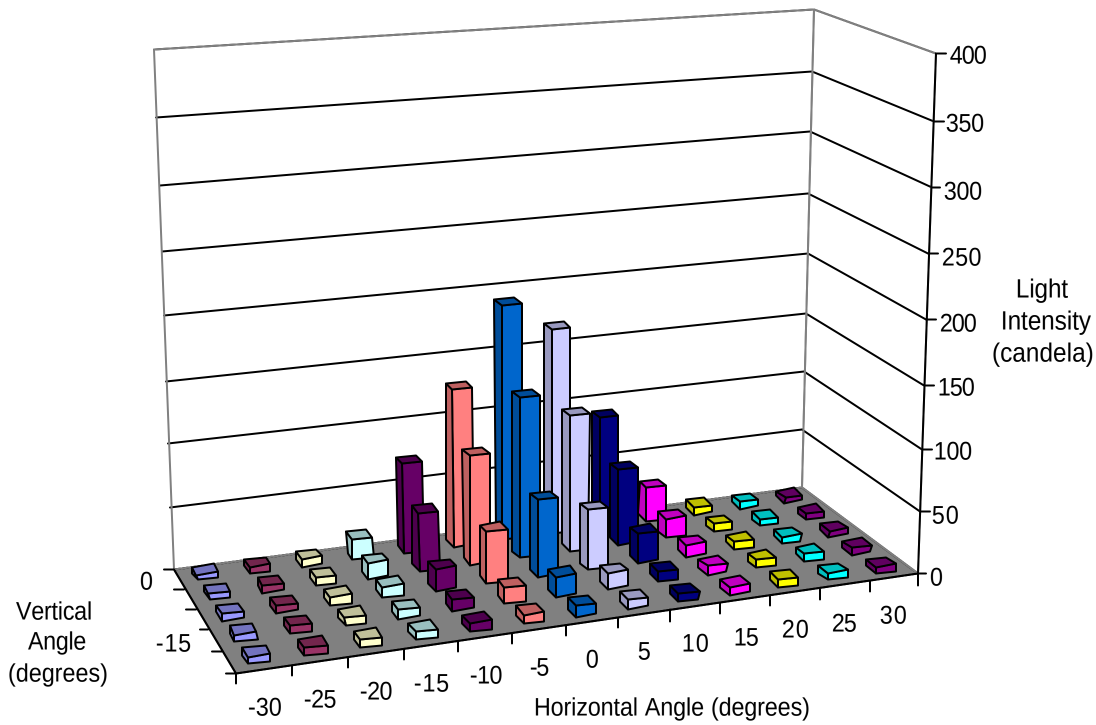

Figure A1.3.8a Output from NPS#1 (Red) signal, 13.0 volts, portion-FD3 of signal on/off, TC test.

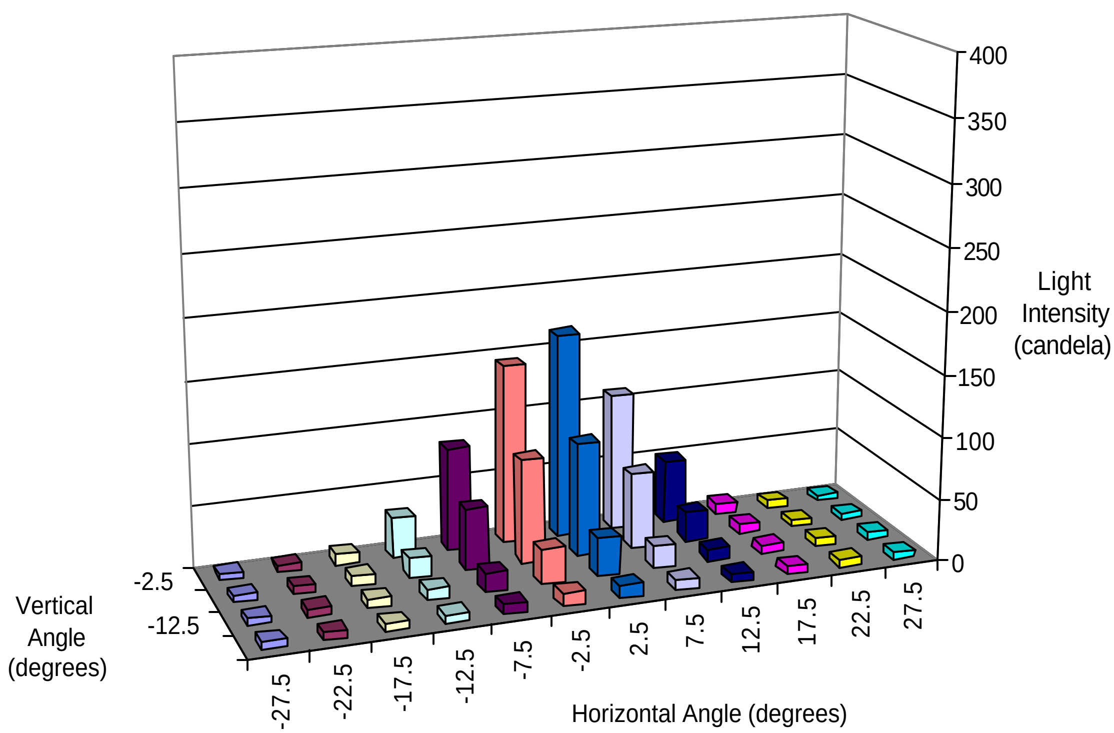

Figure A1.3.8b Output from NPS#1 (Red) signal, 13.0 volts, portion-FD3 of signal on/off, ITE test.

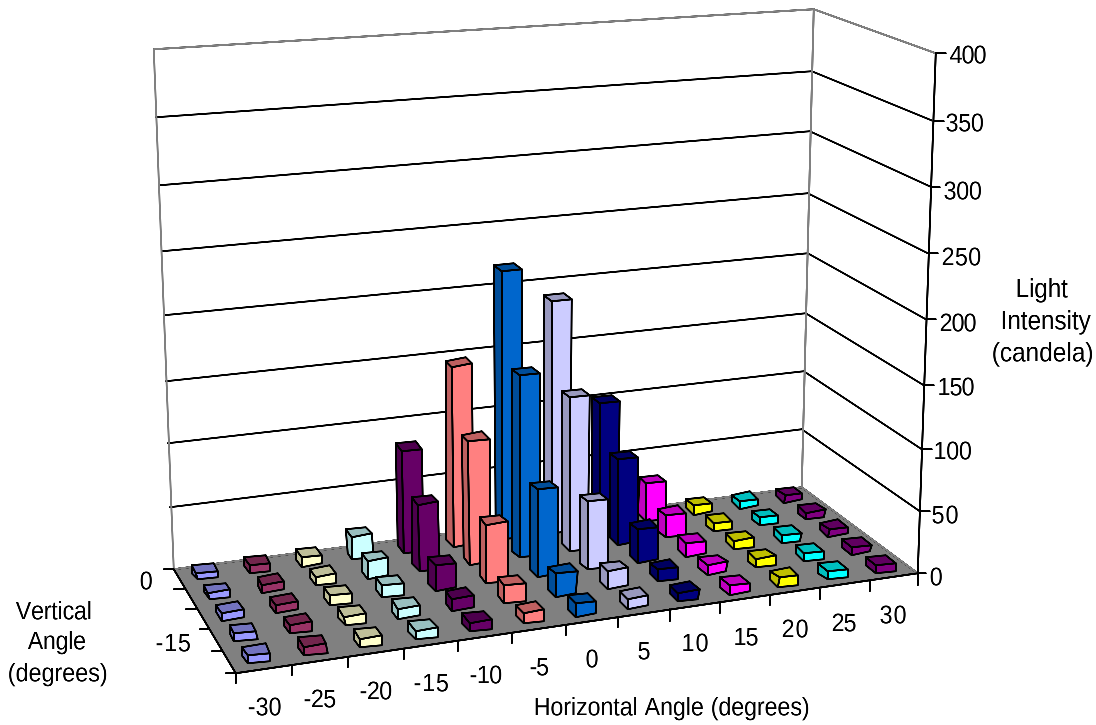

Figure A1.3.9a Output from NPS#1 (Red) signal, 14.0 volts, portion-FD3 of signal on/off, TC test.

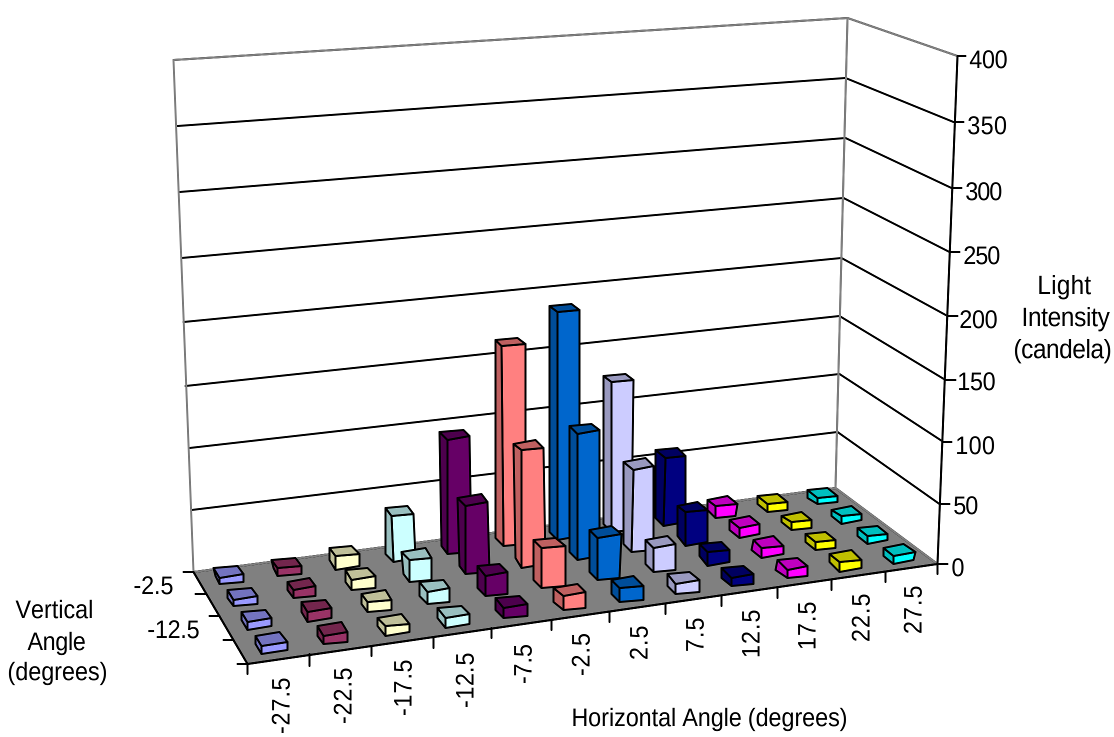

Figure A1.3.9b Output from NPS#1 (Red) signal, 14.0 volts, portion-FD3 of signal on/off, ITE test.

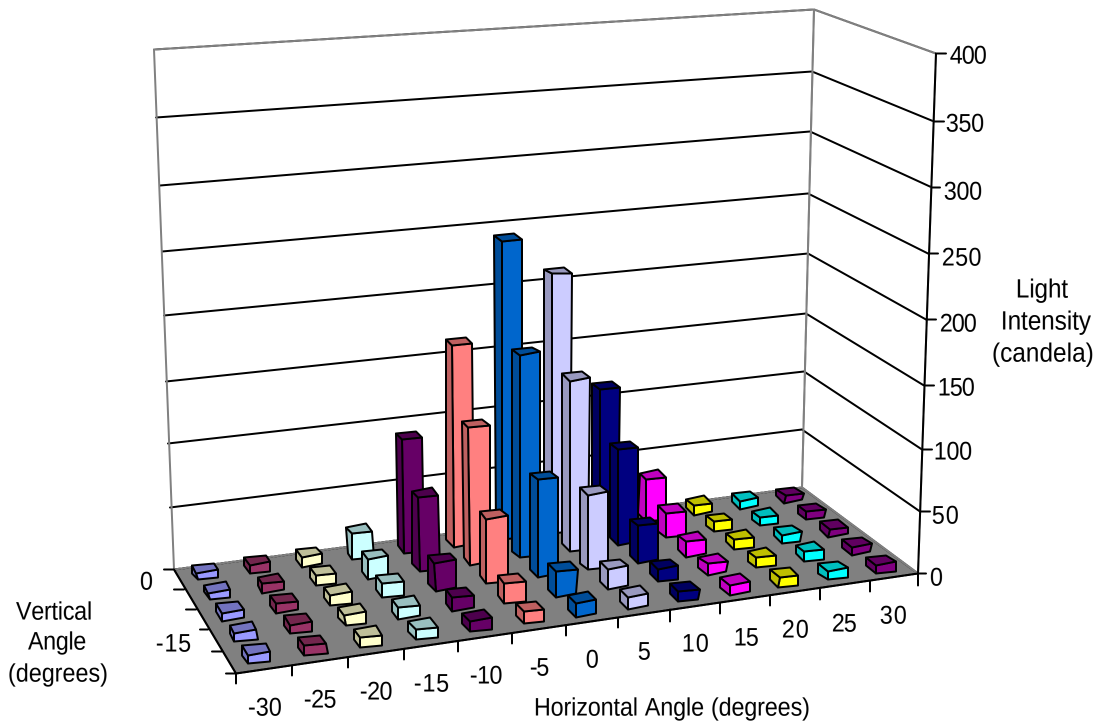

Figure A1.3.10a Output from NPS#1 (Red) signal, 15.0 volts, portion-FD3 of signal on/off, TC test.

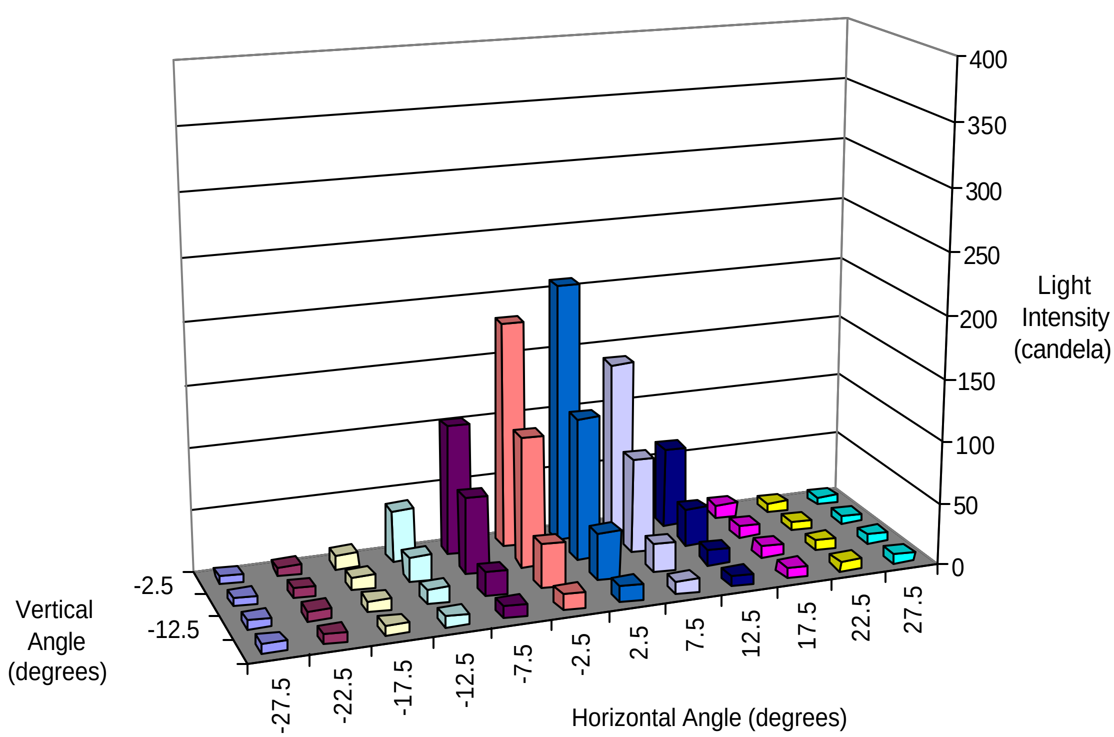

Figure A1.3.10b Output from NPS#1 (Red) signal, 15.0 volts, portion-FD3 of signal on/off, ITE test.

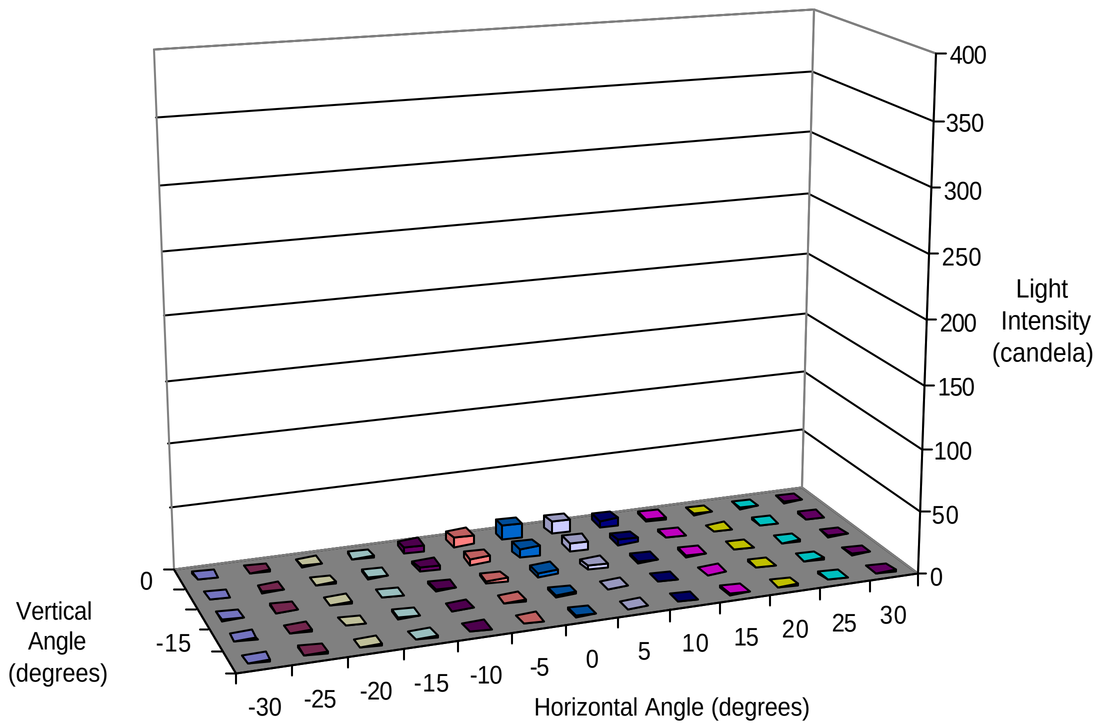

Figure A1.4.1a Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, TC test.

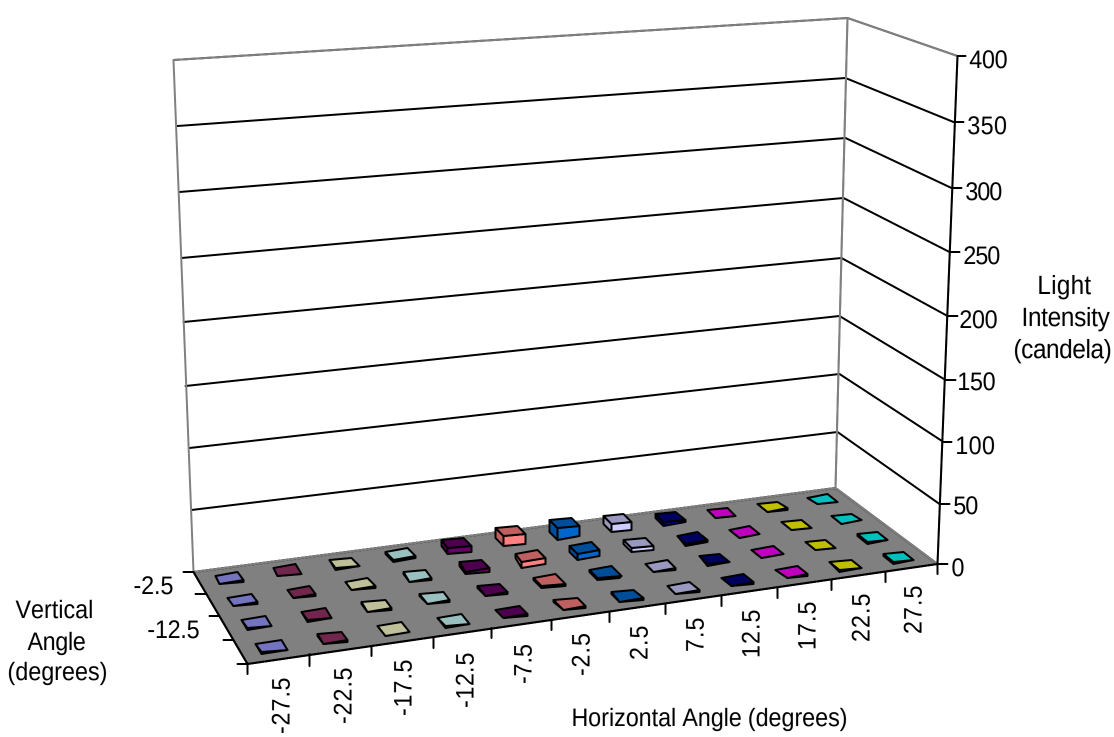

Figure A1.4.1b Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, ITE test.

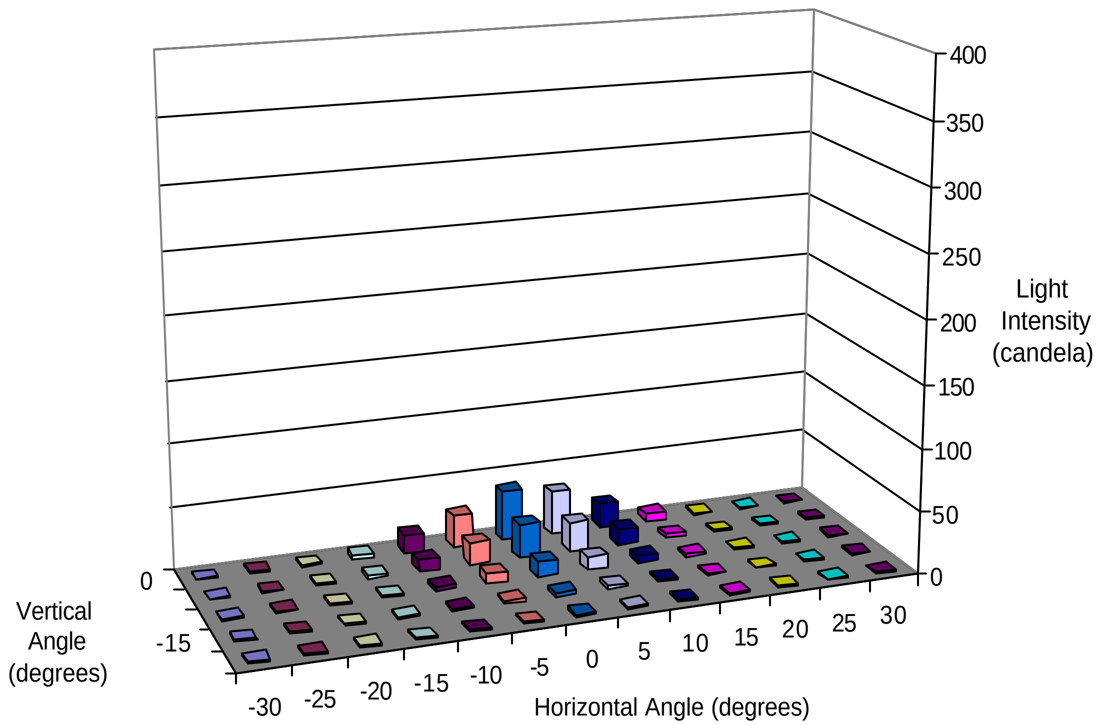

Figure A1.4.2a Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, TC test.

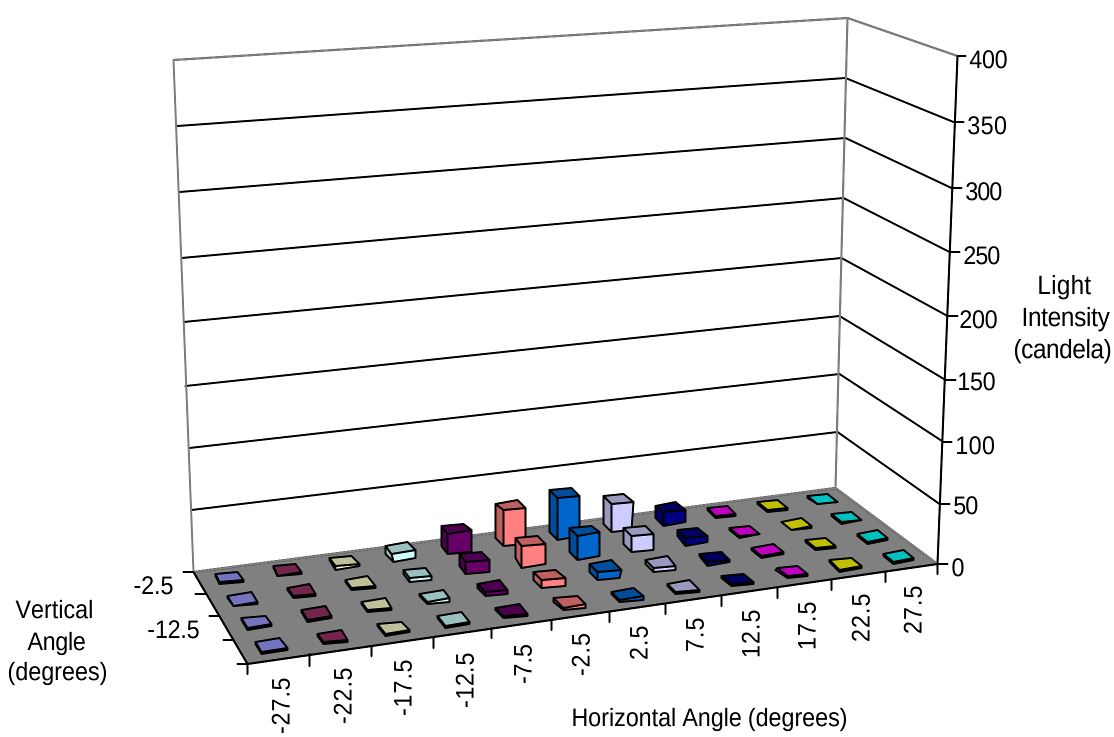

Figure A1.4.2b Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, ITE test.

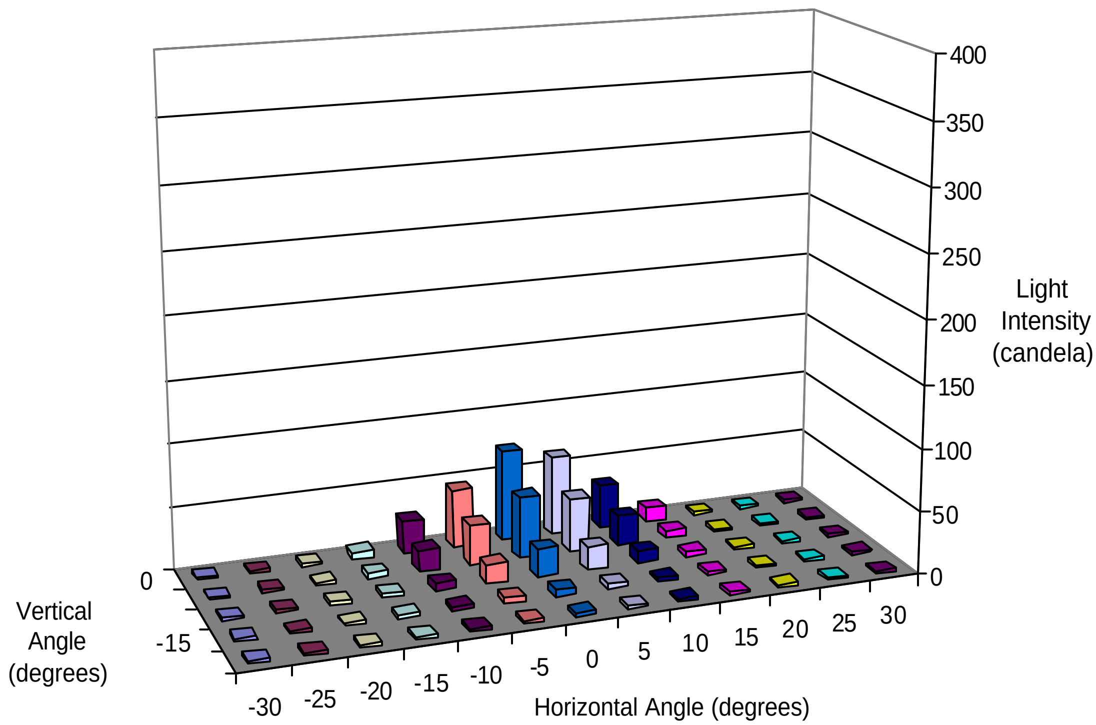

Figure A1.4.3a Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, TC test.

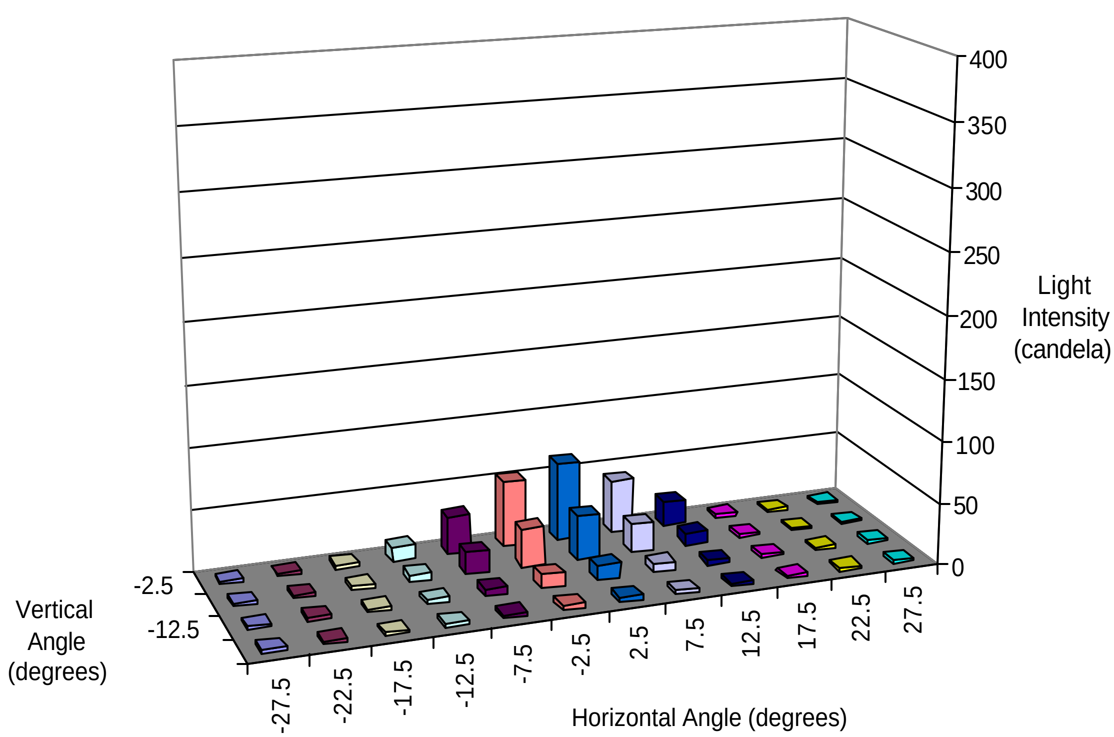

Figure A1.4.3b Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, ITE test.

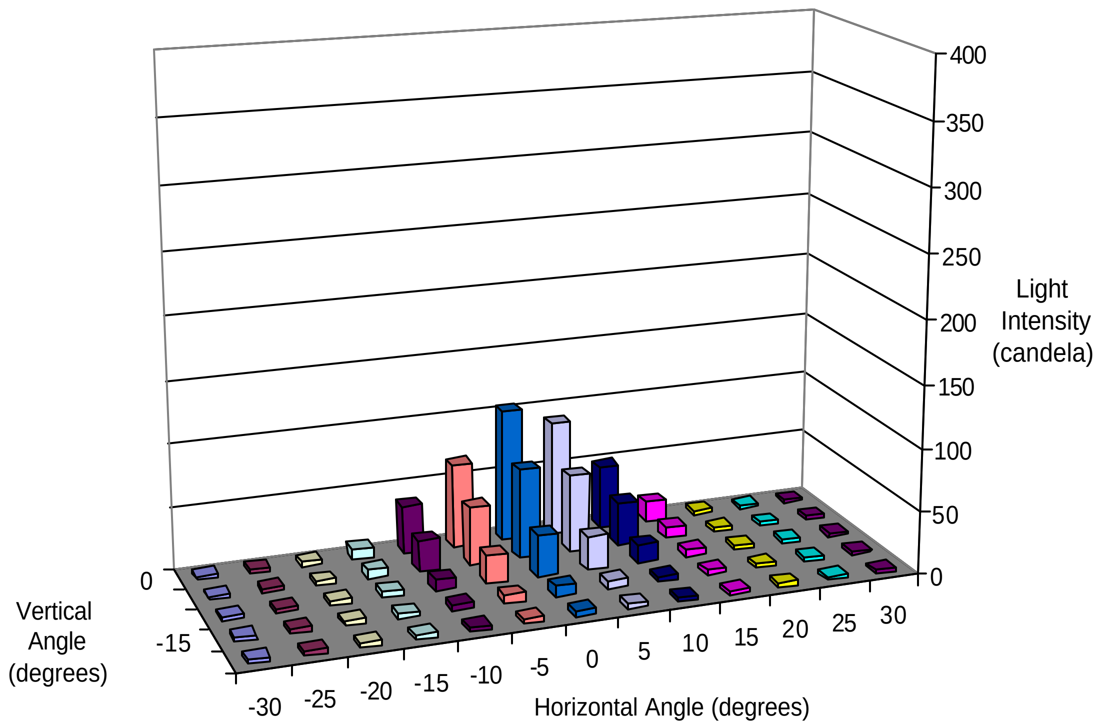

Figure A1.4.4a Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, TC test.

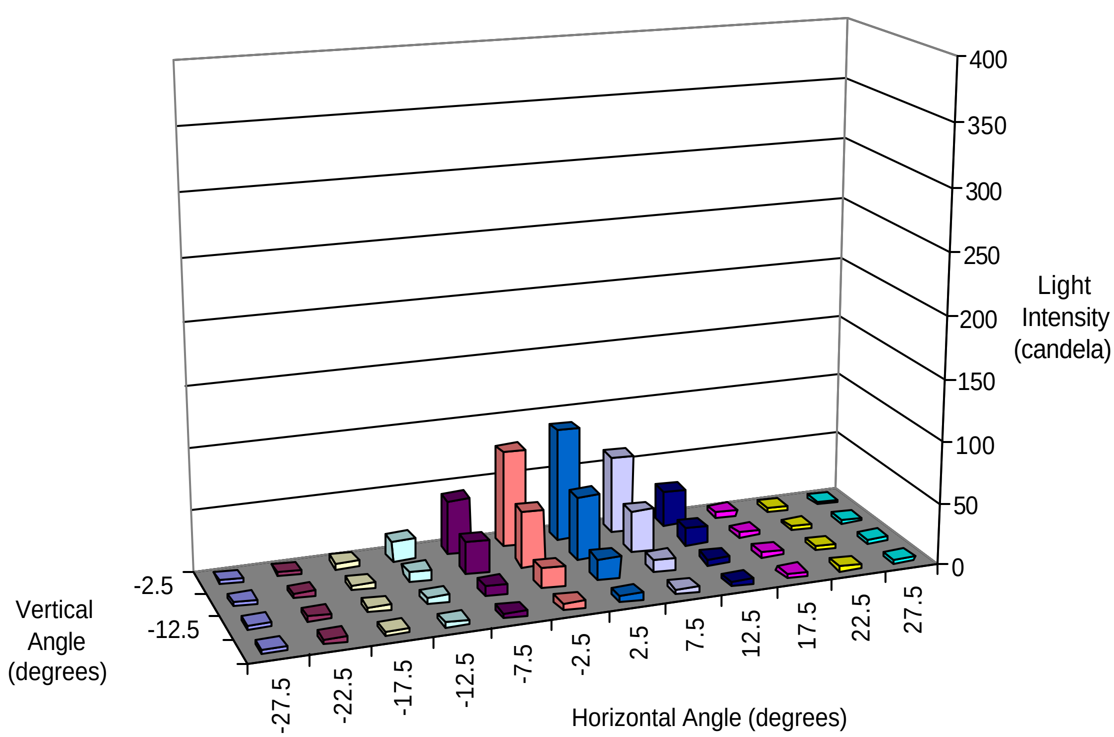

Figure A1.4.4b Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, ITE test.

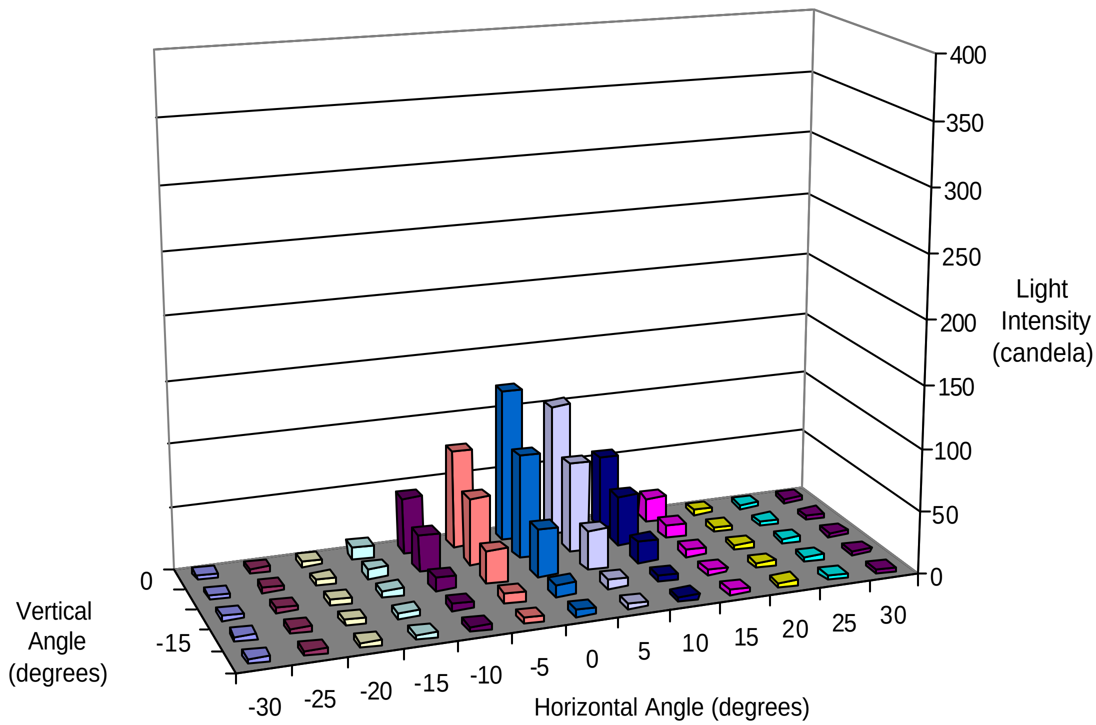

Figure A1.4.5a Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, TC test.

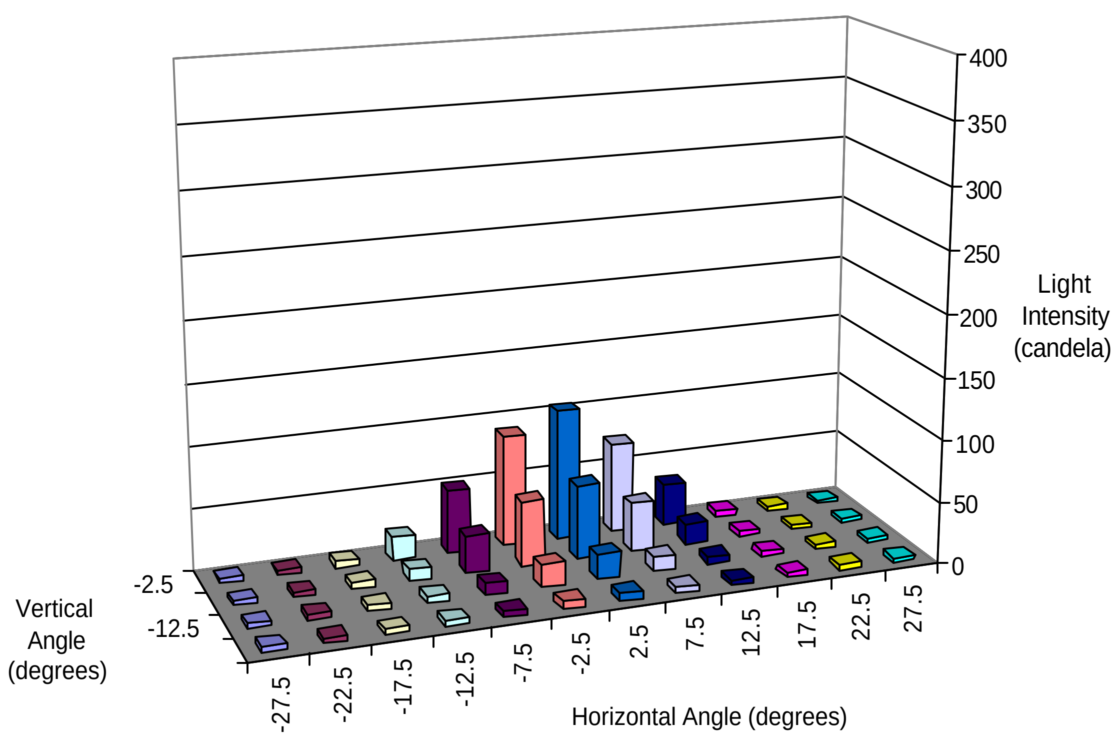

Figure A1.4.5b Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, ITE test.

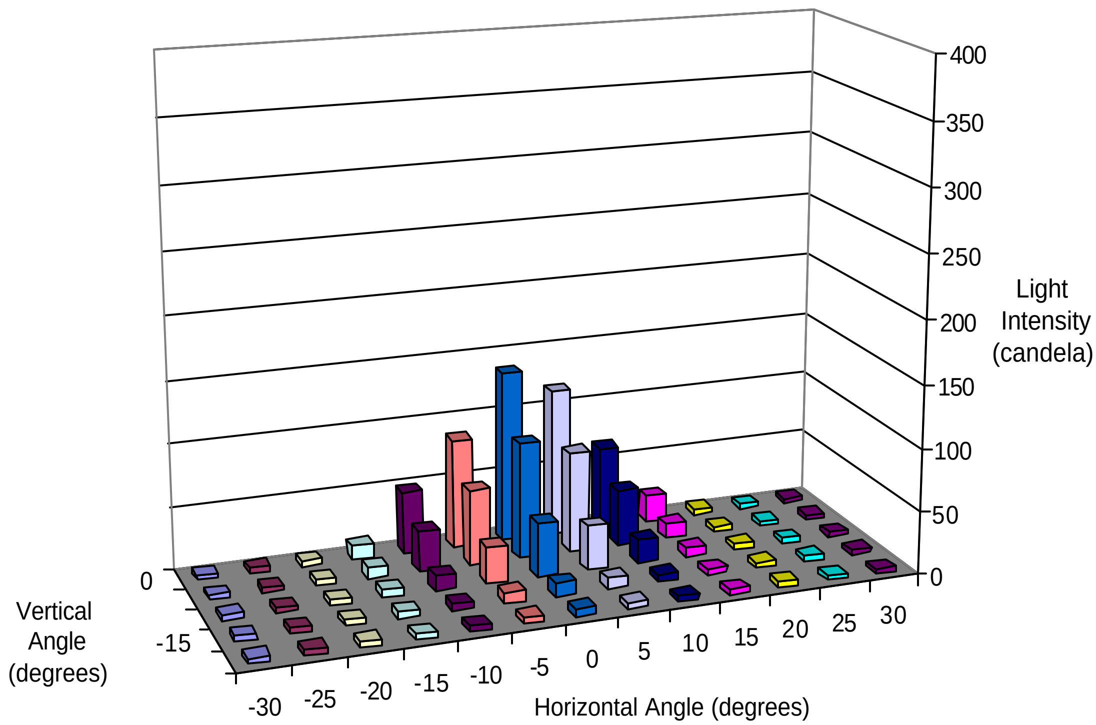

Figure A1.4.6a Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, TC test.

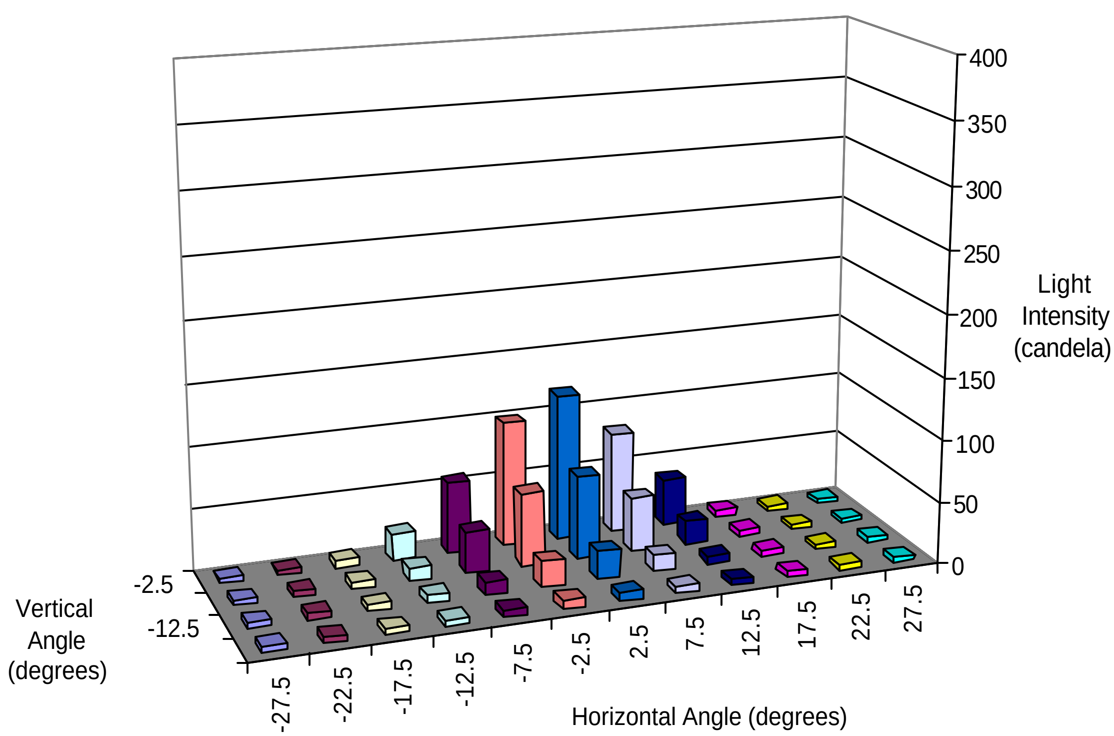

Figure A1.4.6b Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, ITE test.

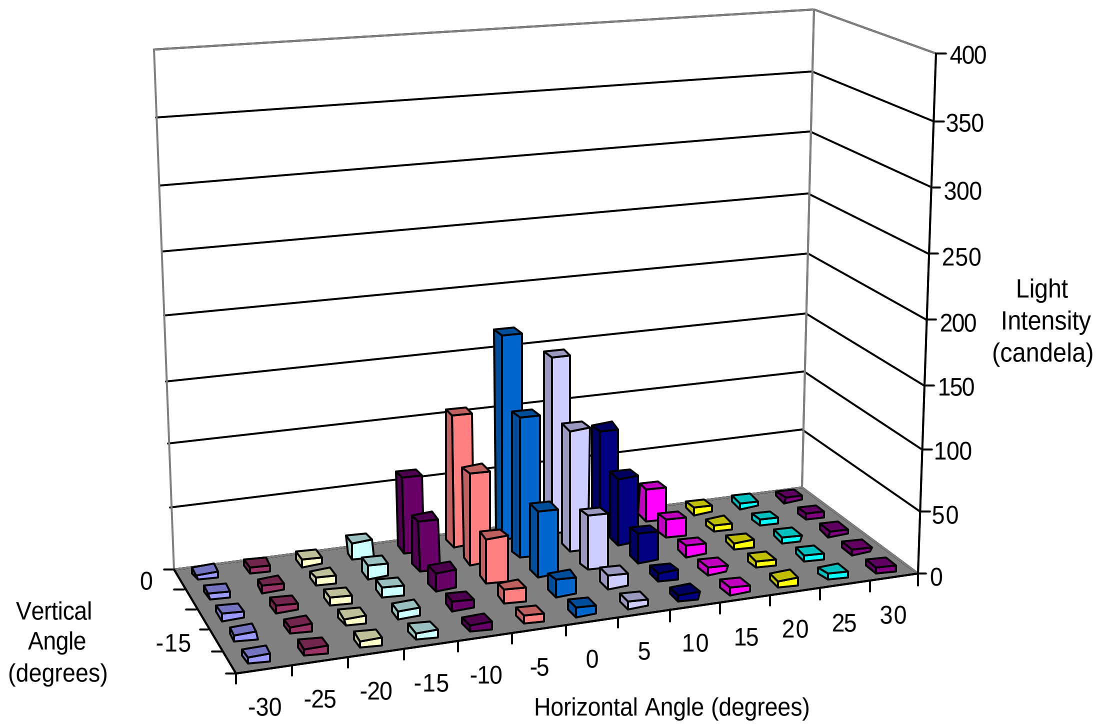

Figure A1.4.7a Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, TC test.

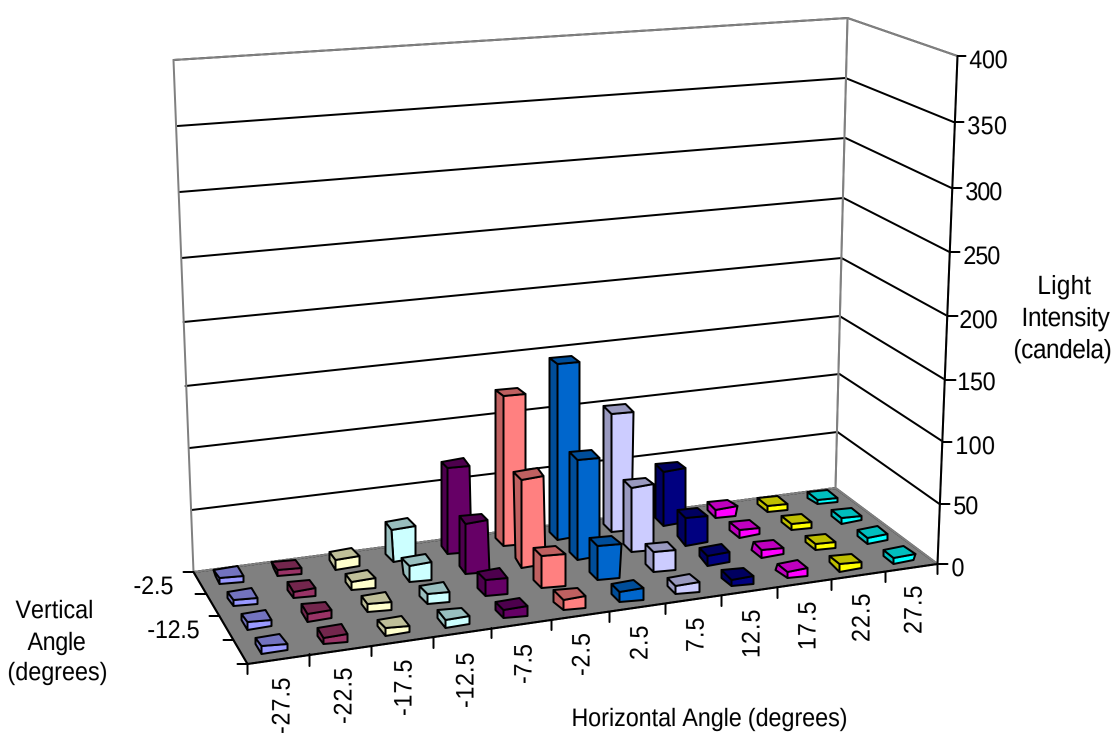

Figure A1.4.7b Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, ITE test.

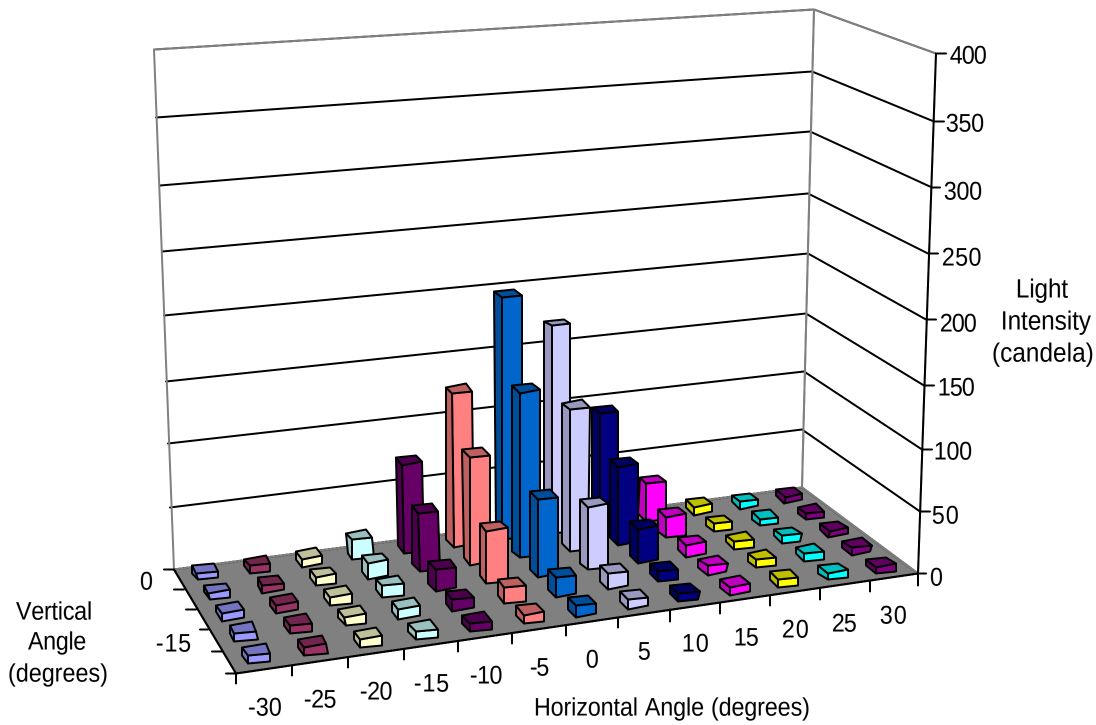

Figure A1.4.8a Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, TC test.

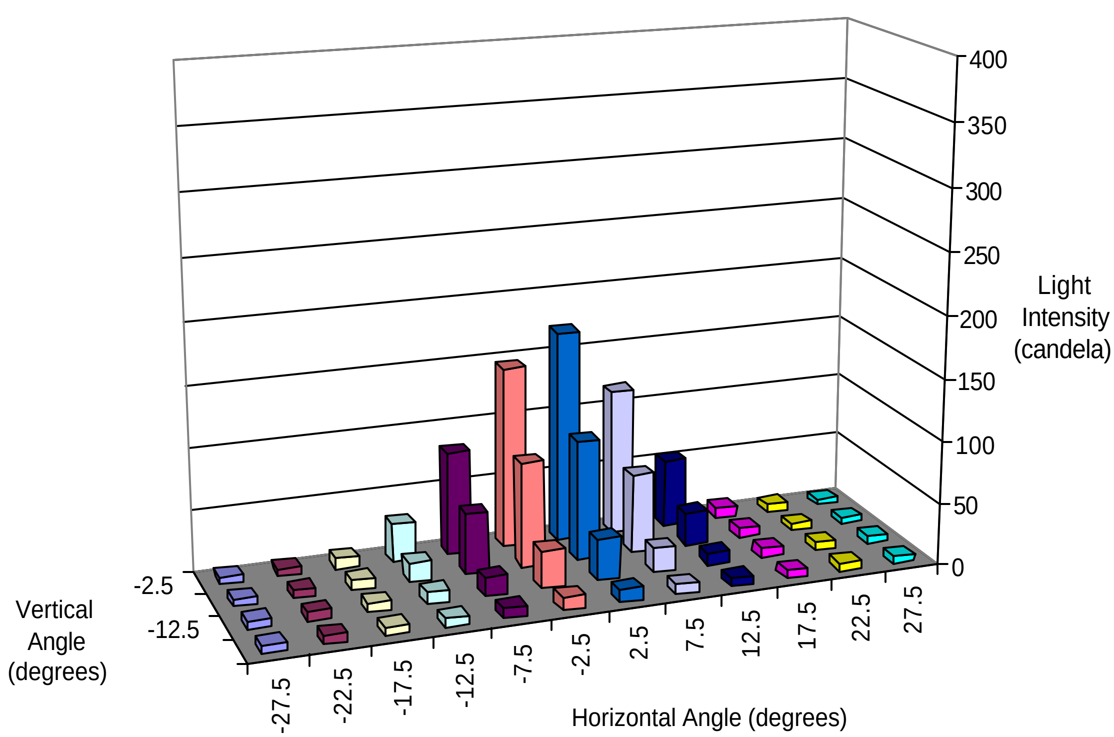

Figure A1.4.8b Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, ITE test.

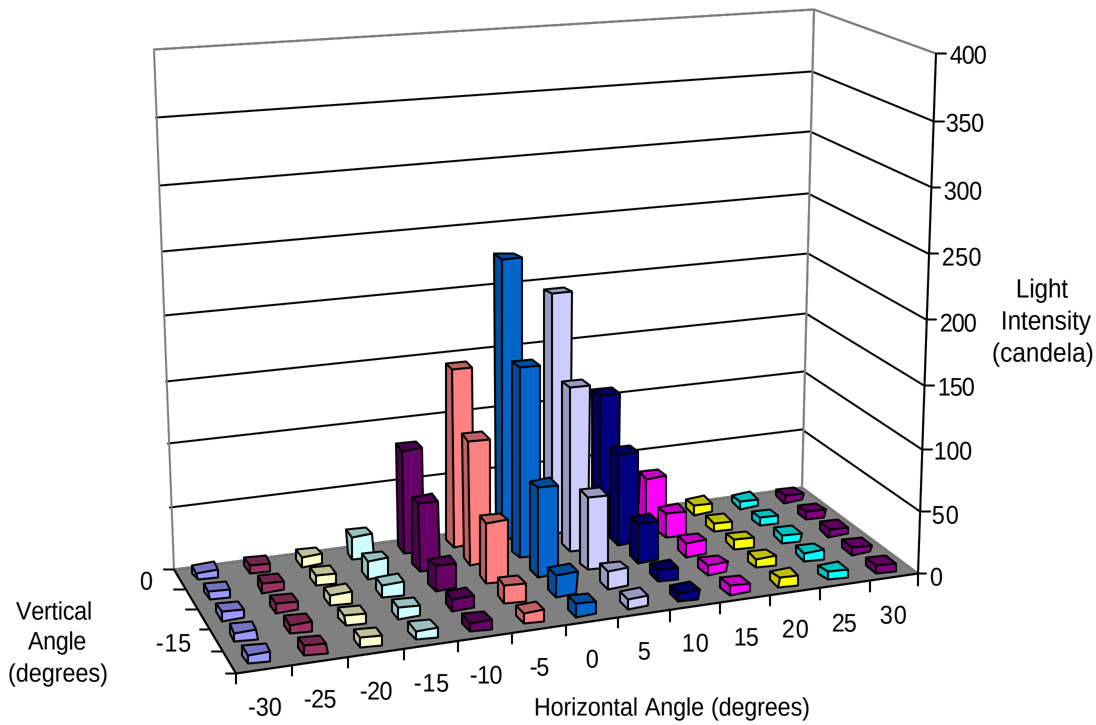

Figure A1.4.9a Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, TC test.

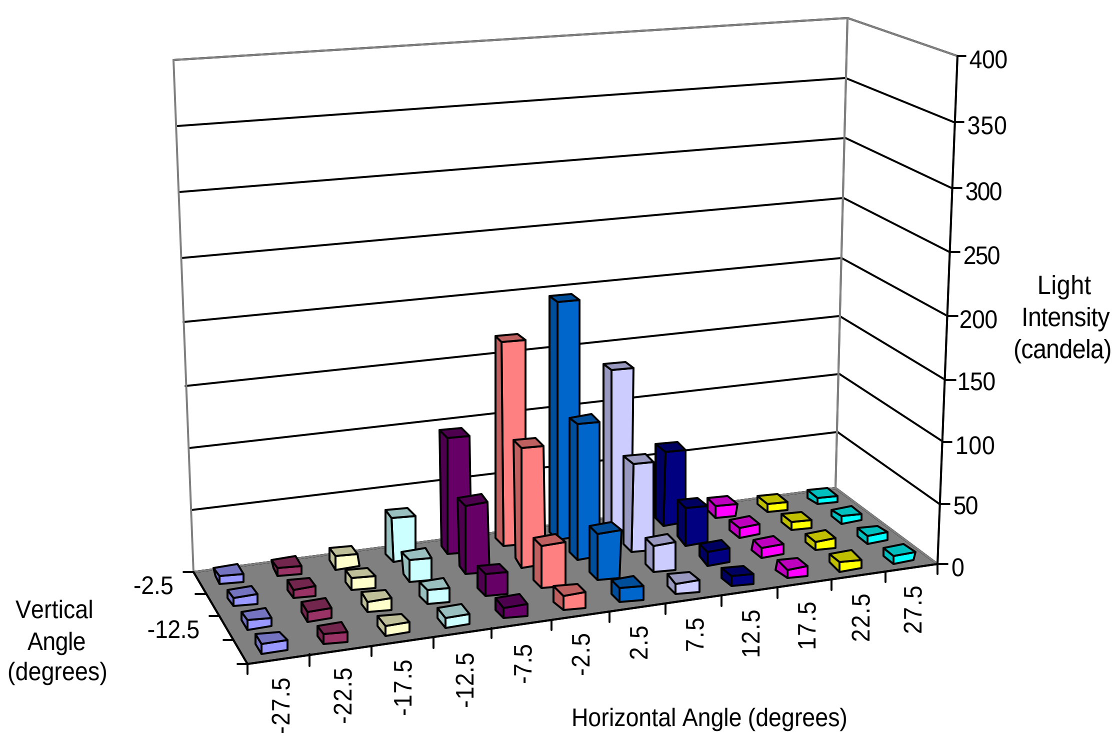

Figure A1.4.9b Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, ITE test.

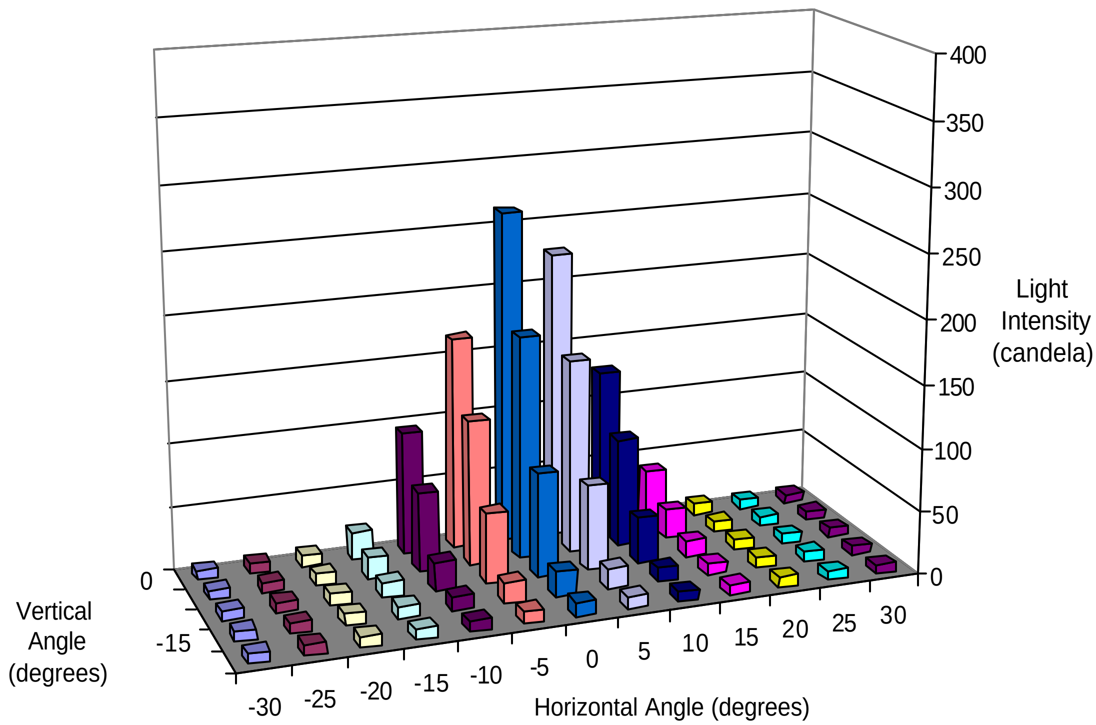

Figure A1.4.10a Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, TC test.

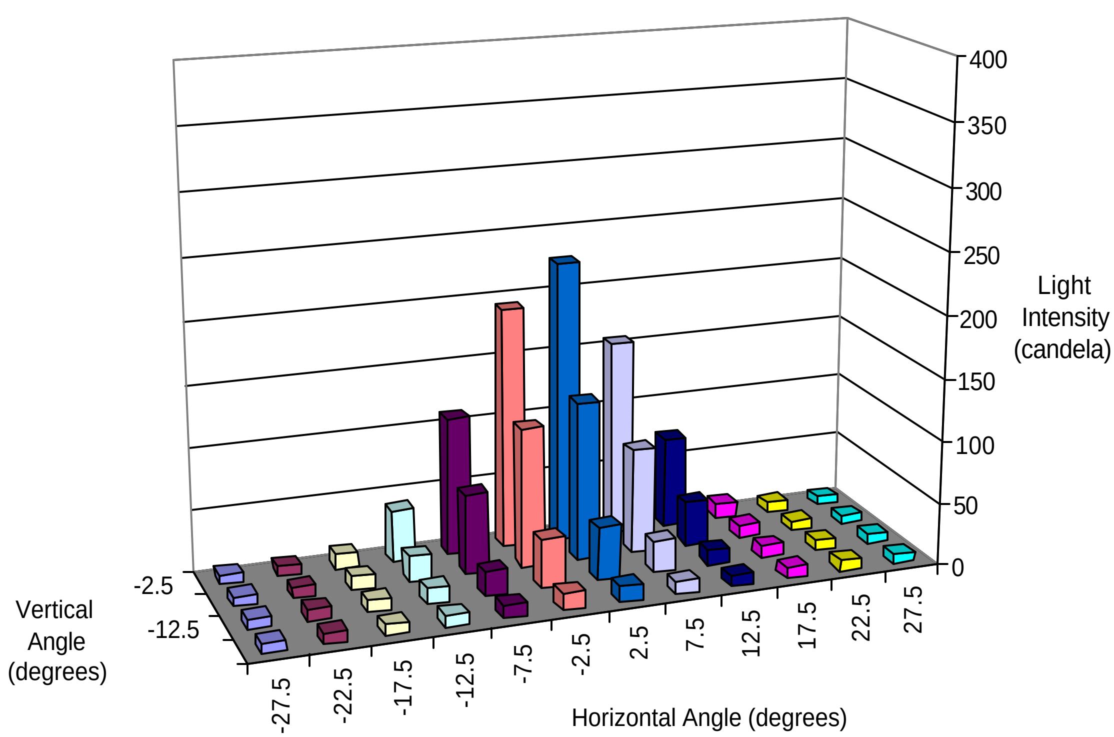

Figure A1.4.10b Output from NPS#1 (Red) signal, 10.0 volts, portion-FEC of signal on/off, ITE test.

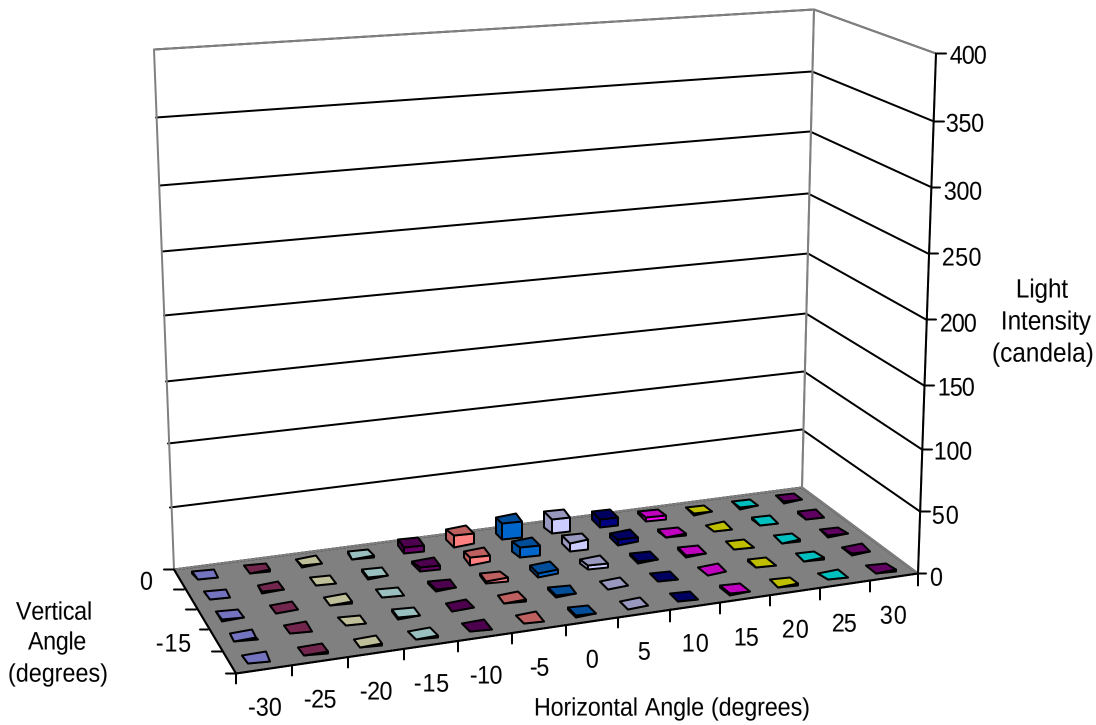

Figure A1.5.1a Output from NPS#1 (Red) signal, 7.0 volts, portion-D3F of signal on/off, TC test.

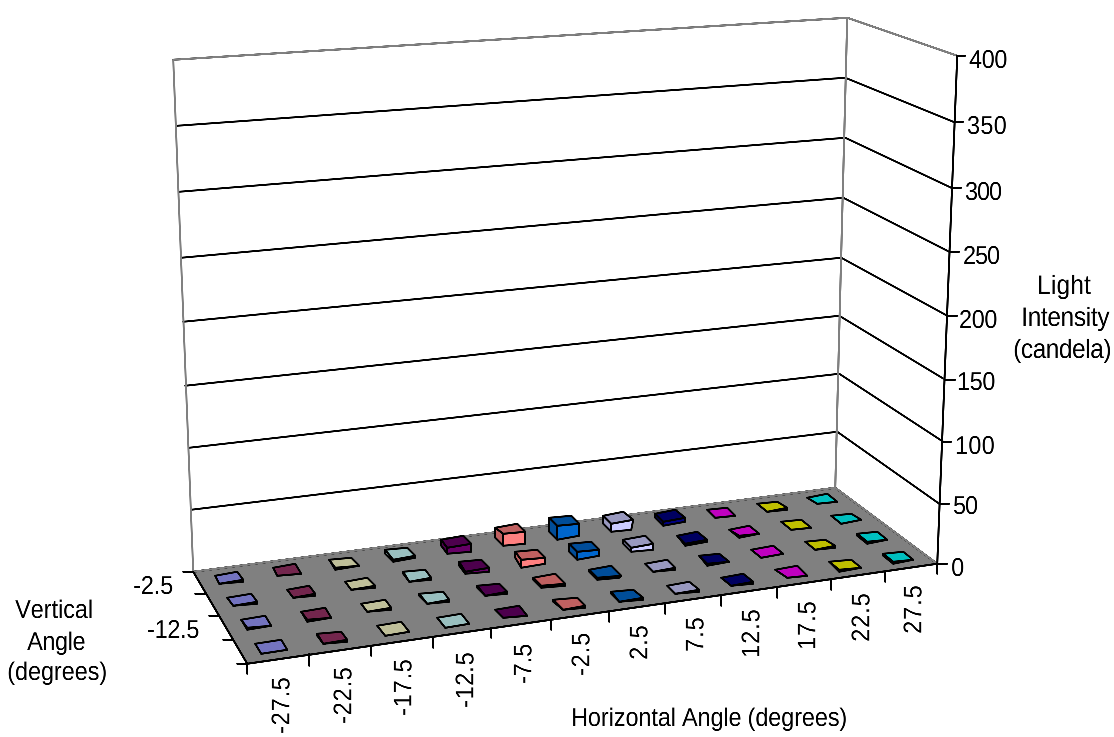

Figure A1.5.1b Output from NPS#1 (Red) signal, 7.0 volts, portion-D3F of signal on/off, ITE test.

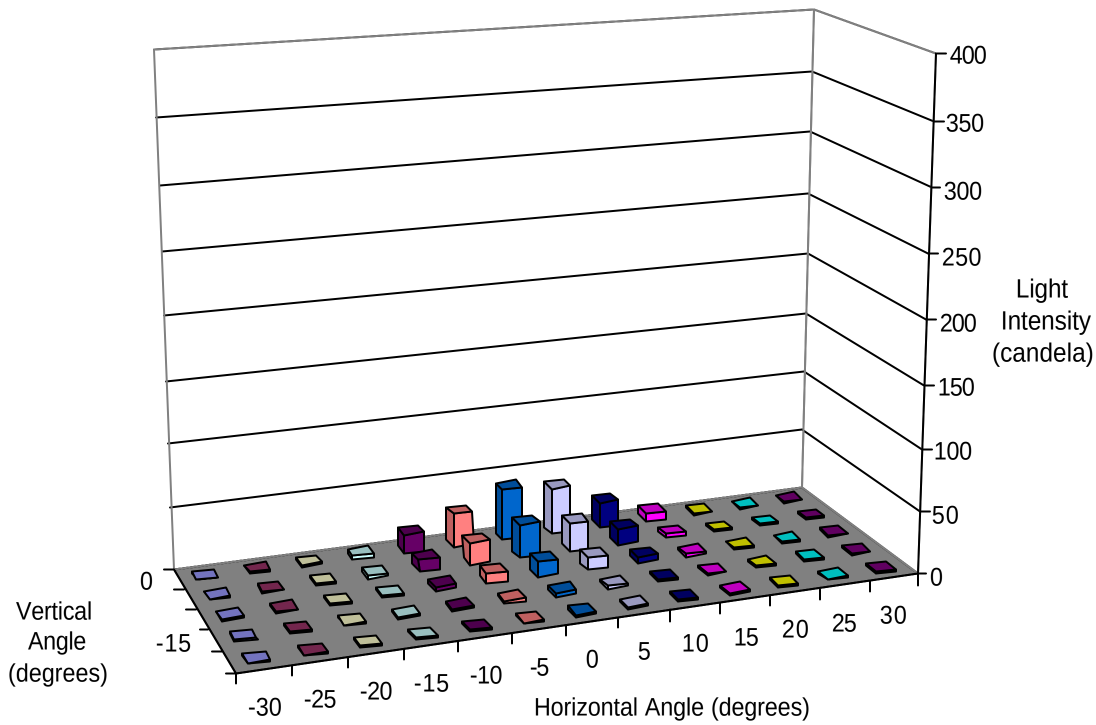

Figure A1.5.2a Output from NPS#1 (Red) signal, 8.0 volts, portion-D3F of signal on/off, TC test.

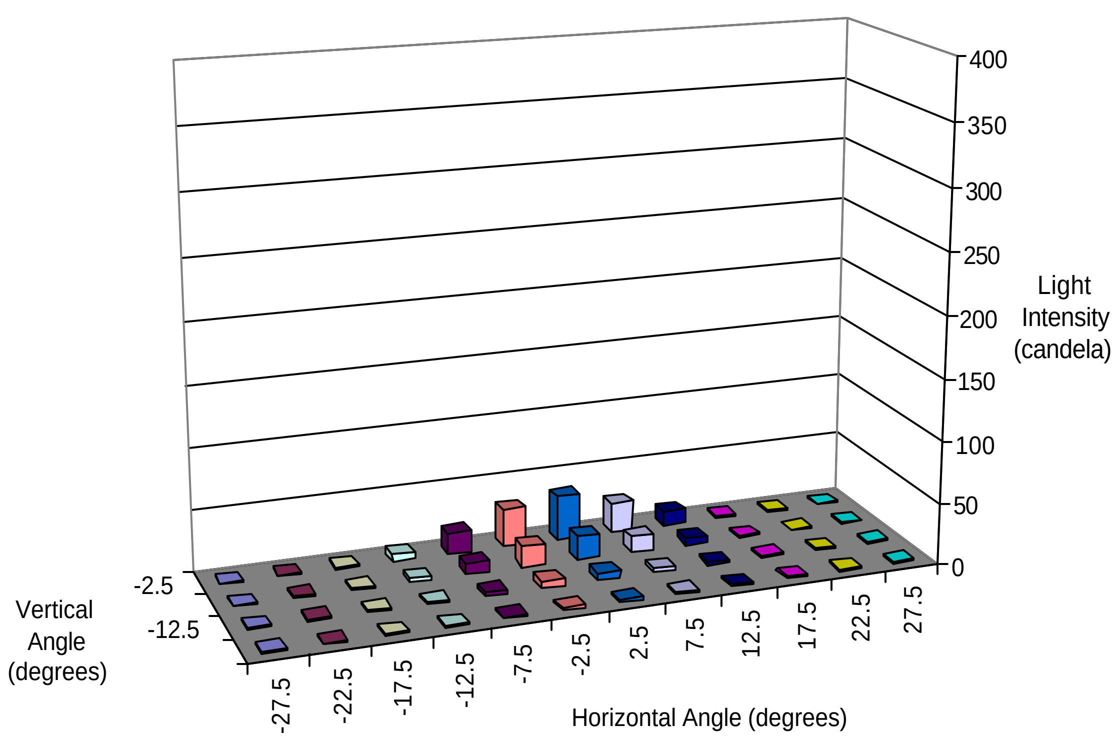

Figure A1.5.2b Output from NPS#1 (Red) signal, 8.0 volts, portion-D3F of signal on/off, ITE test.

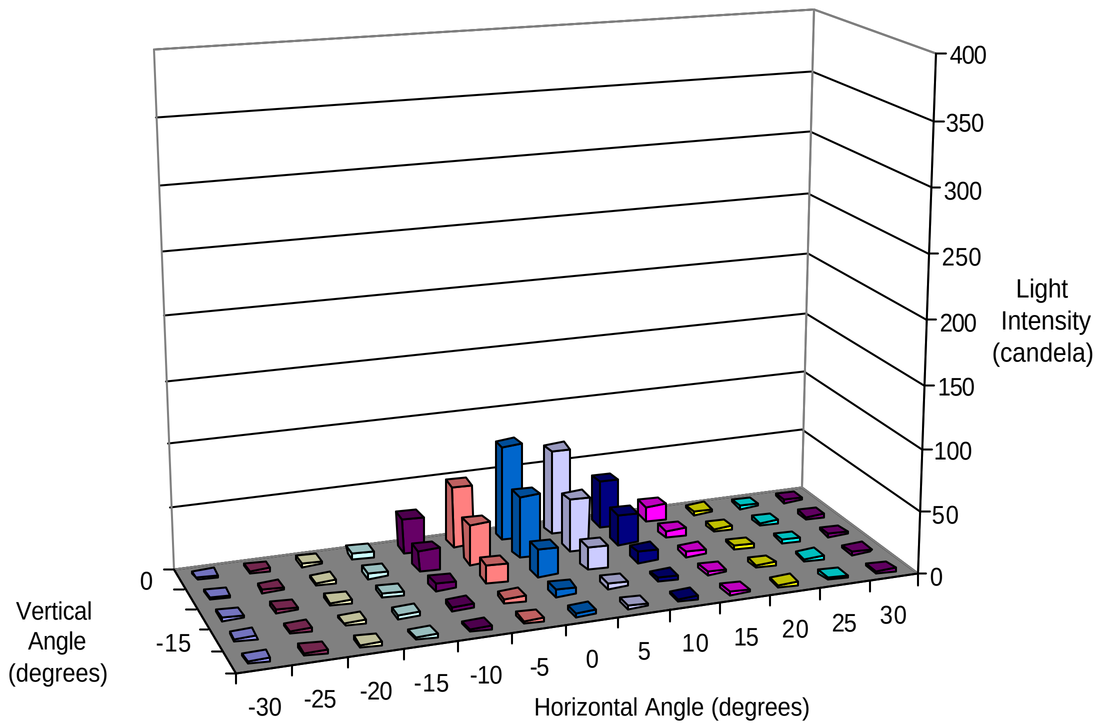

Figure A1.5.3a Output from NPS#1 (Red) signal, 9.0 volts, portion-D3F of signal on/off, TC test.

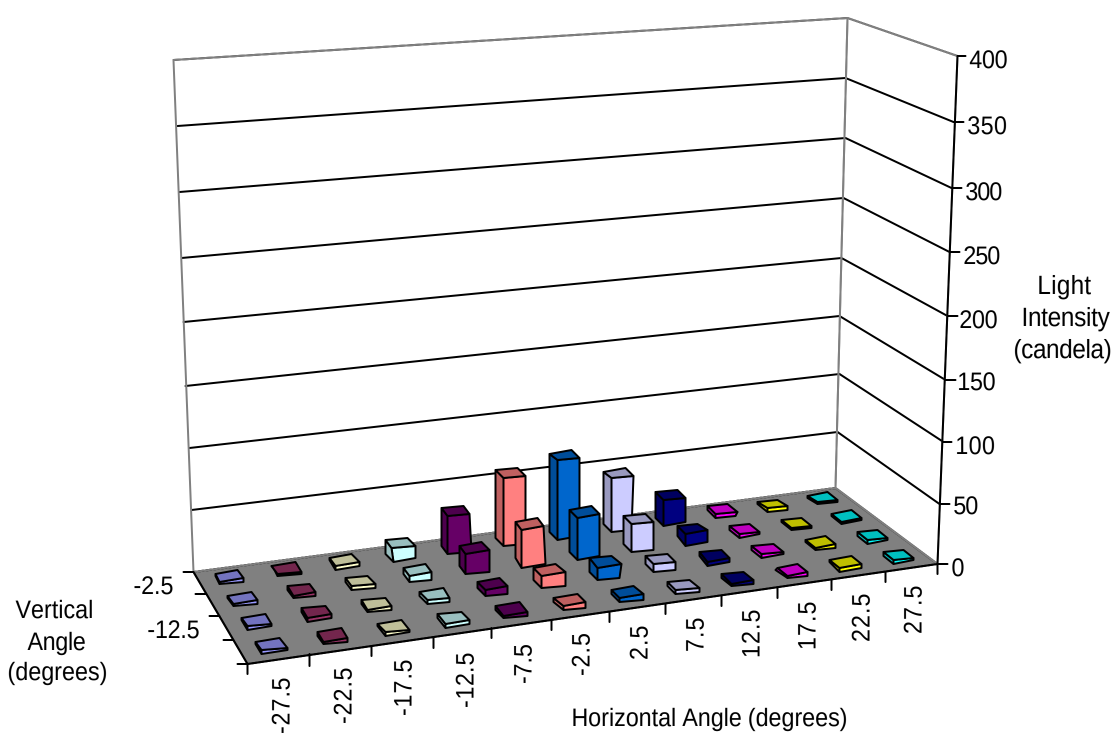

Figure A1.5.3b Output from NPS#1 (Red) signal, 9.0 volts, portion-D3F of signal on/off, ITE test.

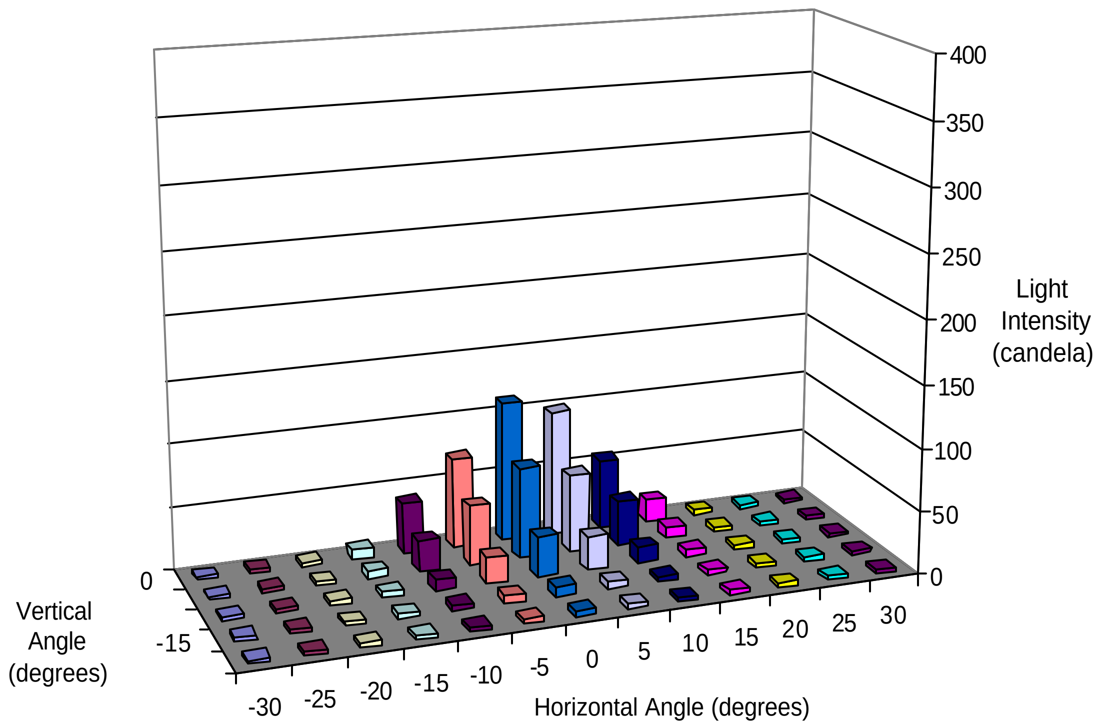

Figure A1.5.4a Output from NPS#1 (Red) signal, 10.0 volts, portion-D3F of signal on/off, TC test.

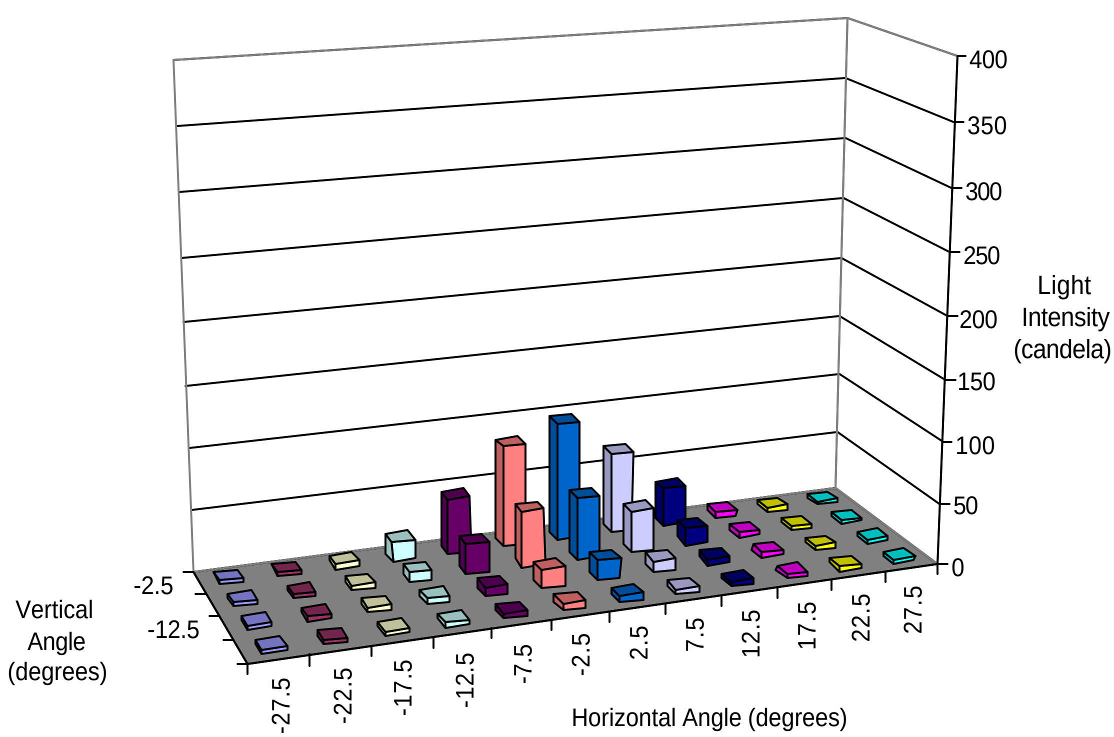

Figure A1.5.4b Output from NPS#1 (Red) signal, 10.0 volts, portion-D3F of signal on/off, ITE test.

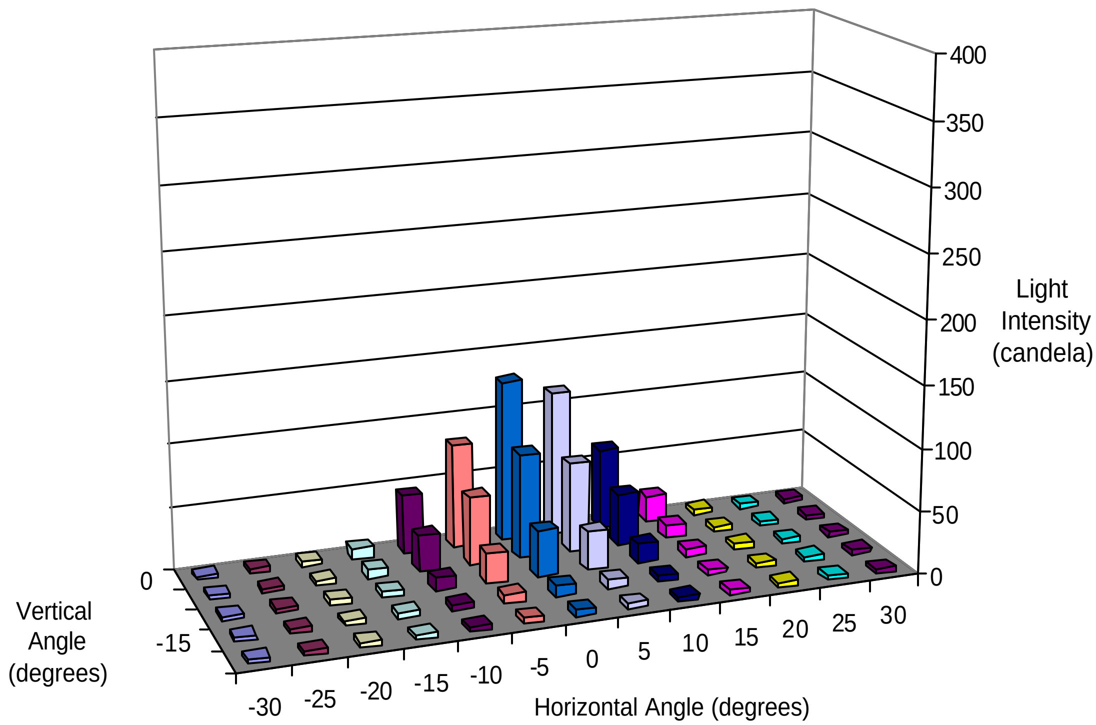

Figure A1.5.5a Output from NPS#1 (Red) signal, 10.5 volts, portion-D3F of signal on/off, TC test.

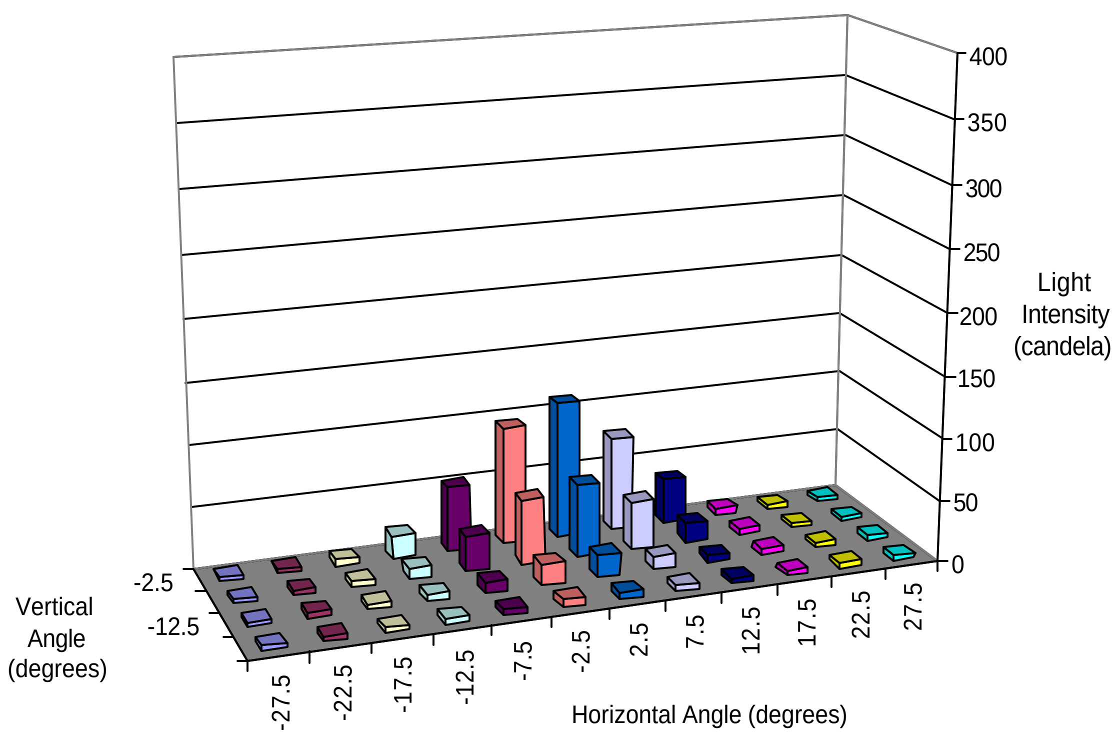

Figure A1.5.5b Output from NPS#1 (Red) signal, 10.5 volts, portion-D3F of signal on/off, ITE test.

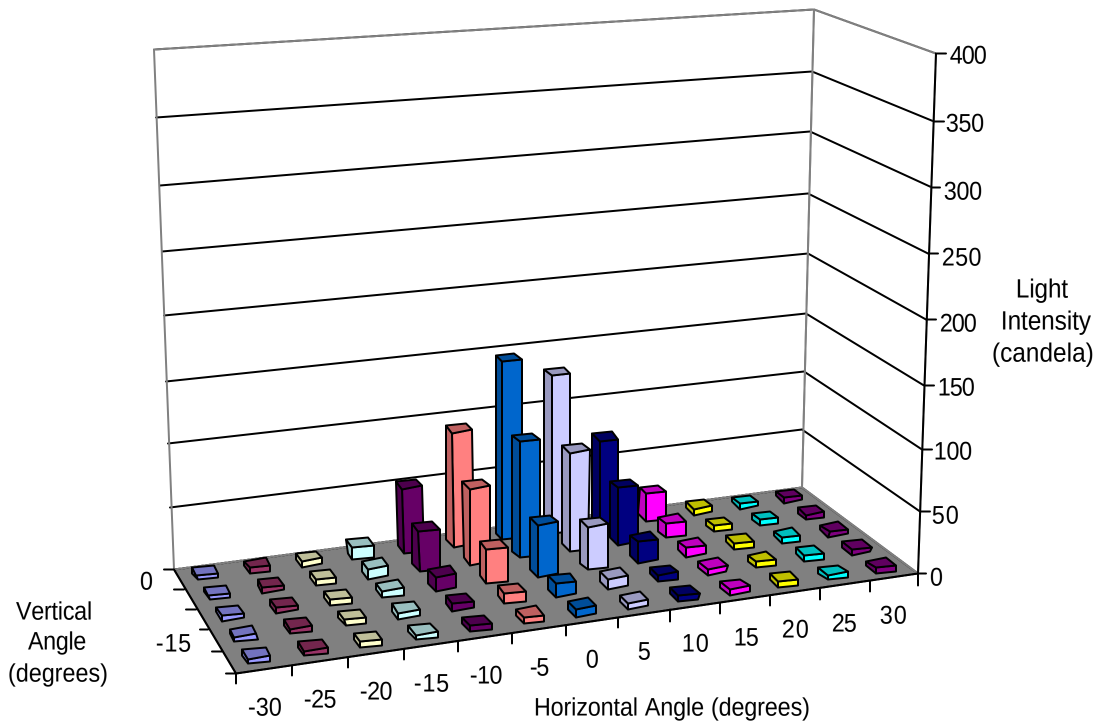

Figure A1.5.6a Output from NPS#1 (Red) signal, 11.0 volts, portion-D3F of signal on/off, TC test.

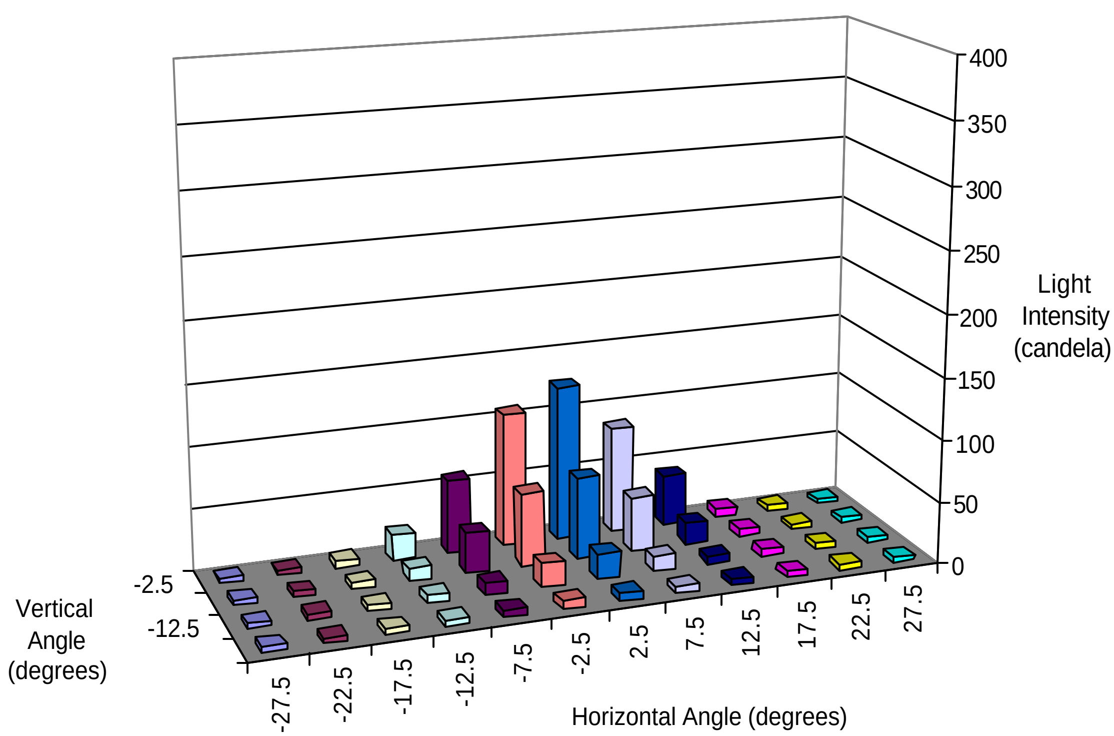

Figure A1.5.6b Output from NPS#1 (Red) signal, 11.0 volts, portion-D3F of signal on/off, ITE test.

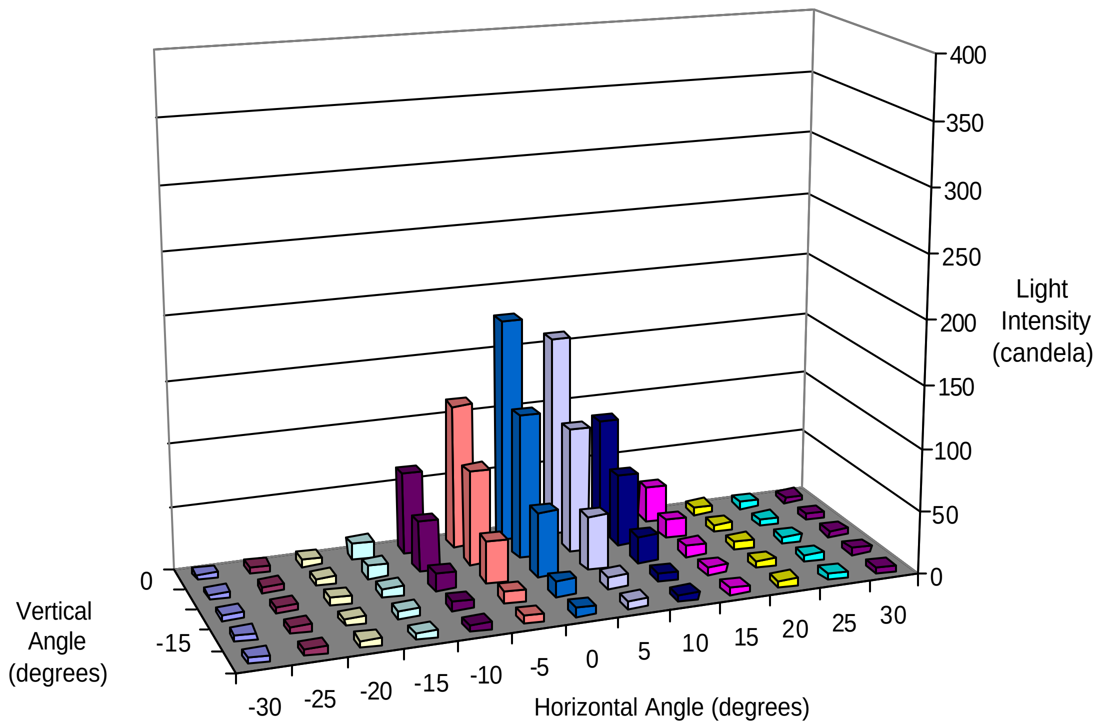

Figure A1.5.7a Output from NPS#1 (Red) signal, 12.0 volts, portion-D3F of signal on/off, TC test.

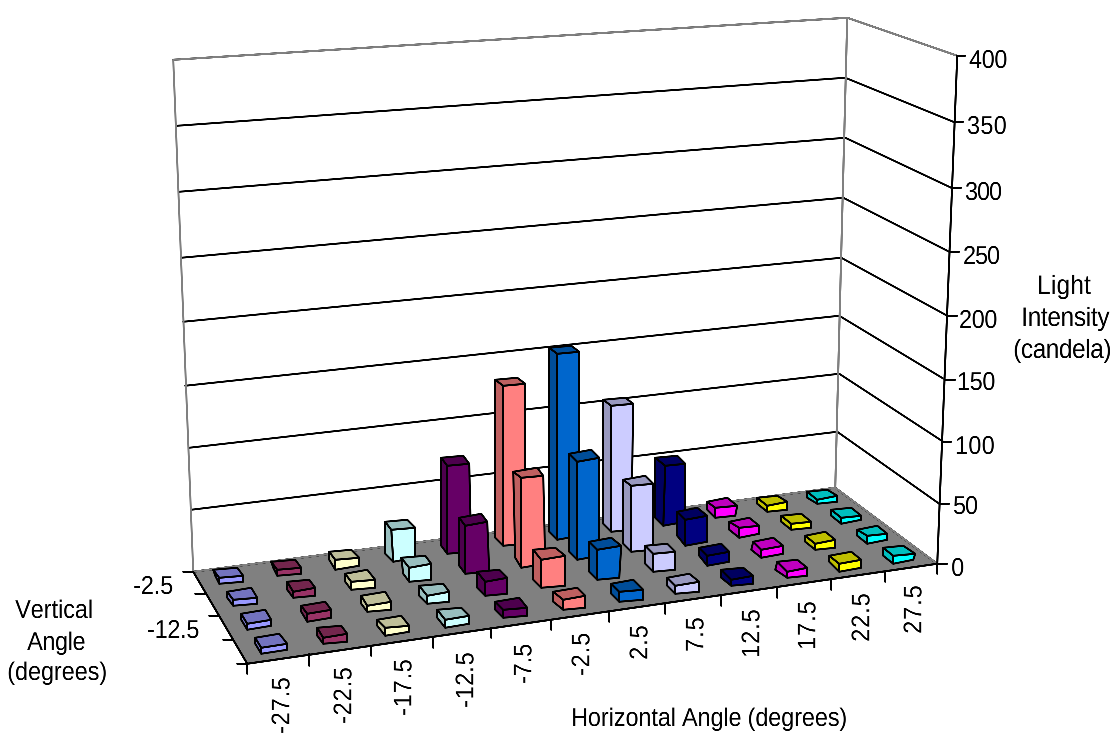

Figure A1.5.7b Output from NPS#1 (Red) signal, 12.0 volts, portion-D3F of signal on/off, ITE test.

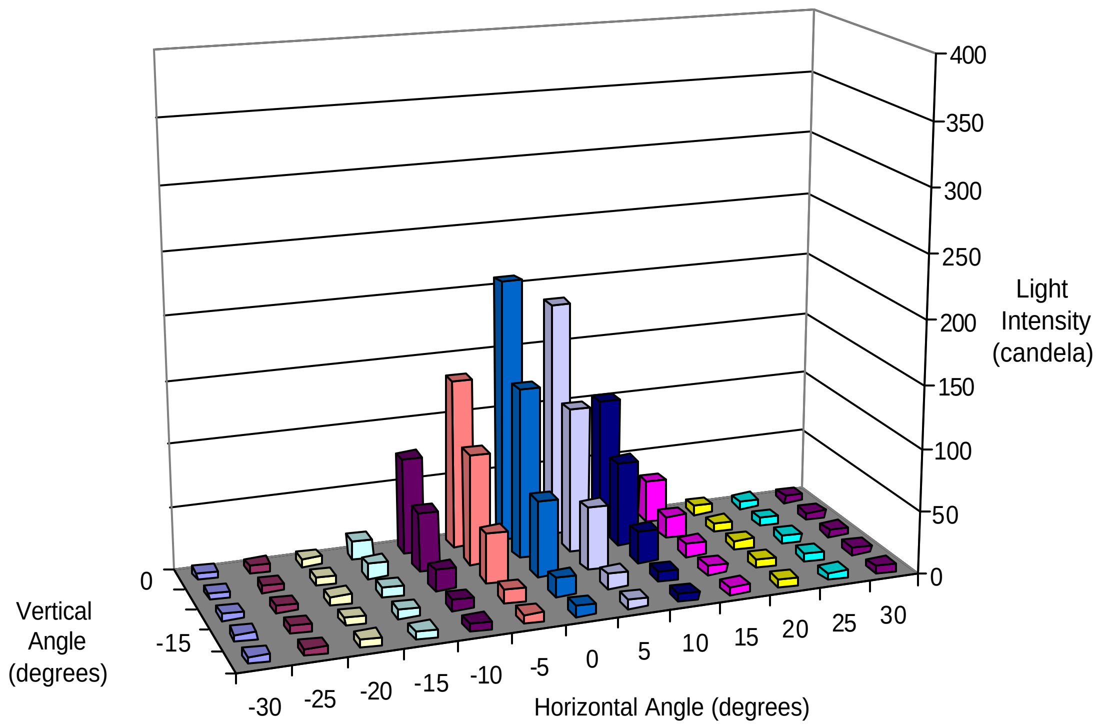

Figure A1.5.8a Output from NPS#1 (Red) signal, 13.0 volts, portion-D3F of signal on/off, TC test.

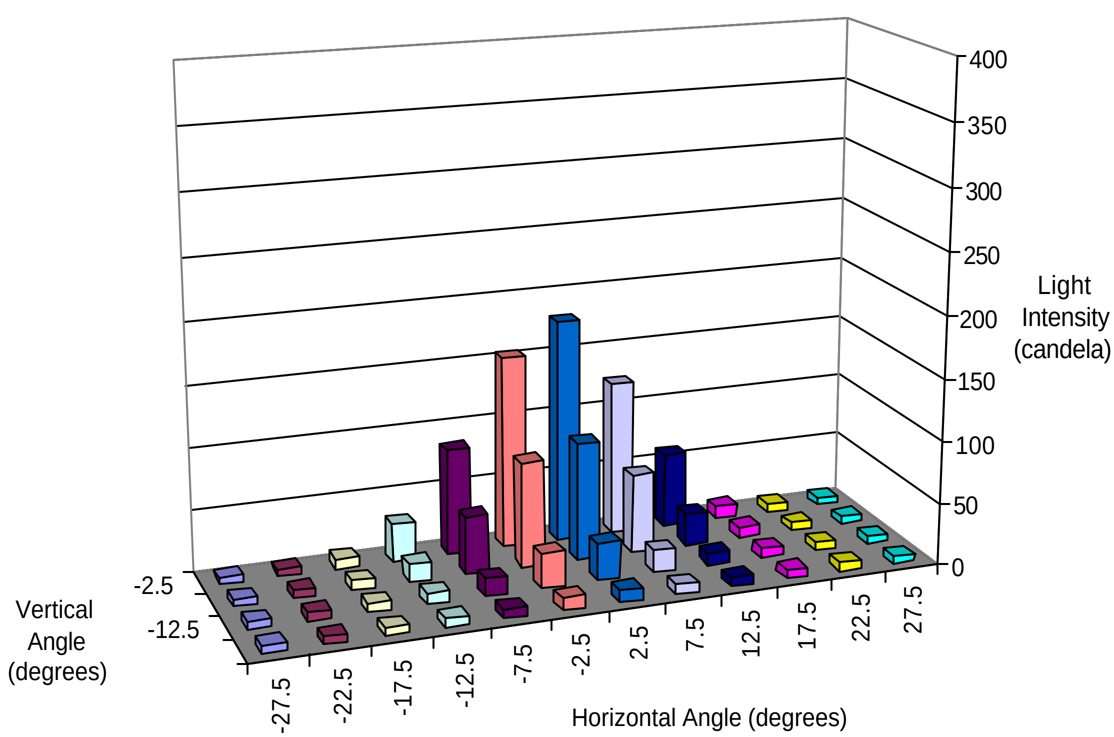

Figure A1.5.8b Output from NPS#1 (Red) signal, 13.0 volts, portion-D3F of signal on/off, ITE test.

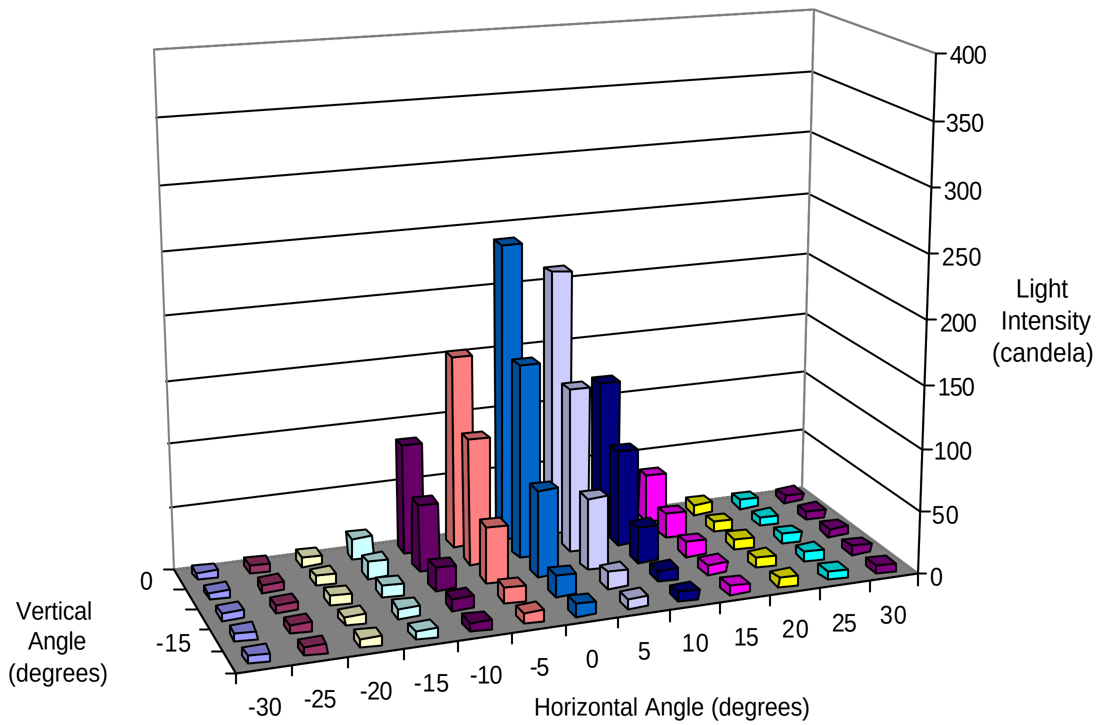

Figure A1.5.9a Output from NPS#1 (Red) signal, 14.0 volts, portion-D3F of signal on/off, TC test.

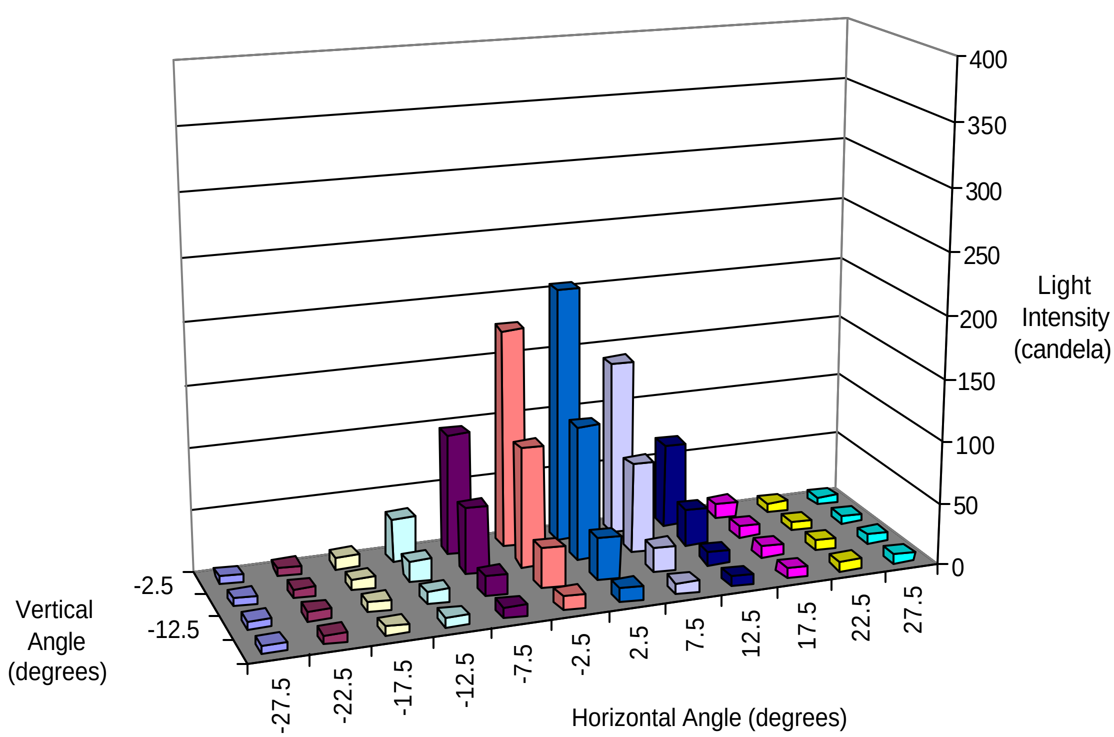

Figure A1.5.9b Output from NPS#1 (Red) signal, 14.0 volts, portion-D3F of signal on/off, ITE test.

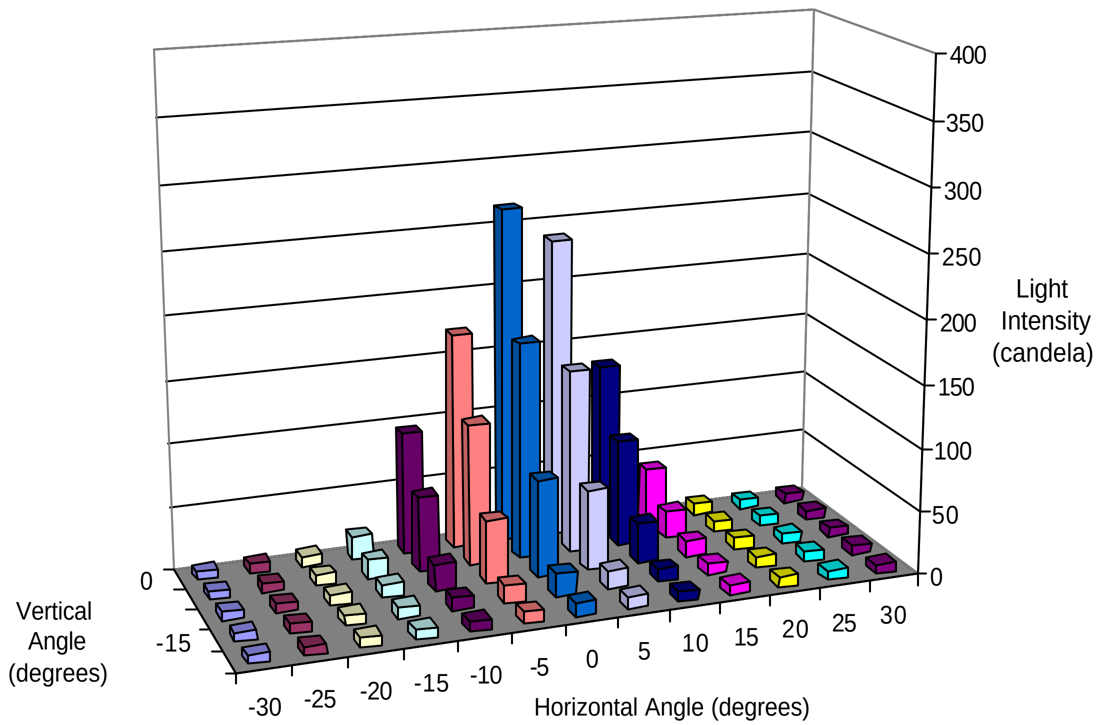

Figure A1.5.10a Output from NPS#1 (Red) signal, 15.0 volts, portion-D3F of signal on/off, TC test.

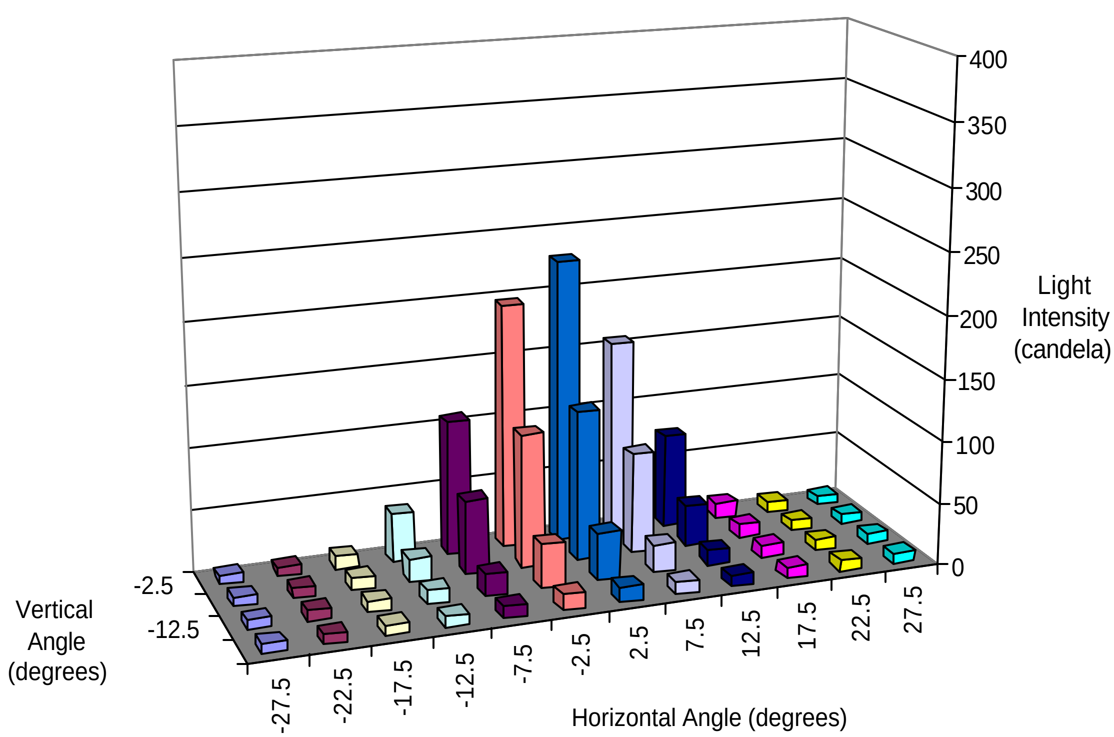

Figure A1.5.10b Output from NPS#1 (Red) signal, 15.0 volts, portion-D3F of signal on/off, ITE test.

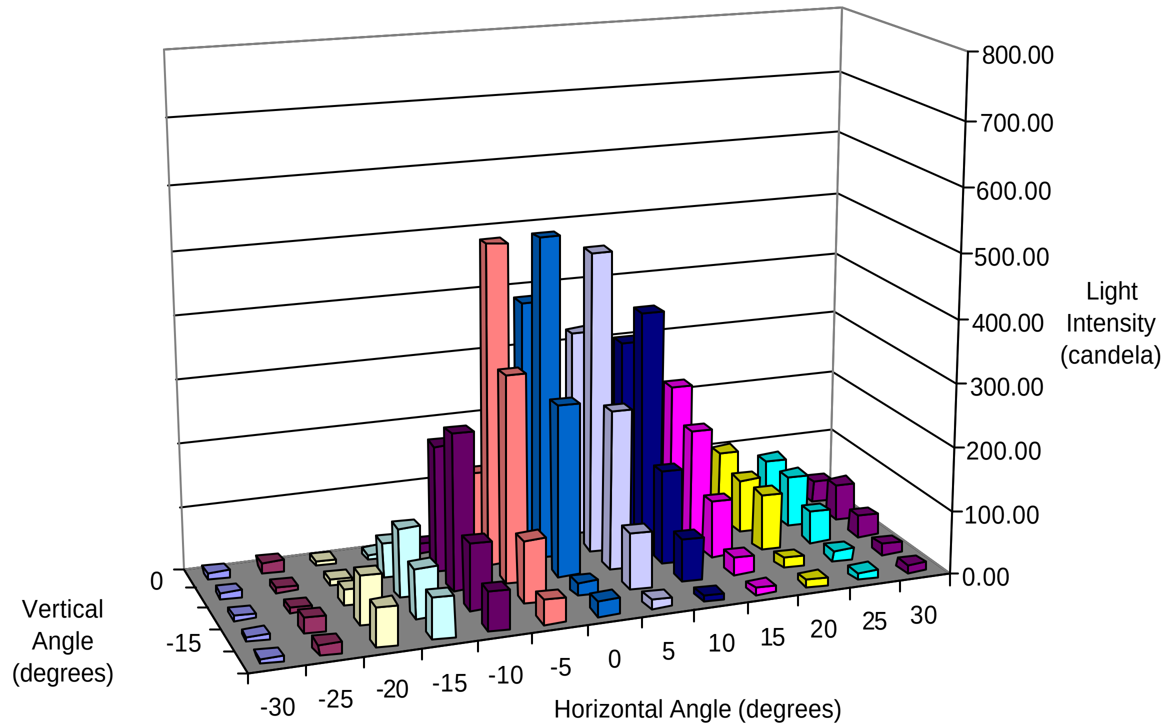

Figure A2.1.1a Output from WPS#2 (Red) signal, 10.5 volts, portion-FFF of signal on/off, TC test.

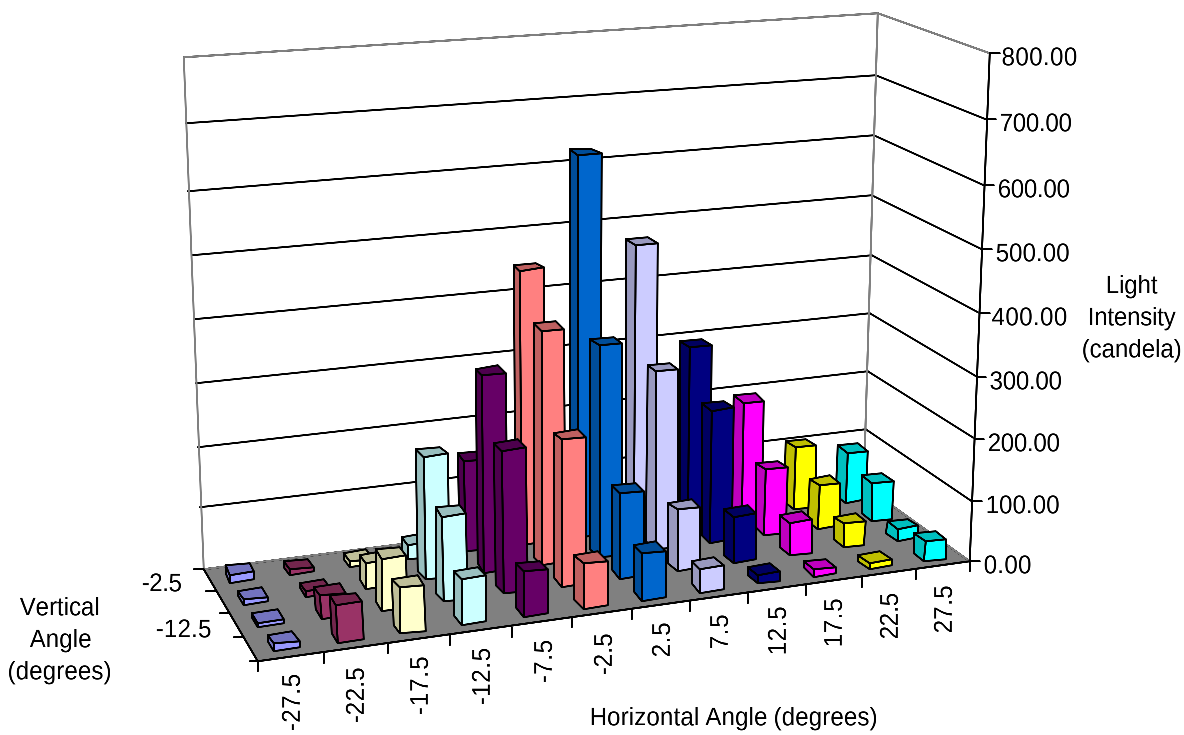

Figure A2.1.1b Output from WPS#2 (Red) signal, 10.5 volts, portion-FFF of signal on/off, ITE test.

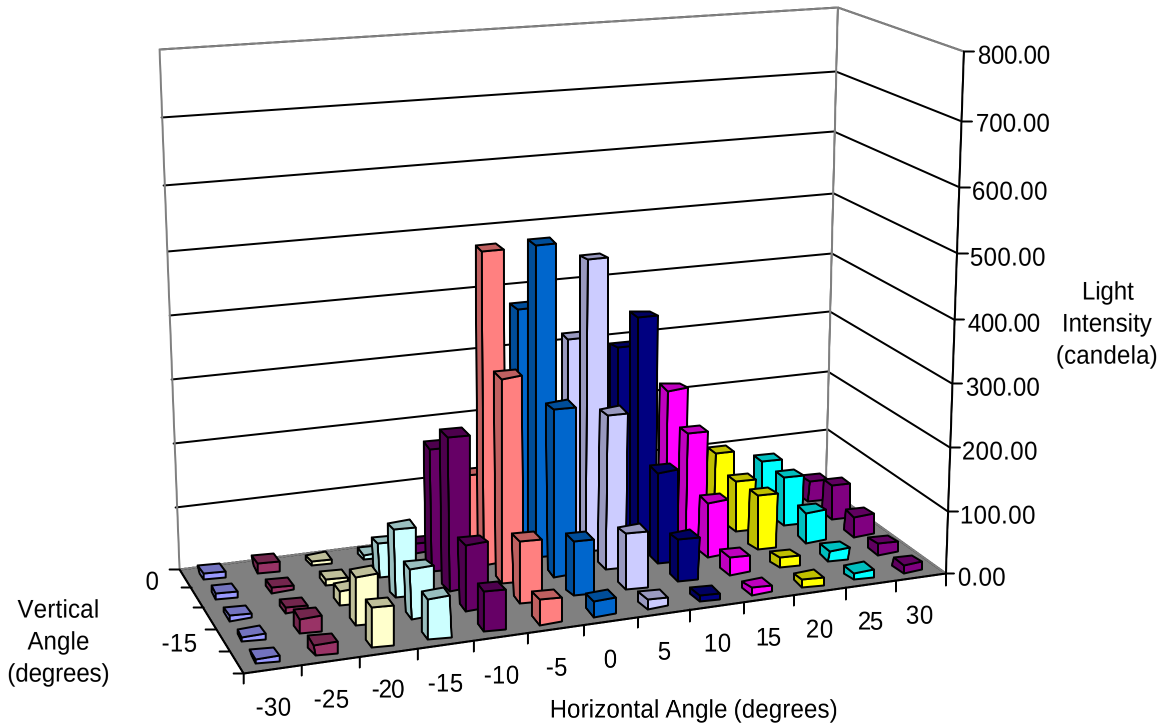

Figure A2.1.2a Output from WPS#2 (Red) signal, 12.0 volts, portion-FFF signal on/off, TC test.

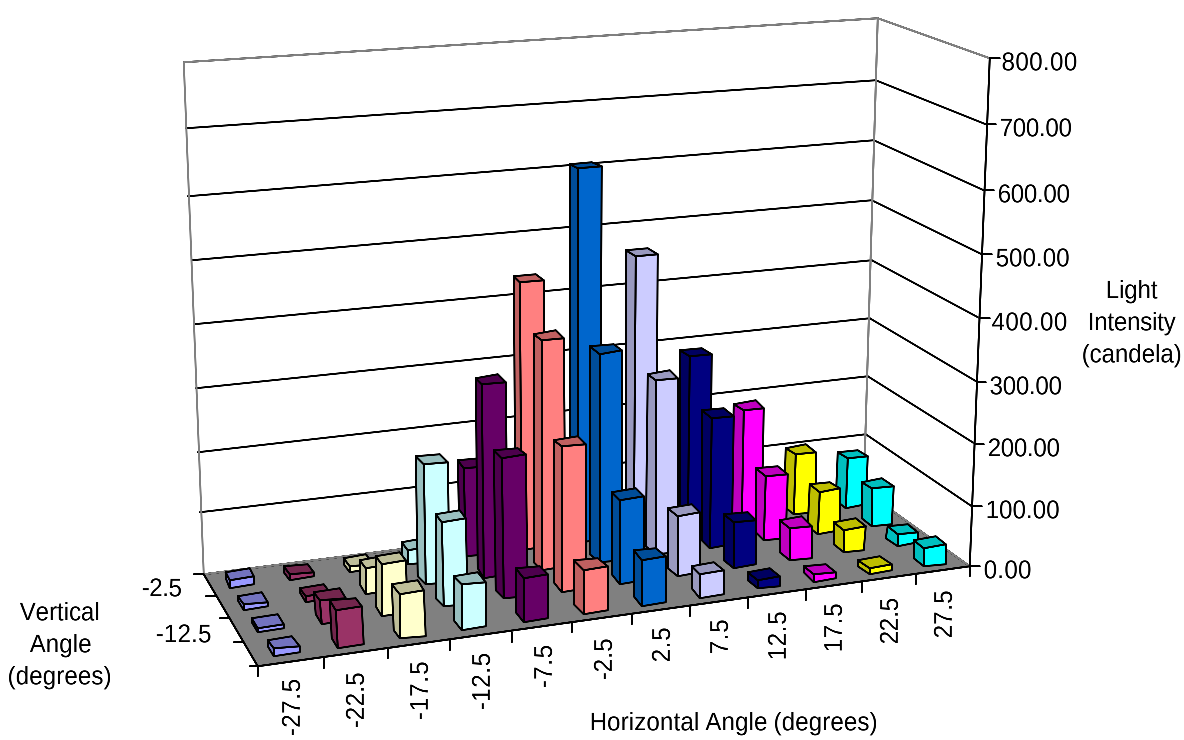

Figure A2.1.2b Output from WPS#2 (Red) signal, 12.0 volts, portion-FFF signal on/off, ITE test.

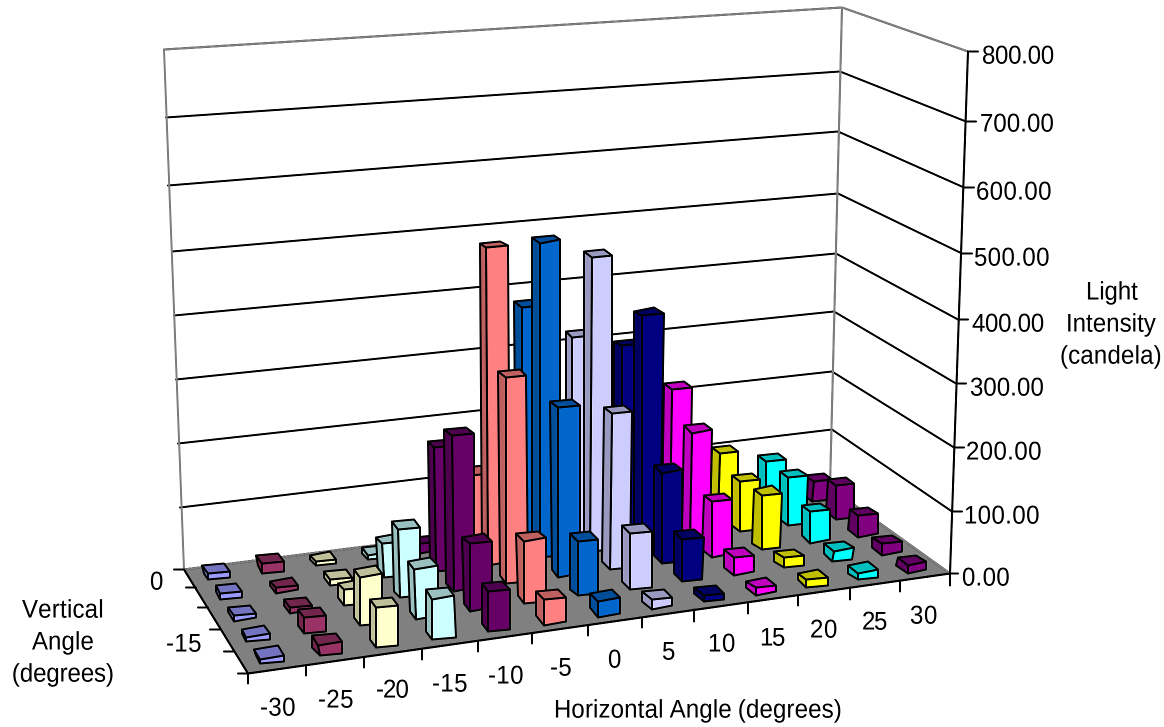

Figure A2.1.3a Output from WPS#2 (Red) signal, 9.0 volts, portion-FFF signal on/off, TC test.

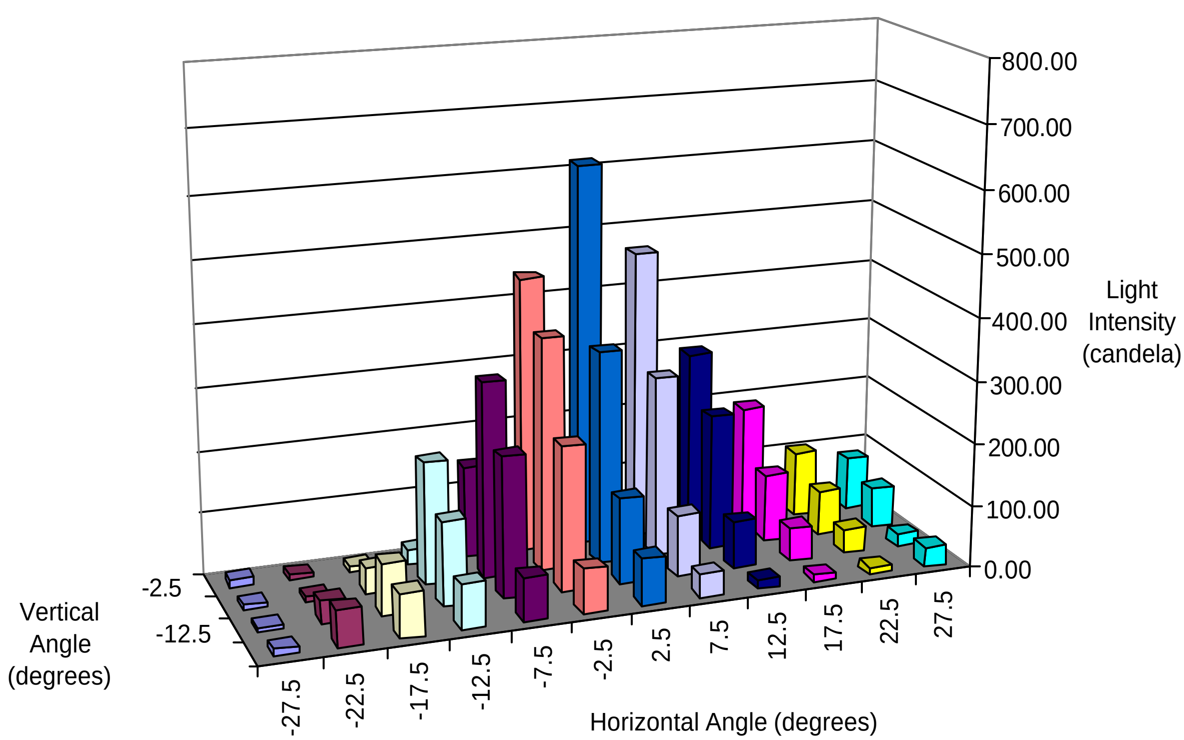

Figure A2.1.3b Output from WPS#2 (Red) signal, 9.0 volts, portion-FFF signal on/off, ITE test.

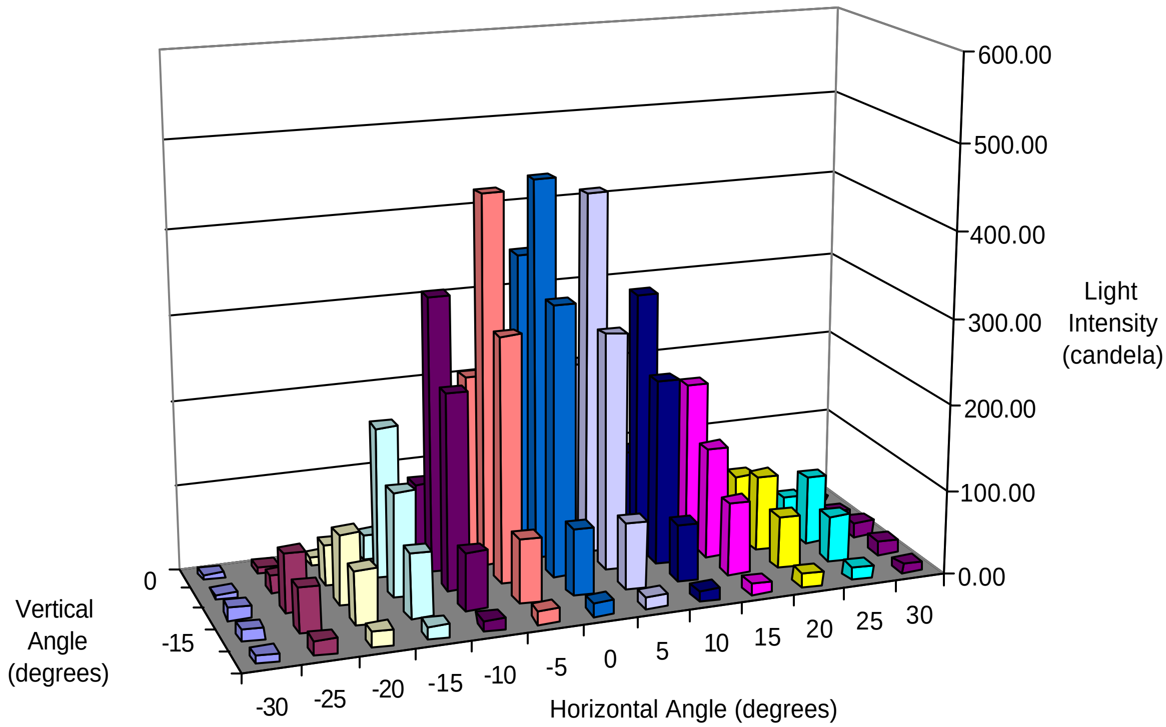

Figure A2.2.1a Output from WPS#2 (Red) signal, 10.5 volts, all elements on, TC test.

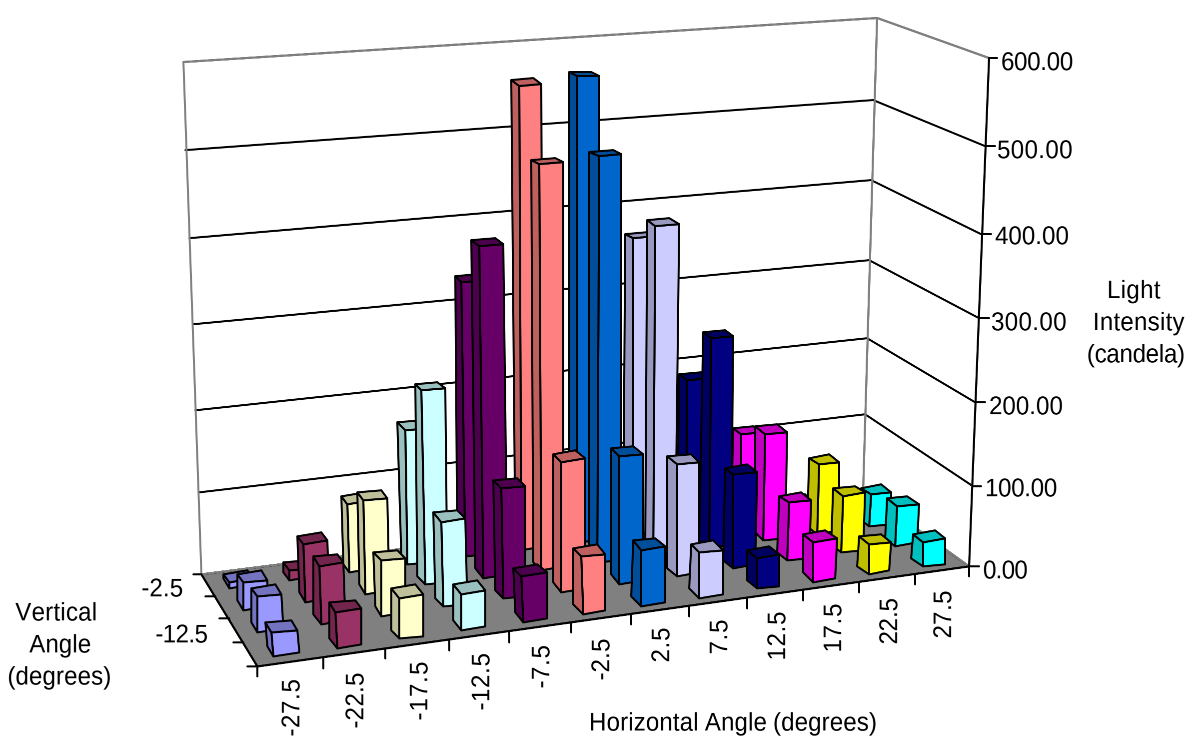

Figure A2.2.1b Output from WPS#2 (Red) signal, 10.5 volts, all elements on, ITE test.

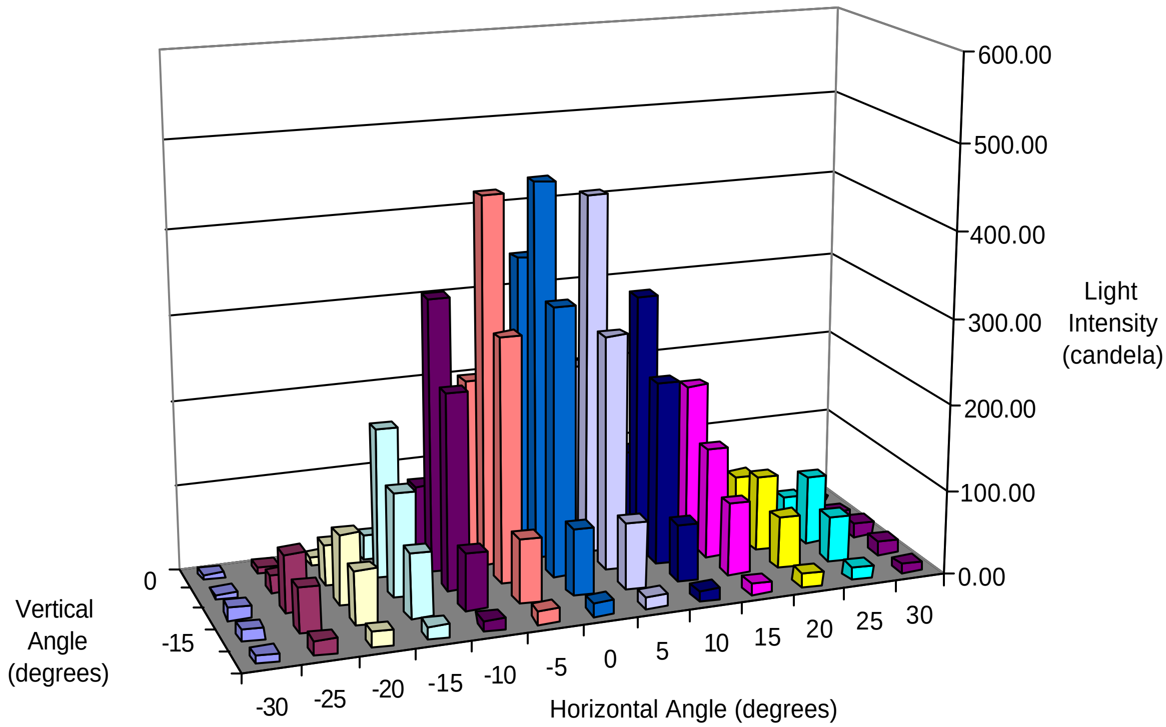

Figure A2.2.2a Output from WPS#2 (Red) signal, 10.5 volts, 191 elements (97.0% on), TC test.

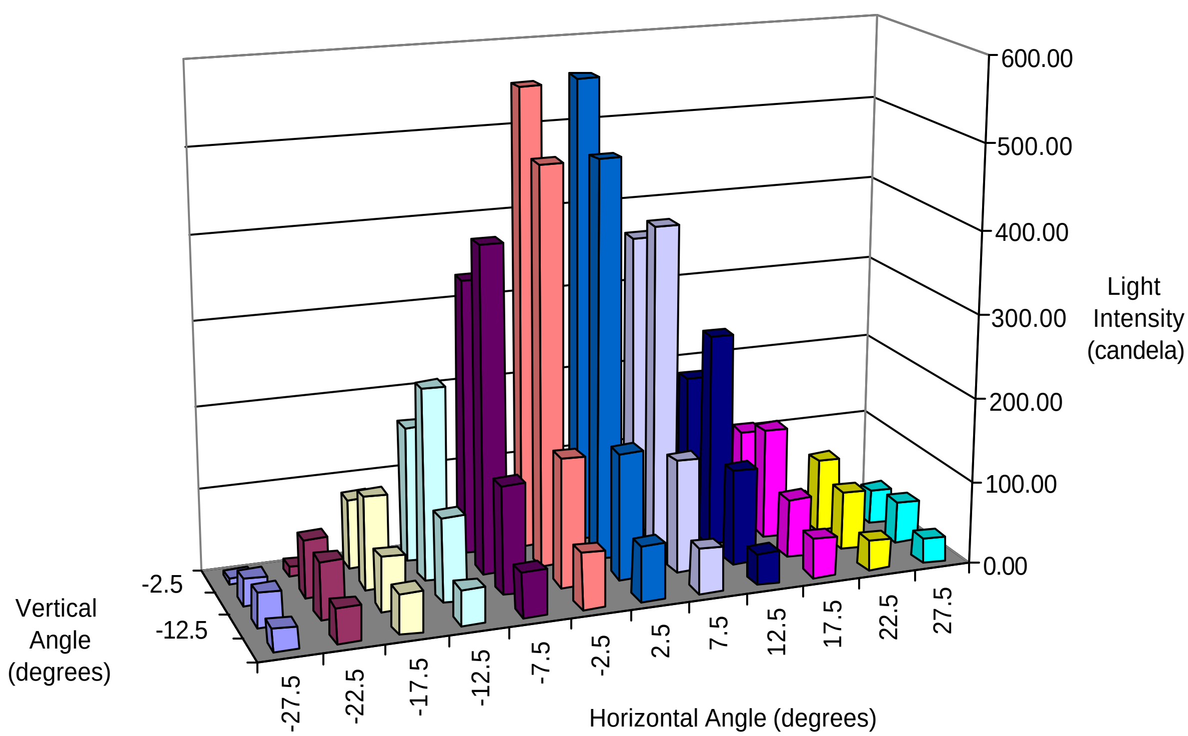

Figure A2.2.2b Output from WPS#2 (Red) signal, 10.5 volts, 191 elements (97.0% on), ITE test.

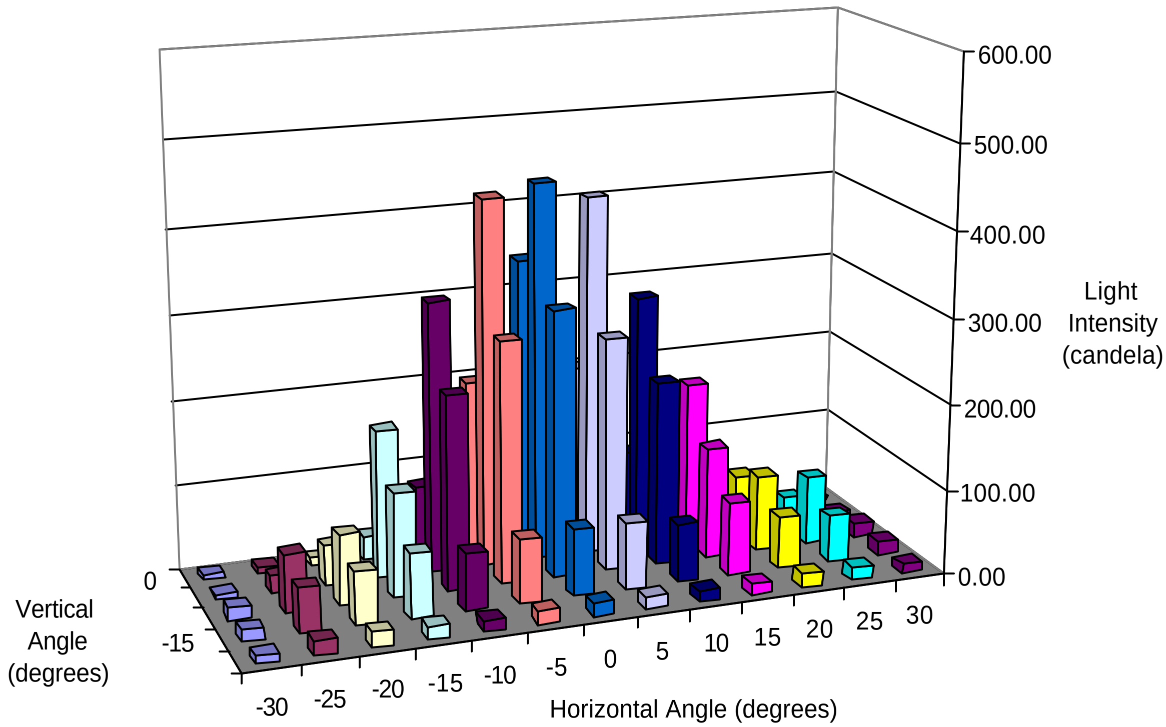

Figure A2.2.3a Output from WPS#2 (Red) signal, 10.5 volts, 186 elements (94.0% on), TC test.

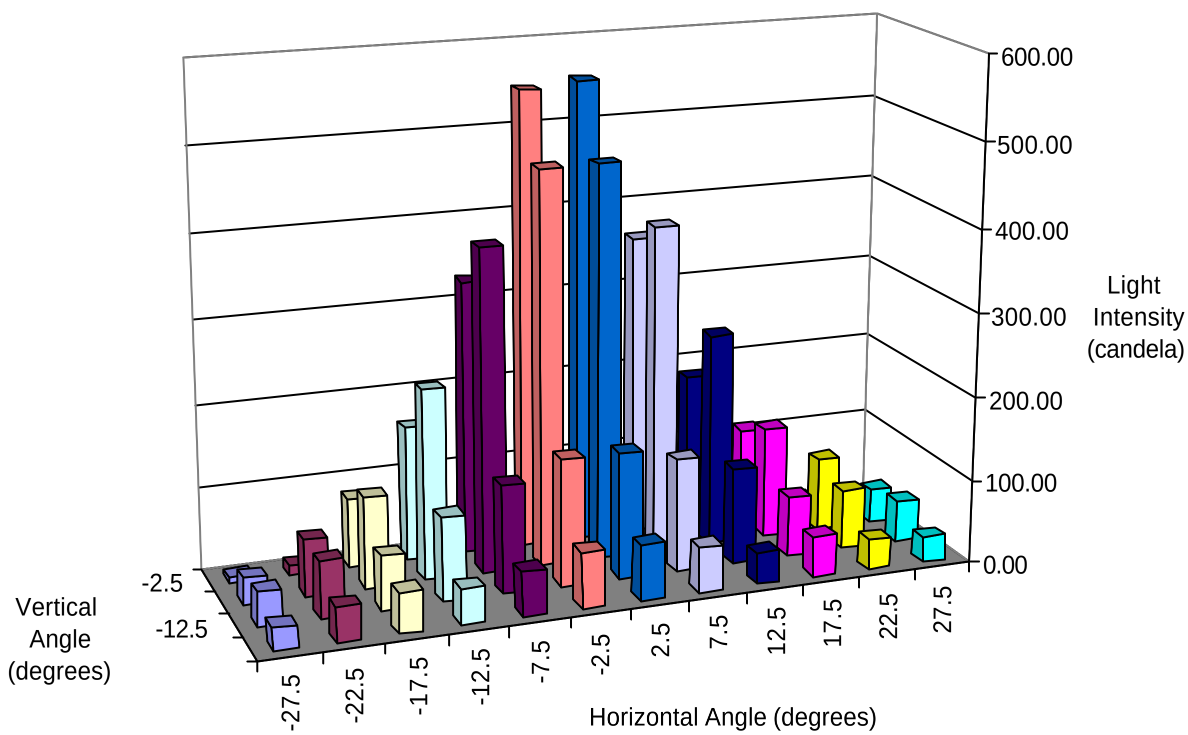

Figure A2.2.3b Output from WPS#2 (Red) signal, 10.5 volts, 186 elements (94.0% on), ITE test.

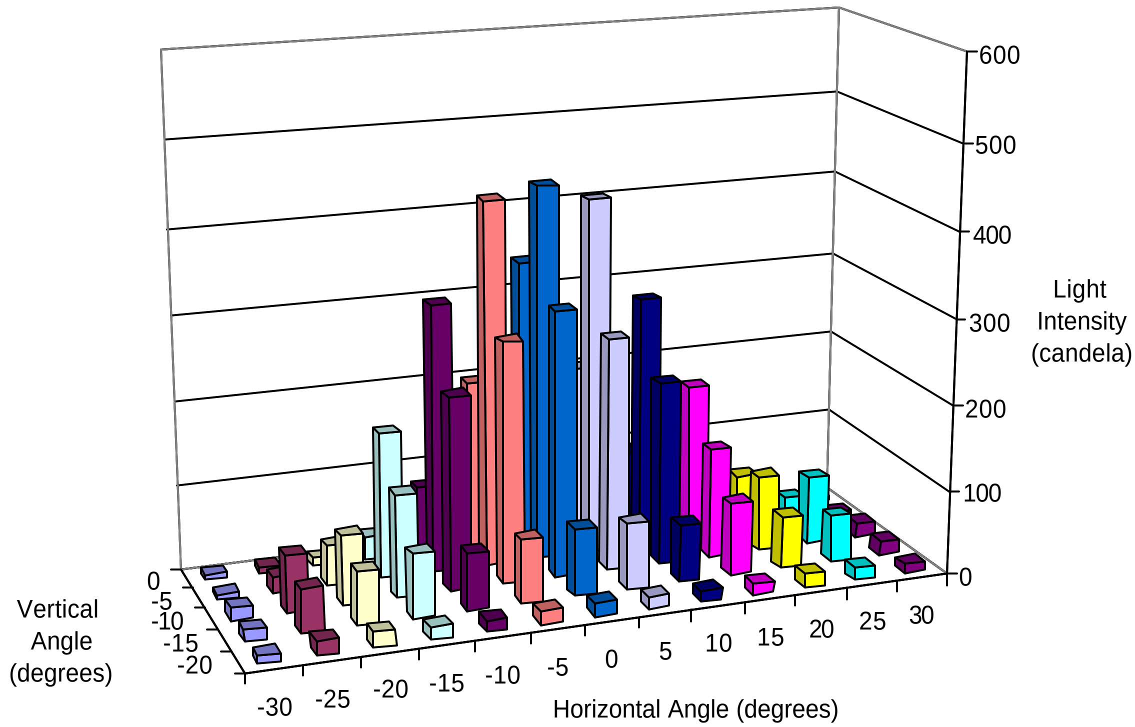

Figure A2.2.4a Output from WPS#2 (Red) signal, 10.5 volts, 181 elements (92.0% on), TC test.

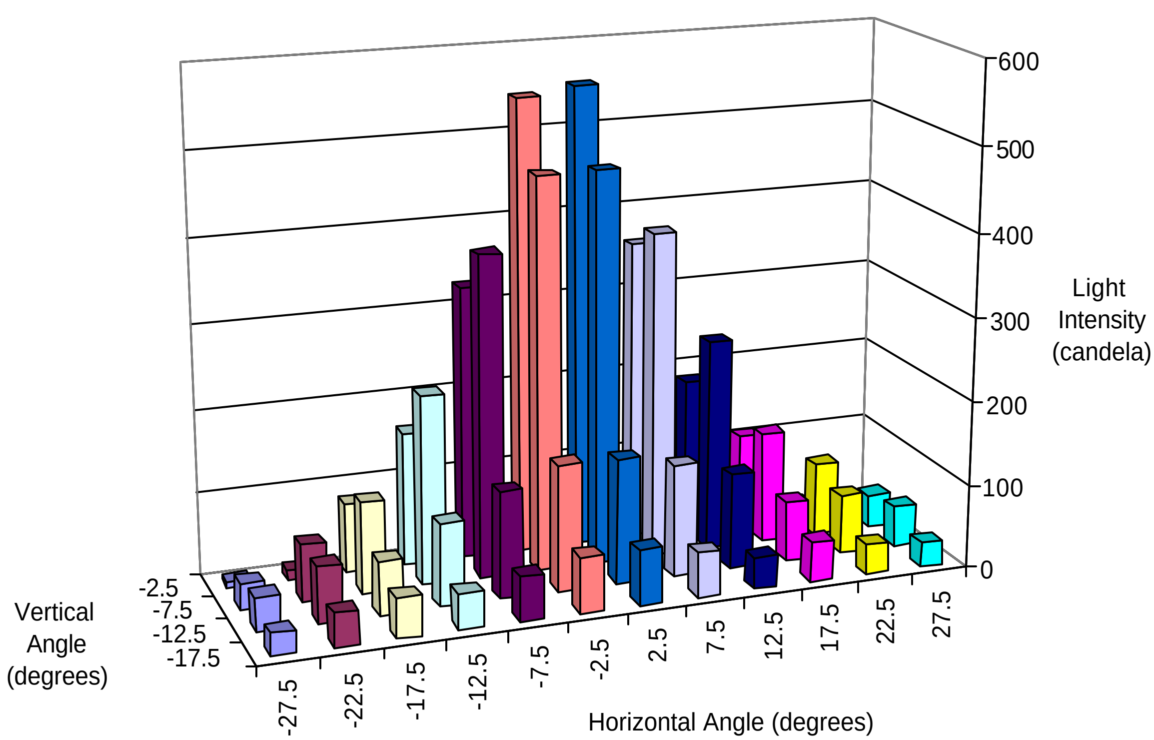

Figure A2.2.4b Output from WPS#2 (Red) signal, 10.5 volts, 181 elements (92.0% on), ITE test.

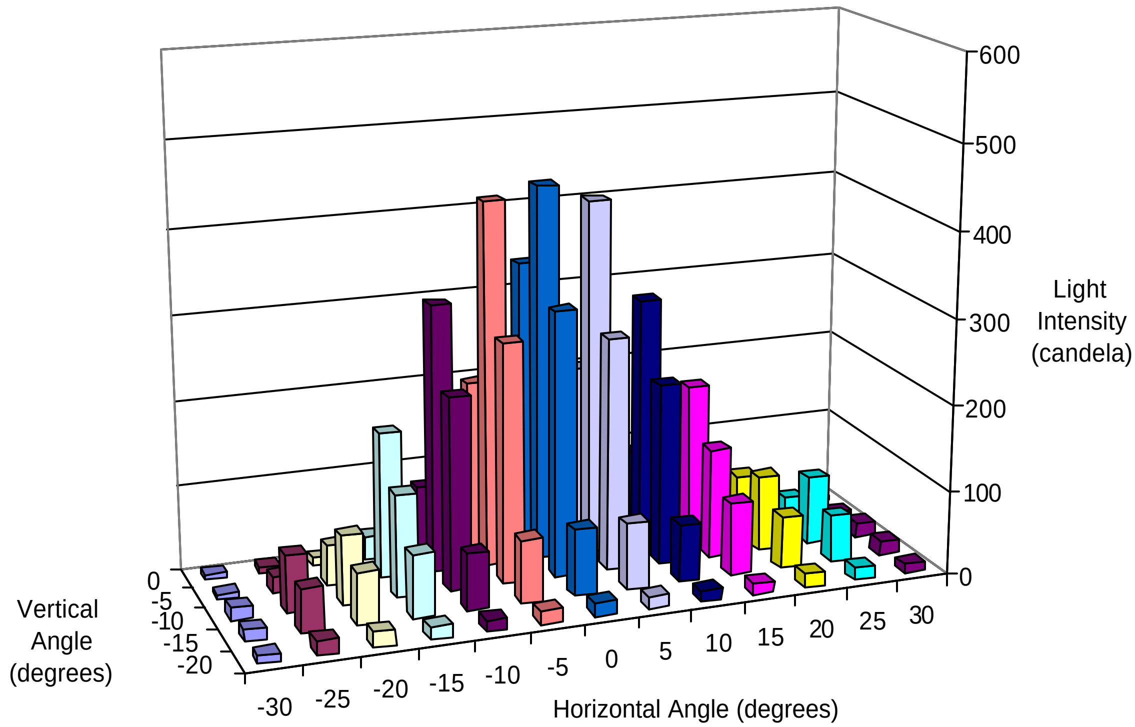

Figure A2.2.5a Output from WPS#2 (Red) signal, 10.5 volts, 176 elements (89.0% on), TC test.

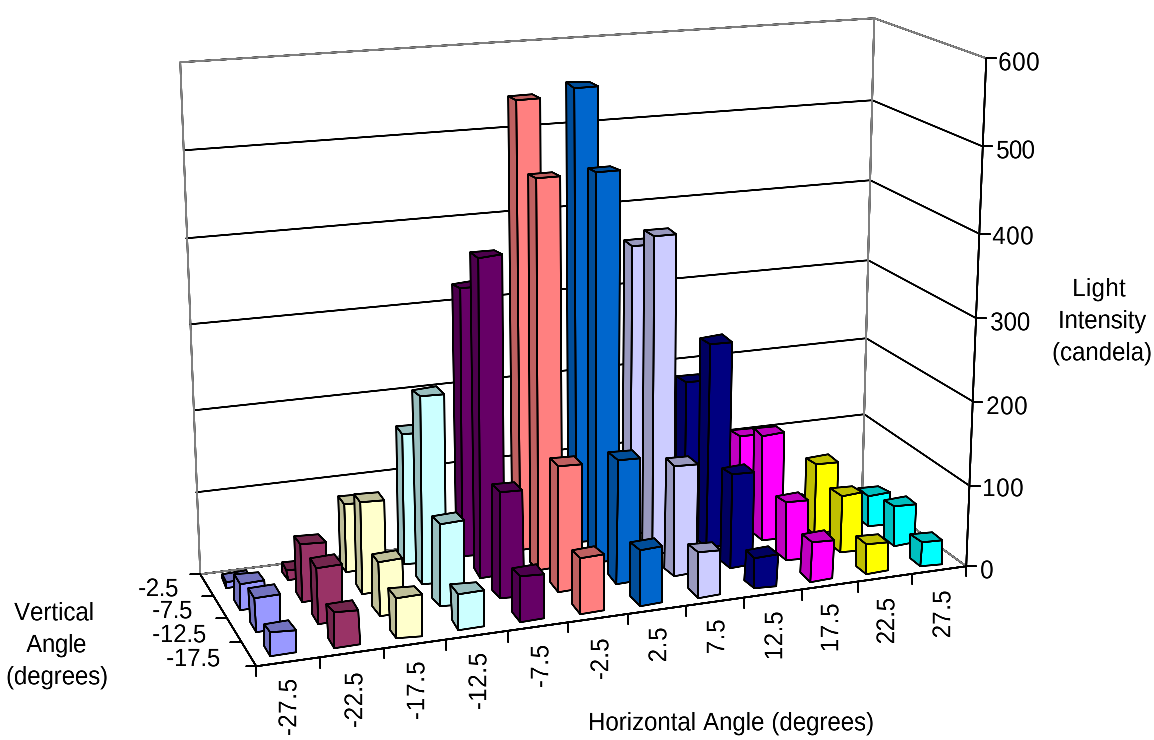

Figure A2.2.5b Output from WPS#2 (Red) signal, 10.5 volts, 176 elements (89.0% on), ITE test.

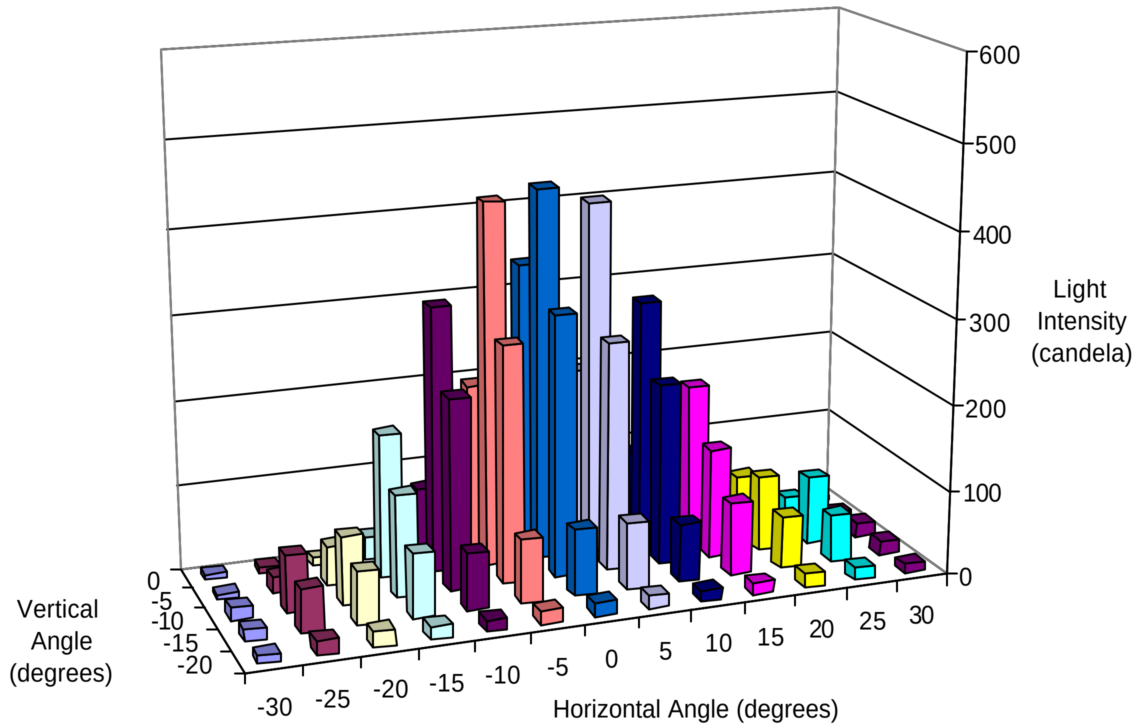

Figure A2.2.6a Output from WPS#2 (Red) signal, 10.5 volts, 171 elements (87.0% on), TC test.

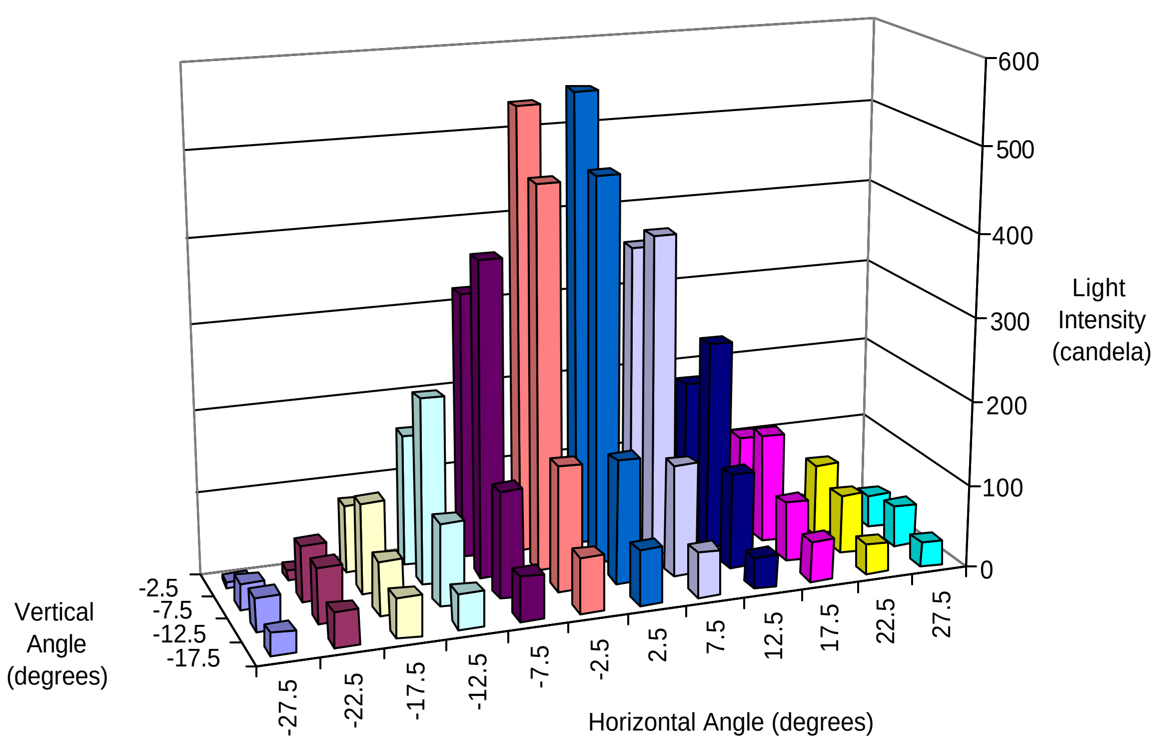

Figure A2.2.6b Output from WPS#2 (Red) signal, 10.5 volts, 171 elements (87.0% on), ITE test.

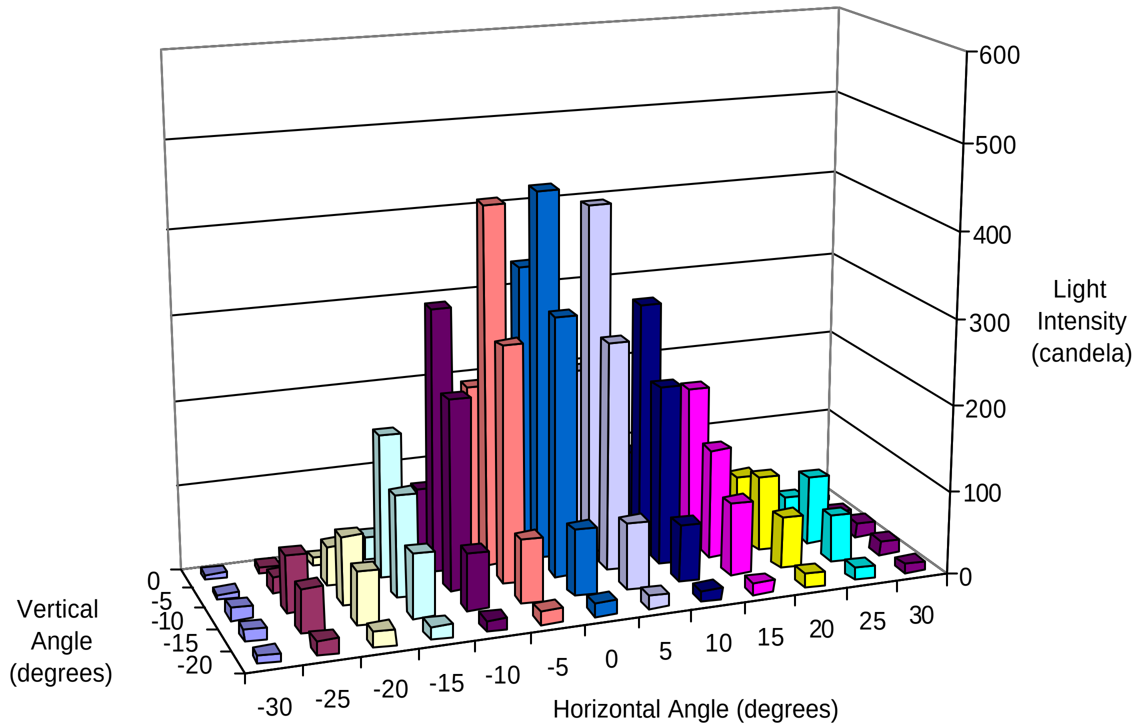

Figure A2.2.7a Output from WPS#2 (Red) signal, 10.5 volts, 166 elements (84.0% on), TC test.

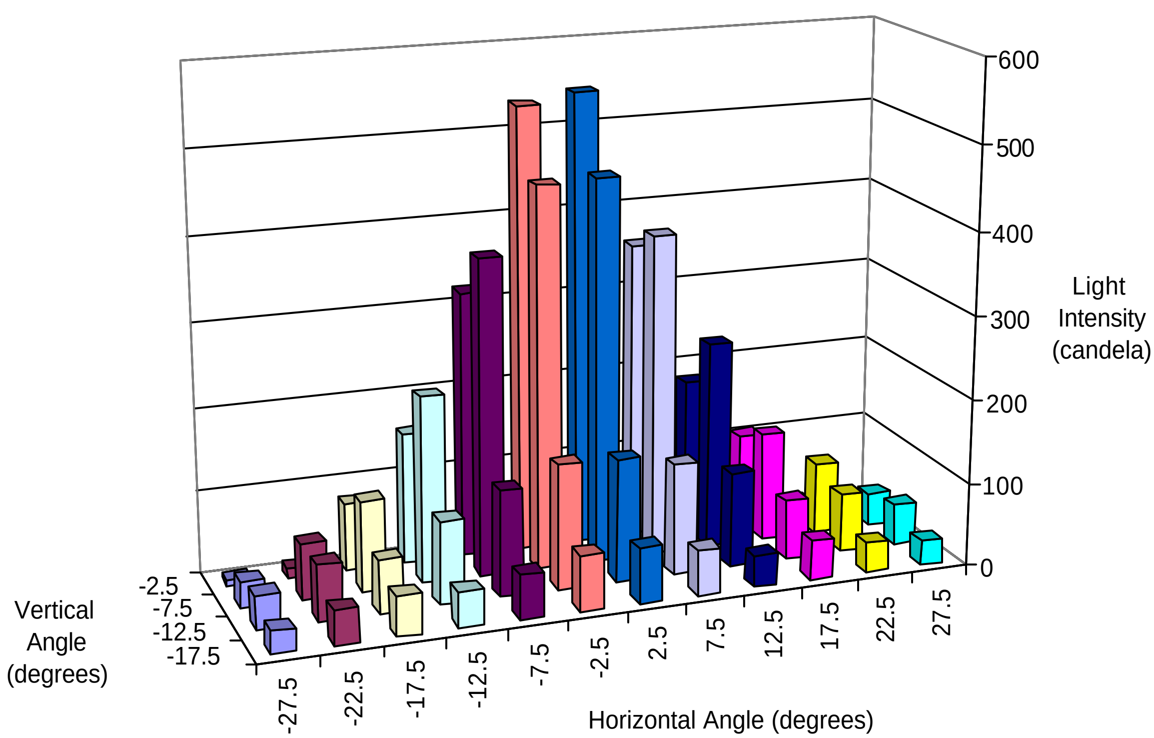

Figure A2.2.7b Output from WPS#2 (Red) signal, 10.5 volts, 166 elements (84.0% on), ITE test.

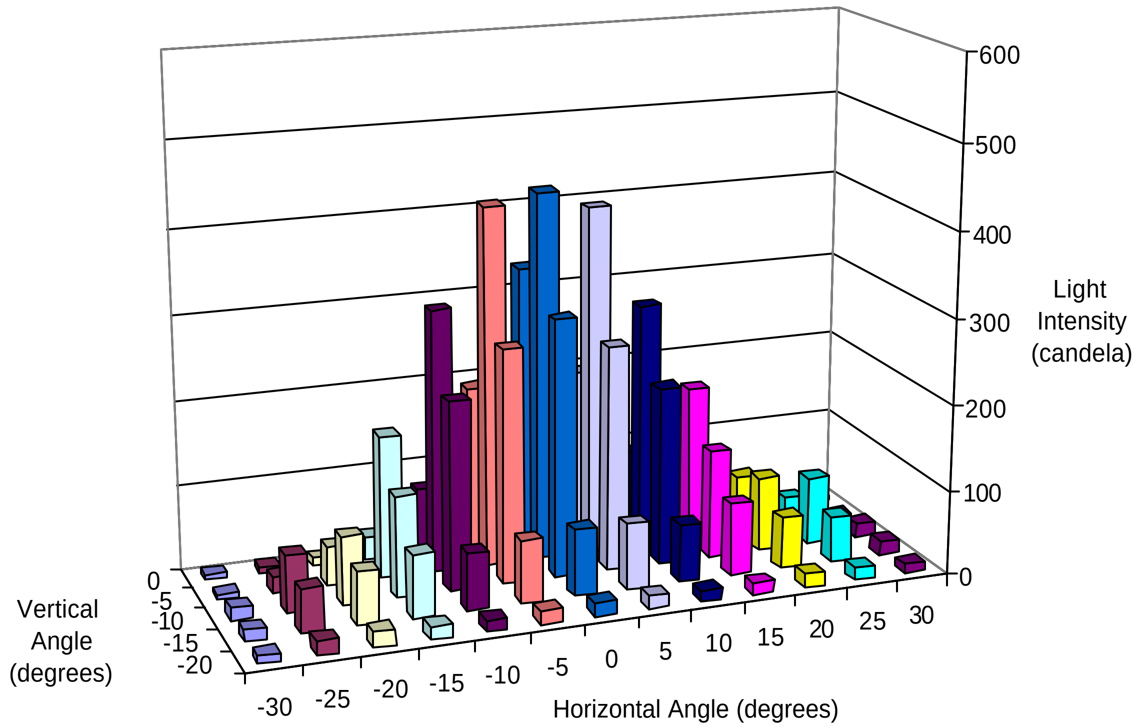

Figure A2.2.8a Output from WPS#2 (Red) signal, 10.5 volts, 161 elements (82.0% on), TC test.

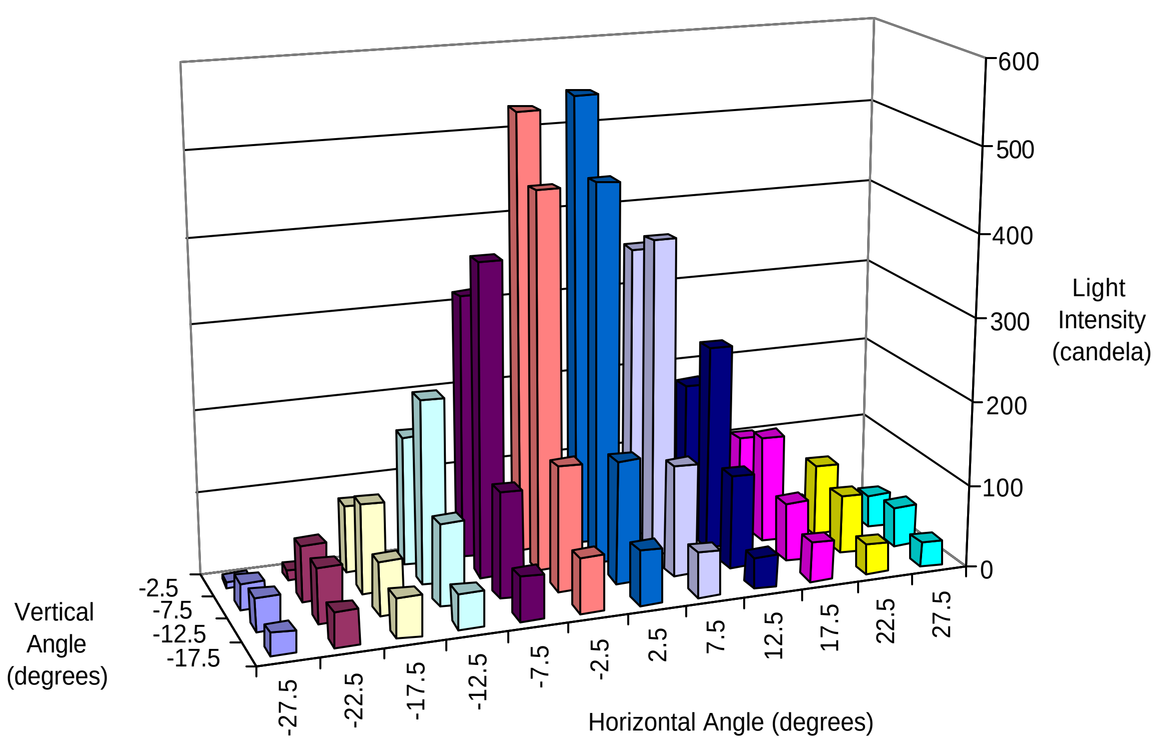

Figure A2.2.8b Output from WPS#2 (Red) signal, 10.5 volts, 161 elements (82.0% on), ITE test.

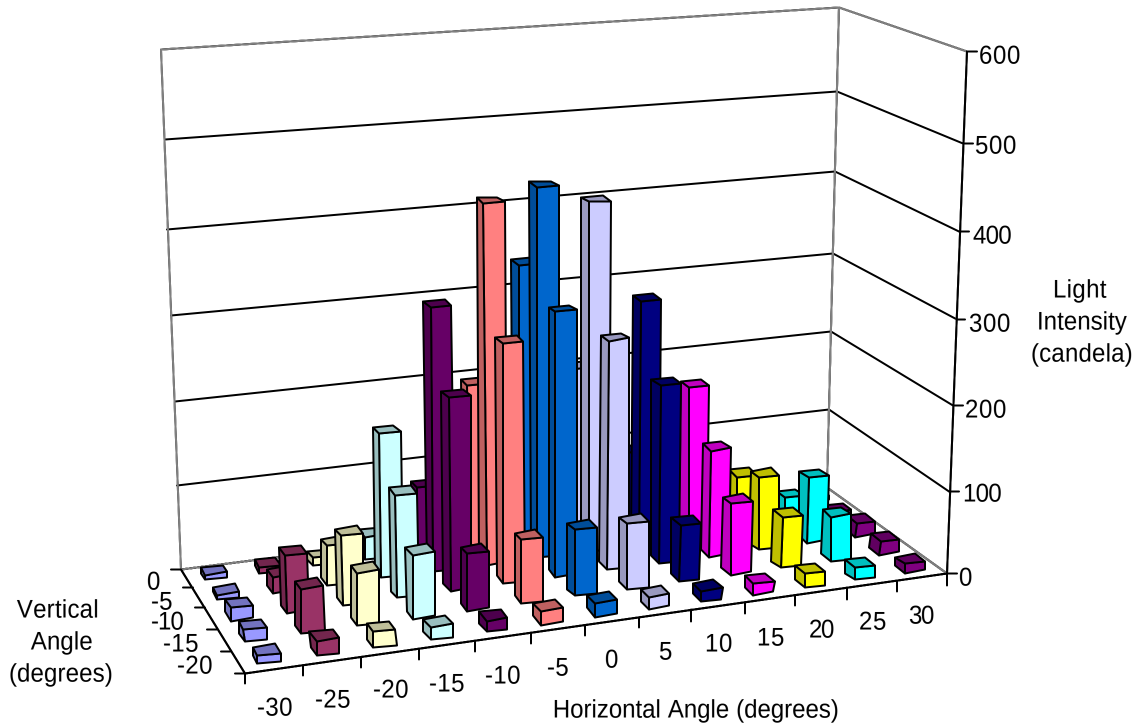

Figure A2.2.9a Output from WPS#2 (Red) signal, 9.0 volts, 176 elements (89.0% on), TC test.

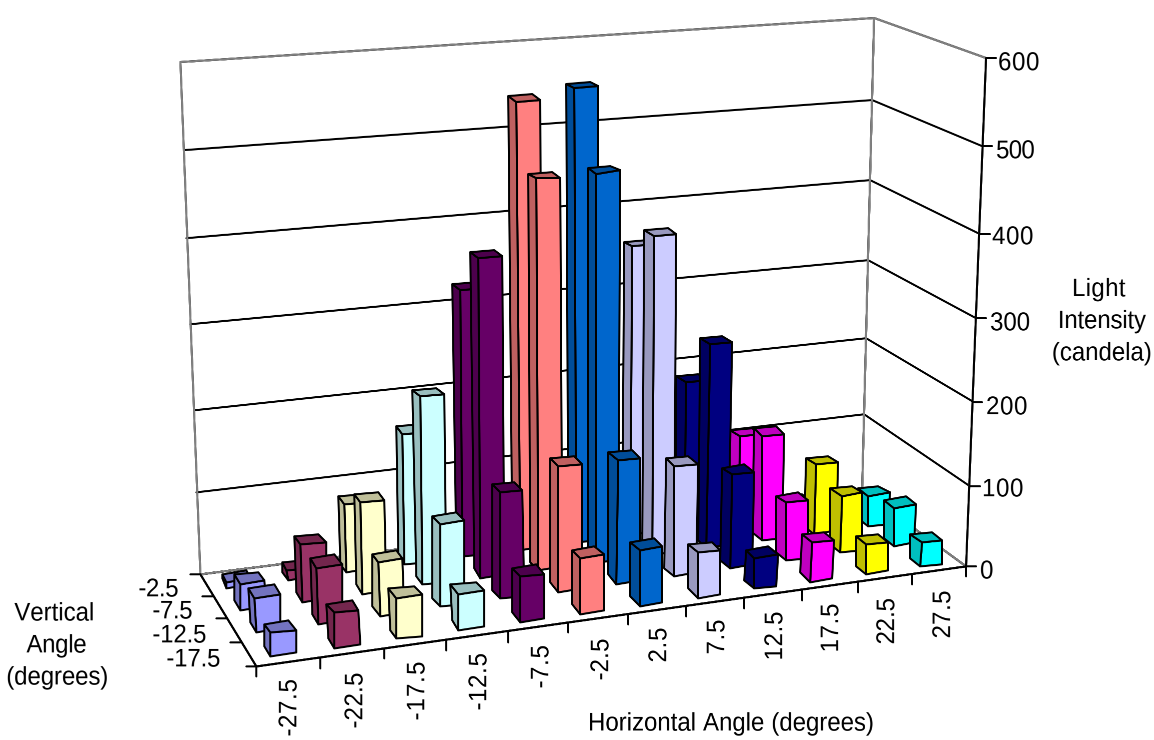

Figure A2.2.9b Output from WPS#2 (Red) signal, 9.0 volts, 176 elements (89.0% on), ITE test.

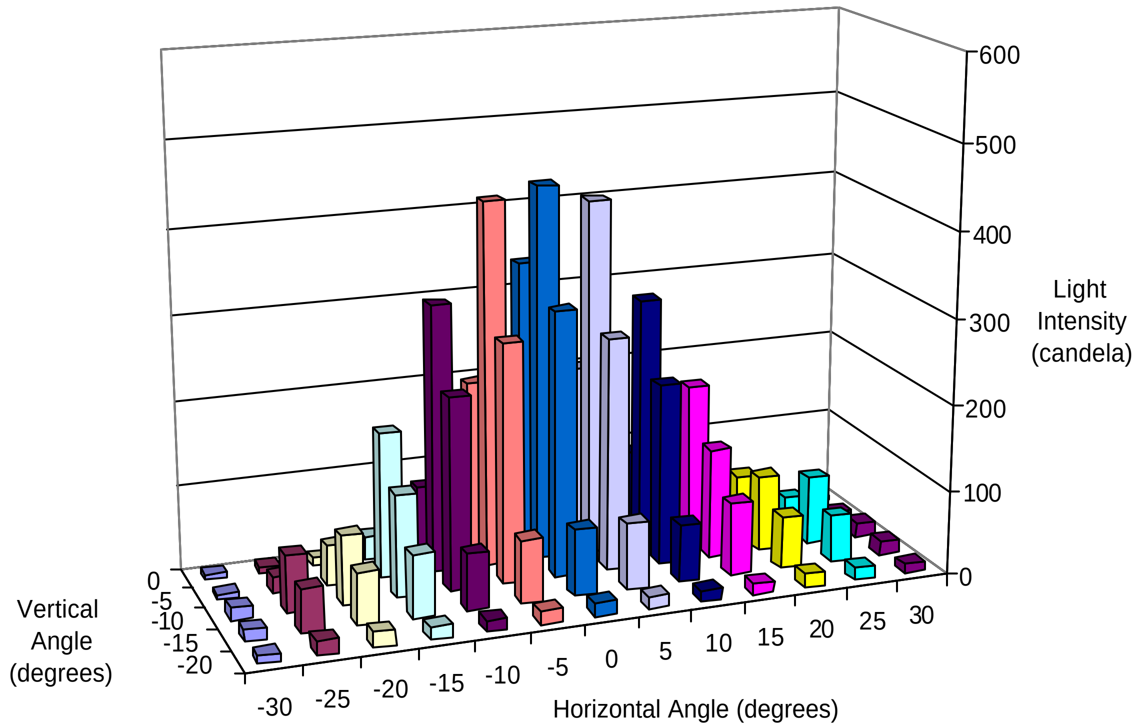

Figure A2.2.10a Output from WPS#2 (Red) signal, 10.5 volts, 176 elements (89.0% on), TC test.

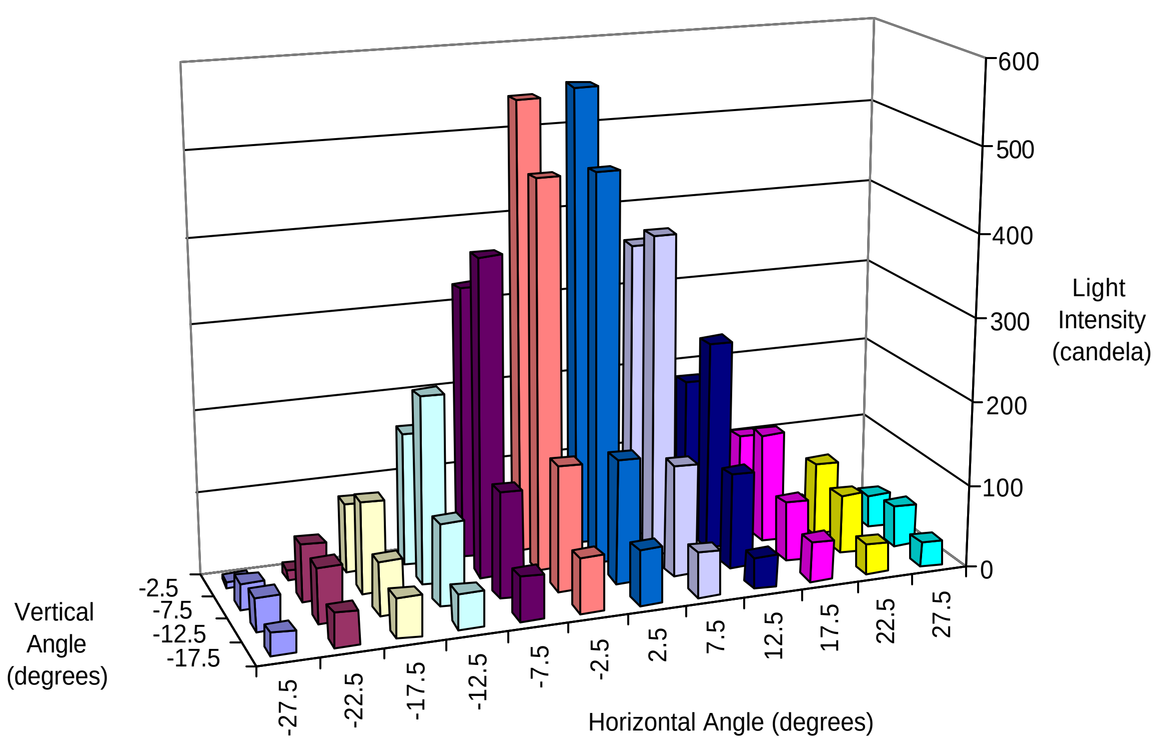

Figure A2.2.10b Output from WPS#2 (Red) signal, 10.5 volts, 176 elements (89.0% on), ITE test.

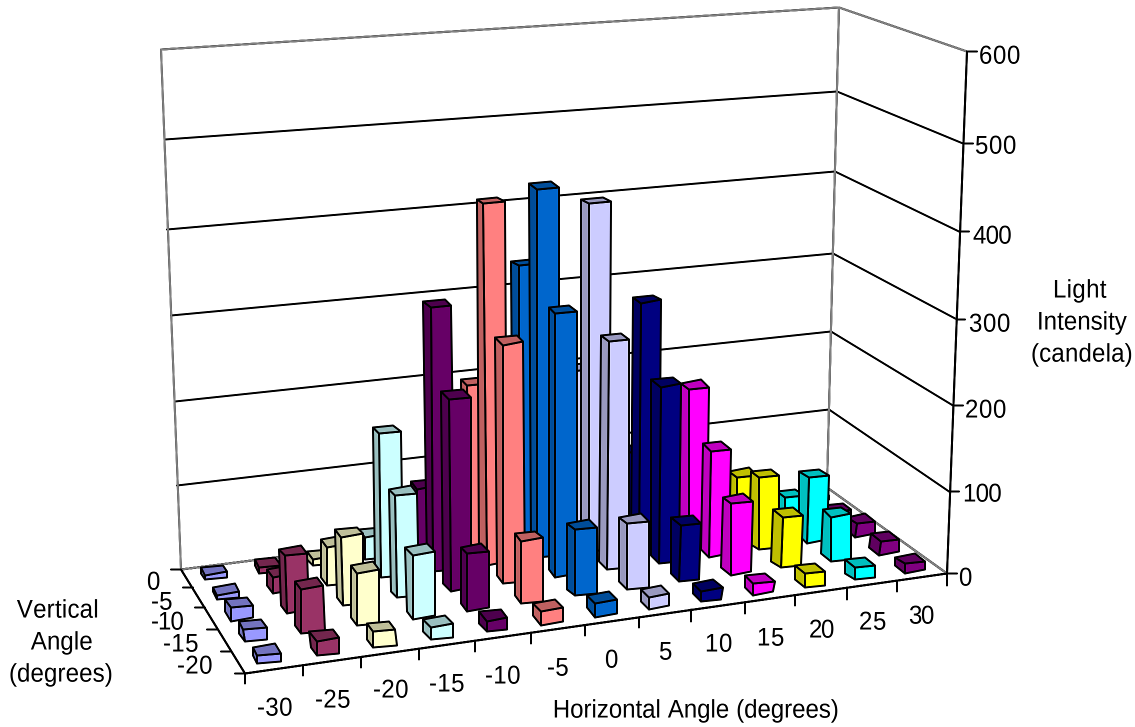

Figure A2.2.11a Output from WPS#2 (Red) signal, 12.0 volts, 176 elements (89.0% on), TC test.

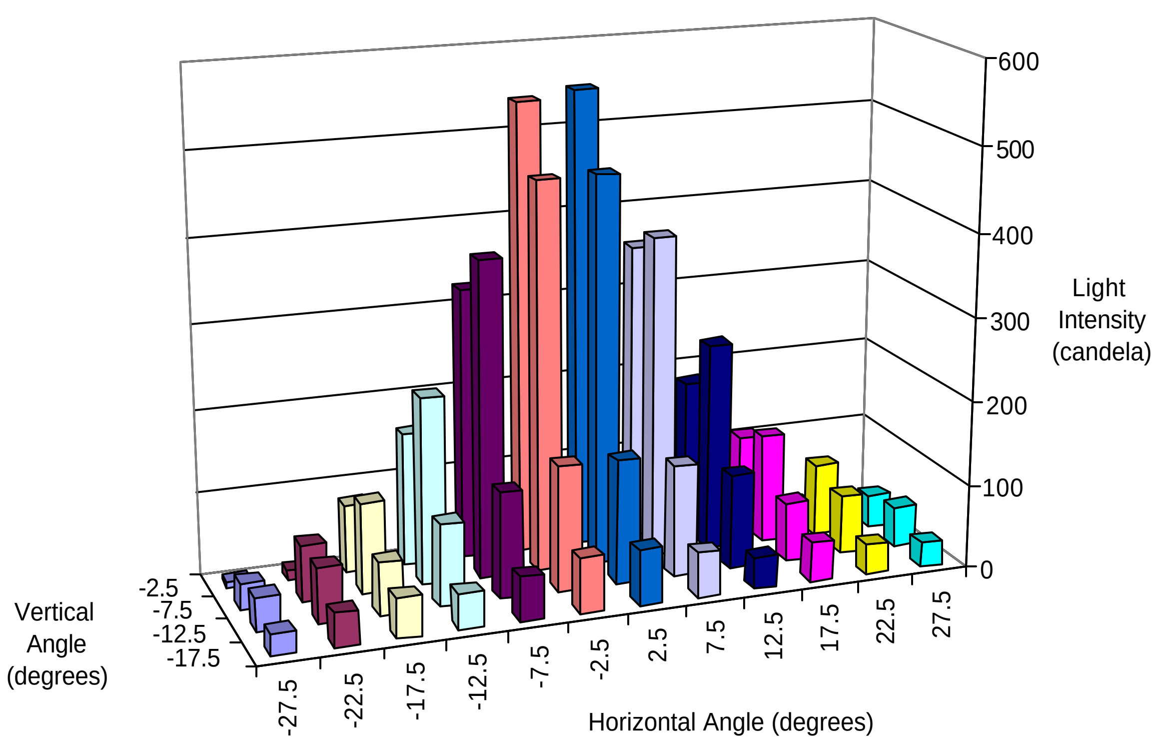

Figure A2.2.11b Output from WPS#2 (Red) signal, 12.0 volts, 176 elements (89.0% on), ITE test.

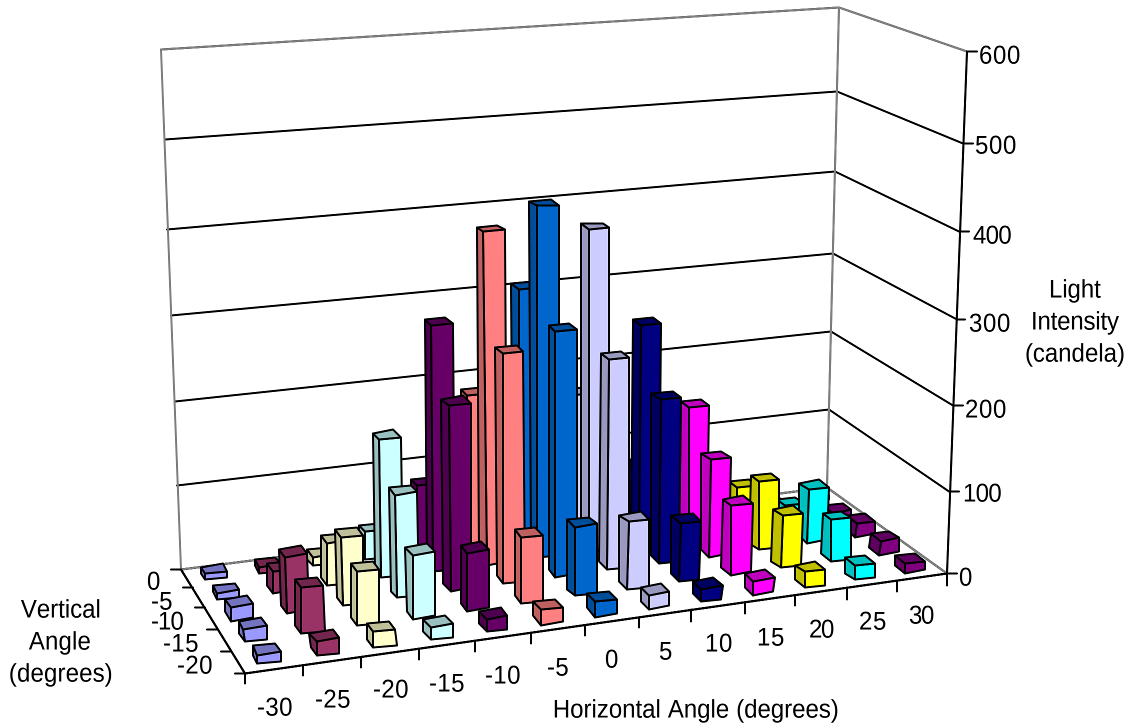

Figure A2.3.1a Output from WPS#2 (Red) signal, 10.5 volts, all elements on, TC test.

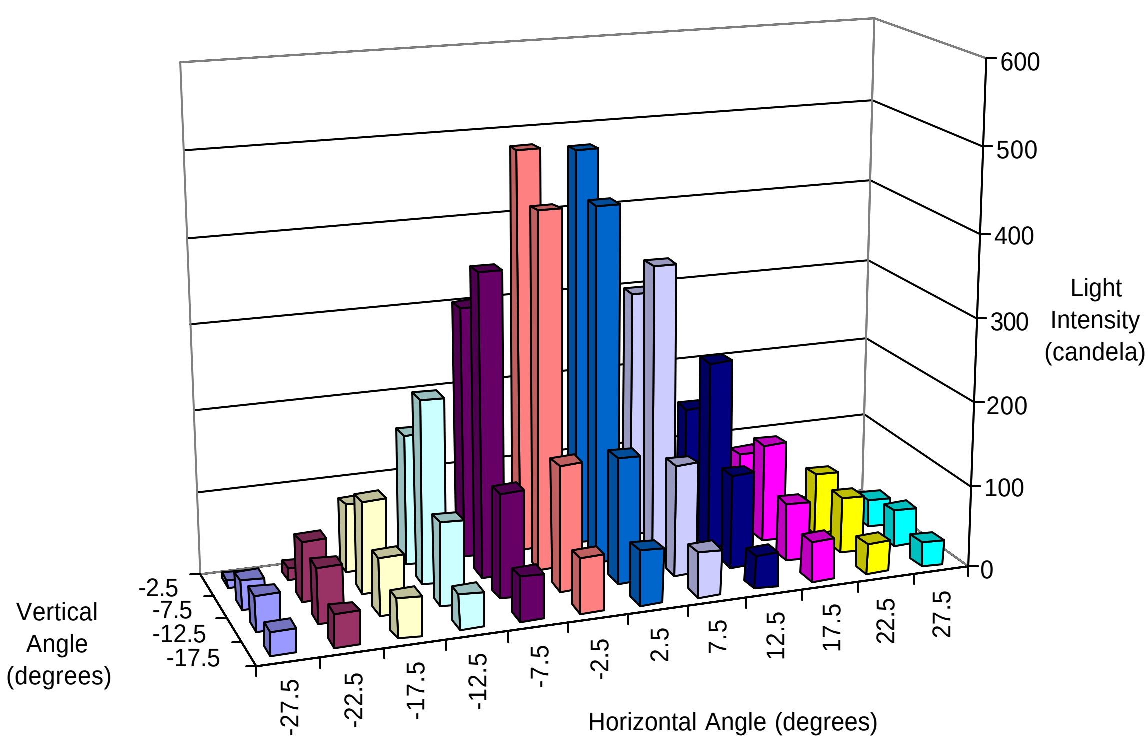

Figure A2.3.1b Output from WPS#2 (Red) signal, 10.5 volts, all elements on, ITE test.

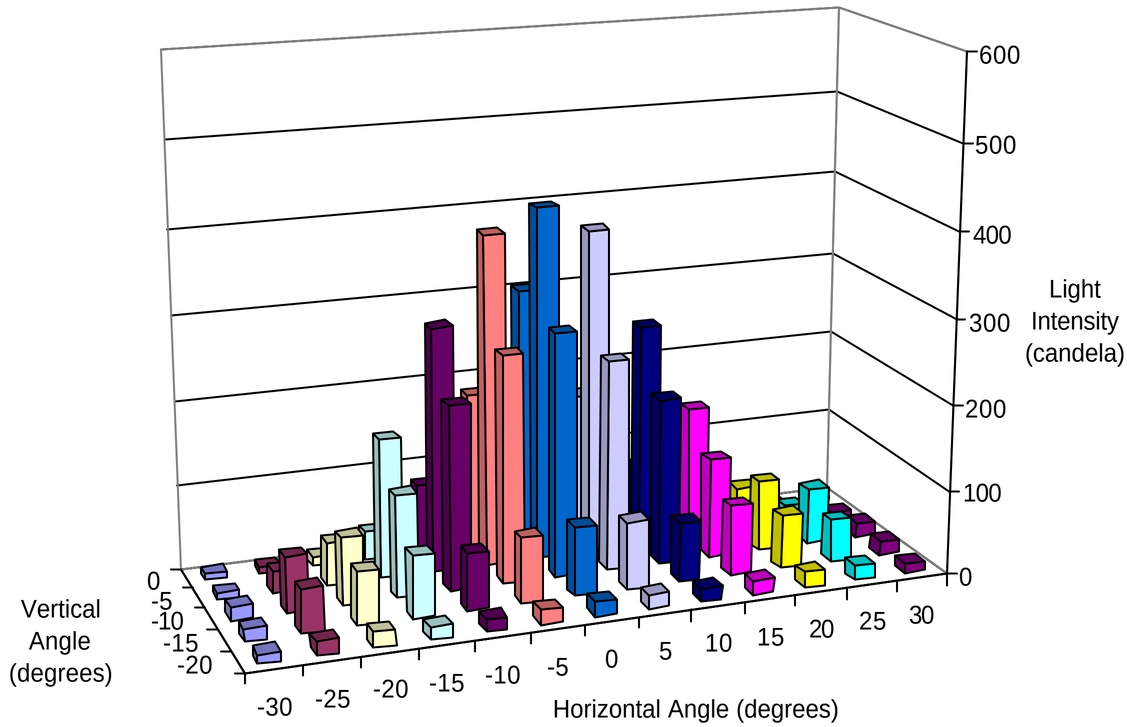

Figure A2.3.2a Output from WPS#2 (Red) signal, 10.5 volts, 191 elements (97.0% on), TC test.

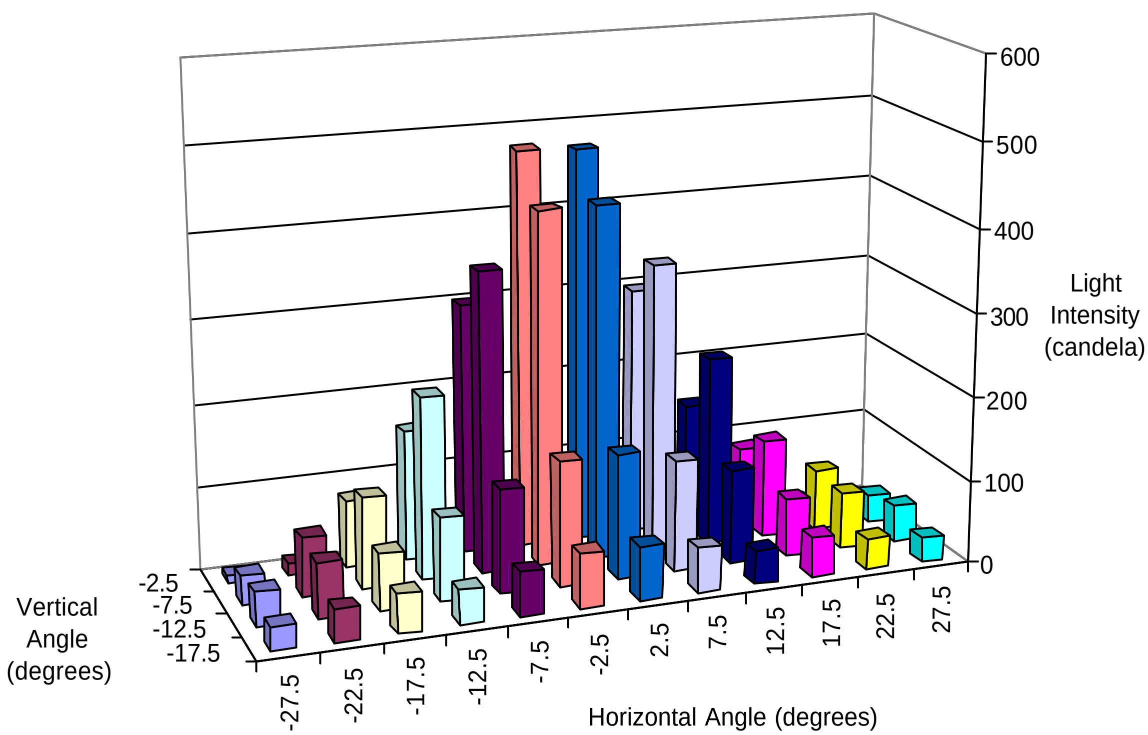

Figure A2.3.2b Output from WPS#2 (Red) signal, 10.5 volts, 191 elements (97.0% on), ITE test.

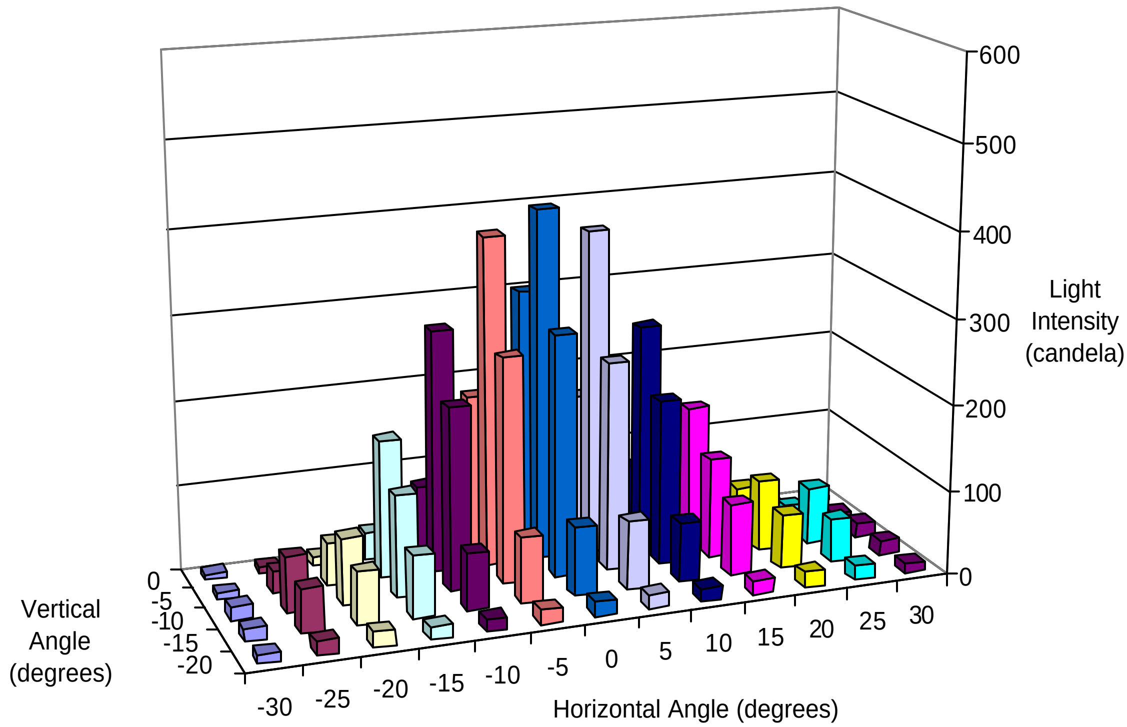

Figure A2.3.3a Output from WPS#2 (Red) signal, 10.5 volts, 186 elements (94.0% on), TC test.

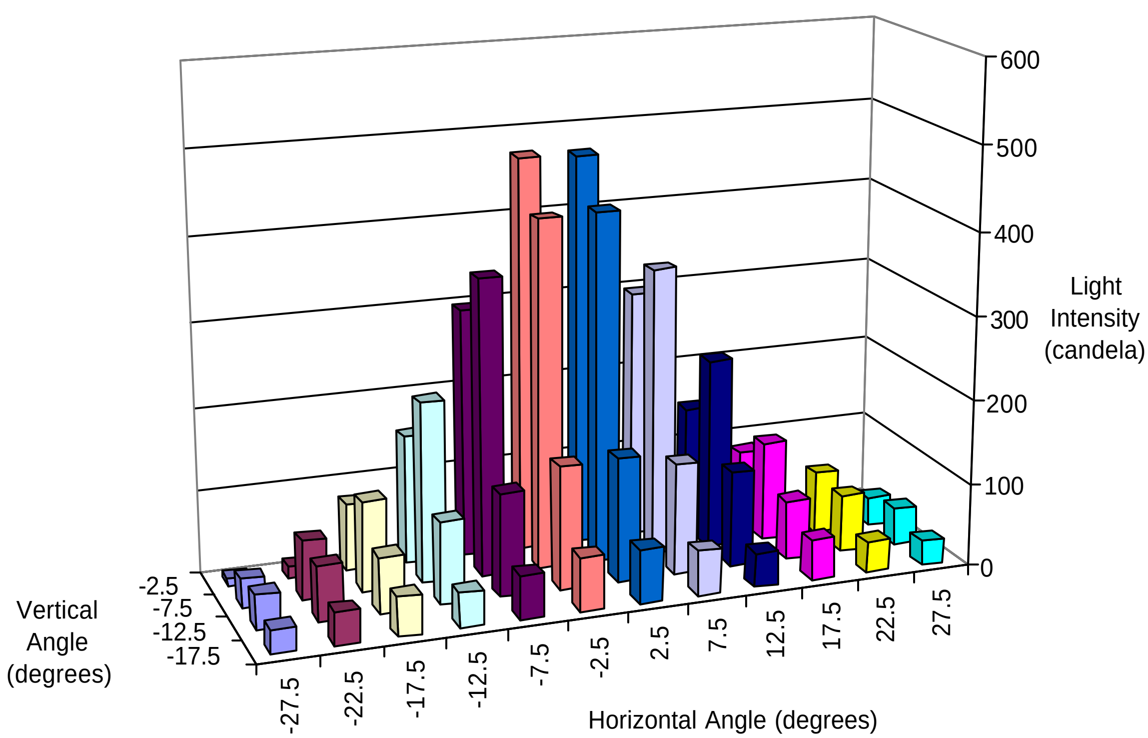

Figure A2.3.3b Output from WPS#2 (Red) signal, 10.5 volts, 186 elements (94.0% on), ITE test.

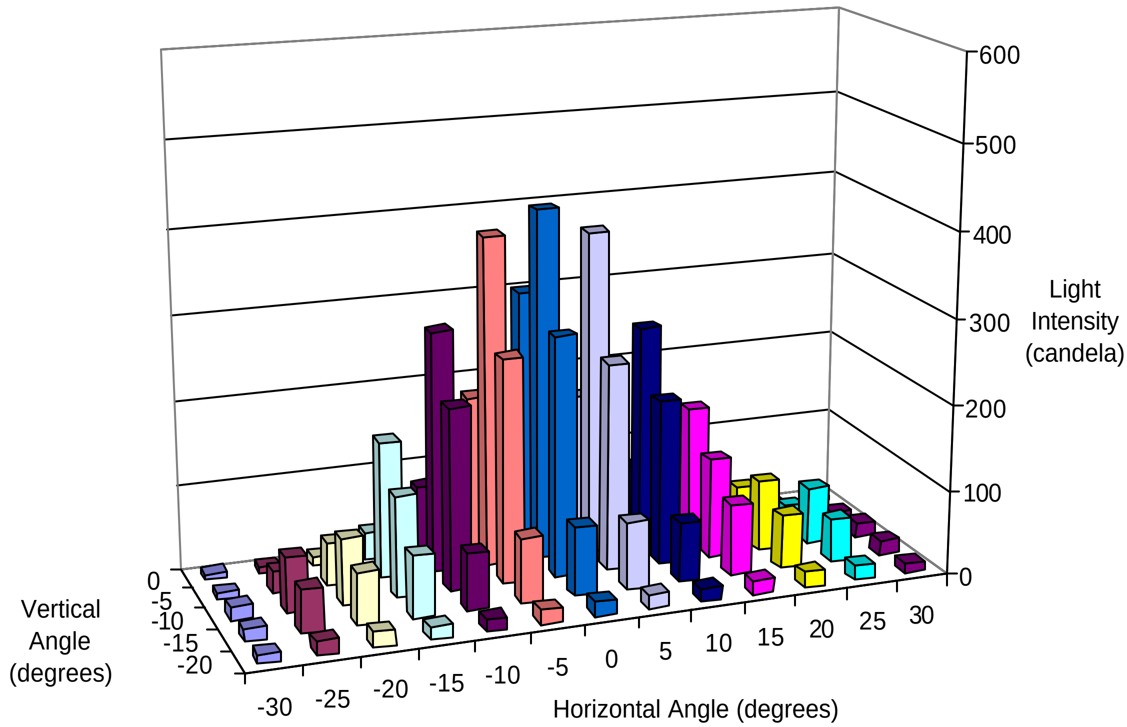

Figure A2.3.4a Output from WPS#2 (Red) signal, 10.5 volts, 181 elements (92.0% on), TC test.

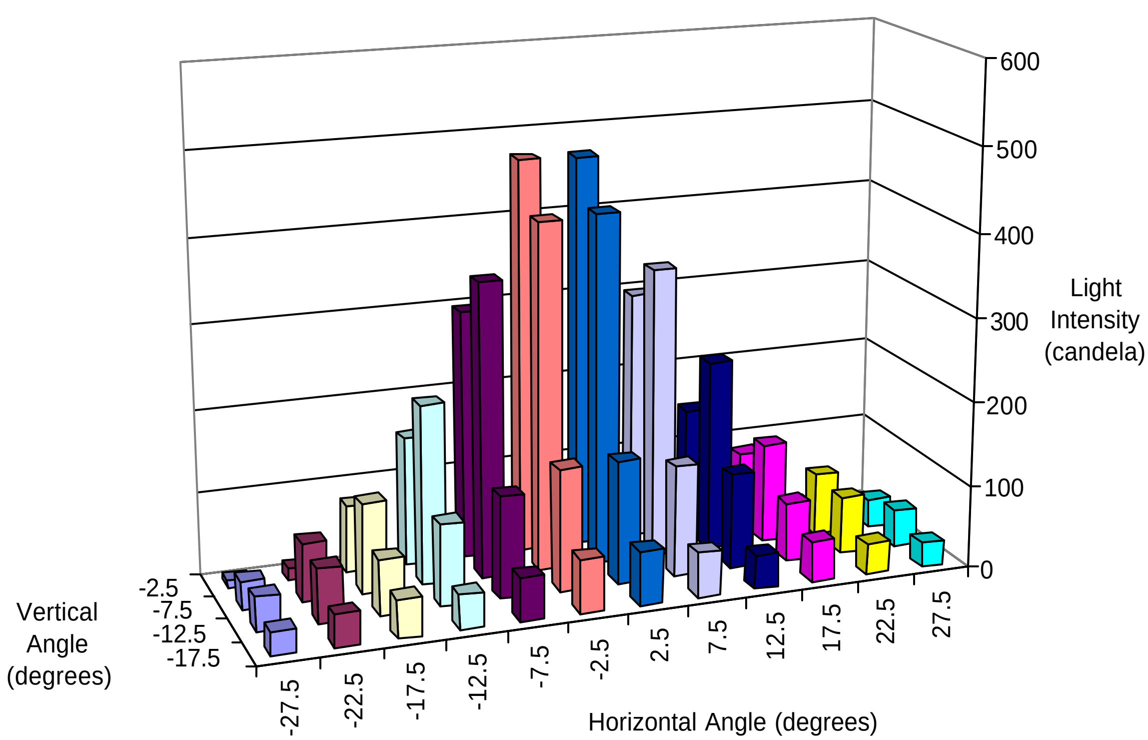

Figure A2.3.4b Output from WPS#2 (Red) signal, 10.5 volts, 181 elements (92.0% on), ITE test.

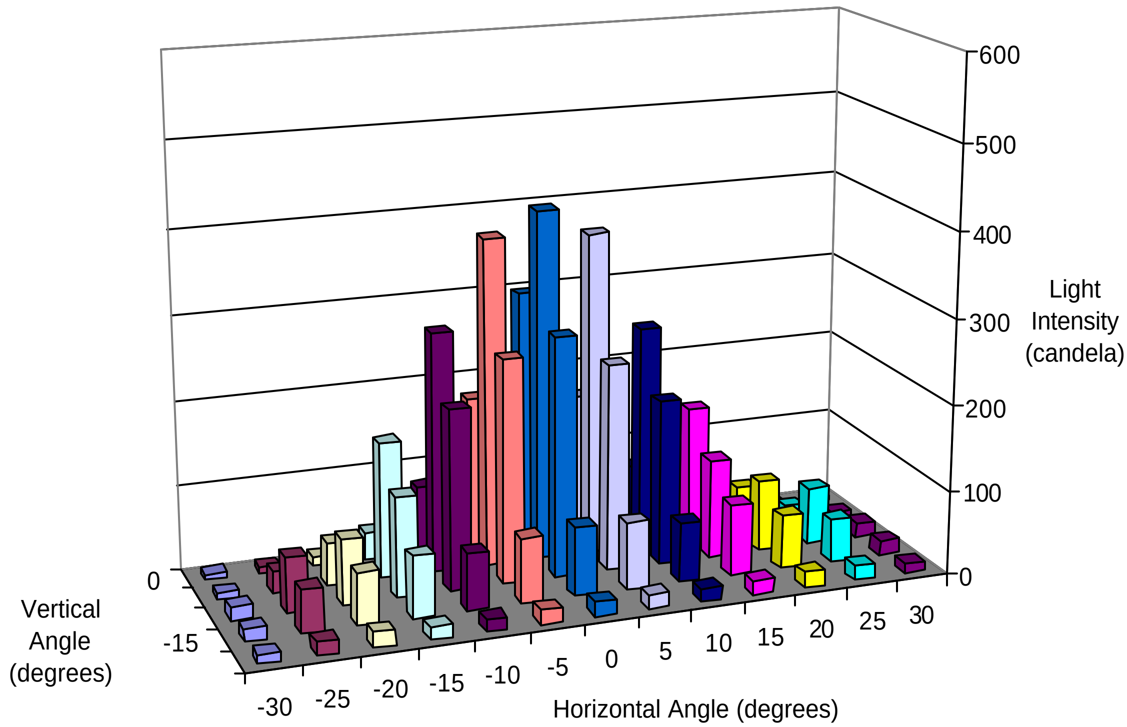

Figure A2.3.5a Output from WPS#2 (Red) signal, 10.5 volts, 176 elements (89.0% on), TC test.

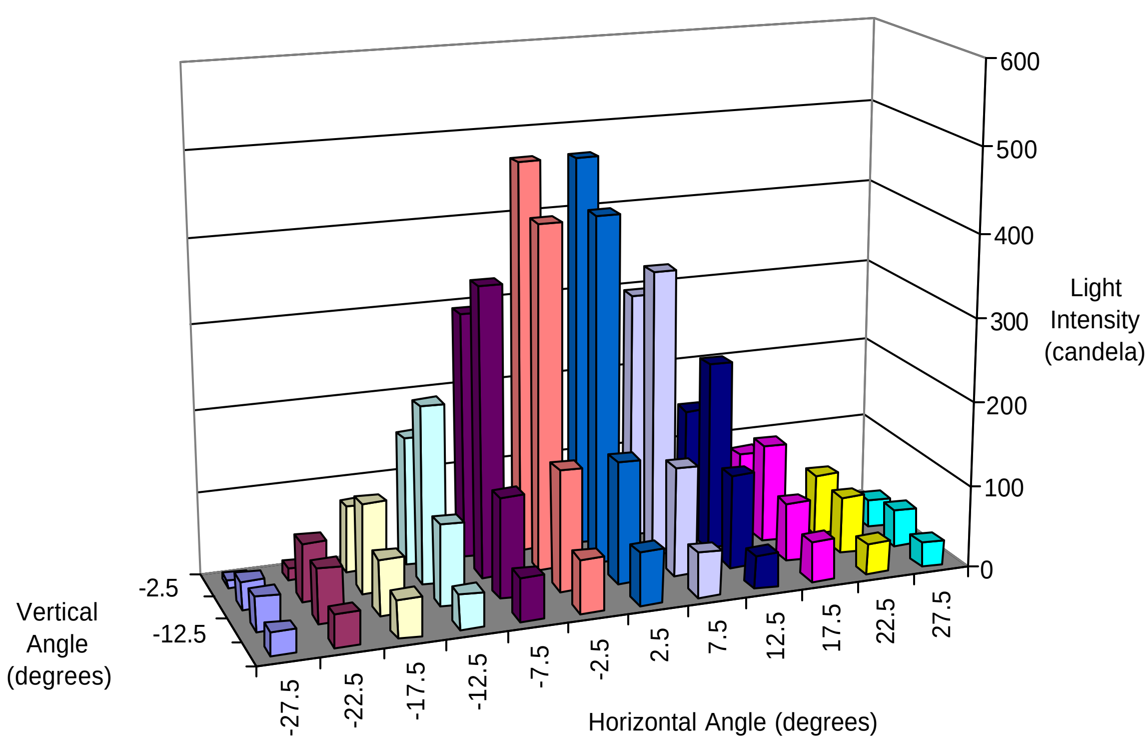

Figure A2.3.5b Output from WPS#2 (Red) signal, 10.5 volts, 176 elements (89.0% on), ITE test.

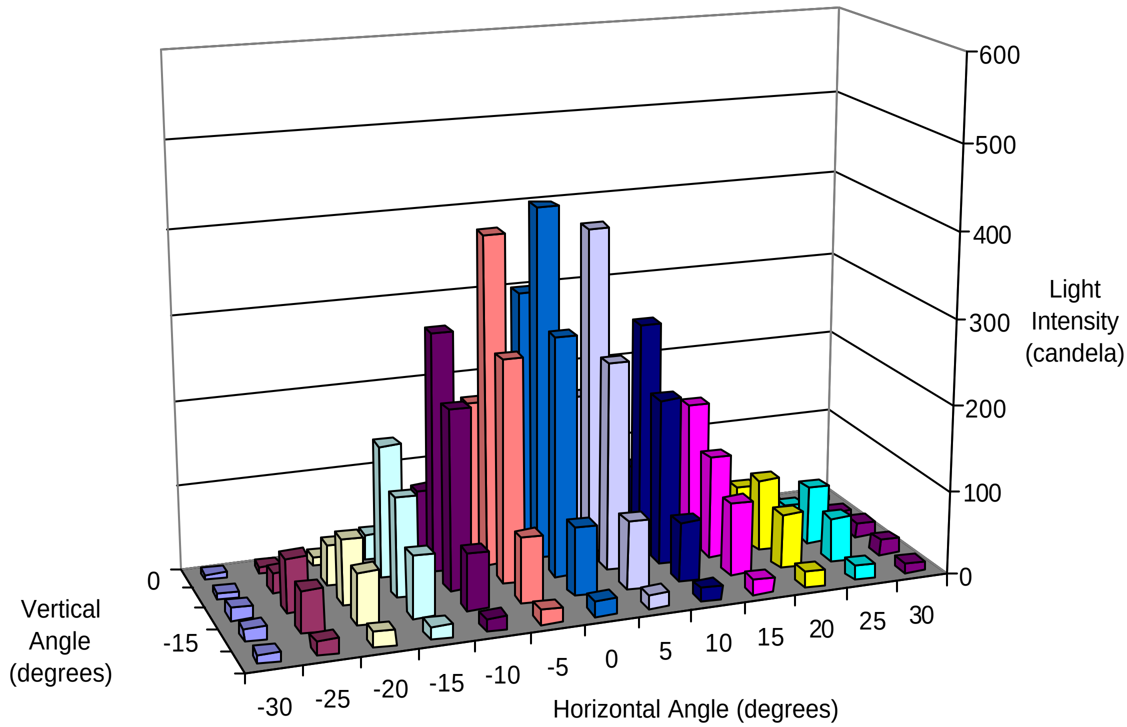

Figure A2.3.6a Output from WPS#2 (Red) signal, 10.5 volts, 171 elements (87.0% on), TC test.

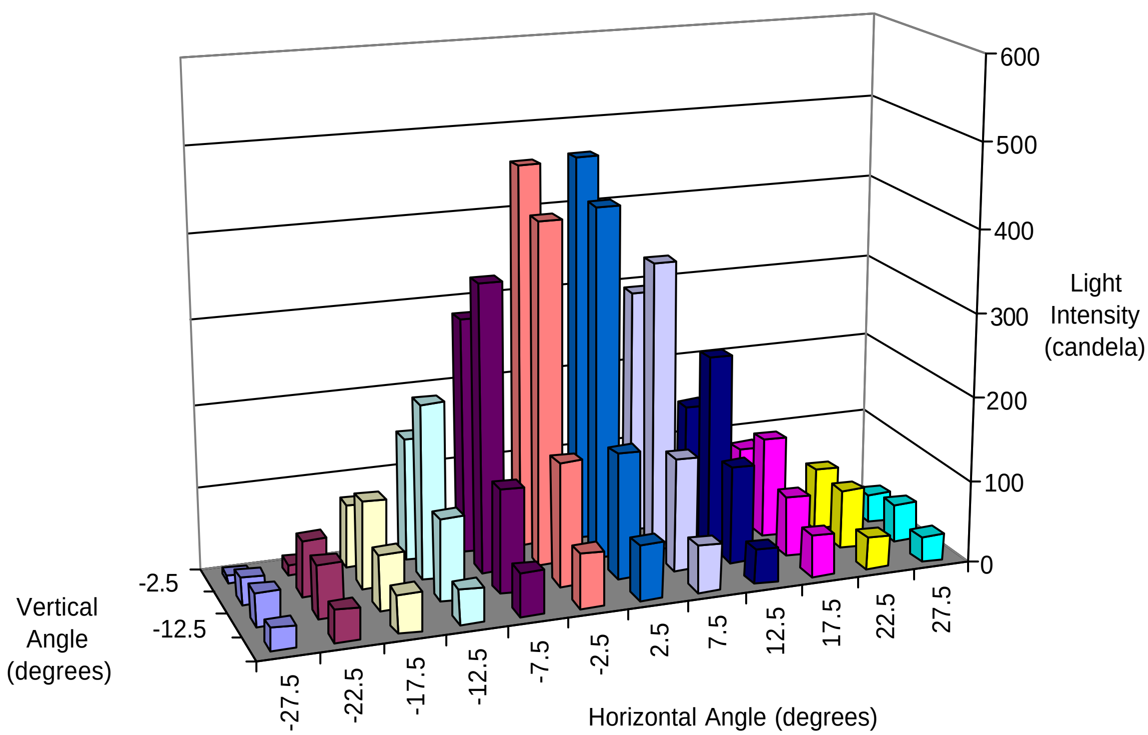

Figure A2.3.6b Output from WPS#2 (Red) signal, 10.5 volts, 171 elements (87.0% on), ITE test.

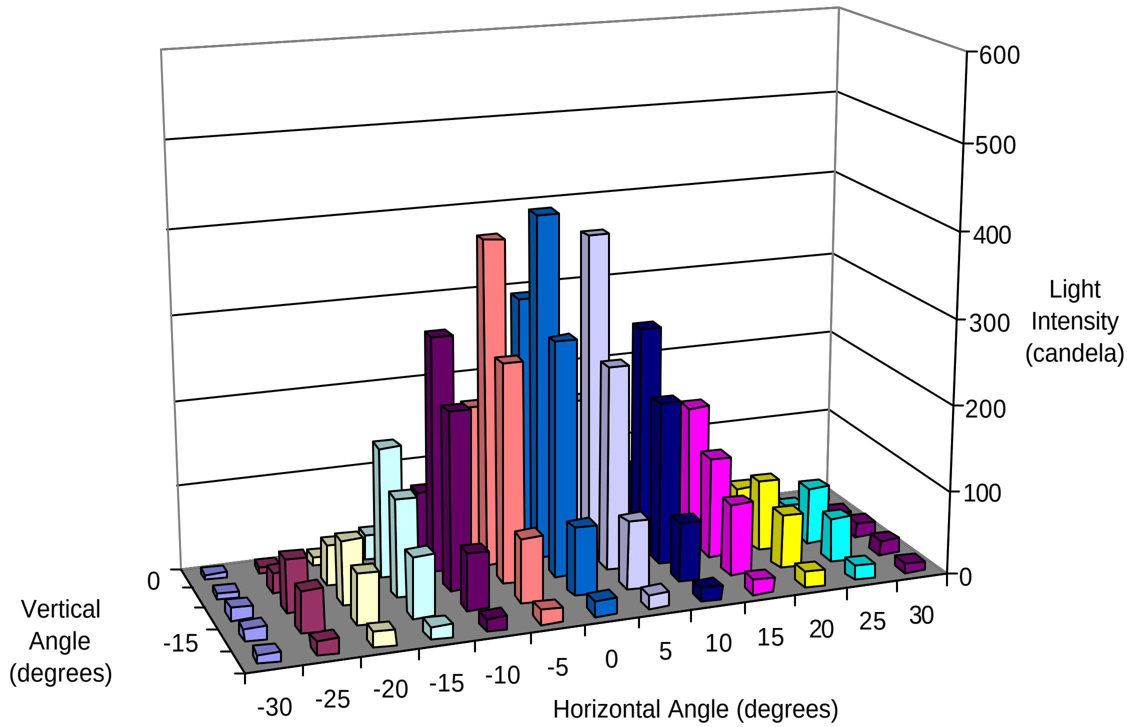

Figure A2.3.7a Output from WPS#2 (Red) signal, 10.5 volts, 166 elements (84.0% on), TC test.

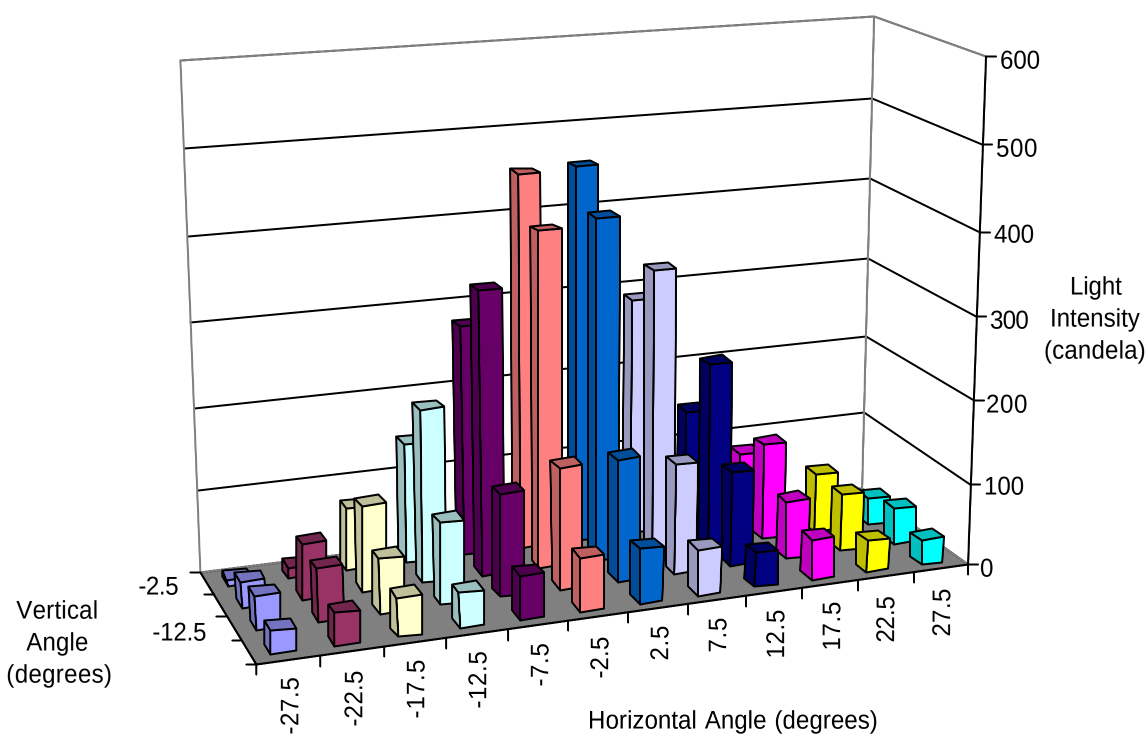

Figure A2.3.7b Output from WPS#2 (Red) signal, 10.5 volts, 166 elements (84.0% on), ITE test.

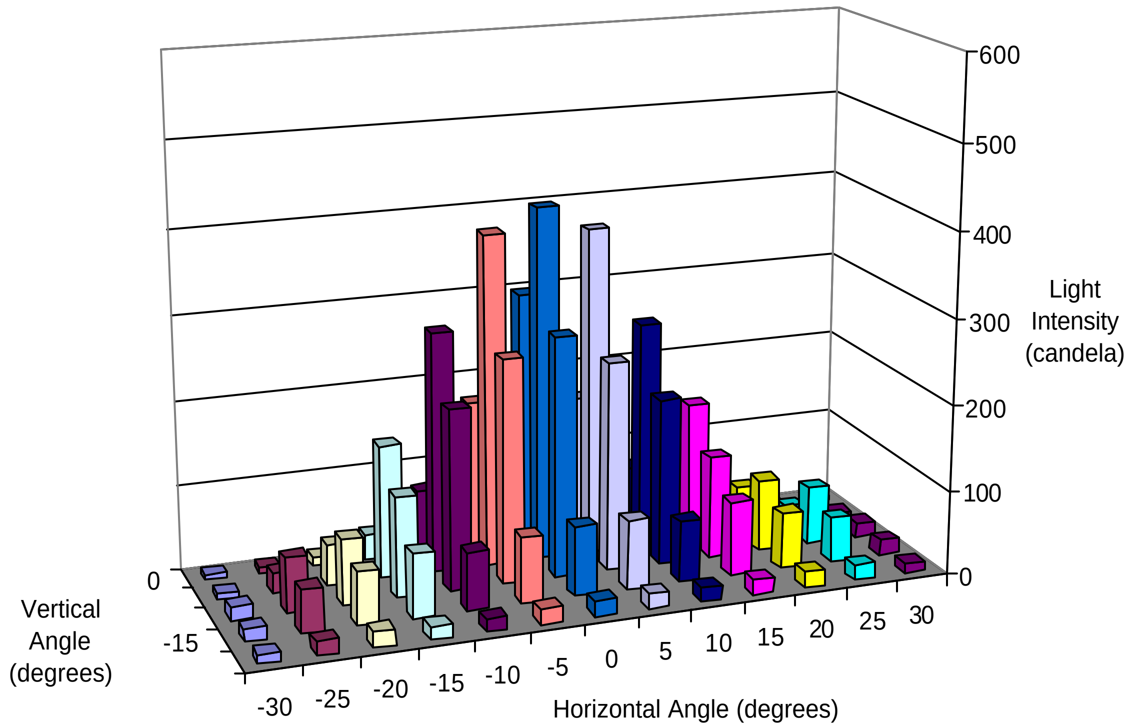

Figure A2.3.8a Output from WPS#2 (Red) signal, 10.5 volts, 161 elements (82.0% on), TC test.

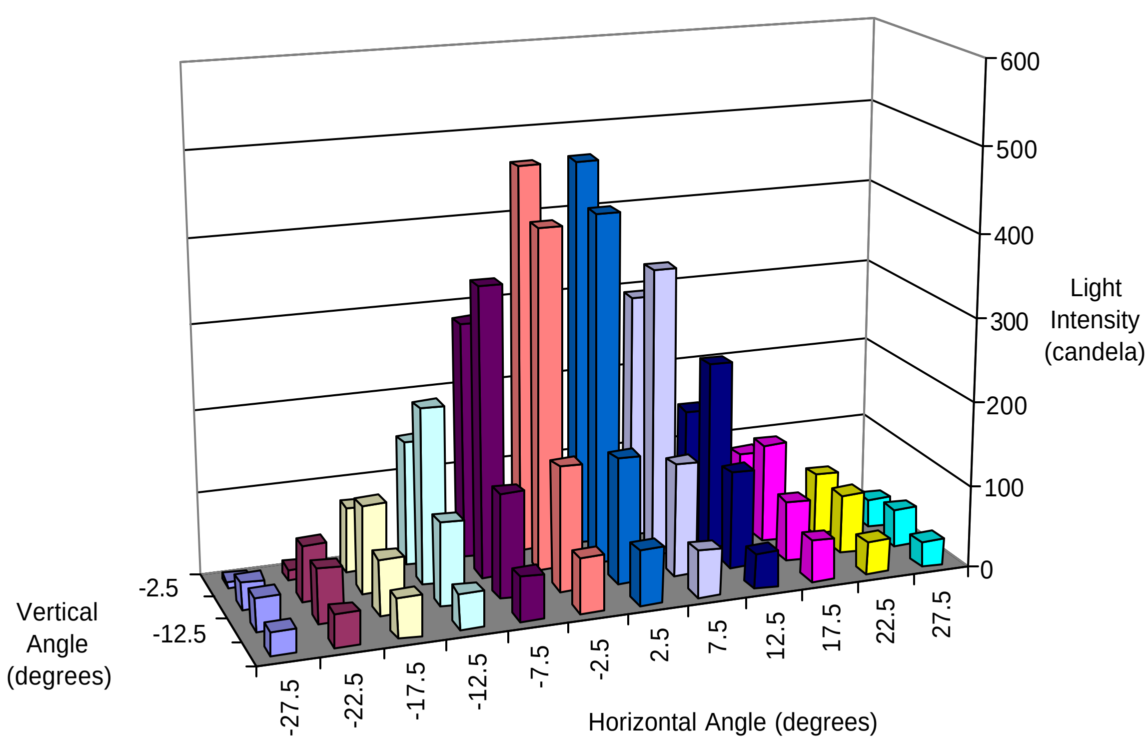

Figure A2.3.8b Output from WPS#2 (Red) signal, 10.5 volts, 161 elements (82.0% on), ITE test.

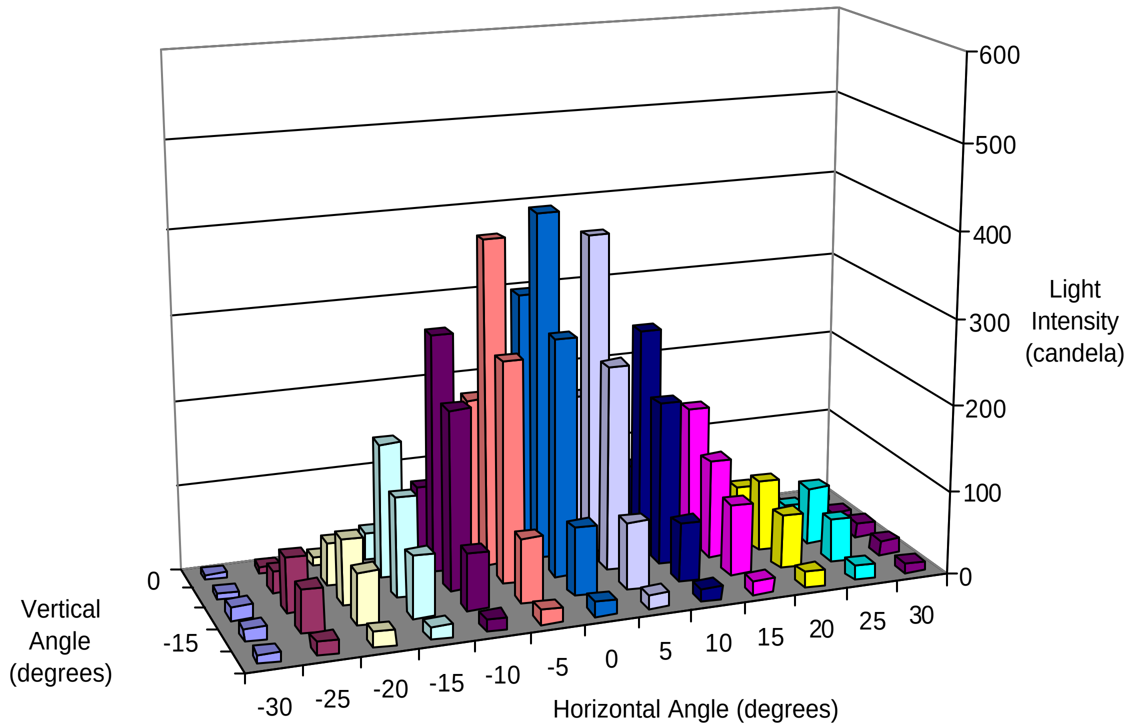

Figure A2.3.9a Output from WPS#2 (Red) signal, 9.0 volts, 176 elements (89.0% on), TC test.

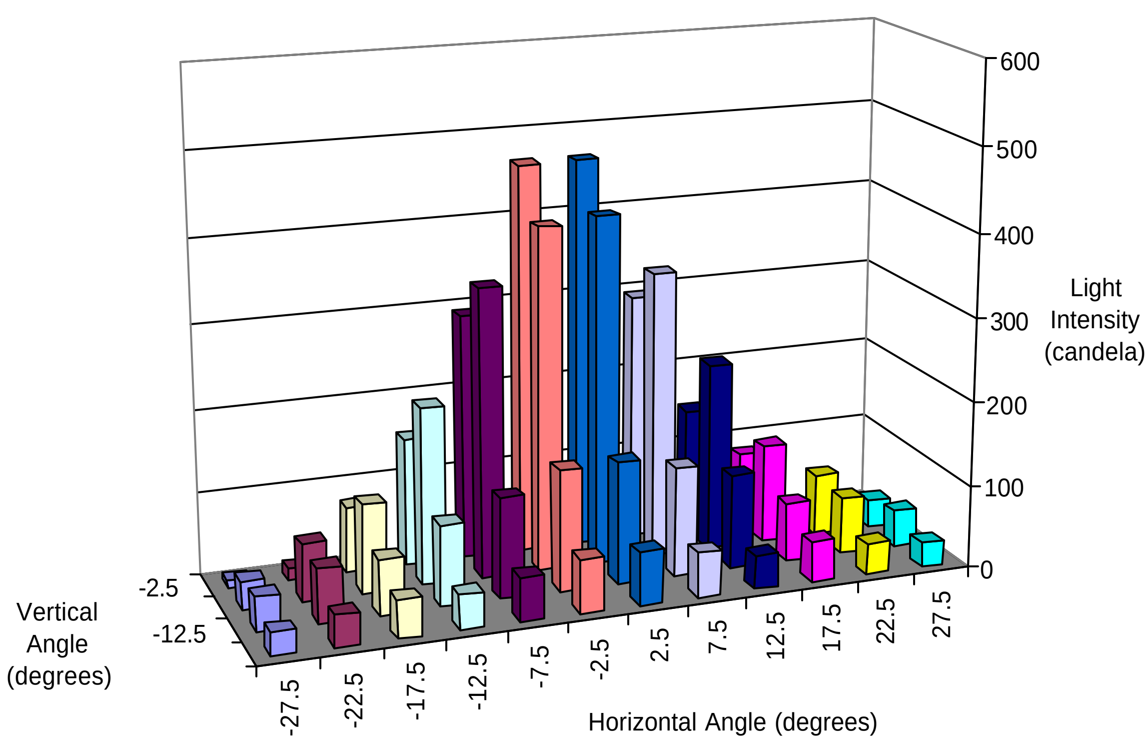

Figure A2.3.9b Output from WPS#2 (Red) signal, 9.0 volts, 176 elements (89.0% on), ITE test.

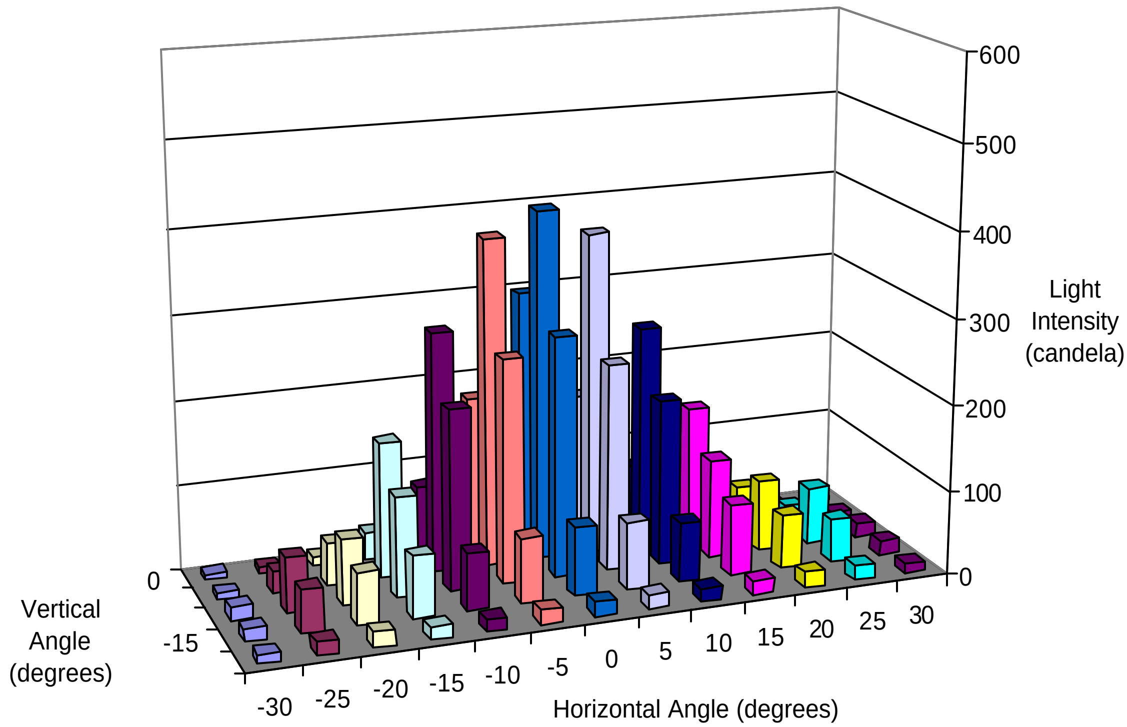

Figure A2.3.10a Output from WPS#2 (Red) signal, 10.5 volts, 176 elements (89.0% on), TC test.

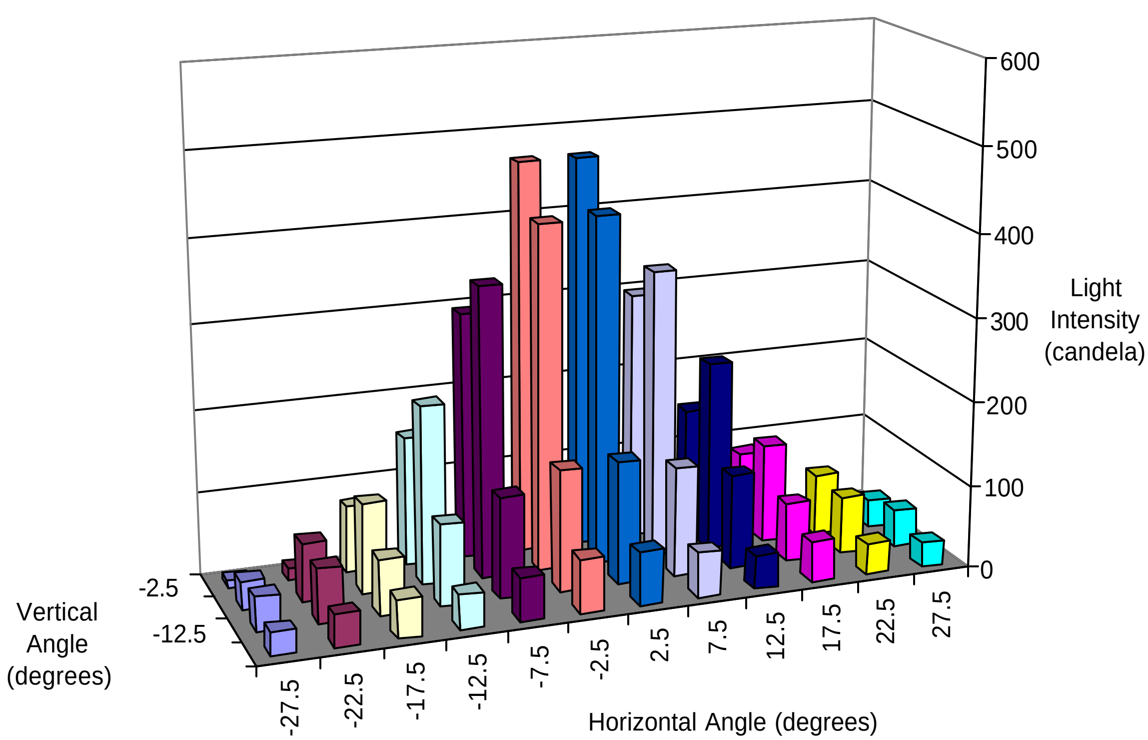

Figure A2.3.10b Output from WPS#2 (Red) signal, 10.5 volts, 176 elements (89.0% on), ITE test.

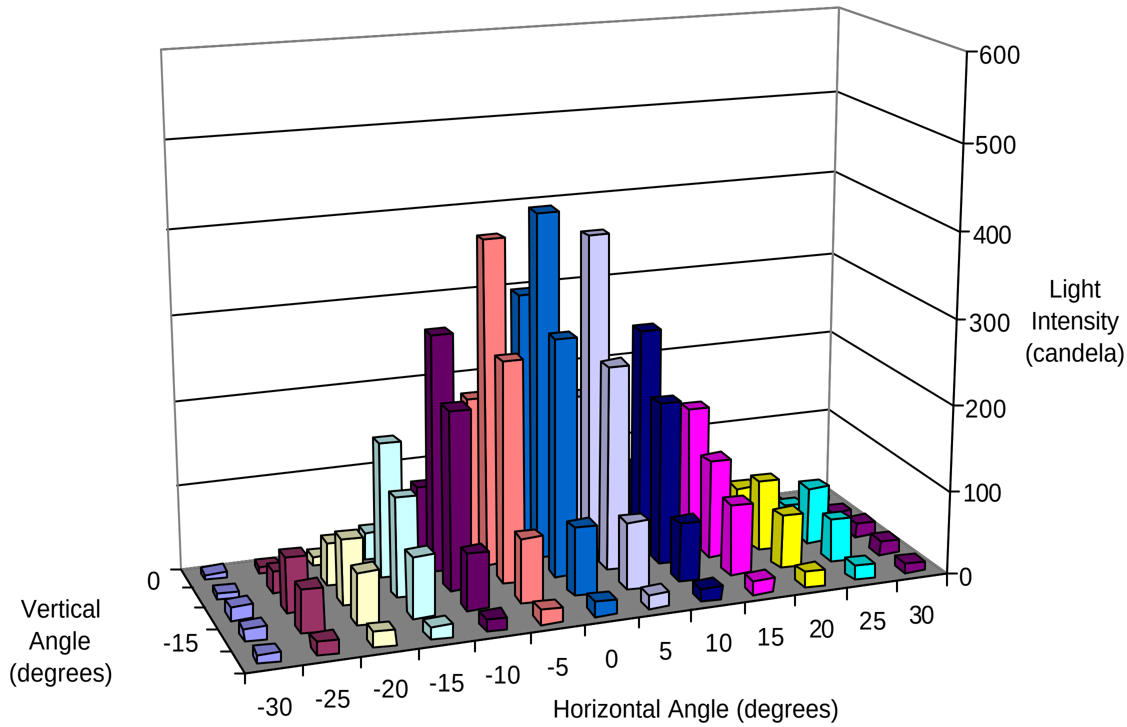

Figure A2.3.11a Output from WPS#2 (Red) signal, 12.0 volts, 176 elements (89.0% on), TC test.

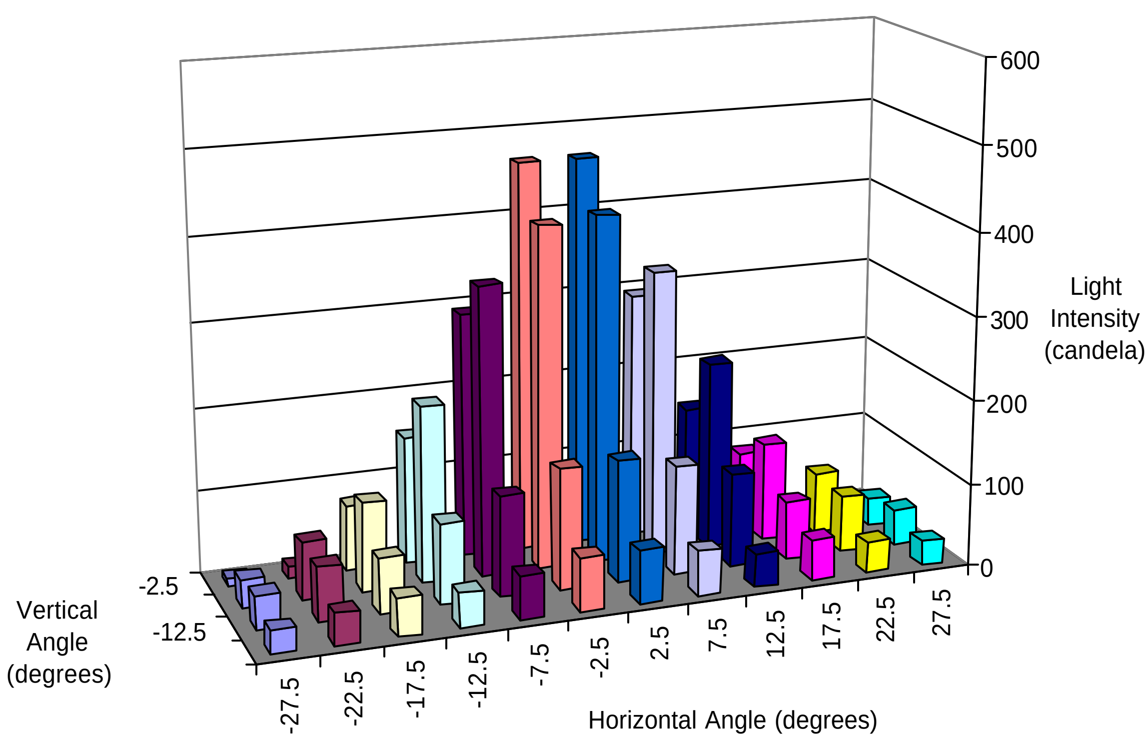

Figure A2.3.11b Output from WPS#2 (Red) signal, 12.0 volts, 176 elements (89.0% on), ITE test.

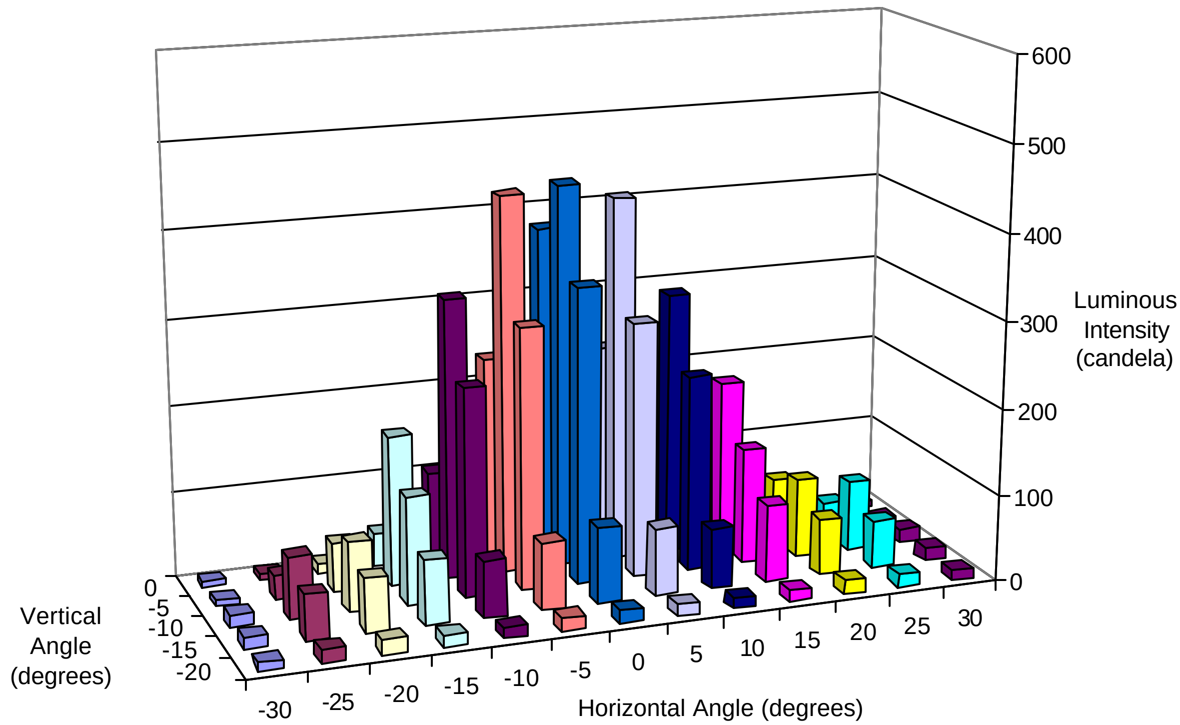

Figure A2.4.1a Output from WPS#2 (Red) signal, 10.5 volts, 196 elements (100% on), TC test.

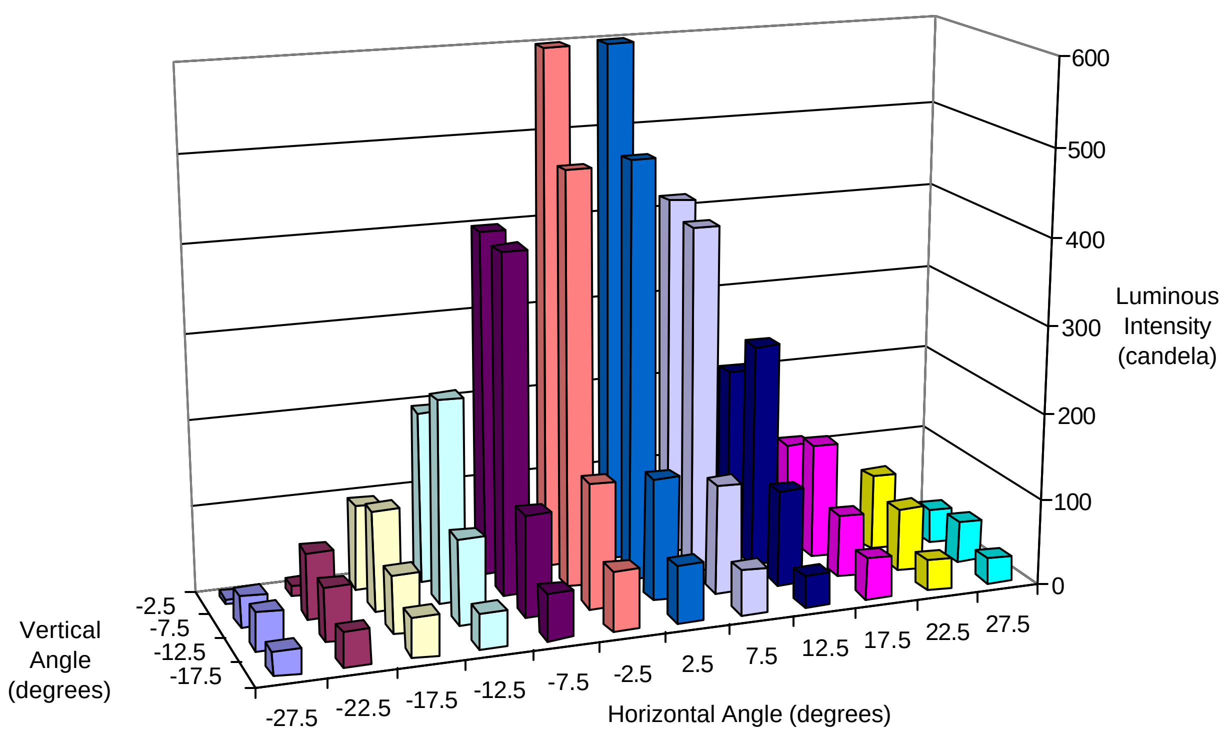

Figure A2.4.1b Output from WPS#2 (Red) signal, 10.5 volts, 196 elements (100% on), ITE test.

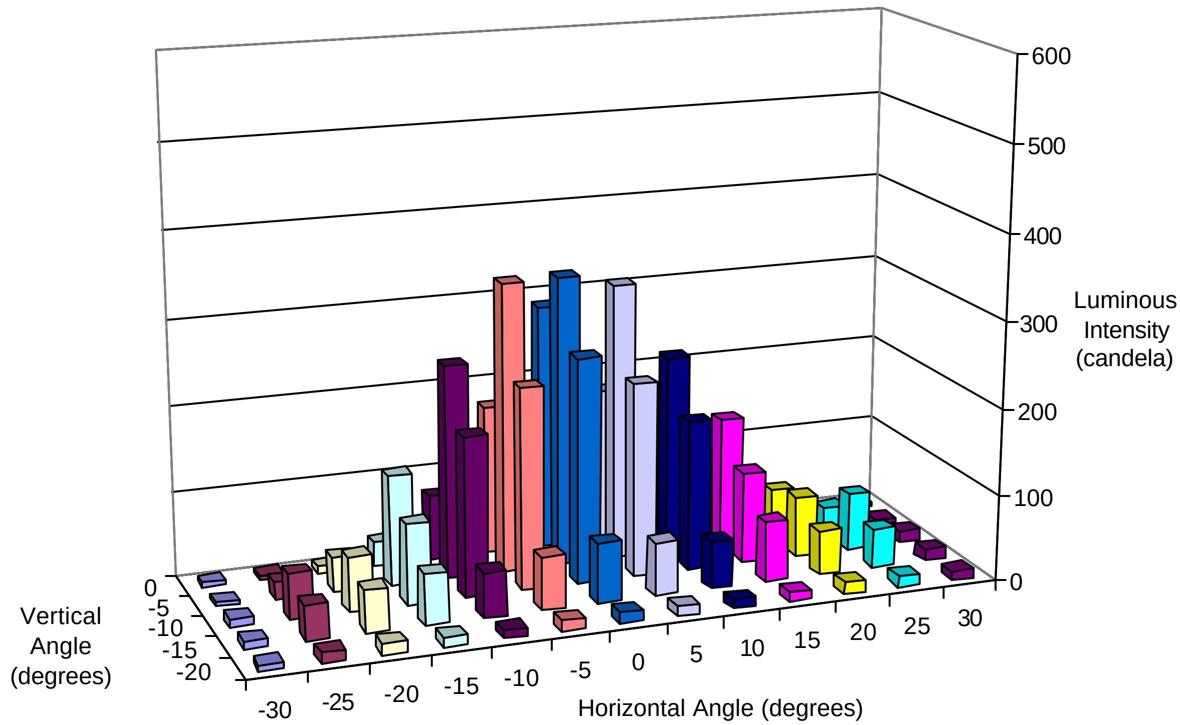

Figure A2.4.2a Output from WPS#2 (Red) signal, 10.5 volts, 180 elements (91.8% on), TC test.

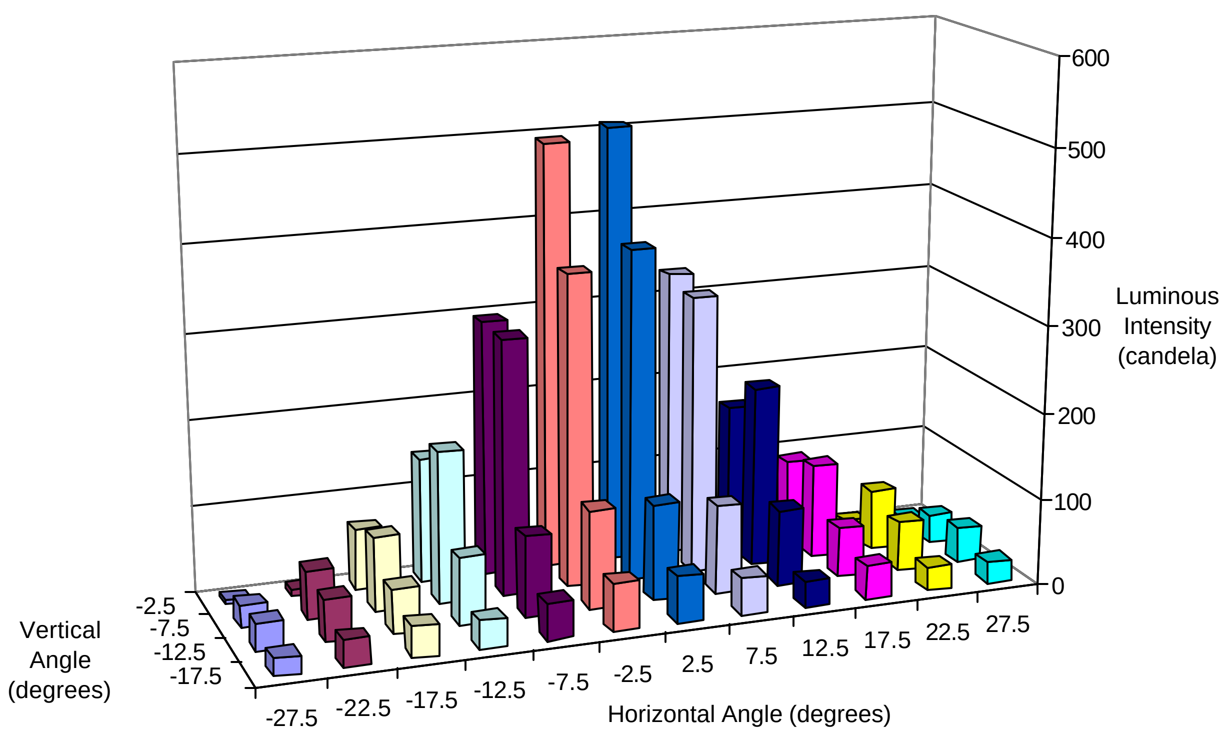

Figure A2.4.2b Output from WPS#2 (Red) signal, 10.5 volts, 180 elements (91.8% on), ITE test.

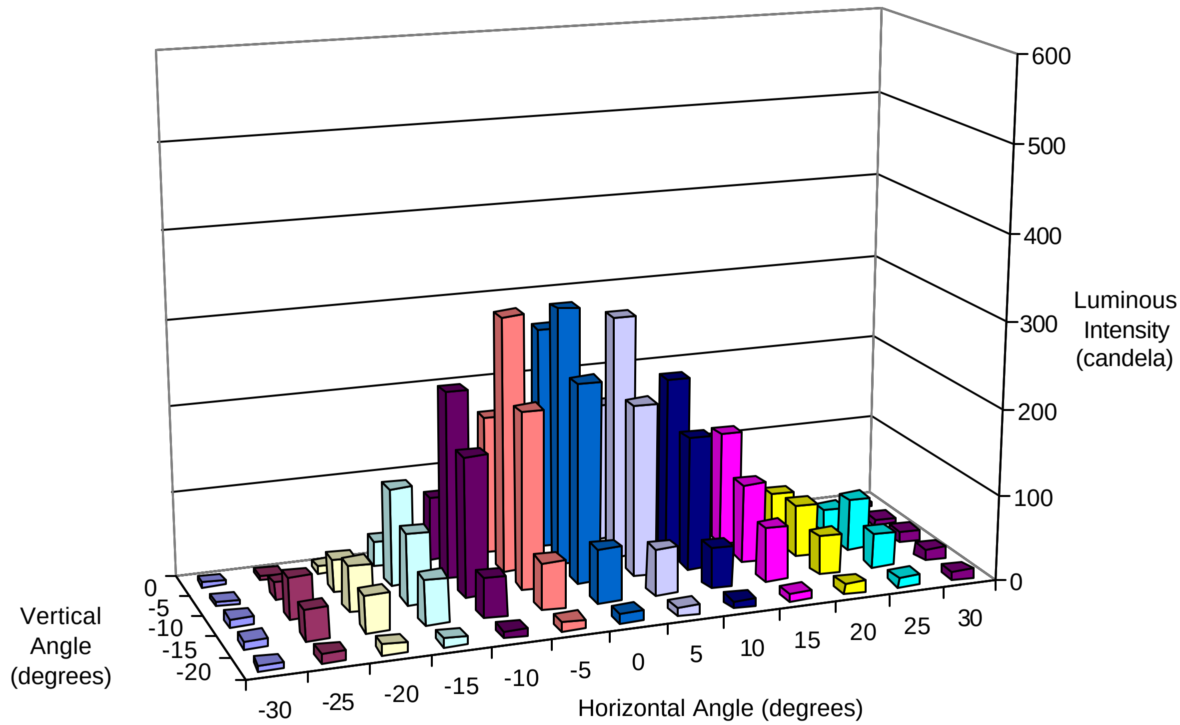

Figure A2.4.3a Output from WPS#2 (Red) signal, 10.5 volts, 164 elements (83.7% on), TC test.

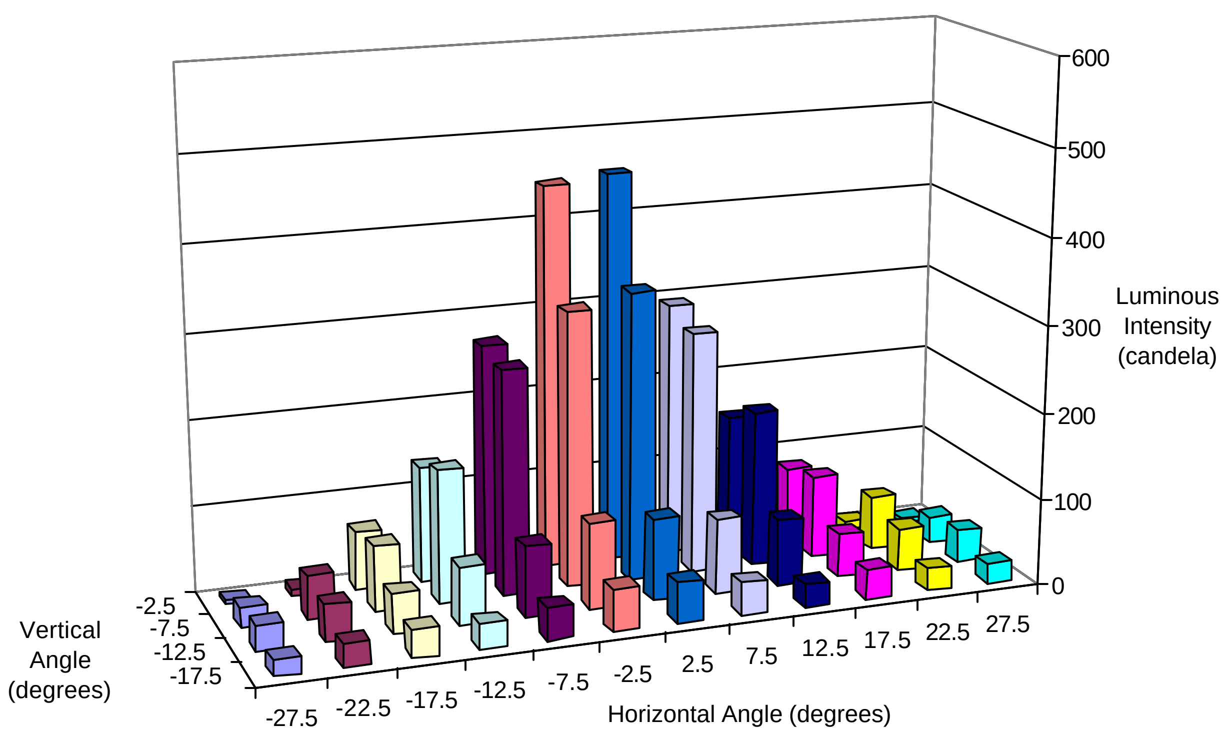

Figure A2.4.3b Output from WPS#2 (Red) signal, 10.5 volts, 164 elements (83.7% on), ITE test.

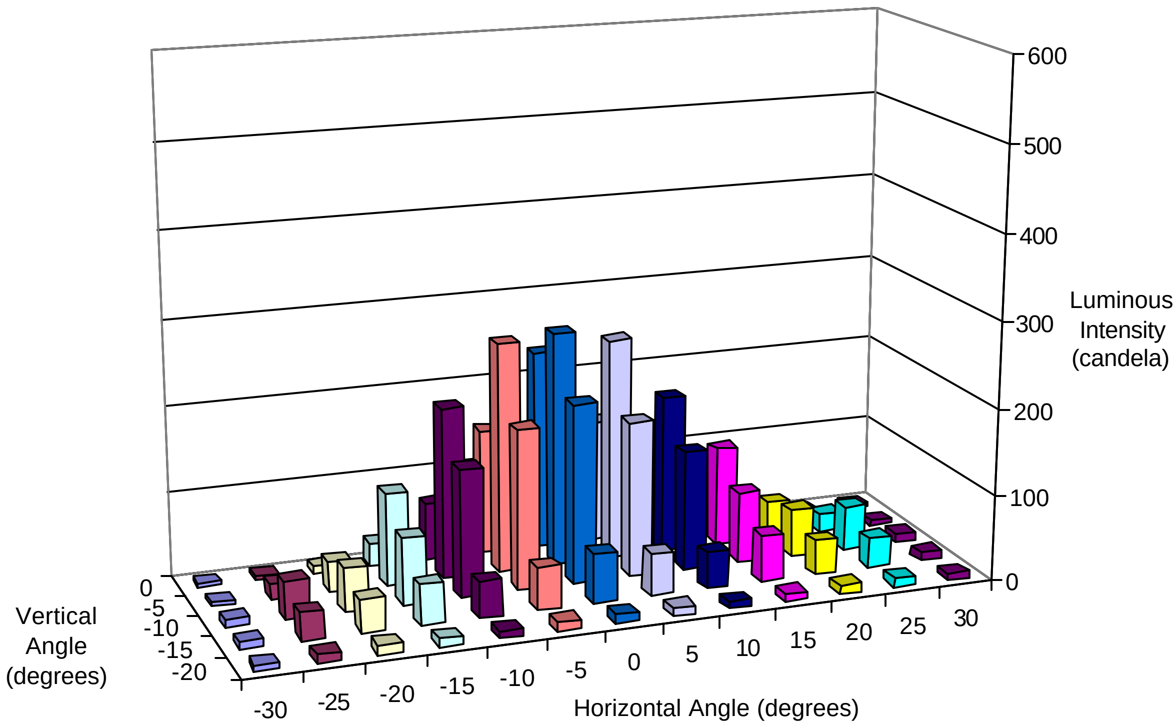

Figure A2.4.4a Output from WPS#2 (Red) signal, 10.5 volts, 148 elements (75.5% on), TC test.

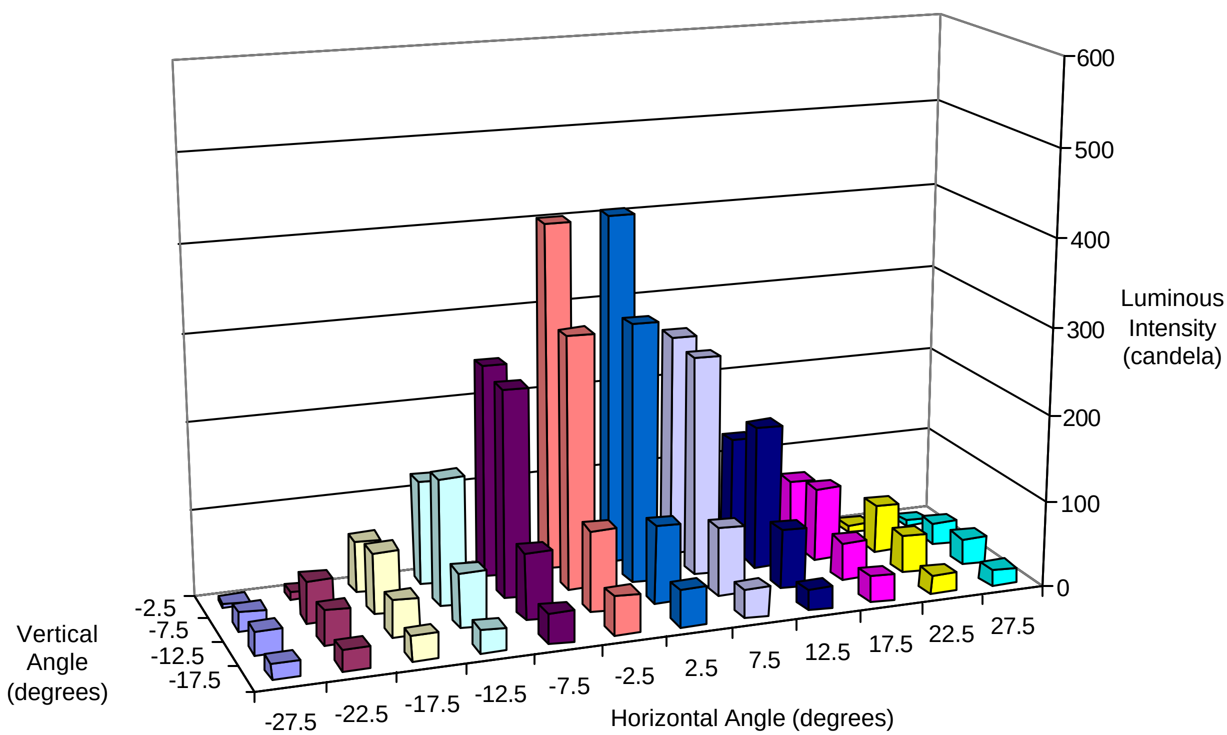

Figure A2.4.4b Output from WPS#2 (Red) signal, 10.5 volts, 148 elements (75.5% on), ITE test.

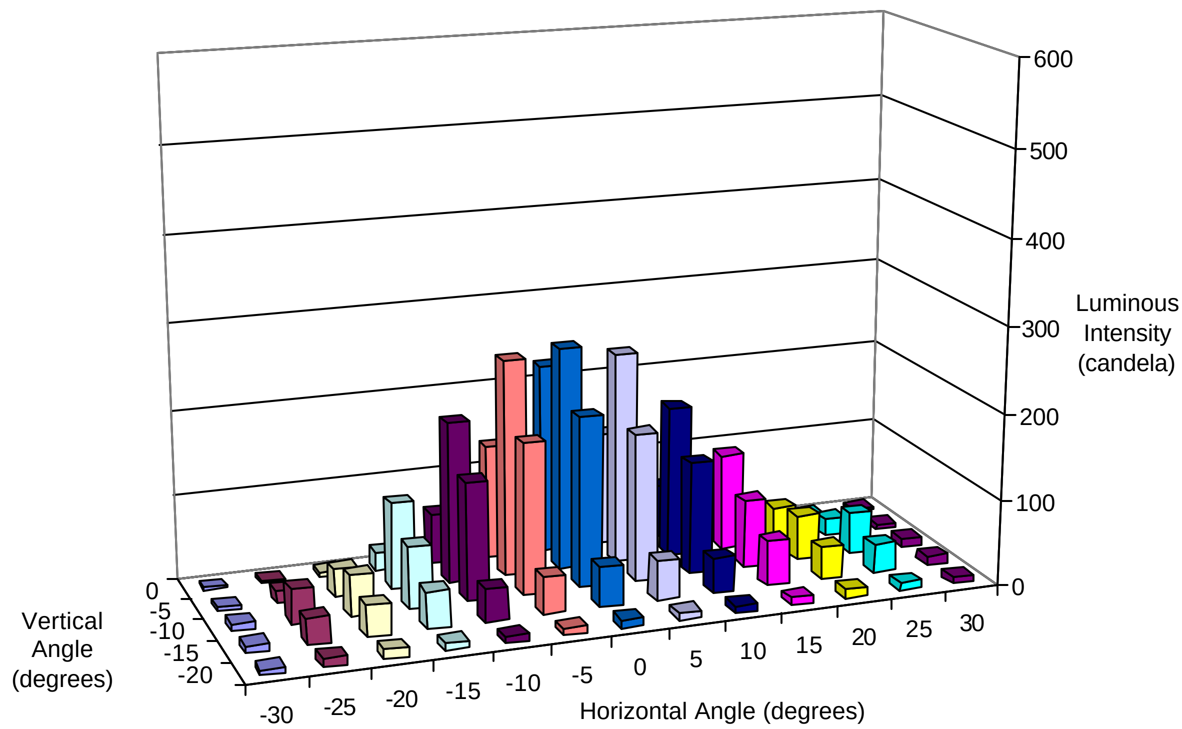

Figure A2.4.5a Output from WPS#2 (Red) signal, 10.5 volts, 132 elements (67.3% on), TC test.

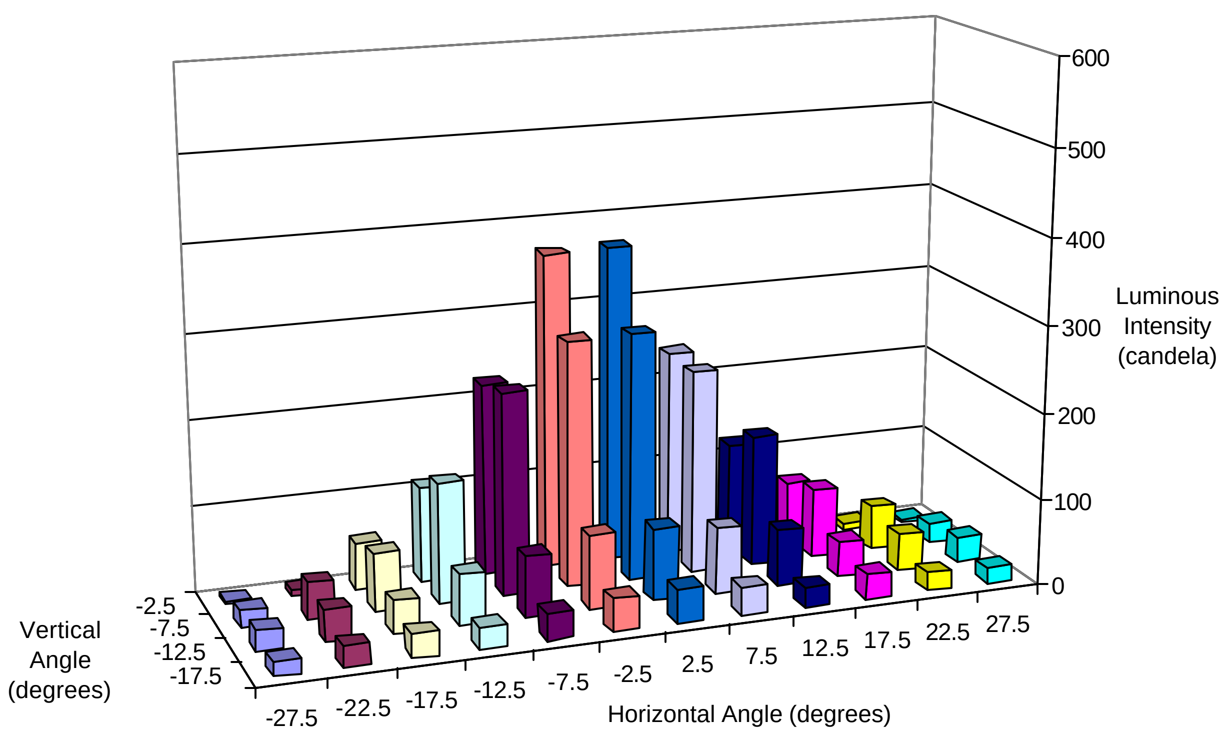

Figure A2.4.5b Output from WPS#2 (Red) signal, 10.5 volts, 132 elements (67.3% on), ITE test.

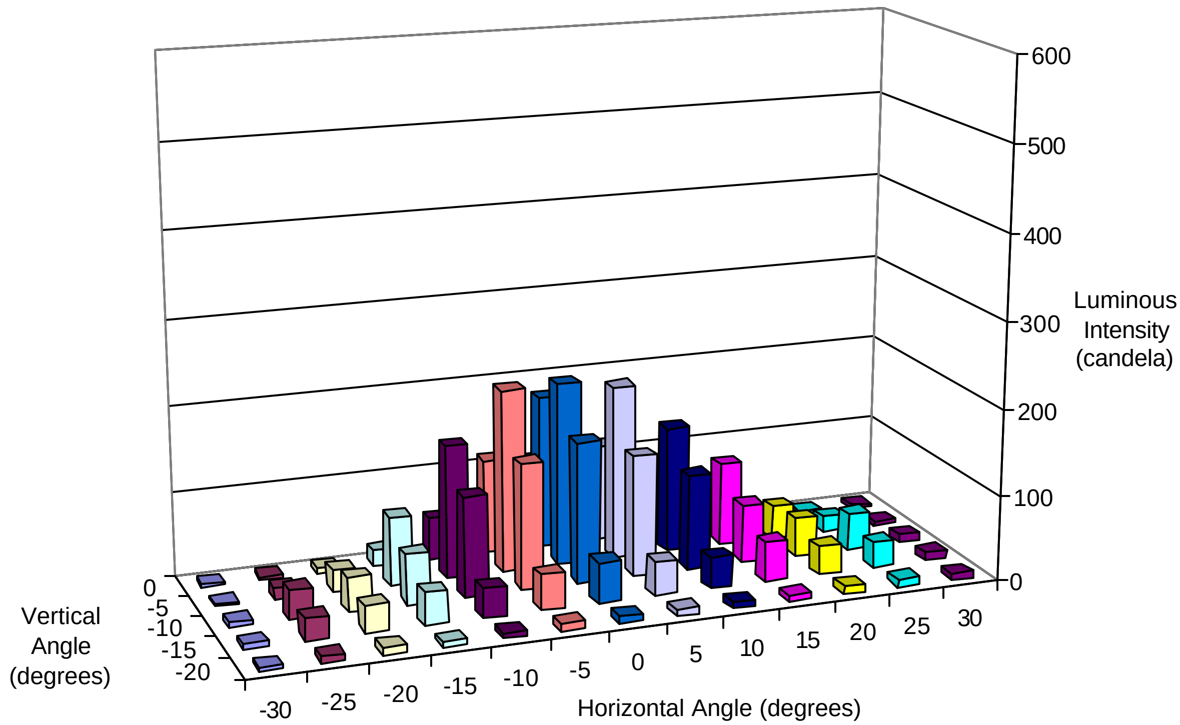

Figure A2.4.6a Output from WPS#2 (Red) signal, 10.5 volts, 116 elements (59.2% on), TC test.

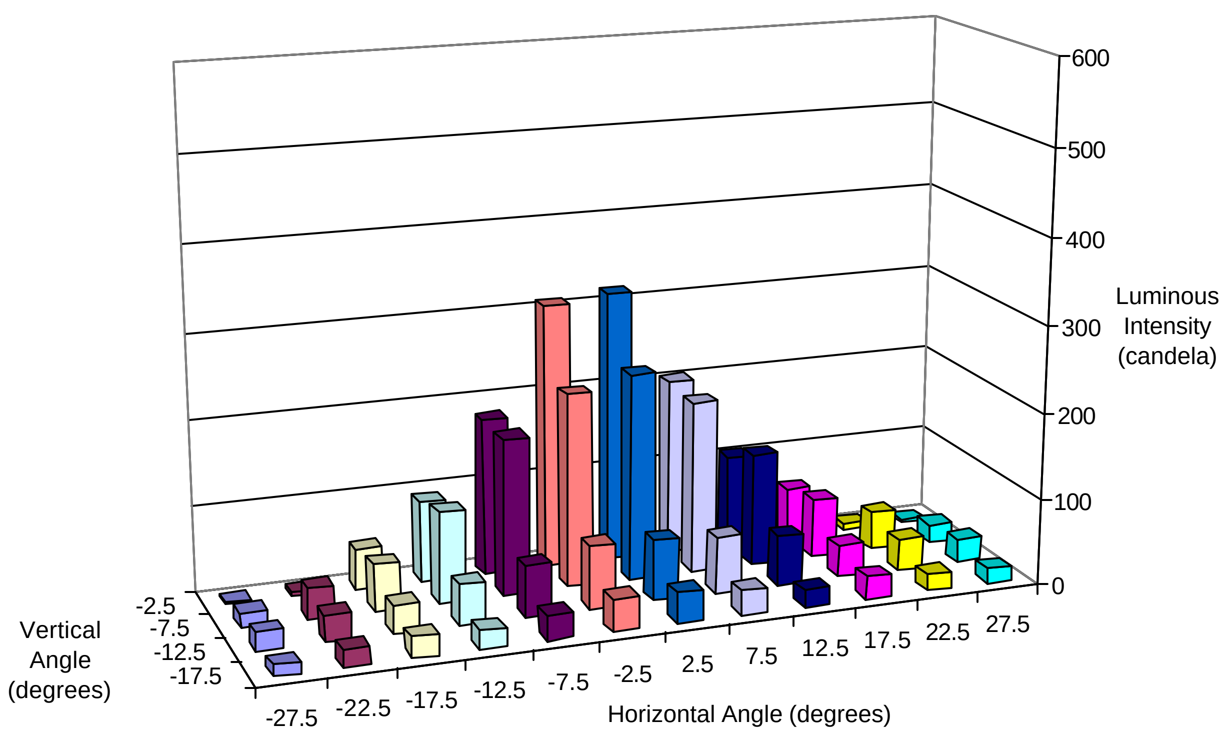

Figure A2.4.6b Output from WPS#2 (Red) signal, 10.5 volts, 116 elements (59.2% on), ITE test.

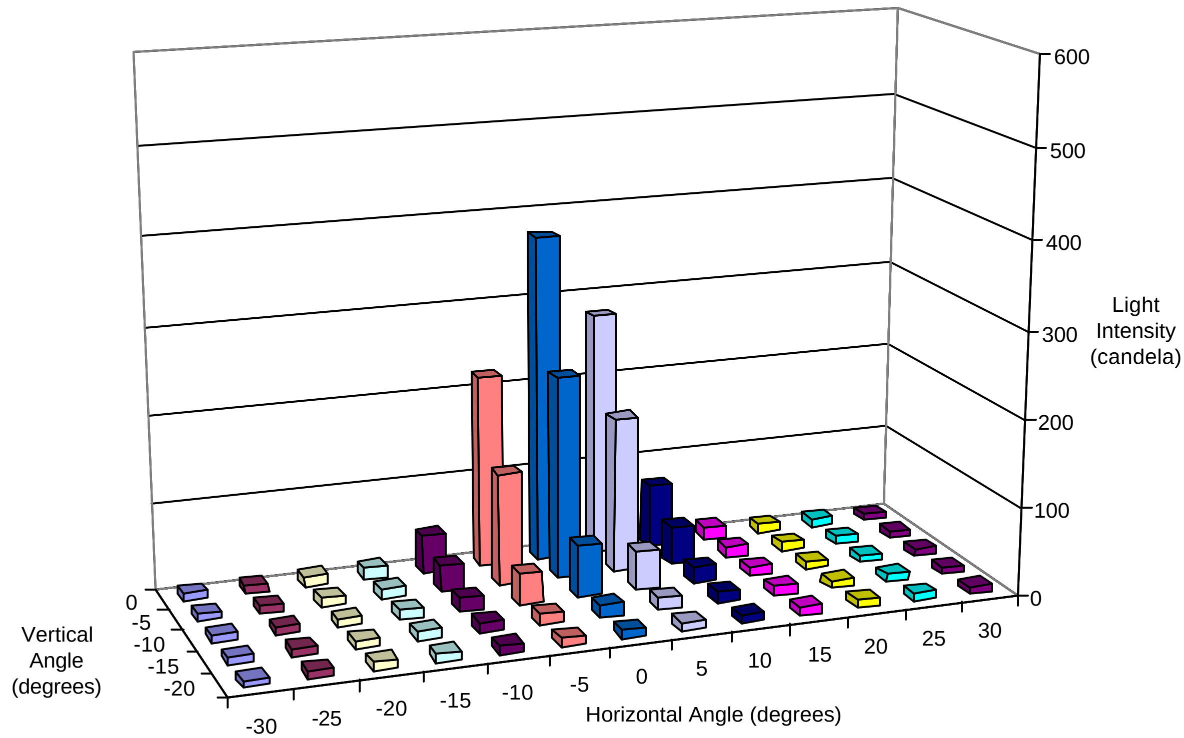

Figure A3.1.1a Output from WPS #3 (Red) signal, 10.5 volts, all elements on, TC test.

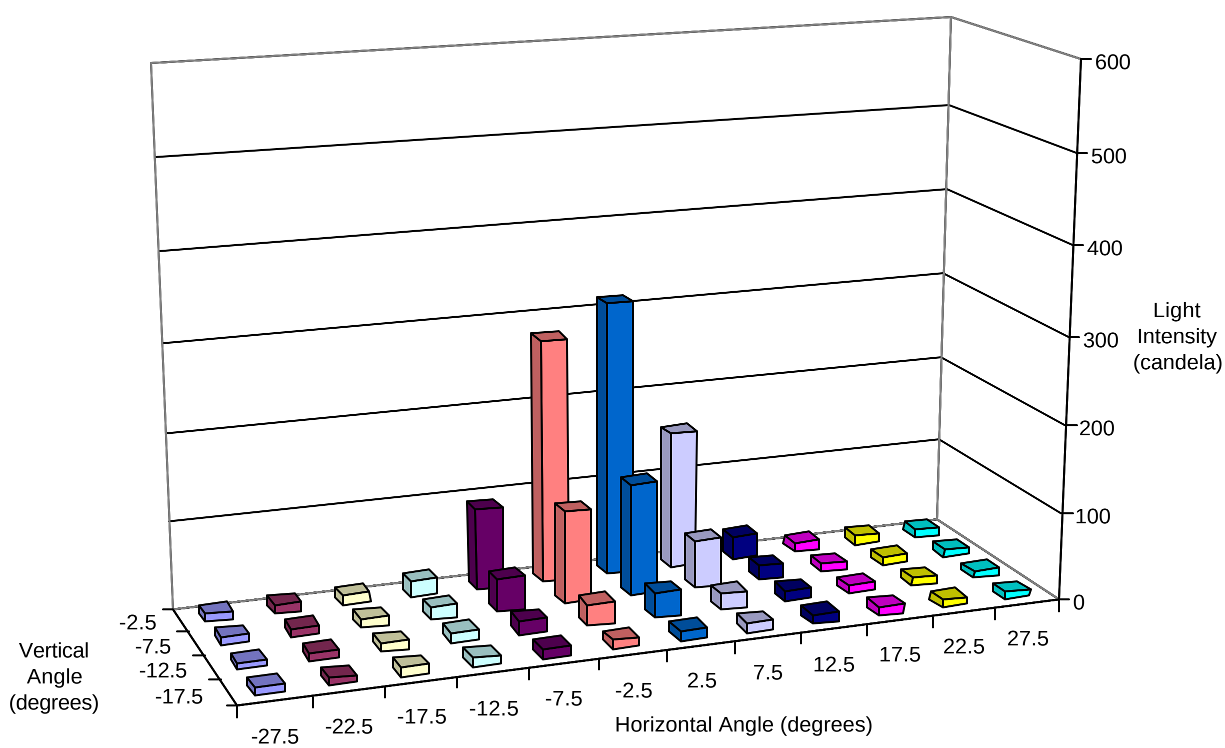

Figure A3.1.1b Output from WPS #3 (Red) signal, 10.5 volts, all elements on, ITE test.

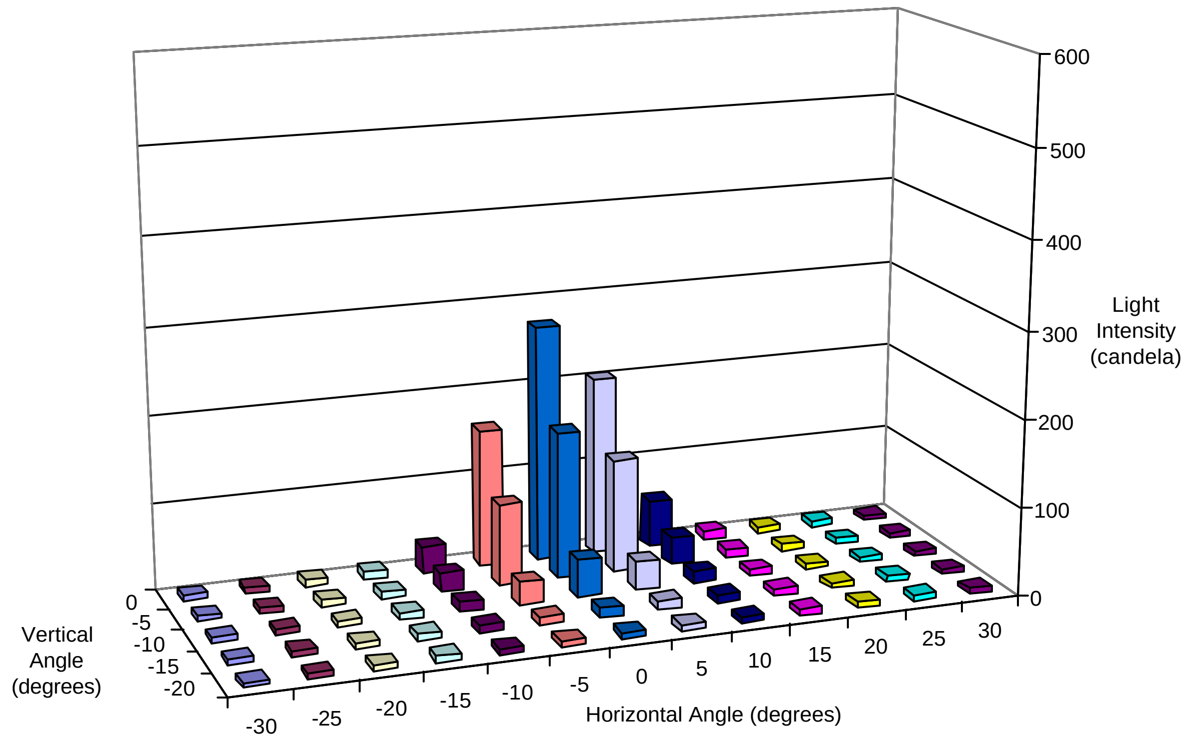

Figure A3.1.2a Output from WPS #3 (Red) signal, 9.0 volts, all elements on, TC test.

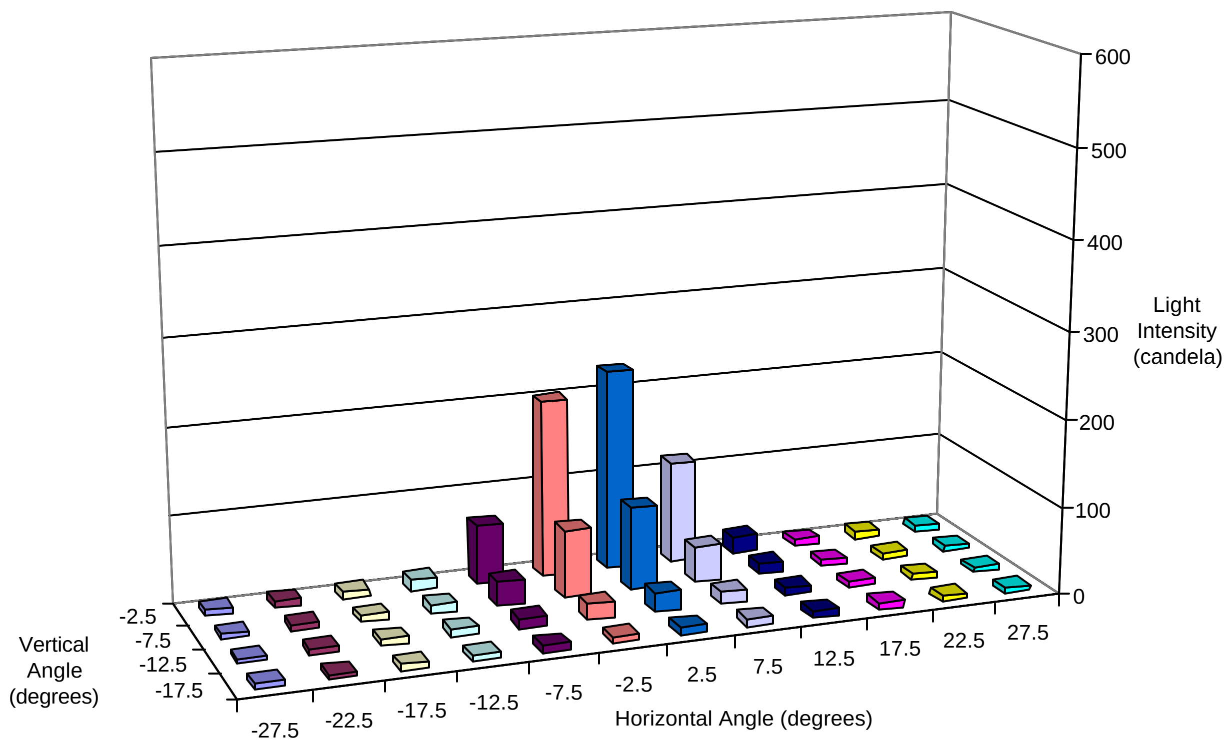

Figure A3.1.2b Output from WPS #3 (Red) signal, 9.0 volts, all elements on, ITE test.

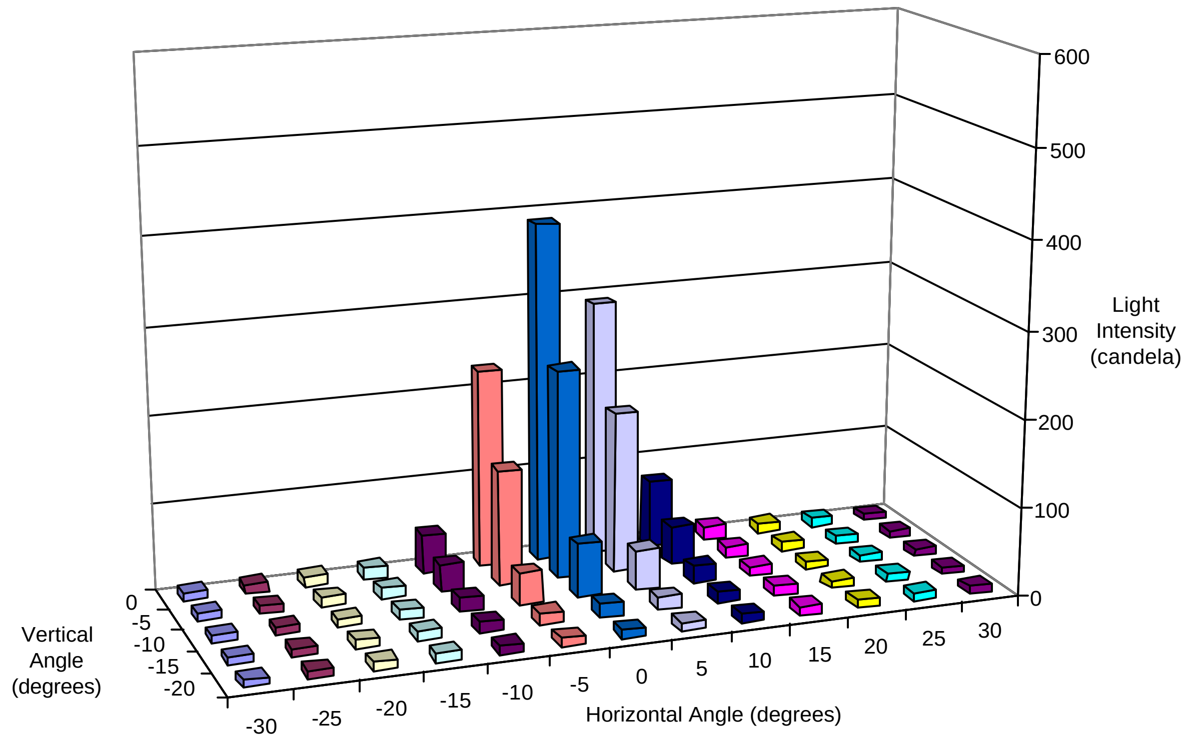

Figure A3.1.3a Output from WPS #3 (Red) signal, 12.0 volts, all elements on, TC test.

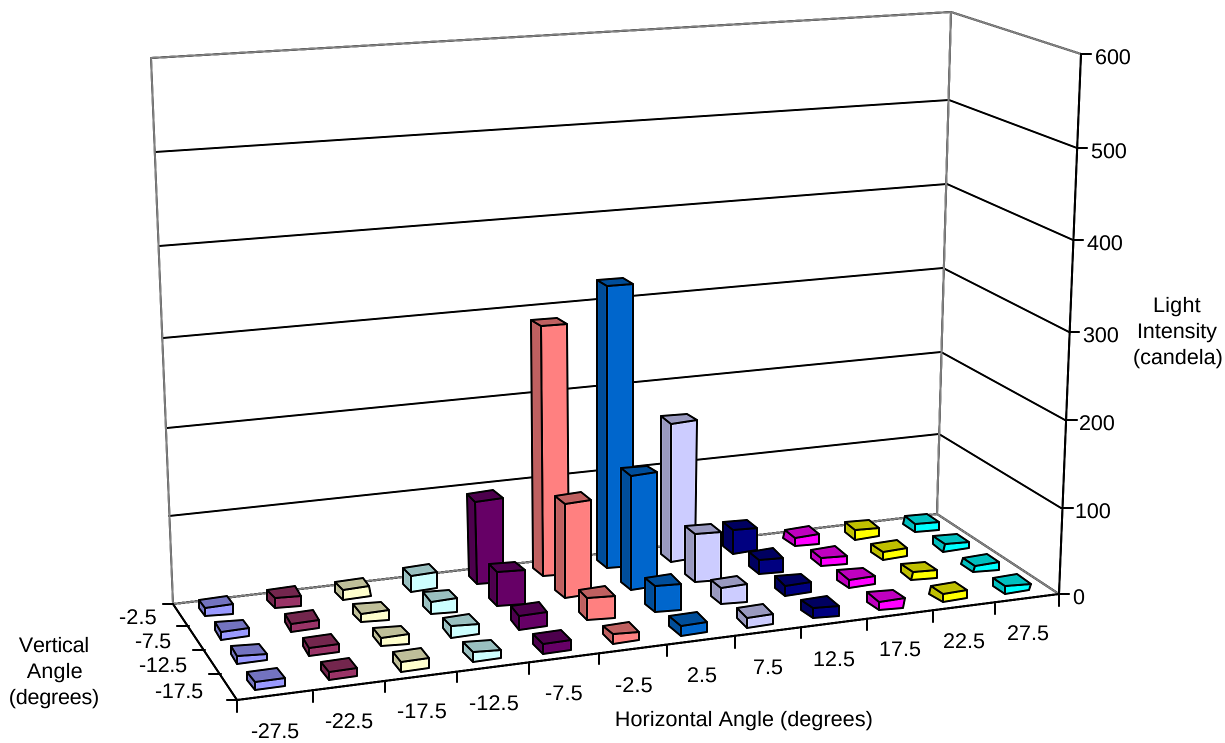

Figure A3.1.3b Output from WPS #3 (Red) signal, 12.0 volts, all elements on, ITE test.

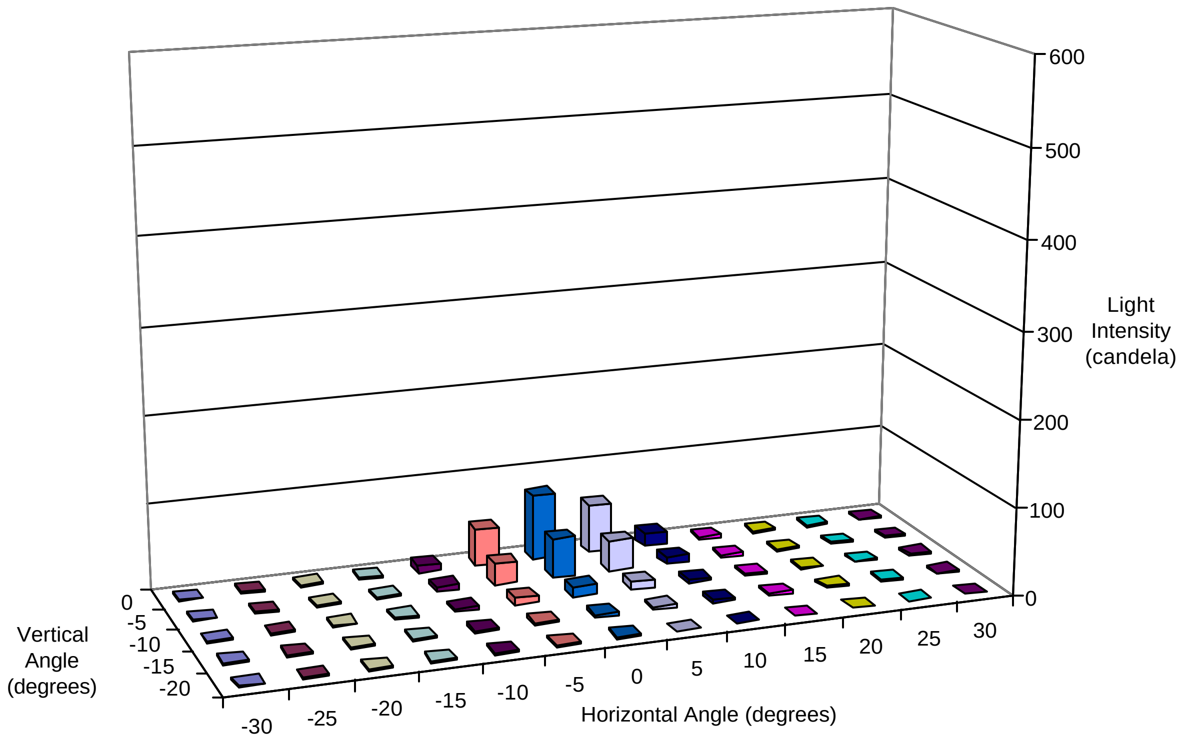

Figure A3.1.4a Output from WPS #3 (Red) signal, 7.5 volts, all elements on, TC test.

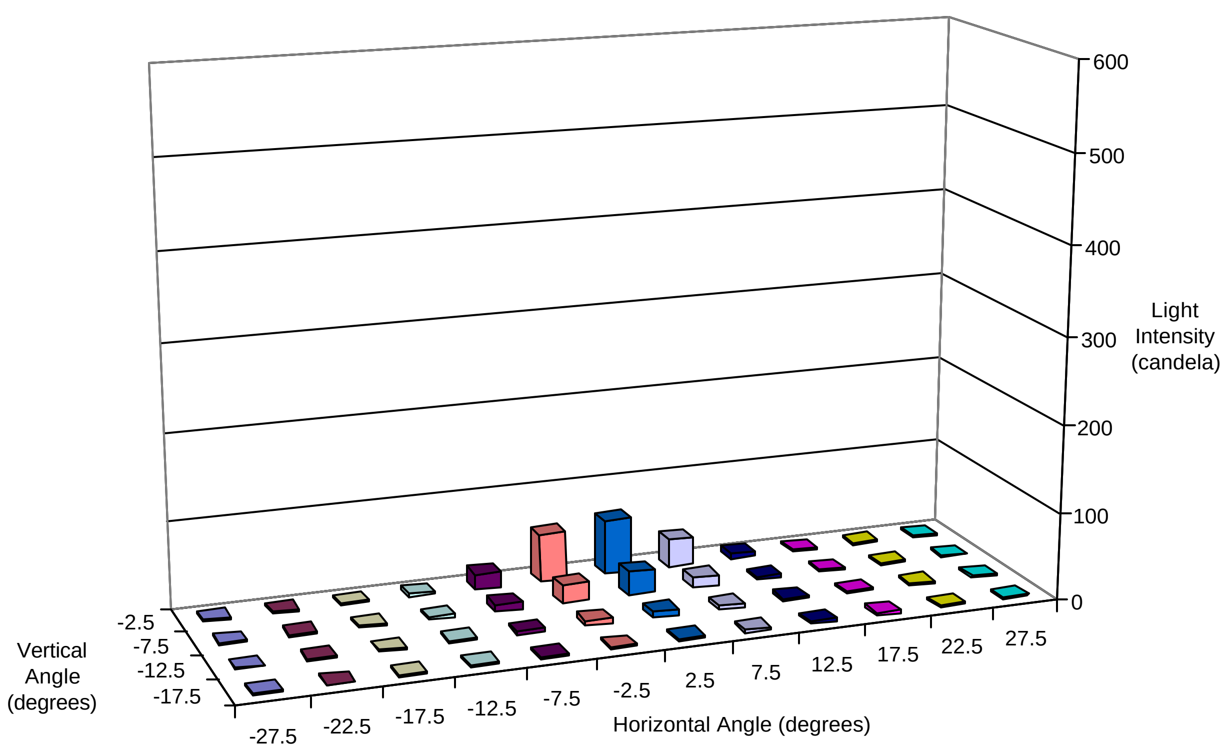

Figure A3.1.4b Output from WPS #3 (Red) signal, 7.5 volts, all elements on, ITE test.

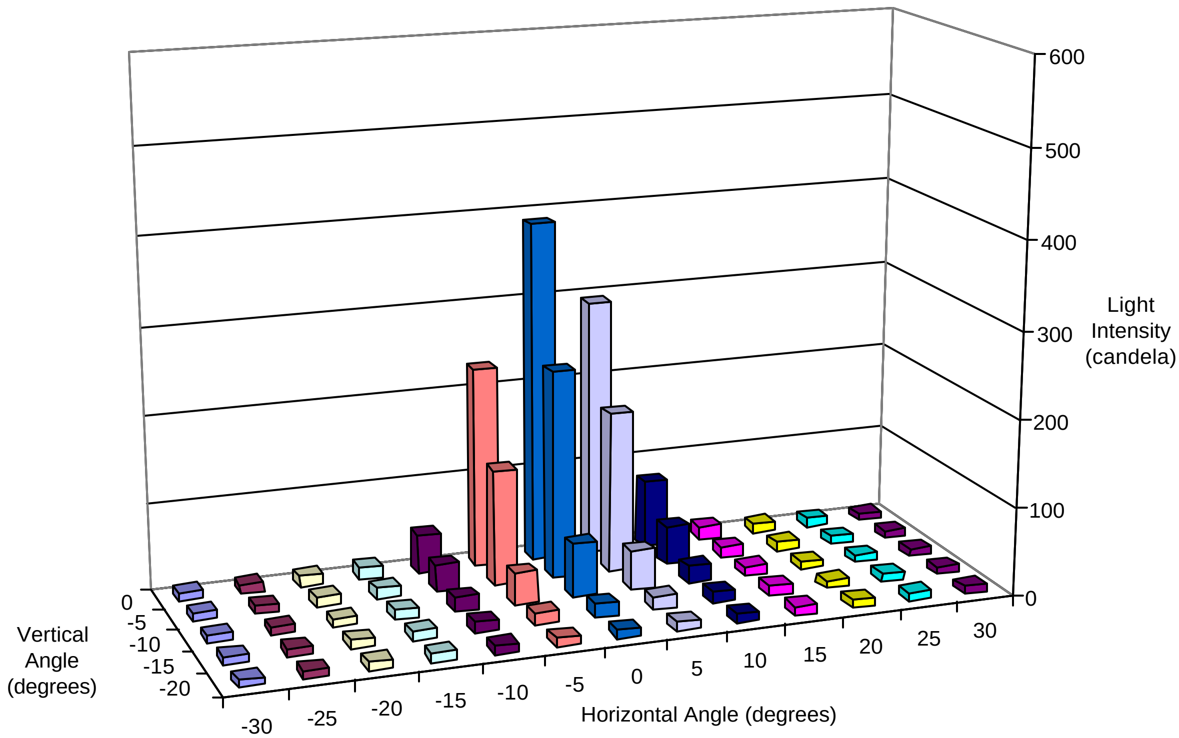

Figure A3.1.5a Output from WPS #3 (Red) signal, 13.5 volts, all elements on, TC test.

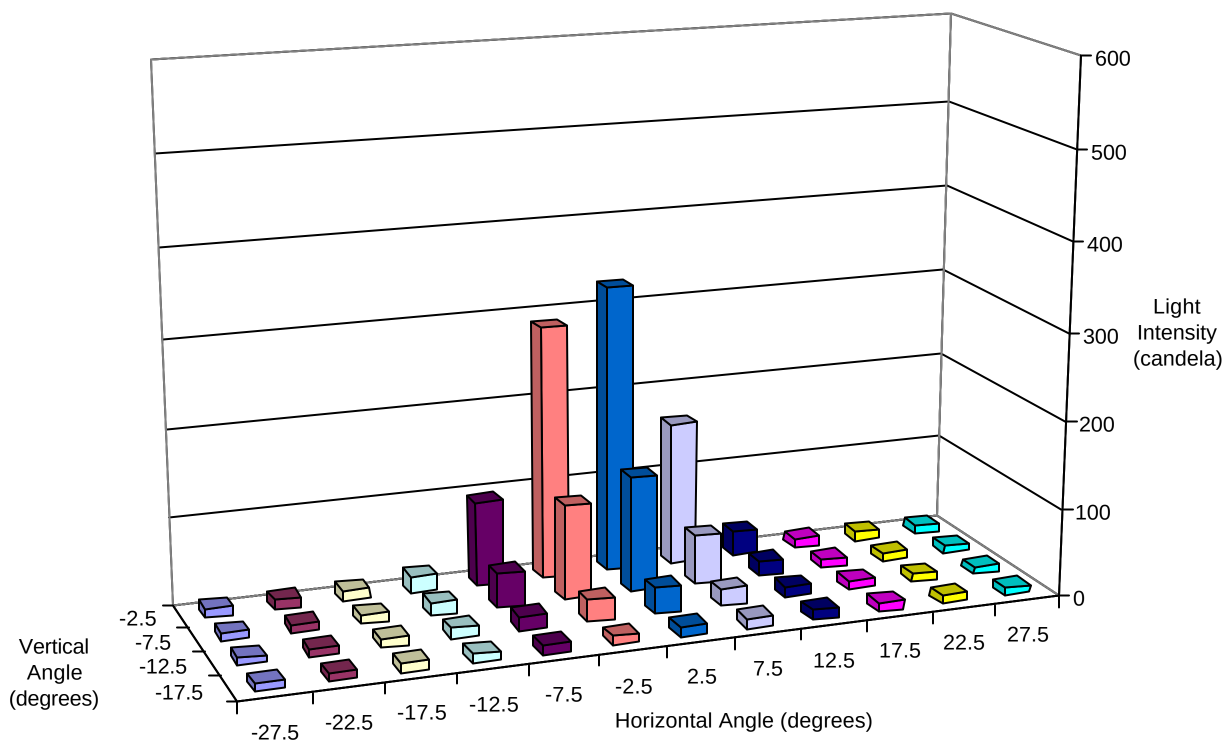

Figure A3.1.5b Output from WPS #3 (Red) signal, 13.5 volts, all elements on, ITE test.

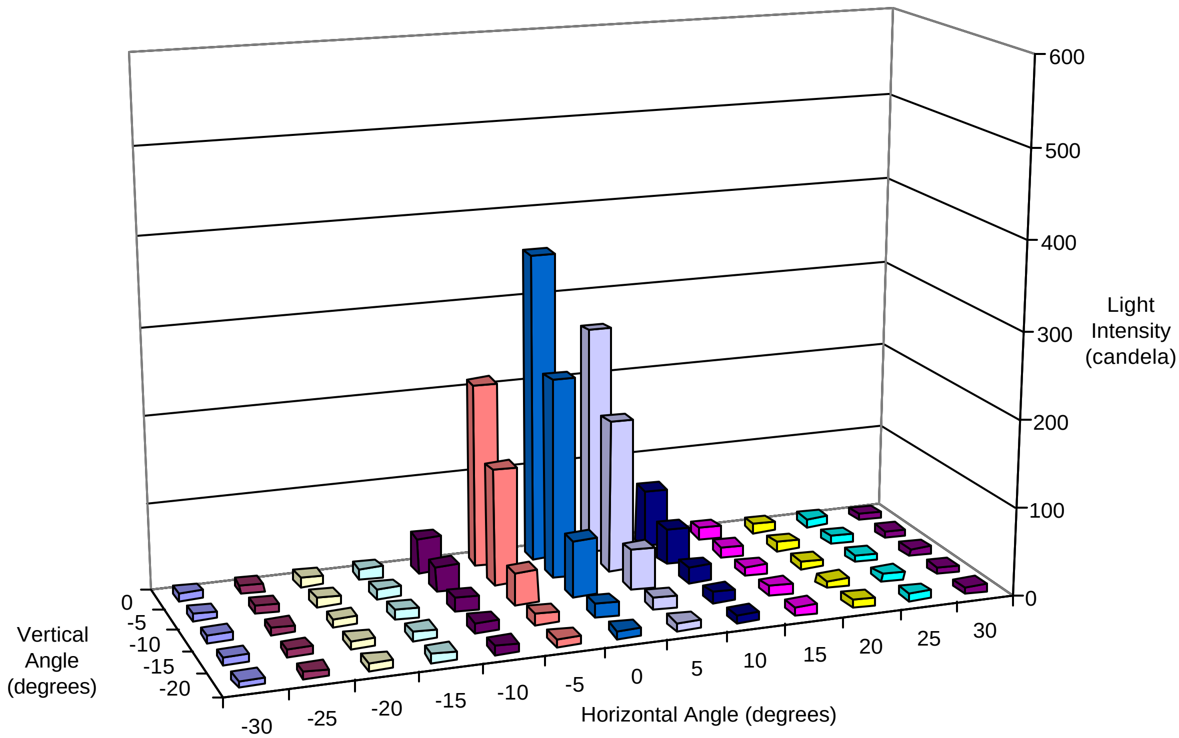

Figure A3.2.1a Output from WPS #3 (Red) signal, 10.5 volts, all elements on, TC test.

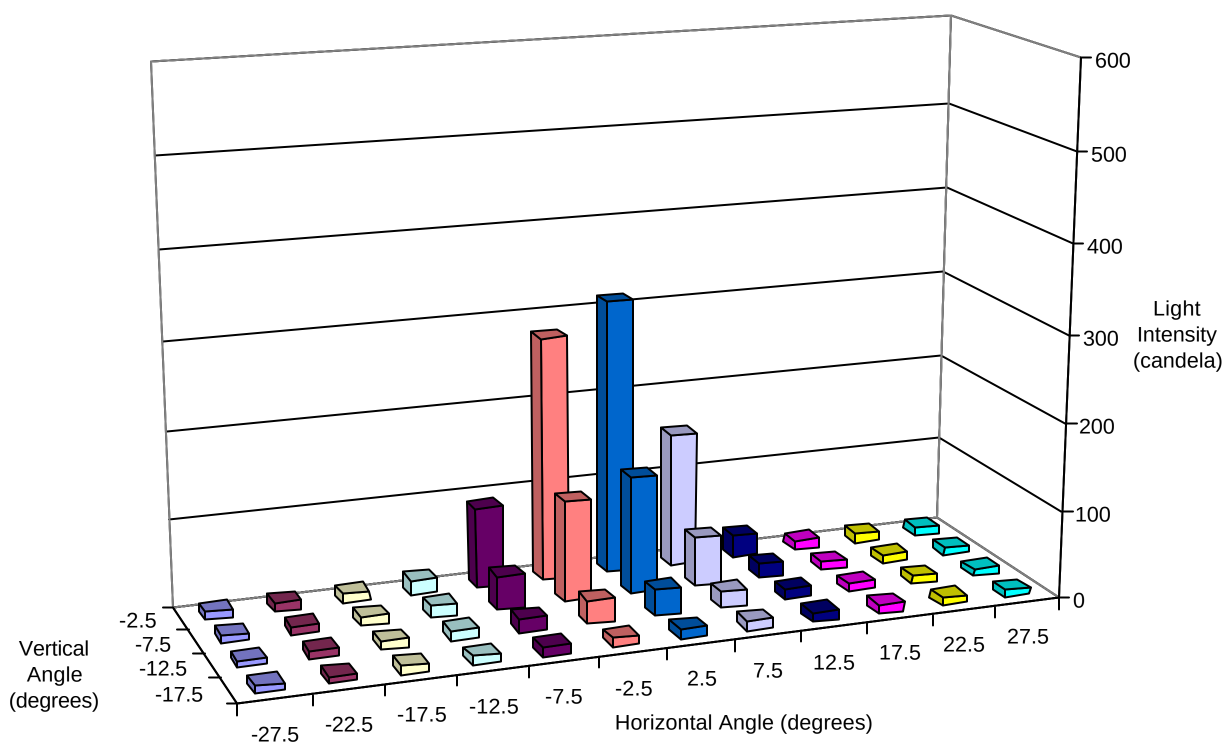

Figure A3.2.2b Output from WPS #3 (Red) signal, 10.5 volts, all elements on, ITE test.

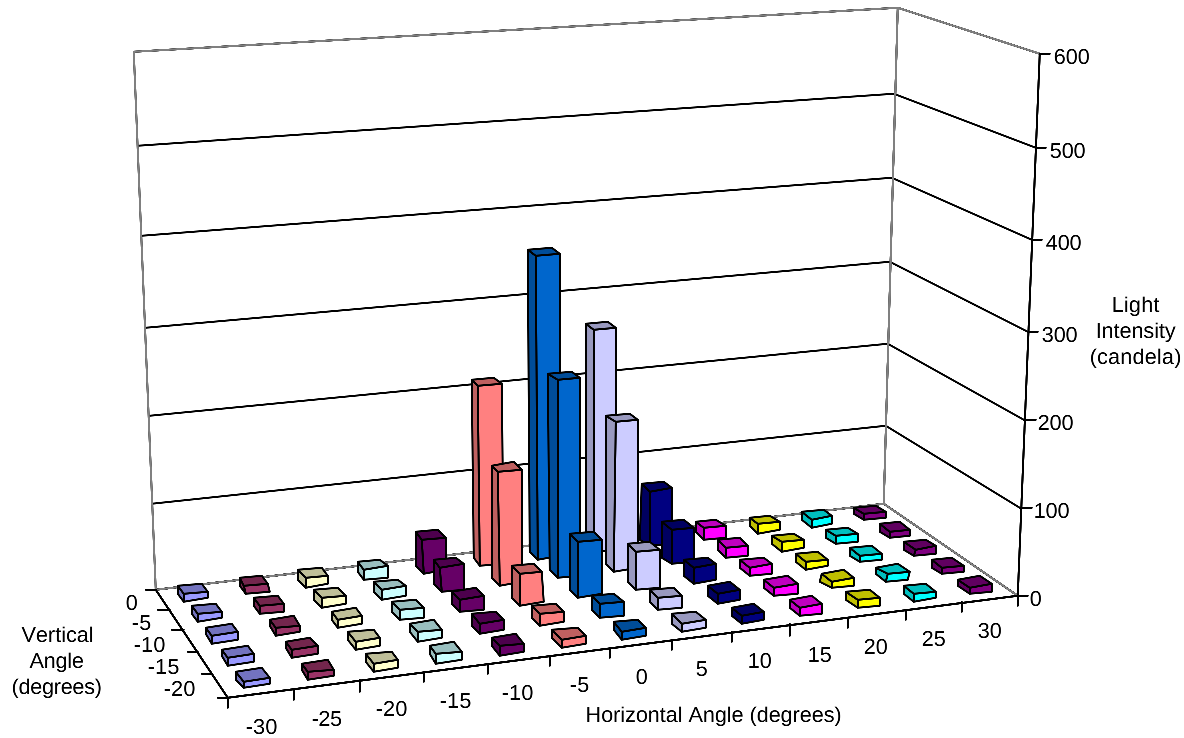

Figure A3.2.2a Output from WPS #3 (Red) signal, 10.5 volts, 239 elements (94.0% on), TC test.

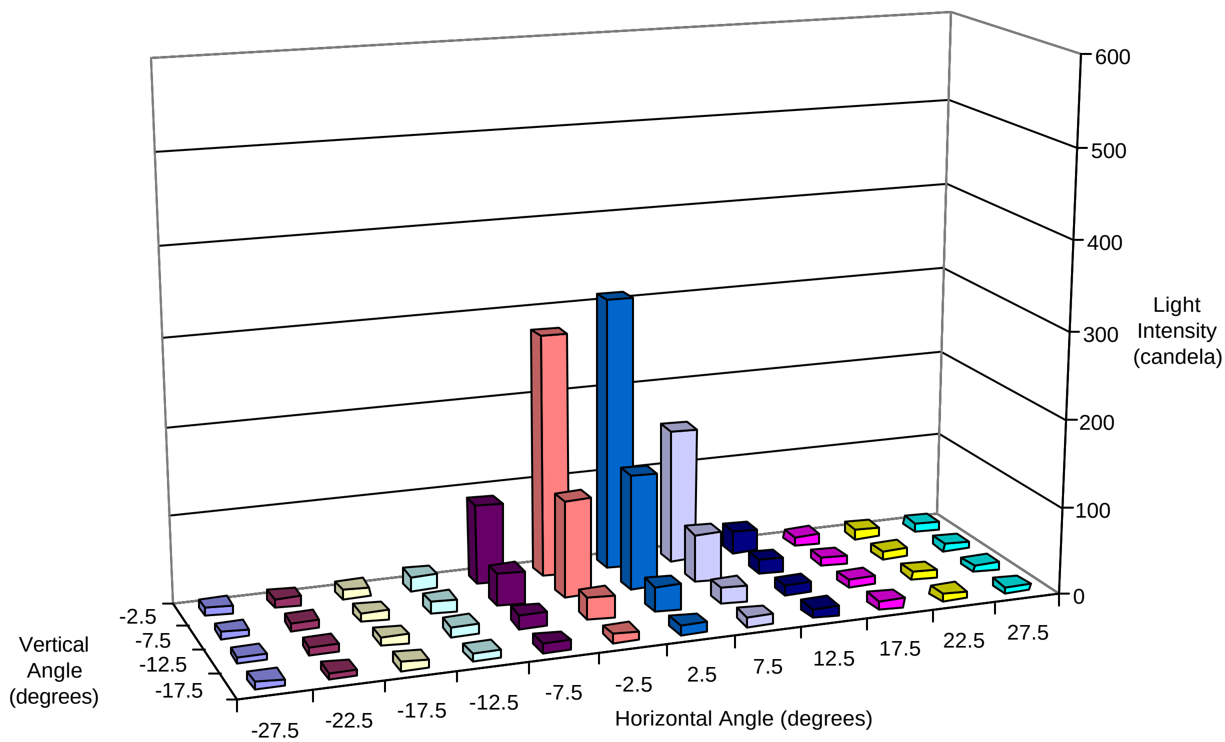

Figure A3.2.2b Output from WPS #3 (Red) signal, 10.5 volts, 239 elements (94.0% on), ITE test.

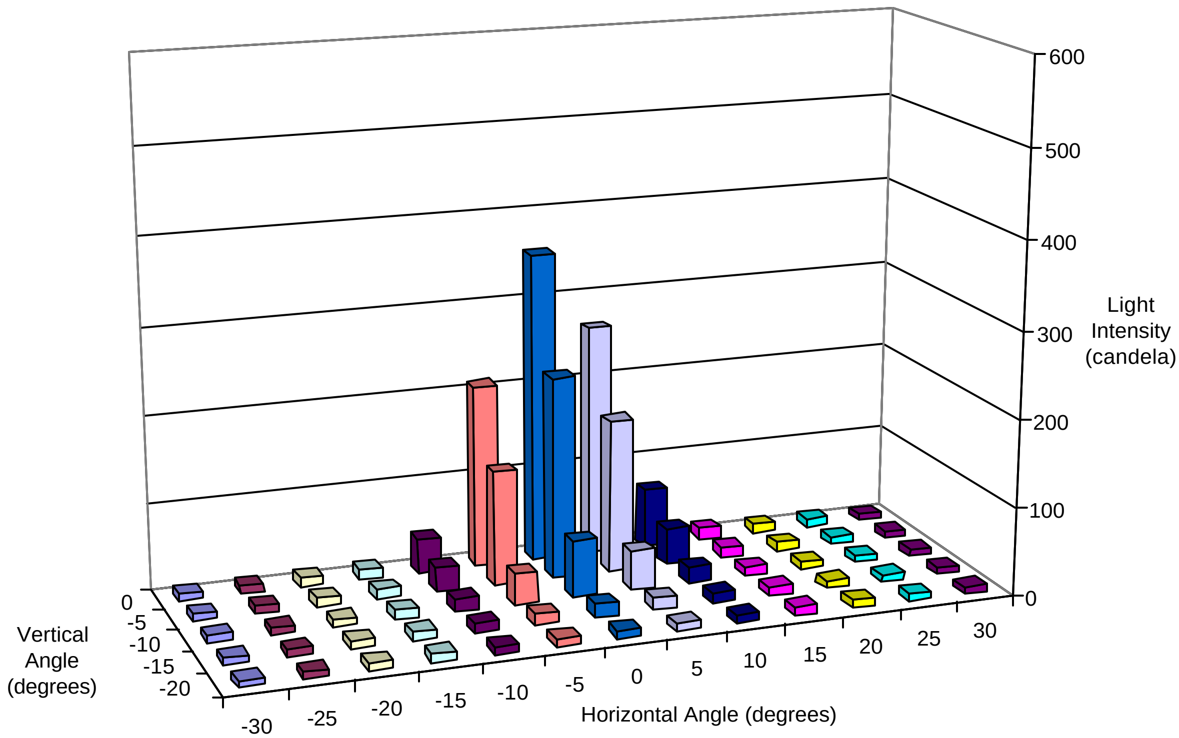

Figure A3.2.3a Output from WPS #3 (Red) signal, 10.5 volts, 224 elements (88.0% on), TC test.

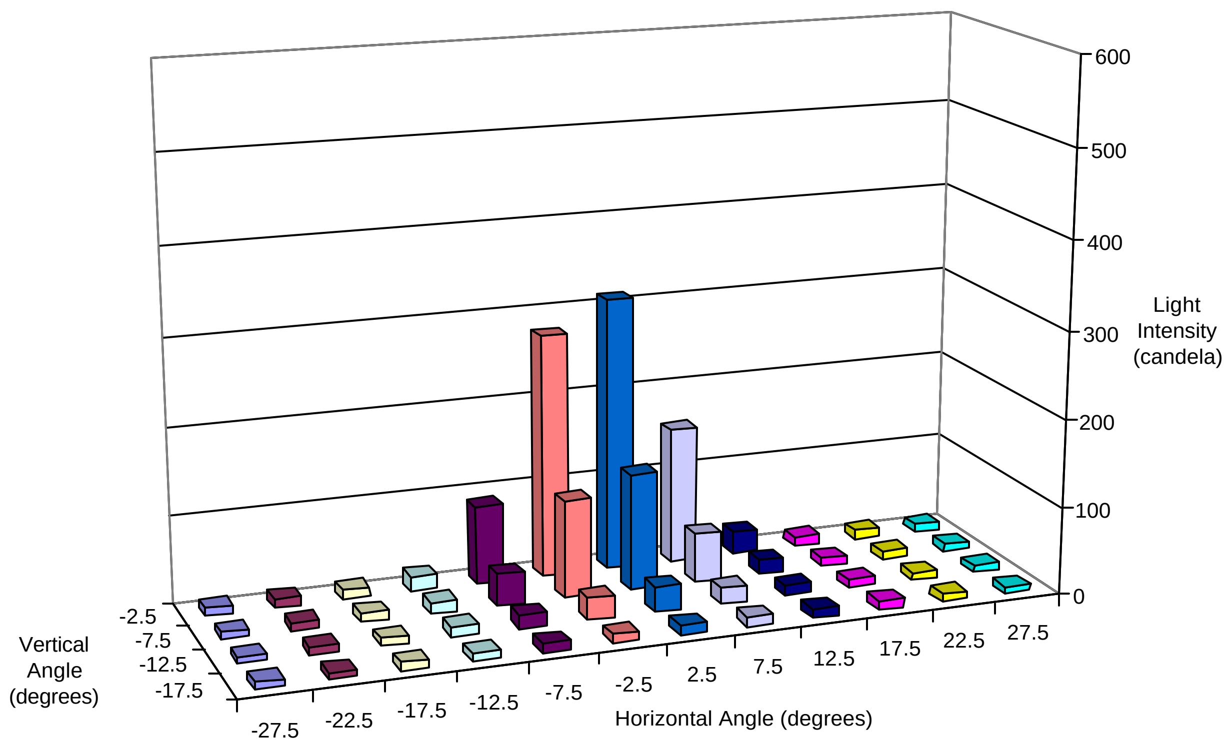

Figure A3.2.3b Output from WPS #3 (Red) signal, 10.5 volts, 224 elements (88.0% on), ITE test.

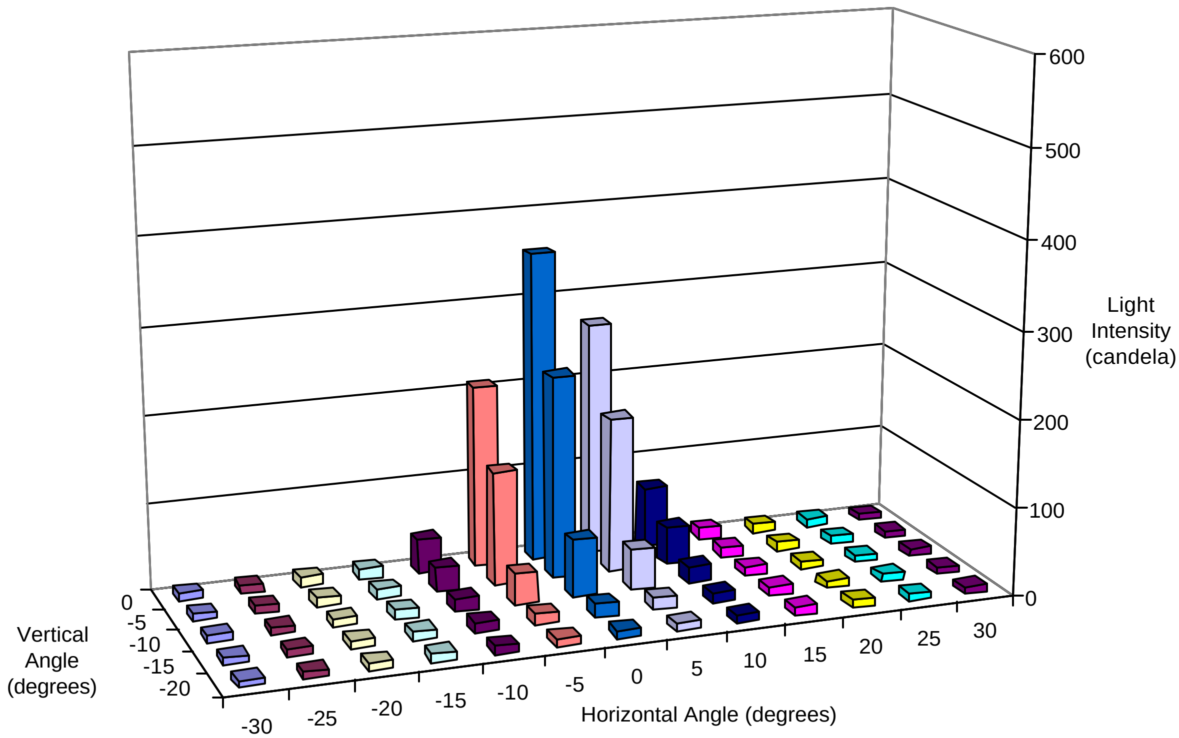

Figure A3.2.4a Output from WPS #3 (Red) signal, 10.5 volts, 209 elements (82.0% on), TC test.

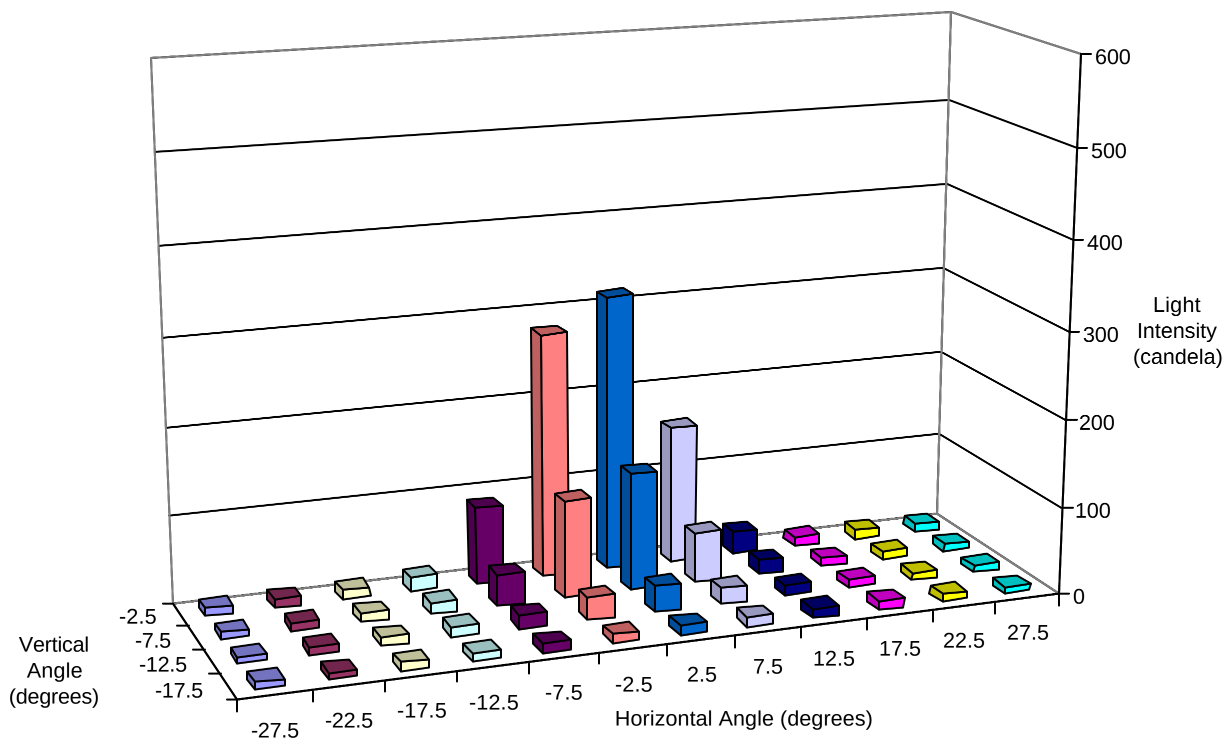

Figure A3.2.4b Output from WPS #3 (Red) signal, 10.5 volts, 209 elements (82.0% on), ITE test.

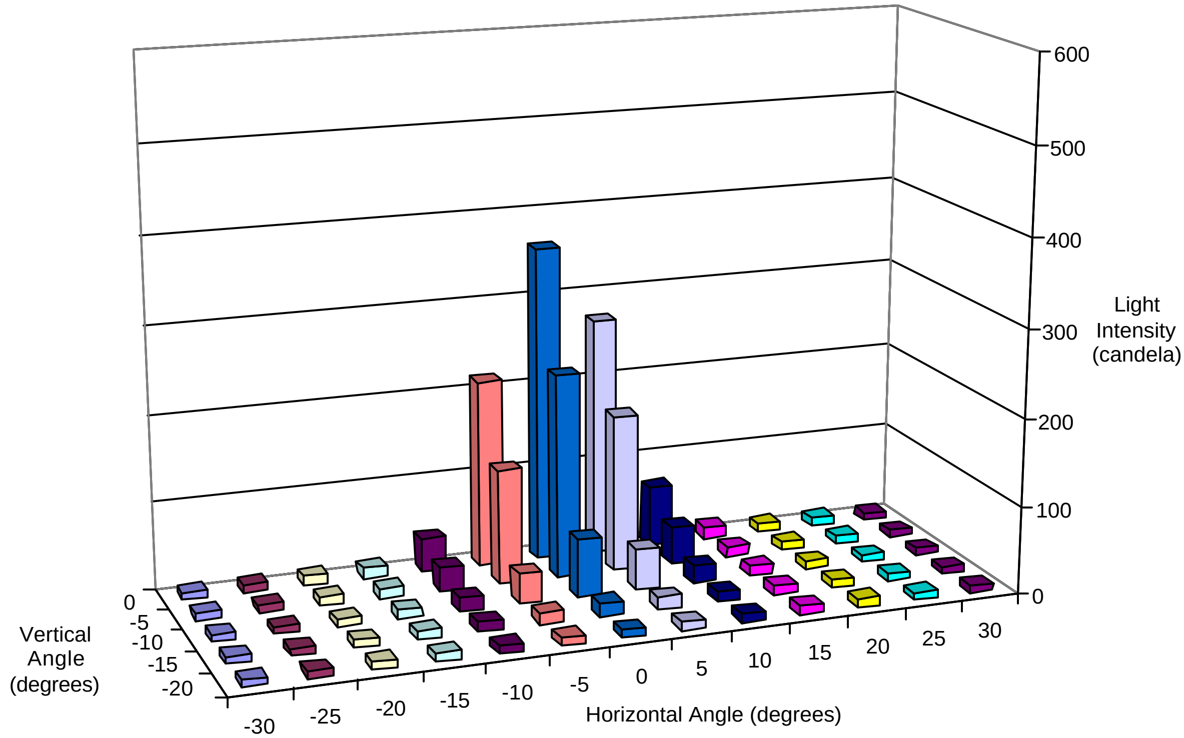

Figure A3.2.5a Output from WPS #3 (Red) signal, 10.5 volts, 194 elements (76.0% on), TC test.

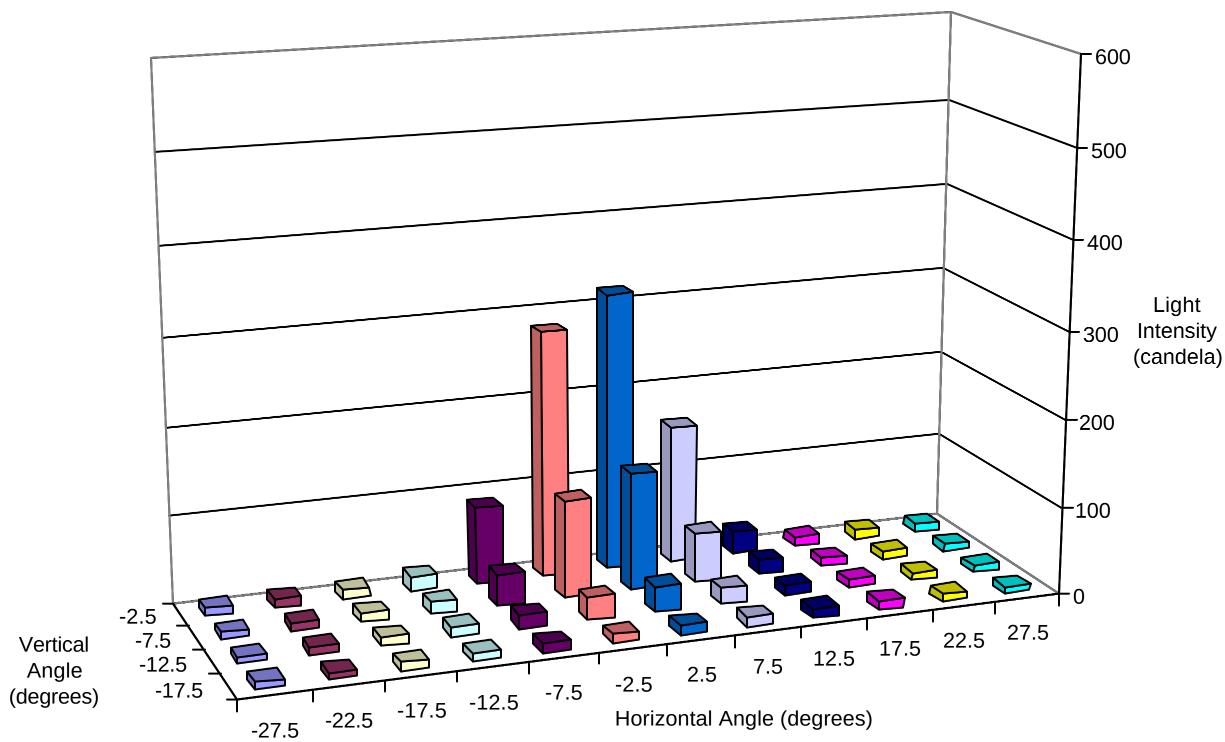

Figure A3.2.5b Output from WPS #3 (Red) signal, 10.5 volts, 194 elements (76.0% on), ITE test.

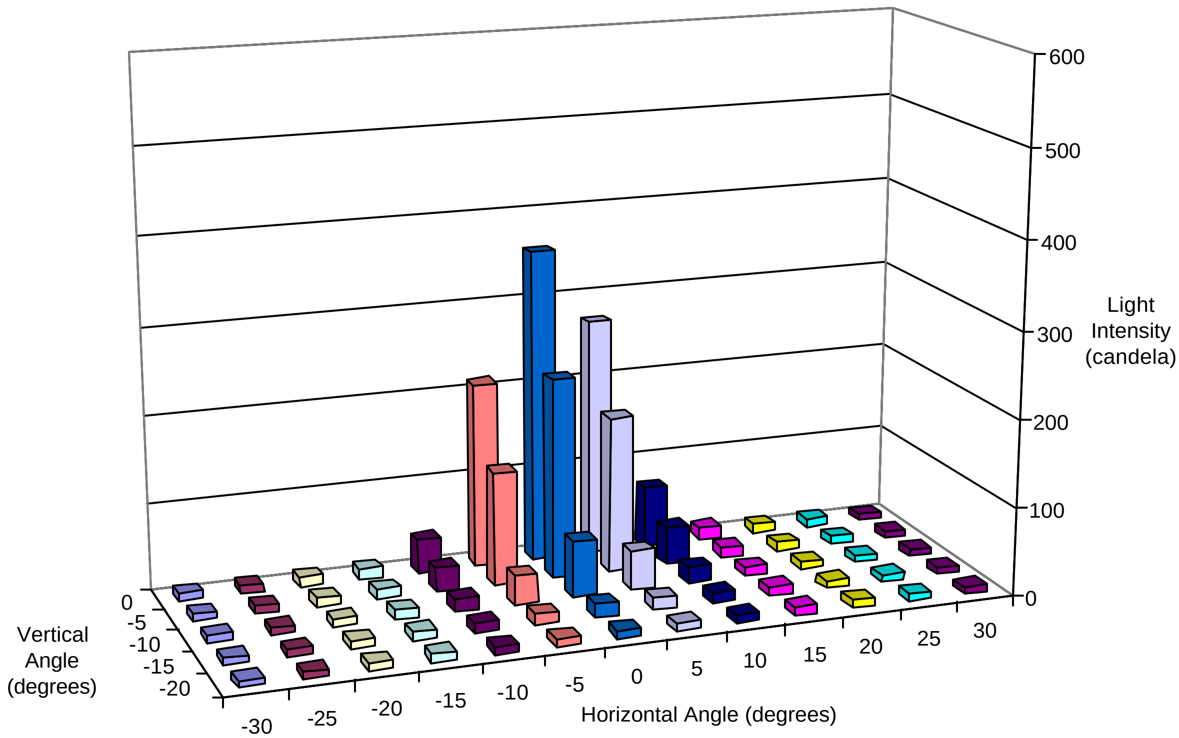

Figure A3.2.6a Output from WPS #3 (Red) signal, 10.5 volts, 179 elements (70.0% on), TC test.

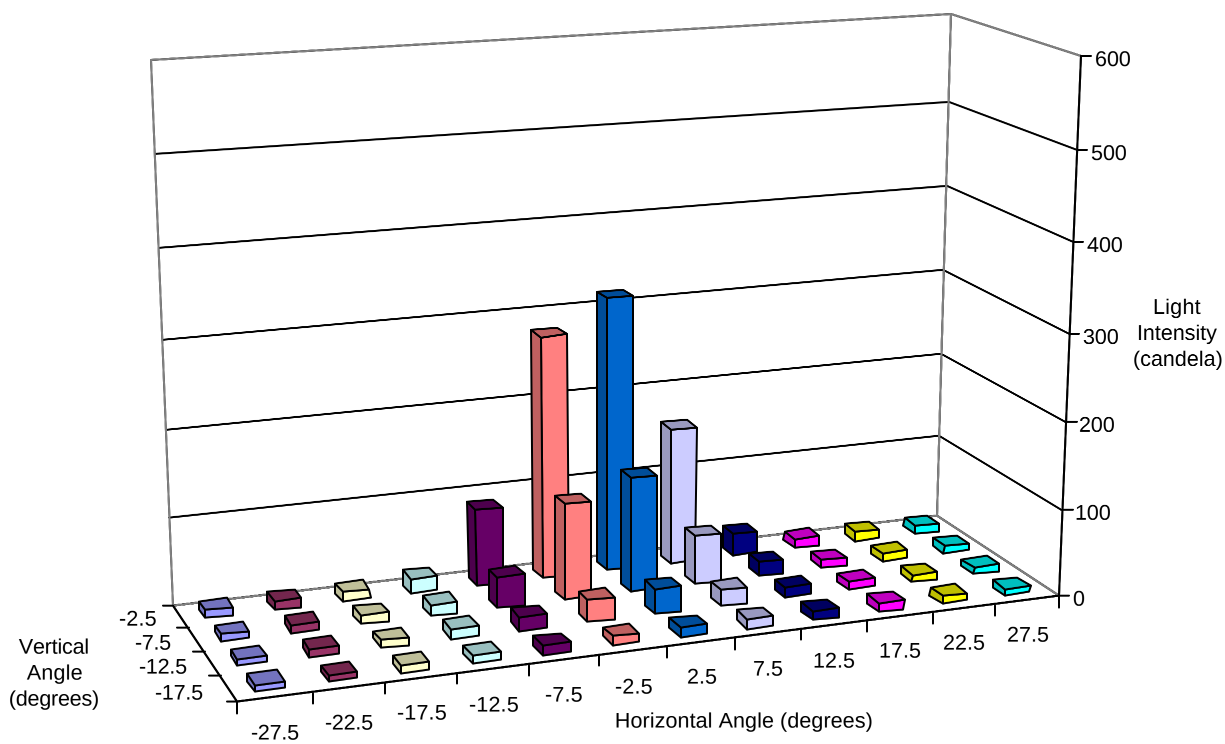

Figure A3.2.6b Output from WPS #3 (Red) signal, 10.5 volts, 179 elements (70.0% on), ITE test.

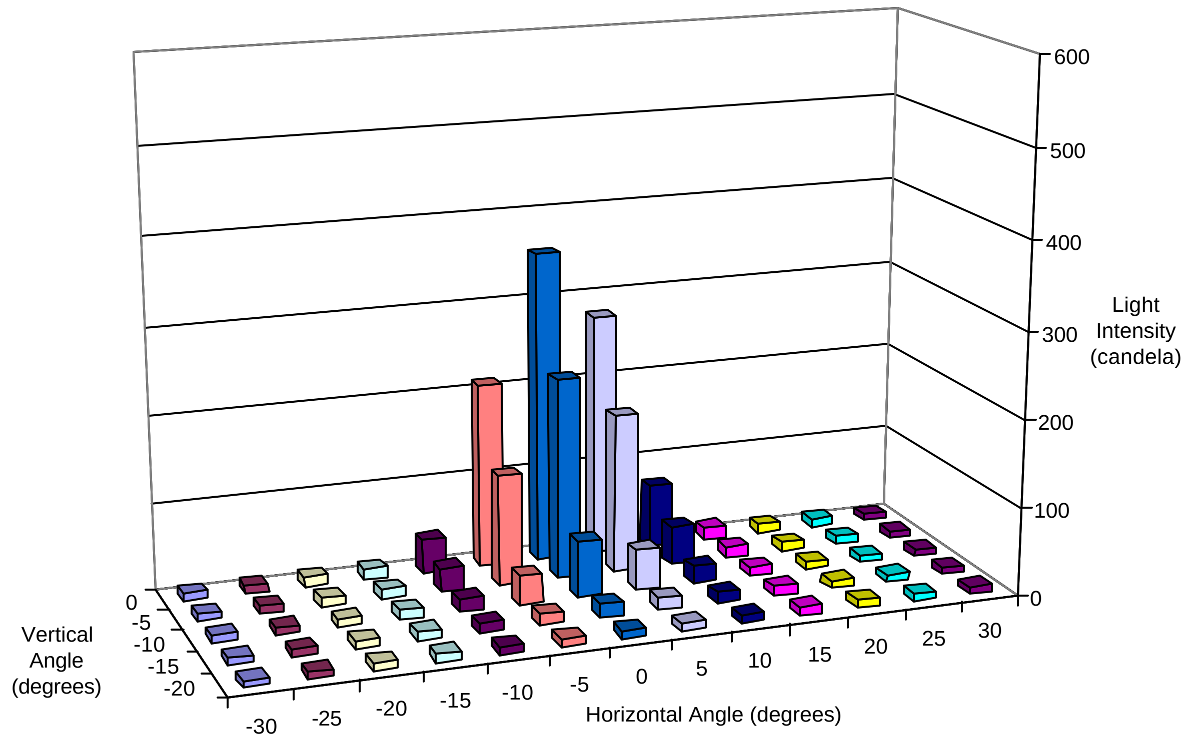

Figure A3.2.7a Output from WPS #3 (Red) signal, 10.5 volts, 164 elements (64.0% on), TC test.

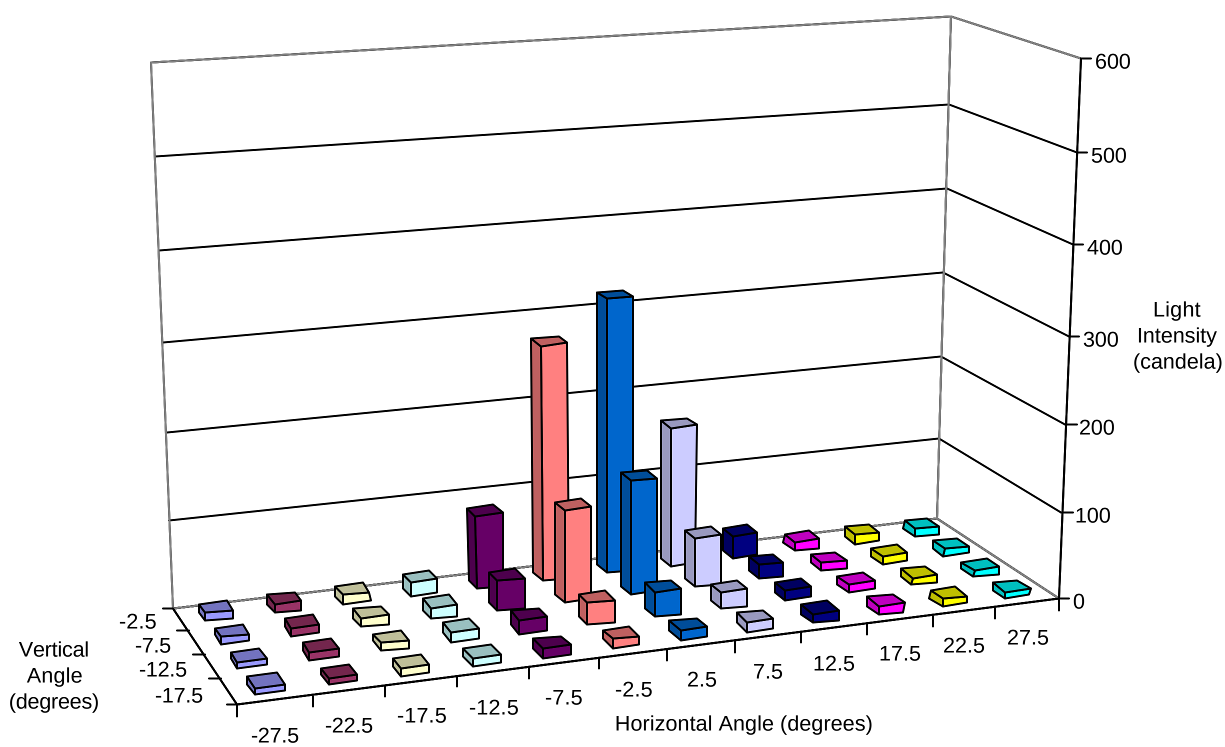

Figure A3.2.7b Output from WPS #3 (Red) signal, 10.5 volts, 164 elements (64% on), ITE test.

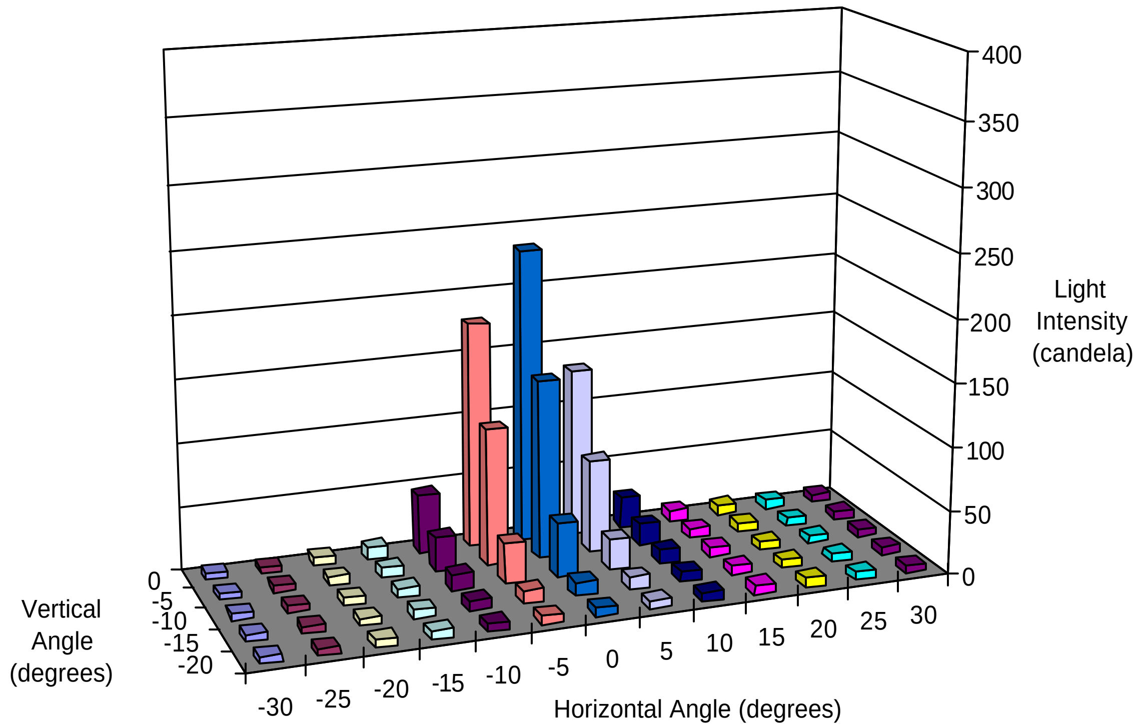

Figure A3.3.1a Output from WPS #3 (Red) signal, 9.0 volts, all elements on, TC test.

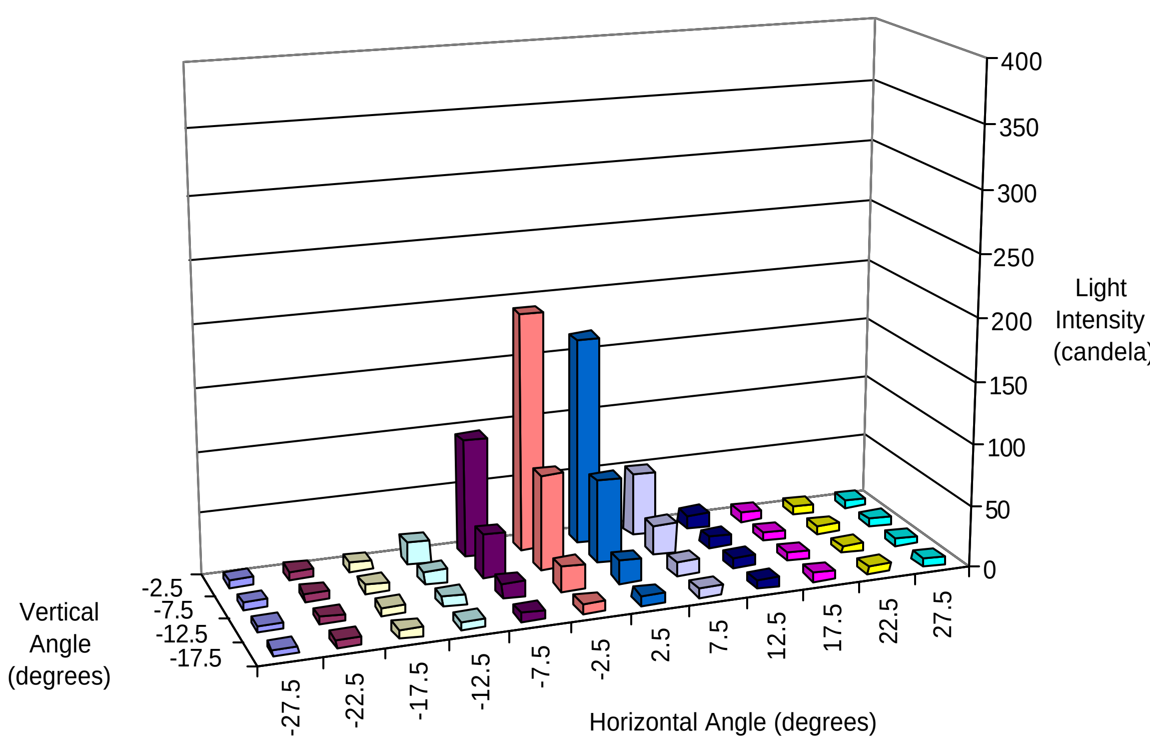

Figure A3.3.1b Output from WPS #3 (Red) signal, 9.0 volts, all elements on, ITE test.

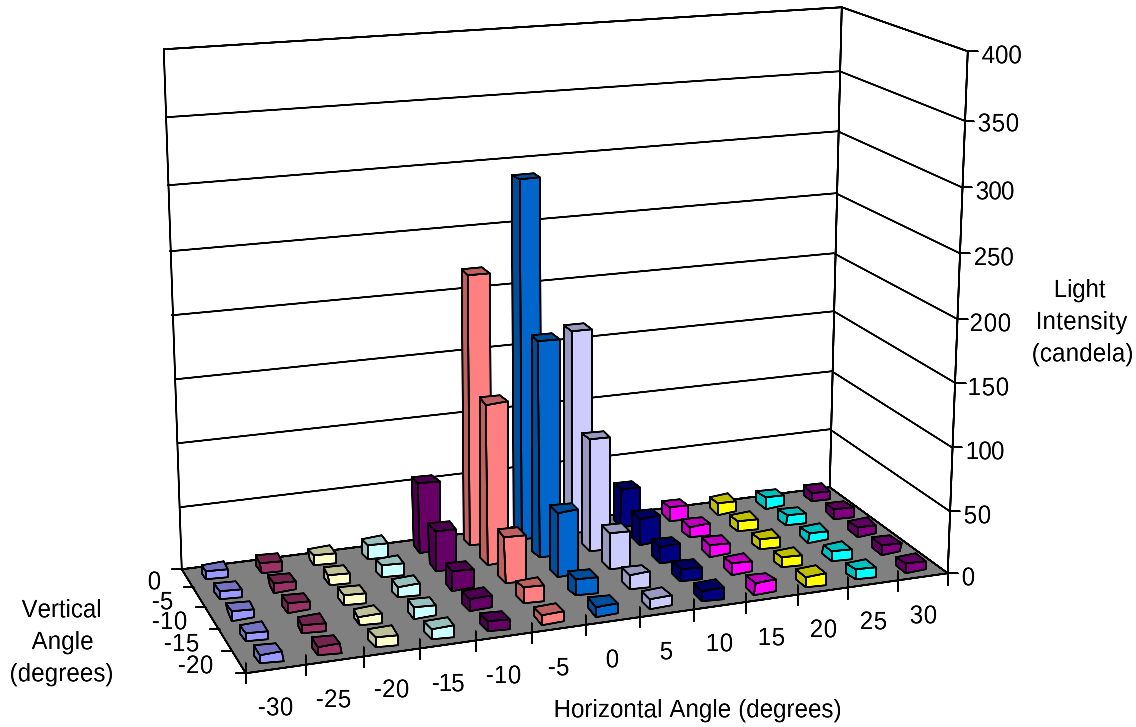

Figure A3.3.2a Output from WPS #3 (Red) signal, 10.0 volts, all elements on, TC test.

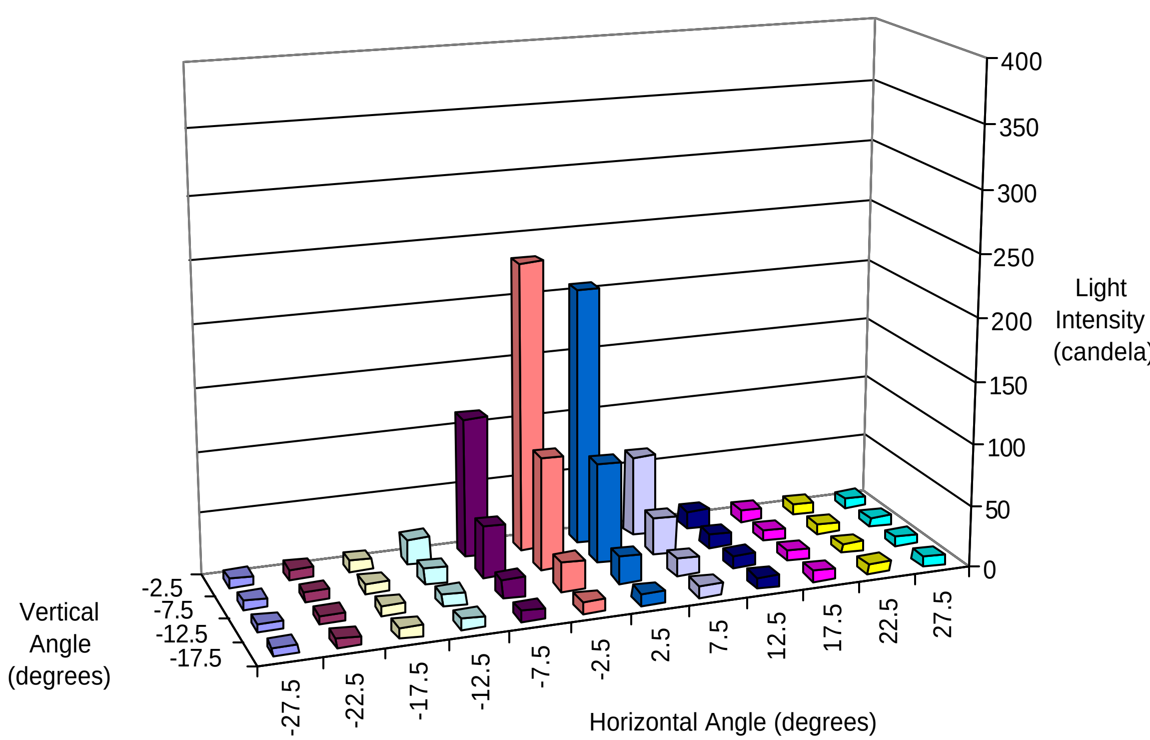

Figure A3.3.2b Output from WPS #3 (Red) signal, 10.0 volts, all elements on, ITE test.

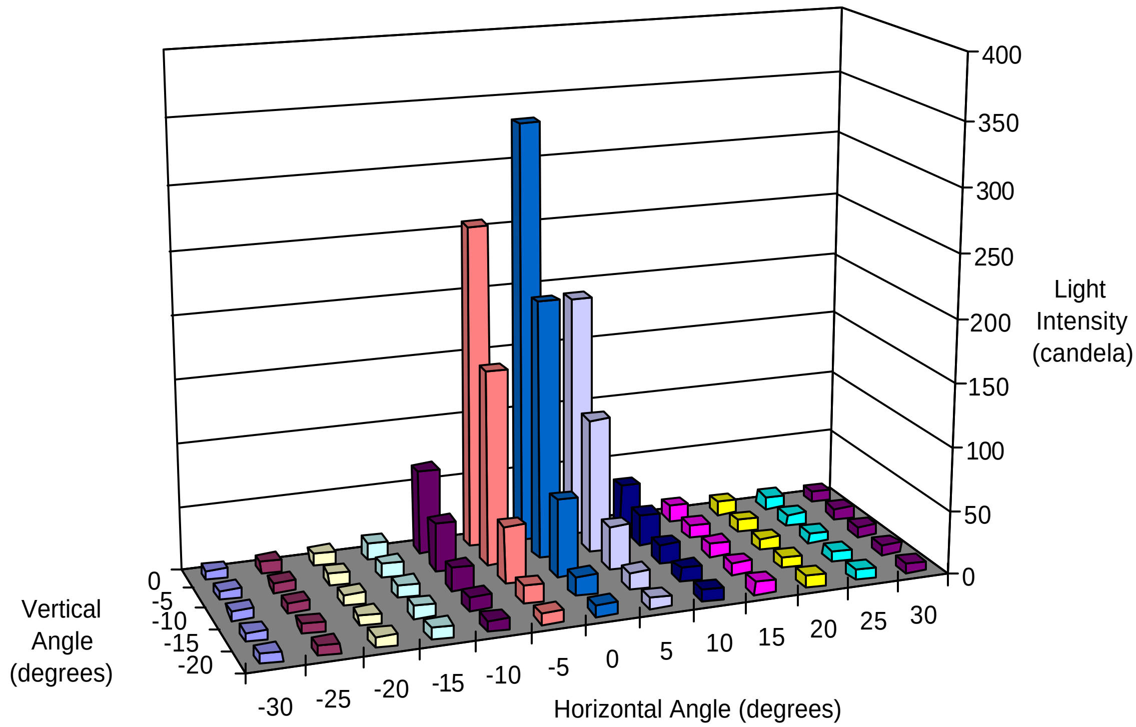

Figure A3.3.3a Output from WPS #3 (Red) signal, 12.0 volts, all elements on, TC test.

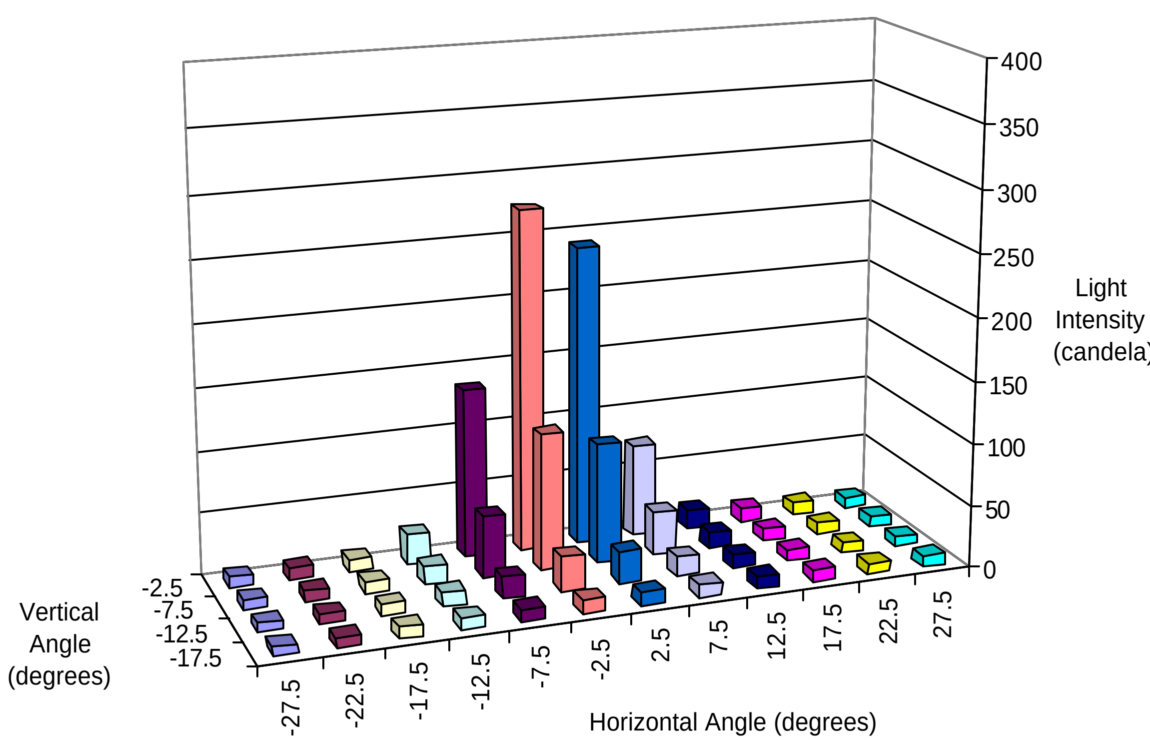

Figure A3.3.3b Output from WPS #3 (Red) signal, 12.0 volts, all elements on, ITE test.

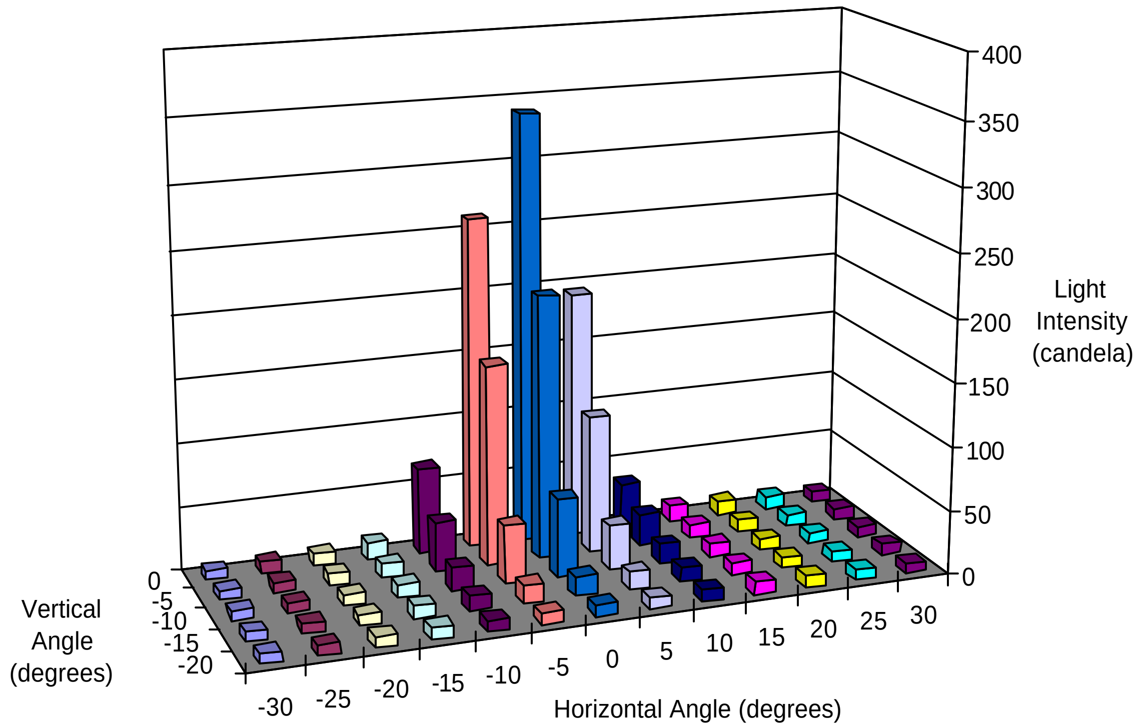

Figure A3.3.4a Output from WPS #3 (Red) signal, 13.5 volts, all elements on, TC test.

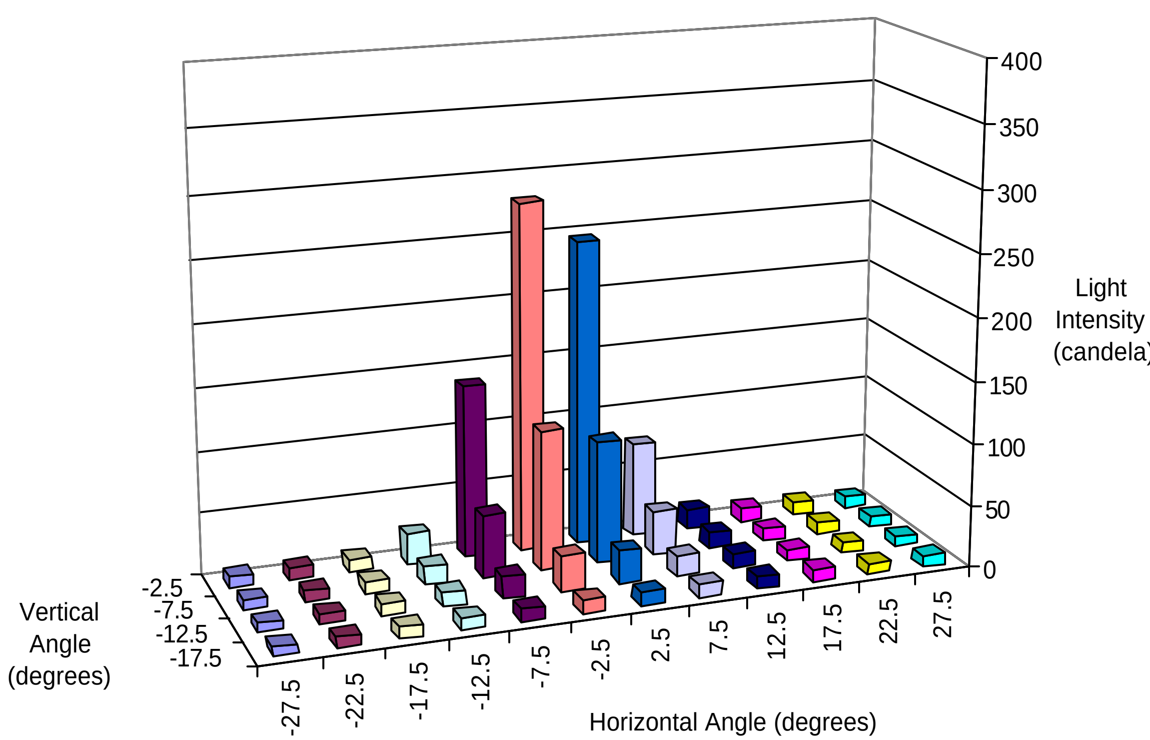

Figure A3.3.4b Output from WPS #3 (Red) signal, 13.5 volts, all elements on, ITE test.

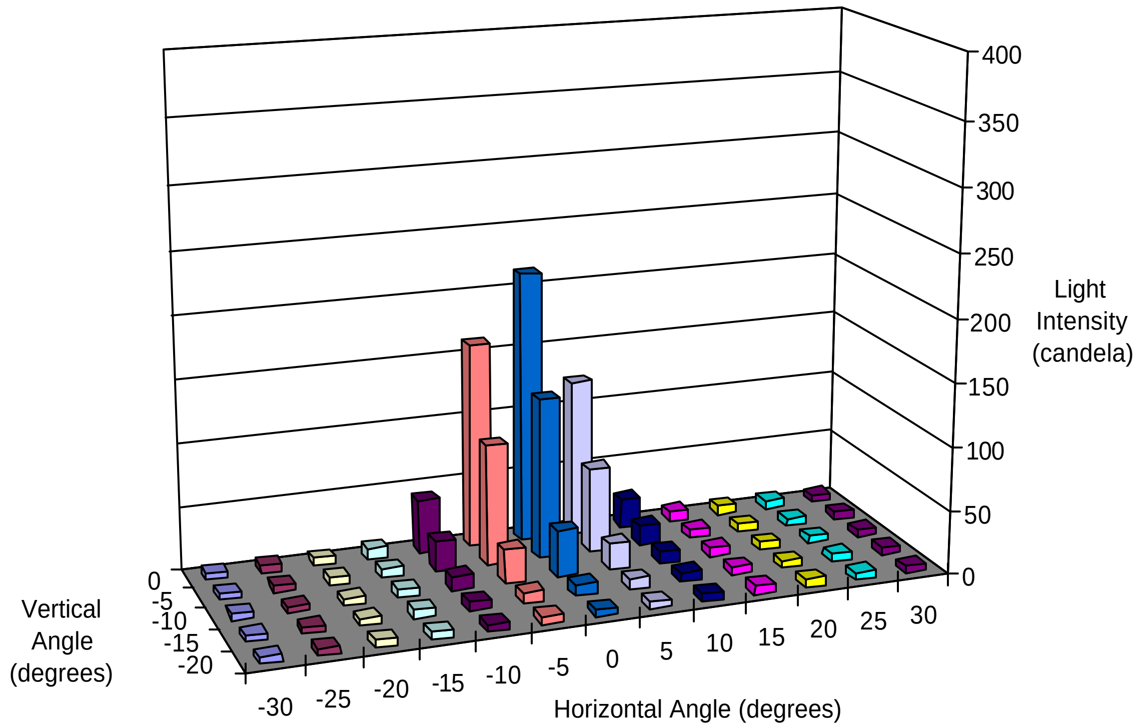

Figure A3.3.5a Output from WPS #3 (Red) signal, 9.0 volts, 239 elements (94.0% on), TC test.

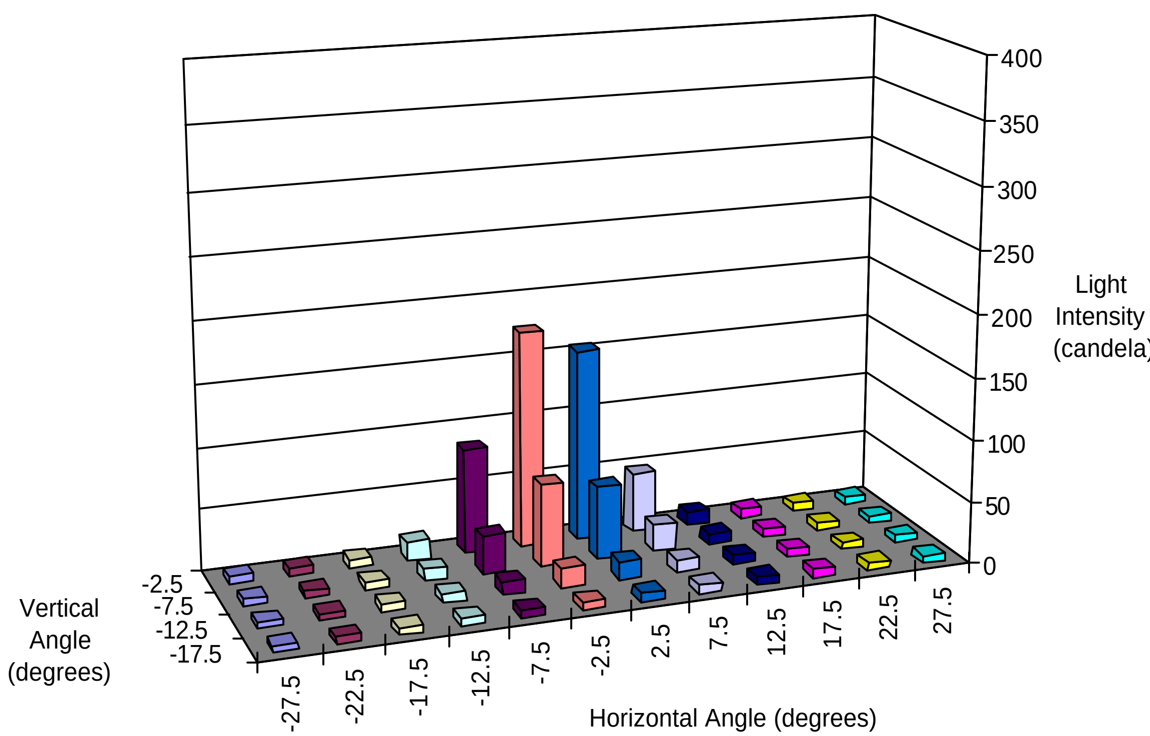

Figure A3.3.5b Output from WPS #3 (Red) signal, 9.0 volts, 239 elements (94.0% on), ITE test.

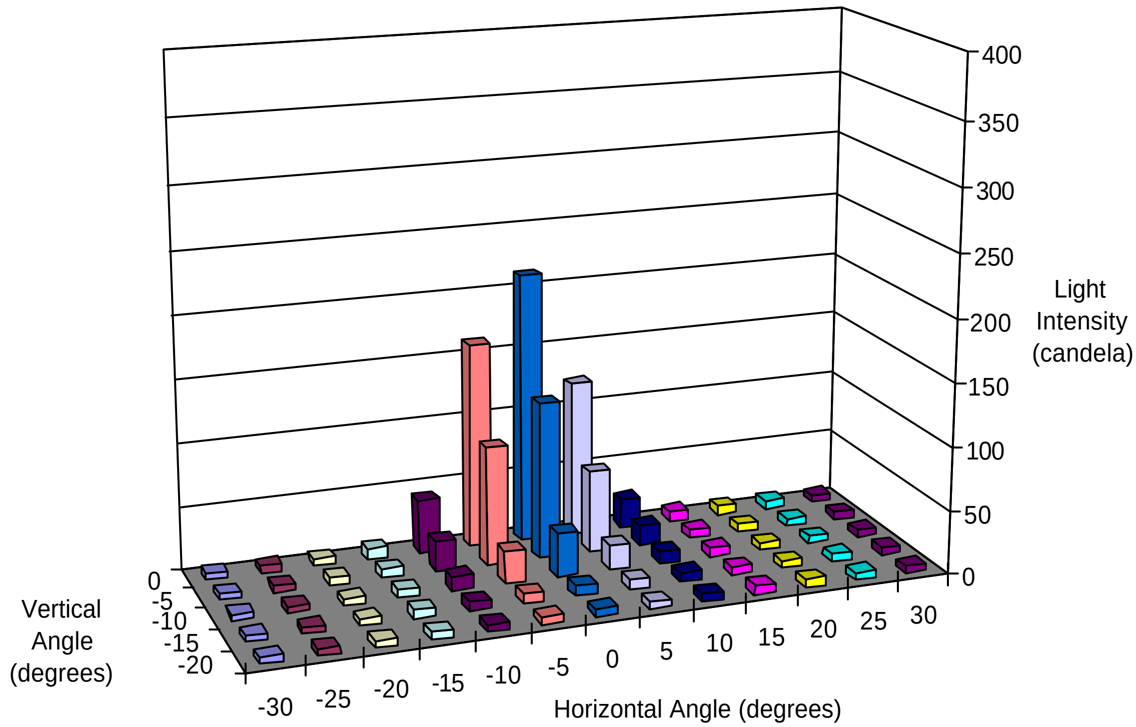

Figure A3.3.6a Output from WPS #3 (Red) signal, 9.0 volts, 224 elements (88.0% on), TC test.

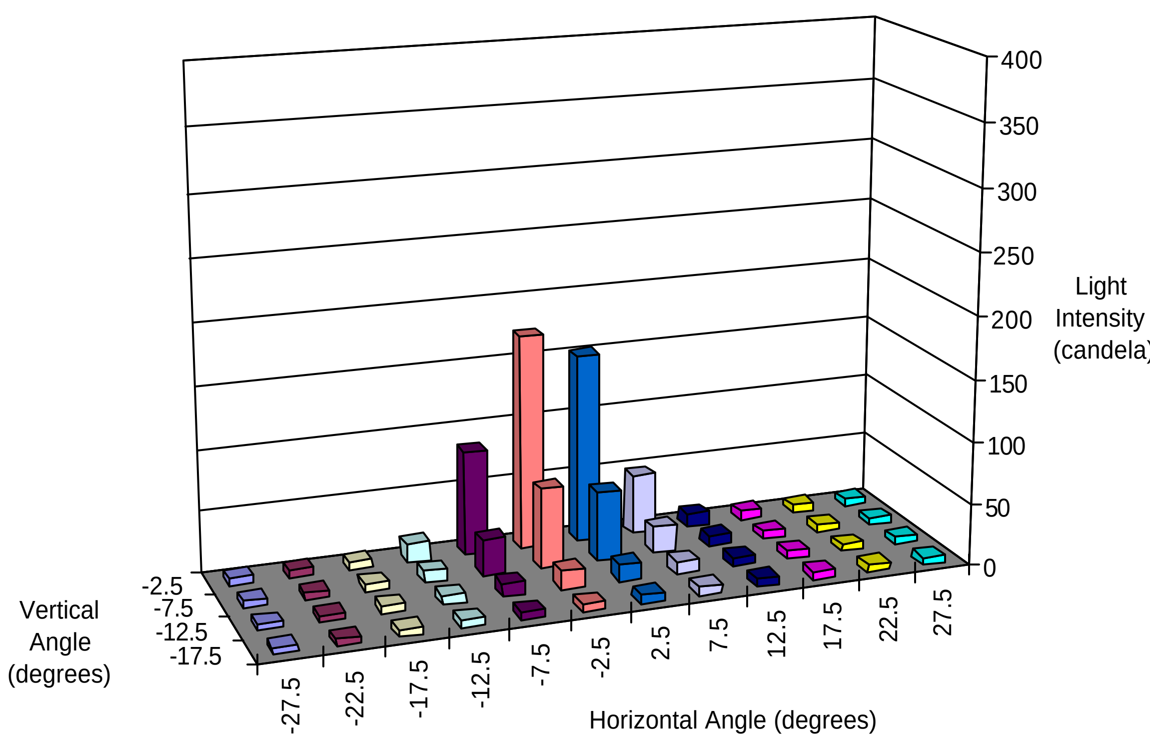

Figure A3.3.6b Output from WPS #3 (Red) signal, 9.0 volts, 224 elements (88.0% on), ITE test.

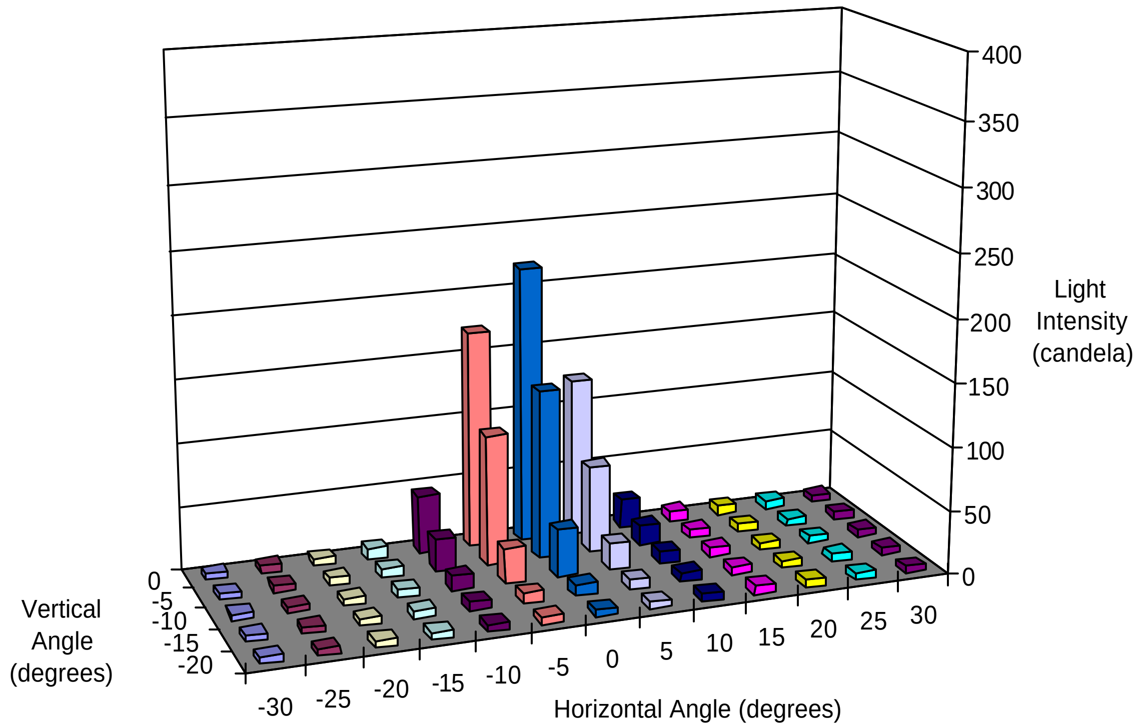

Figure A3.3.7a Output from WPS #3 (Red) signal, 9.0 volts, 209 elements (82.0% on), TC test.

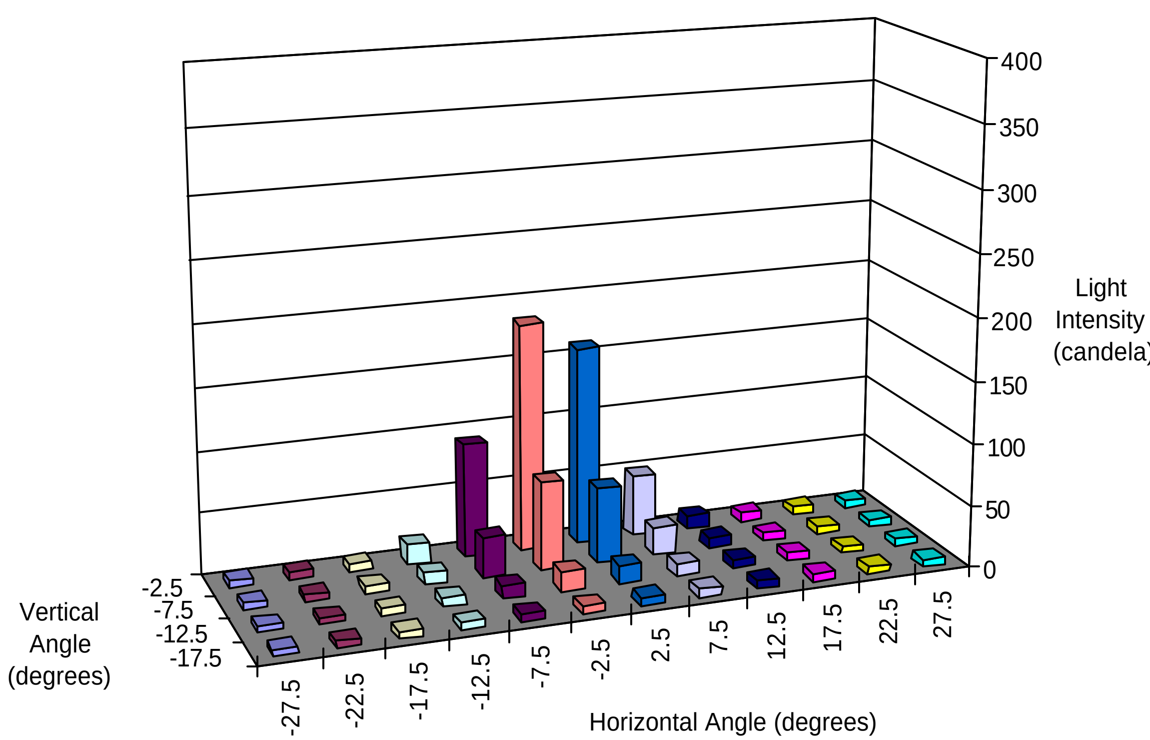

Figure A3.3.7b Output from WPS #3 (Red) signal, 9.0 volts, 209 elements (82.0% on), ITE test.

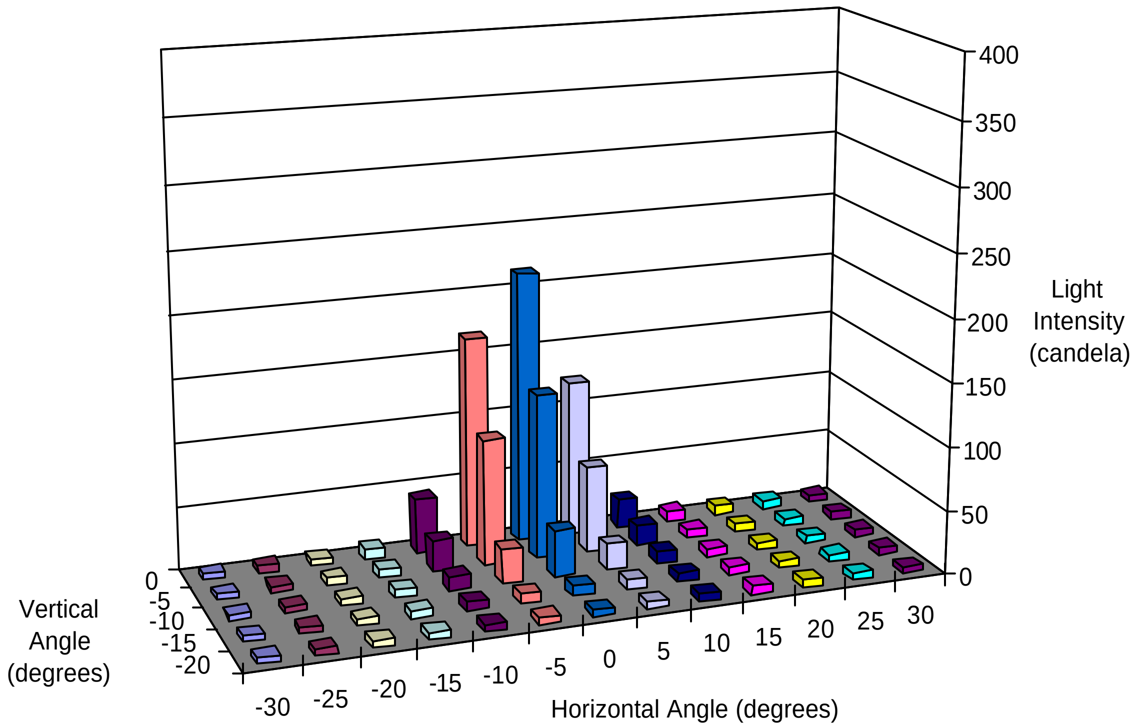

Figure A3.3.8a Output from WPS #3 (Red) signal, 9.0 volts, 194 elements (76.0% on), TC test.

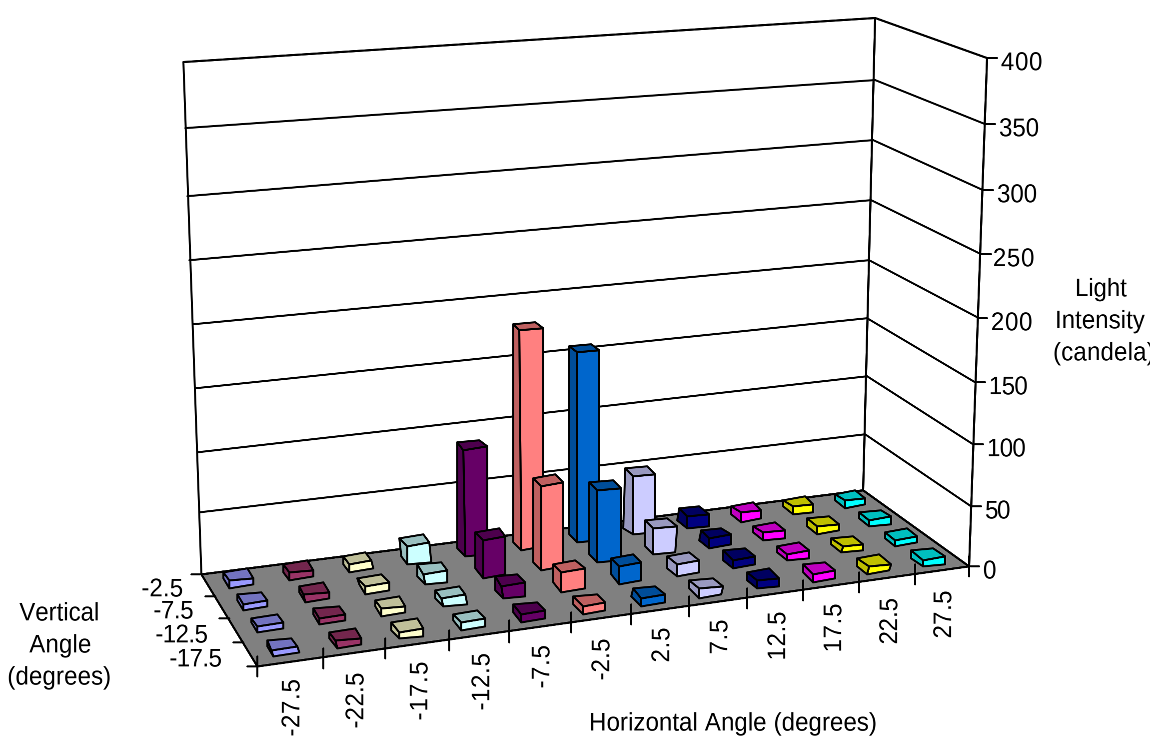

Figure A3.3.8b Output from WPS #3 (Red) signal, 9.0 volts, 194 elements (76.0% on), ITE test.

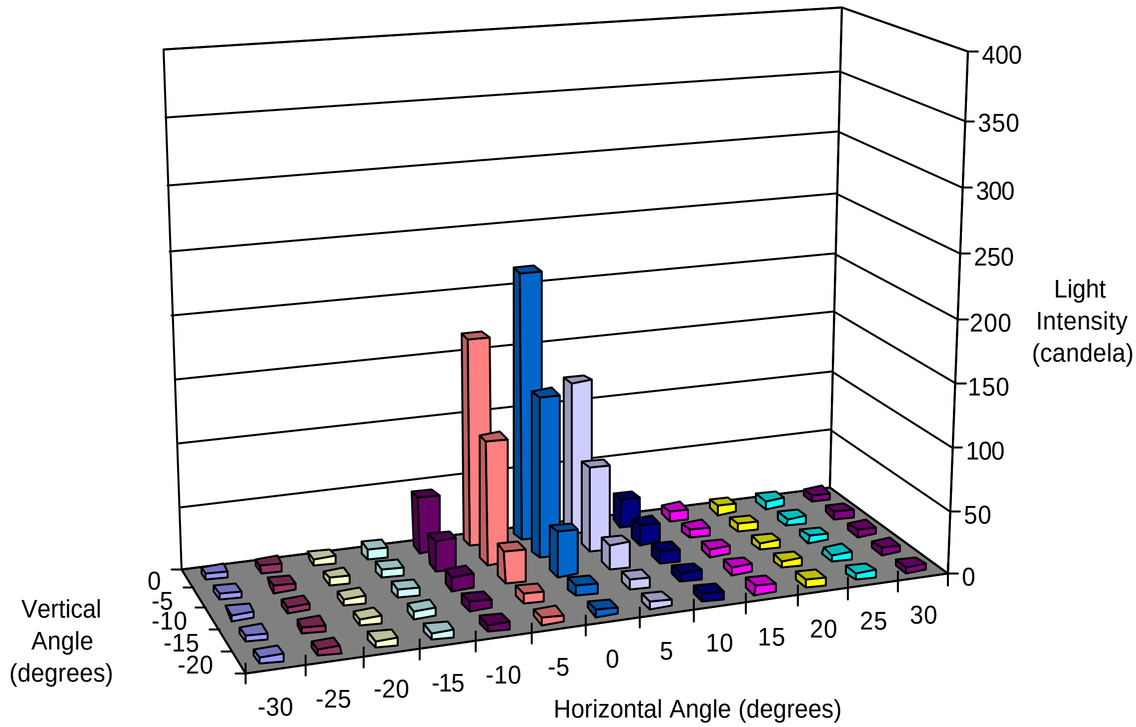

Figure A3.3.9a Output from WPS #3 (Red) signal, 9.0 volts, 179 elements (70.0% on), TC test.

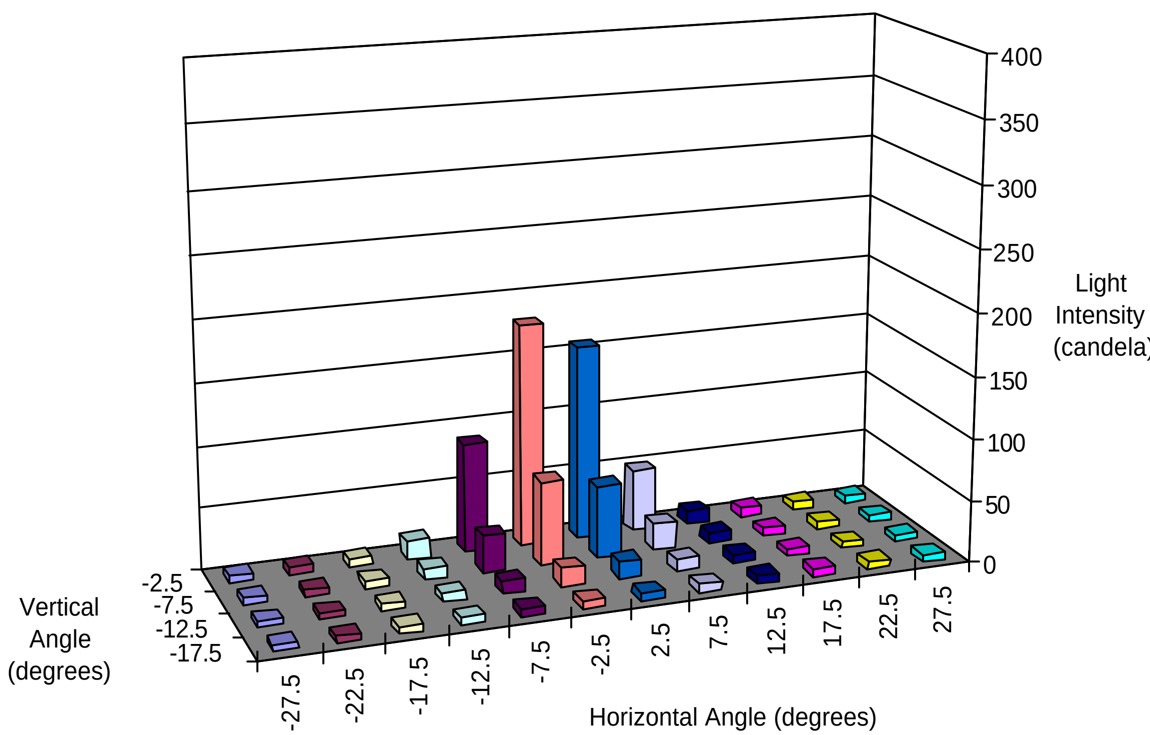

Figure A3.3.9b Output from WPS #3 (Red) signal, 9.0 volts, 179 elements (70.0% on), ITE test.

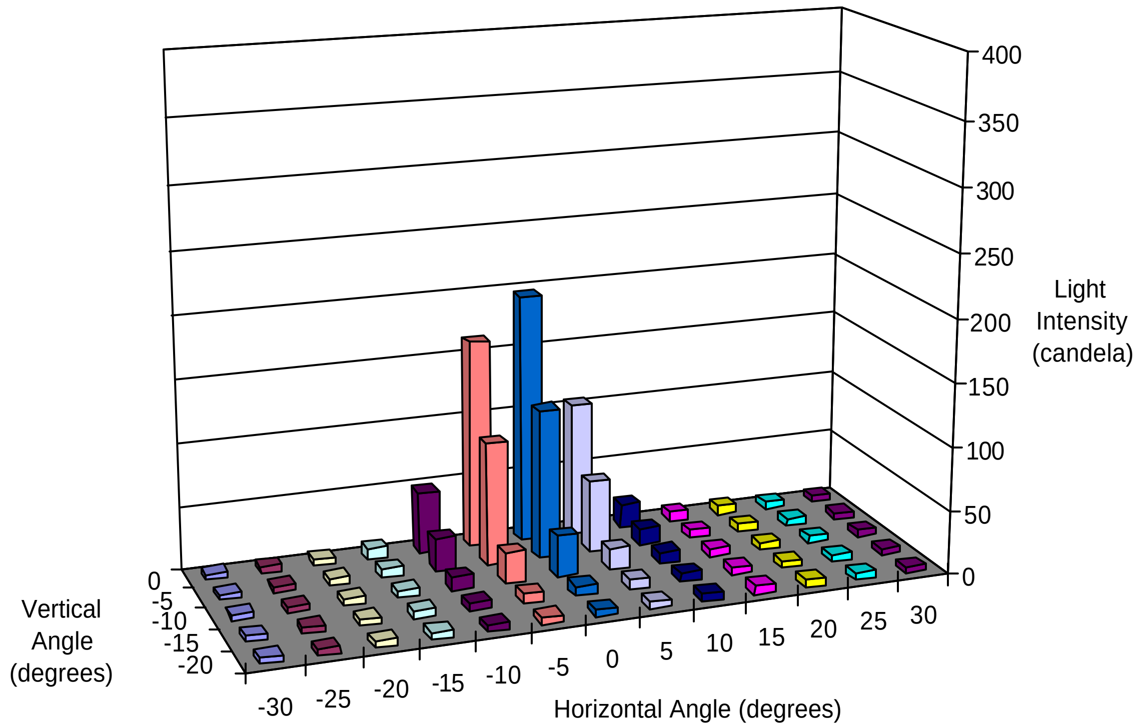

Figure A3.3.10a Output from WPS #3 (Red) signal, 9.0 volts, 164 elements (64.0% on), TC test.

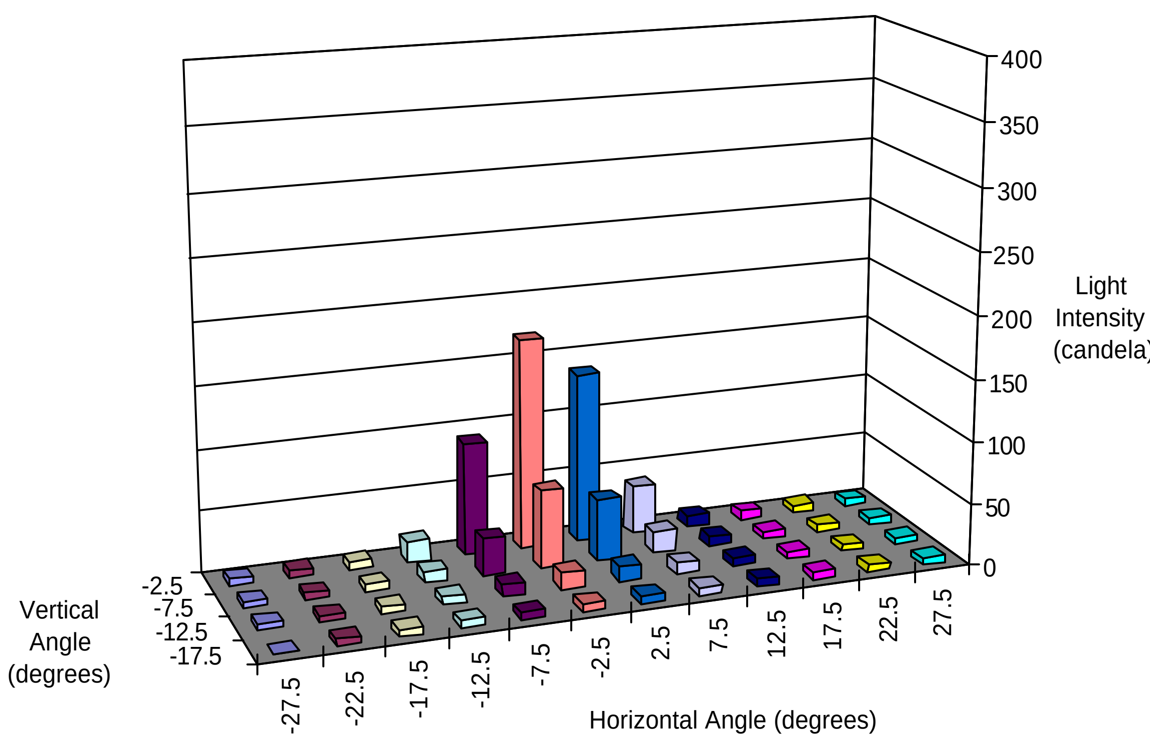

Figure A3.3.10b Output from WPS #3 (Red) signal, 9.0 volts, 164 elements (64.0% on), ITE test.

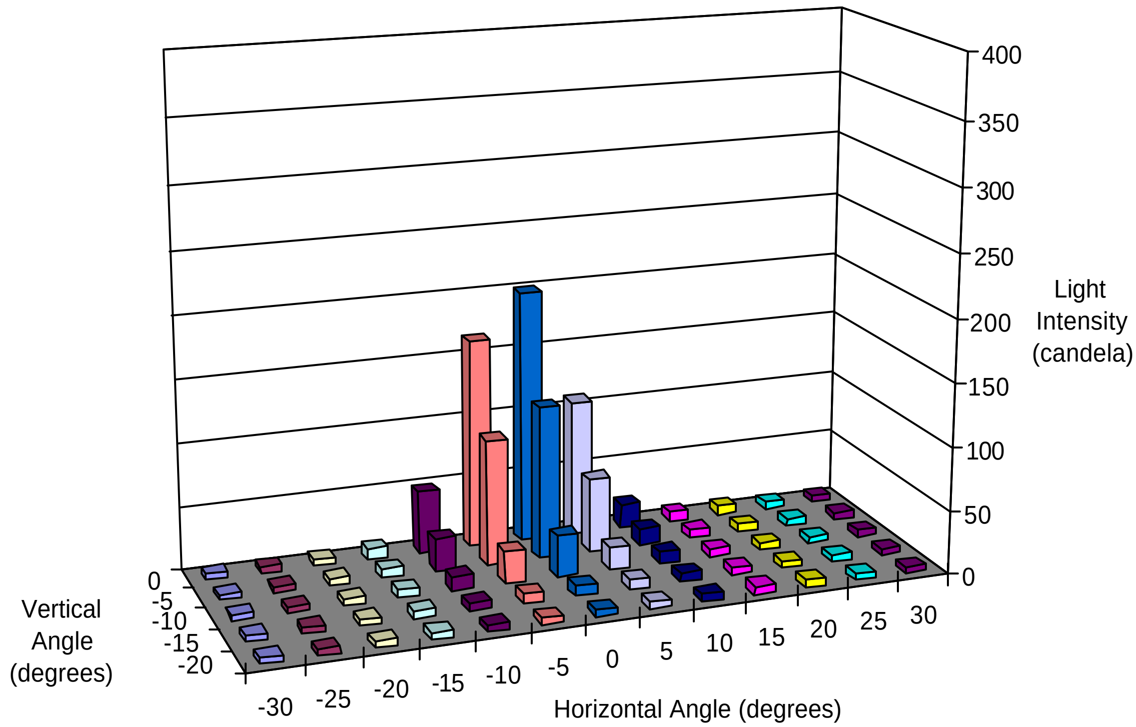

Figure A3.3.11a Output from WPS #3 (Red) signal, 9.0 volts, 149 elements (58.0% on), TC test.

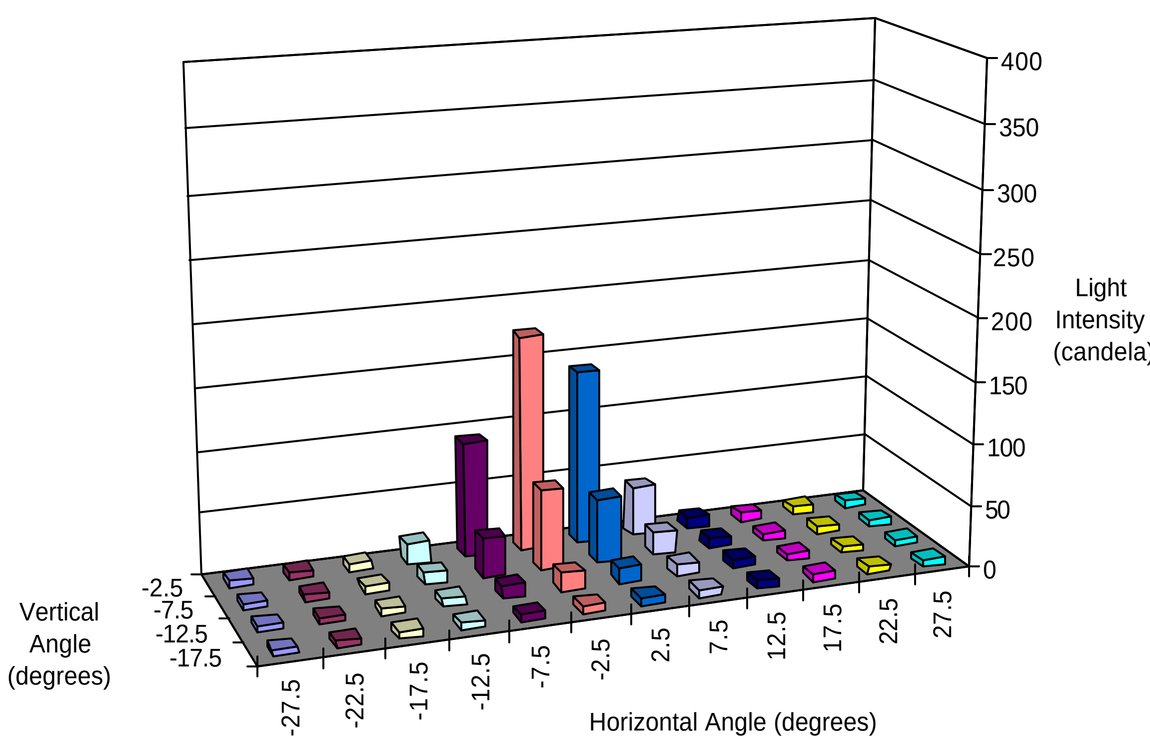

Figure A3.3.11b Output from WPS #3 (Red) signal, 9.0 volts, 149 elements (58.0% on), ITE test.

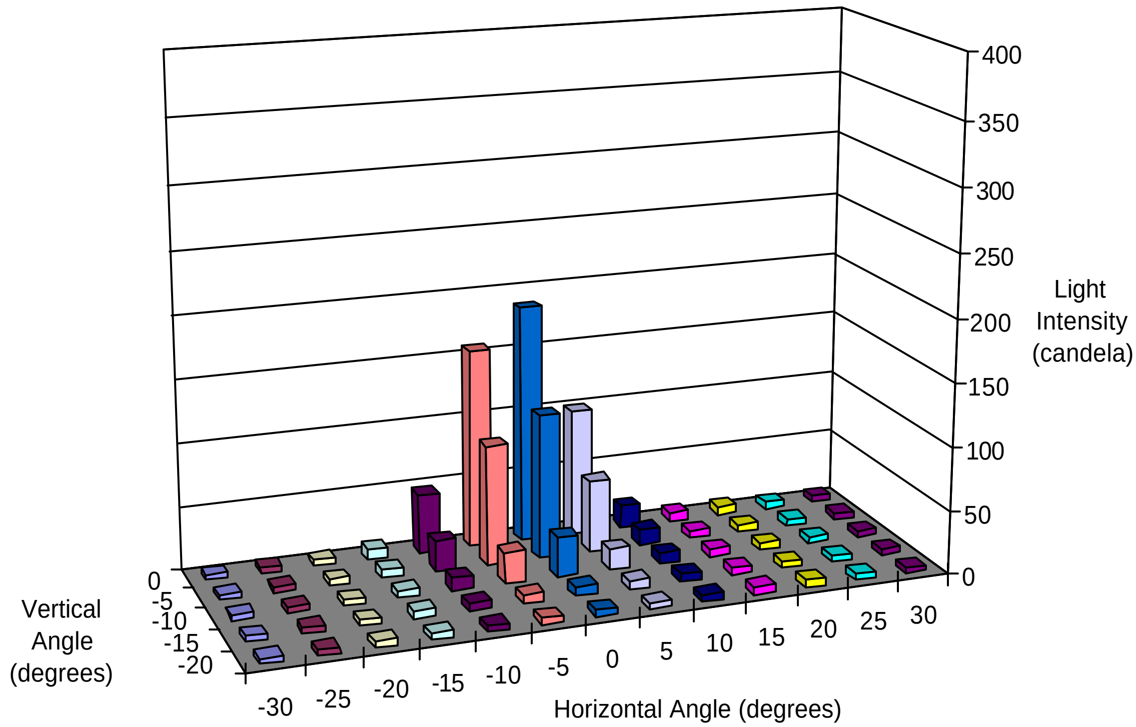

Figure A3.3.12a Output from WPS #3 (Red) signal, 9.0 volts, 134 elements (52.0% on), TC test.

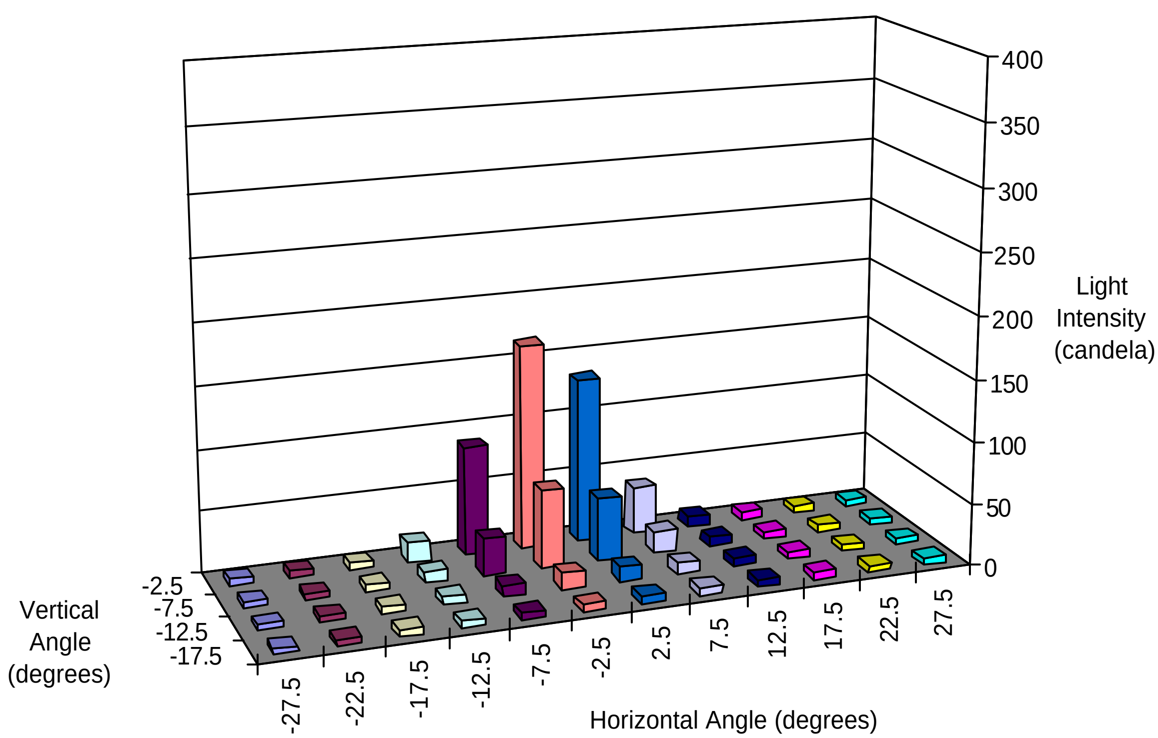

Figure A3.3.12b Output from WPS #3 (Red) signal, 9.0 volts, 134 elements (52.0% on), ITE test.

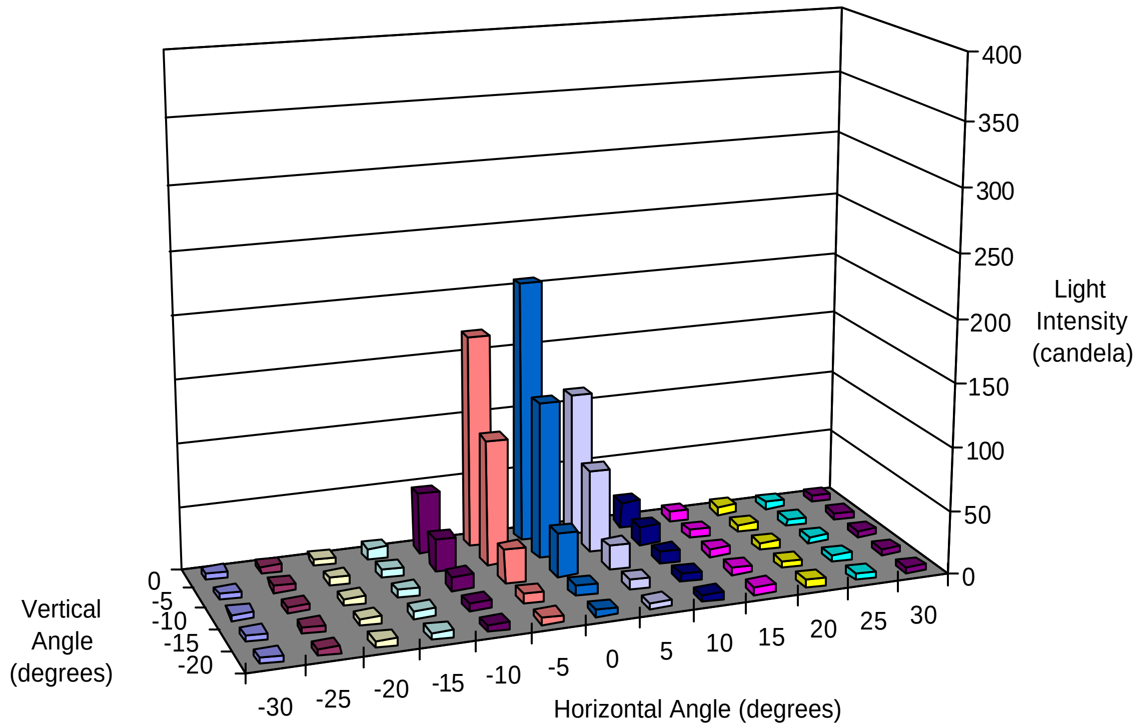

Figure A3.3.13a Output from WPS #3 (Red) signal, 9.0 volts, 119 elements (46.0% on), TC test.

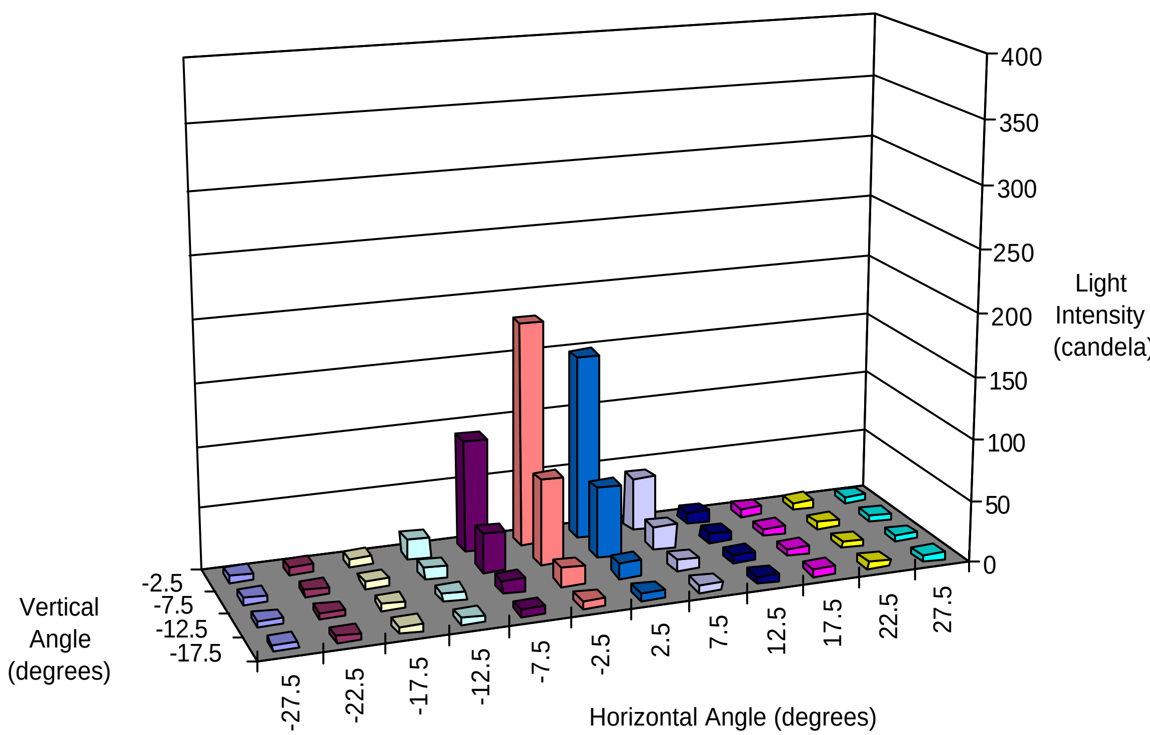

Figure A3.3.13b Output from WPS #3 (Red) signal, 9.0 volts, 119 elements (46.0% on), ITE test.

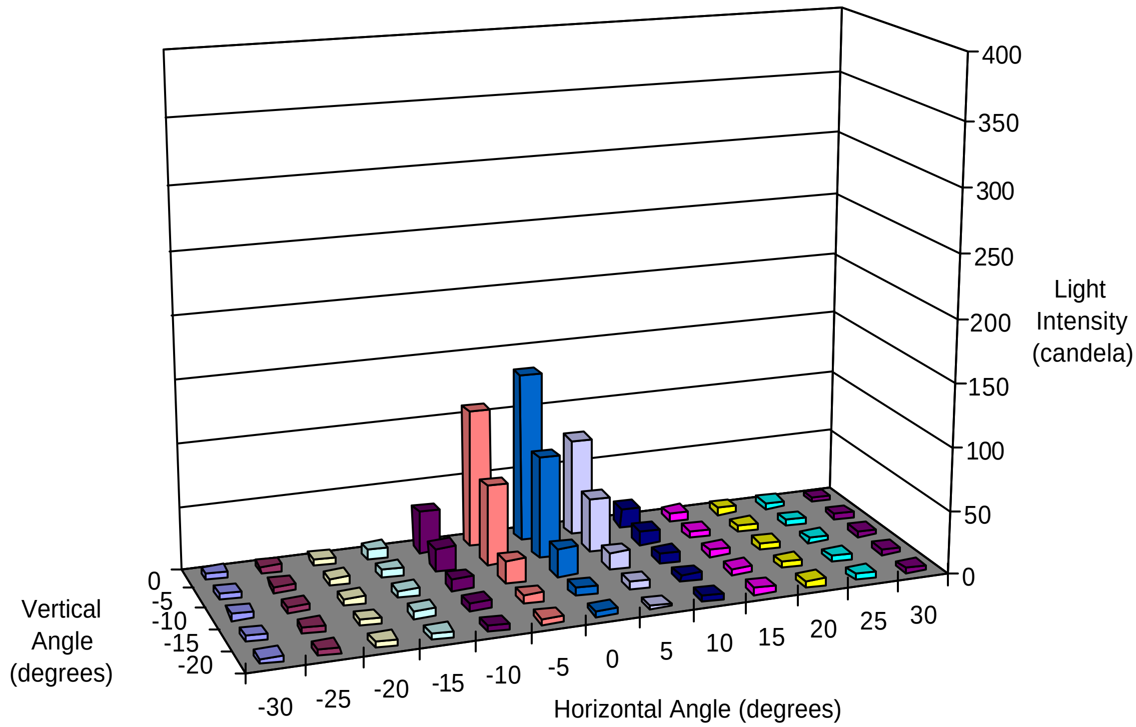

Figure A3.3.14a Output from WPS #3 (Red) signal, 9.0 volts, 104 elements (40.0% on), TC test.

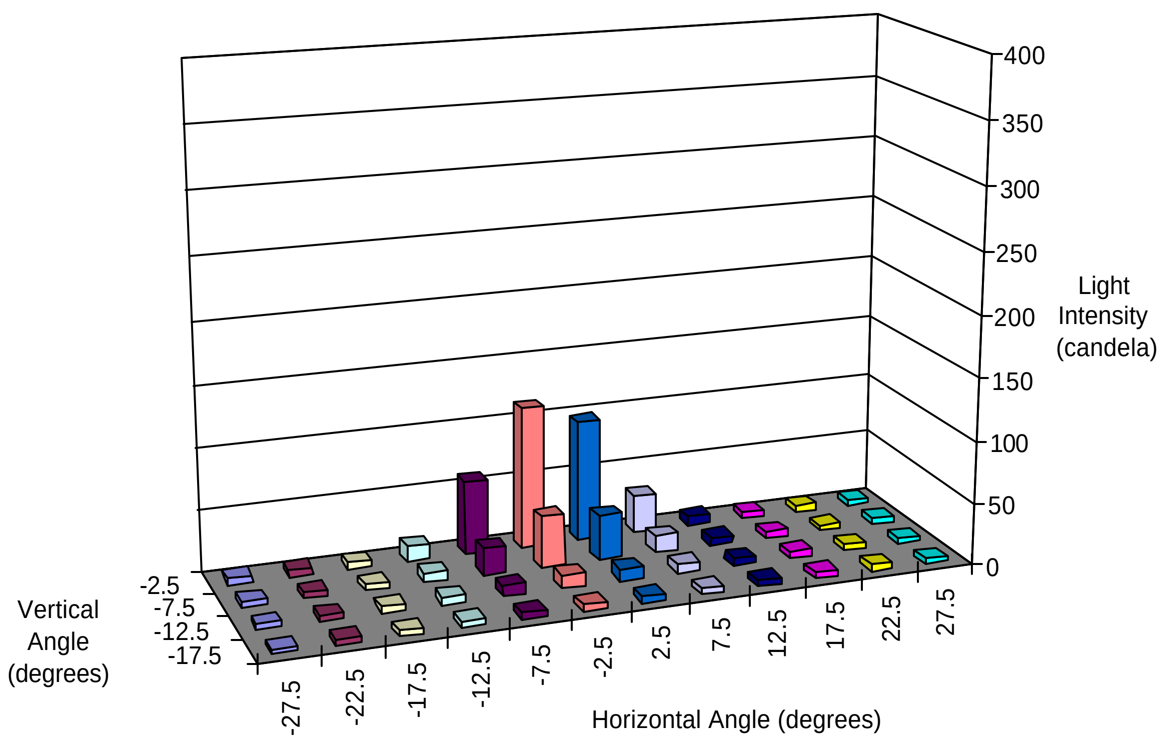

Figure A3.3.14b Output from WPS #3 (Red) signal, 9.0 volts, 104 elements (40.0% on), ITE test.

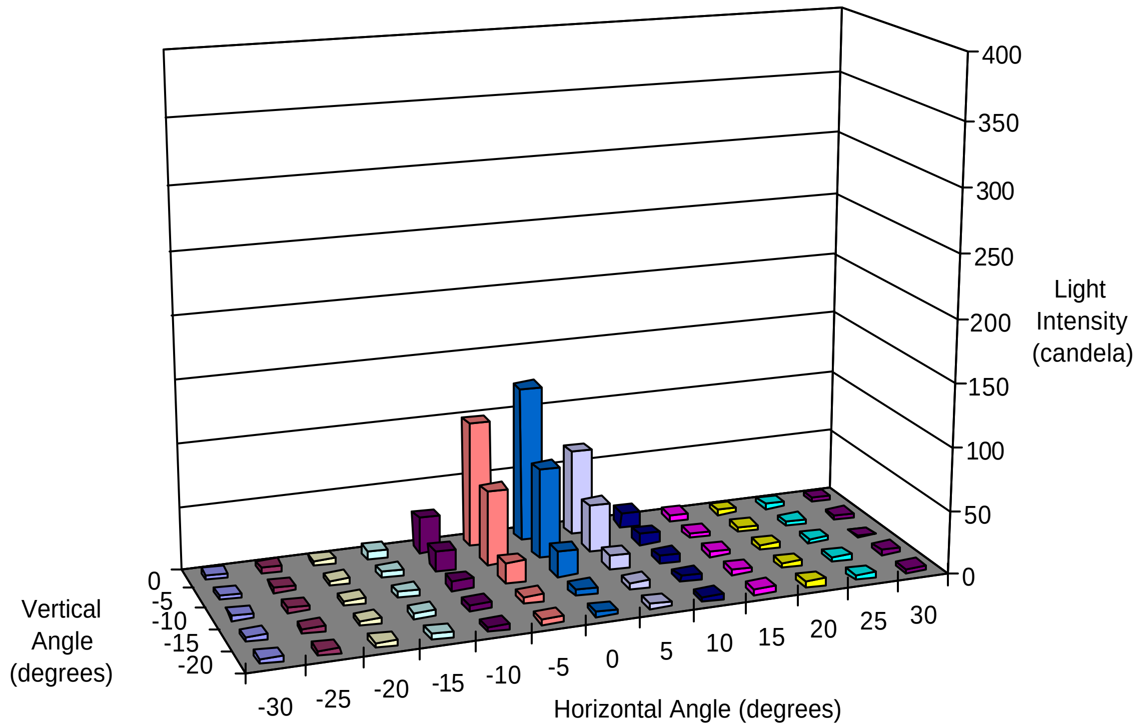

Figure A3.3.15a Output from WPS #3 (Red) signal, 9.0 volts, 89 elements (35.0% on), TC test.

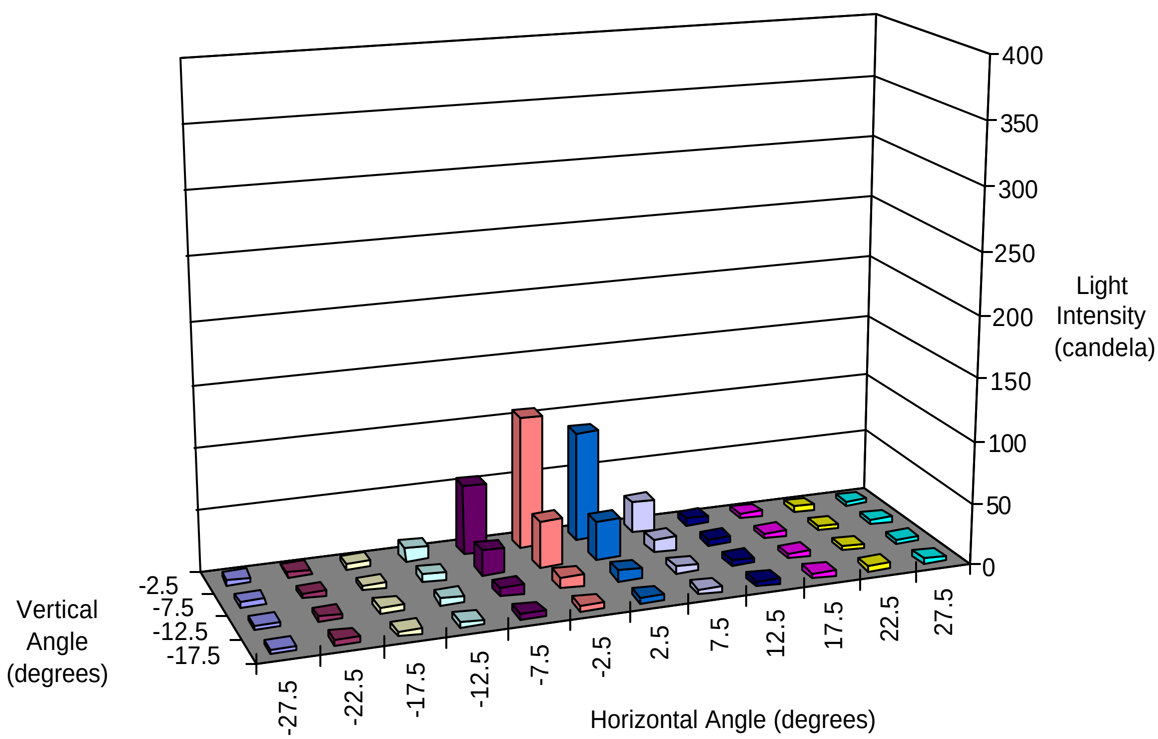

Figure A3.3.15b Output from WPS #3 (Red) signal, 9.0 volts, 89 elements (35.0% on), ITE test.

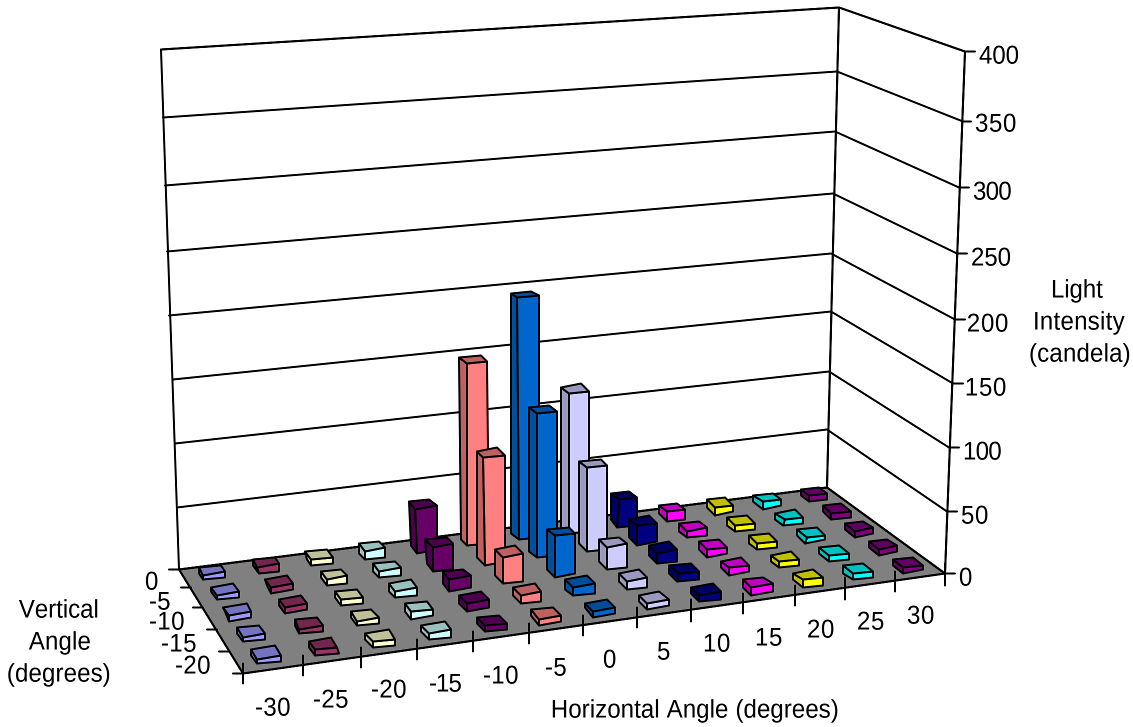

Figure A3.3.16a Output from WPS #3 (Red) signal, 9.0 volts, 74 elements (29.0% on), TC test.

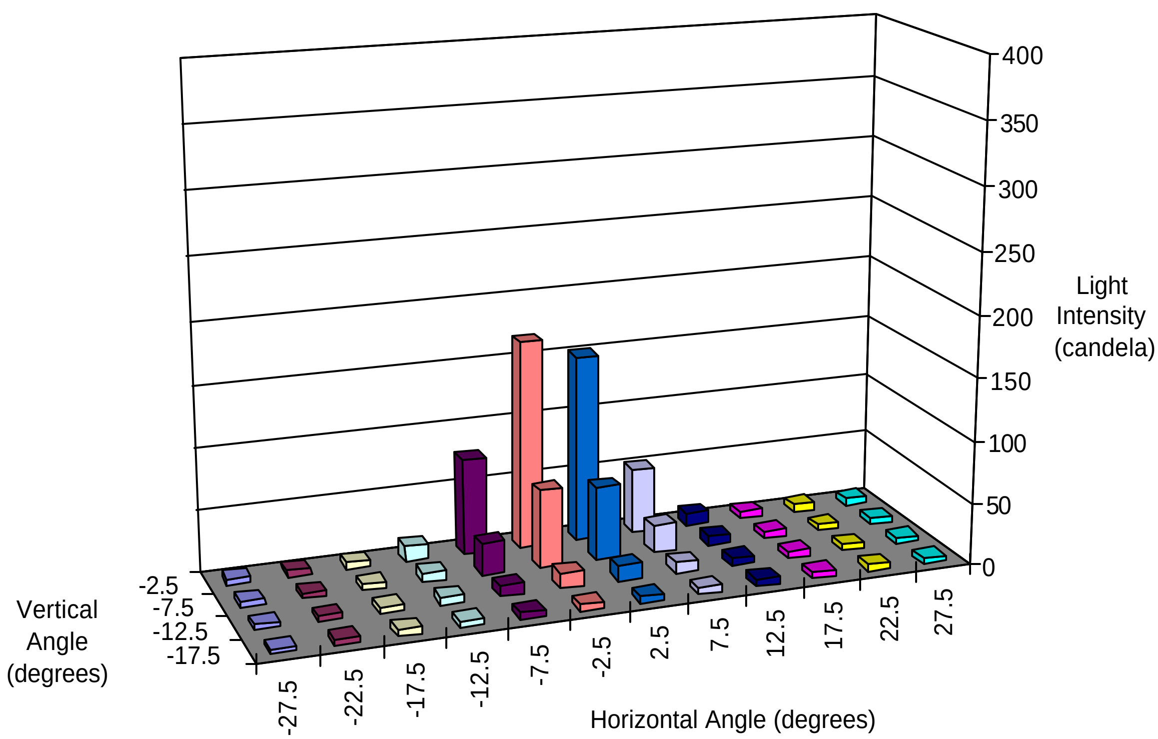

Figure A3.3.16b Output from WPS #3 (Red) signal, 9.0 volts, 74 elements (29.0% on), ITE test.

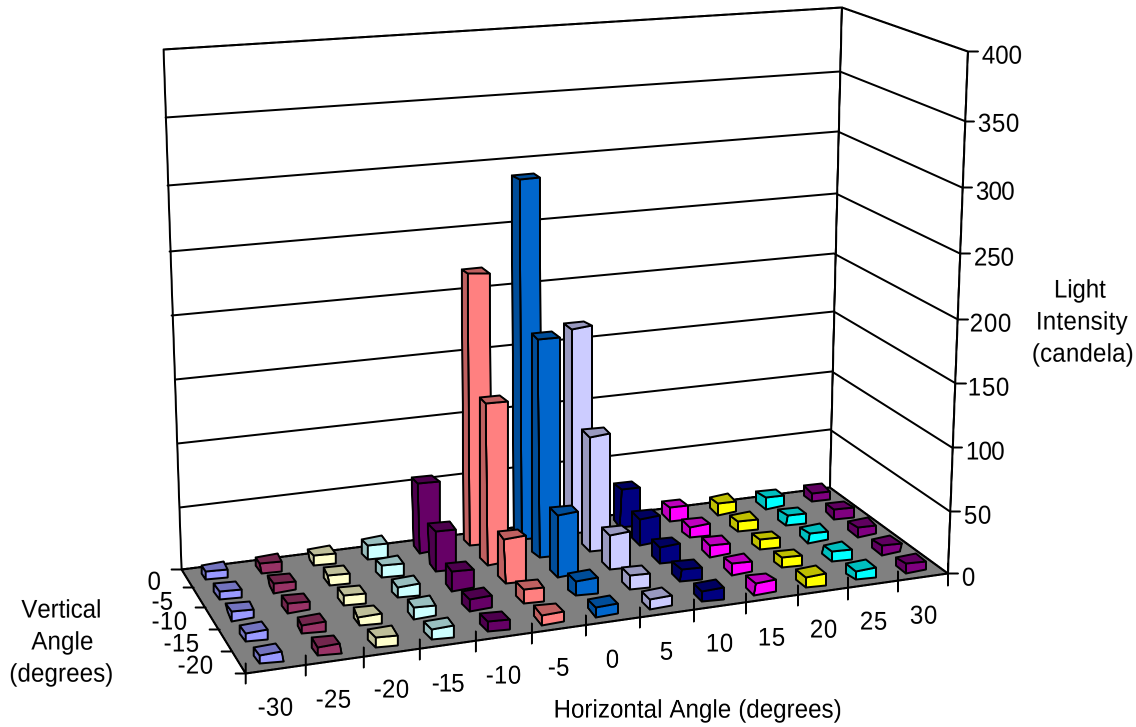

Figure A3.3.17a Output from WPS #3 (Red) signal, 10.0 volts, 239 elements (94.0% on), TC test.

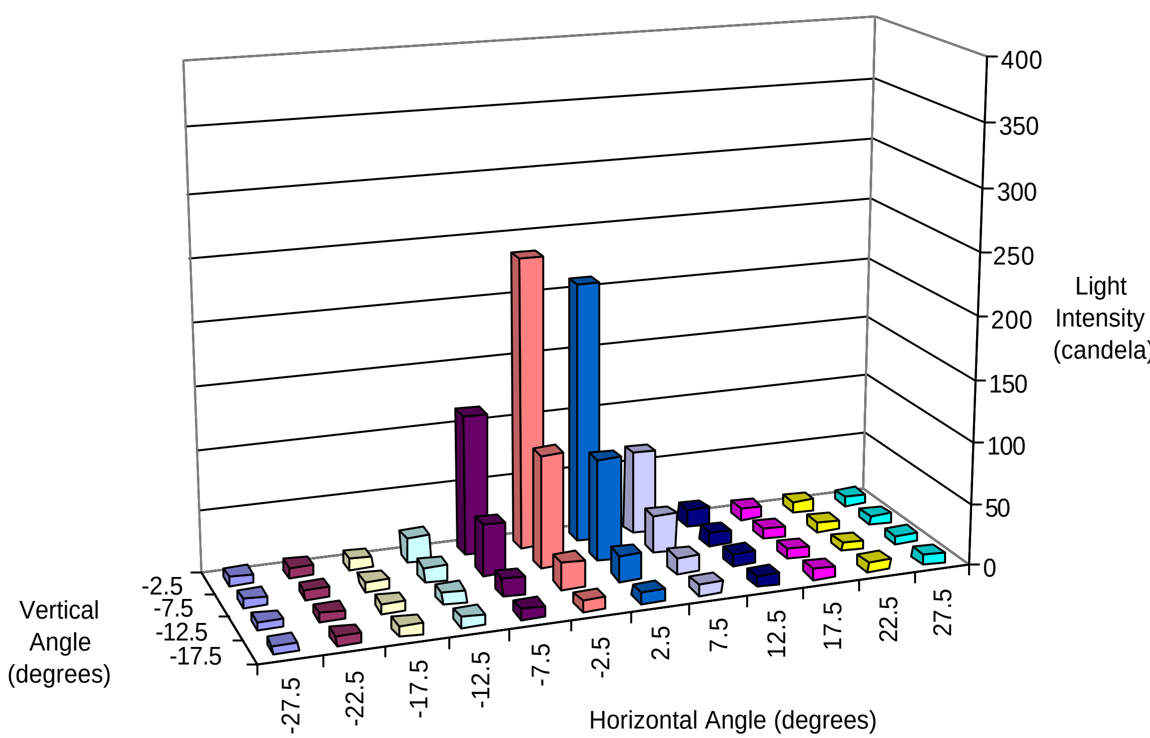

Figure A3.3.17b Output from WPS #3 (Red) signal, 10.0 volts, 239 elements (94.0% on), ITE test.

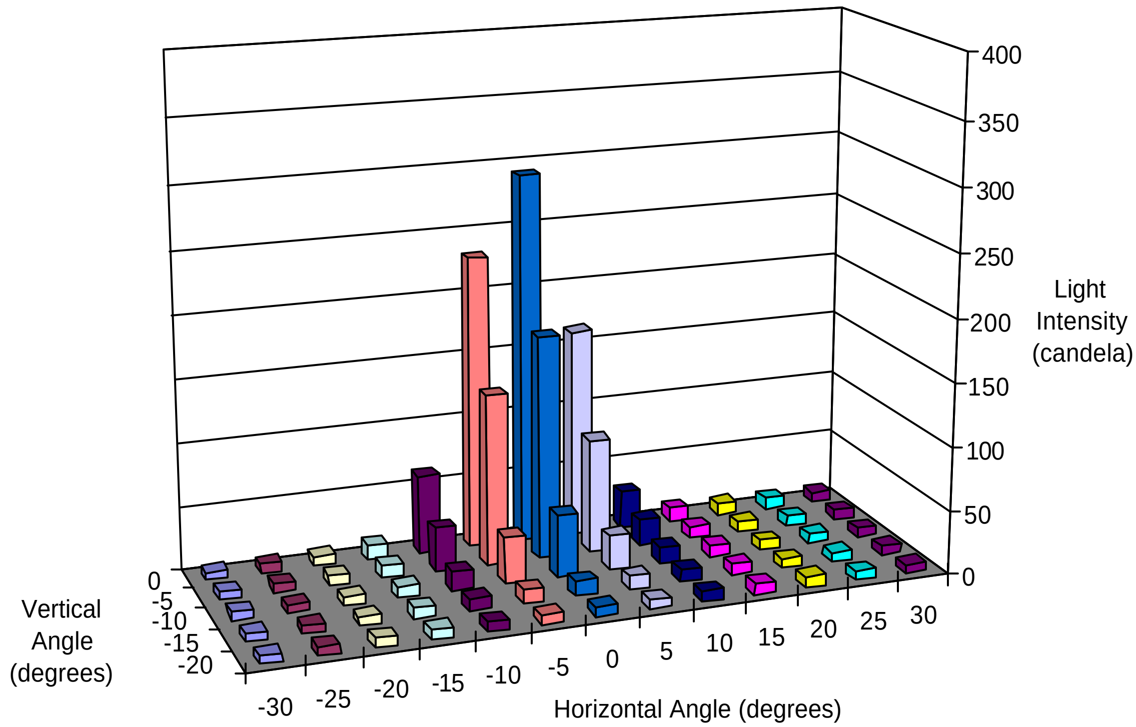

Figure A3.3.18a Output from WPS #3 (Red) signal, 10.0 volts, 224 elements (88.0% on), TC test.

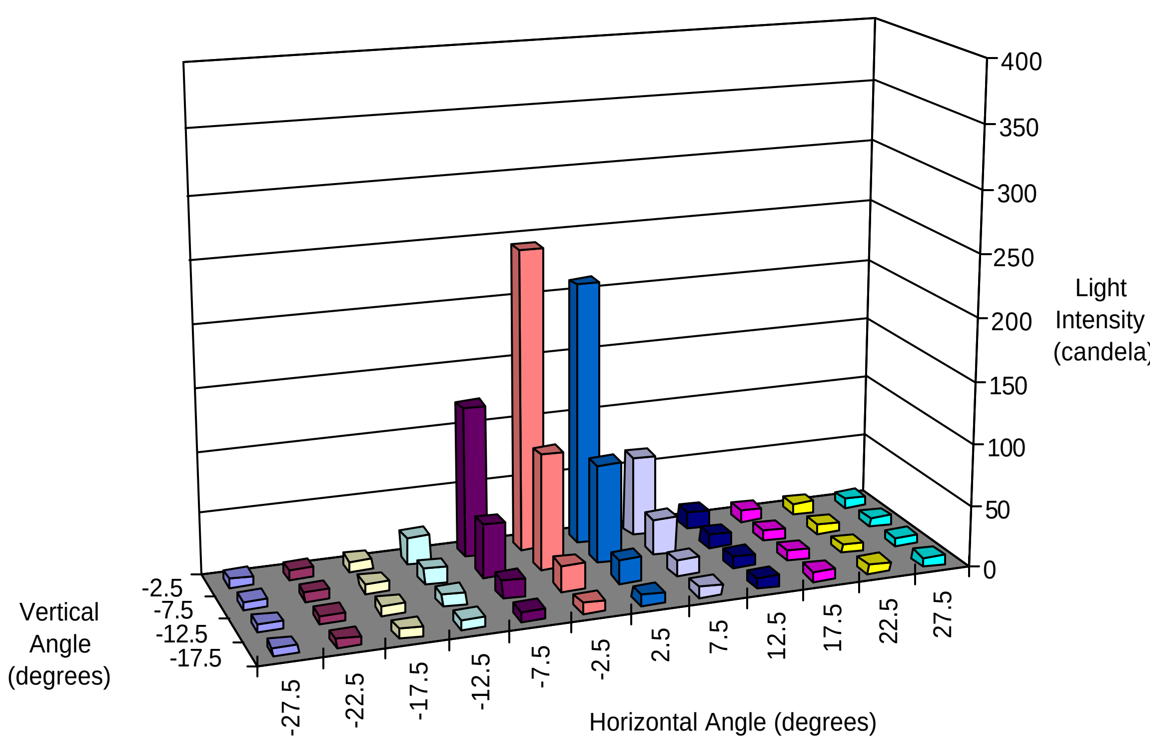

Figure A3.3.18b Output from WPS #3 (Red) signal, 10.0 volts, 224 elements (88.0% on), ITE test.

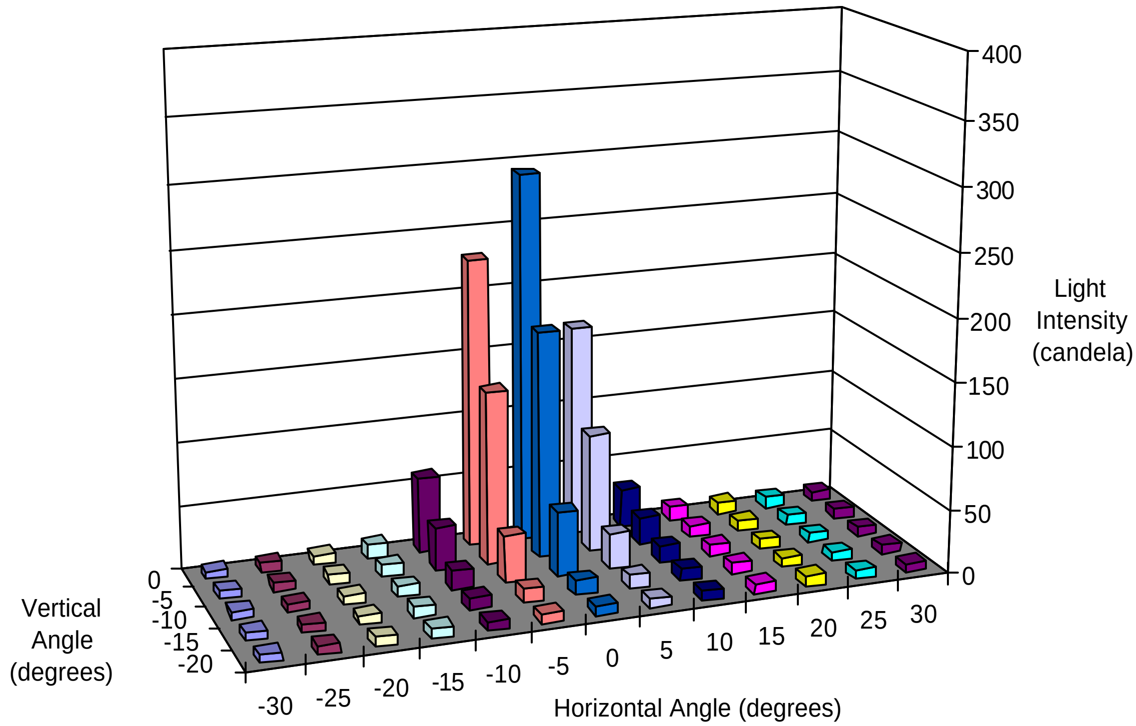

Figure A3.3.19a Output from WPS #3 (Red) signal, 10.0 volts, 209 elements (82.0% on), TC test.

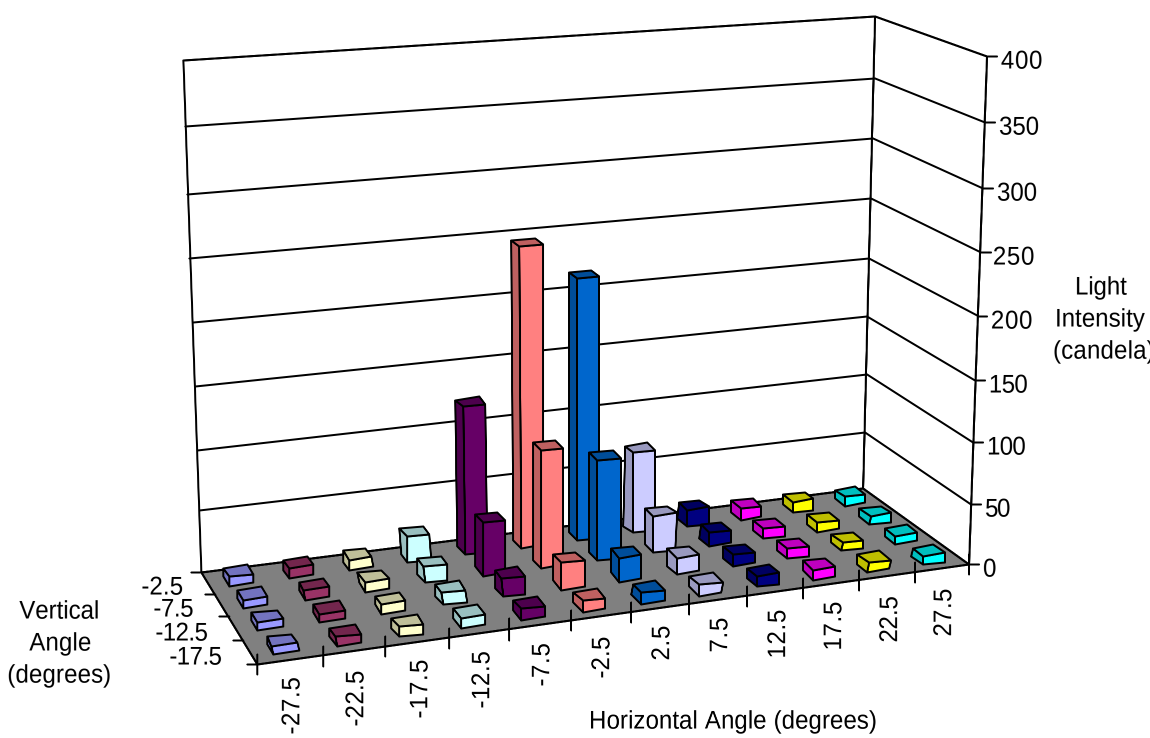

Figure A3.3.19b Output from WPS #3 (Red) signal, 10.0 volts, 209 elements (82.0% on), ITE test.

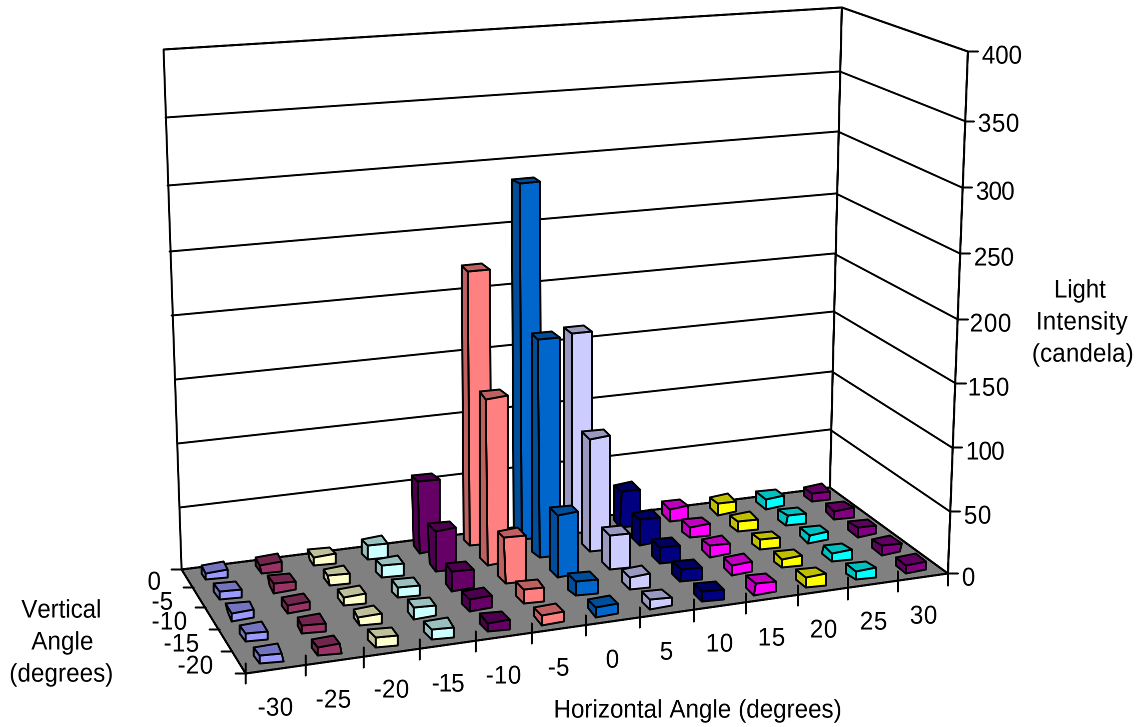

Figure A3.3.20a Output from WPS #3 (Red) signal, 10.0 volts, 194 elements (76.0% on), TC test.

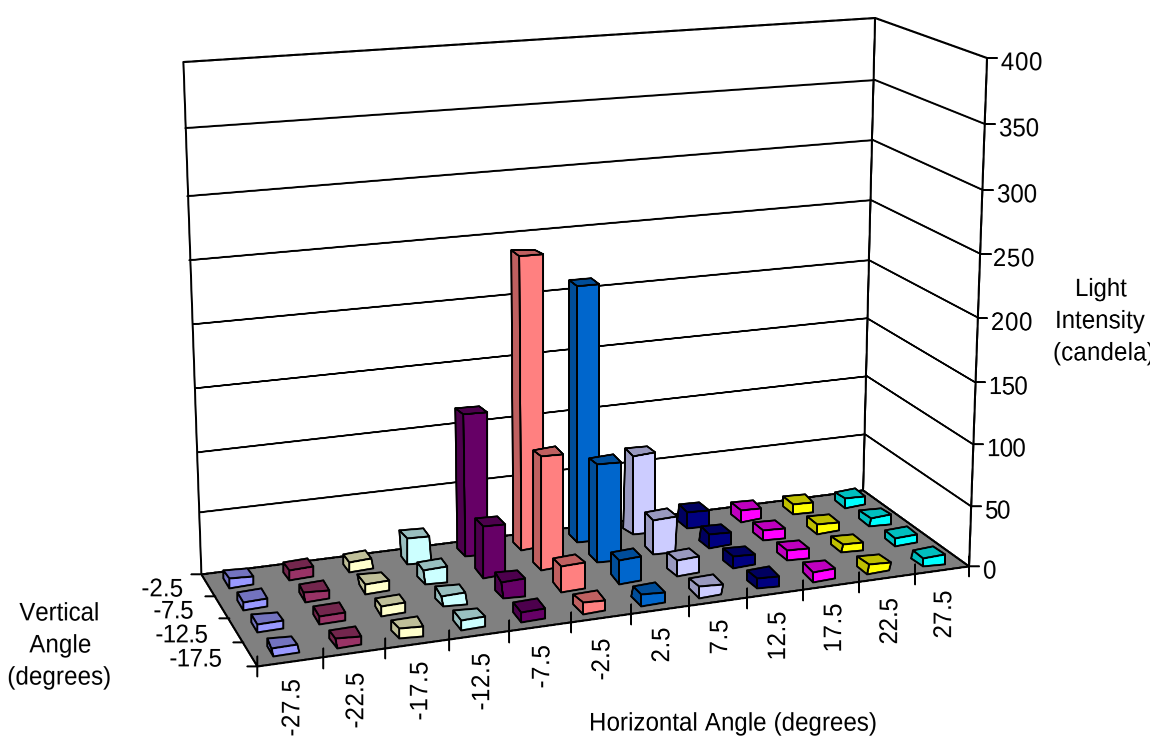

Figure A3.3.20b Output from WPS #3 (Red) signal, 10.0 volts, 194 elements (76.0% on), ITE test.

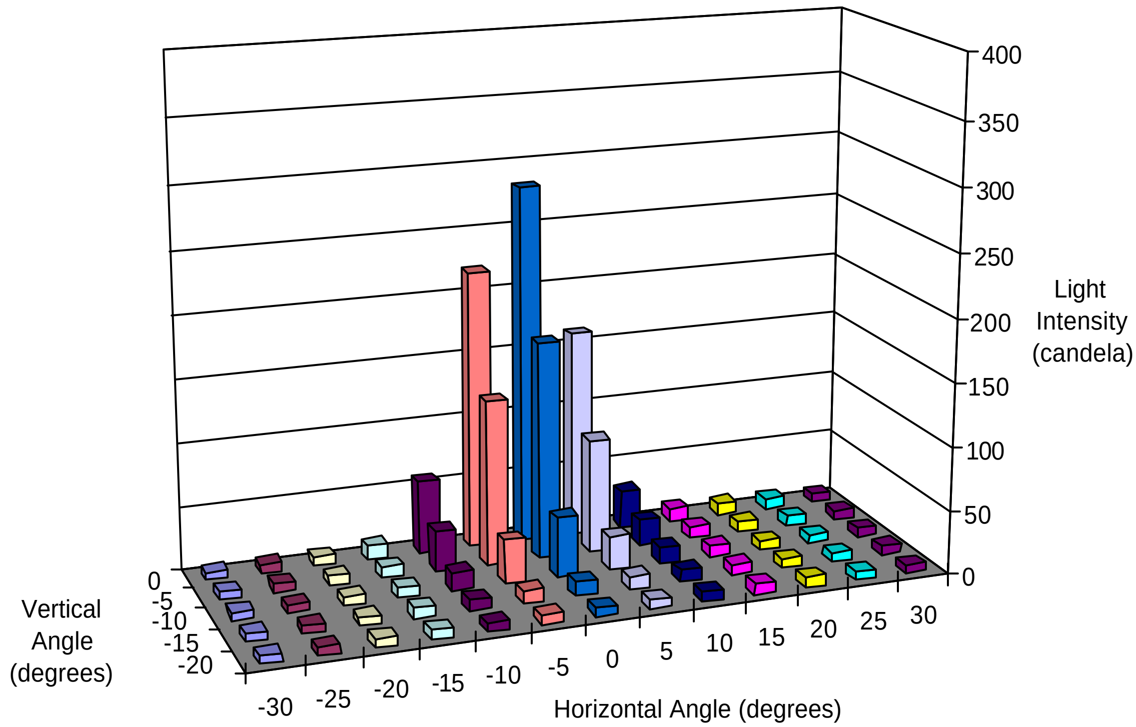

Figure A3.3.21a Output from WPS #3 (Red) signal, 10.0 volts, 179 elements (70.0% on), TC test.

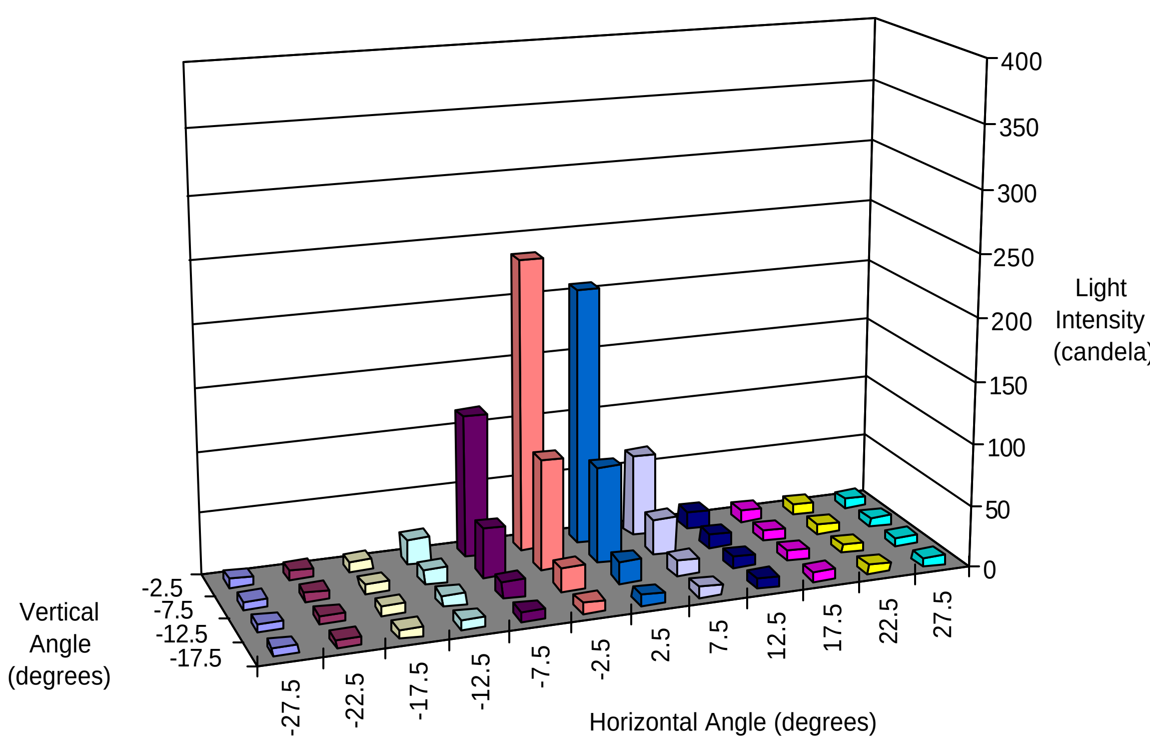

Figure A3.3.21b Output from WPS #3 (Red) signal, 10.0 volts, 179 elements (70.0% on), ITE test.

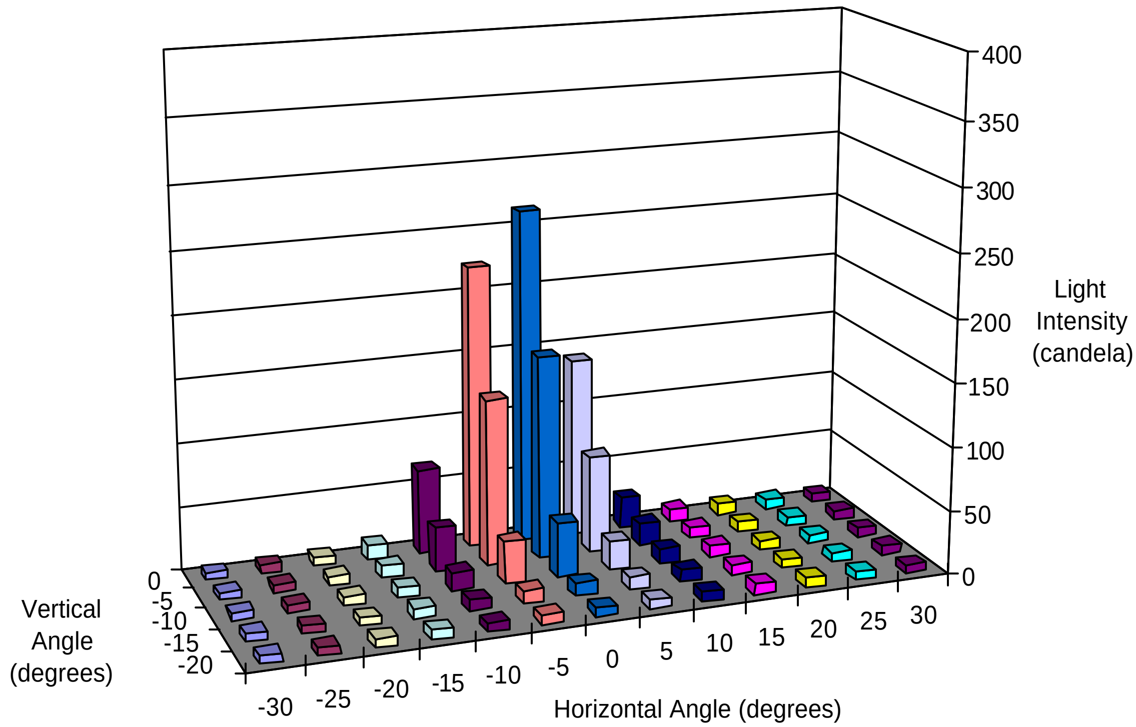

Figure A3.3.22a Output from WPS #3 (Red) signal, 10.0 volts, 164 elements (64.0% on), TC test.

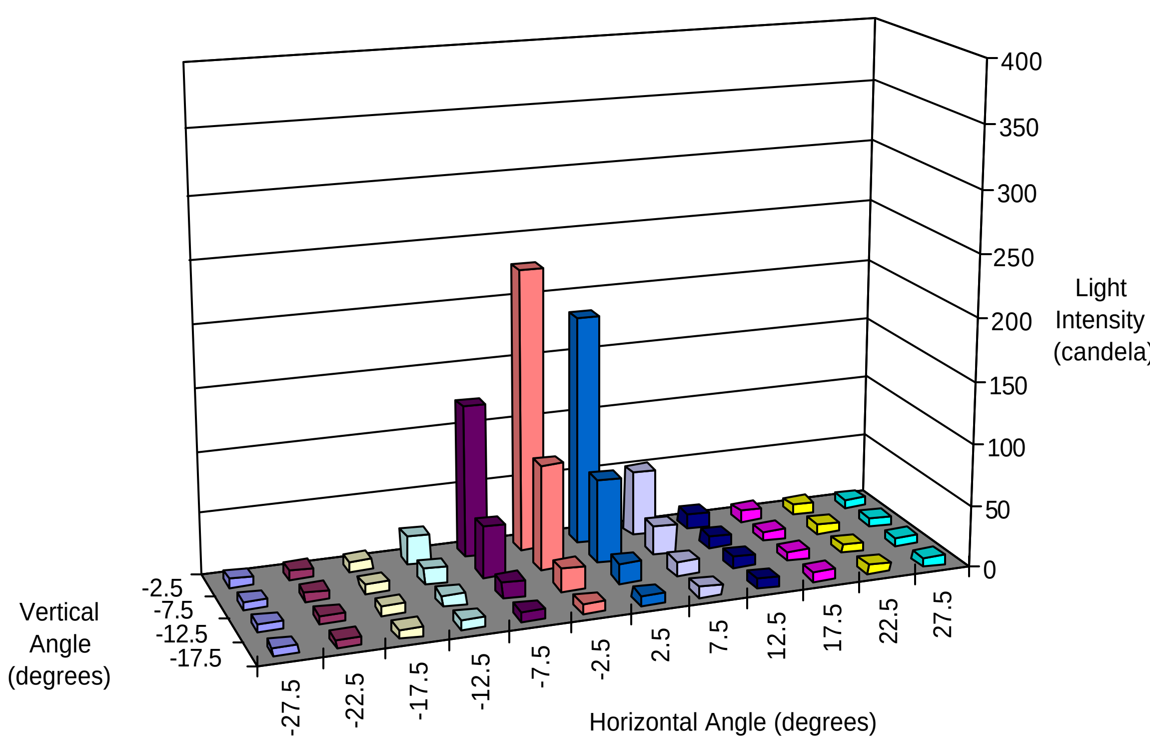

Figure A3.3.22b Output from WPS #3 (Red) signal, 10.0 volts, 164 elements (64.0% on), ITE test.

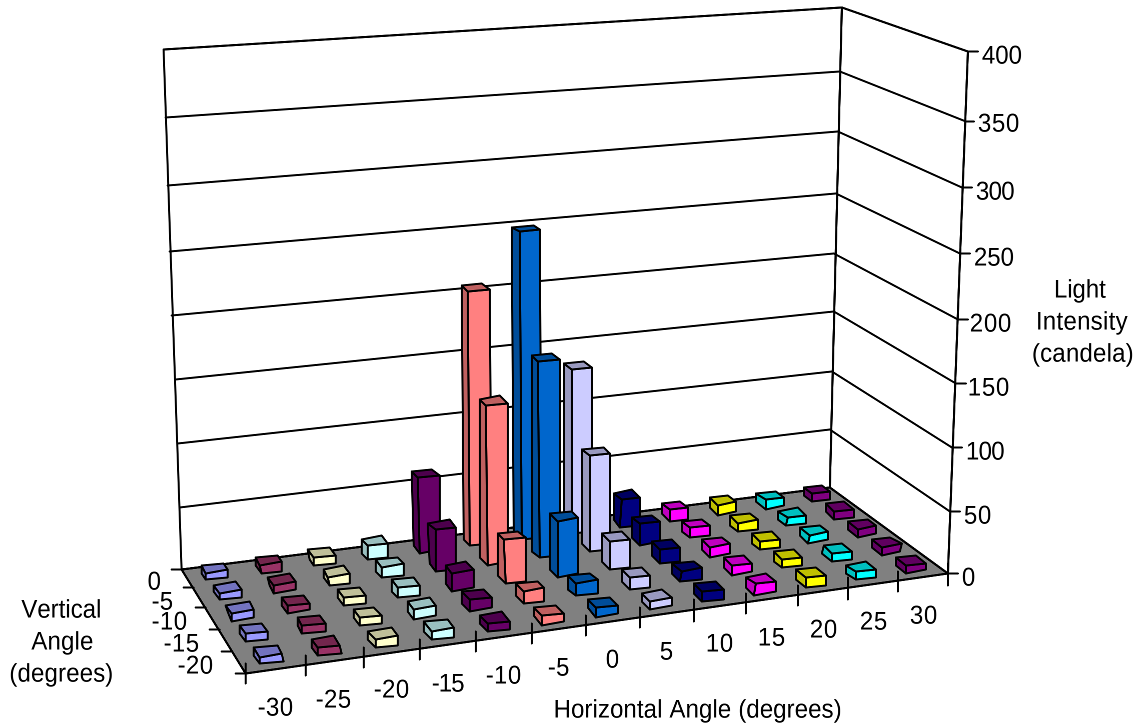

Figure A3.3.23a Output from WPS #3 (Red) signal, 10.0 volts, 149 elements (58.0% on), TC test.

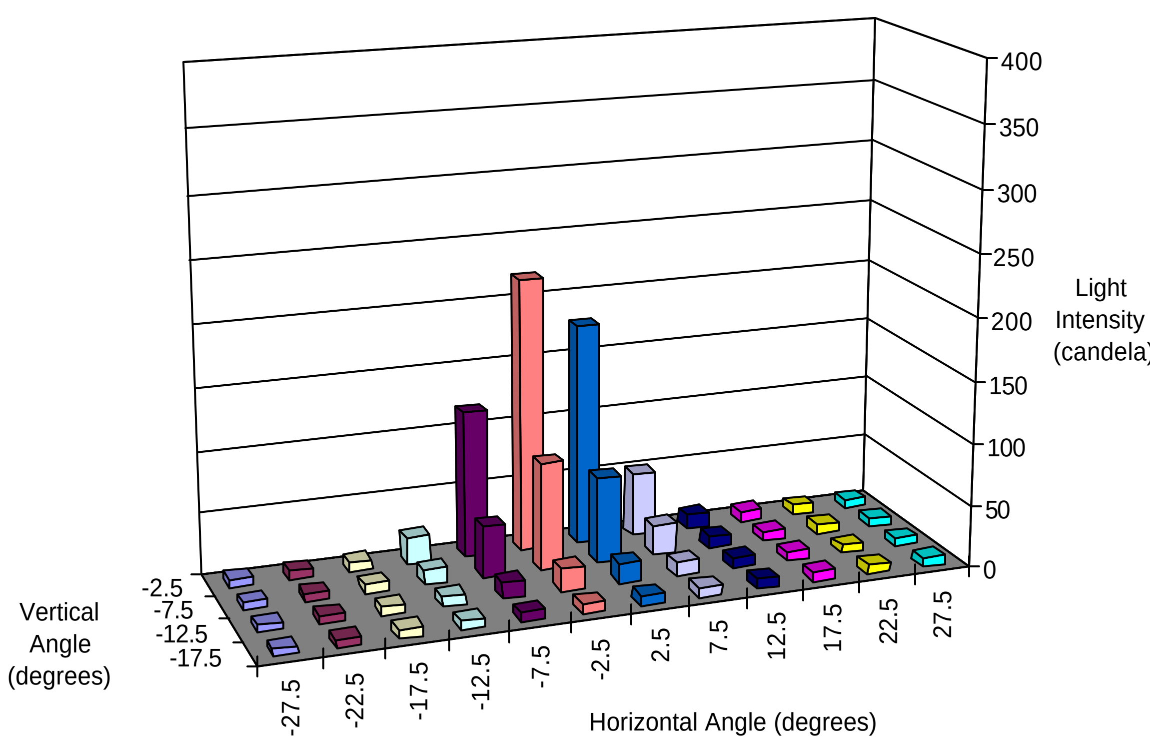

Figure A3.3.23b Output from WPS #3 (Red) signal, 10.0 volts, 149 elements (58.0% on), ITE test.

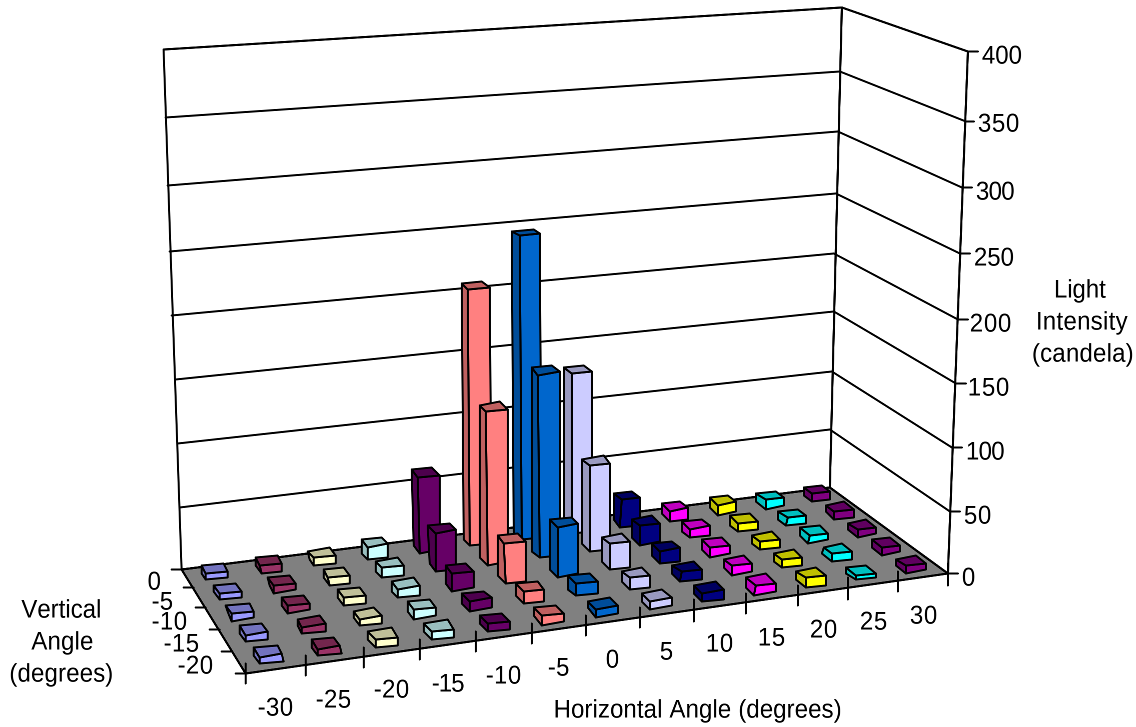

Figure A3.3.24a Output from WPS #3 (Red) signal, 10.0 volts, 134 elements (52.0% on), TC test.

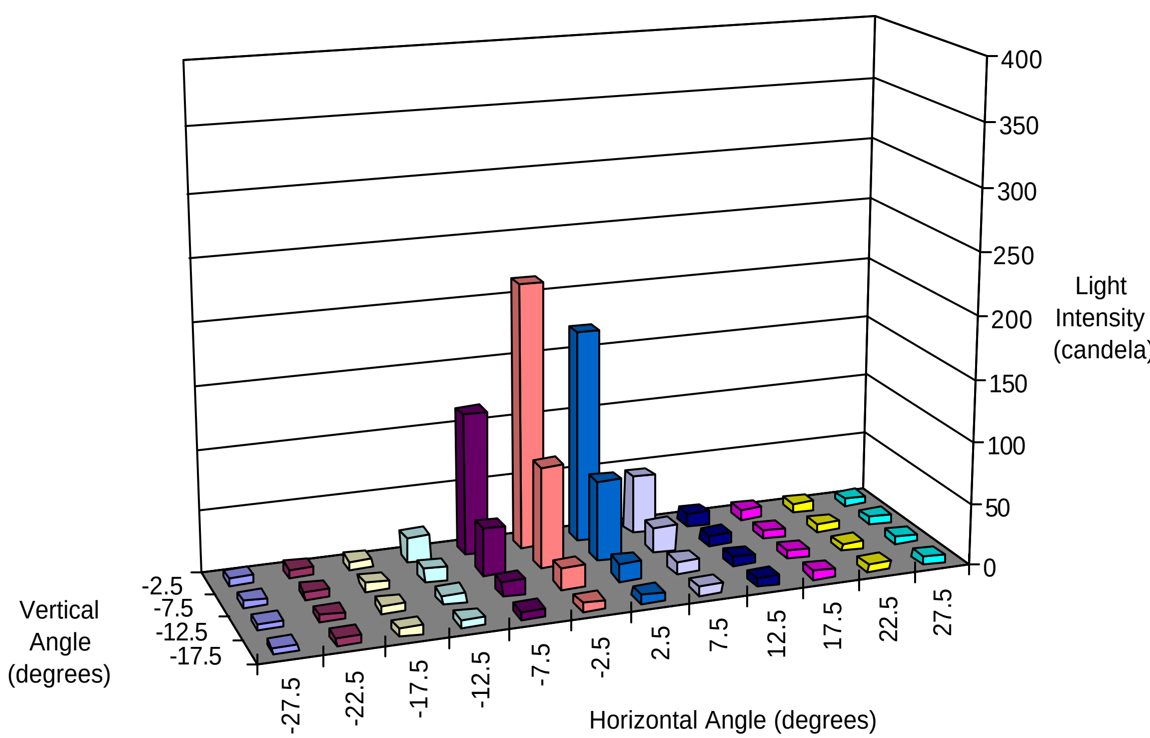

Figure A3.3.24b Output from WPS #3 (Red) signal, 10.0 volts, 134 elements (52.0% on), ITE test.

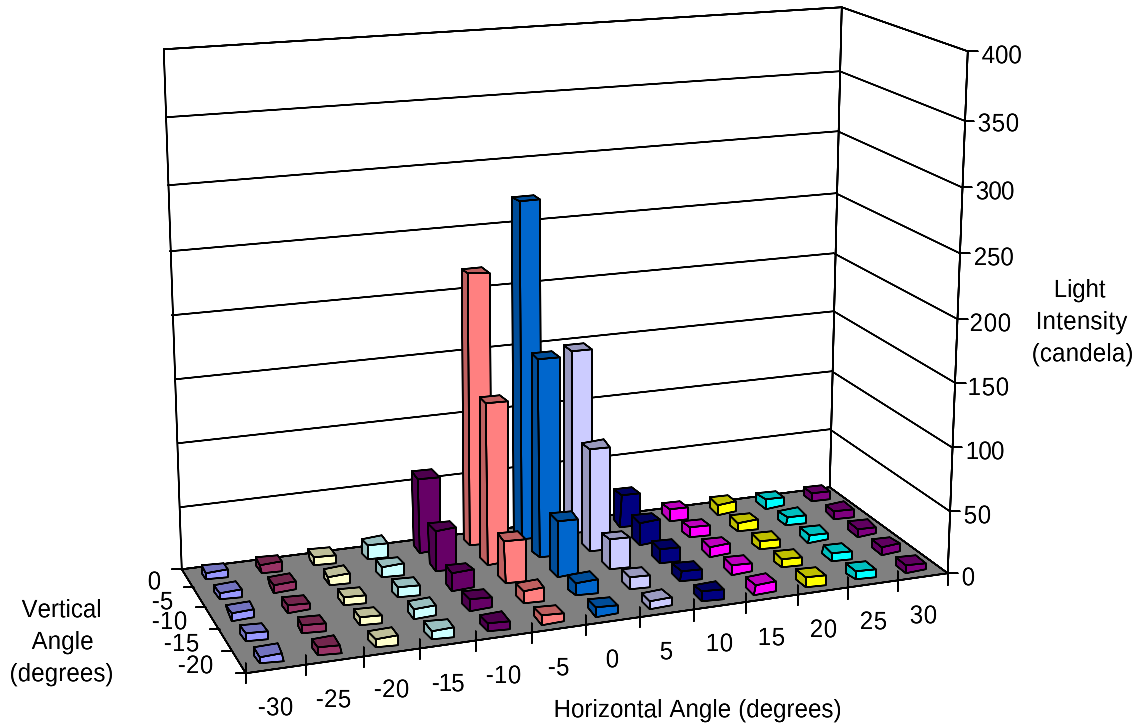

Figure A3.3.25a Output from WPS #3 (Red) signal, 10.0 volts, 119 elements (46.0% on), TC test.

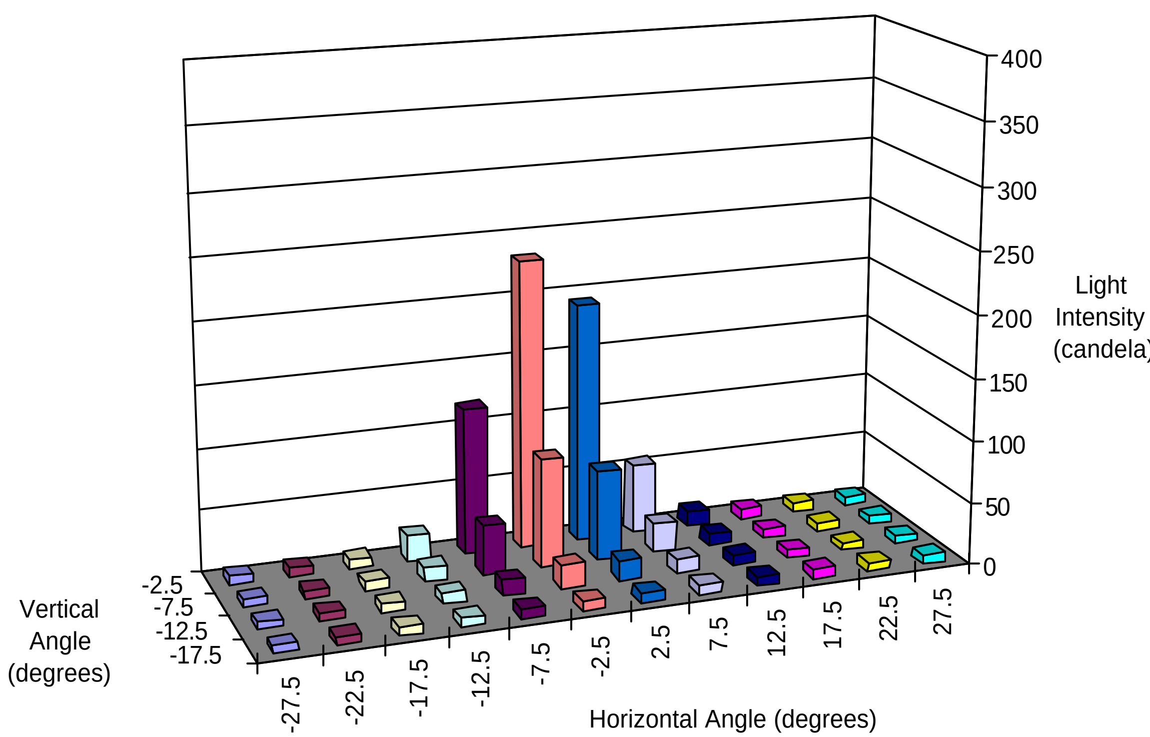

Figure A3.3.25b Output from WPS #3 (Red) signal, 10.0 volts, 119 elements (46.0% on), ITE test.

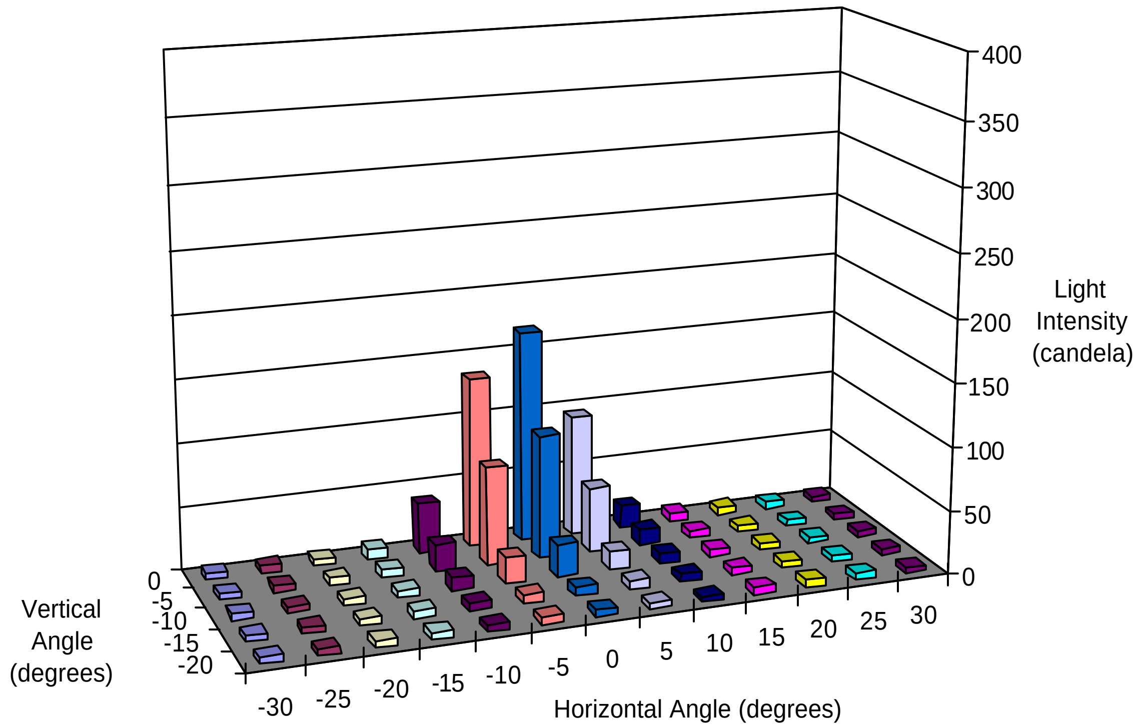

Figure A3.3.26a Output from WPS #3 (Red) signal, 10.0 volts, 104 elements (40.0% on), TC test.

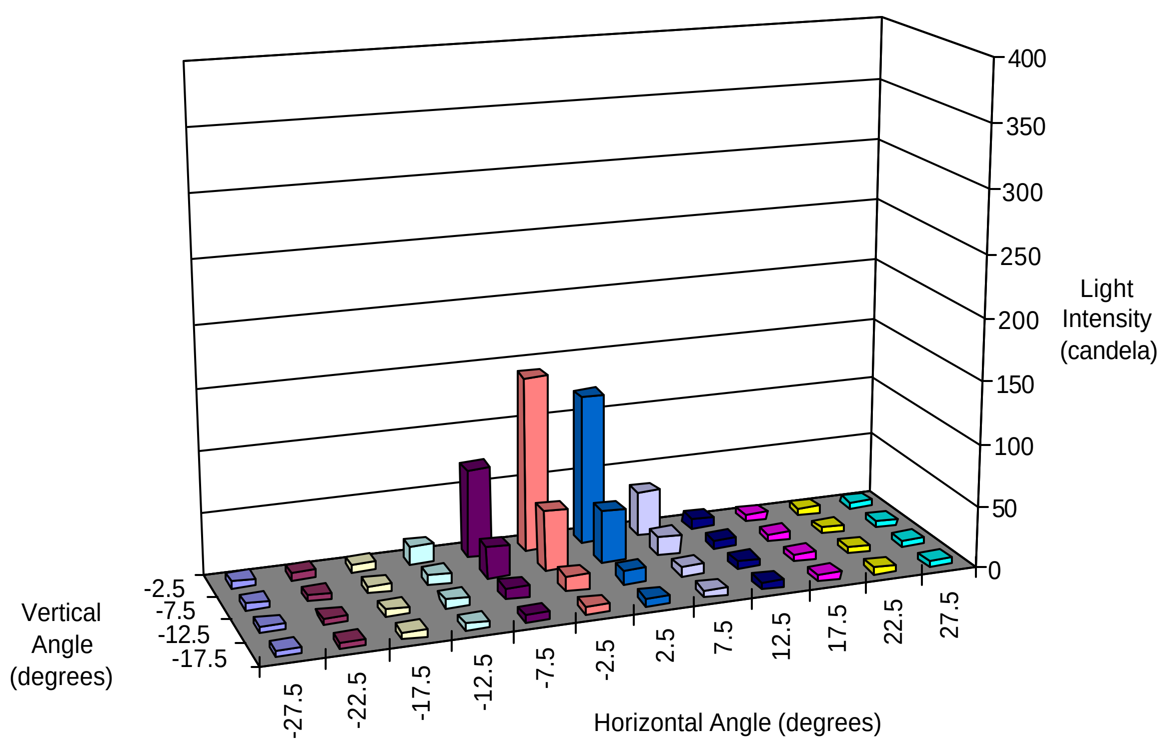

Figure A3.3.26b Output from WPS #3 (Red) signal, 10.0 volts, 104 elements (40.0% on), ITE test.

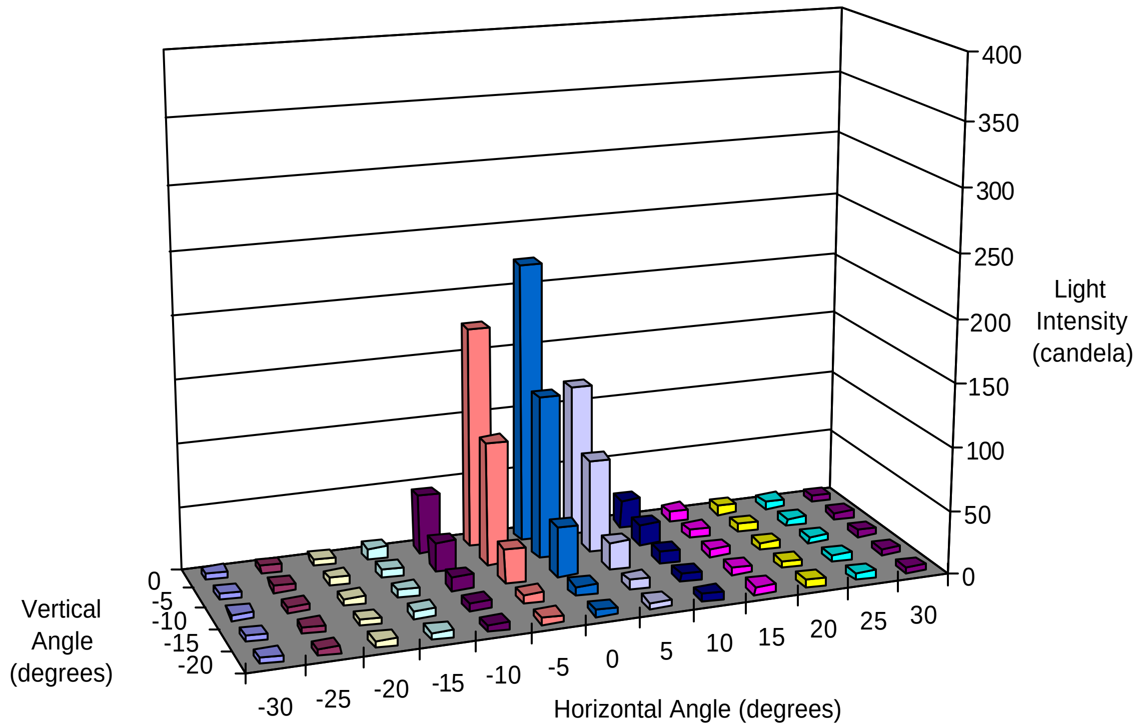

Figure A3.3.27a Output from WPS #3 (Red) signal, 10.0 volts, 89 elements (35.0% on), TC test.

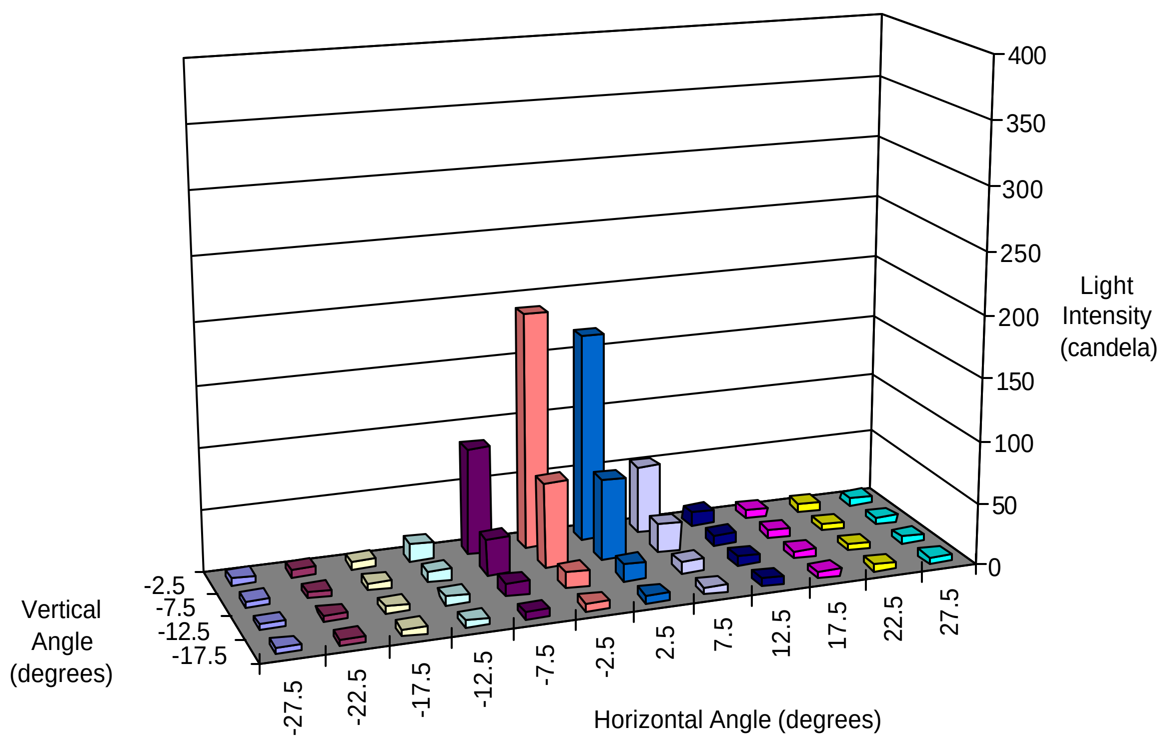

Figure A3.3.27b Output from WPS #3 (Red) signal, 10.0 volts, 89 elements (35.0% on), ITE test.

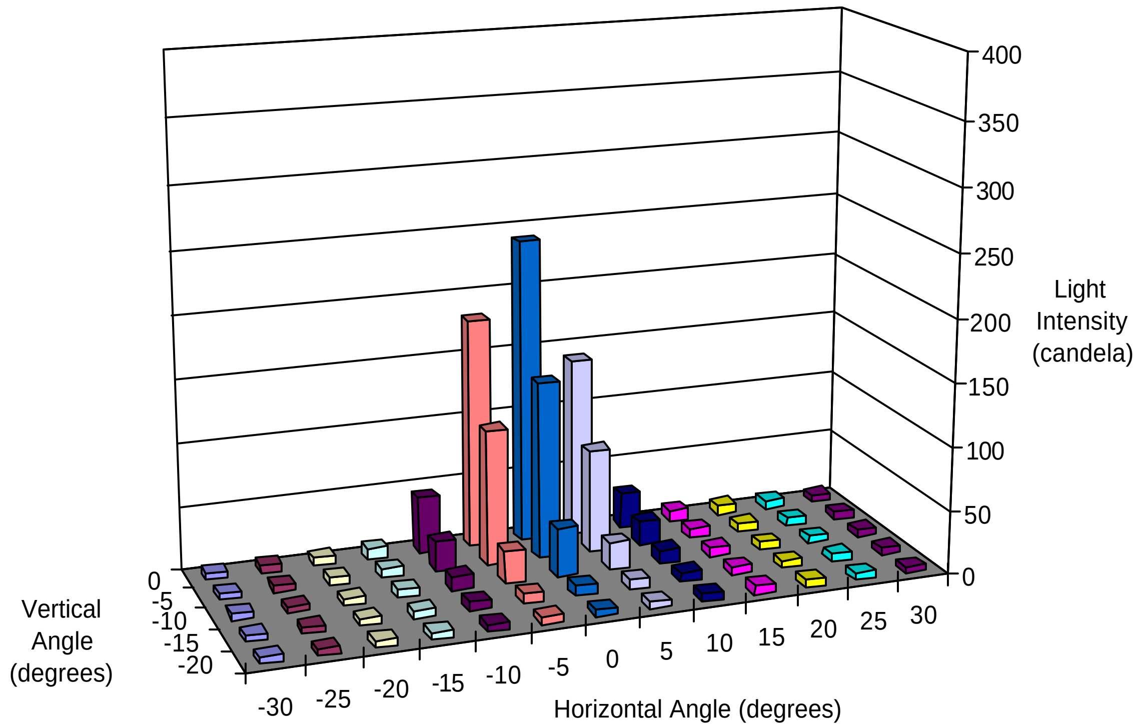

Figure A3.3.28a Output from WPS #3 (Red) signal, 10.0 volts, 74 elements (29.0% on), TC test.

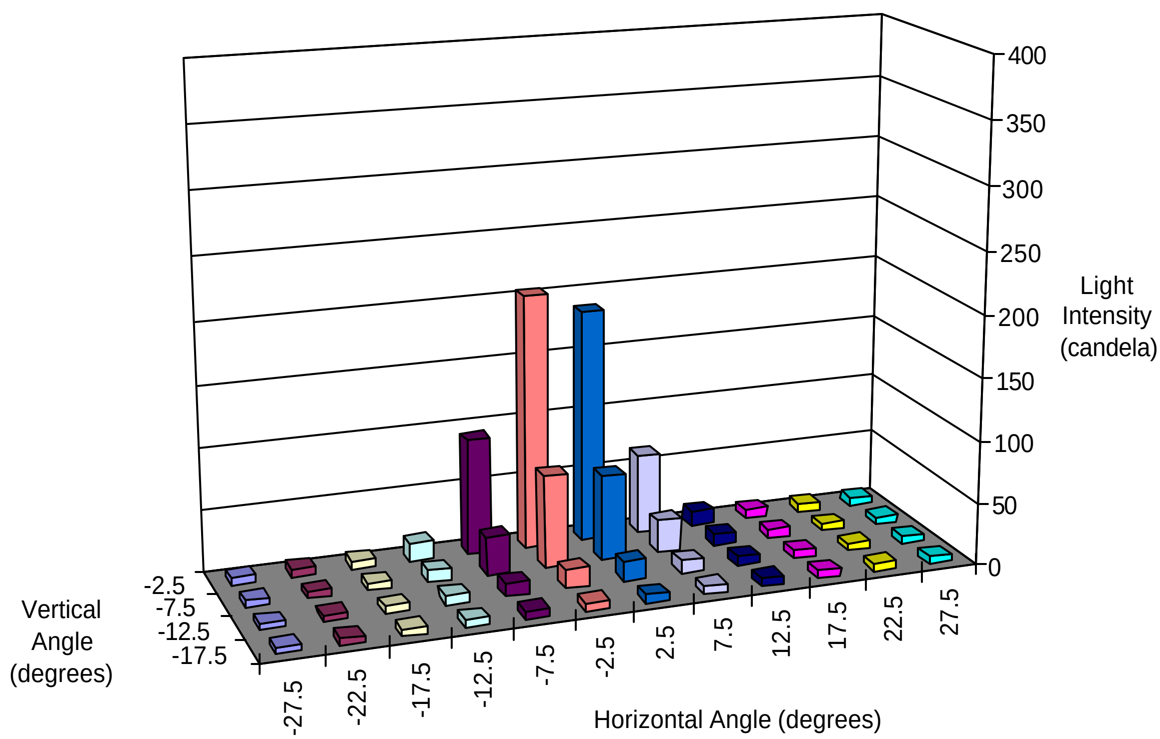

Figure A3.3.28b Output from WPS #3 (Red) signal, 10.0 volts, 74 elements (29.0% on), ITE test.

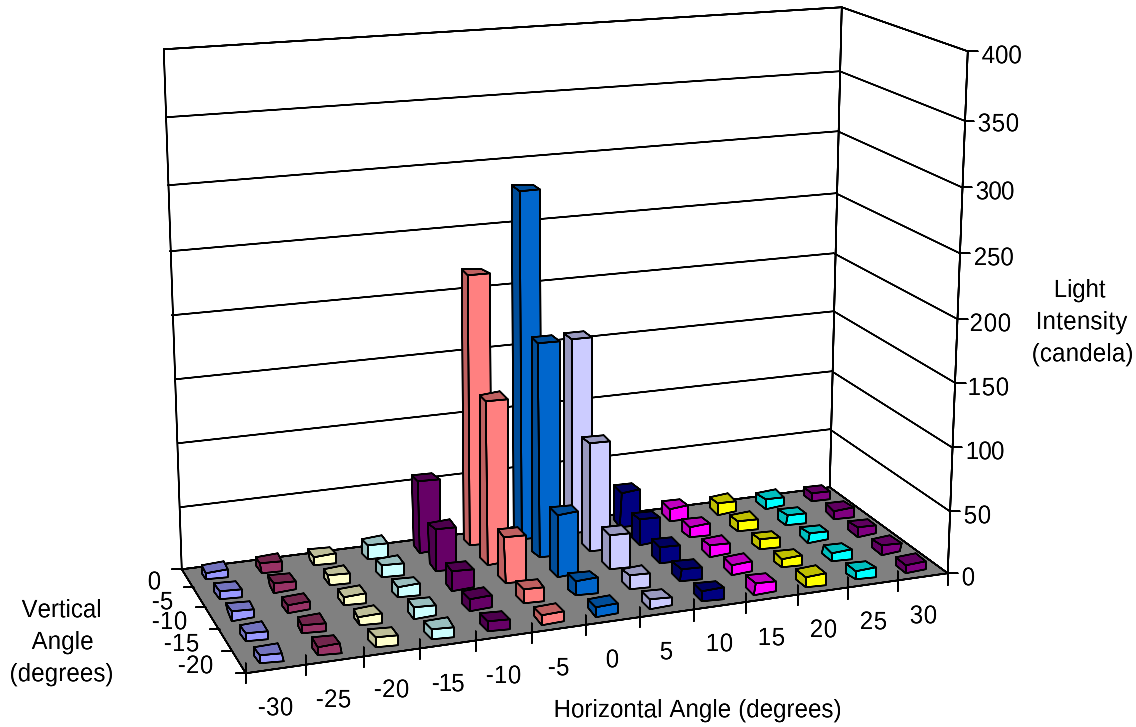

Figure A3.3.29a Output from WPS #3 (Red) signal, 12.0 volts, 239 elements (94.0% on), TC test.

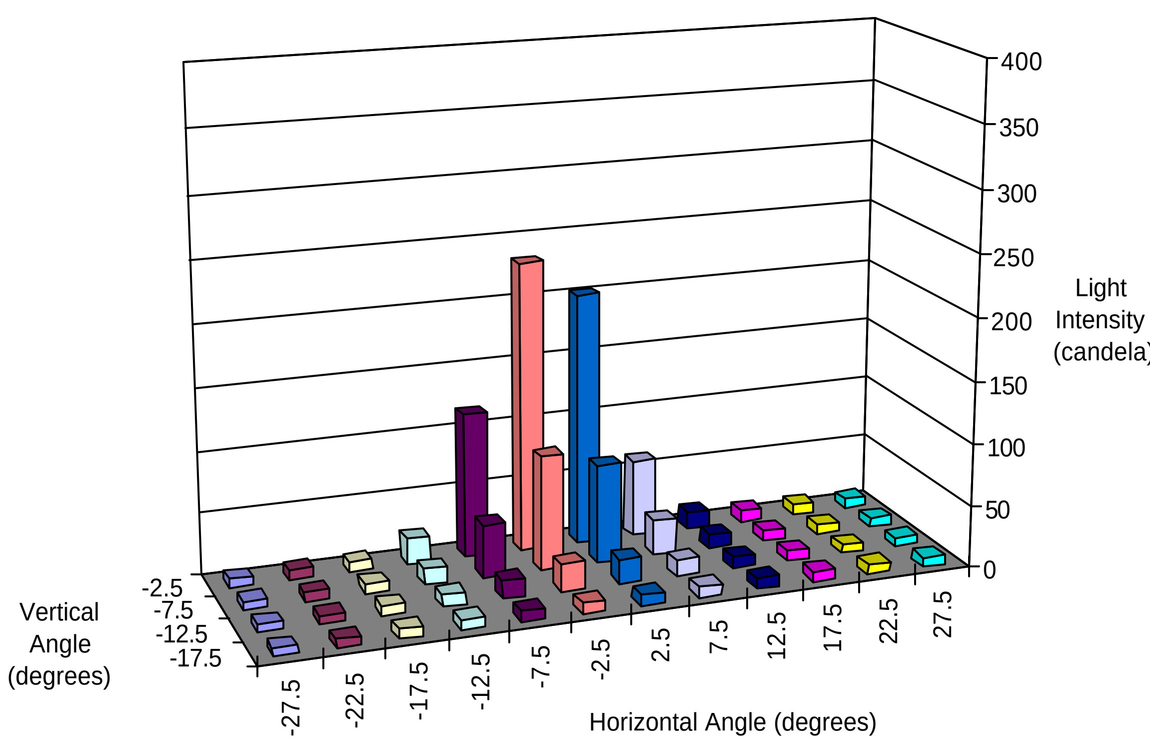

Figure A3.3.29b Output from WPS #3 (Red) signal, 12.0 volts, 239 elements (94.0% on), ITE test.

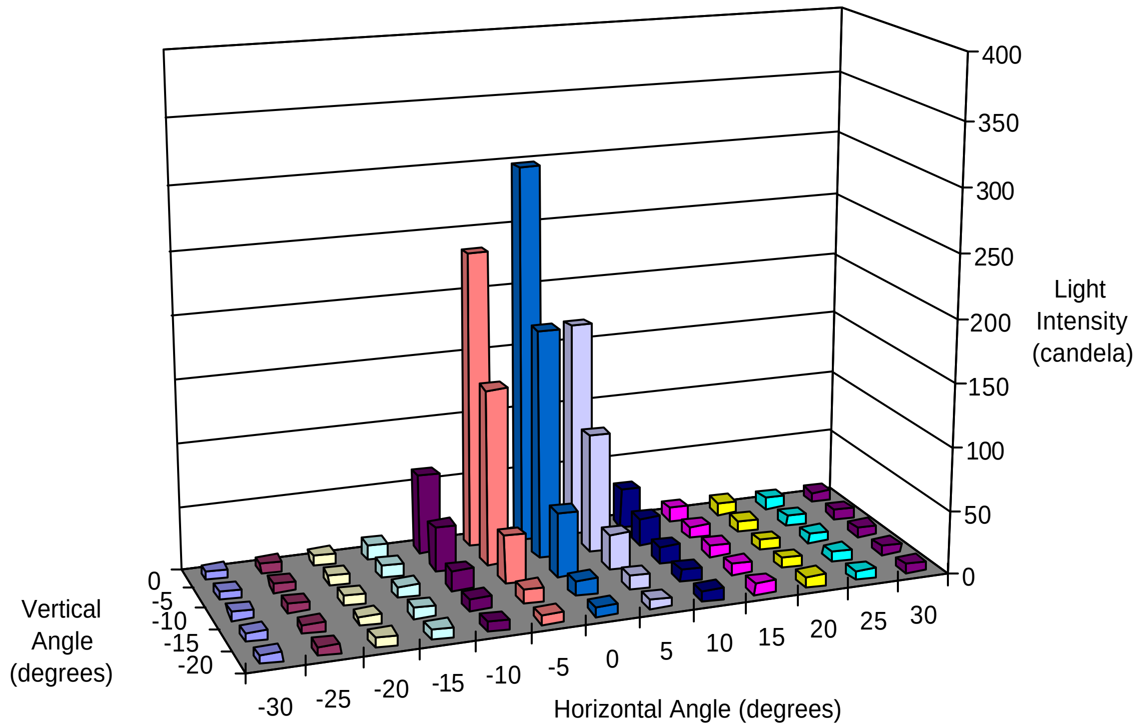

Figure A3.3.30a Output from WPS #3 (Red) signal, 12.0 volts, 224 elements (88.0% on), TC test.

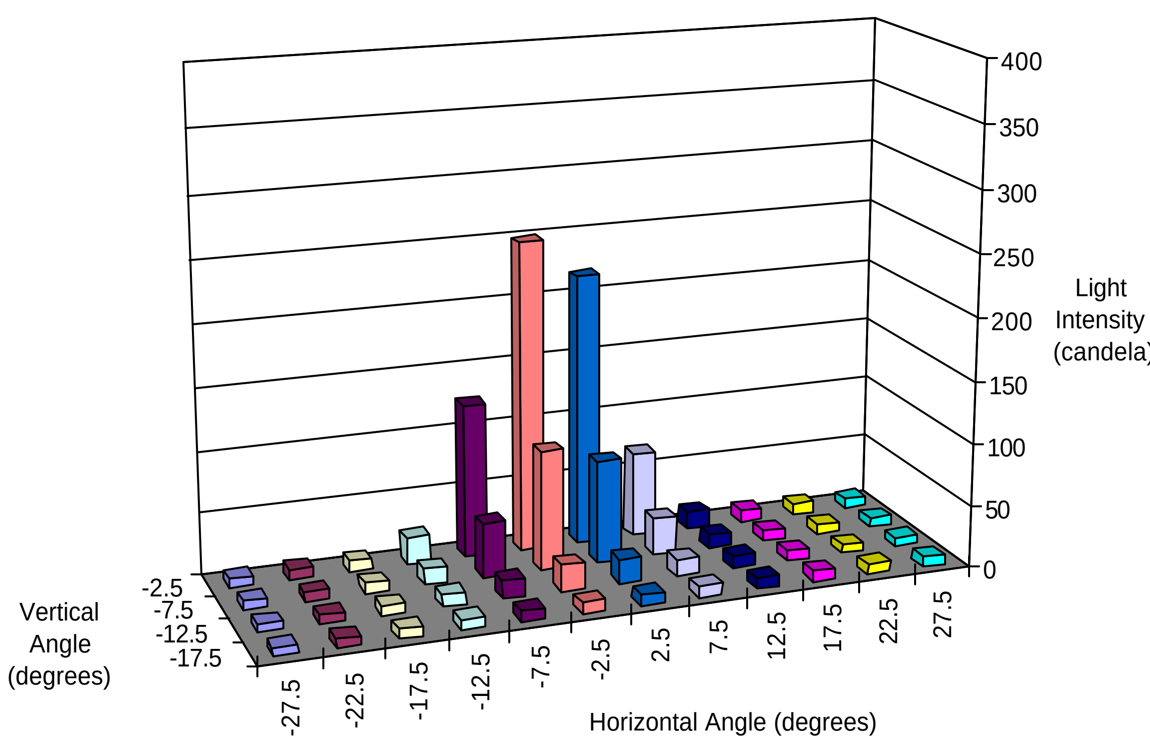

Figure A3.3.30b Output from WPS #3 (Red) signal, 12.0 volts, 224 elements (88.0% on), ITE test.

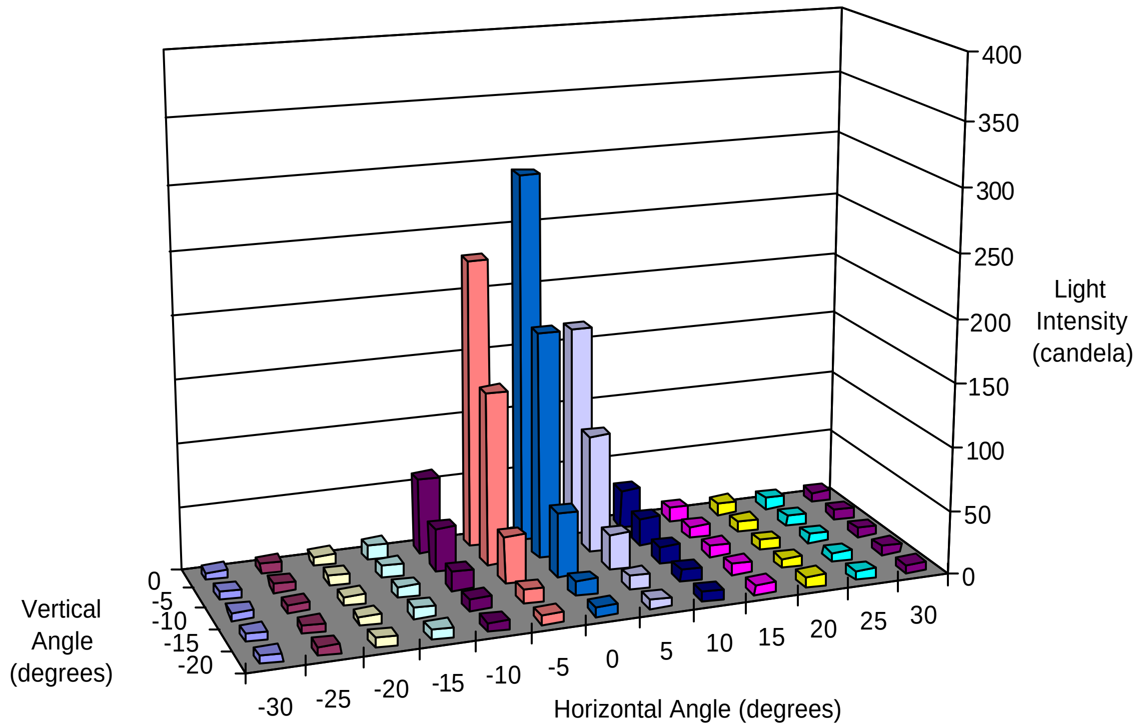

Figure A3.3.31a Output from WPS #3 (Red) signal, 12.0 volts, 209 elements (82.0% on), TC test.

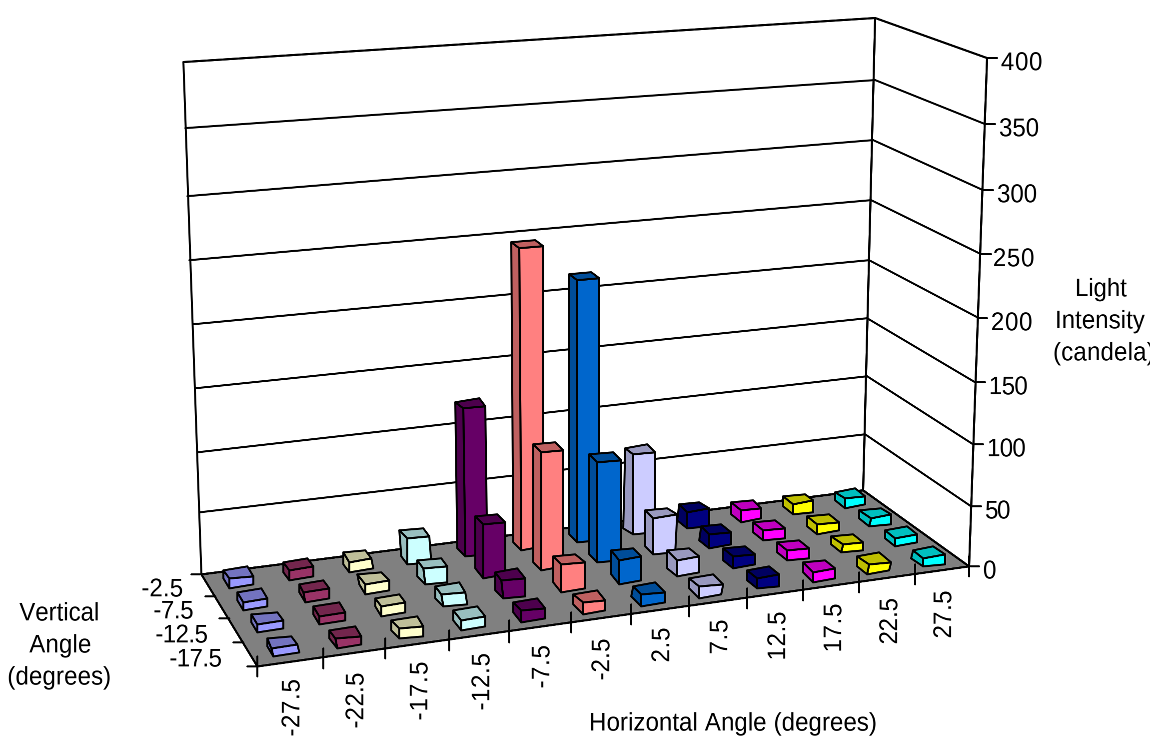

Figure A3.3.31b Output from WPS #3 (Red) signal, 12.0 volts, 209 elements (82.0% on), ITE test.

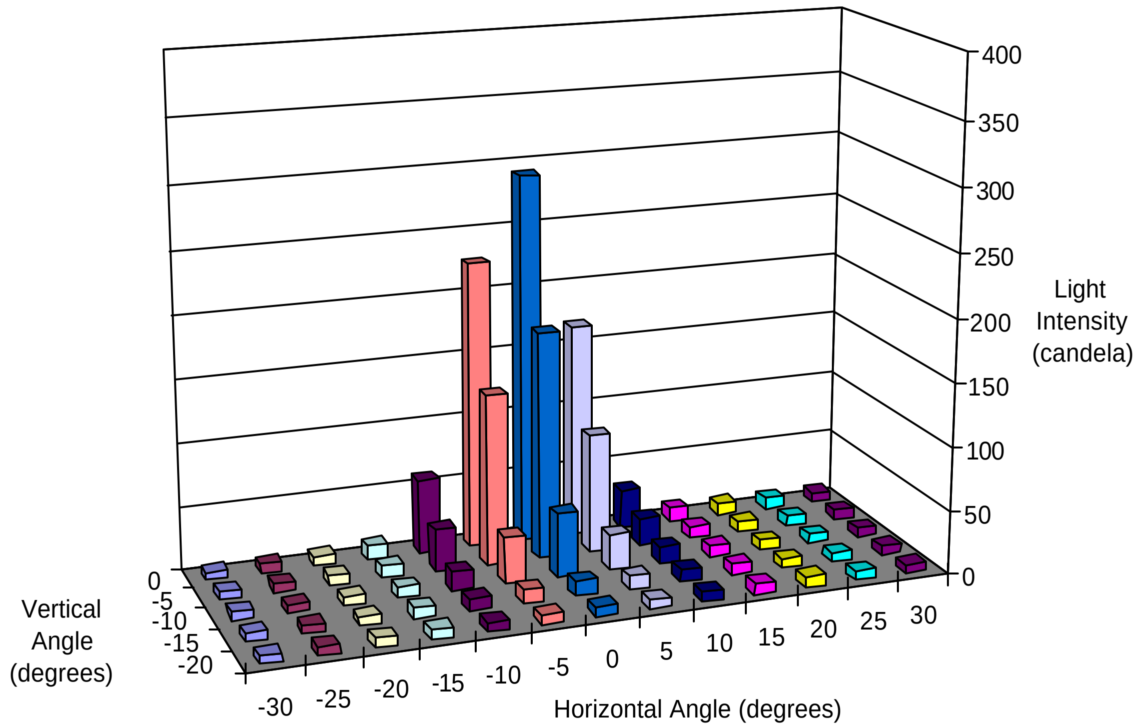

Figure A3.3.32a Output from WPS #3 (Red) signal, 12.0 volts, 194 elements (76.0% on), TC test.

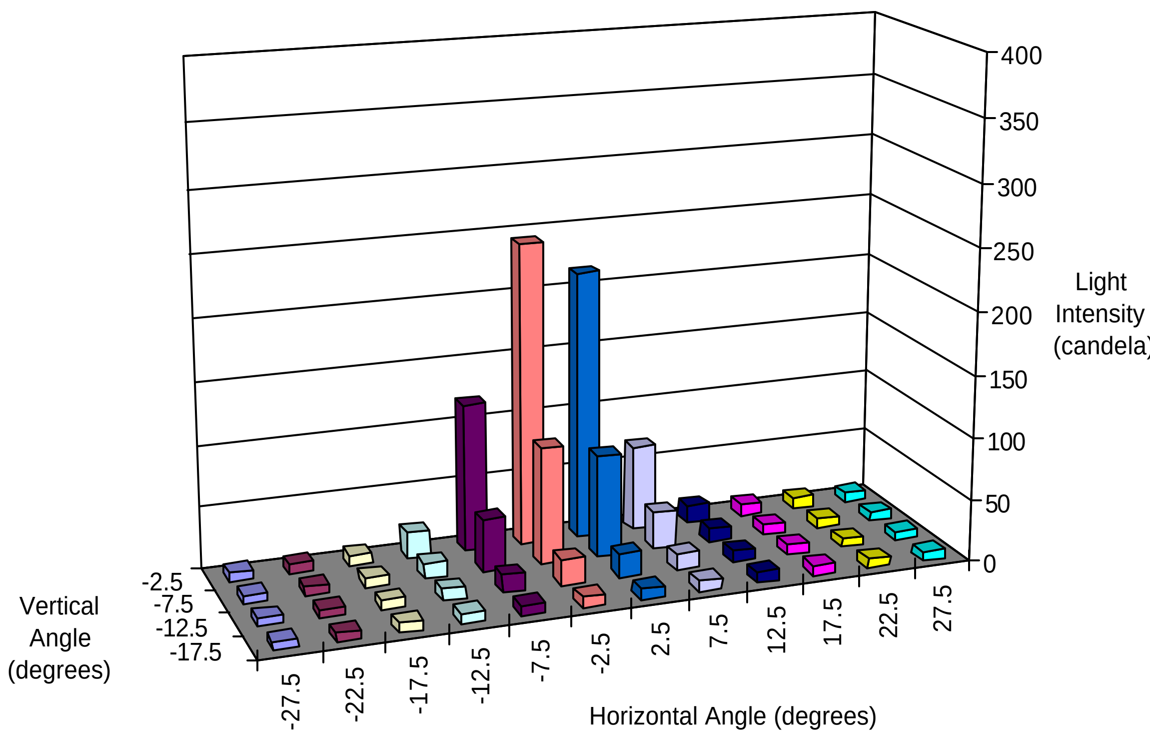

Figure A3.3.32b Output from WPS #3 (Red) signal, 12.0 volts, 194 elements (76.0% on), ITE test.

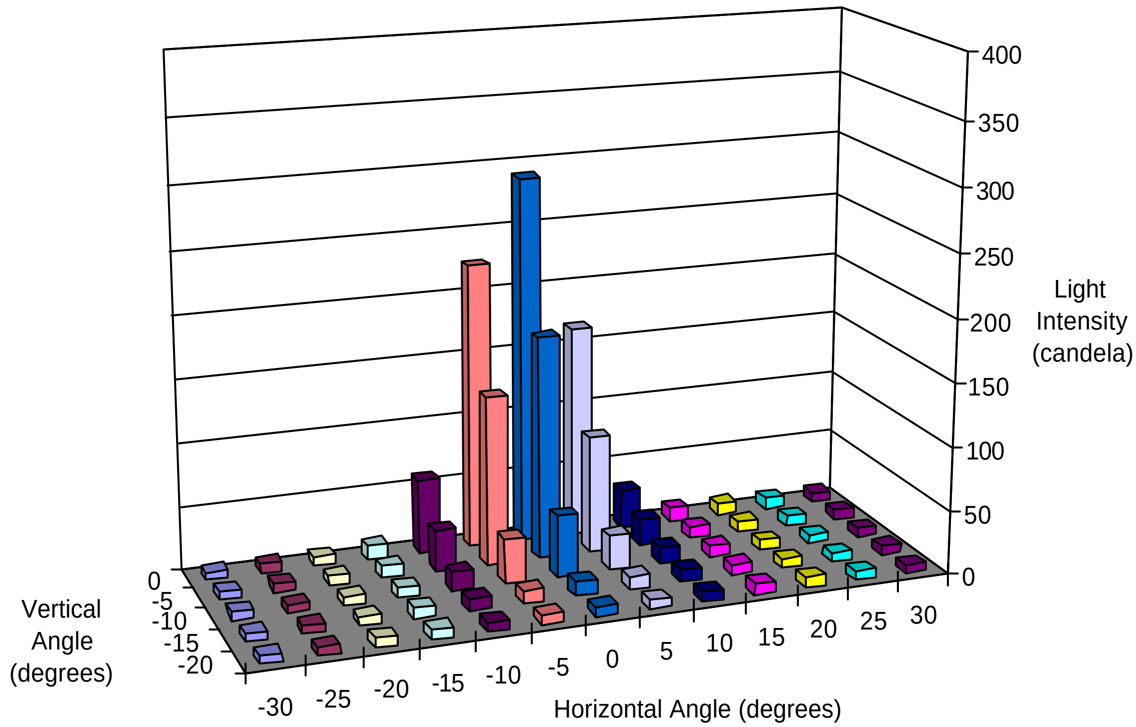

Figure A3.3.33a Output from WPS #3 (Red) signal, 12.0 volts, 179 elements (70.0% on), TC test.

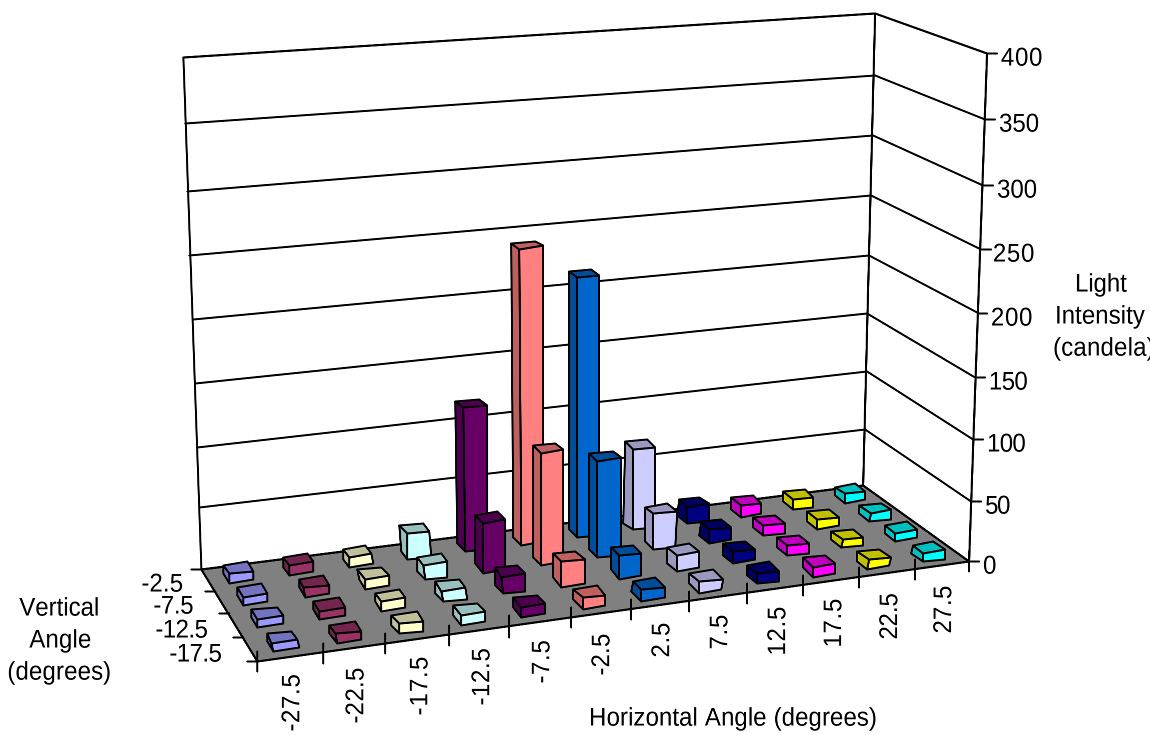

Figure A3.3.33b Output from WPS #3 (Red) signal, 12.0 volts, 179 elements (70.0% on), ITE test.

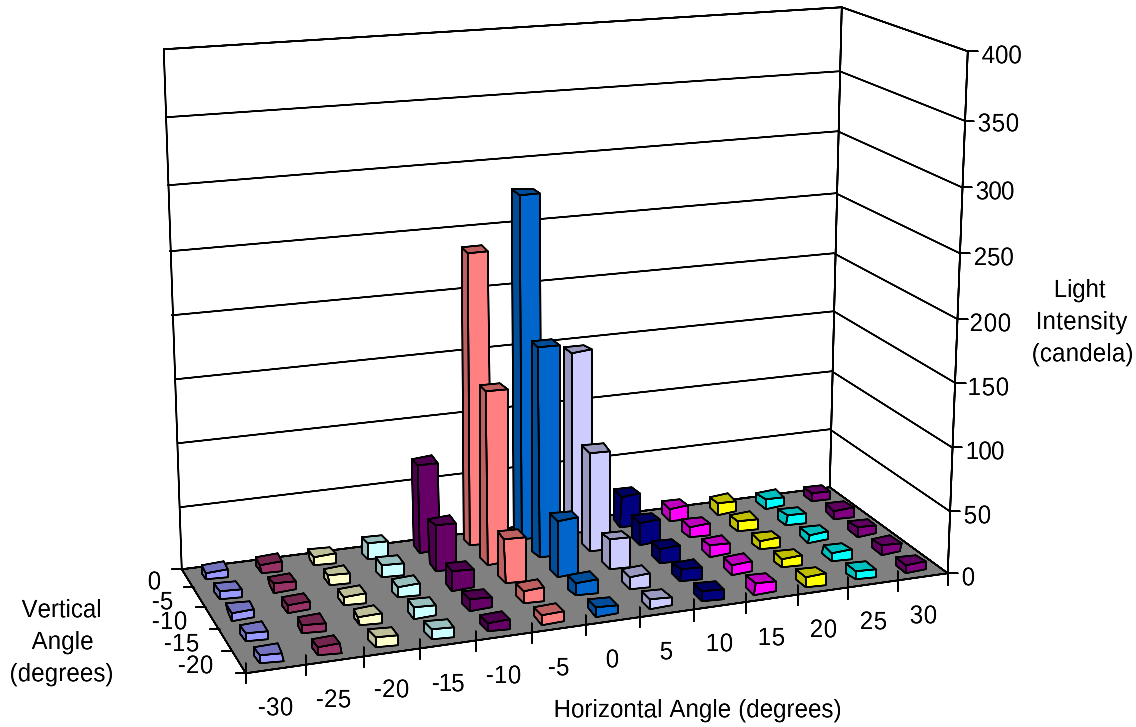

Figure A3.3.34a Output from WPS #3 (Red) signal, 12.0 volts, 164 elements (64.0% on), TC test.

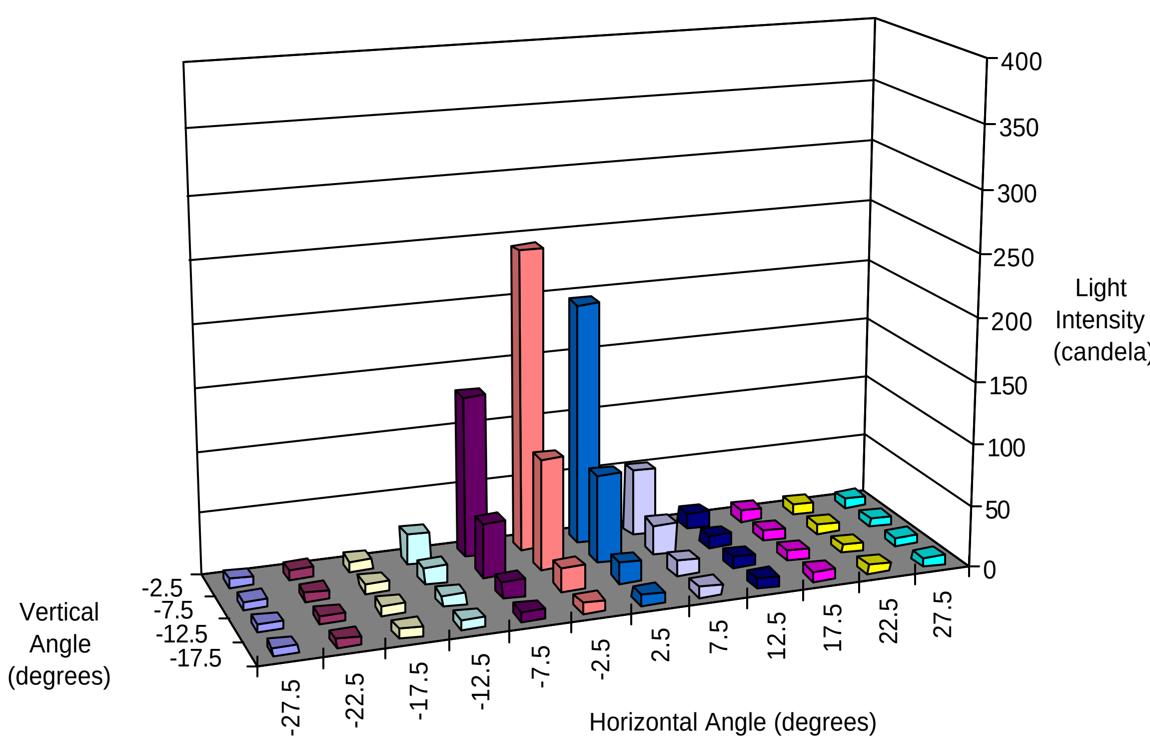

Figure A3.3.34b Output from WPS #3 (Red) signal, 12.0 volts, 164 elements (64.0% on), ITE test.

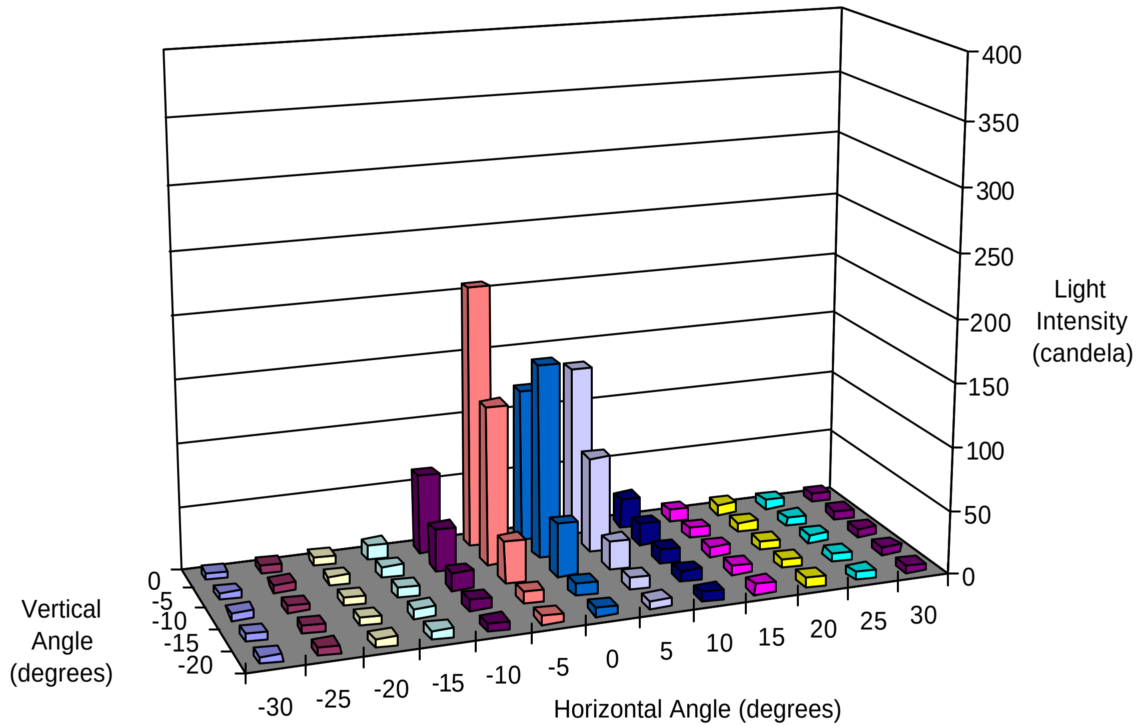

Figure A3.3.35a Output from WPS #3 (Red) signal, 12.0 volts, 149 elements (58.0% on), TC test.

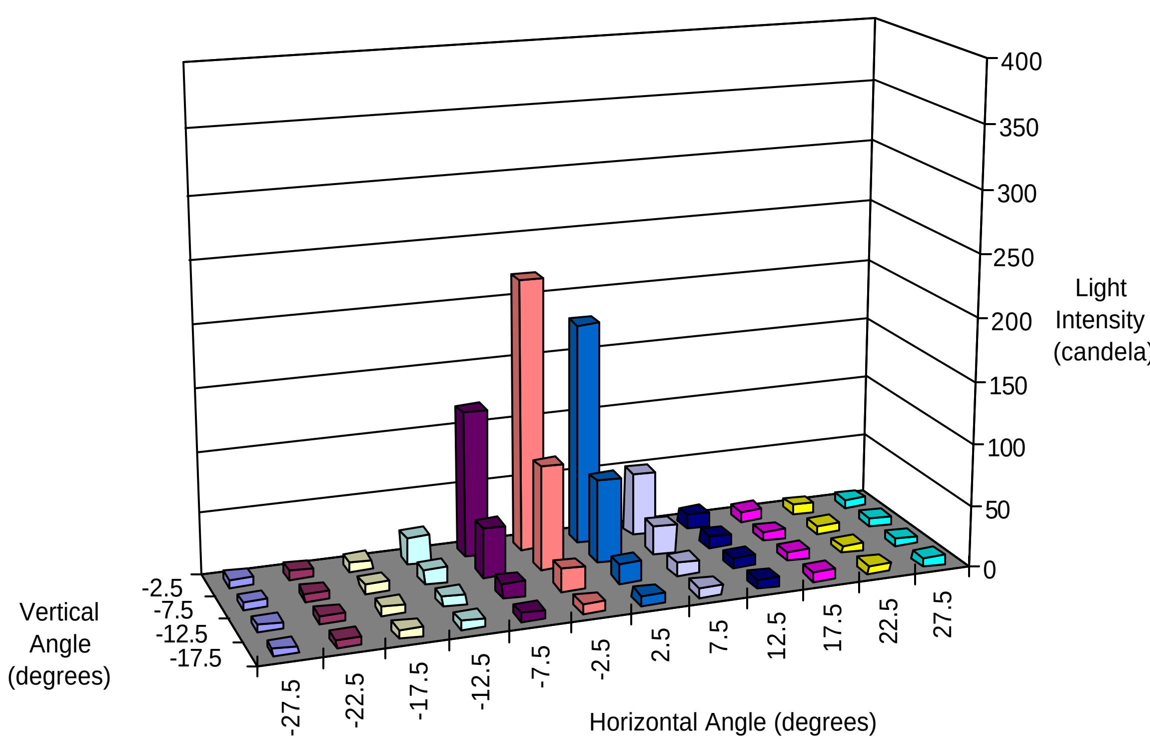

Figure A3.3.35b Output from WPS #3 (Red) signal, 12.0 volts, 149 elements (58.0% on), ITE test.

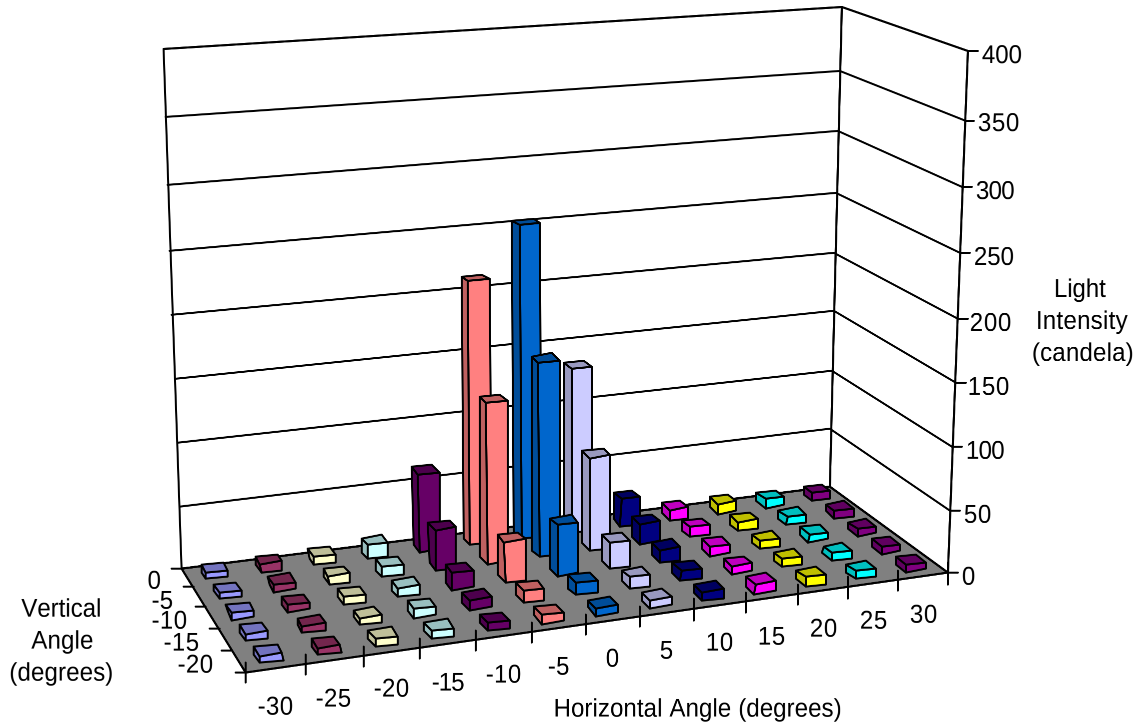

Figure A3.3.36a Output from WPS #3 (Red) signal, 12.0 volts, 134 elements (52.0% on), TC test.

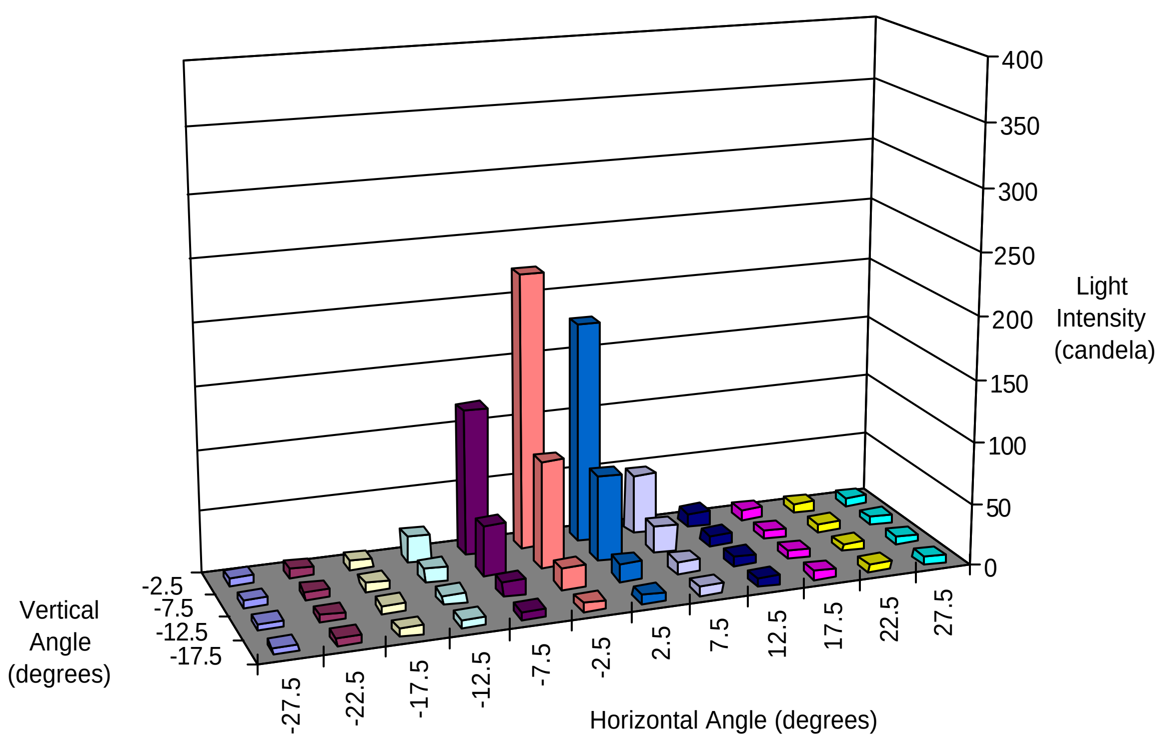

Figure A3.3.36b Output from WPS #3 (Red) signal, 12.0 volts, 134 elements (52.0% on), ITE test.

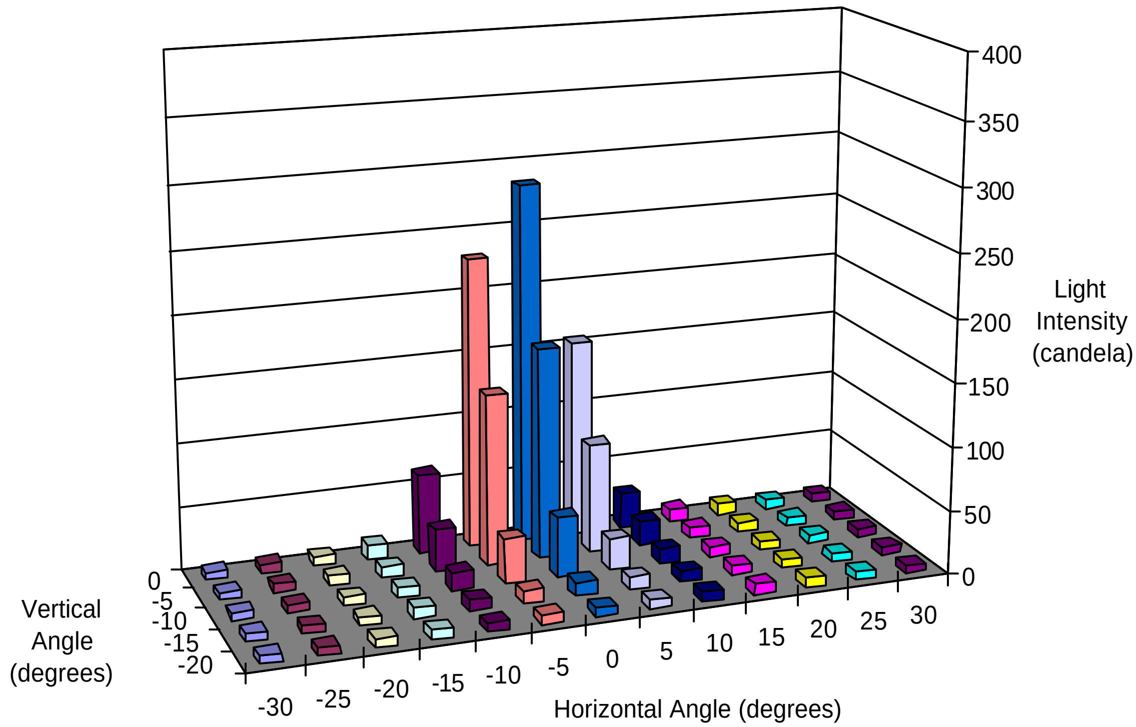

Figure A3.3.37a Output from WPS #3 (Red) signal, 12.0 volts, 119 elements (46.0% on), TC test.

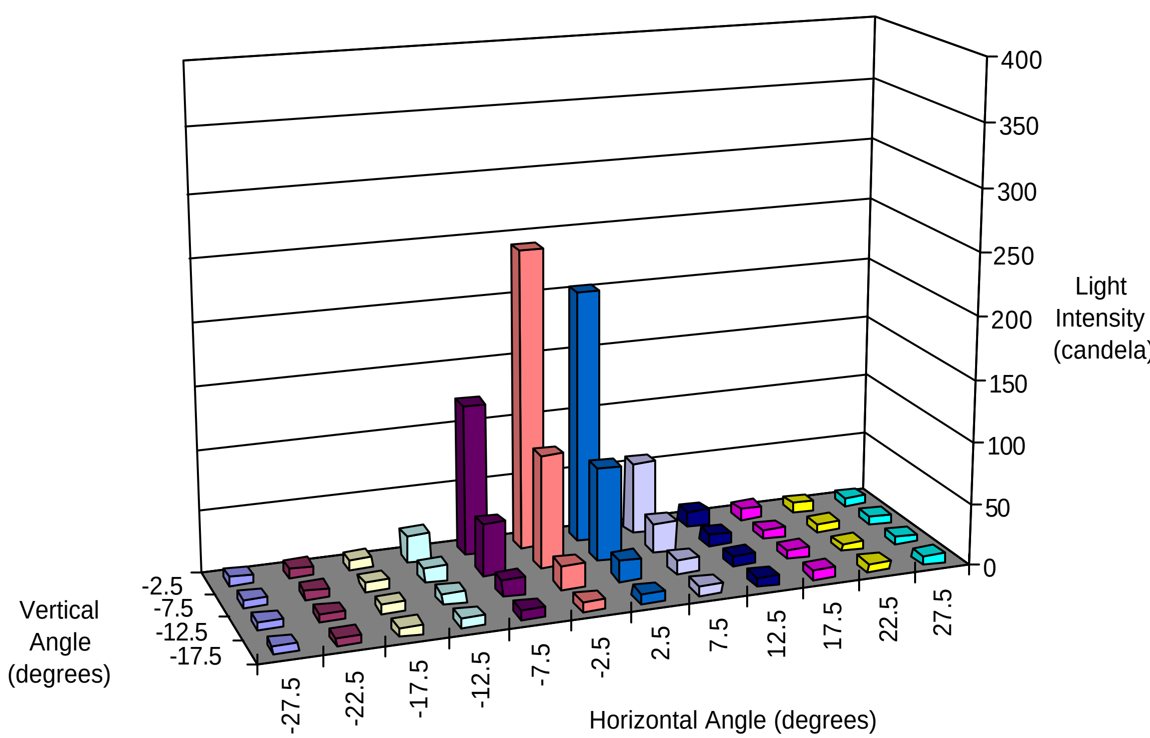

Figure A3.3.37b Output from WPS #3 (Red) signal, 12.0 volts, 119 elements (46.0% on), ITE test.

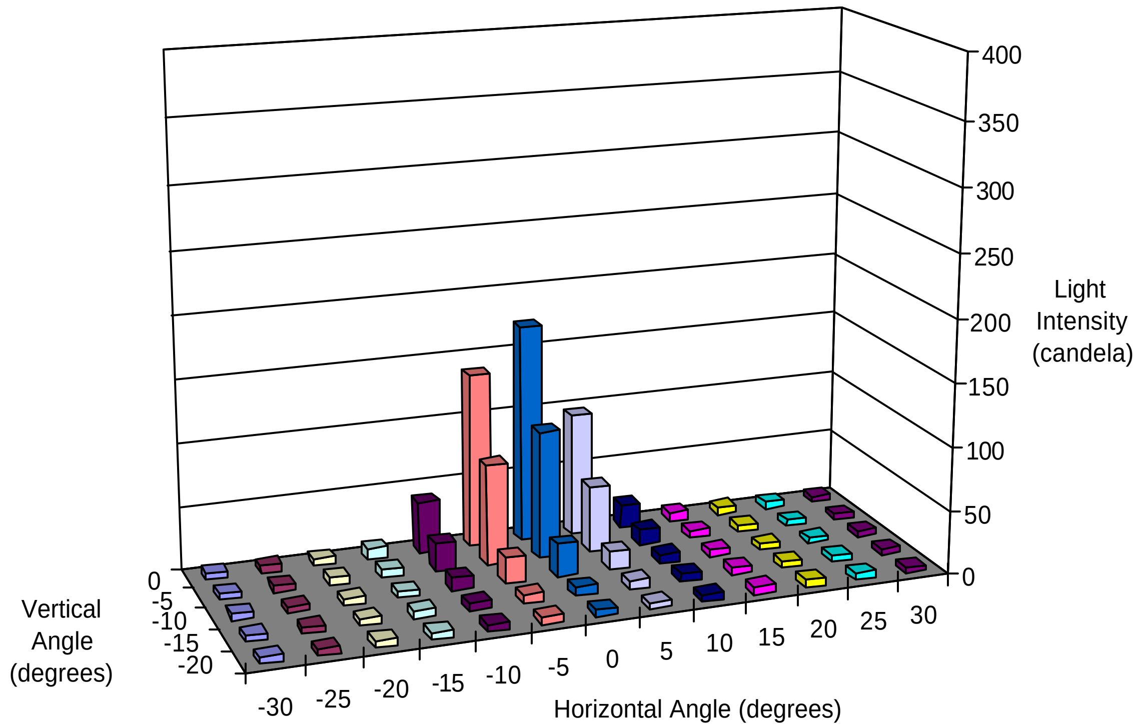

Figure A3.3.38a Output from WPS #3 (Red) signal, 12.0 volts, 104 elements (40.0% on), TC test.

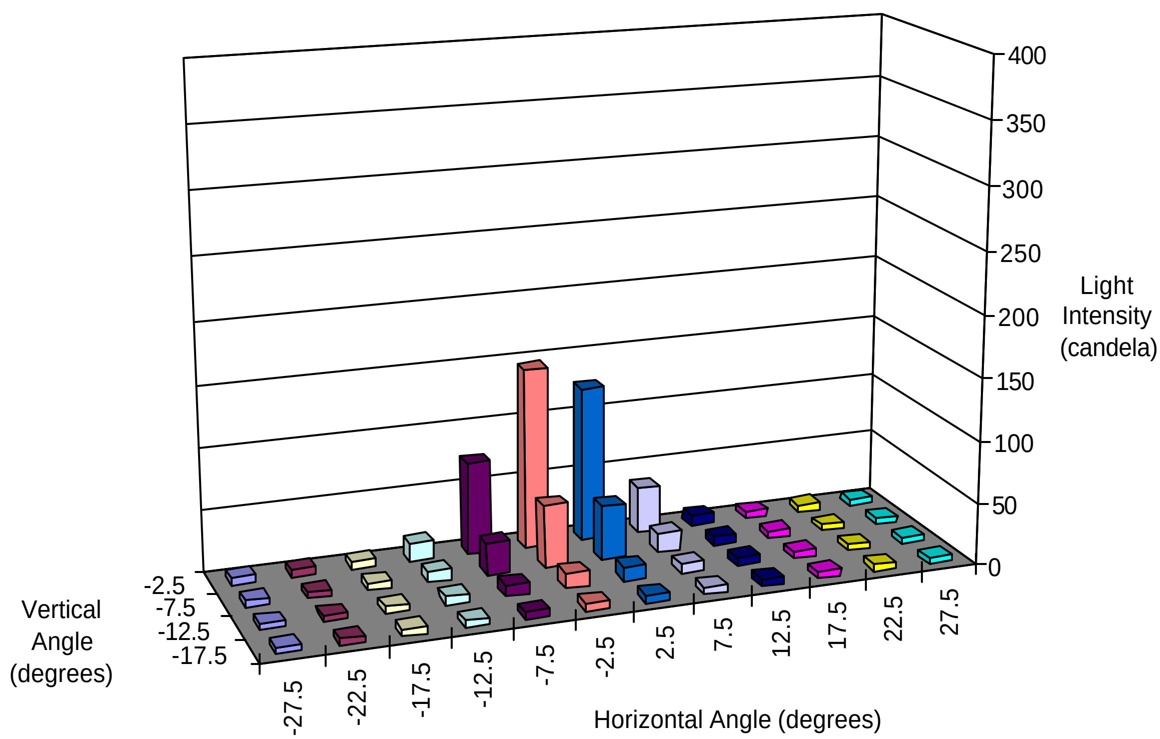

Figure A3.3.38b Output from WPS #3 (Red) signal, 12.0 volts, 104 elements (40.0% on), ITE test.

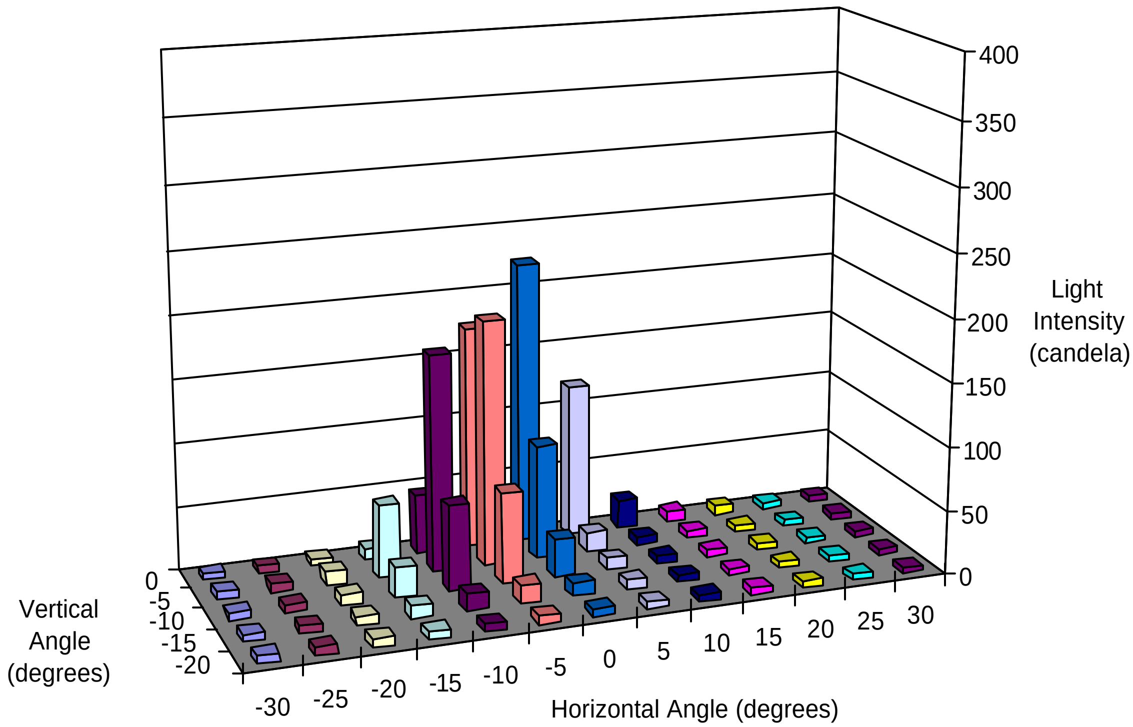

Figure A3.3.39a Output from WPS #3 (Red) signal, 12.0 volts, 89 elements (35.0% on), TC test.

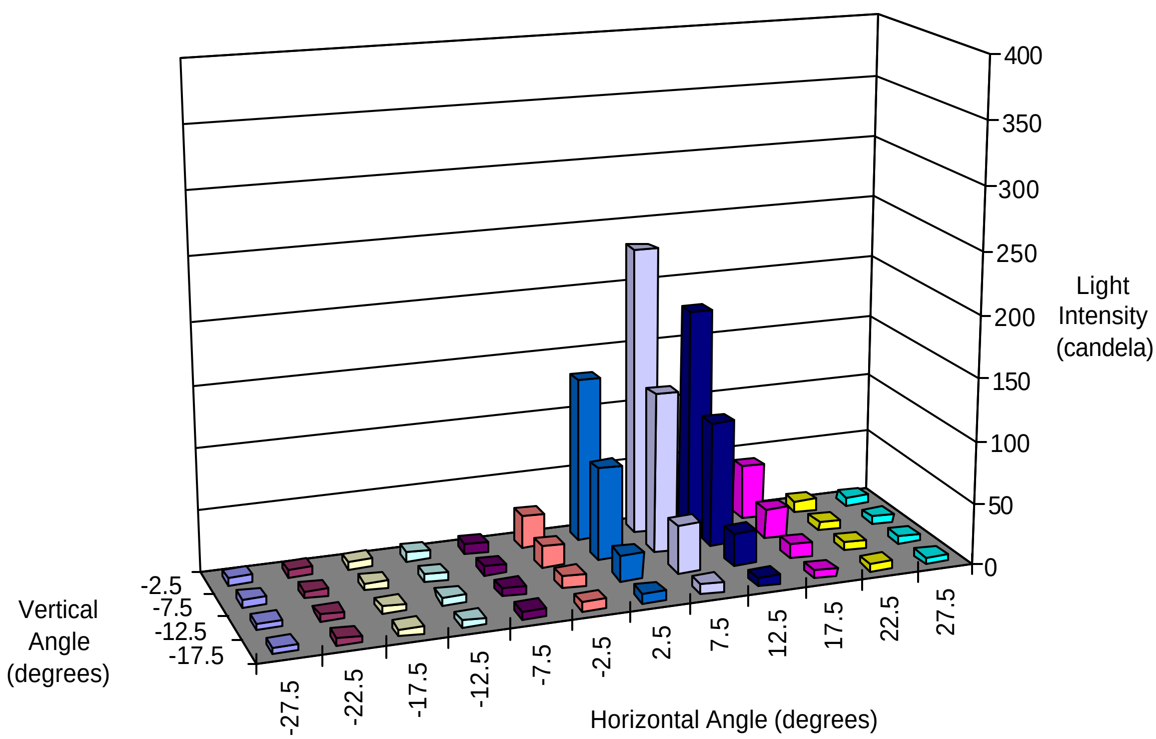

Figure A3.3.39b Output from WPS #3 (Red) signal, 12.0 volts, 89 elements (35.0% on), ITE test.

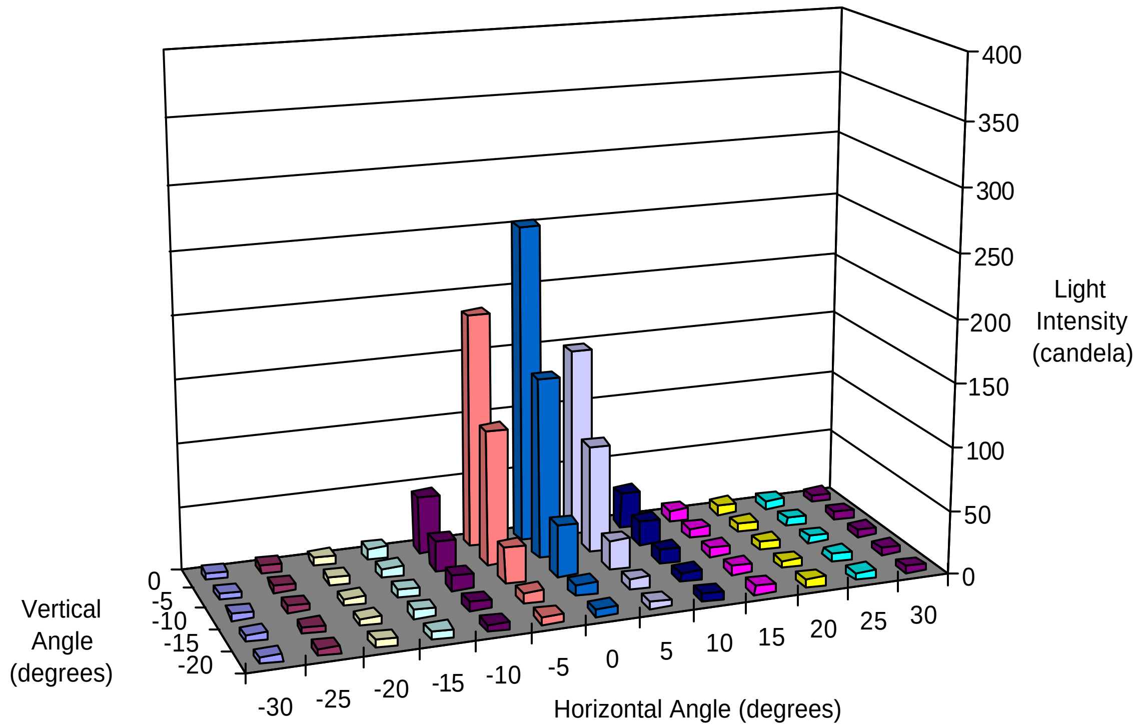

Figure A3.3.40a Output from WPS #3 (Red) signal, 12.0 volts, 74 elements (29.0% on), TC test.

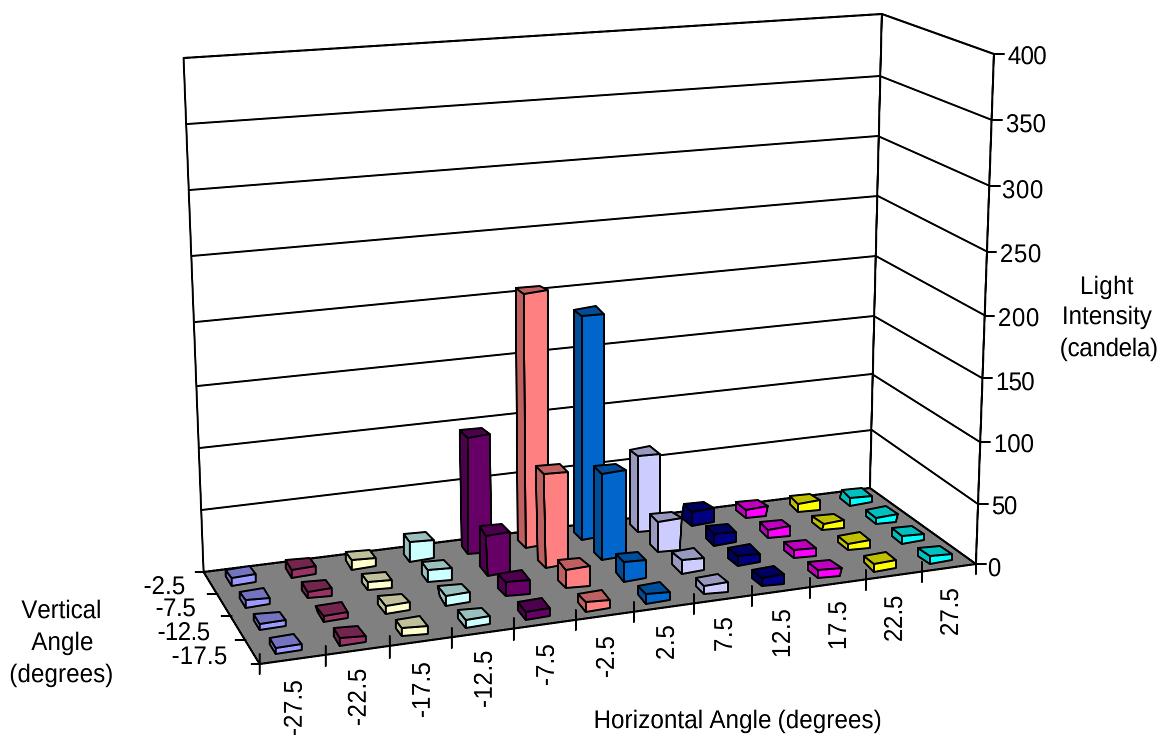

Figure A3.3.40b Output from WPS #3 (Red) signal, 12.0 volts, 74 elements (29.0% on), ITE test.

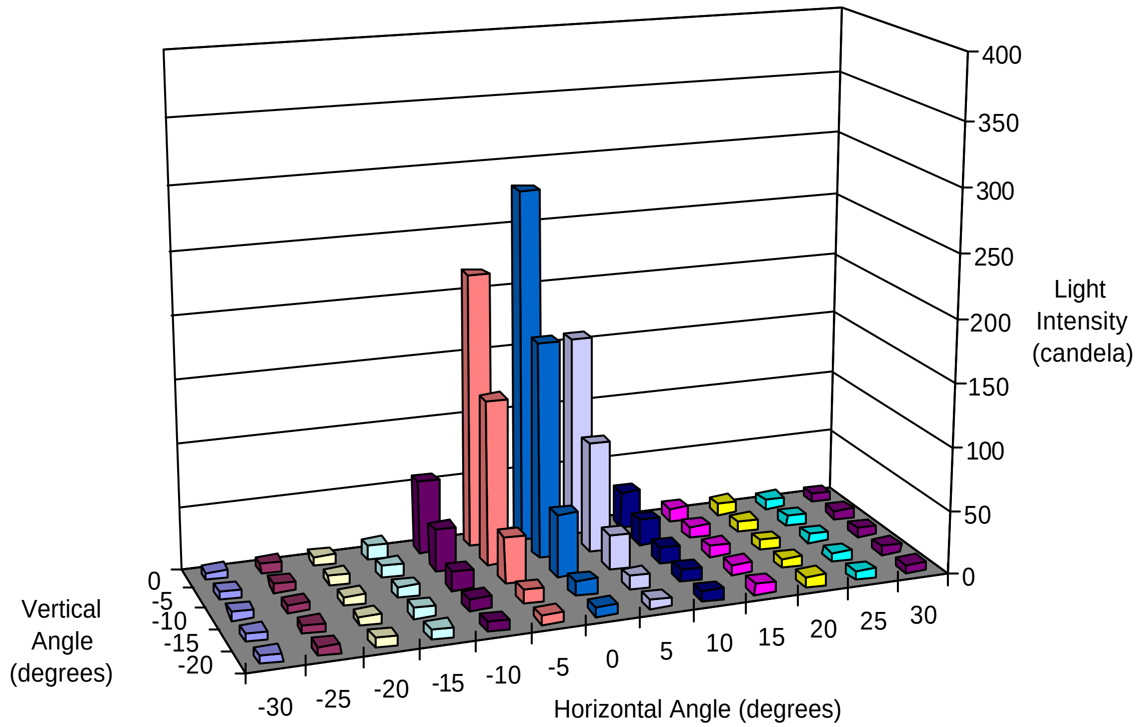

Figure A3.3.41a Output from WPS #3 (Red) signal, 13.5 volts, 239 elements (94.0% on), TC test.

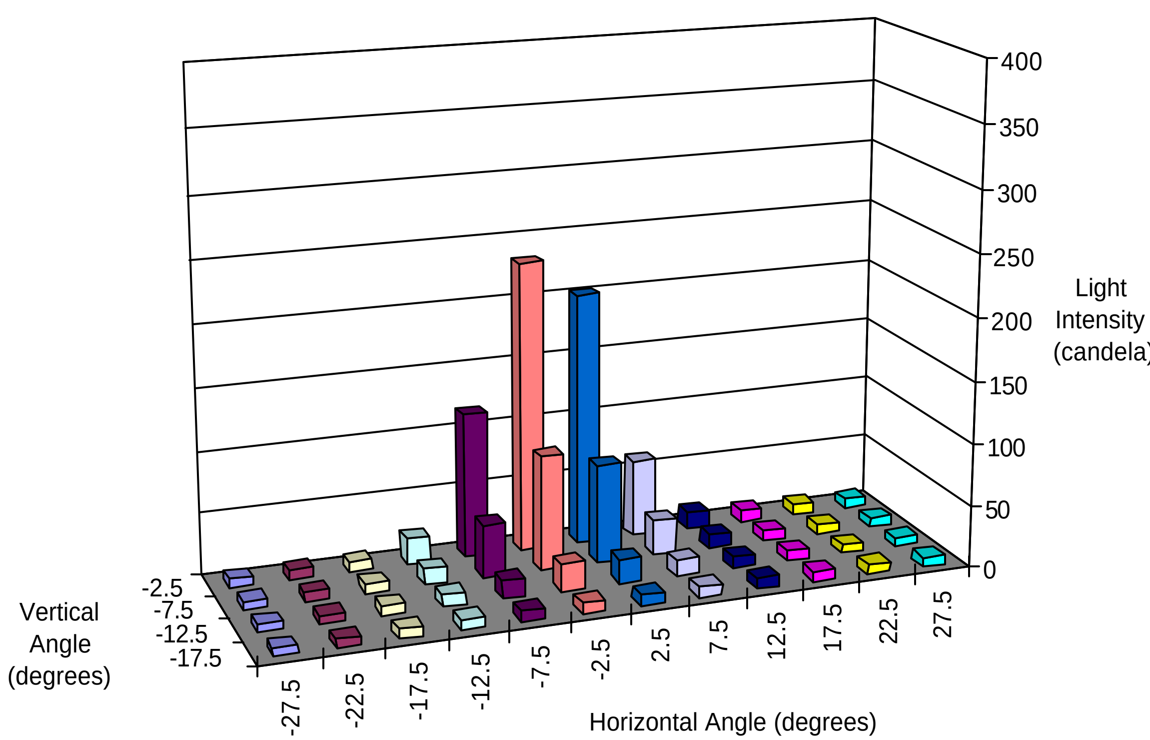

Figure A3.3.41b Output from WPS #3 (Red) signal, 13.5 volts, 239 elements (94.0% on), ITE test.

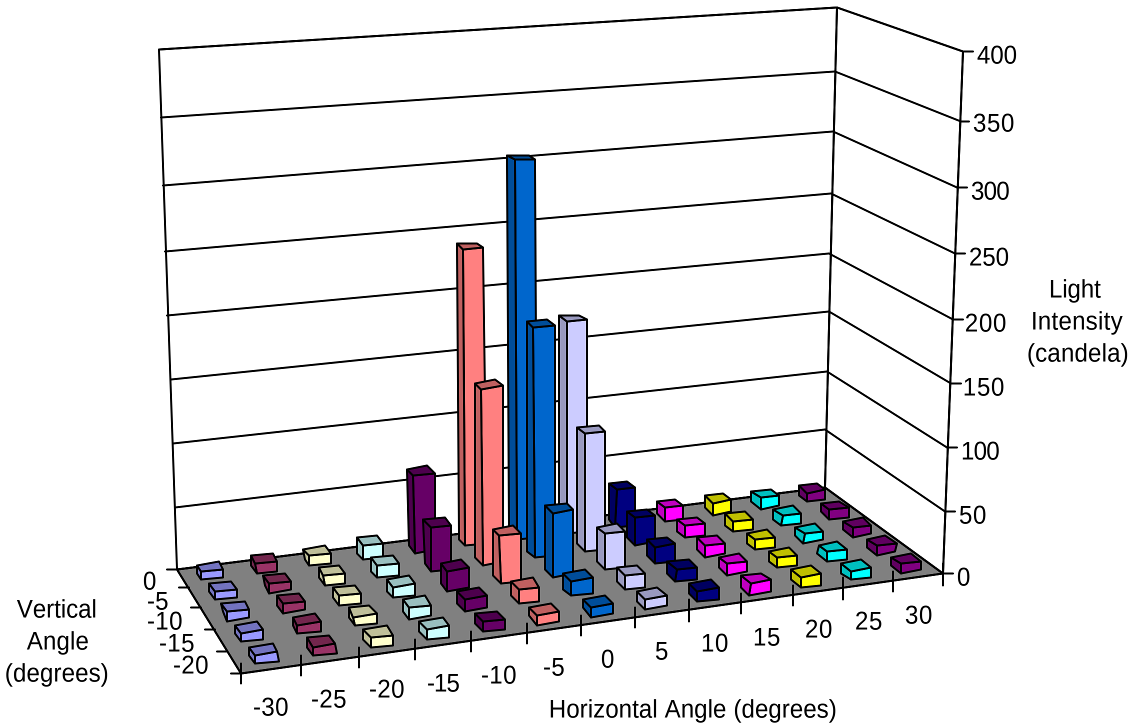

Figure A3.3.42a Output from WPS #3 (Red) signal, 13.5 volts, 228 elements (88.0% on), TC test.

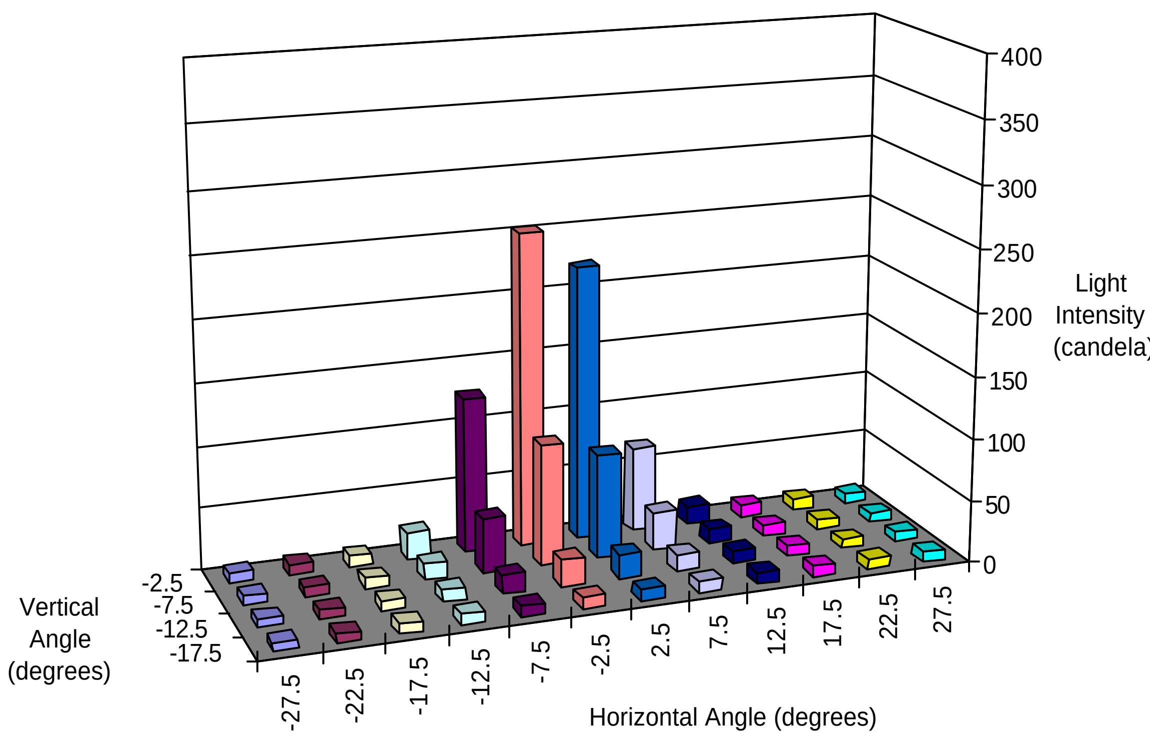

Figure A3.3.42b Output from WPS #3 (Red) signal, 13.5 volts, 224 elements (88.0% on), ITE test.

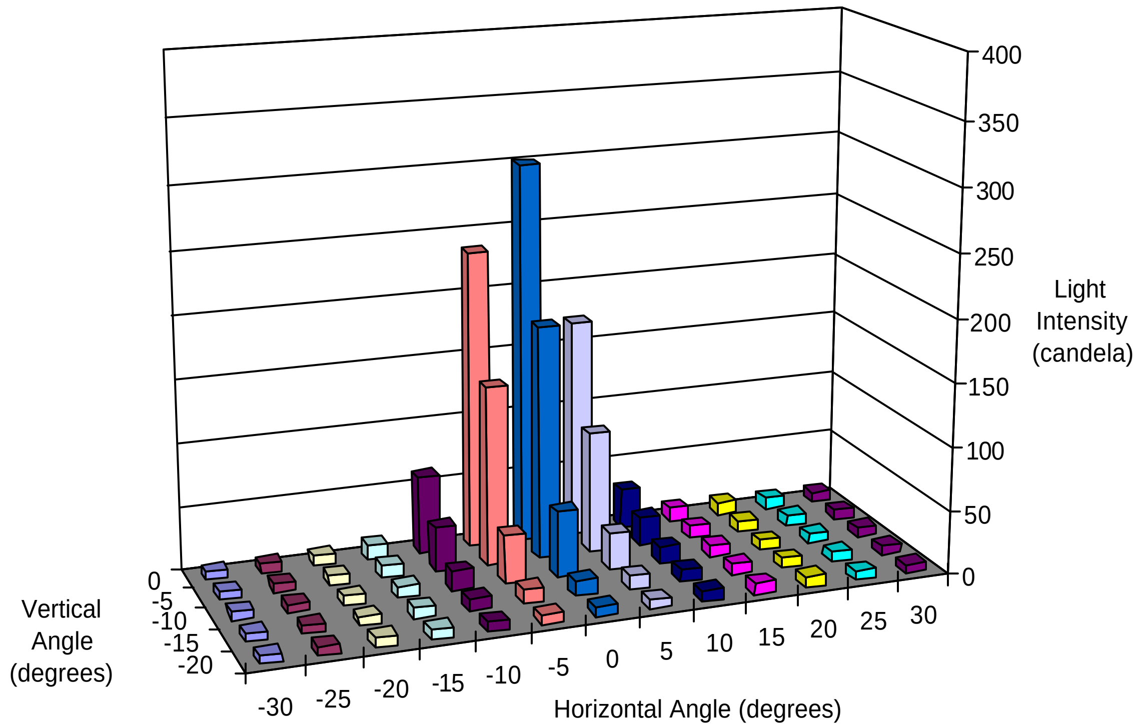

Figure A3.3.43a Output from WPS #3 (Red) signal, 13.5 volts, 209 elements (82.0% on), TC test.

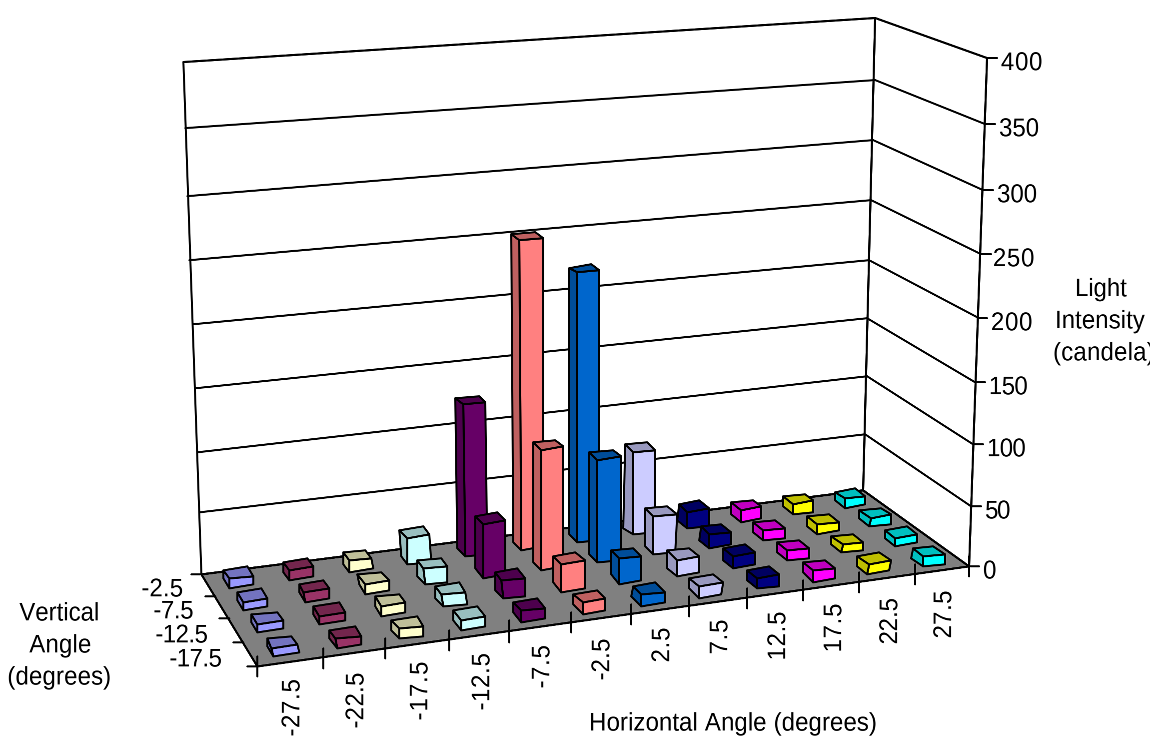

Figure A3.3.43b Output from WPS #3 (Red) signal, 13.5 volts, 209 elements (82.0% on), ITE test.

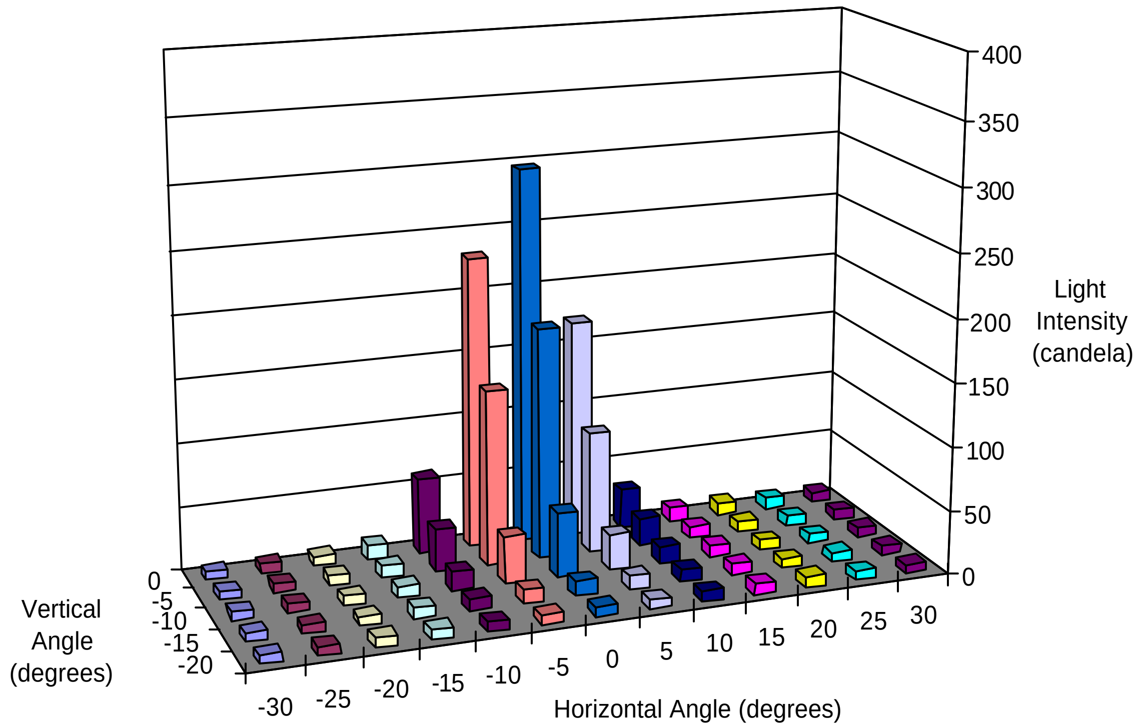

Figure A3.3.44a Output from WPS #3 (Red) signal, 13.5 volts, 194 elements (76.0% on), TC test.

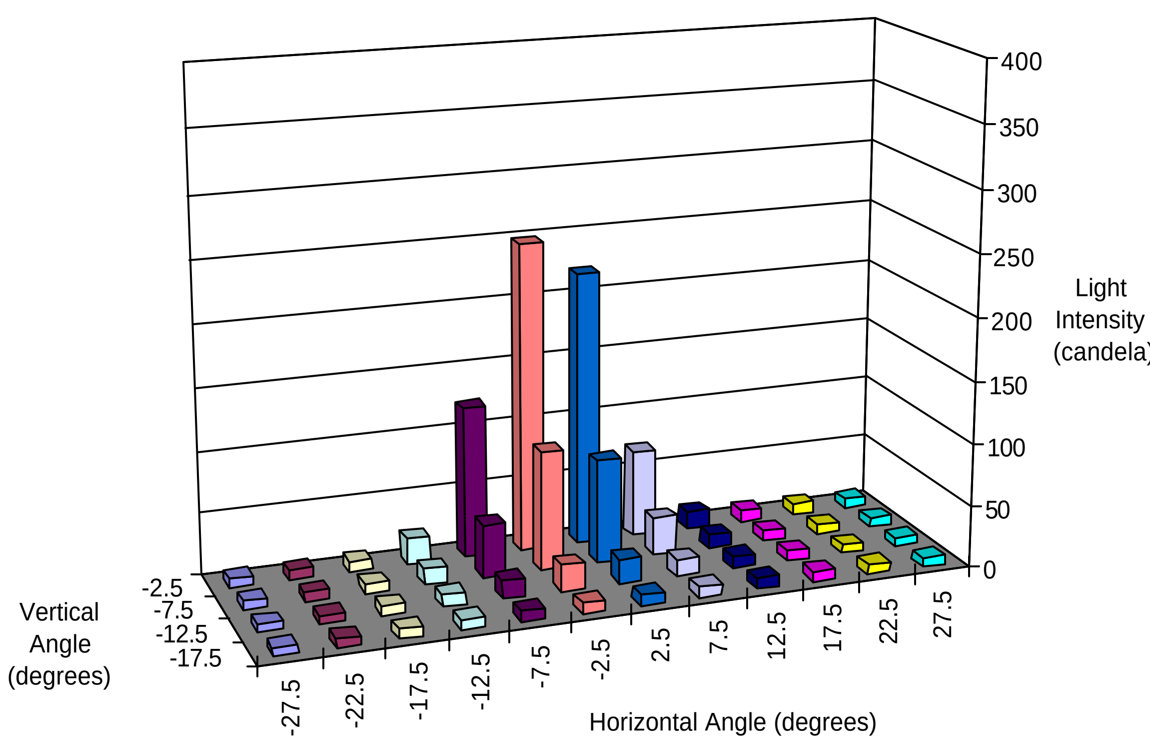

Figure A3.3.44b Output from WPS #3 (Red) signal, 13.5 volts, 194 elements (76.0% on), ITE test.

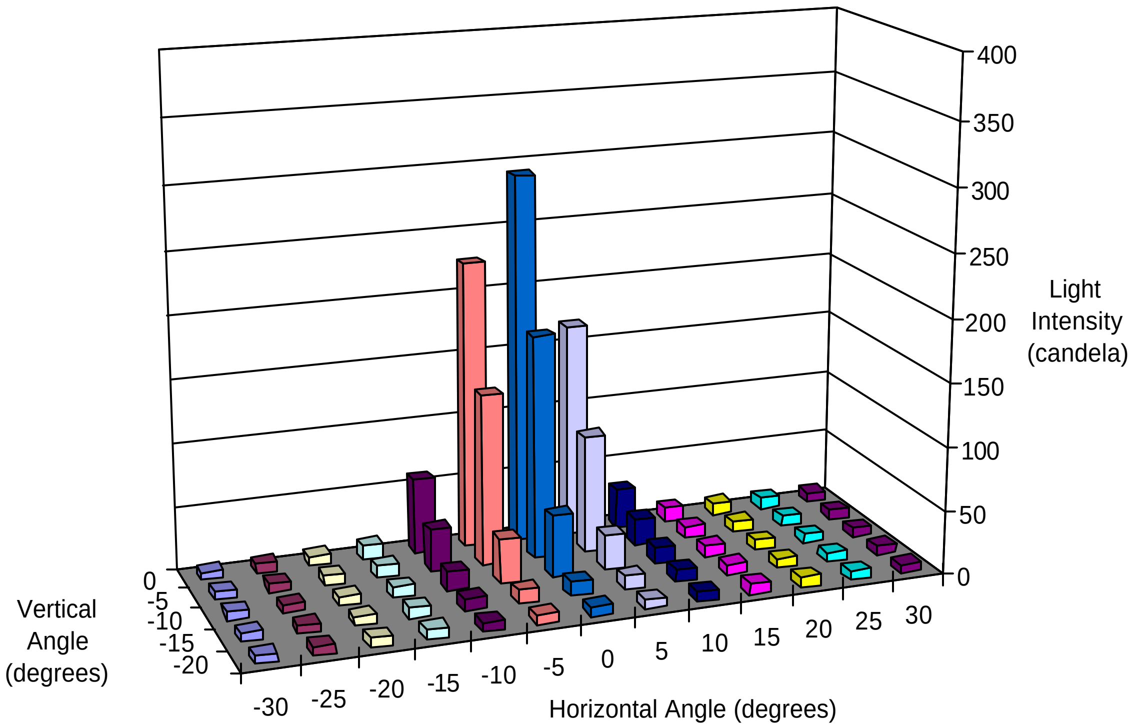

Figure A3.3.45a Output from WPS #3 (Red) signal, 13.5 volts, 179 elements (70.0% on), TC test.

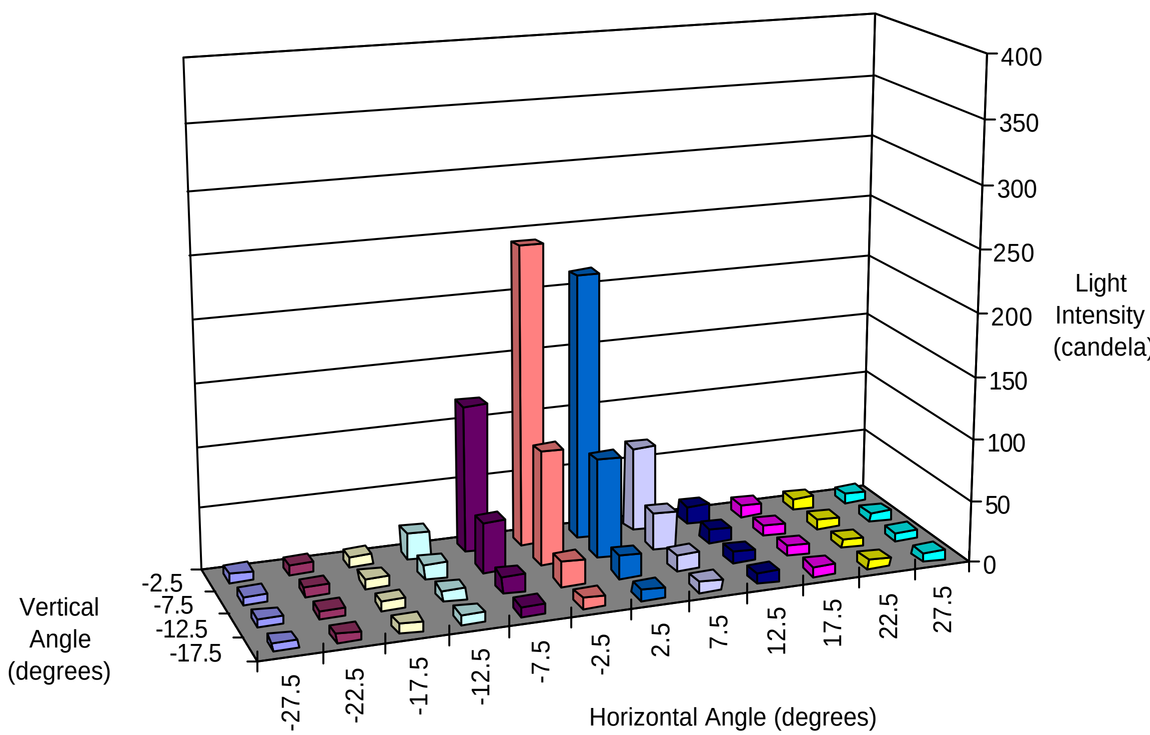

Figure A3.3.45b Output from WPS #3 (Red) signal, 13.5 volts, 179 elements (70.0% on), ITE test.

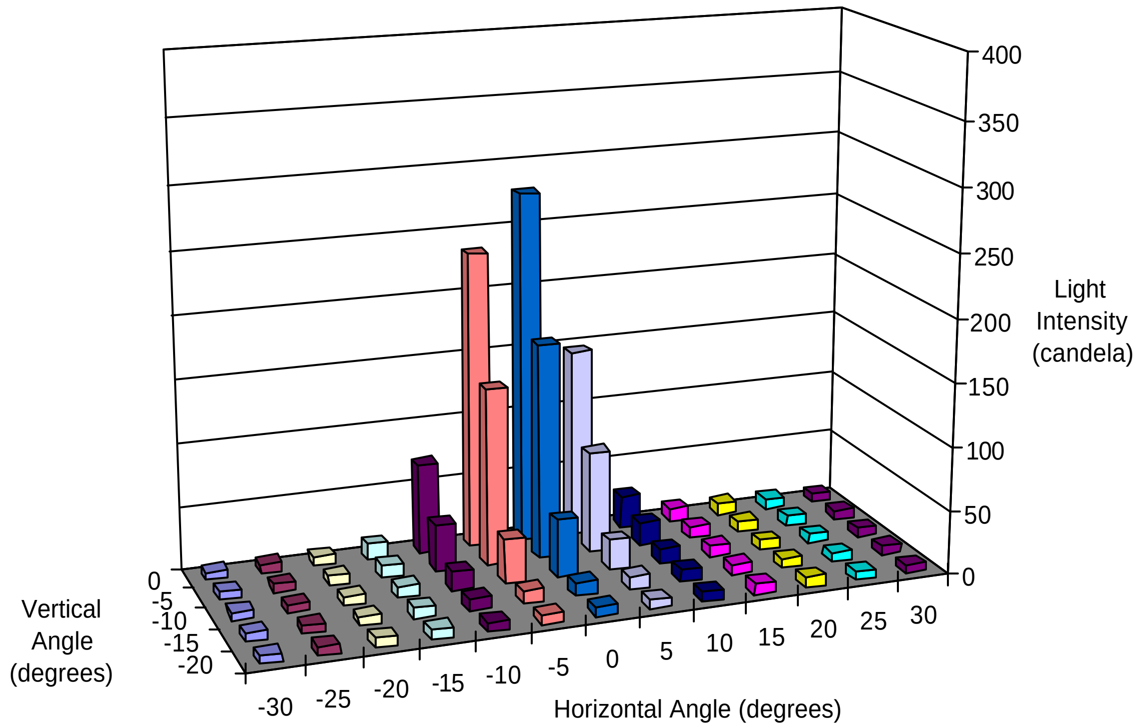

Figure A3.3.46a Output from WPS #3 (Red) signal, 13.5 volts, 164 elements (64.0% on), TC test.

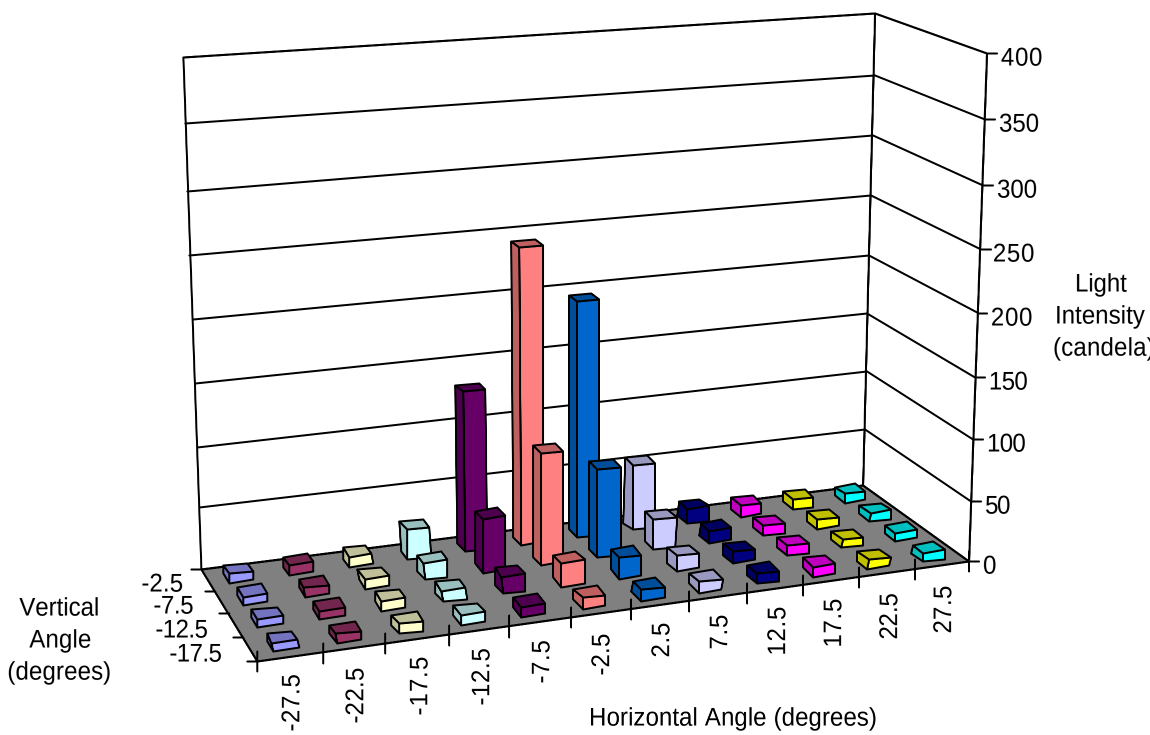

Figure A3.3.46b Output from WPS #3 (Red) signal, 13.5 volts, 164 elements (64.0% on), ITE test.

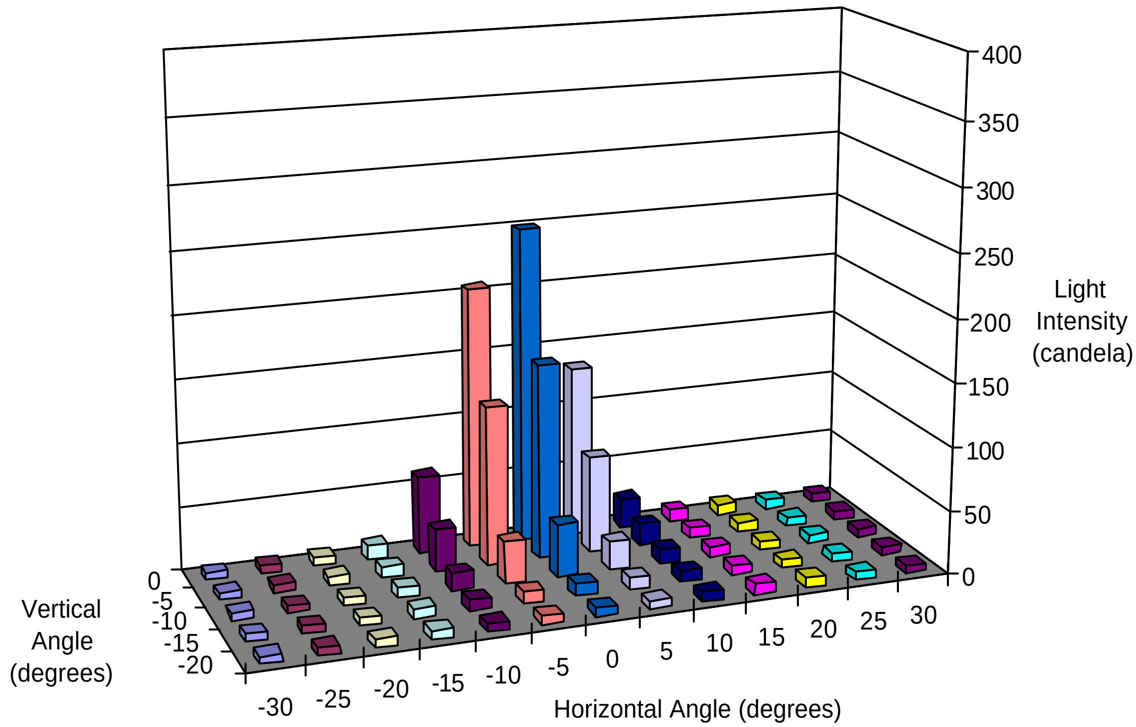

Figure A3.3.47a Output from WPS #3 (Red) signal, 13.5 volts, 149 elements (58.0% on), TC test.

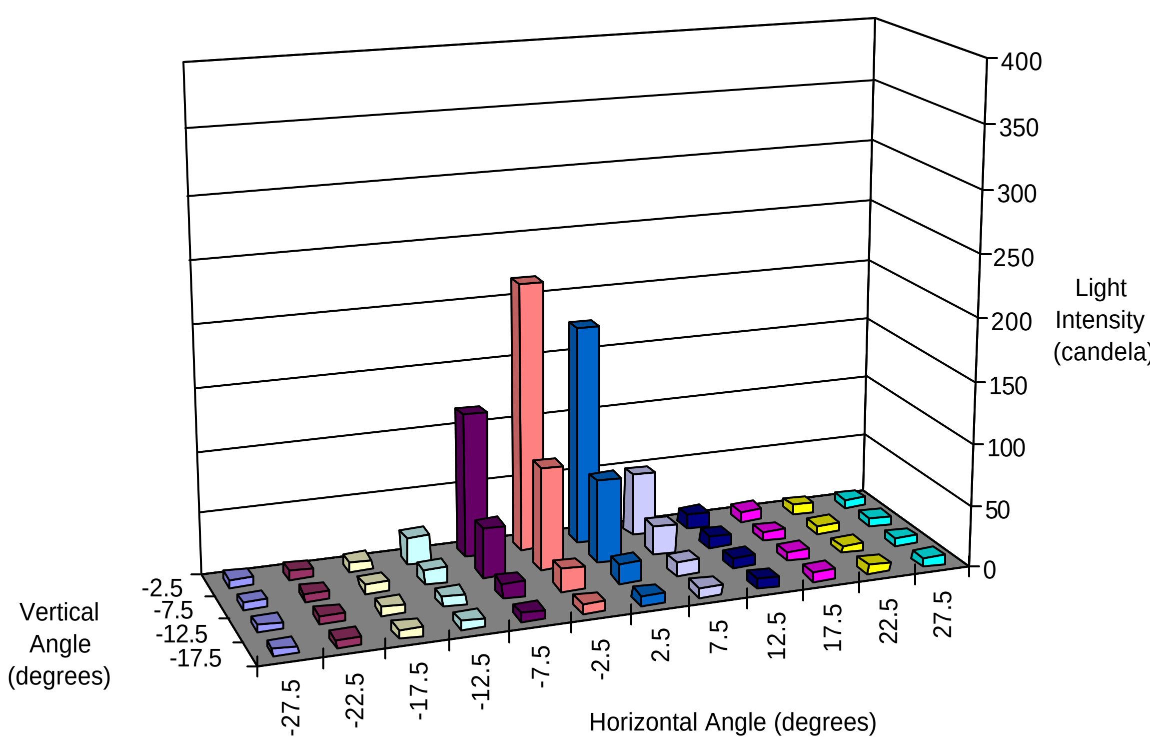

Figure A3.3.47b Output from WPS #3 (Red) signal, 13.5 volts, 149 elements (58.0% on), ITE test.

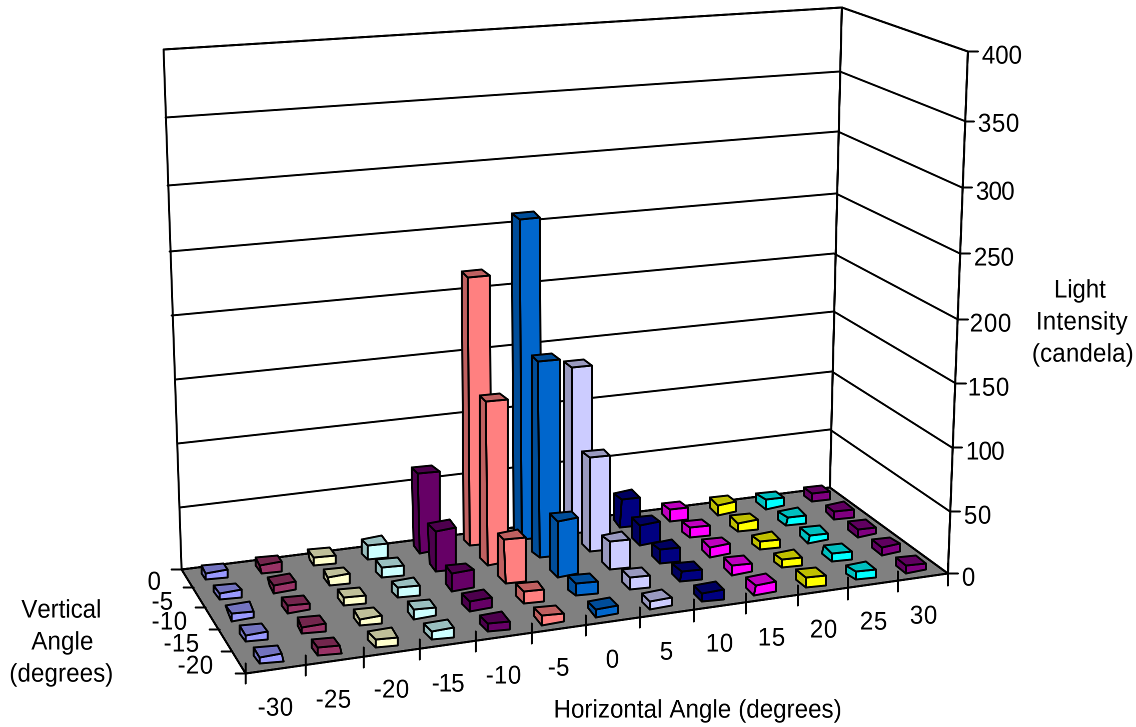

Figure A3.3.48a Output from WPS #3 (Red) signal, 13.5 volts, 134 elements (52.0% on), TC test.

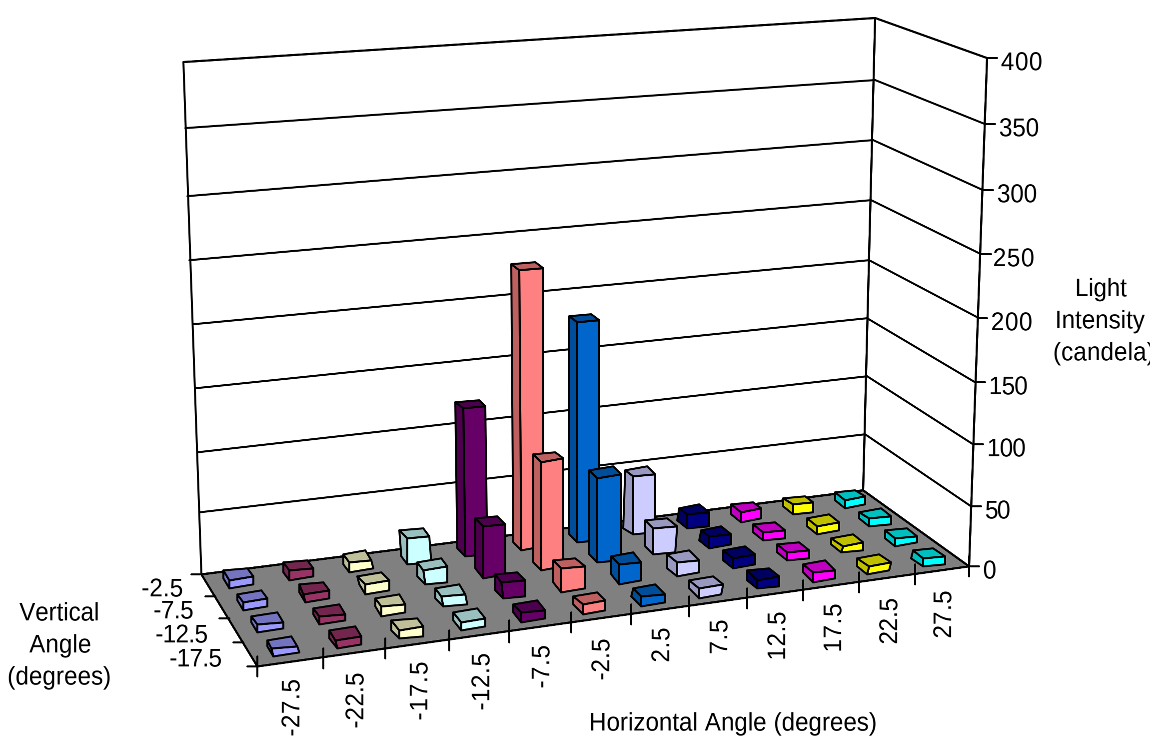

Figure A3.3.48b Output from WPS #3 (Red) signal, 13.5 volts, 134 elements (52.0% on), ITE test.

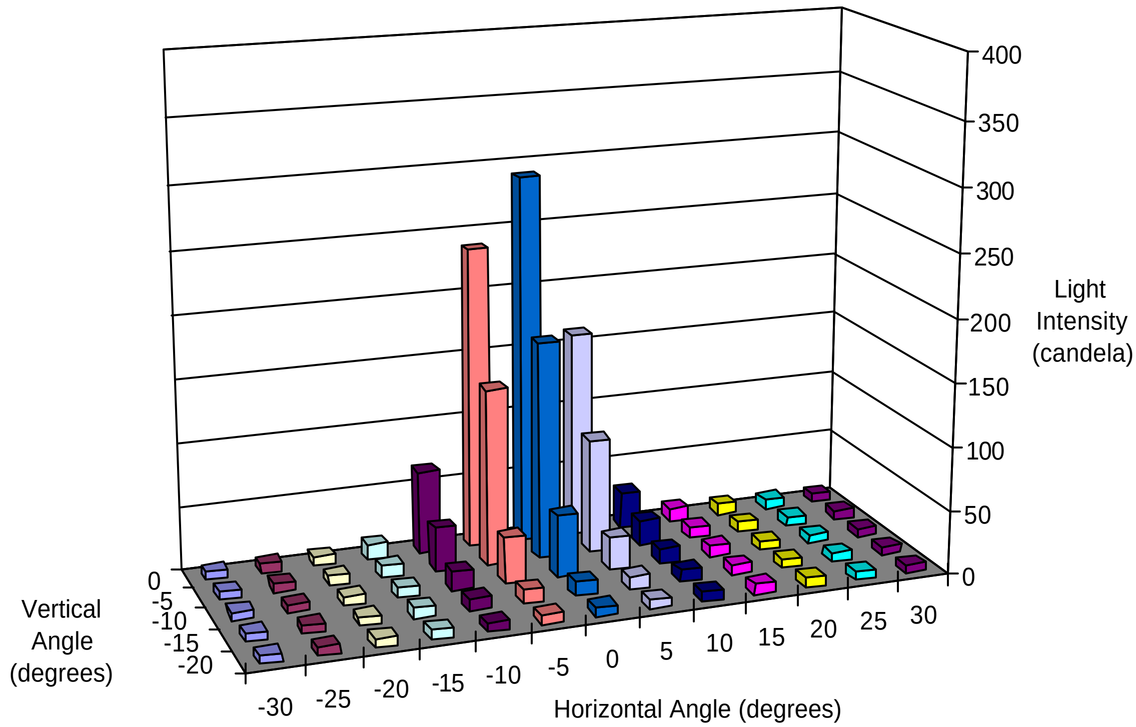

Figure A3.3.49a Output from WPS #3 (Red) signal, 13.5 volts, 119 elements (46.0% on), TC test.

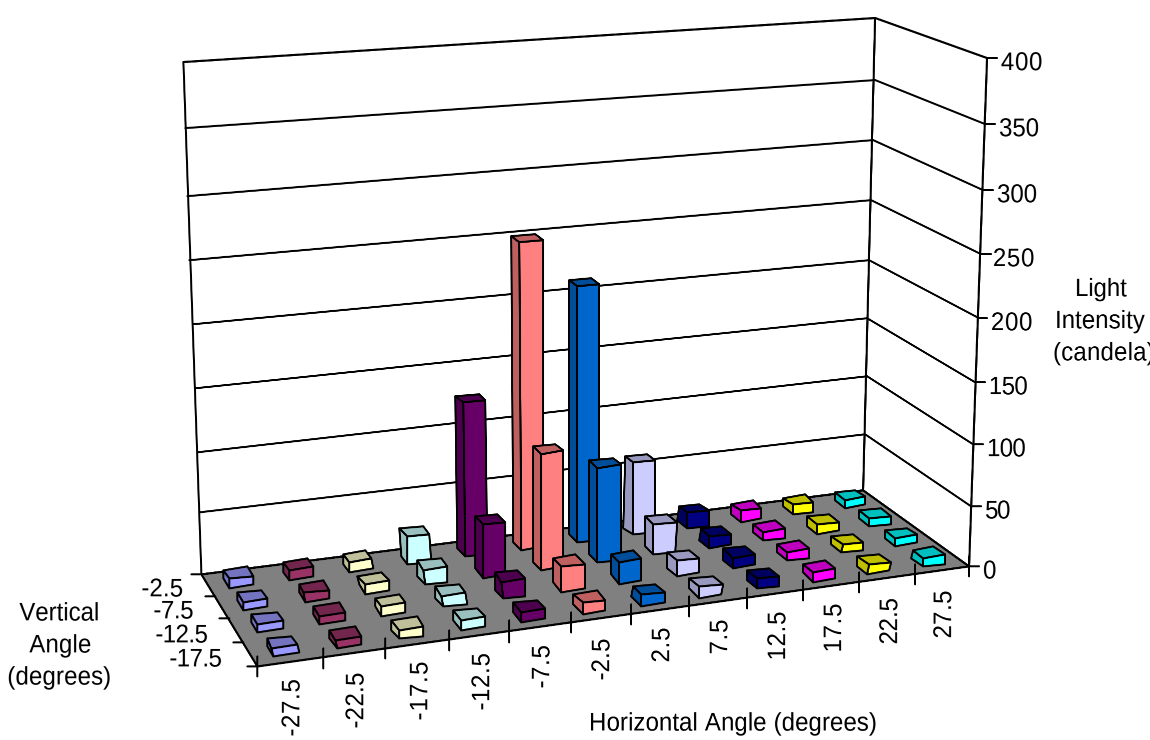

Figure A3.3.49b Output from WPS #3 (Red) signal, 13.5 volts, 119 elements (46.0% on), ITE test.

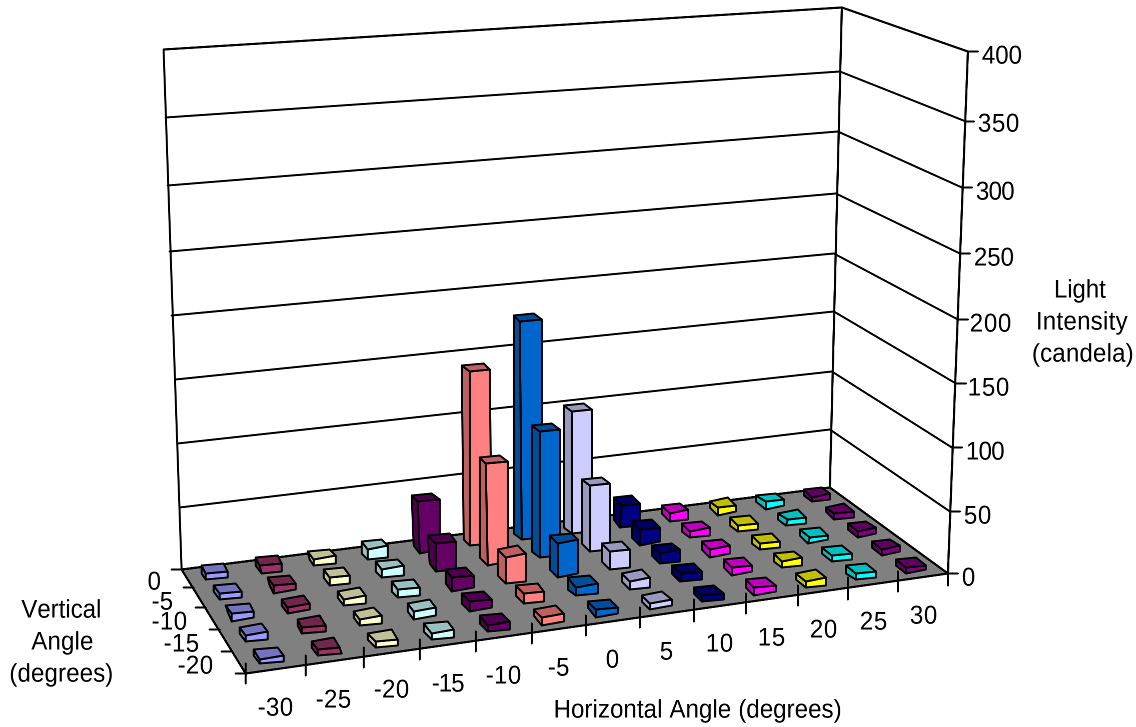

Figure A3.3.50a Output from WPS #3 (Red) signal, 13.5 volts, 104 elements (40.0% on), TC test.

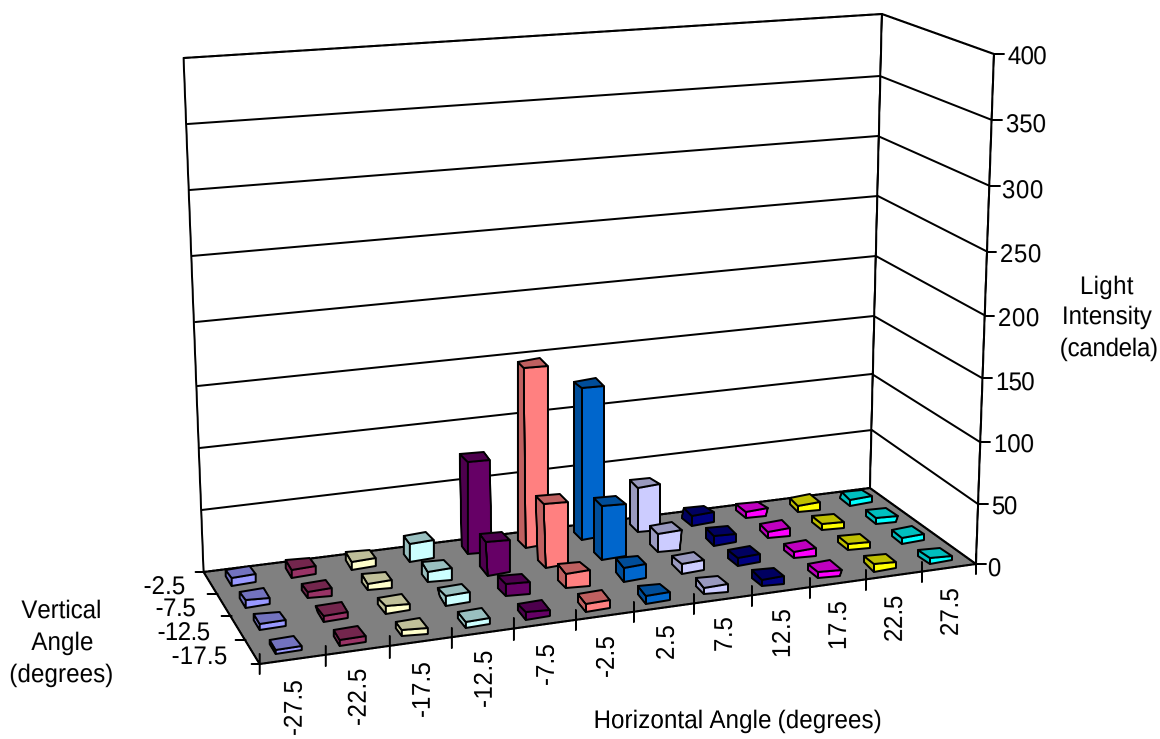

Figure A3.3.50b Output from WPS #3 (Red) signal, 13.5 volts, 104 elements (40.0% on), ITE test.

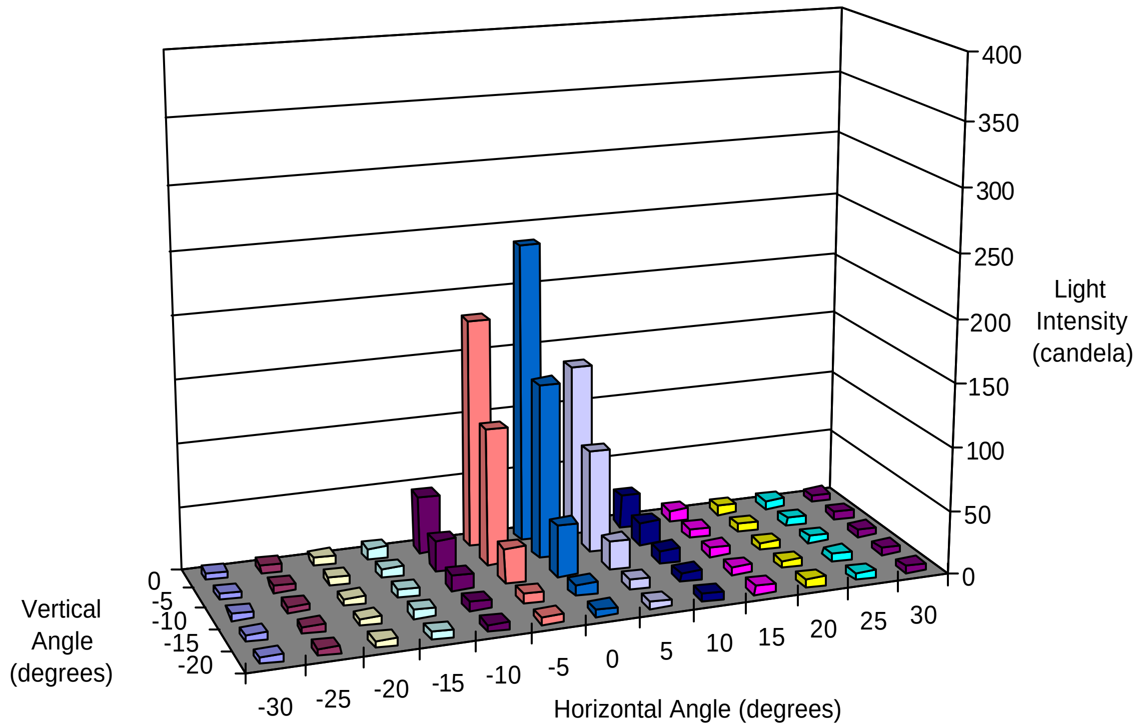

Figure A3.3.51a Output from WPS #3 (Red) signal, 13.5 volts, 89 elements (35.0% on), TC test.

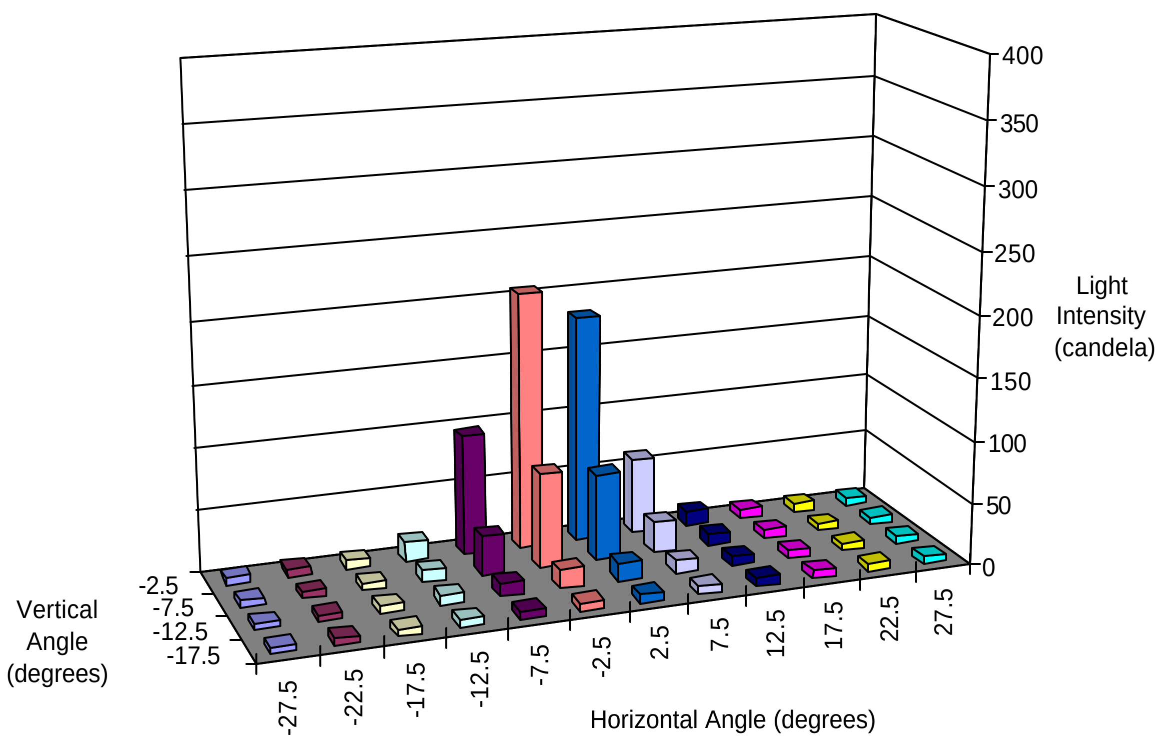

Figure A3.3.51b Output from WPS #3 (Red) signal, 13.5 volts, 89 elements (35.0% on), ITE test.

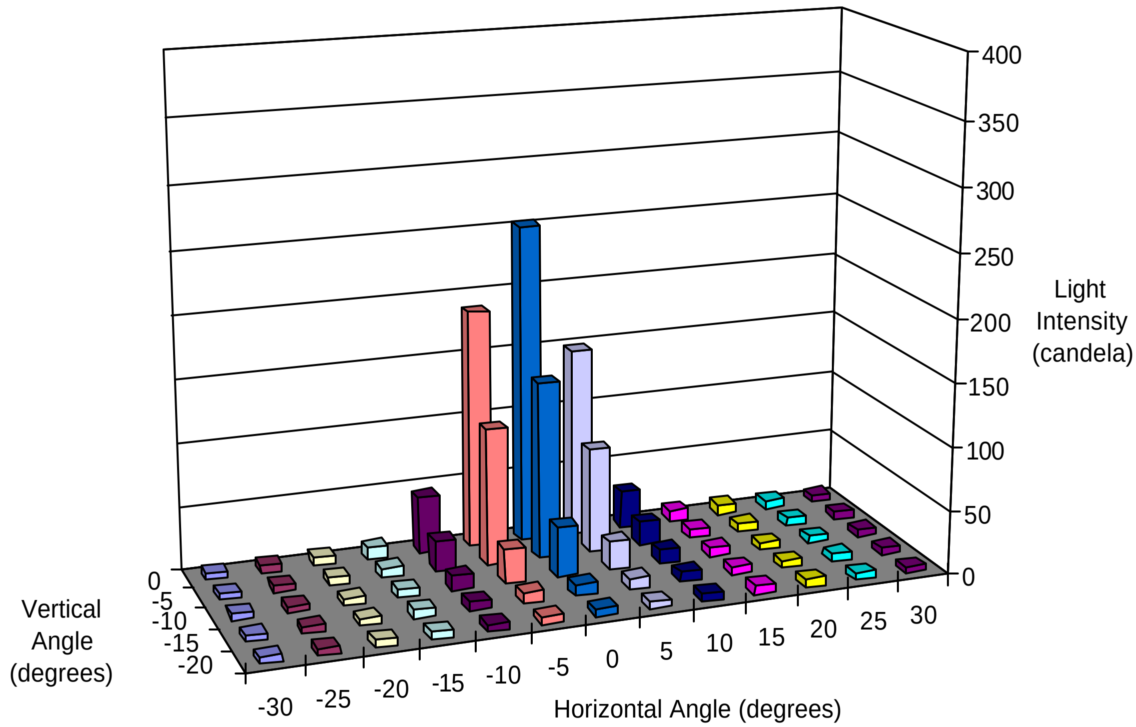

Figure A3.3.52a Output from WPS #3 (Red) signal, 13.5 volts, 74 elements (29.0% on), TC test.

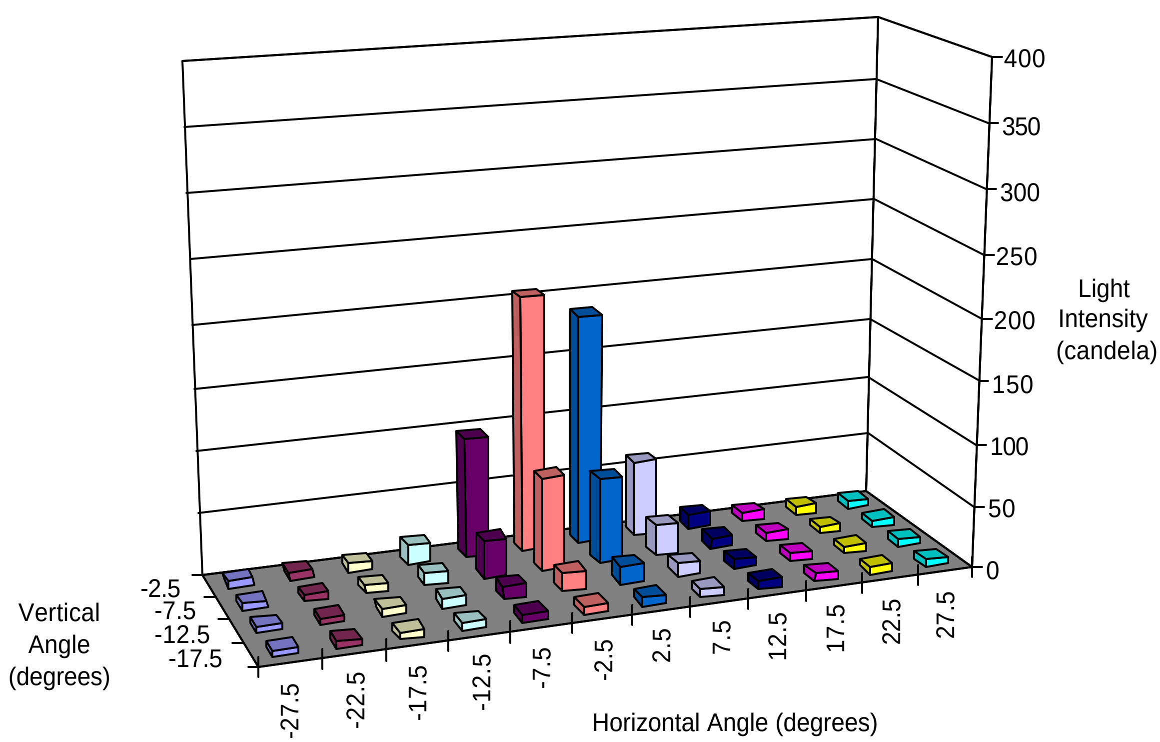

Figure A3.3.52b Output from WPS #3 (Red) signal, 13.5 volts, 74 elements (29.0% on), ITE test.

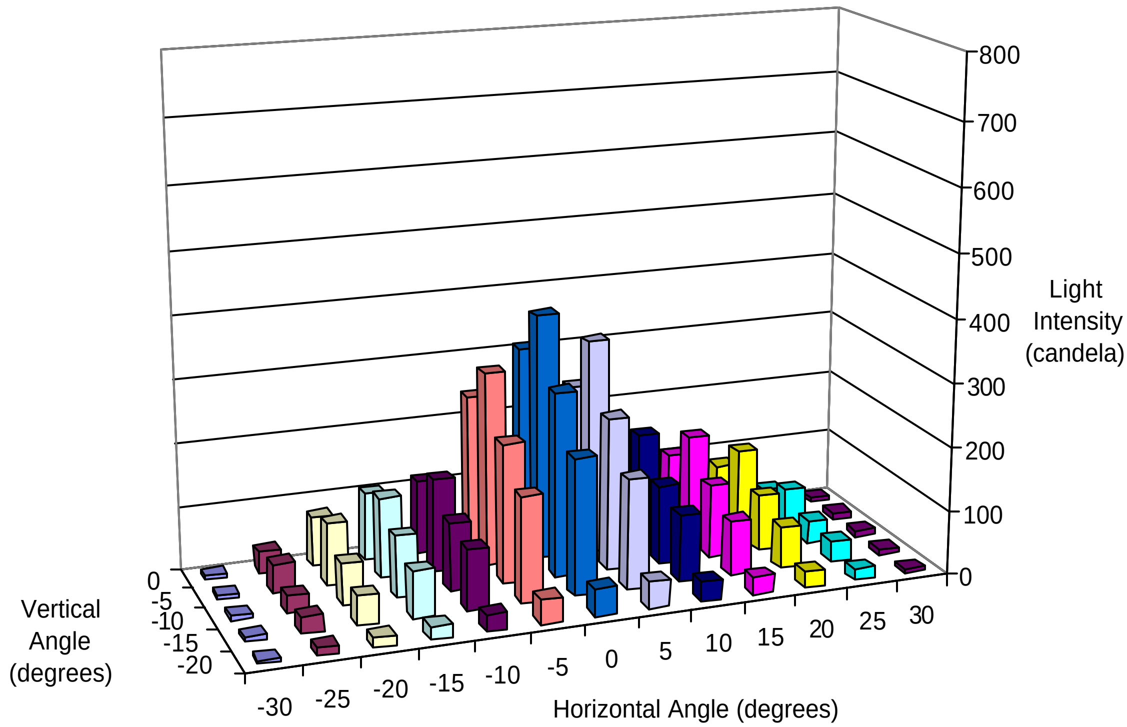

Figure A4.1.1a Output from NPS #4 (Red) signal, 12.0 volts, all elements on, TC test.

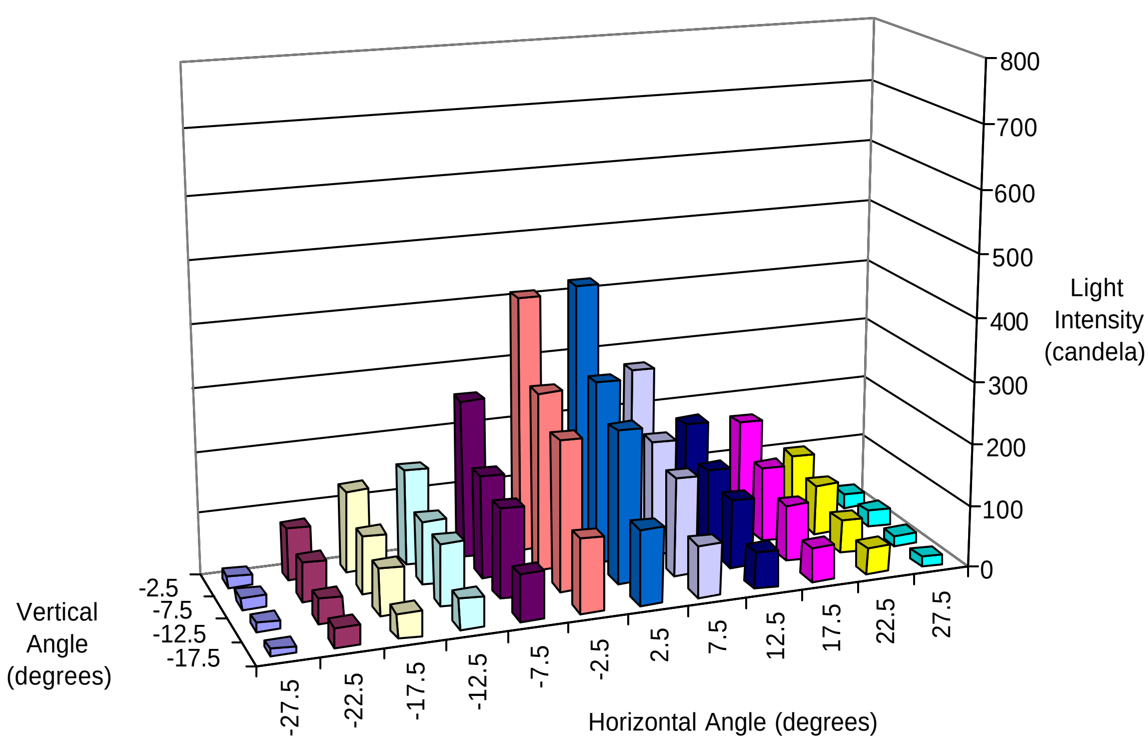

Figure A4.1.1b Output from NPS #4 (Red) signal, 12.0 volts, all elements on, ITE test.

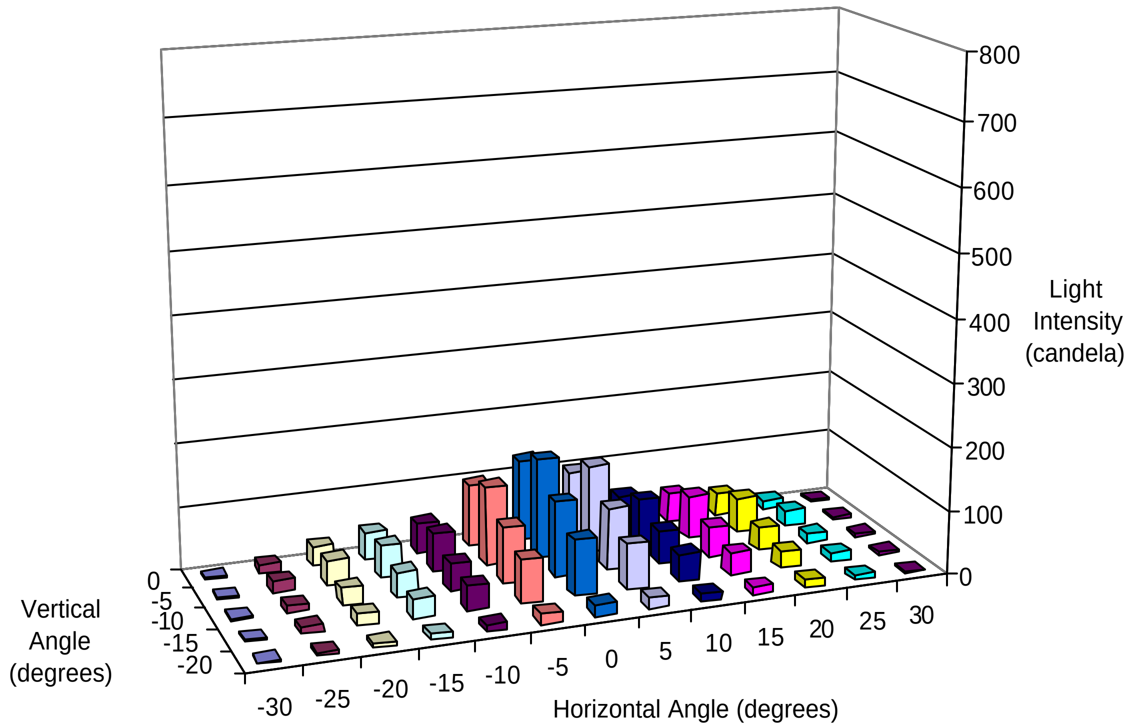

Figure A4.1.2a Output from NPS #4 (Red) signal, 10.5 volts, all elements on, TC test.

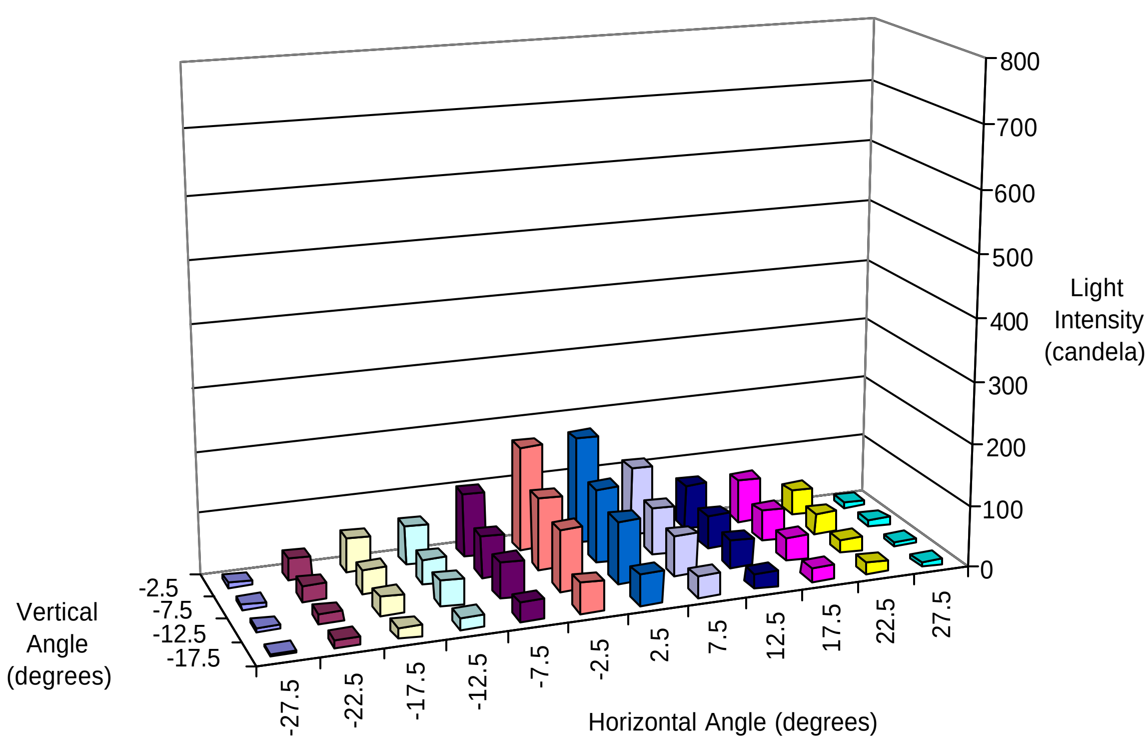

Figure A4.1.2b Output from NPS #4 (Red) signal, 10.5 volts, all elements on, ITE test.

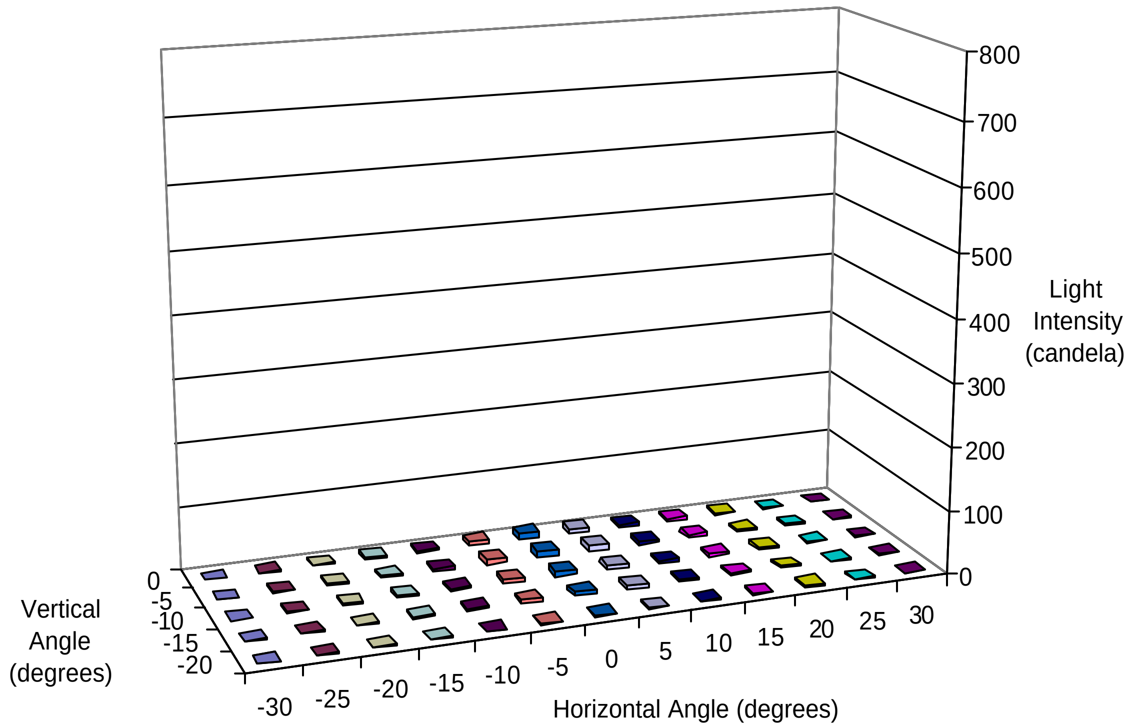

Figure A4.1.3a Output from NPS #4 (Red) signal, 9.0 volts, all elements on, TC test.

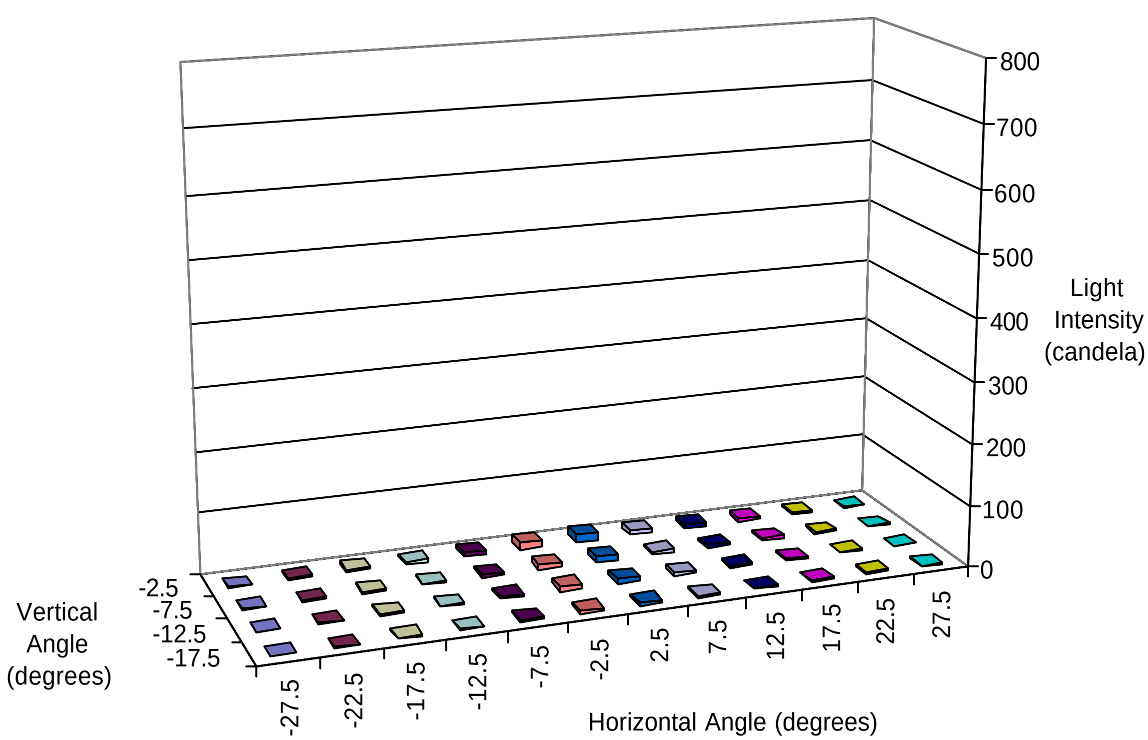

Figure A4.1.3b Output from NPS #4 (Red) signal, 9.0 volts, all elements on, ITE test.

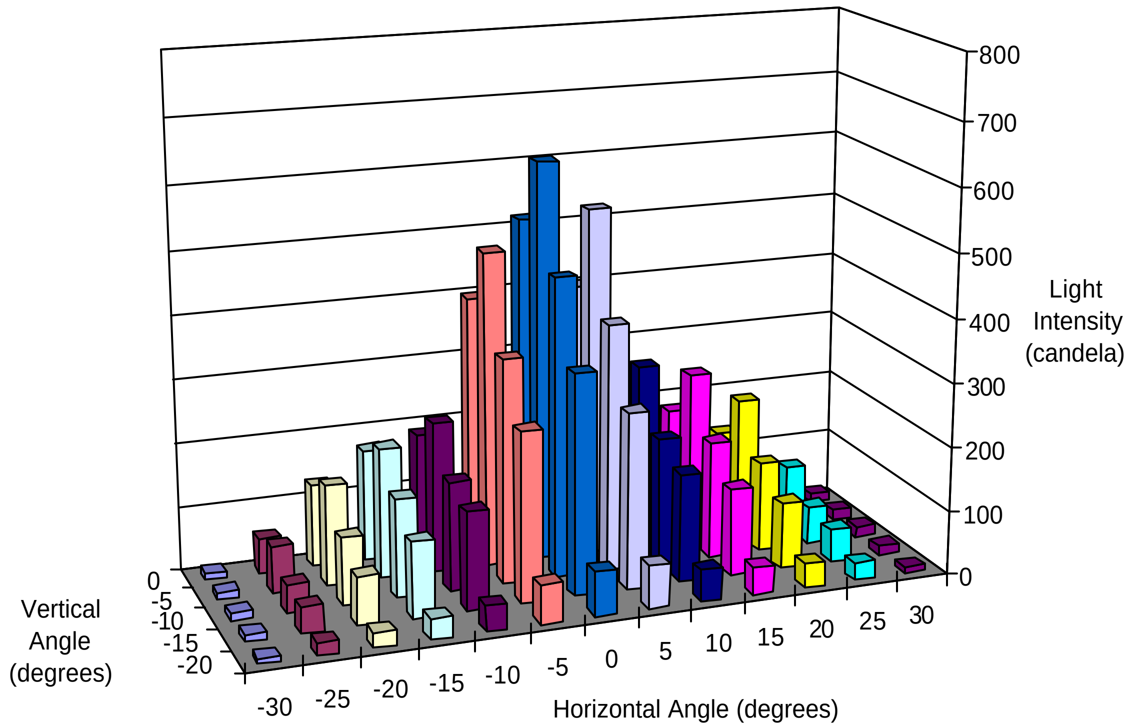

Figure A4.1.4a Output from NPS #4 (Red) signal, 13.5 volts, all elements on, TC test.

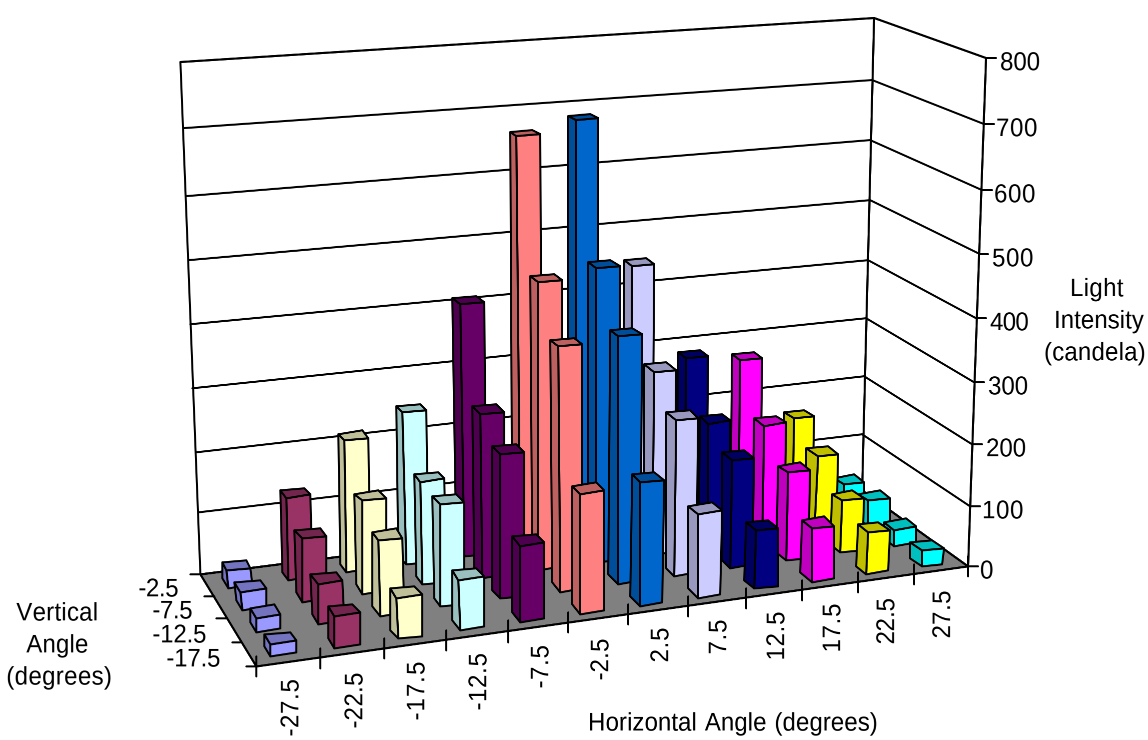

Figure A4.1.4b Output from NPS #4 (Red) signal, 13.5 volts, all elements on, ITE test.

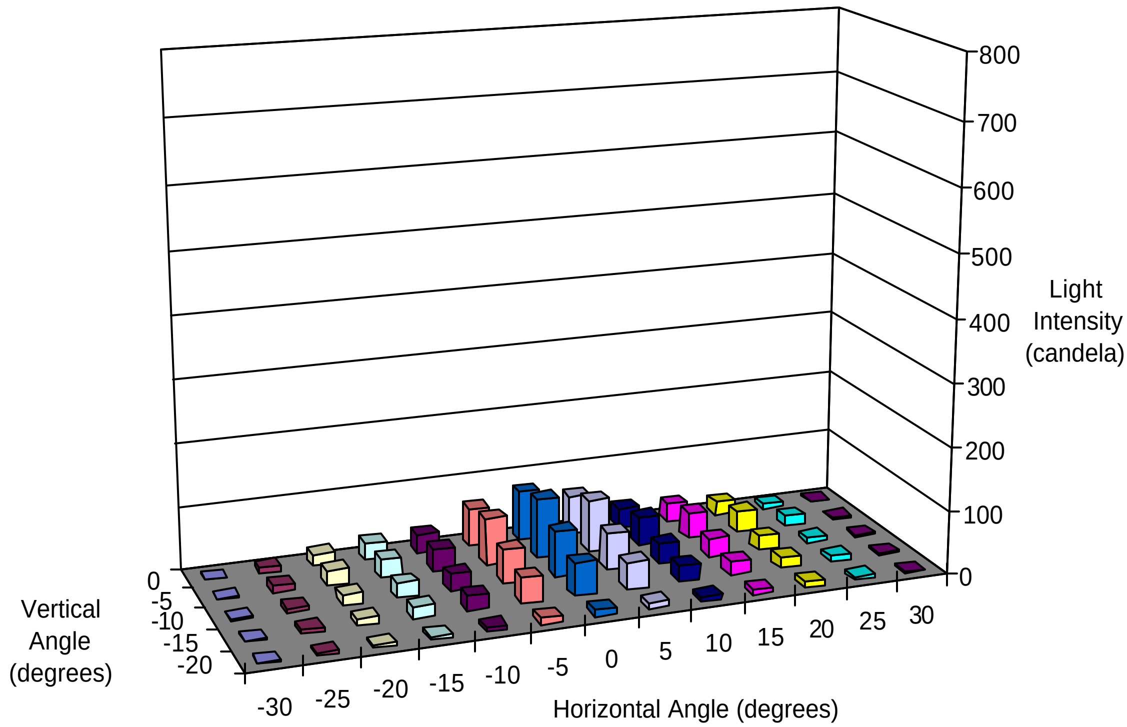

Figure A4.1.5a Output from NPS #4 (Red) signal, 10.0 volts, all elements on, TC test.

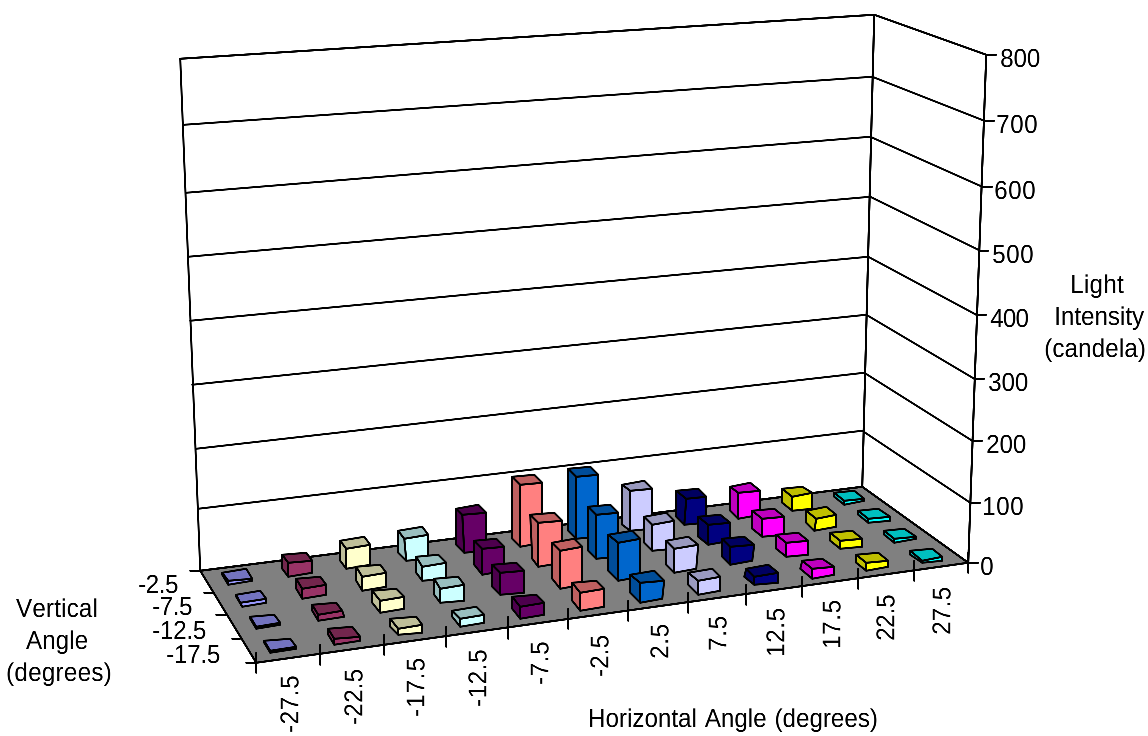

Figure A4.1.5b Output from NPS #4 (Red) signal, 10.0 volts, all elements on, ITE test.

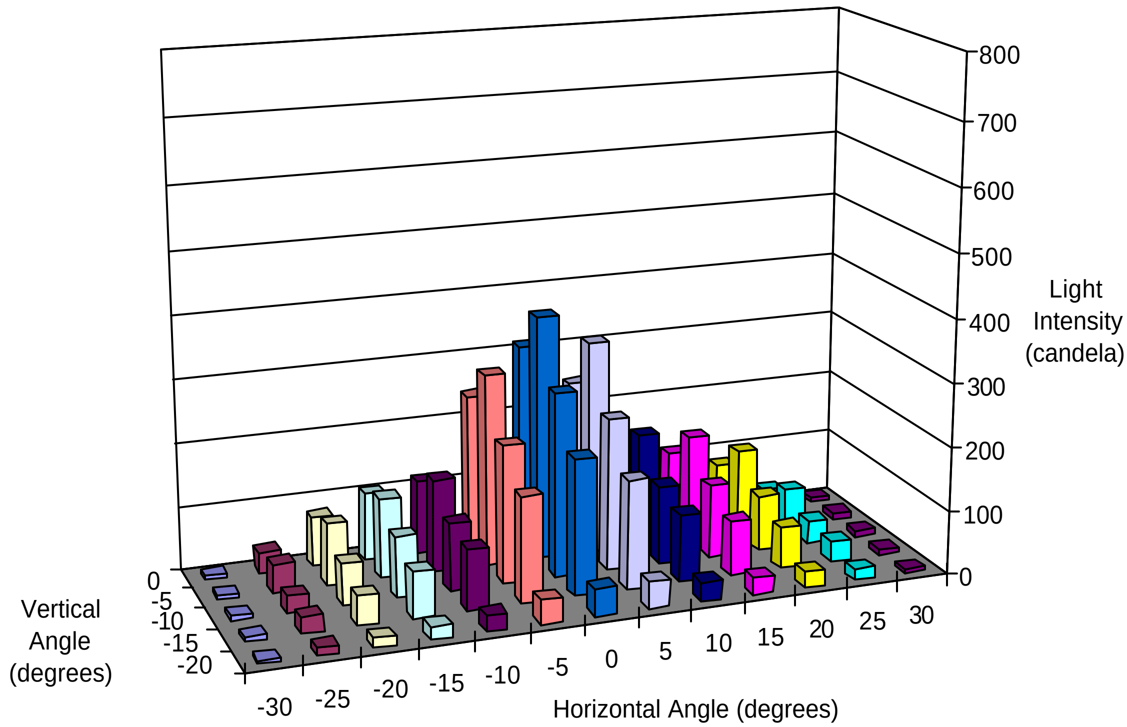

Figure A4.1.6a Output from NPS #4 (Red) signal, 12.0 volts, all elements on, TC test.

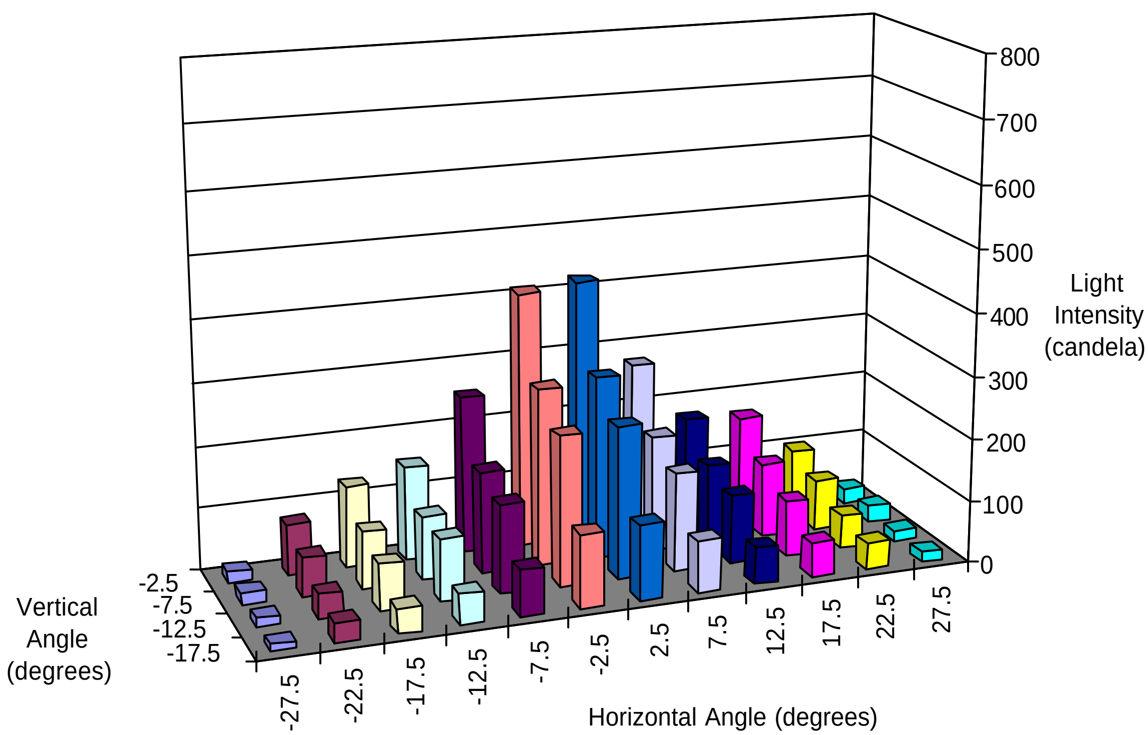

Figure A4.1.6b Output from NPS #4 (Red) signal, 12.0 volts, all elements on, ITE test.

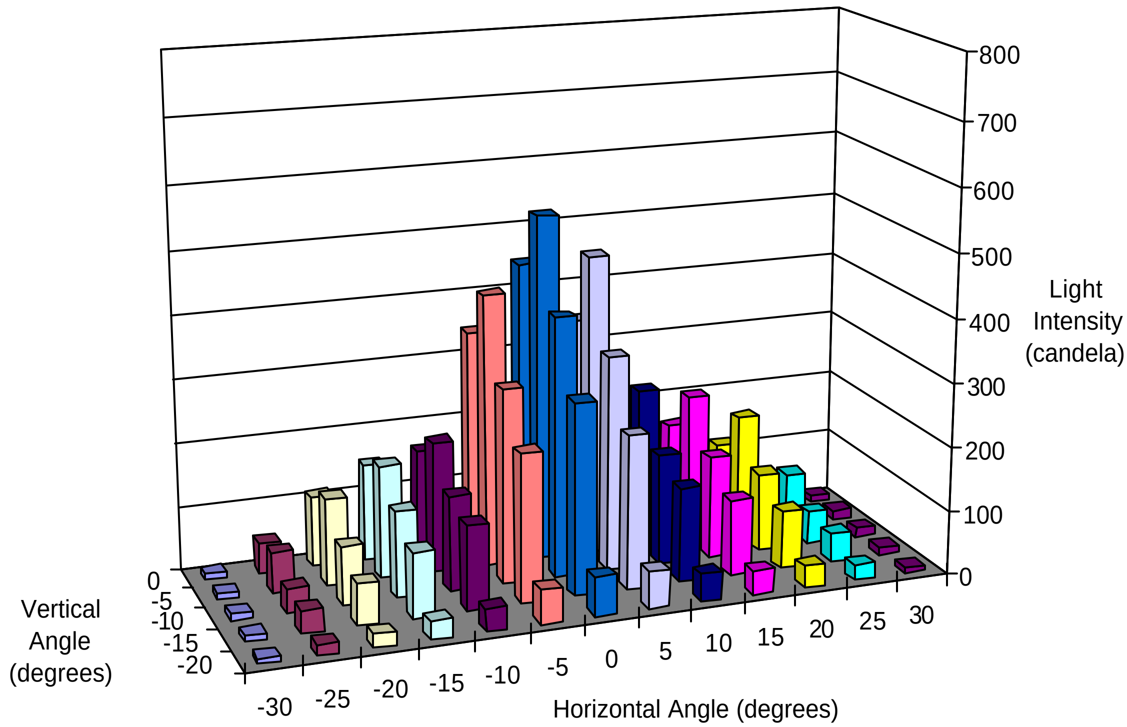

Figure A4.1.7a Output from NPS #4 (Red) signal, 13.0 volts, all elements on, TC test.

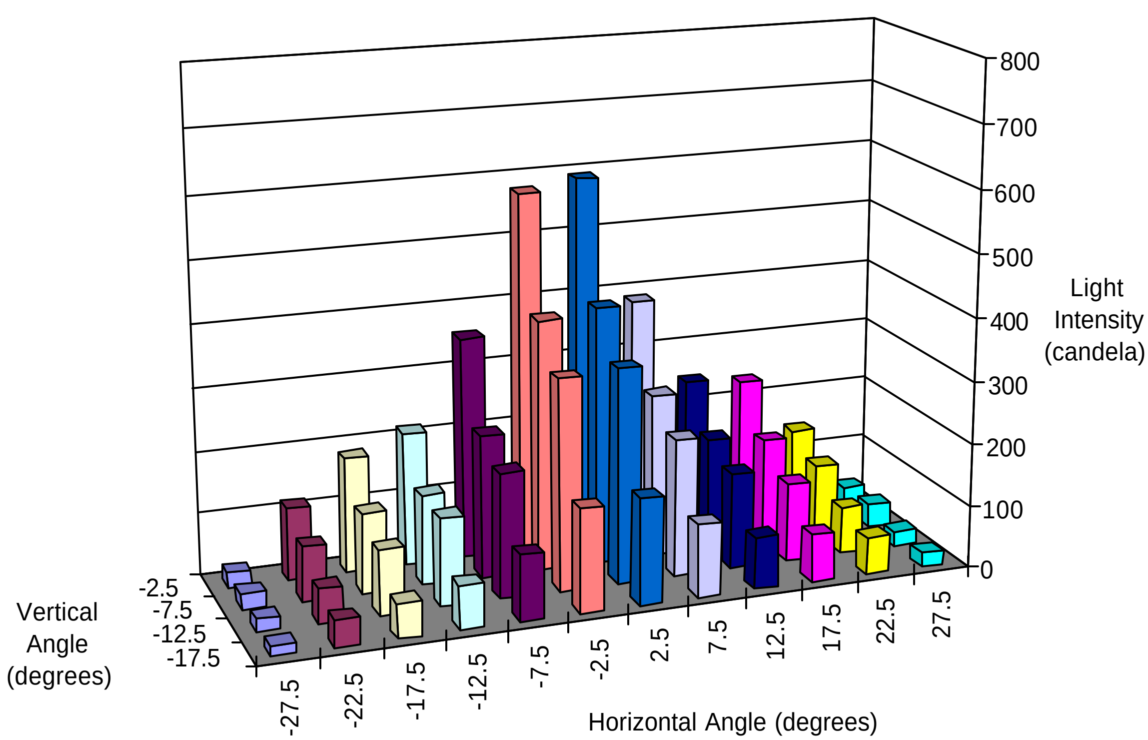

Figure A4.1.7b Output from NPS #4 (Red) signal, 13.0 volts, all elements on, ITE test.

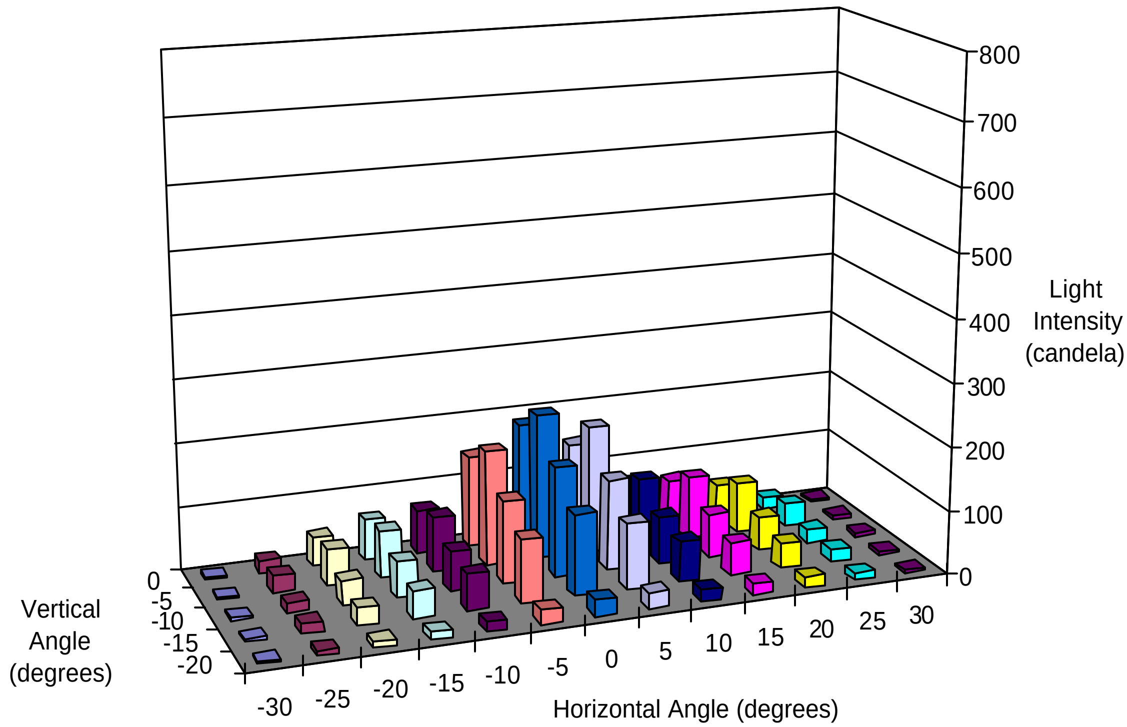

Figure A4.1.8a Output from NPS #4 (Red) signal, 11.0 volts, all elements on, TC test.

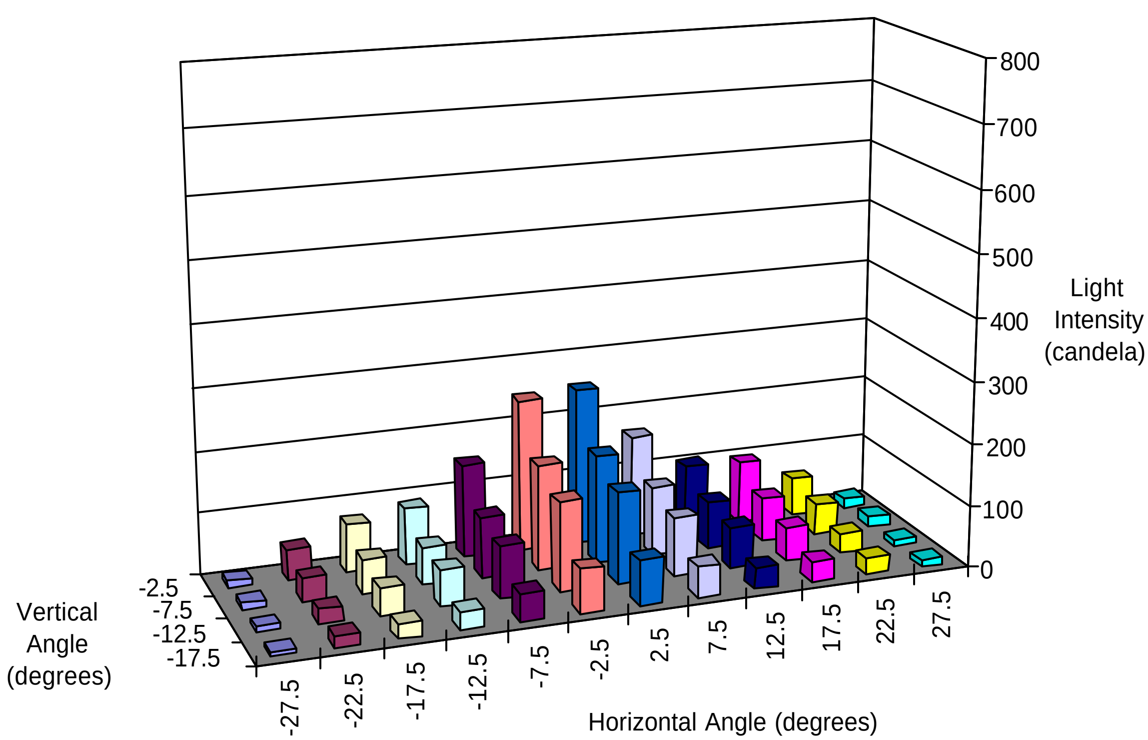

Figure A4.1.8b Output from NPS #4 (Red) signal, 11.0 volts, all elements on, ITE test.

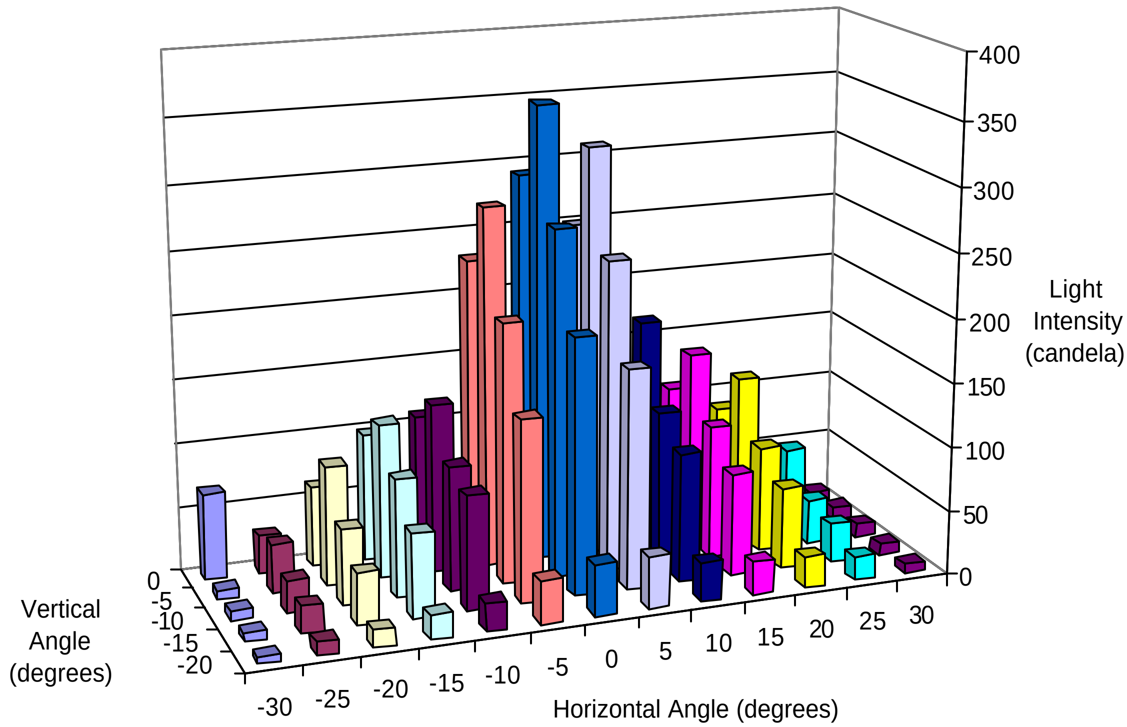

Figure A4.2.1a Output from NPS #4 (Red) signal, 12.0 volts, all elements on, TC test.

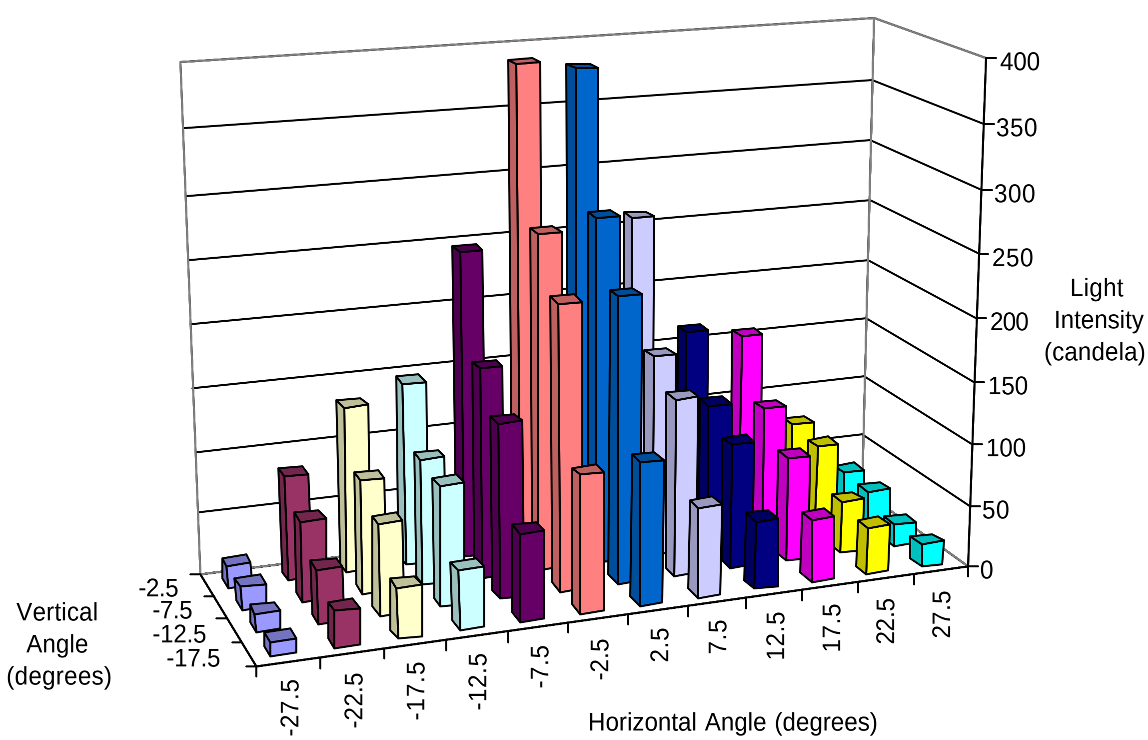

Figure A4.2.1b Output from NPS #4 (Red) signal, 12.0 volts, all elements on, ITE test.

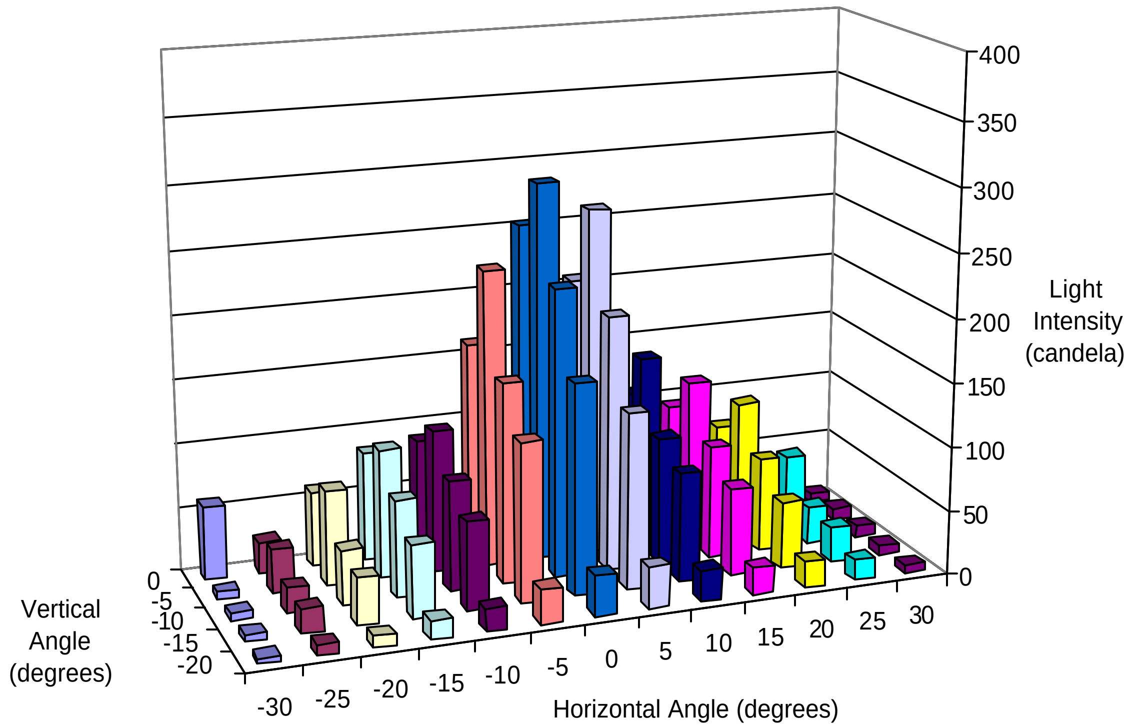

Figure A4.2.2a Output from NPS #4 (Red) signal, 12.0 volts, 91 elements (75.0% on), TC test.

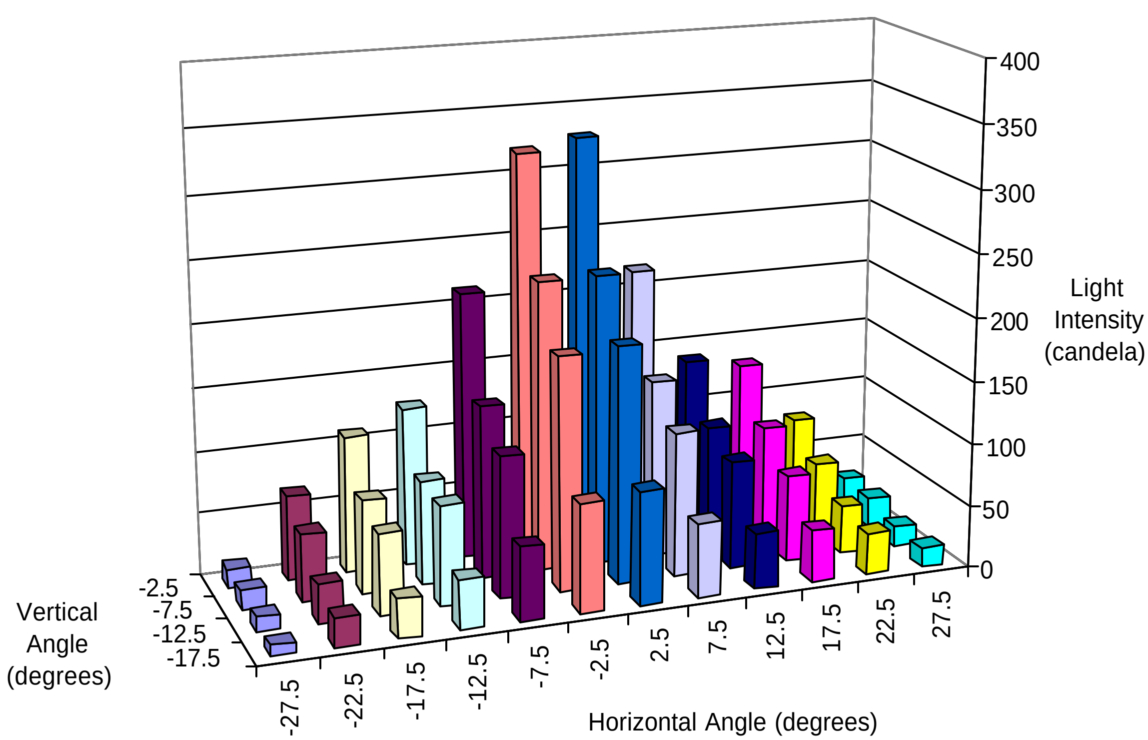

Figure A4.2.2b Output from NPS #4 (Red) signal, 12.0 volts, 91 elements (75.0% on), ITE test.

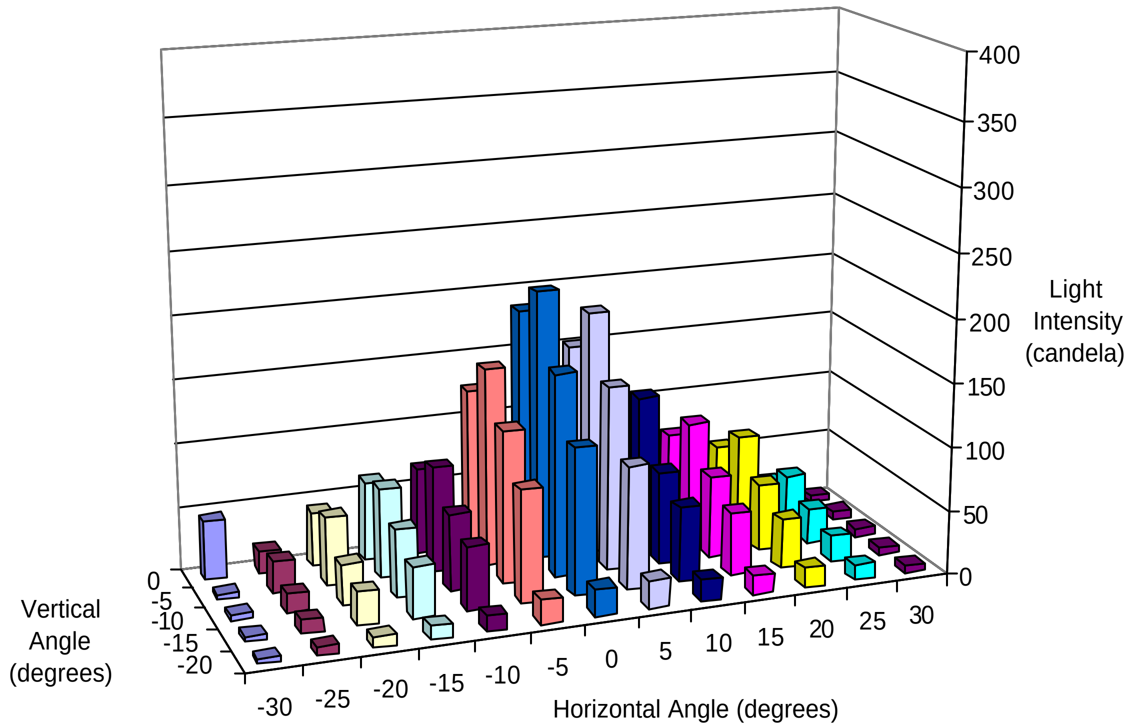

Figure A4.2.3a Output from NPS #4 (Red) signal, 12.0 volts, 61 elements (50.0% on), TC test.

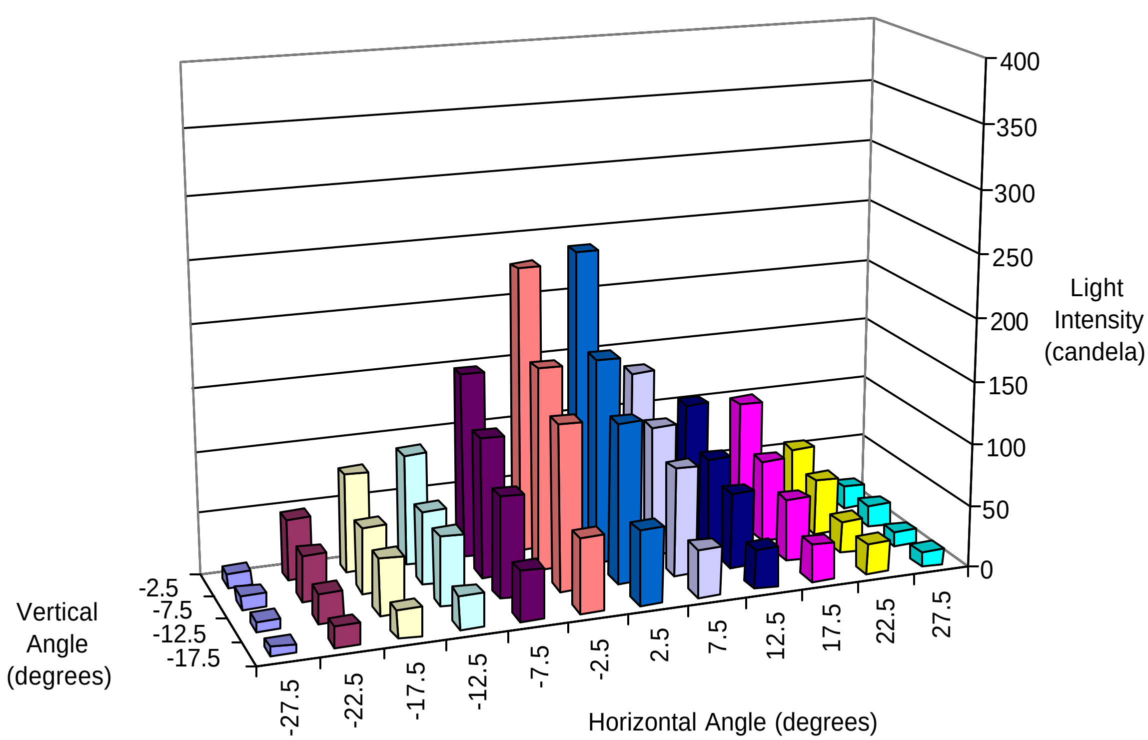

Figure A4.2.3b Output from NPS #4 (Red) signal, 12.0 volts, 61 elements (50.0% on), ITE test.

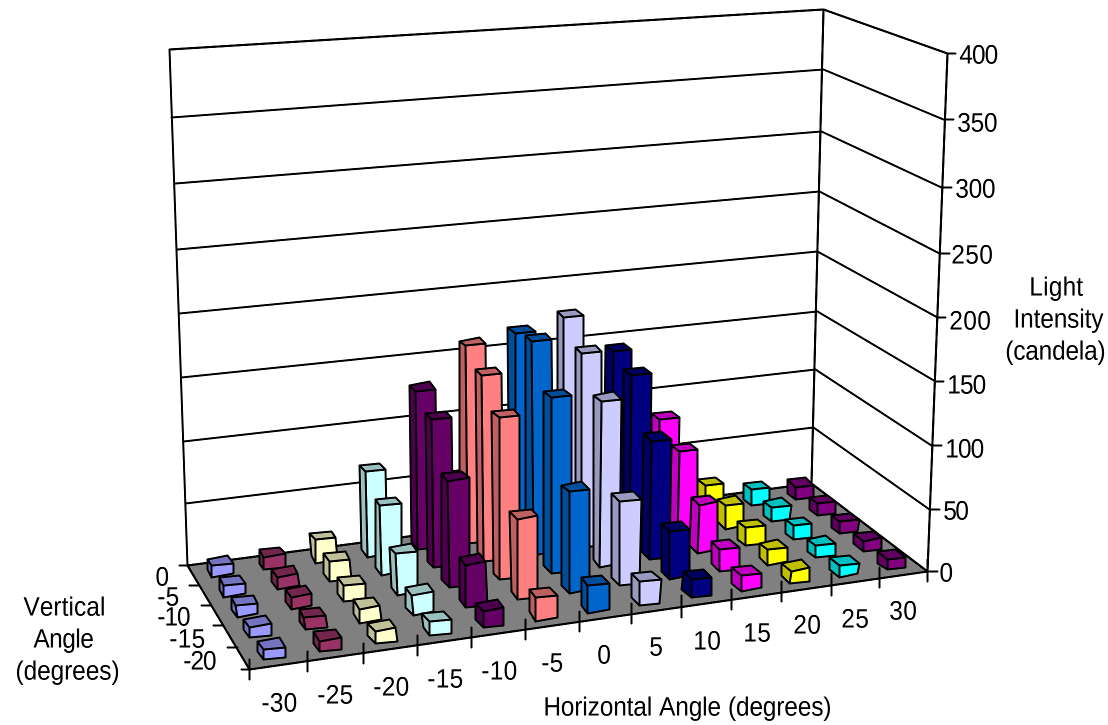

Figure A5.1a Output from WPS #5 (Red) signal, 7.5 volts, all elements on, TC test.

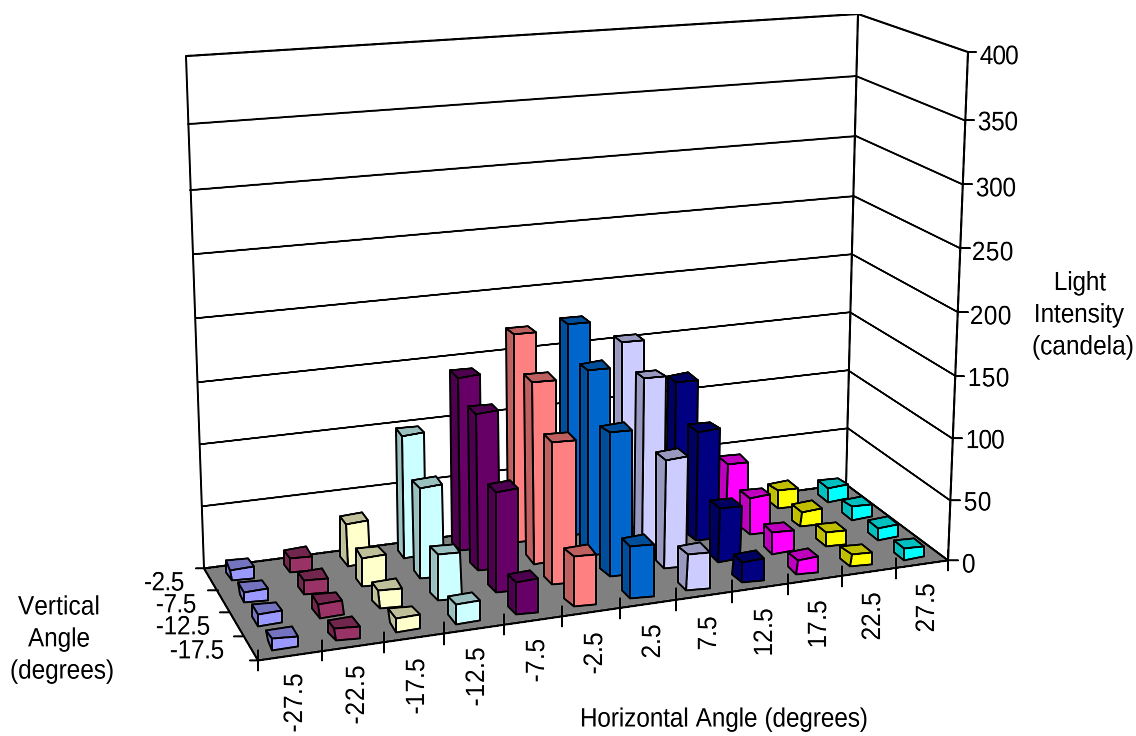

Figure A5.1b Output from WPS #5 (Red) signal, 7.5 volts, all elements on, ITE test.

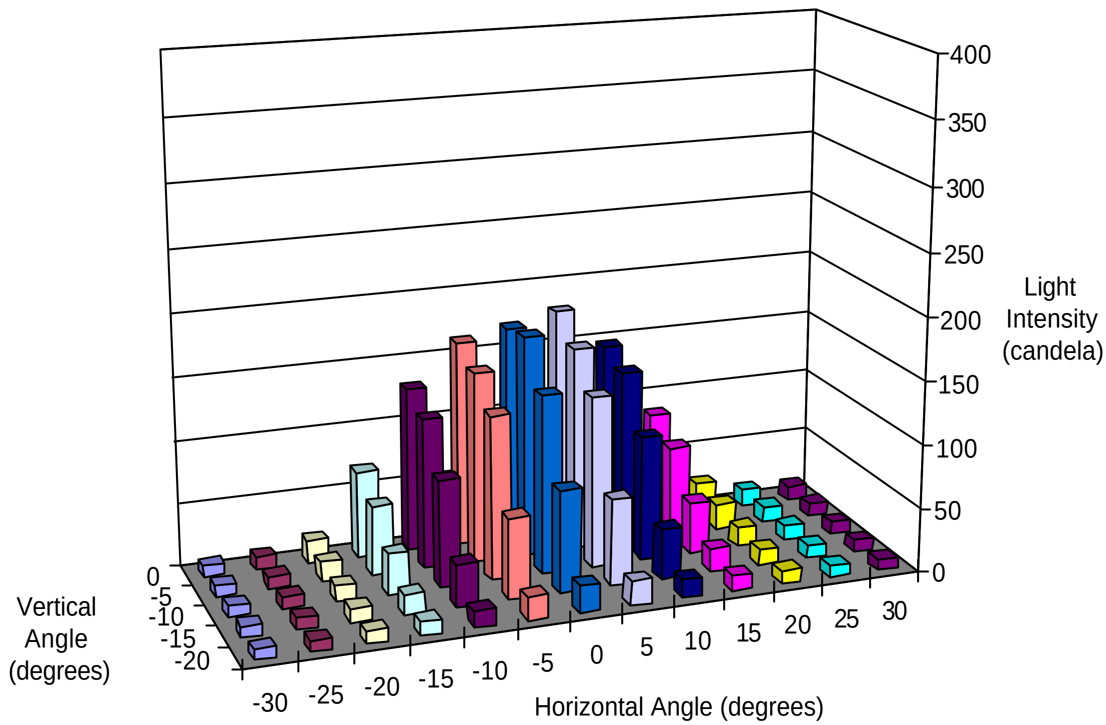

Figure A5.2a Output from WPS #5 (Red) signal, 9.0 volts, all elements on, TC test.

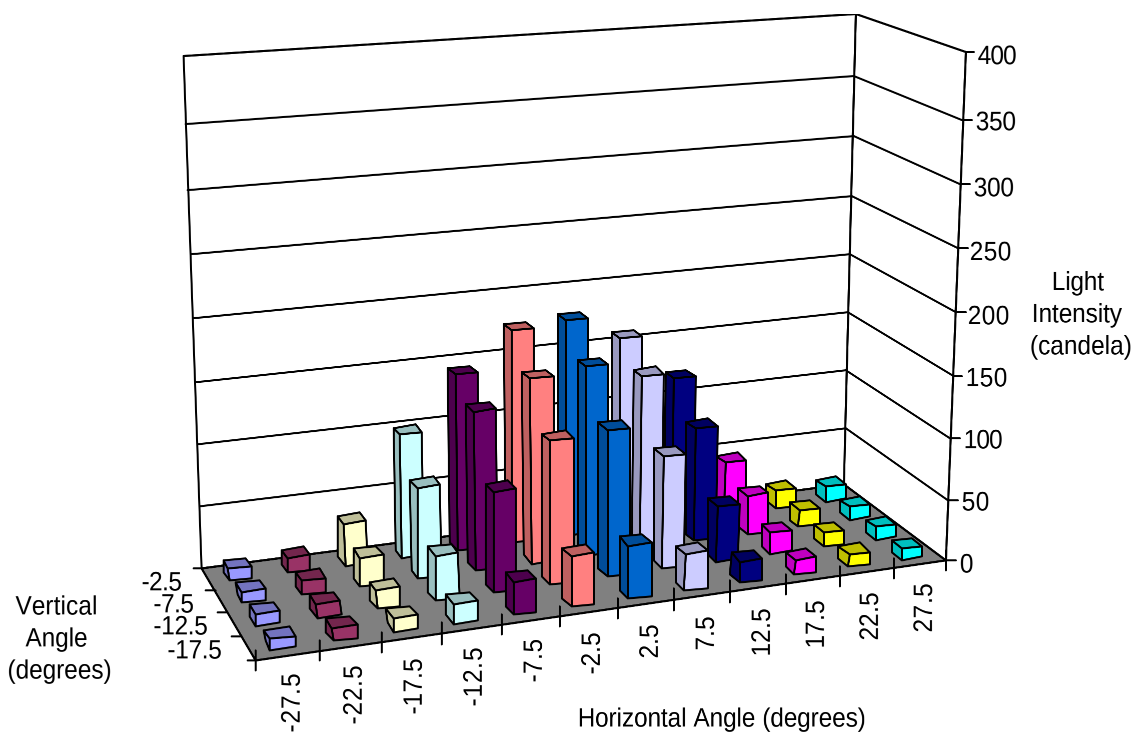

Figure A5.2b Output from WPS #5 (Red) signal, 9.0 volts, all elements on, ITE test.

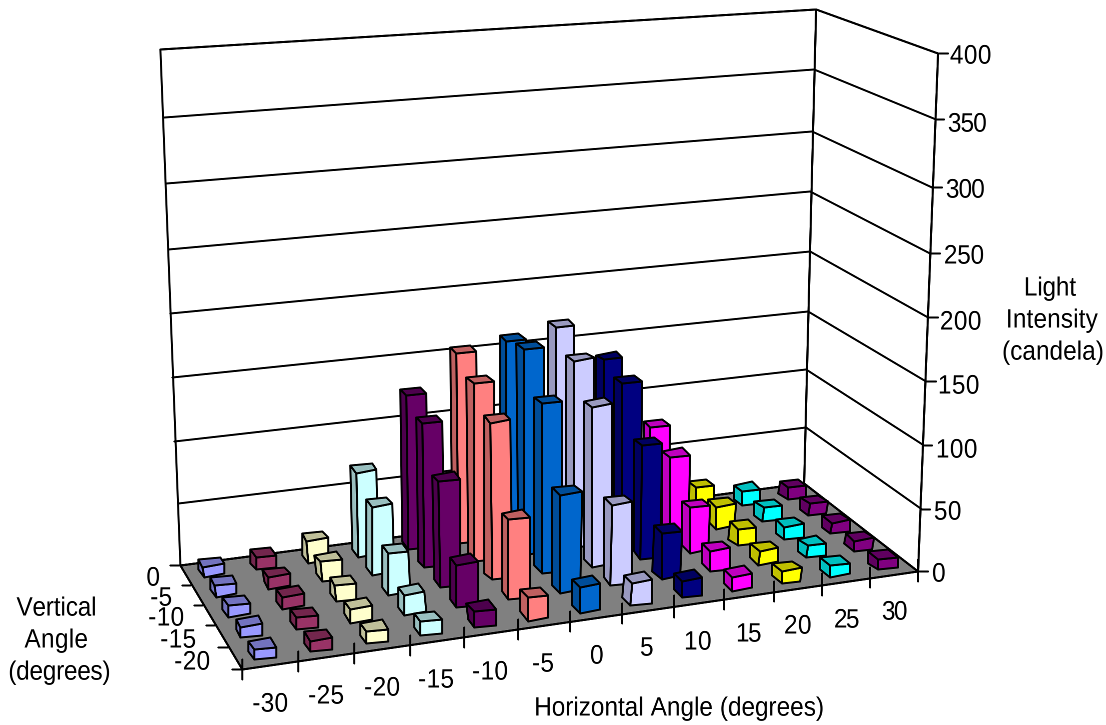

Figure A5.3a Output from WPS #5 (Red) signal, 10.0 volts, all elements on, TC test.

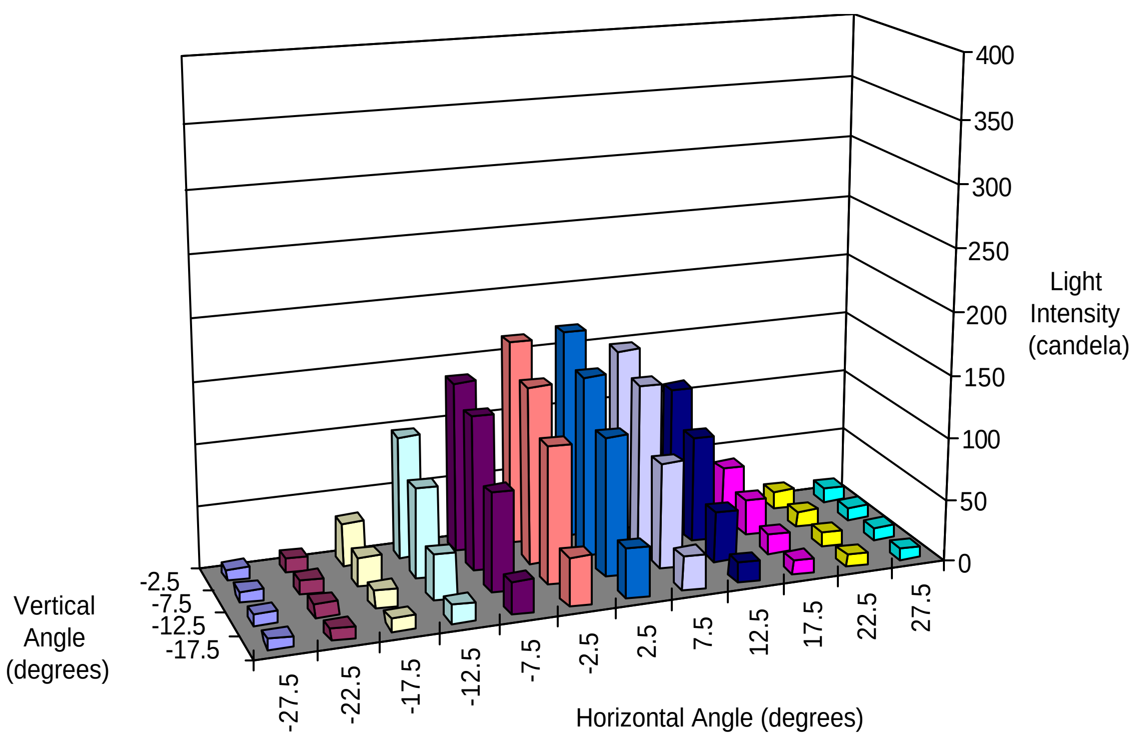

Figure A5.3b Output from WPS #5 (Red) signal, 10.0 volts, all elements on, ITE test.

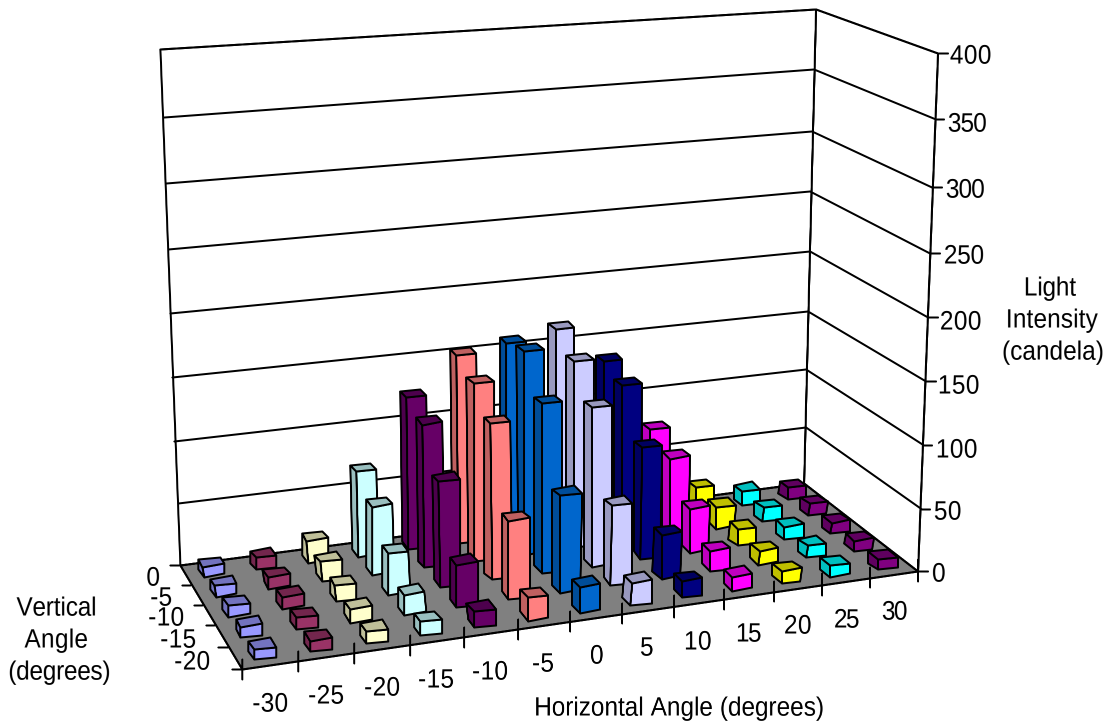

Figure A5.4a Output from WPS #5 (Red) signal, 10.5 volts, all elements on, TC test.

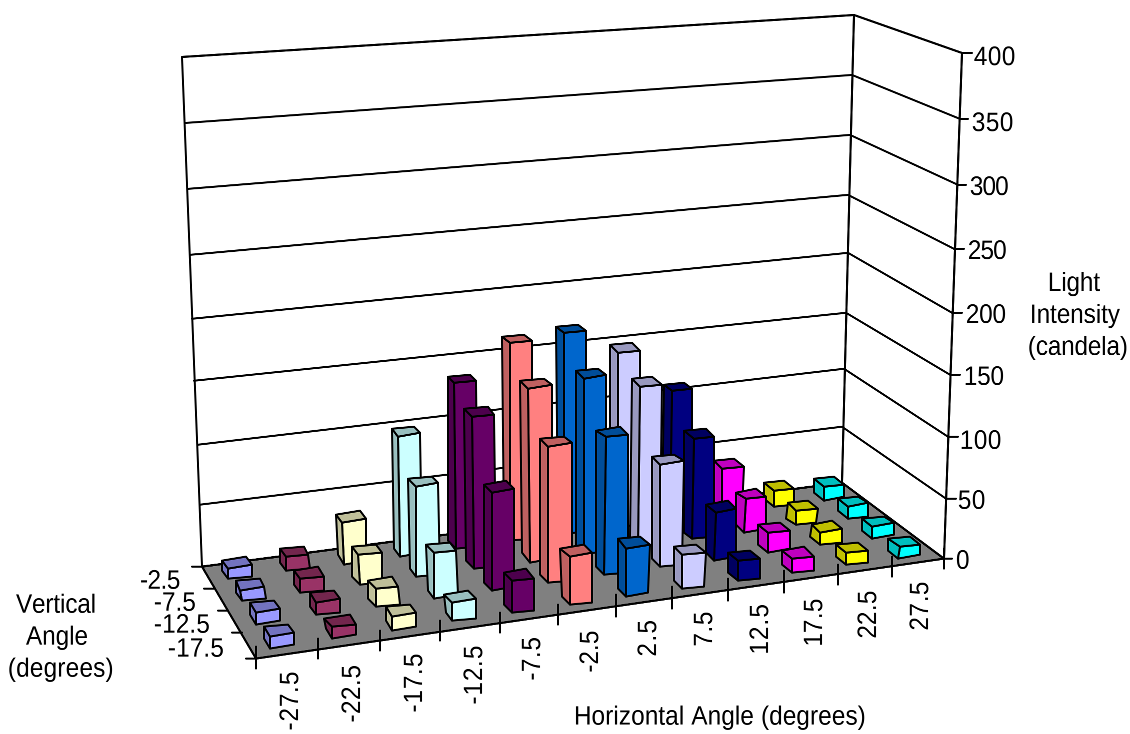

Figure A5.4b Output from WPS #5 (Red) signal, 10.5 volts, all elements on, ITE test.

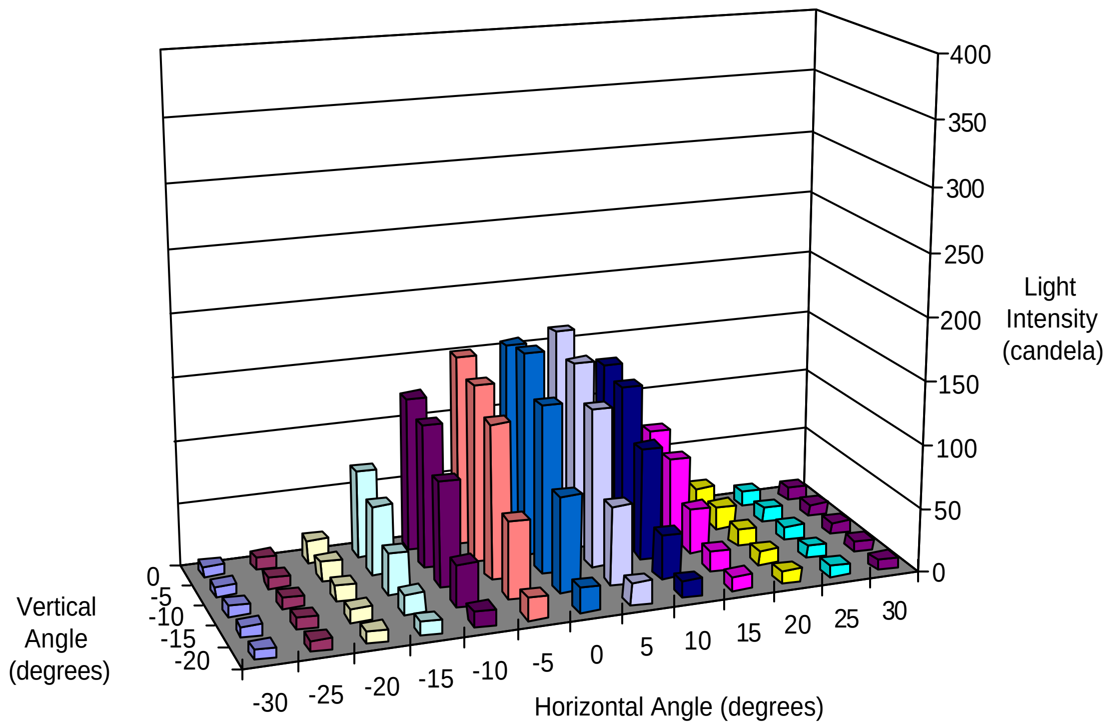

Figure A5.5a Output from WPS #5 (Red) signal, 12.0 volts, all elements on, TC test.

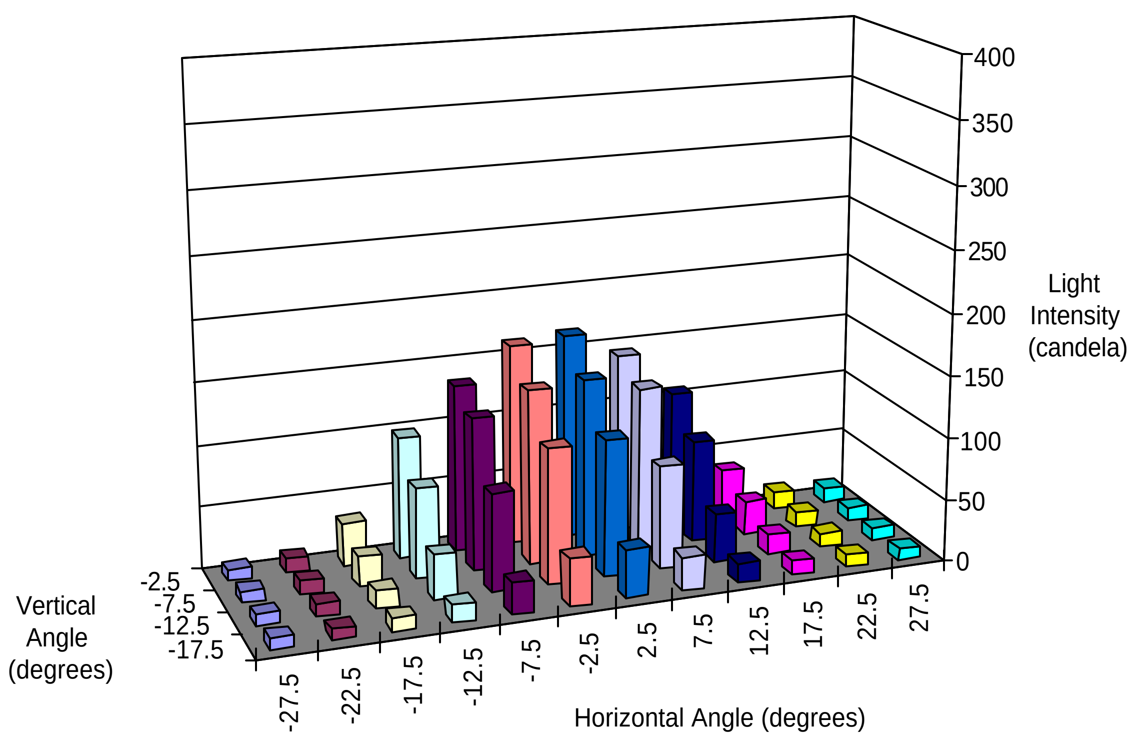

Figure A5.5b Output from WPS #5 (Red) signal, 12.0 volts, all elements on, ITE test.

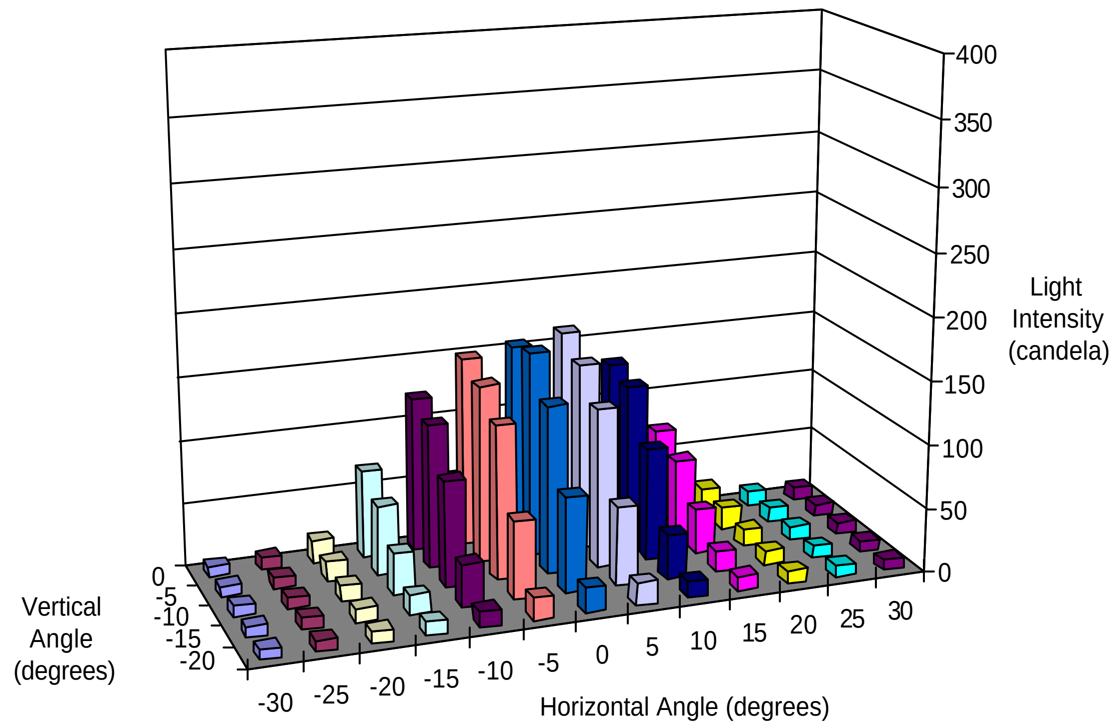

Figure A5.6a Output from WPS #5 (Red) signal, 13.5 volts, all elements on, TC test.

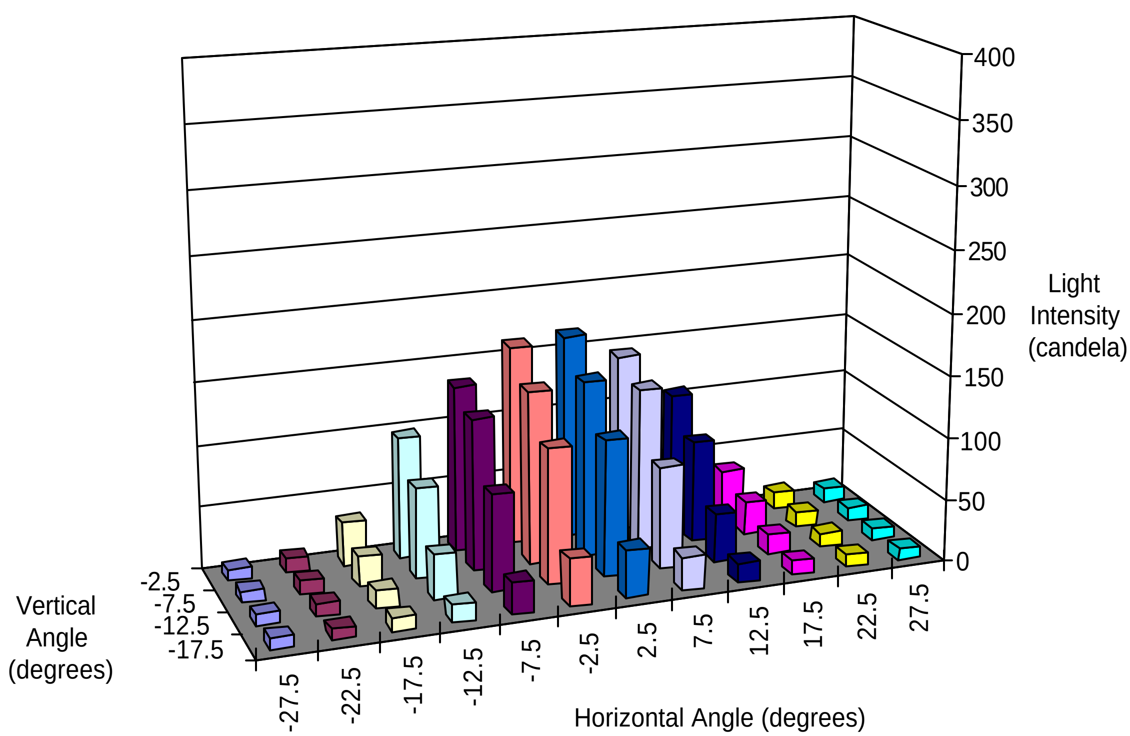

Figure A5.6b Output from WPS #5 (Red) signal, 13.5 volts, all elements on, ITE test.

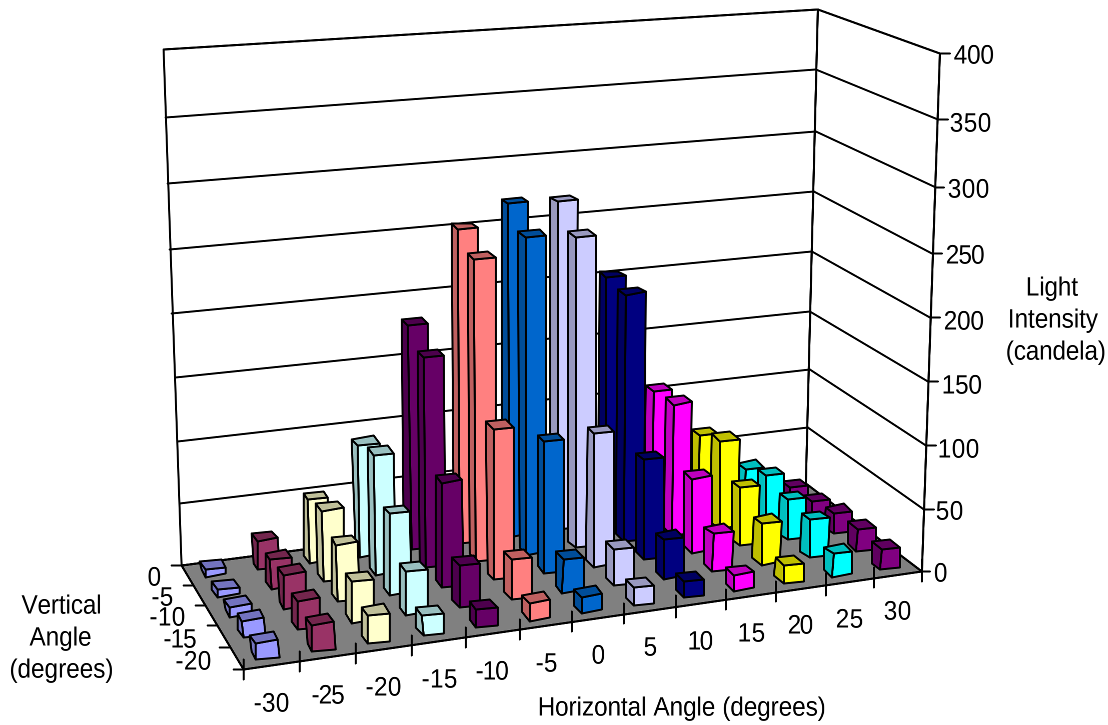

Figure A6.1.1a Output from WPS #6 (Red) signal, 7.5 volts, all elements on, TC test.

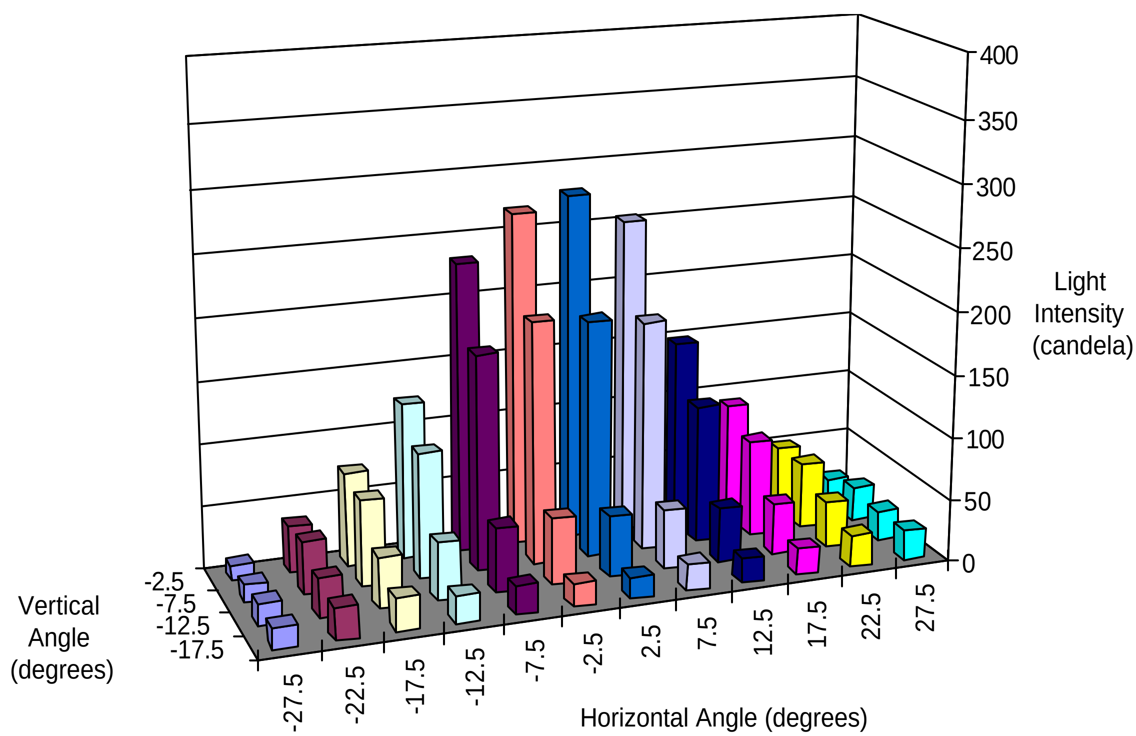

Figure A6.1.1b Output from WPS #6 (Red) signal, 7.5 volts, all elements on, ITE test.

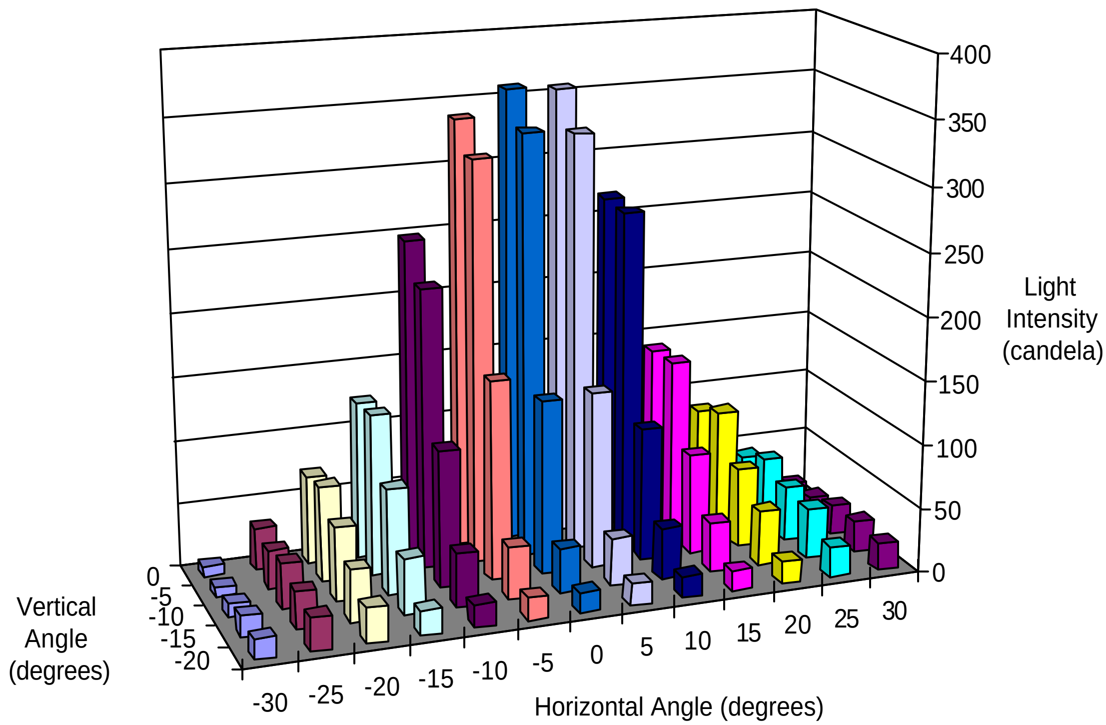

Figure A6.1.2a Output from WPS #6 (Red) signal, 9.0 volts, all elements on, TC test.

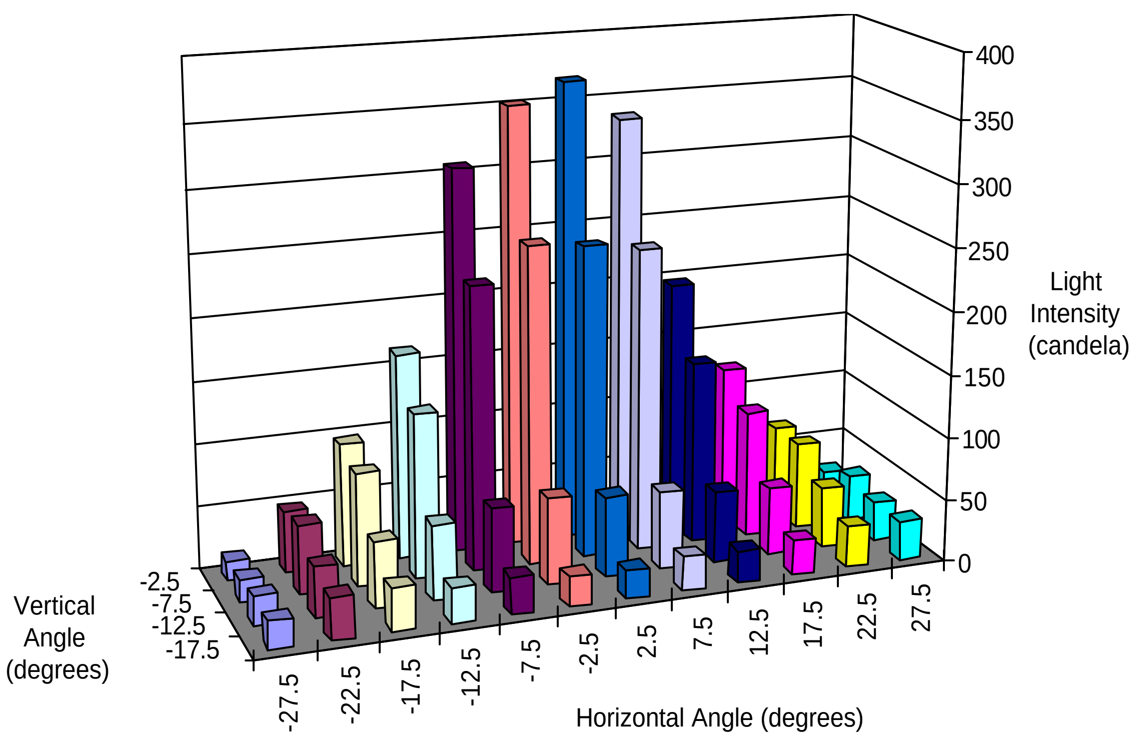

Figure A6.1.2b Output from WPS #6 (Red) signal, 9.0 volts, all elements on, ITE test.

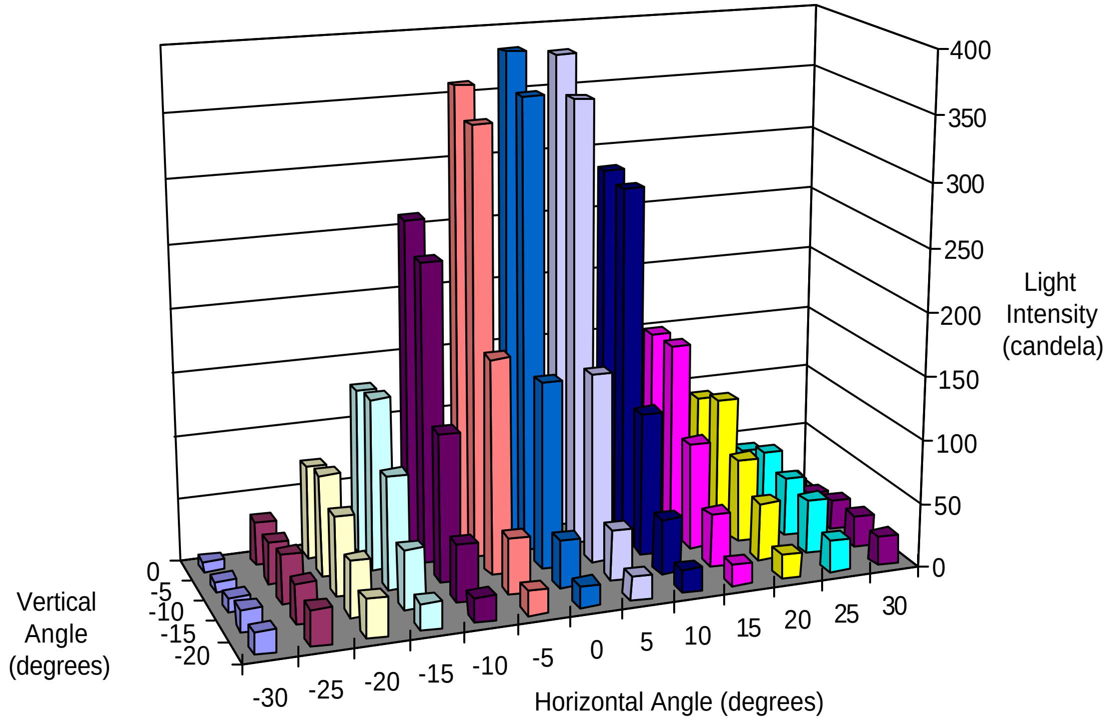

Figure A6.1.3a Output from WPS #6 (Red) signal, 10.0 volts, all elements on, TC test.

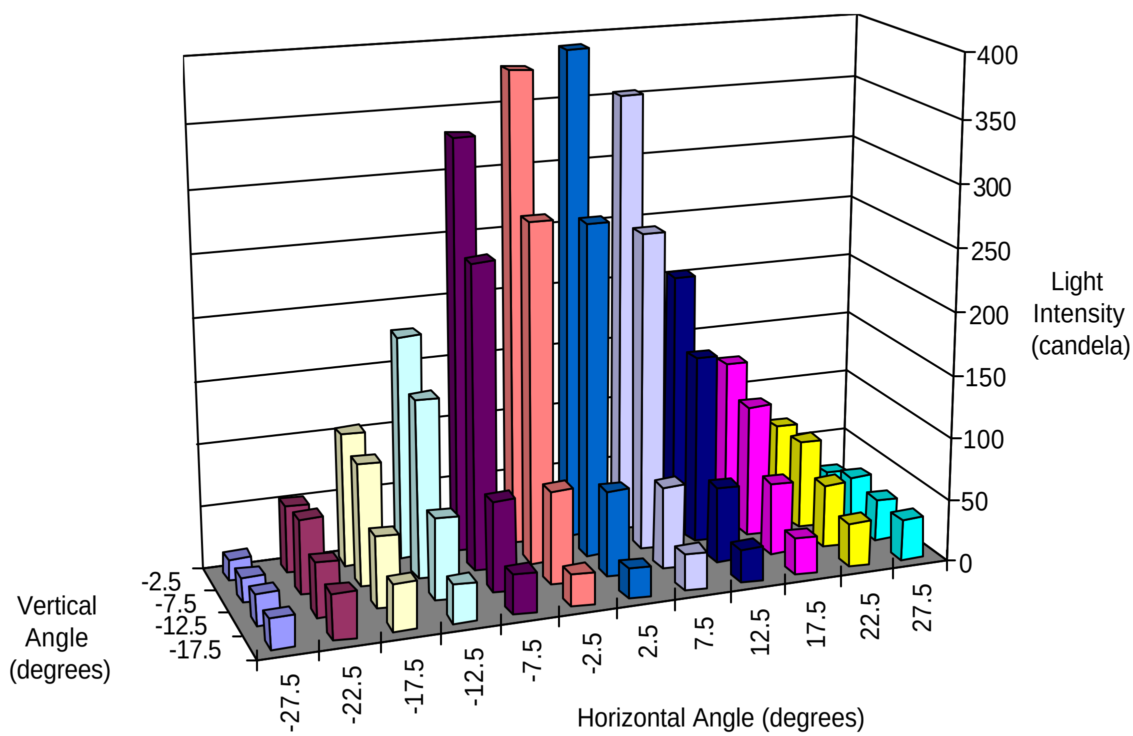

Figure A6.1.3b Output from WPS #6 (Red) signal, 10.0 volts, all elements on, ITE test.

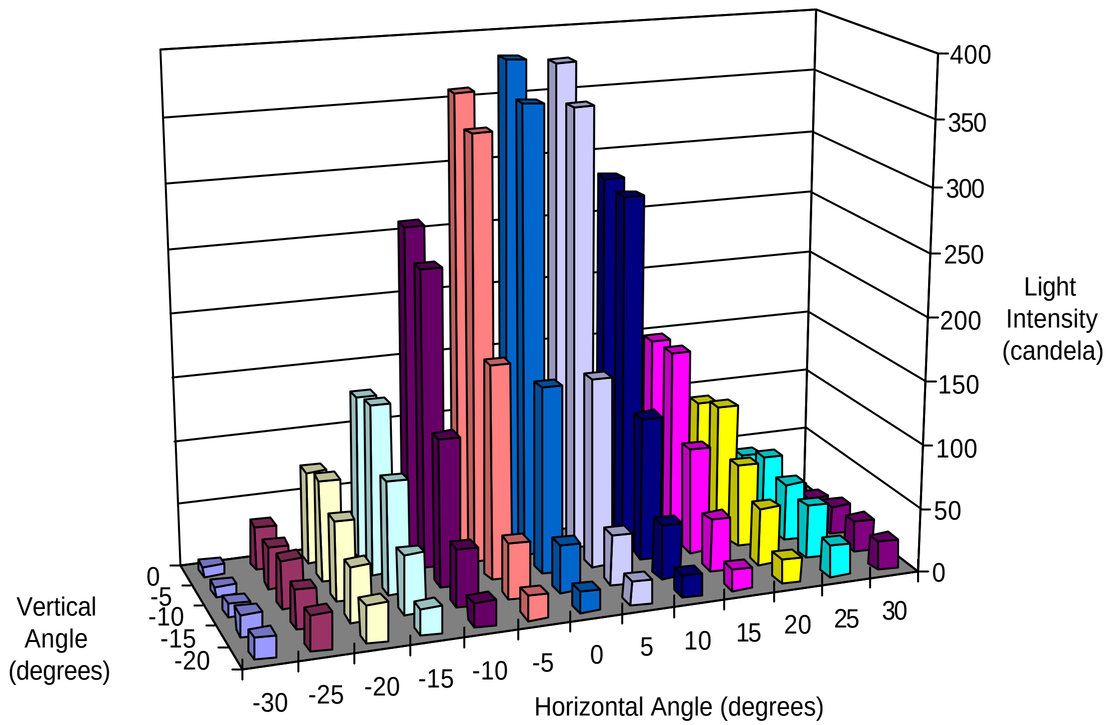

Figure A6.1.4a Output from WPS #6 (Red) signal, 10.5 volts, all elements on, TC test.

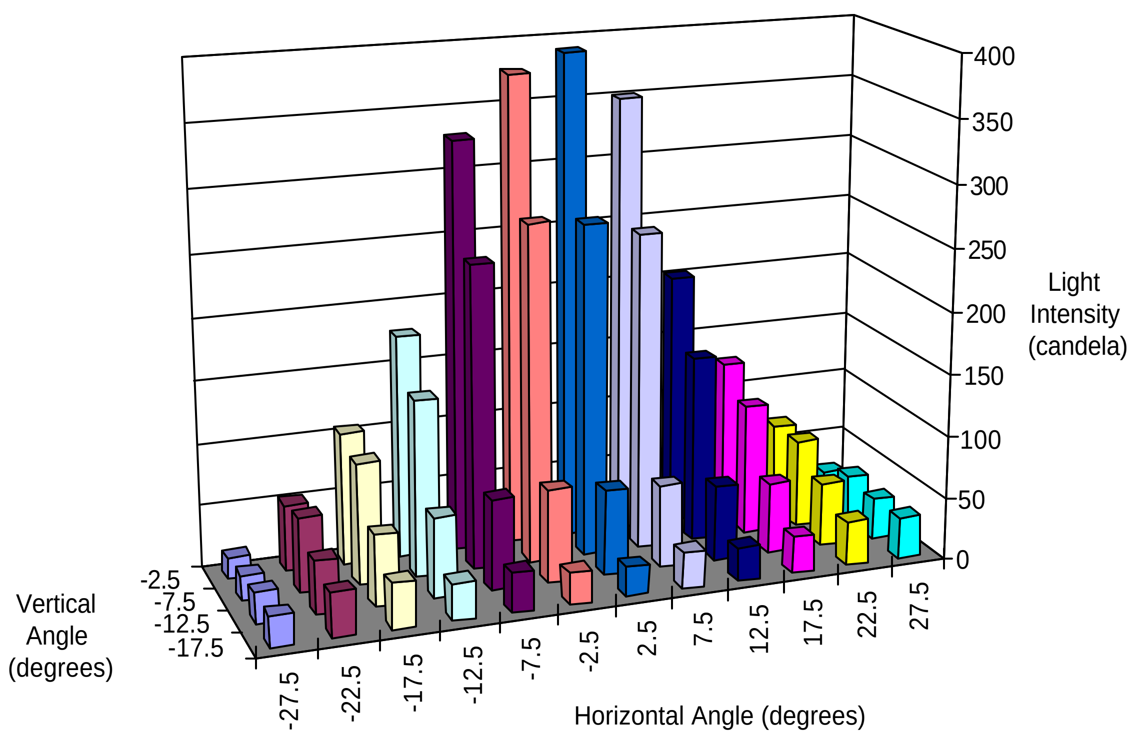

Figure A6.1.4b Output from WPS #6 (Red) signal, 10.5 volts, all elements on, ITE test.

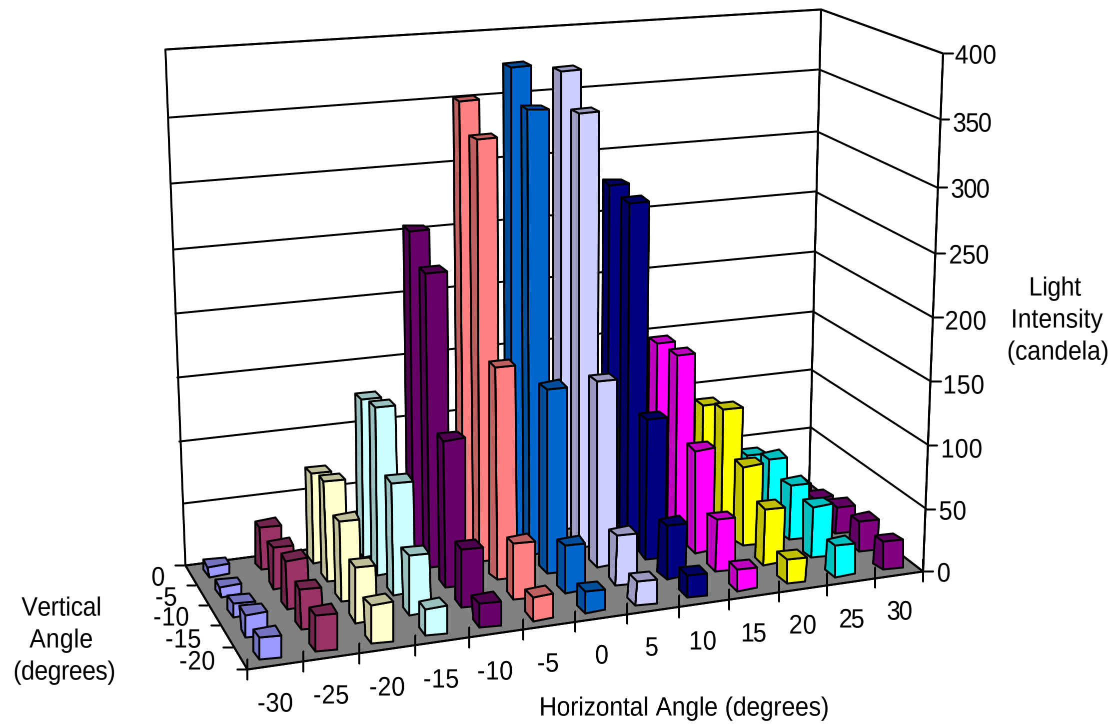

Figure A6.1.5a Output from WPS #6 (Red) signal, 12.0 volts, all elements on, TC test.

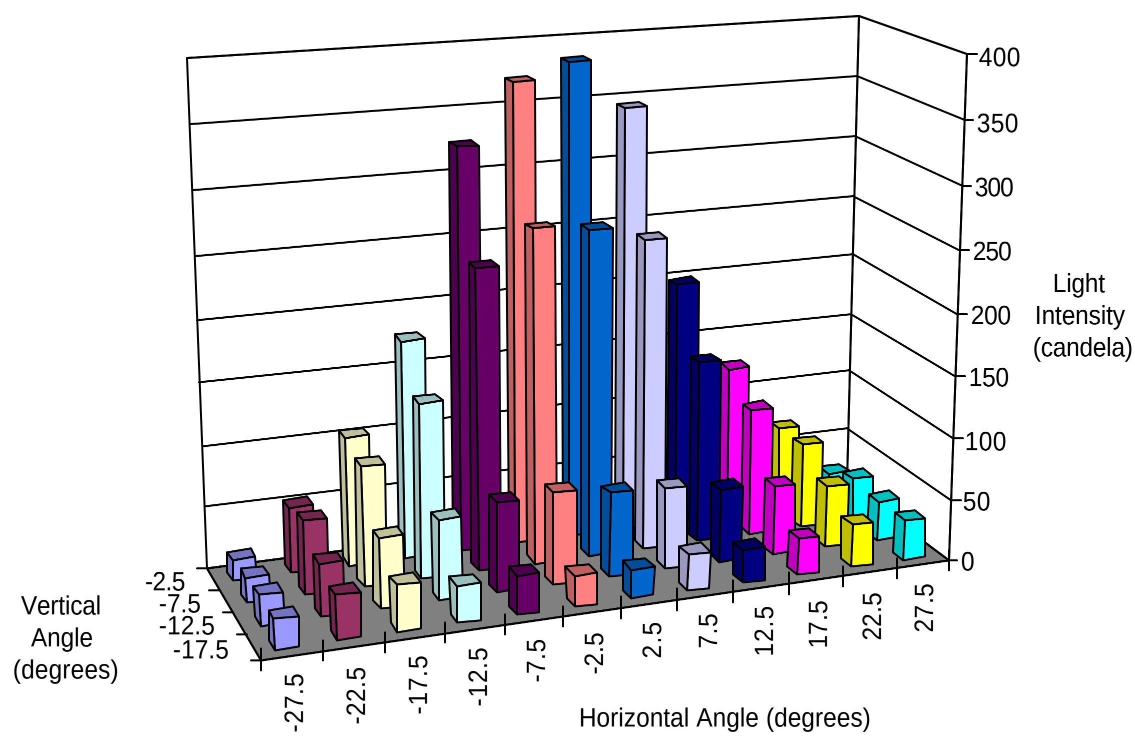

Figure A6.1.5b Output from WPS #6 (Red) signal, 12.0 volts, all elements on, ITE test.

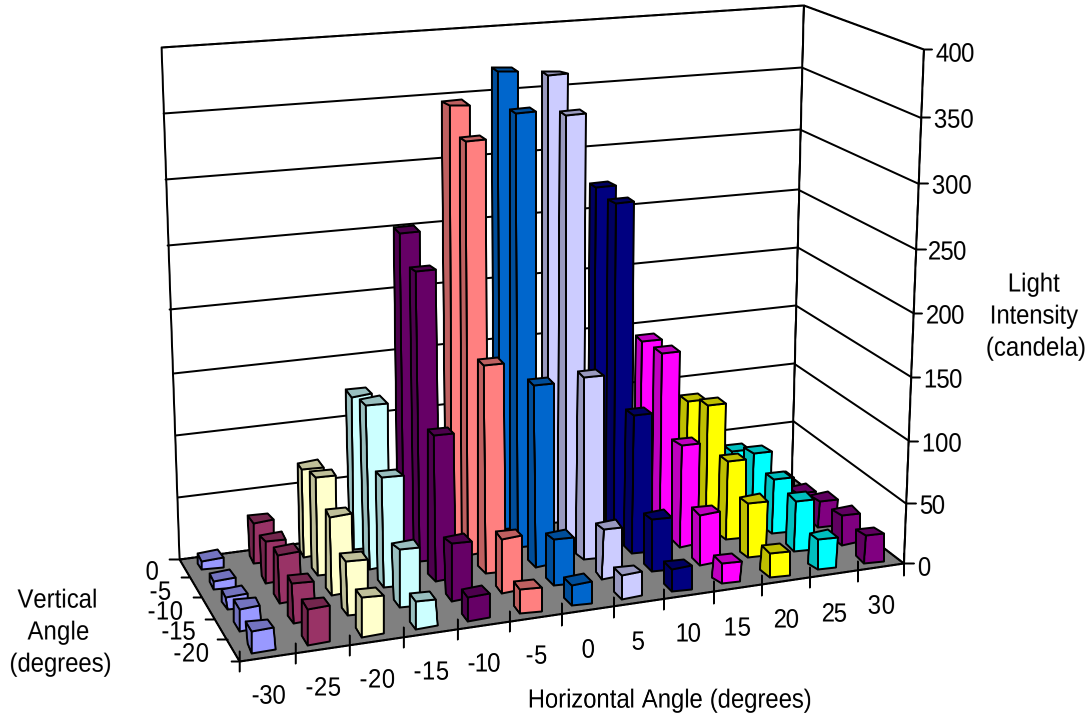

Figure A6.1.6a Output from WPS #6 (Red) signal, 13.5 volts, all elements on, TC test.

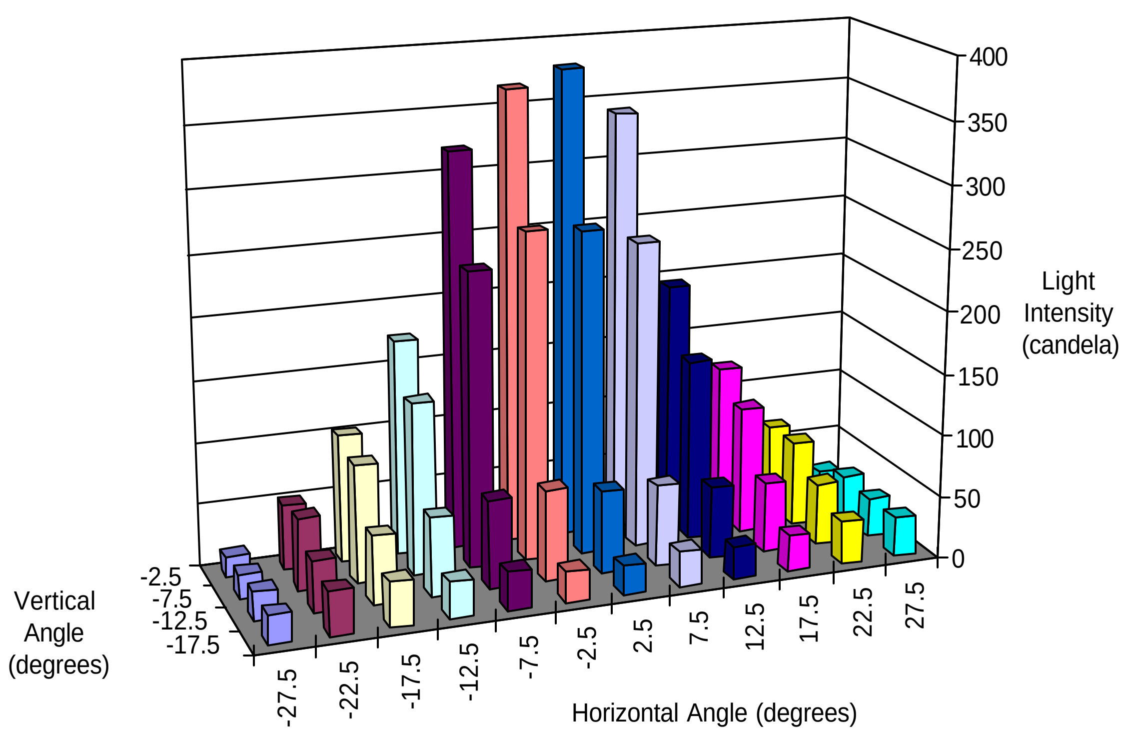

Figure A6.1.6b Output from WPS #6 (Red) signal, 13.5 volts, all elements on, ITE test.

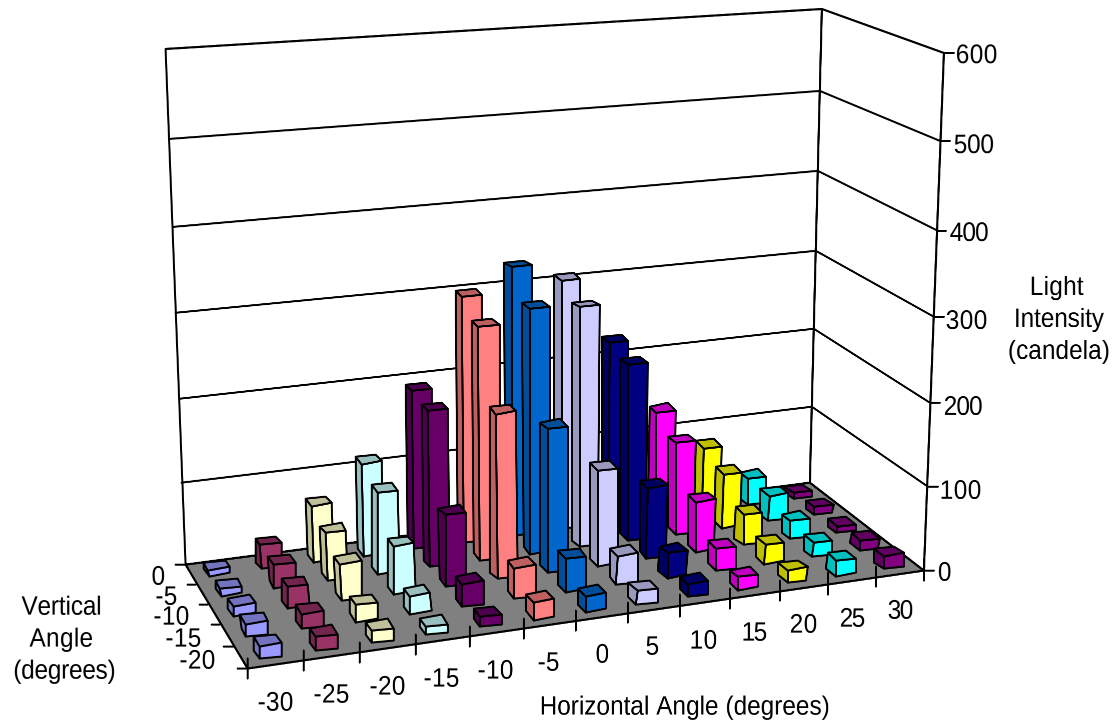

Figure A6.2.1a Output from WPS #6 (Red) signal, 7.5 volts, all elements on, TC test.

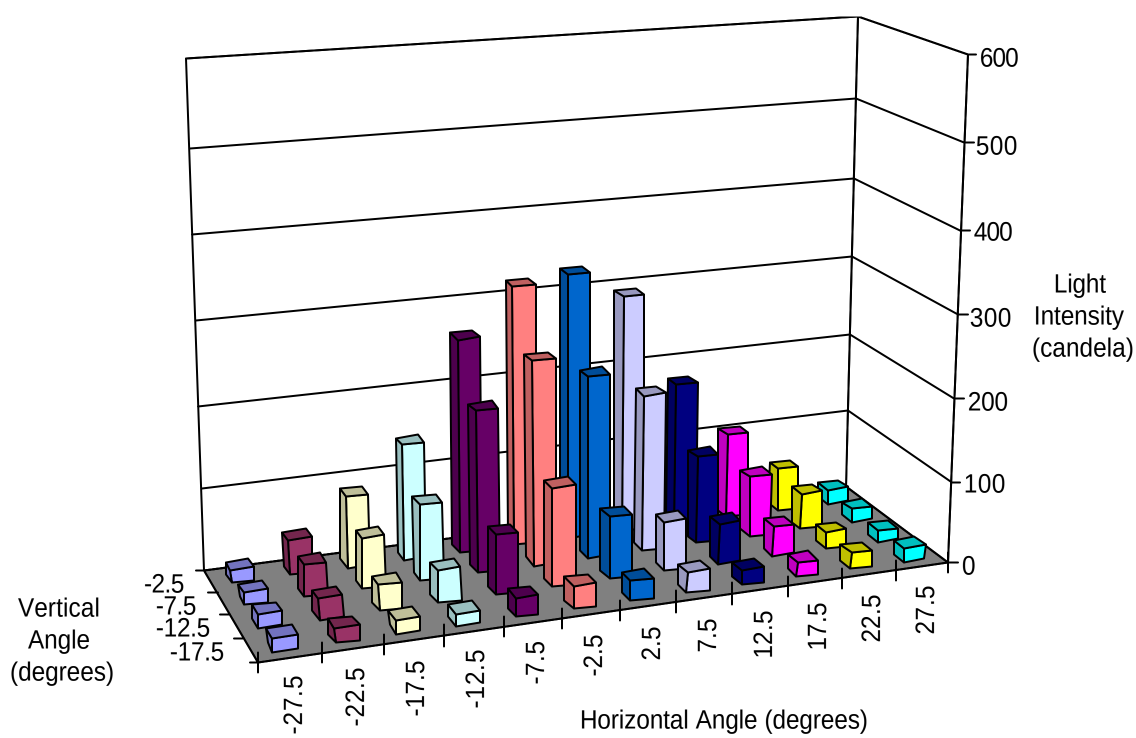

Figure A6.2.1b Output from WPS #6 (Red) signal, 7.5 volts, all elements on, ITE test.

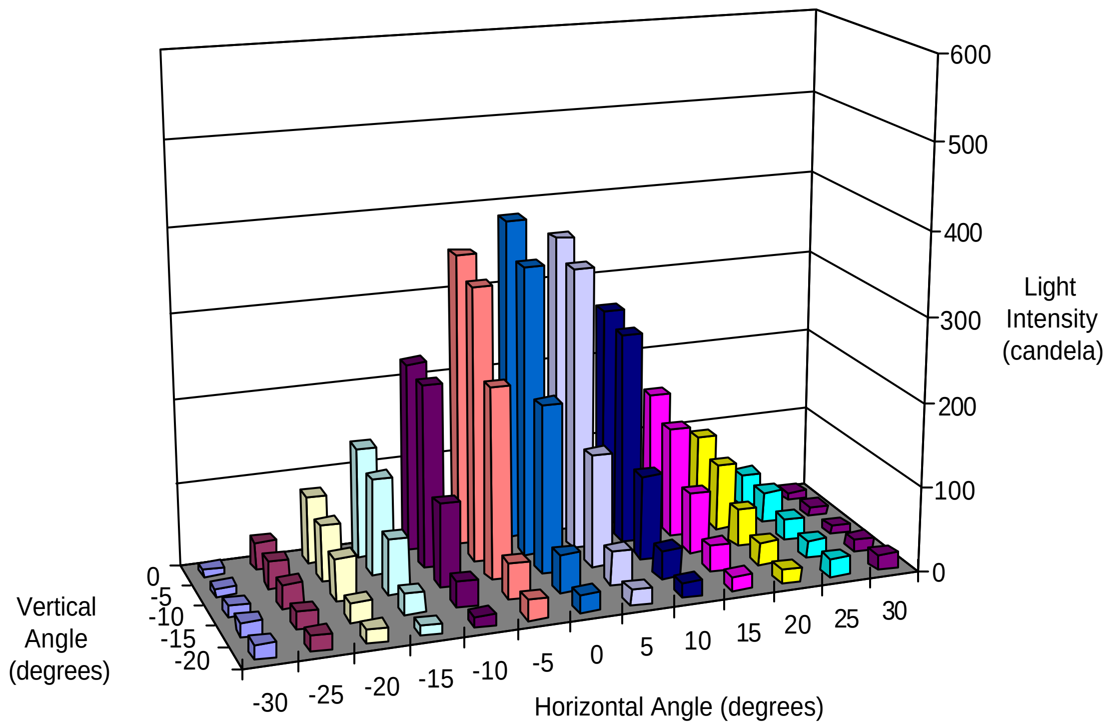

Figure A6.2.2a Output from WPS #6 (Red) signal, 9.0 volts, all elements on, TC test.

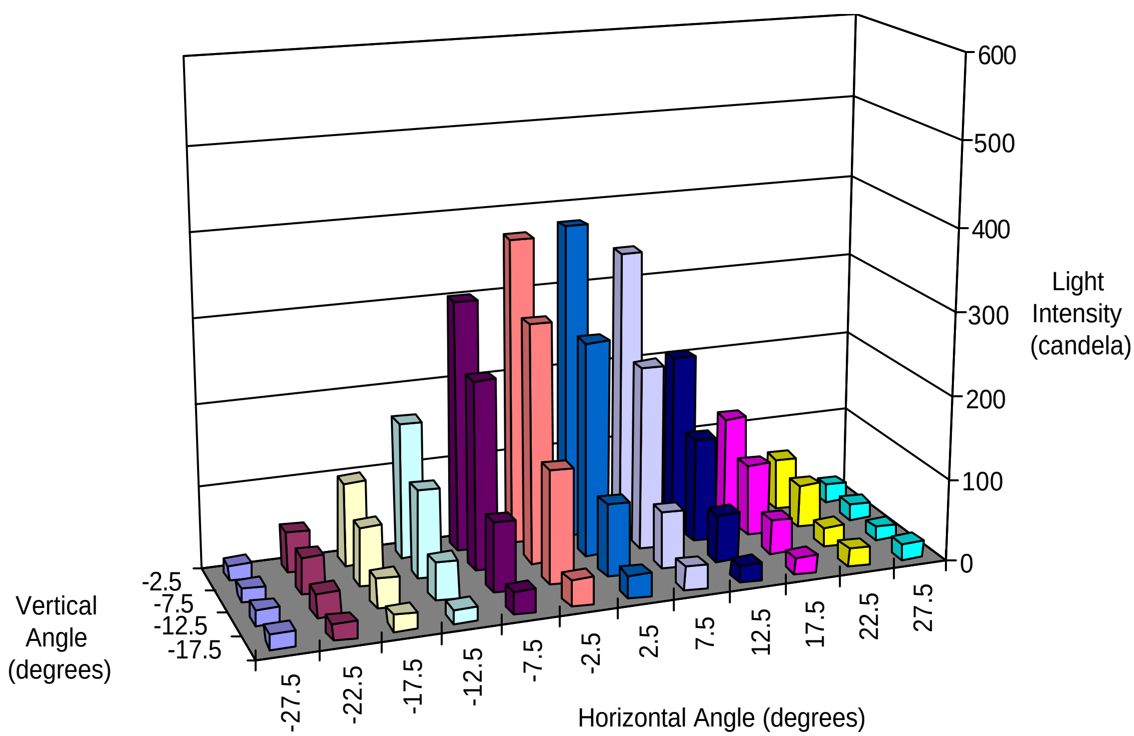

Figure A6.2.2b Output from WPS #6 (Red) signal, 9.0 volts, all elements on, ITE test.

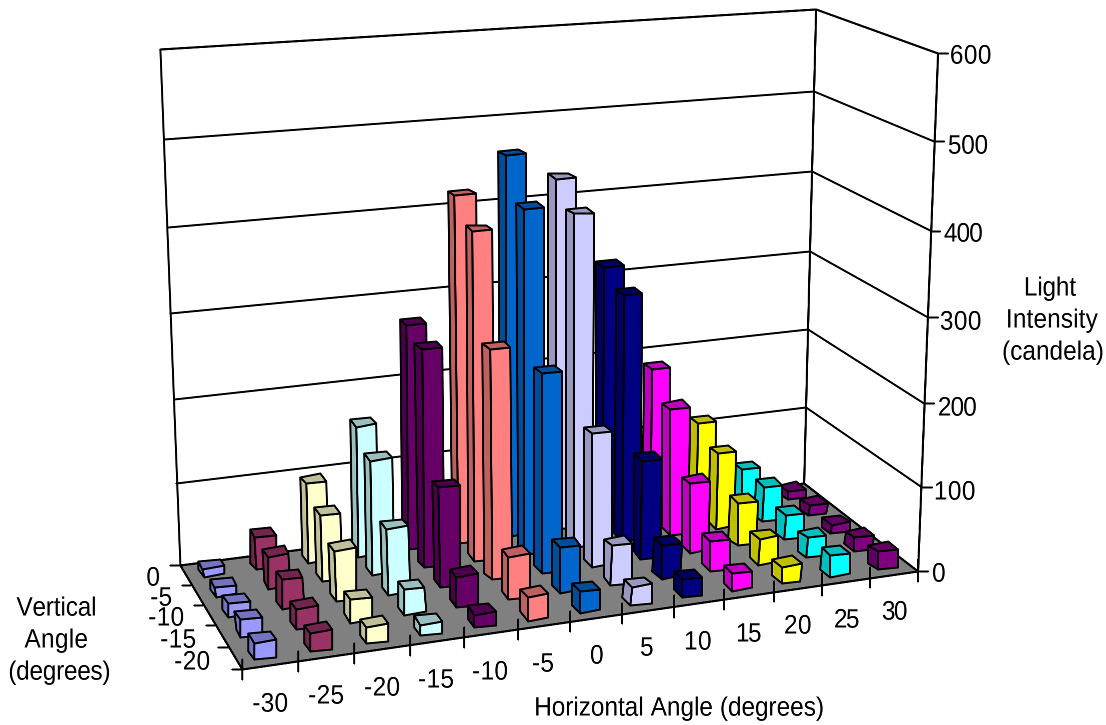

Figure A6.2.3a Output from WPS #6 (Red) signal, 10.0 volts, all elements on, TC test.

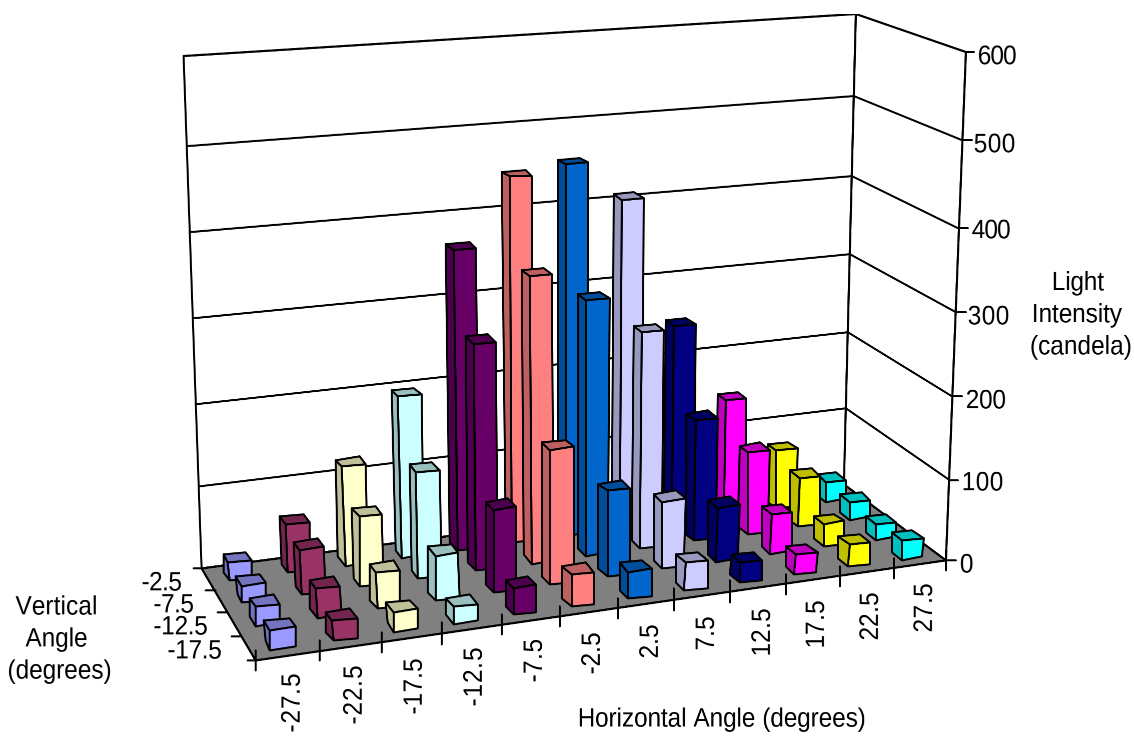

Figure A6.2.3b Output from WPS #6 (Red) signal, 10.0 volts, all elements on, ITE test.

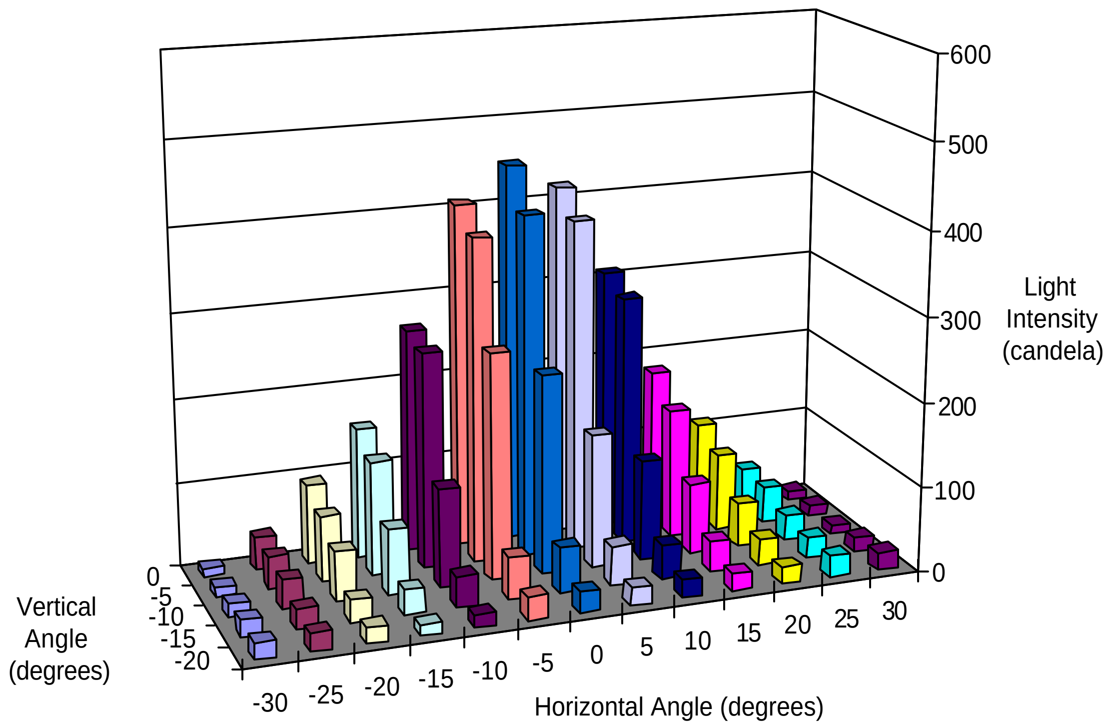

Figure A6.2.4a Output from WPS #6 (Red) signal, 10.5 volts, all elements on, TC test.

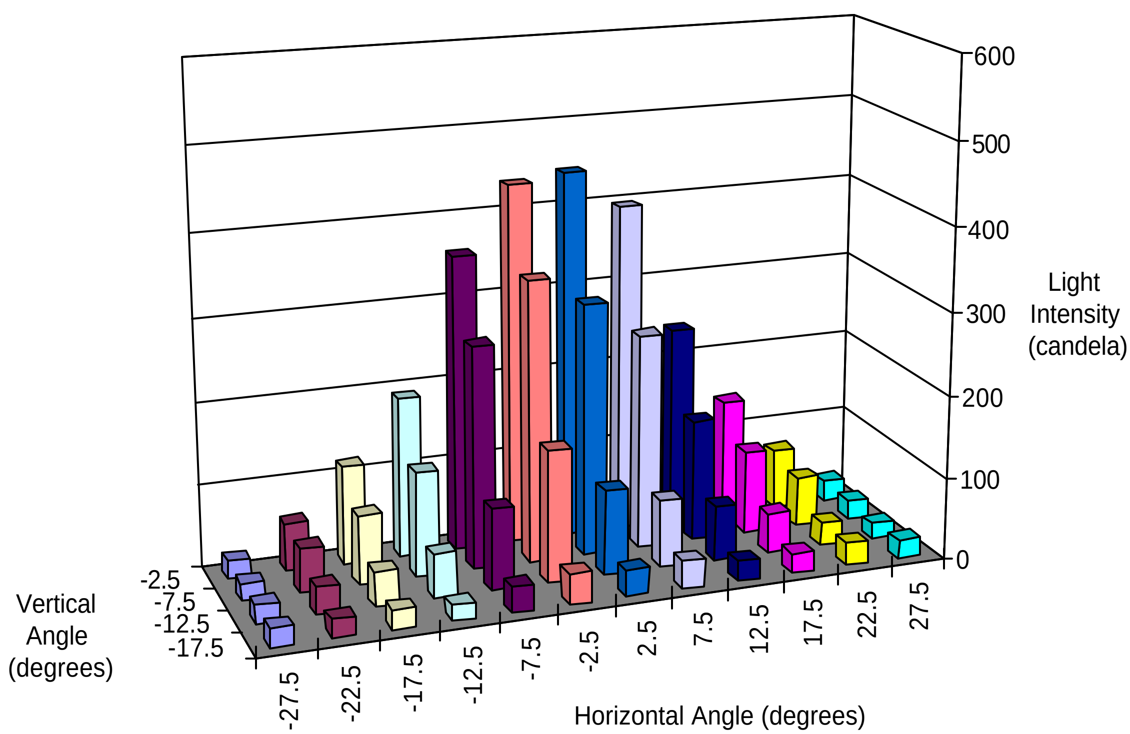

Figure A6.2.4b Output from WPS #6 (Red) signal, 10.5 volts, all elements on, ITE test.

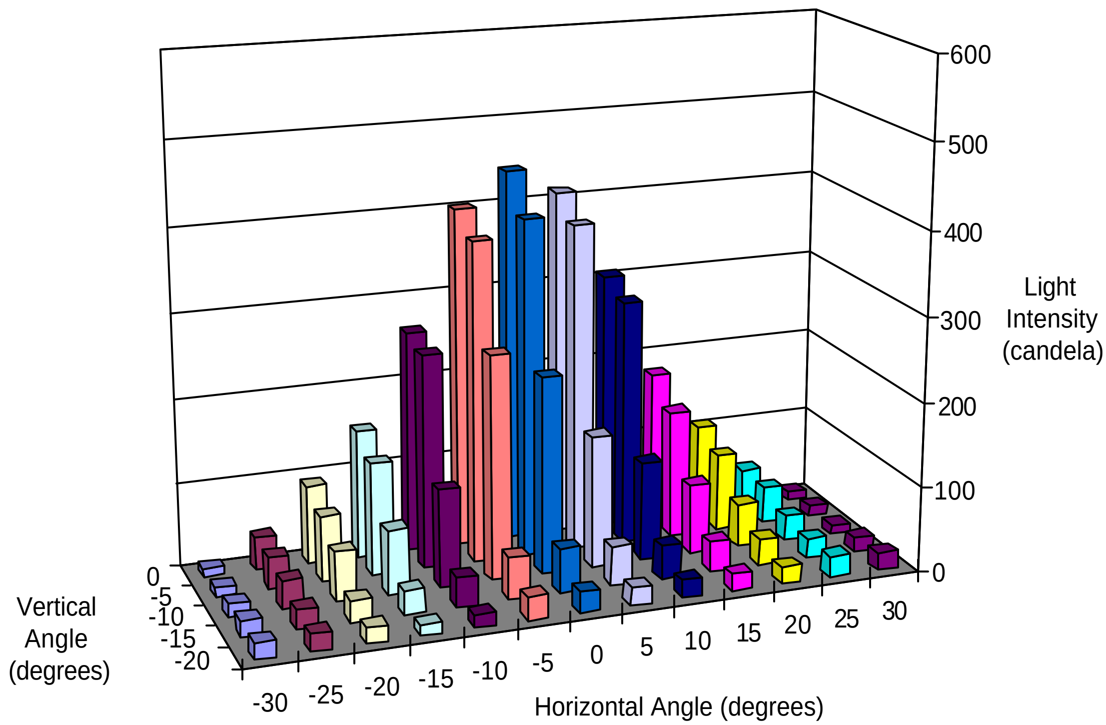

Figure A6.2.5a Output from WPS #6 (Red) signal, 12.0 volts, all elements on, TC test.

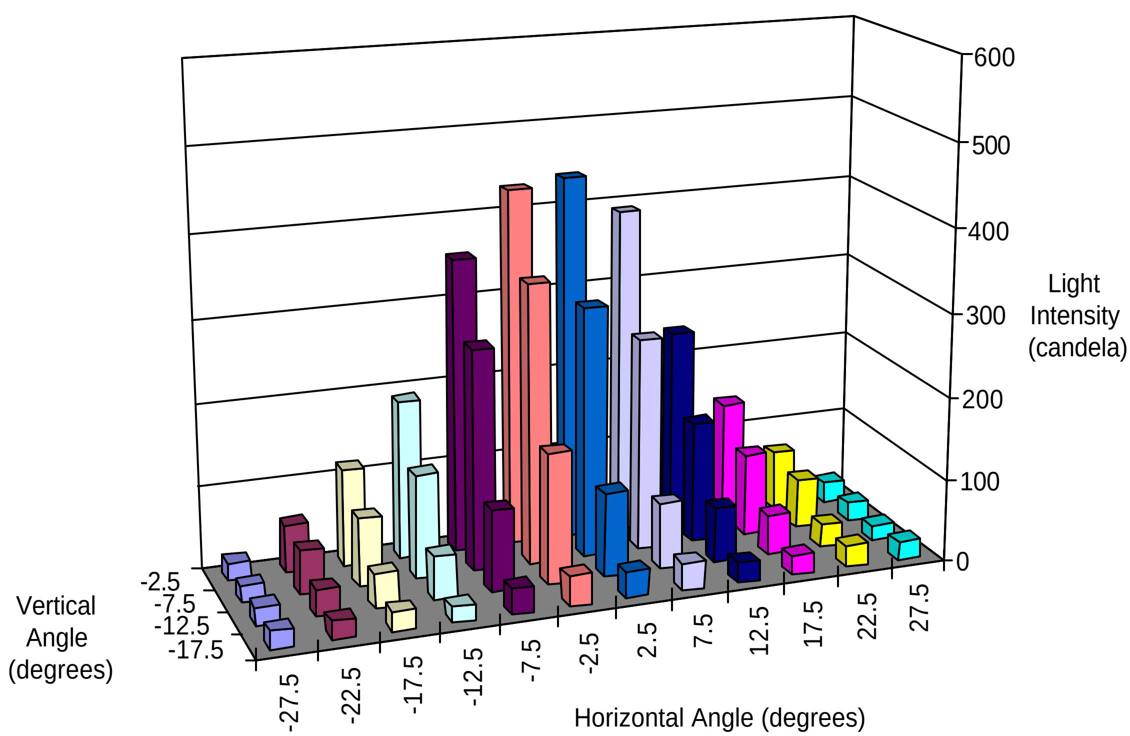

Figure A6.2.5b Output from WPS #6 (Red) signal, 12.0 volts, all elements on, ITE test.

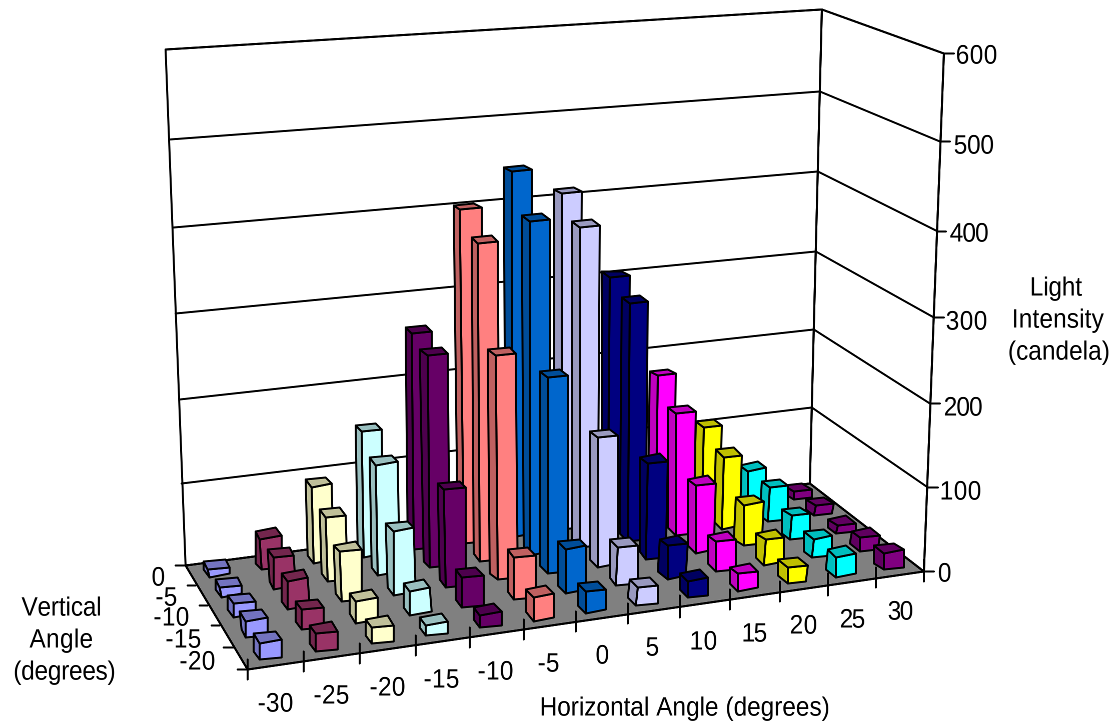

Figure A6.2.6a Output from WPS #6 (Red) signal, 13.5 volts, all elements on, TC test.

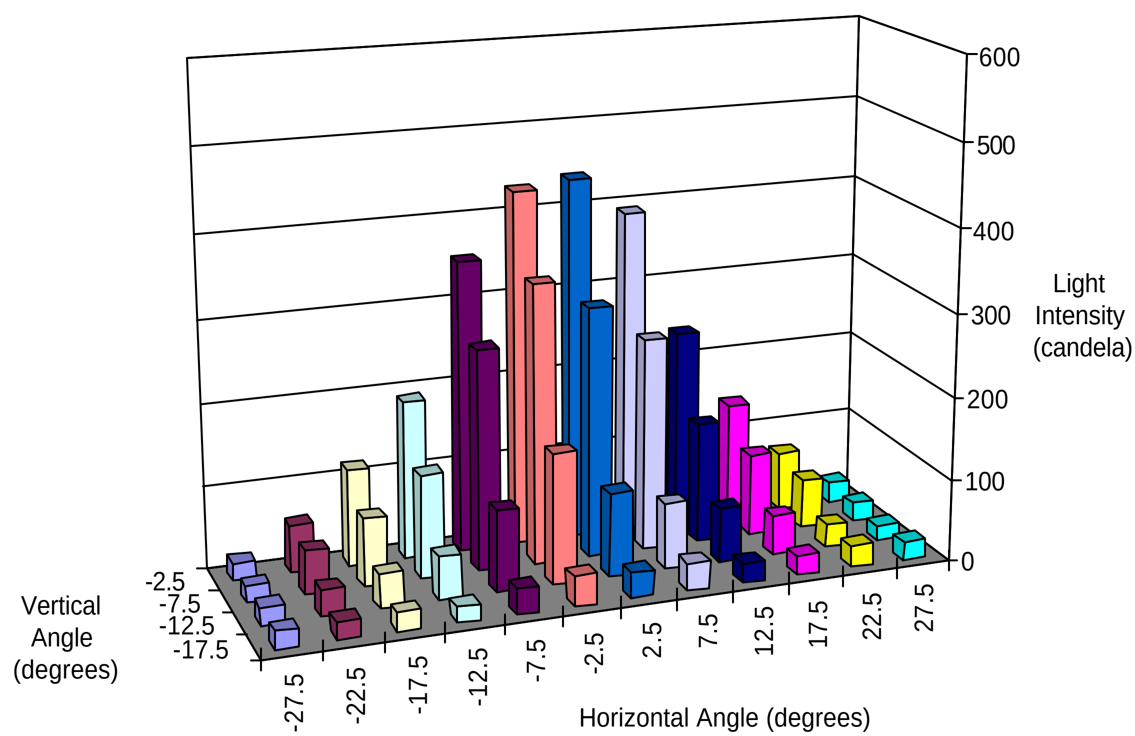

Figure A6.2.6b Output from WPS #6 (Red) signal, 13.5 volts, all elements on, ITE test.

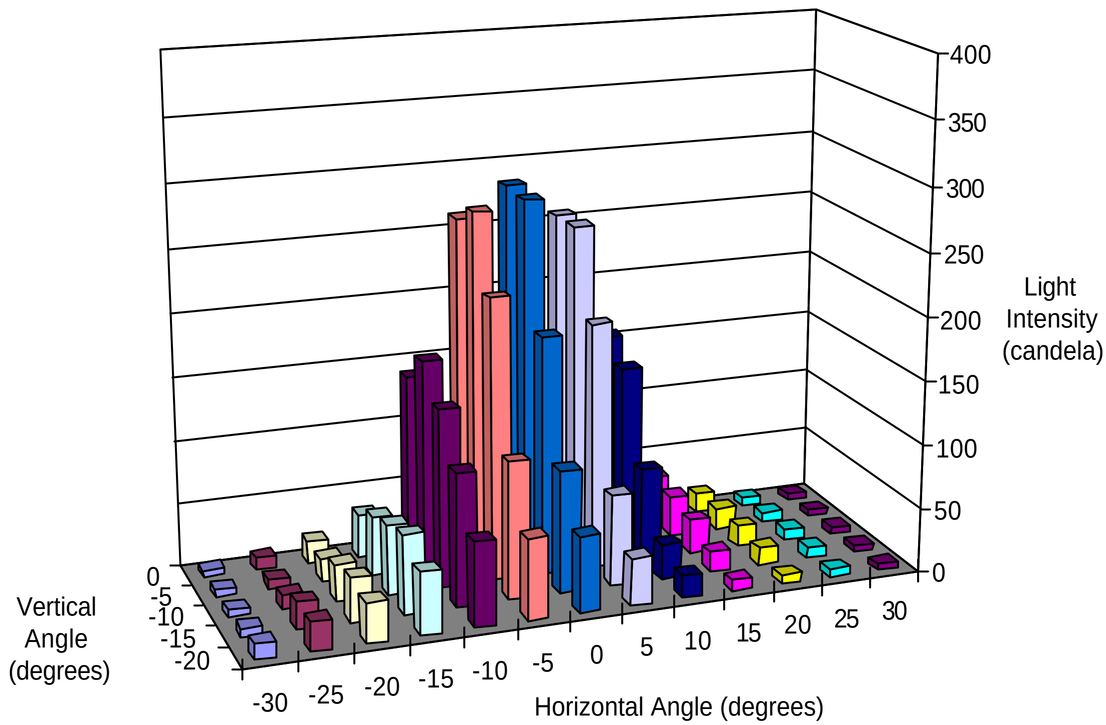

Figure A6.3.1a Output from WPS #6 (Red) signal, 7.5 volts, all elements on, TC test.

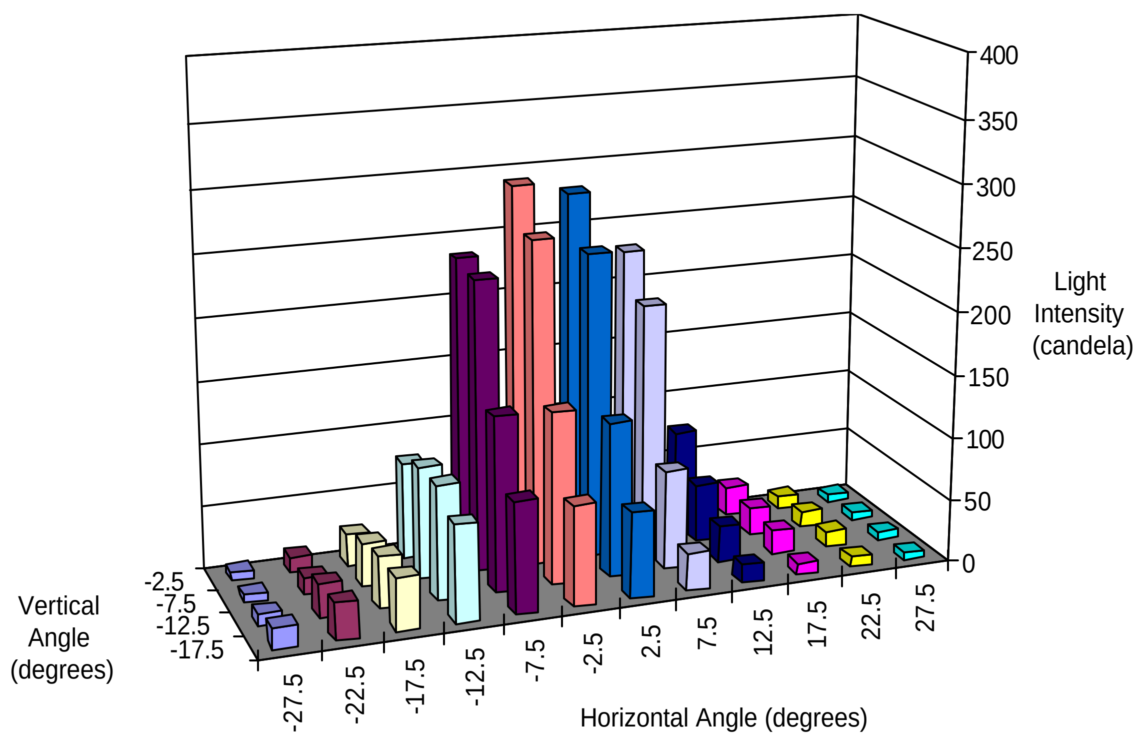

Figure A6.3.1b Output from WPS #6 (Red) signal, 7.5 volts, all elements on, ITE test.

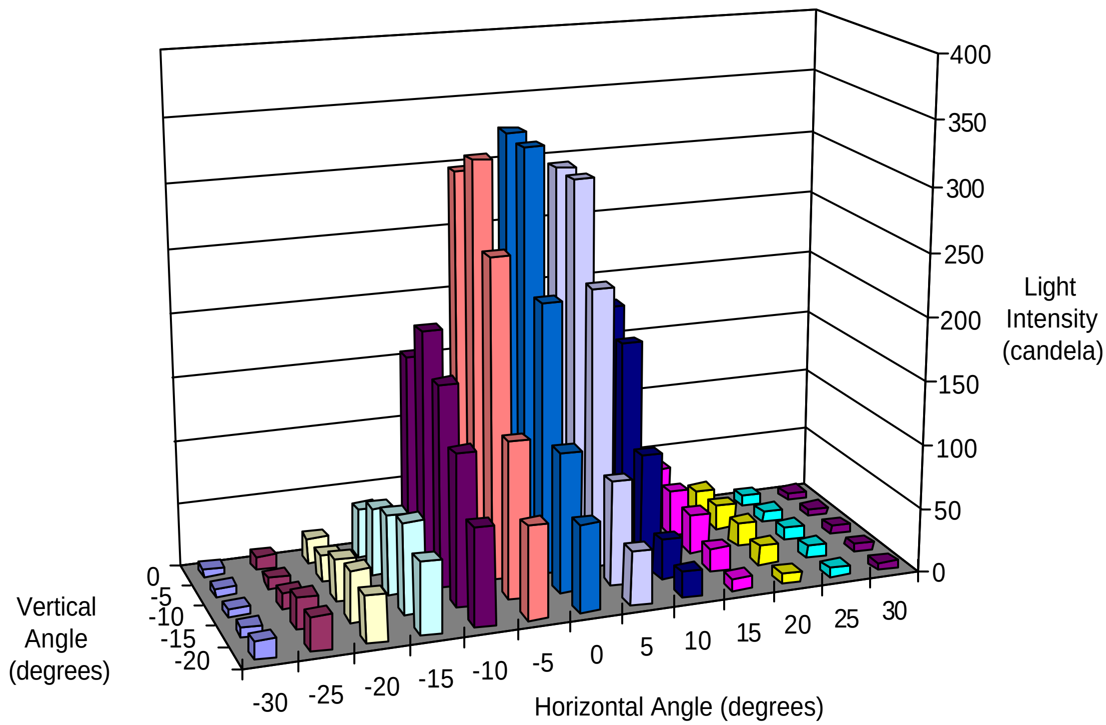

Figure A6.3.2a Output from WPS #6 (Red) signal, 9.0 volts, all elements on, TC test.

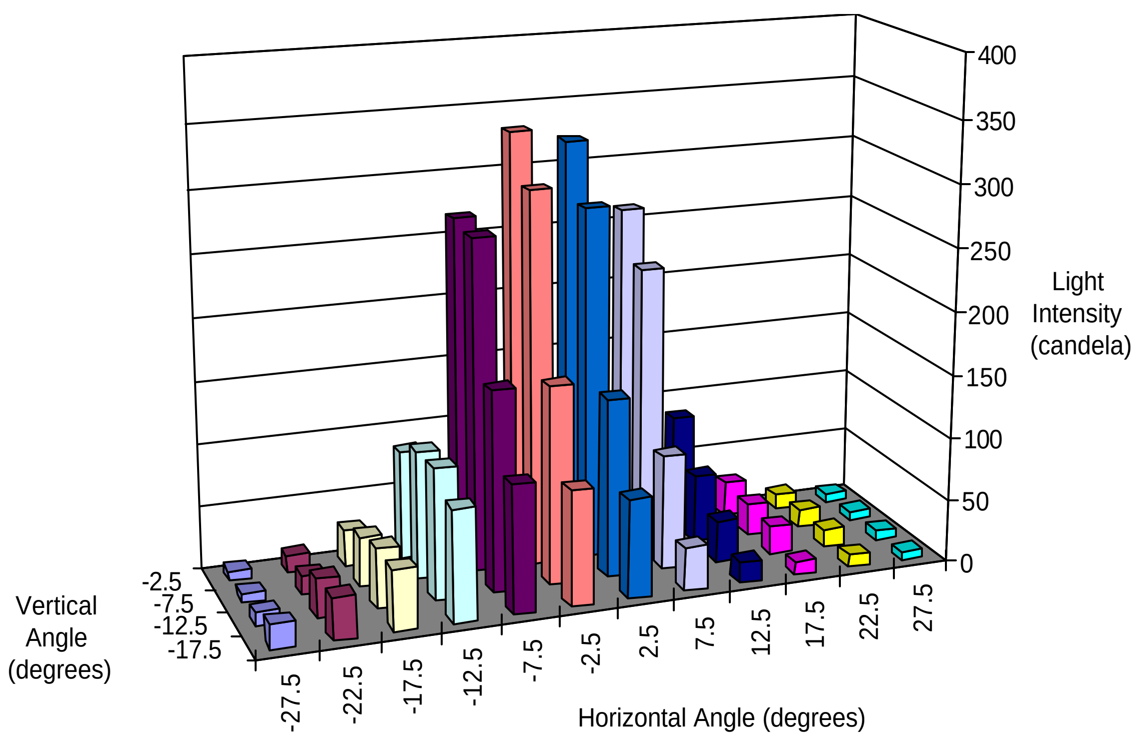

Figure A6.3.2b Output from WPS #6 (Red) signal, 9.0 volts, all elements on, ITE test.

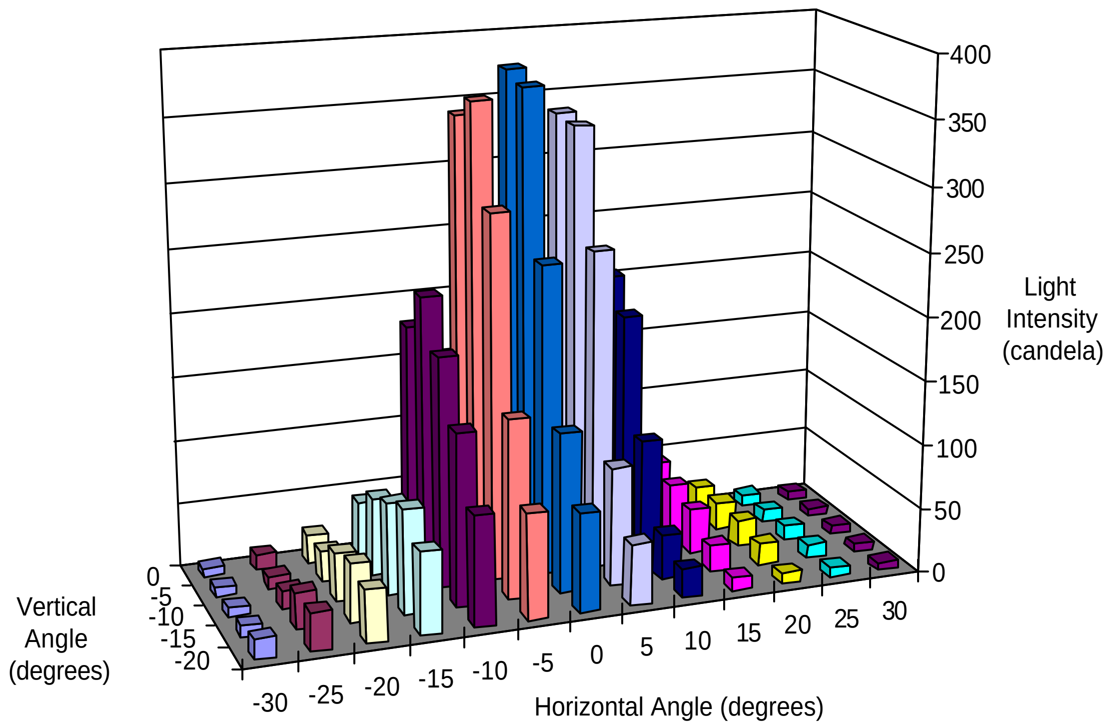

Figure A6.3.3a Output from WPS #6 (Red) signal, 10.0 volts, all elements on, TC test.

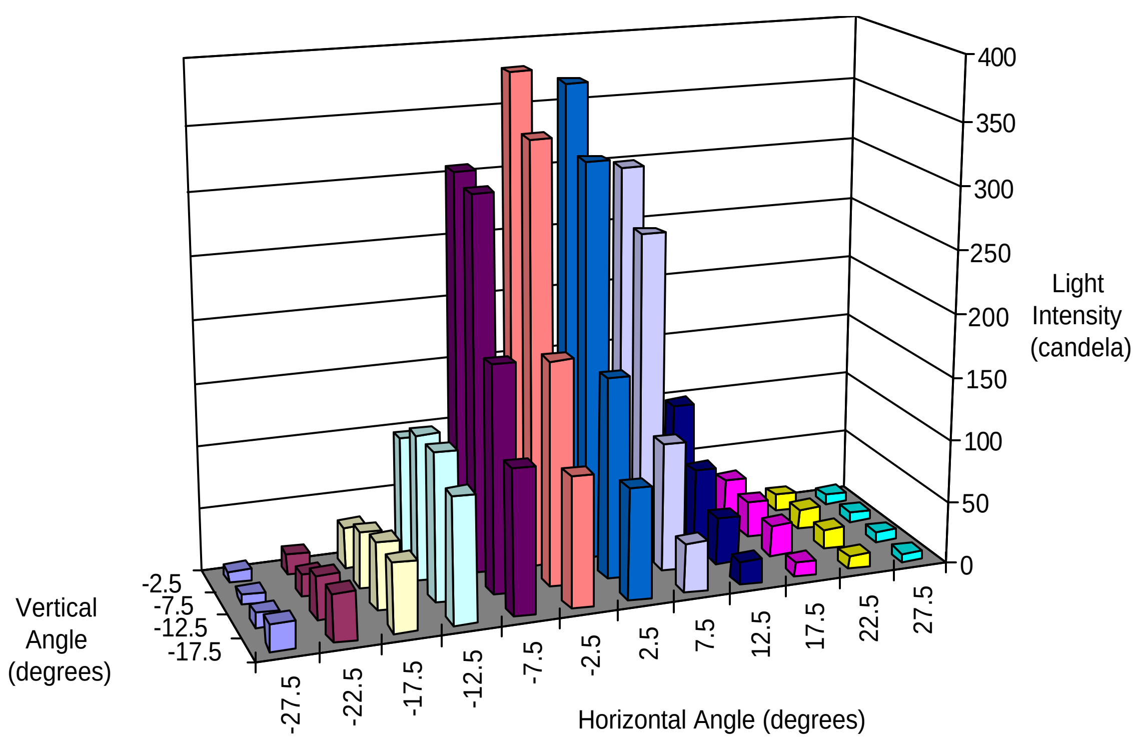

Figure A6.3.3b Output from WPS #6 (Red) signal, 10.0 volts, all elements on, ITE test.

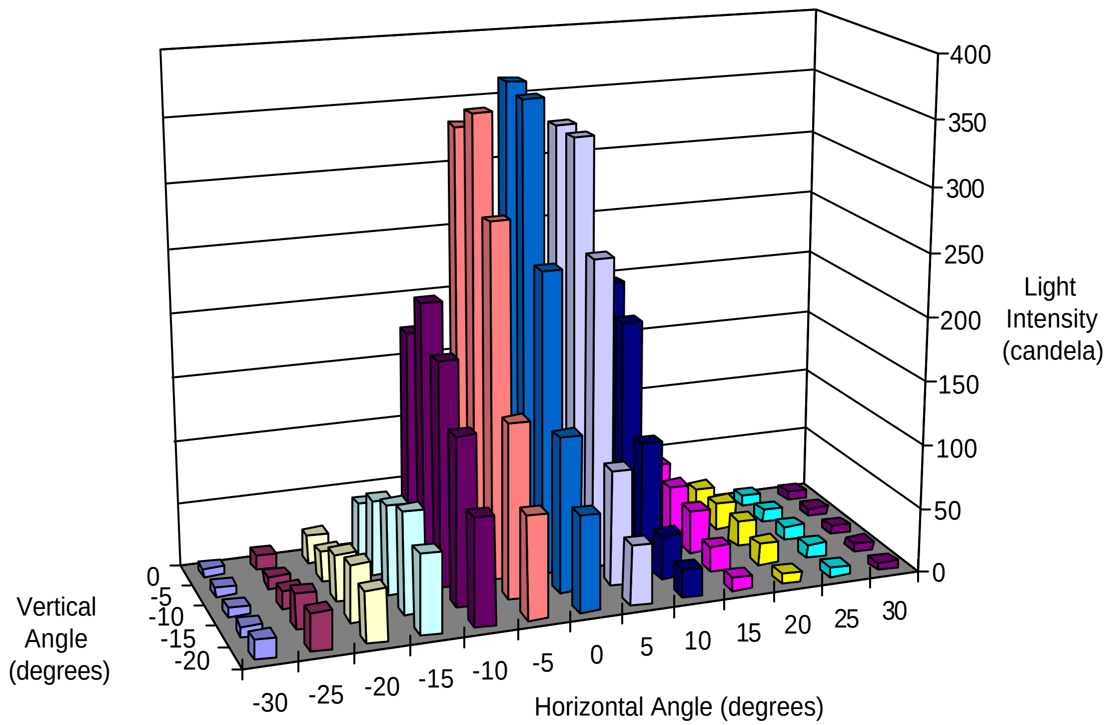

Figure A6.3.4a Output from WPS #6 (Red) signal, 10.5 volts, all elements on, TC test.

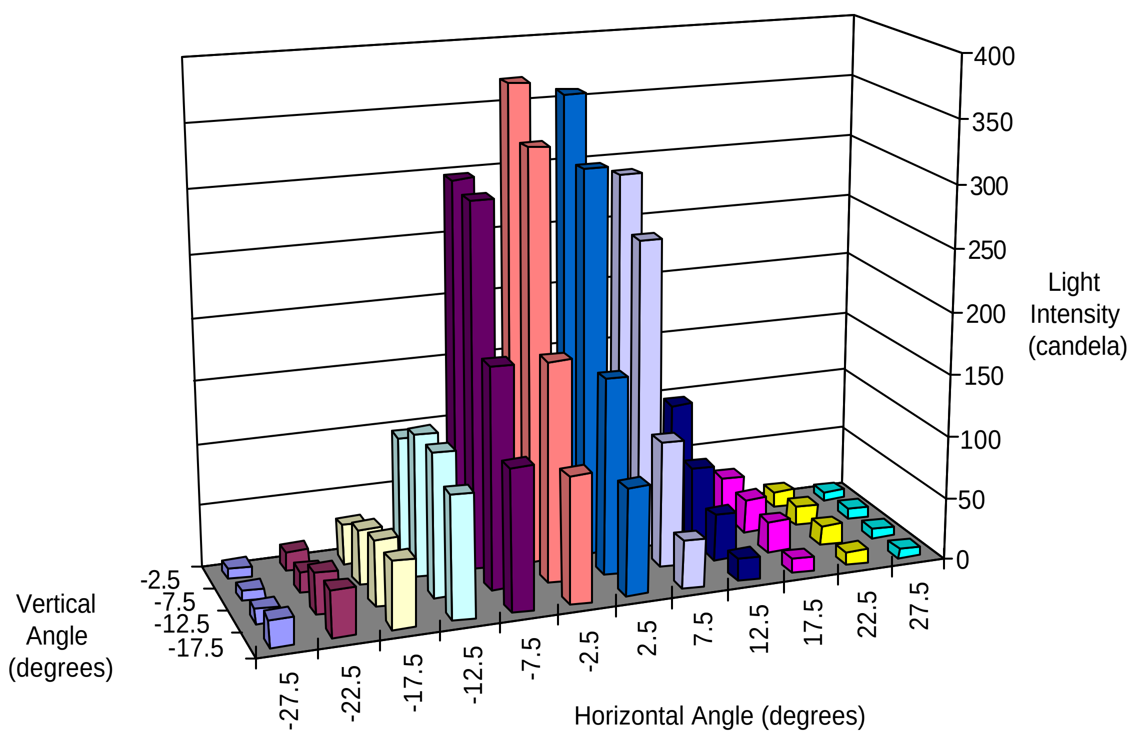

Figure A6.3.4b Output from WPS #6 (Red) signal, 10.5 volts, all elements on, ITE test.

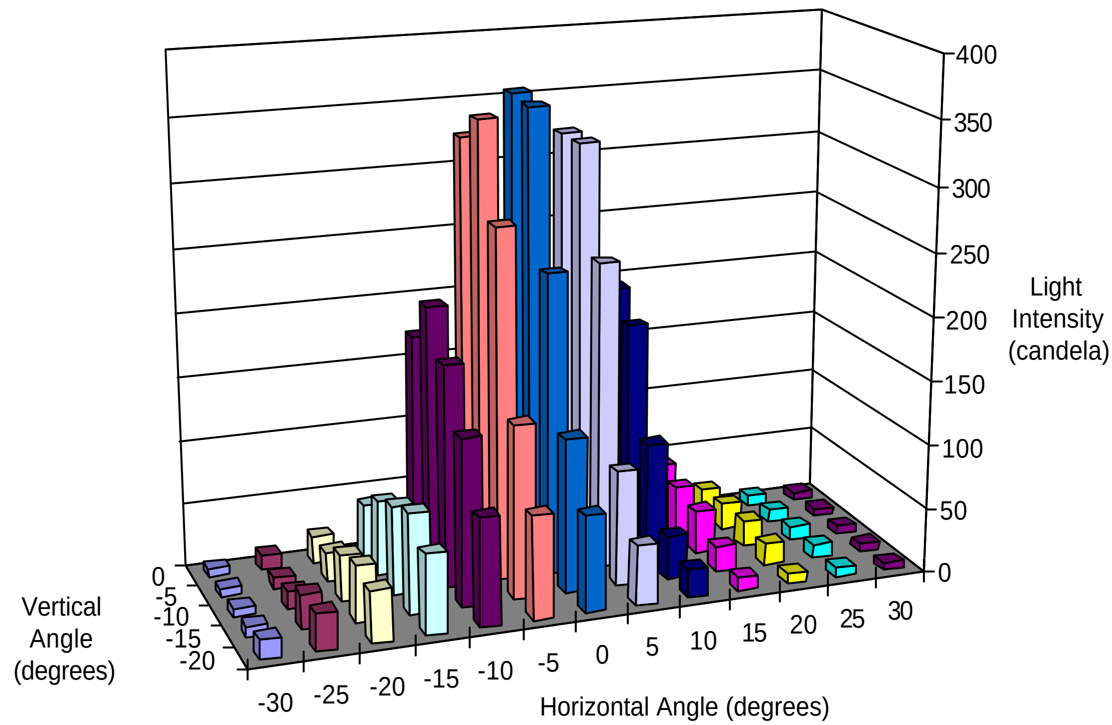

Figure A6.3.5a Output from WPS #6 (Red) signal, 12.0 volts, all elements on, TC test.

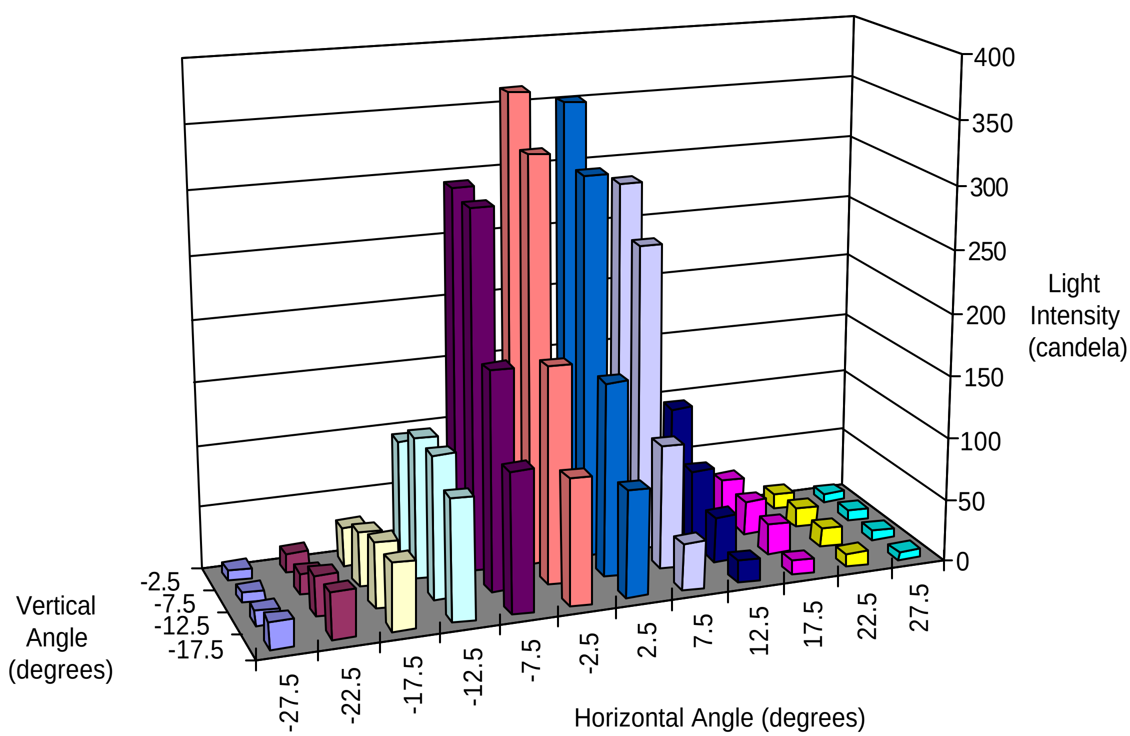

Figure A6.3.5b Output from WPS #6 (Red) signal, 12.0 volts, all elements on, ITE test.

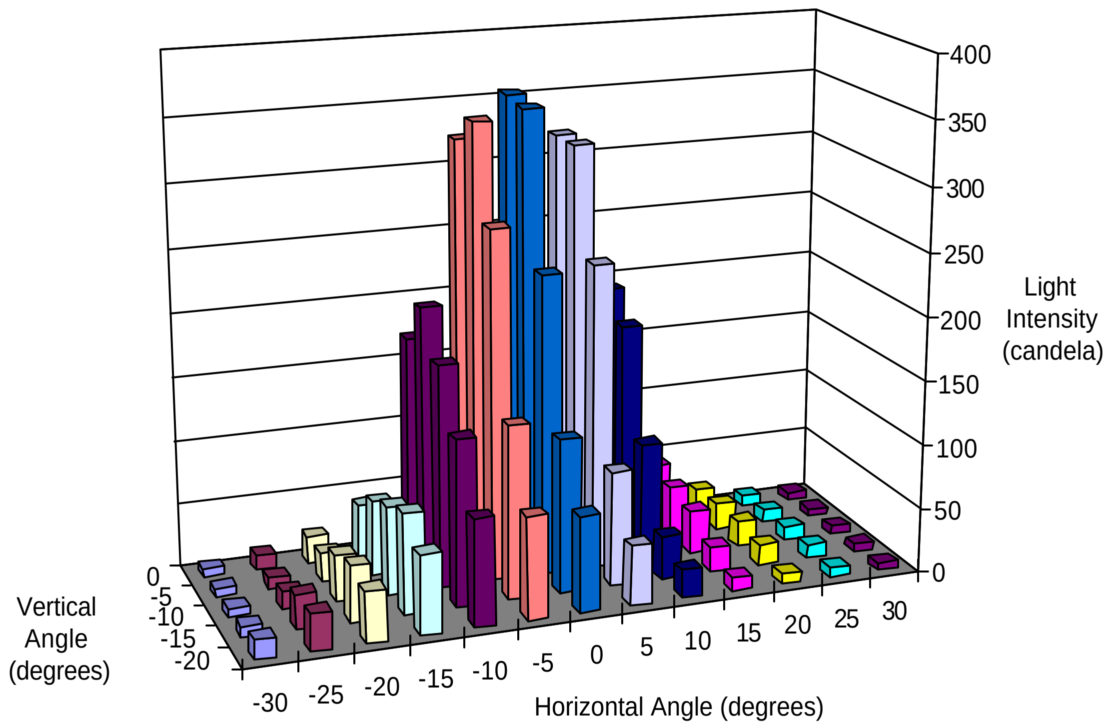

Figure A6.3.6a Output from WPS #6 (Red) signal, 13.5 volts, all elements on, TC test.

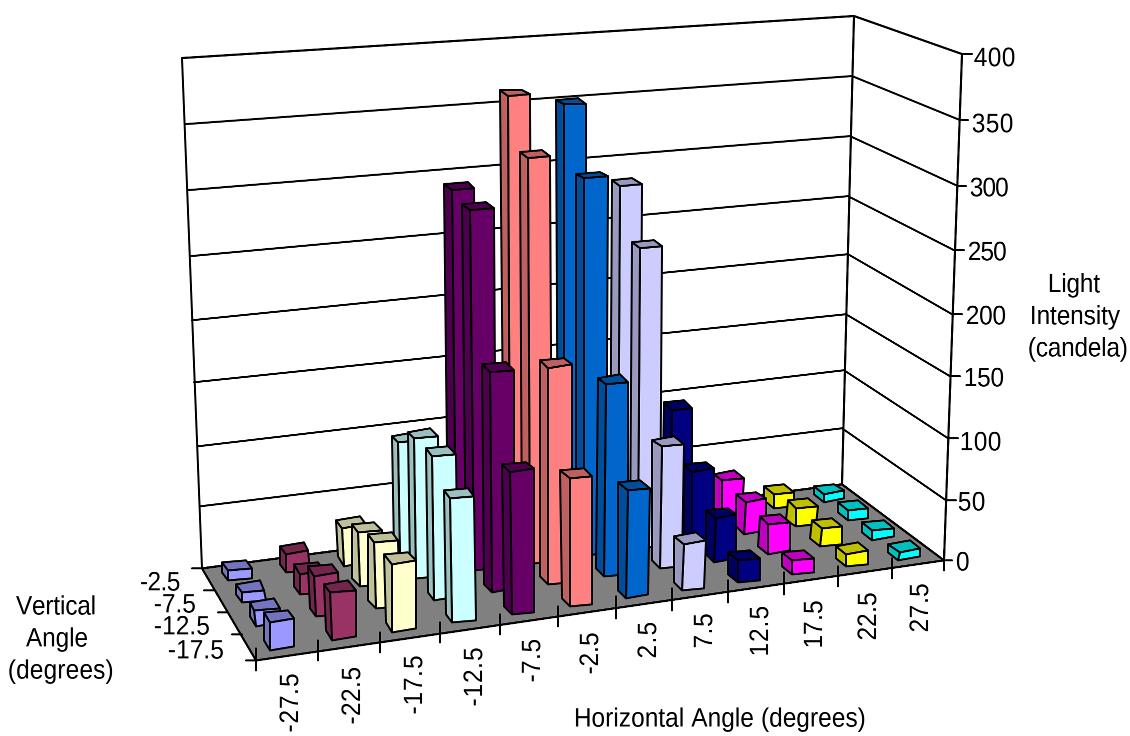

Figure A6.3.6b Output from WPS #6 (Red) signal, 13.5 volts, all elements on, ITE test.

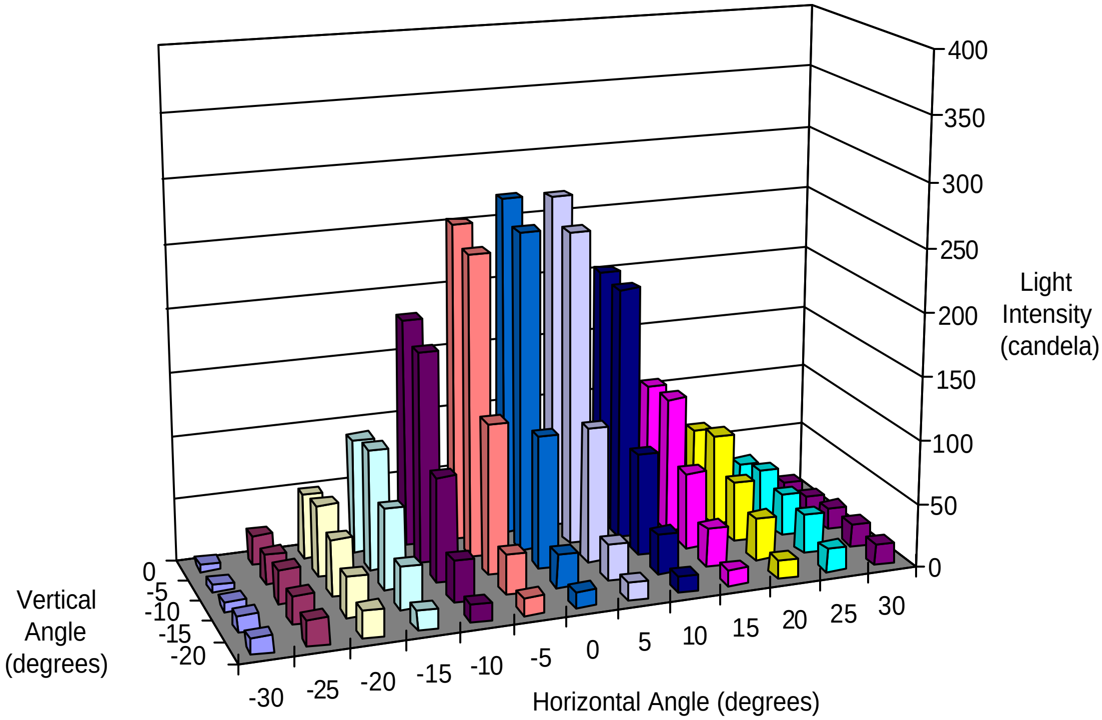

Figure A6.4.1a Output from WPS #6 (Red) signal, 7.5 volts, all elements on, TC test.

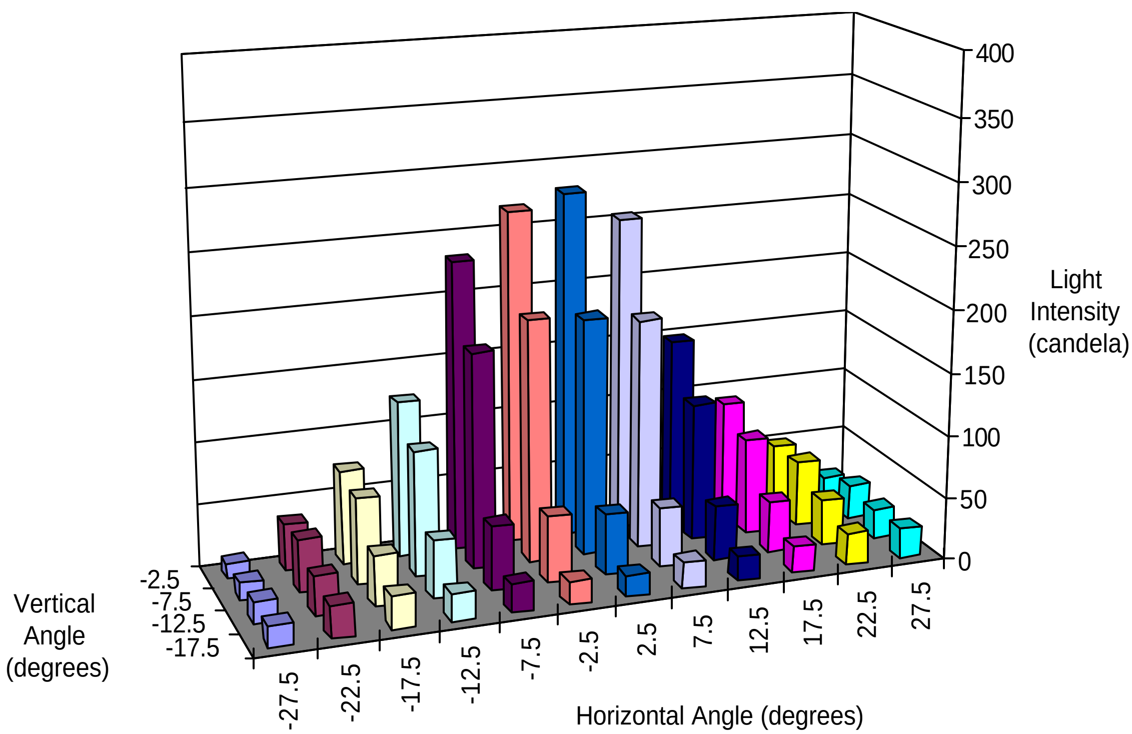

Figure A6.4.1b Output from WPS #6 (Red) signal, 7.5 volts, all elements on, ITE test.

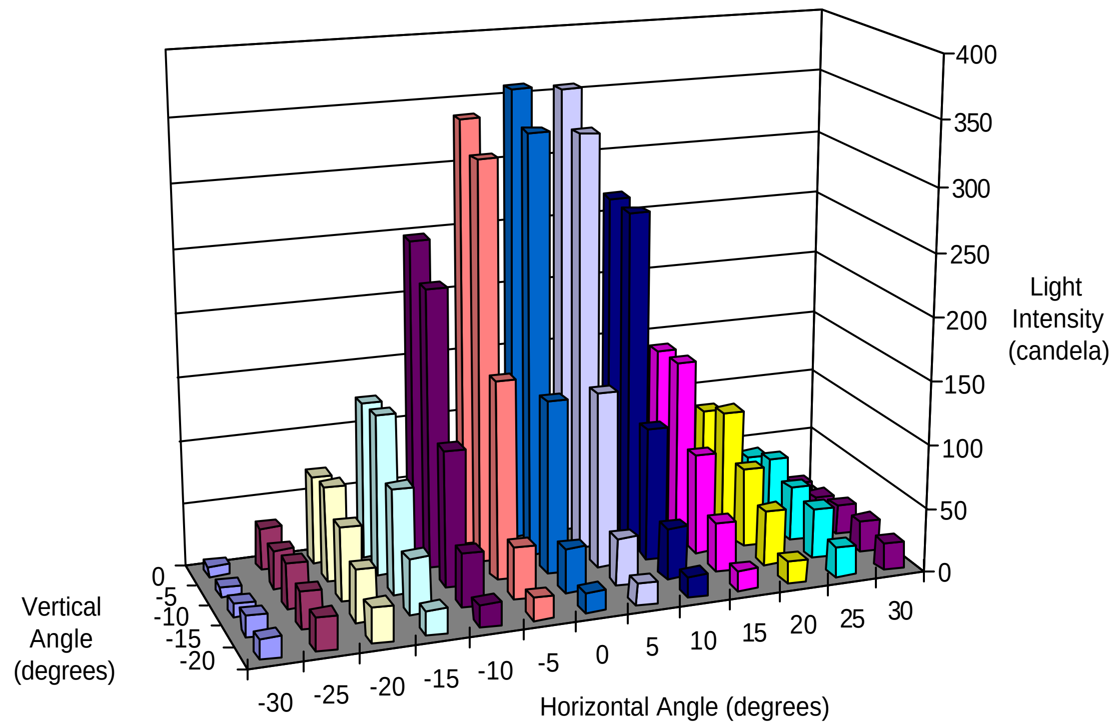

Figure A6.4.2a Output from WPS #6 (Red) signal, 9.0 volts, all elements on, TC test.

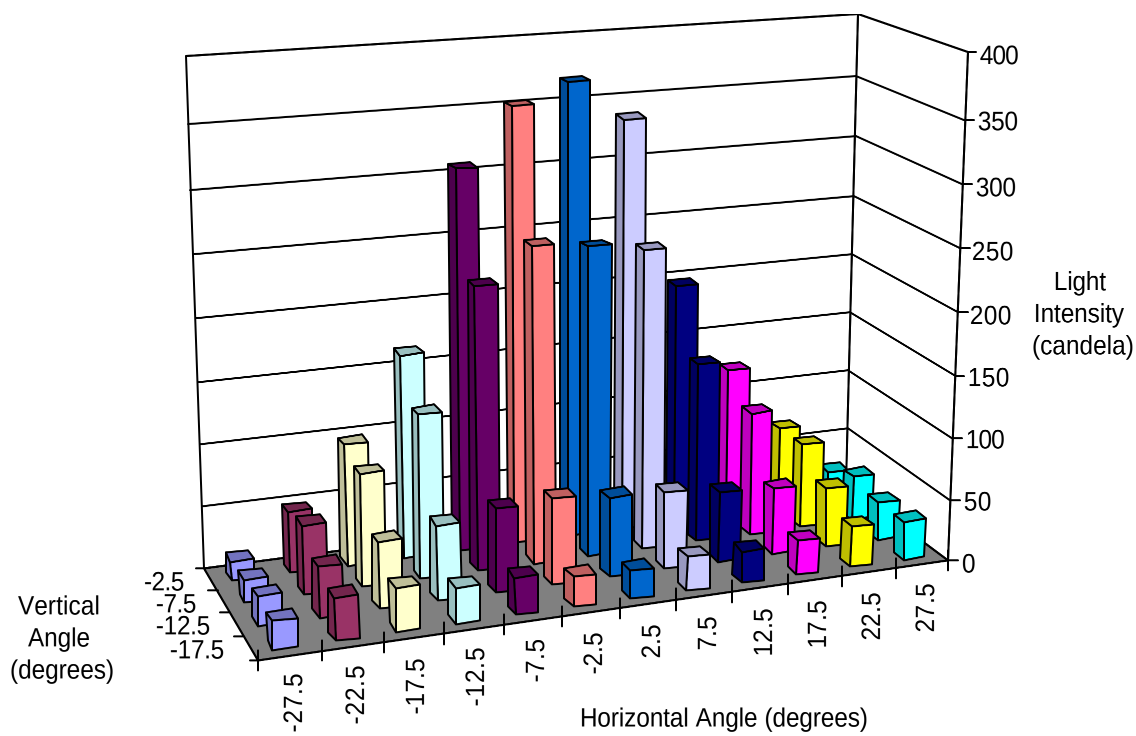

Figure A6.4.2b Output from WPS #6 (Red) signal, 9.0 volts, all elements on, ITE test.

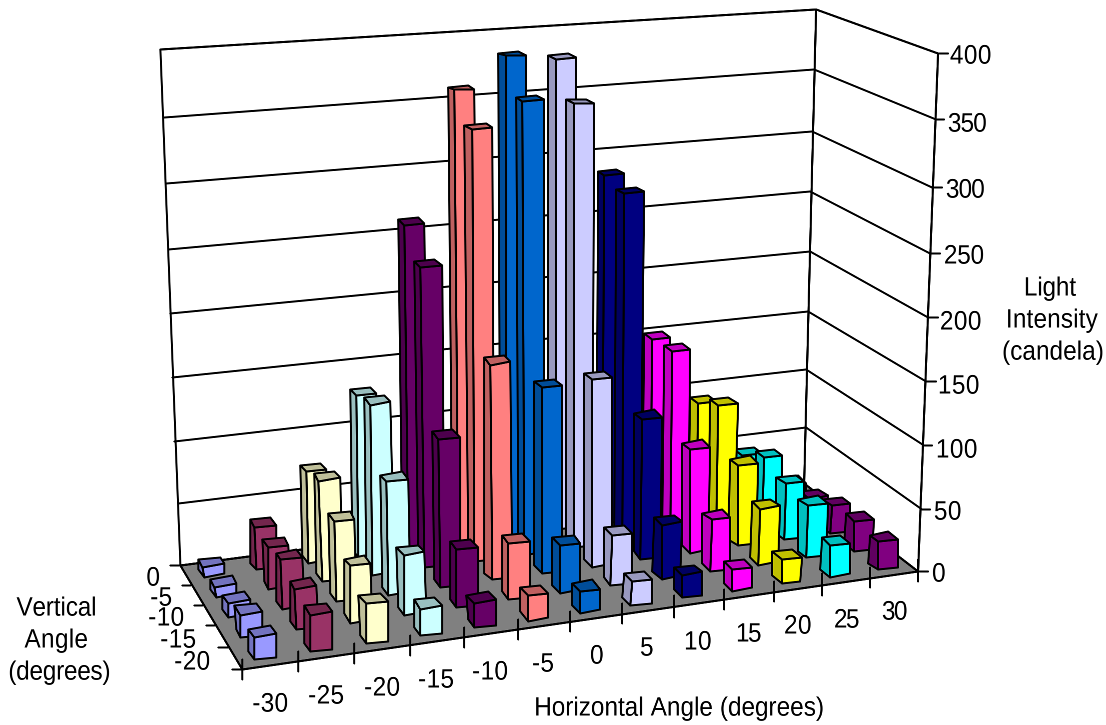

Figure A6.4.3a Output from WPS #6 (Red) signal, 10.0 volts, all elements on, TC test.

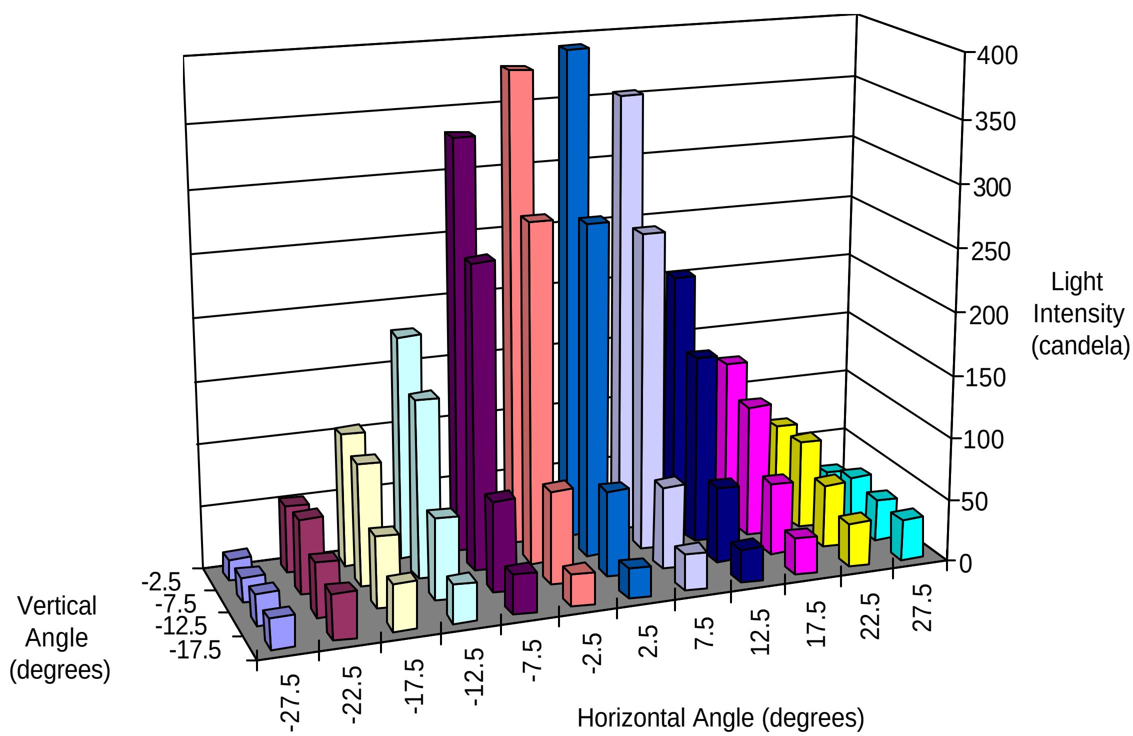

Figure A6.4.3b Output from WPS #6 (Red) signal, 10.0 volts, all elements on, ITE test.

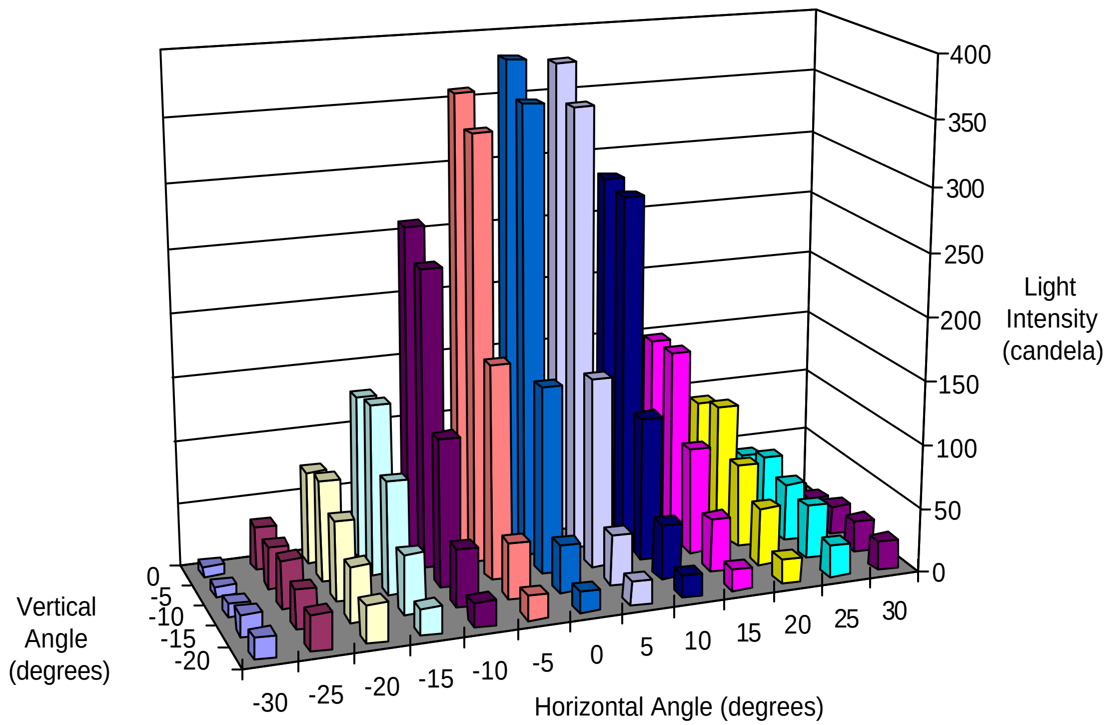

Figure A6.4.4a Output from WPS #6 (Red) signal, 10.5 volts, all elements on, TC test.

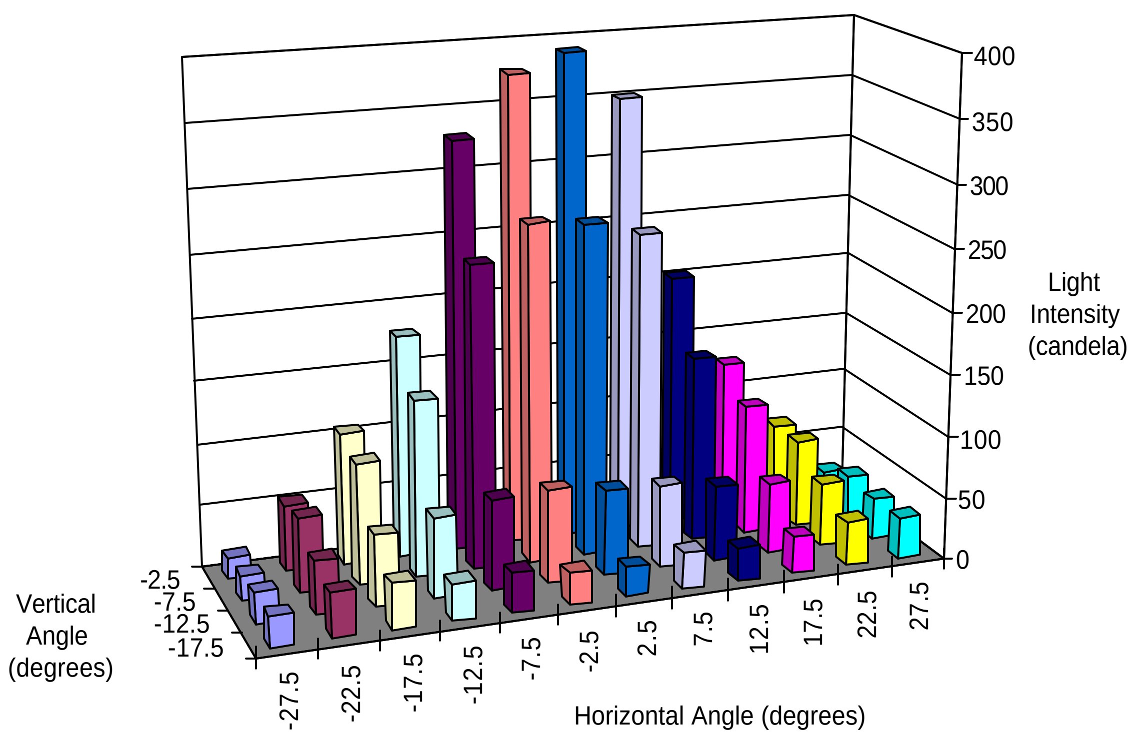

Figure A6.4.4b Output from WPS #6 (Red) signal, 10.5 volts, all elements on, ITE test.

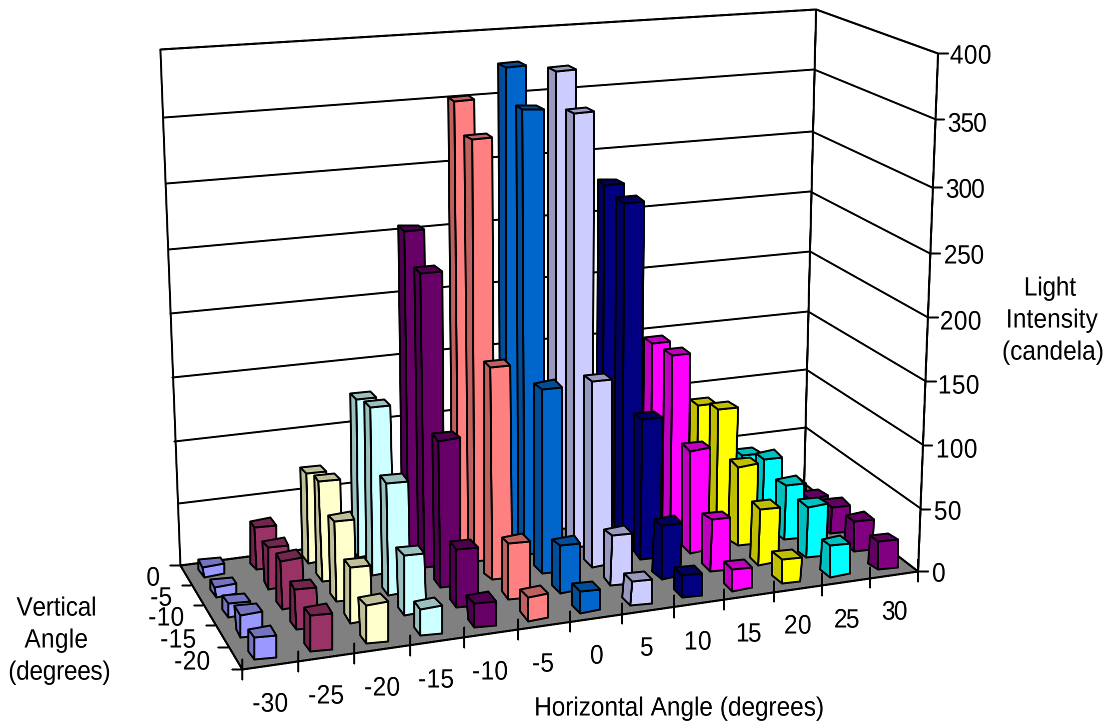

Figure A6.4.5a Output from WPS #6 (Red) signal, 12.0 volts, all elements on, TC test.

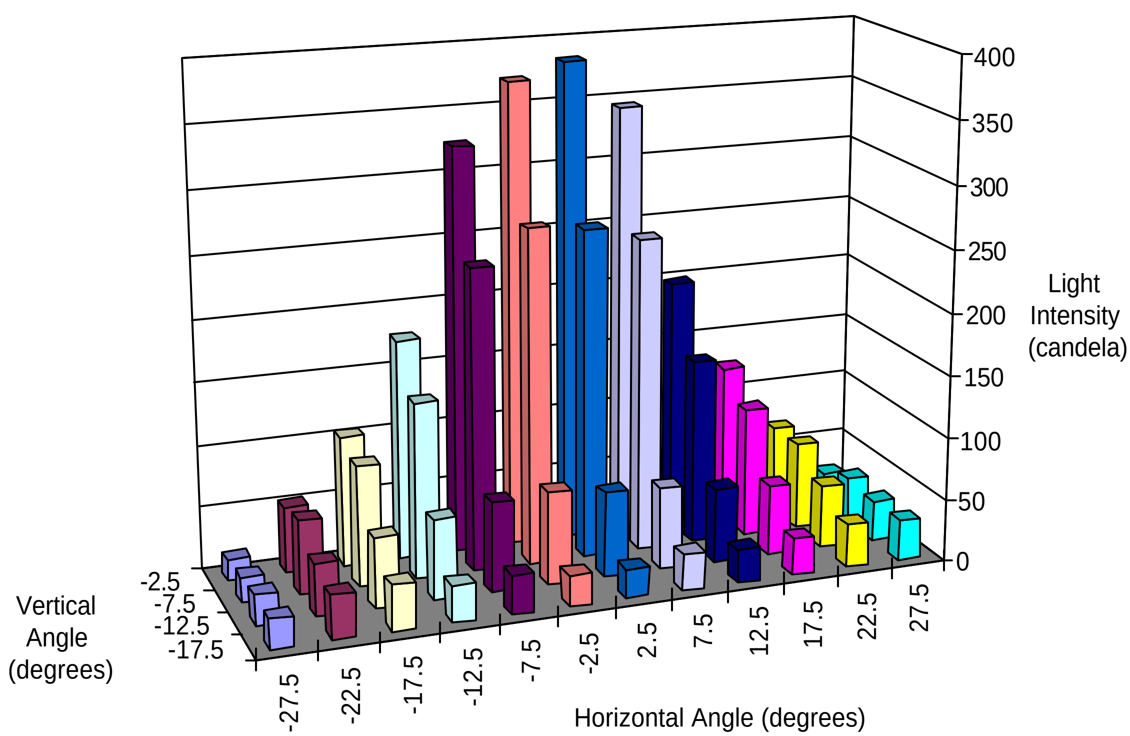

Figure A6.4.5b Output from WPS #6 (Red) signal, 12.0 volts, all elements on, ITE test.

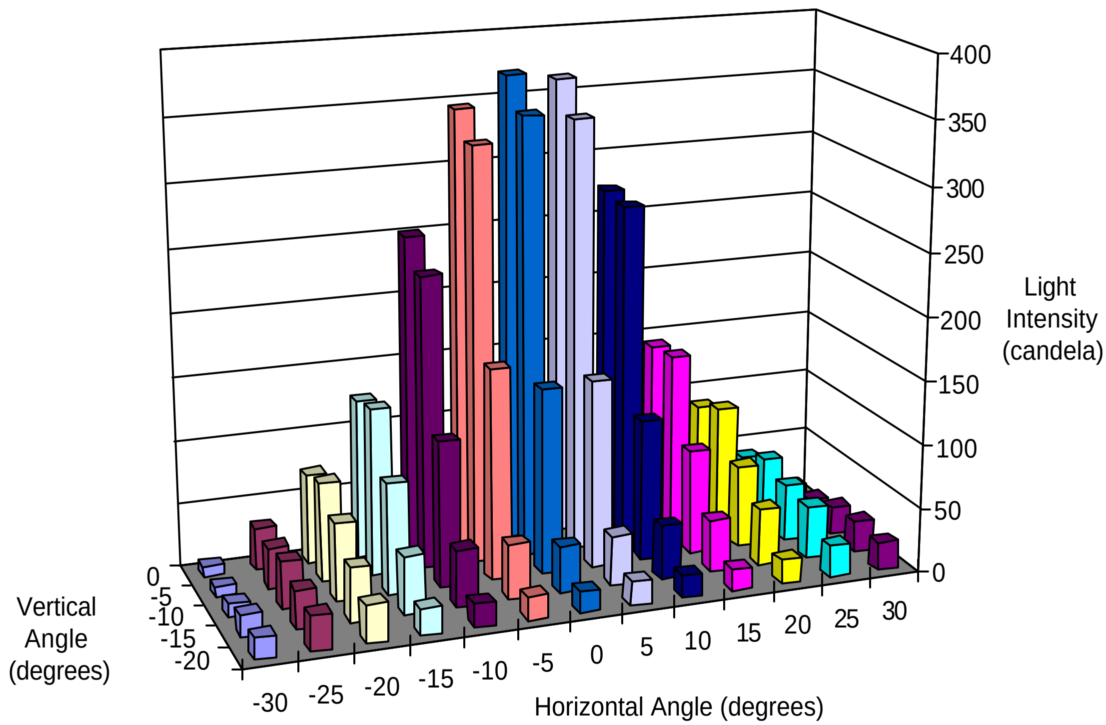

Figure A6.4.6a Output from WPS #6 (Red) signal, 13.5 volts, all elements on, TC test.

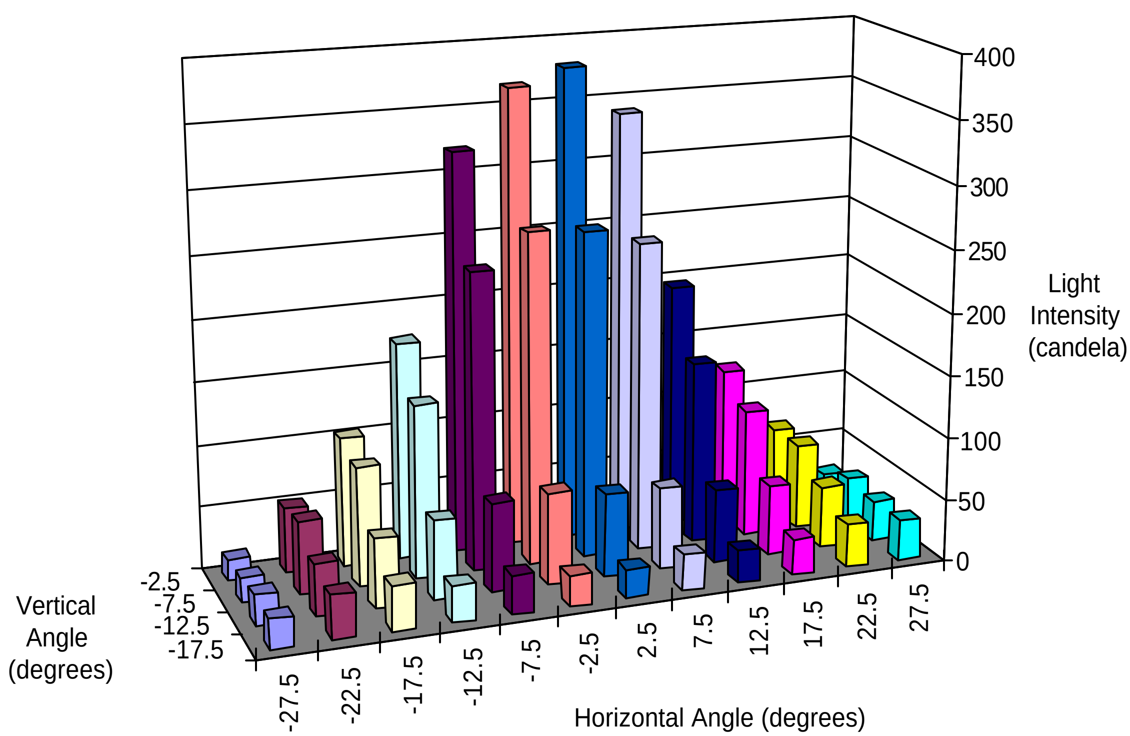

Figure A6.4.6b Output from WPS #6 (Red) signal, 13.5 volts, all elements on, ITE test.

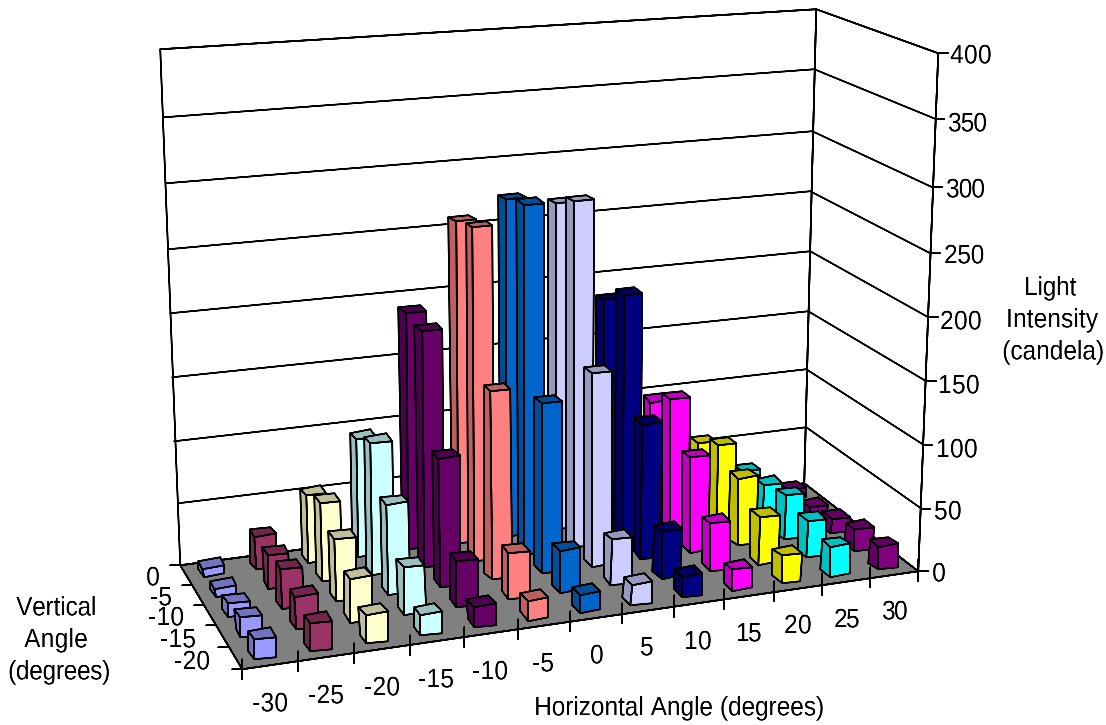

Figure A6.5.1a Output from WPS #6 (Red) signal, 7.5 volts, all elements on, TC test.

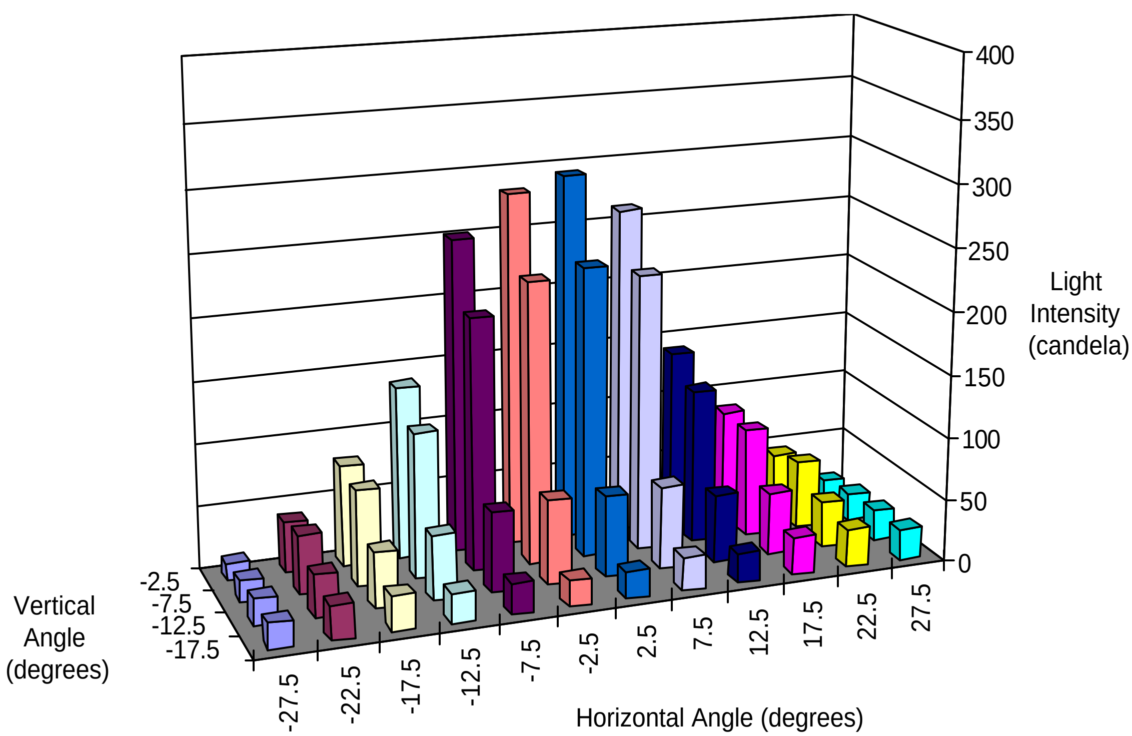

Figure A6.5.1b Output from WPS #6 (Red) signal, 7.5 volts, all elements on, ITE test.

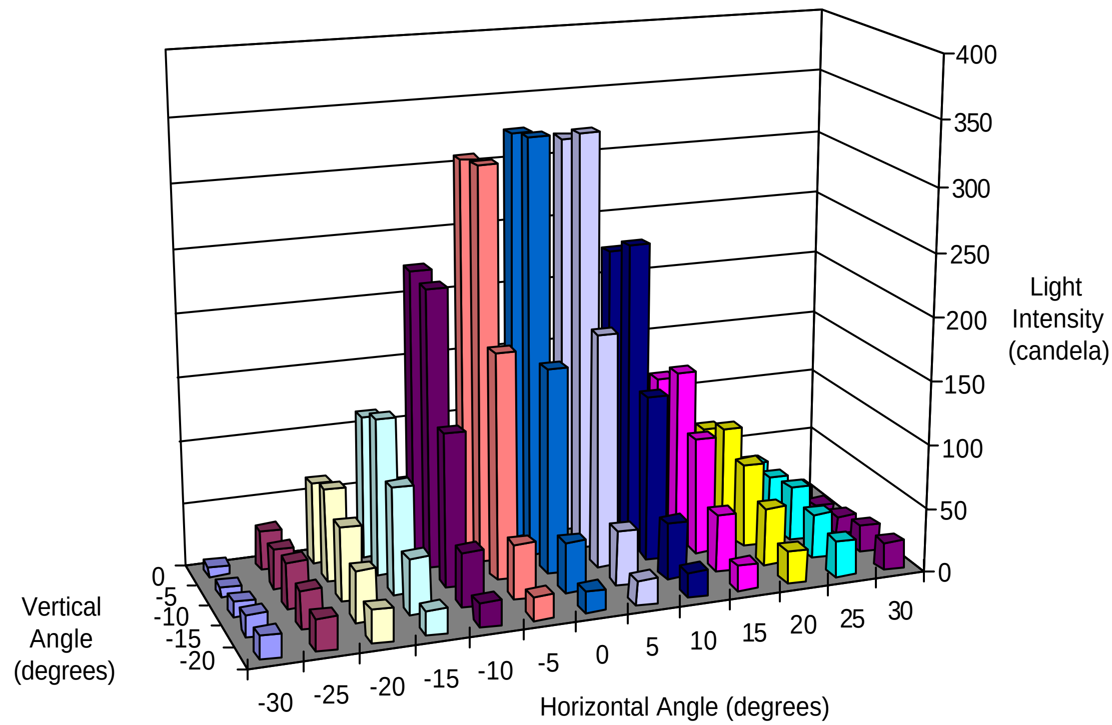

Figure A6.5.2a Output from WPS #6 (Red) signal, 9.0 volts, all elements on, TC test.

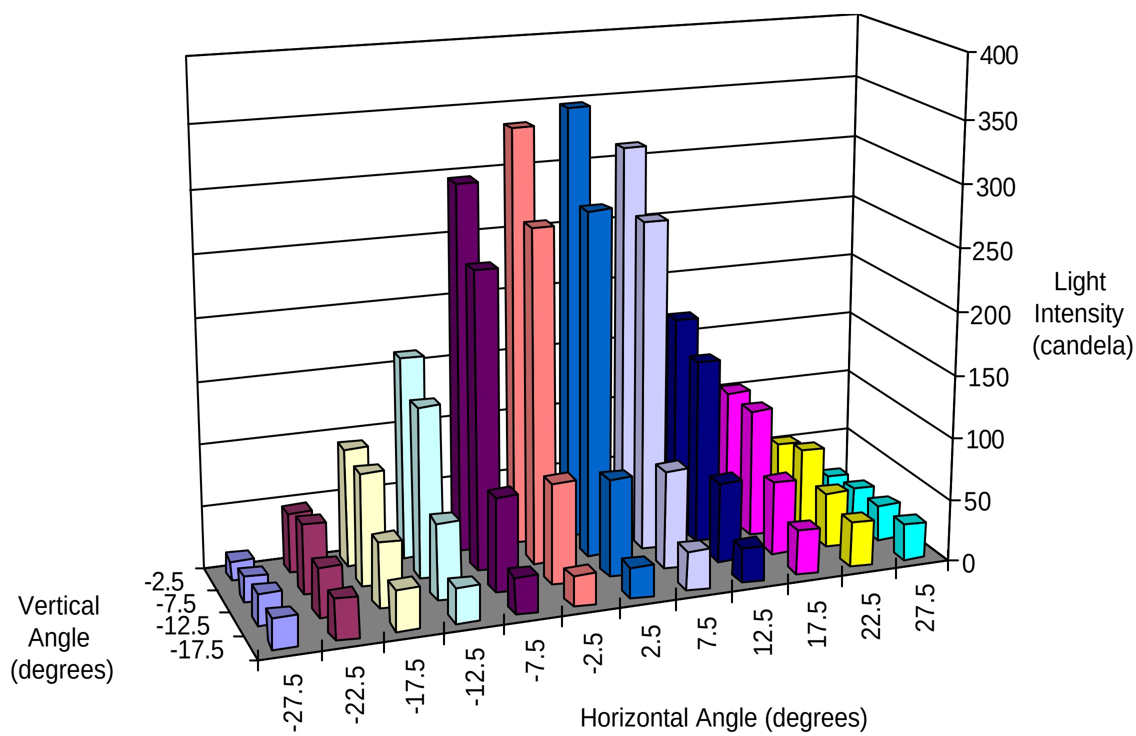

Figure A6.5.2b Output from WPS #6 (Red) signal, 9.0 volts, all elements on, ITE test.

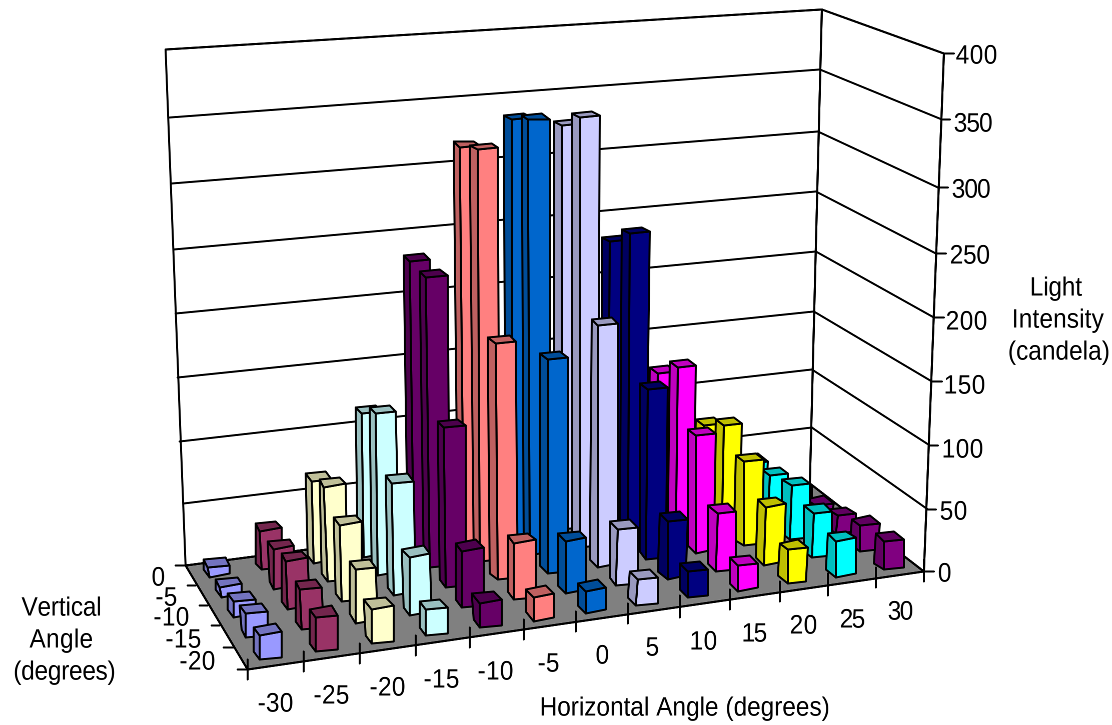

Figure A6.5.3a Output from WPS #6 (Red) signal, 10.0 volts, all elements on, TC test.

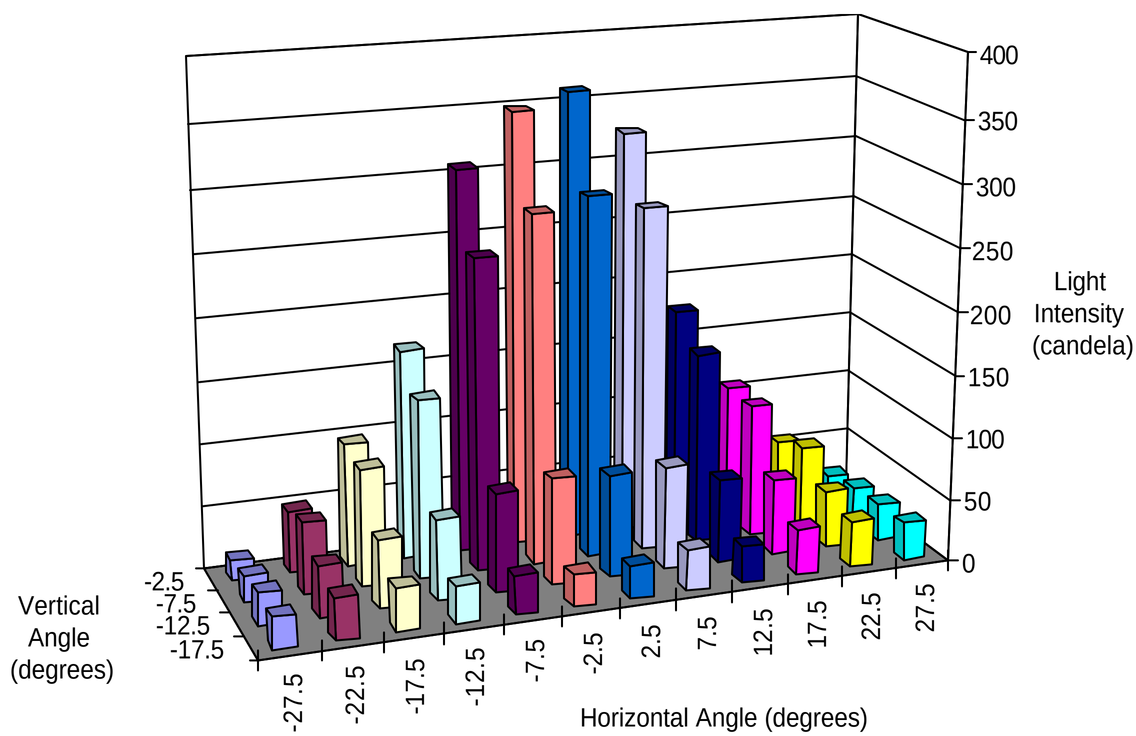

Figure A6.5.3b Output from WPS #6 (Red) signal, 10.0 volts, all elements on, ITE test.

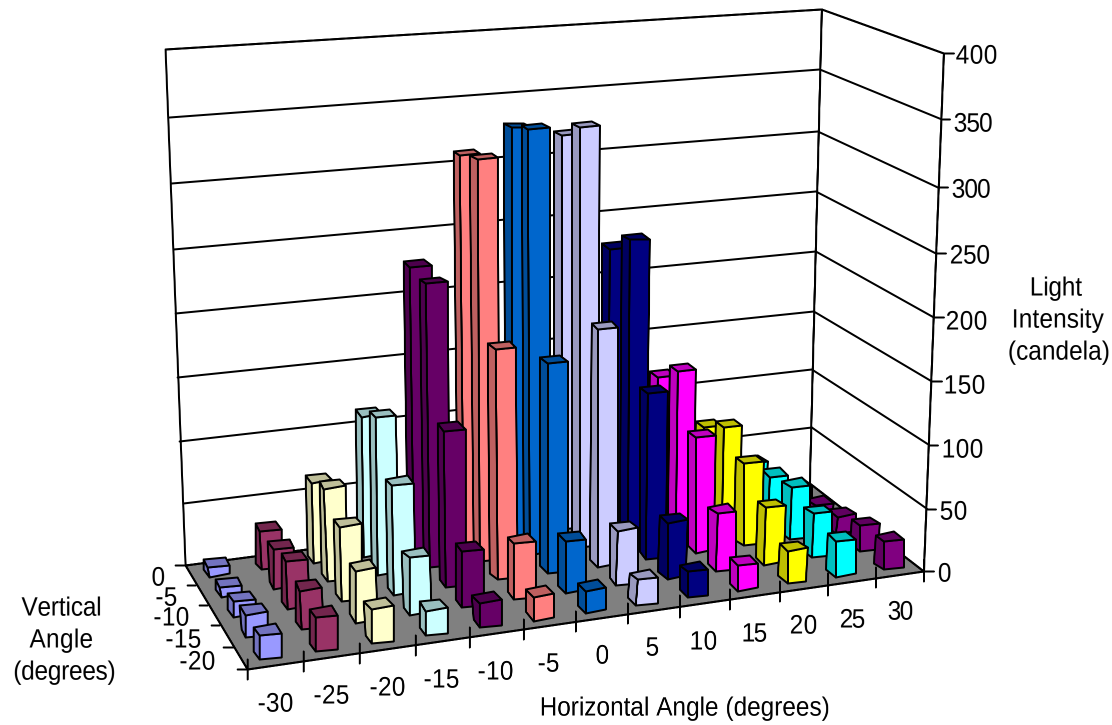

Figure A6.5.4a Output from WPS #6 (Red) signal, 10.5 volts, all elements on, TC test.

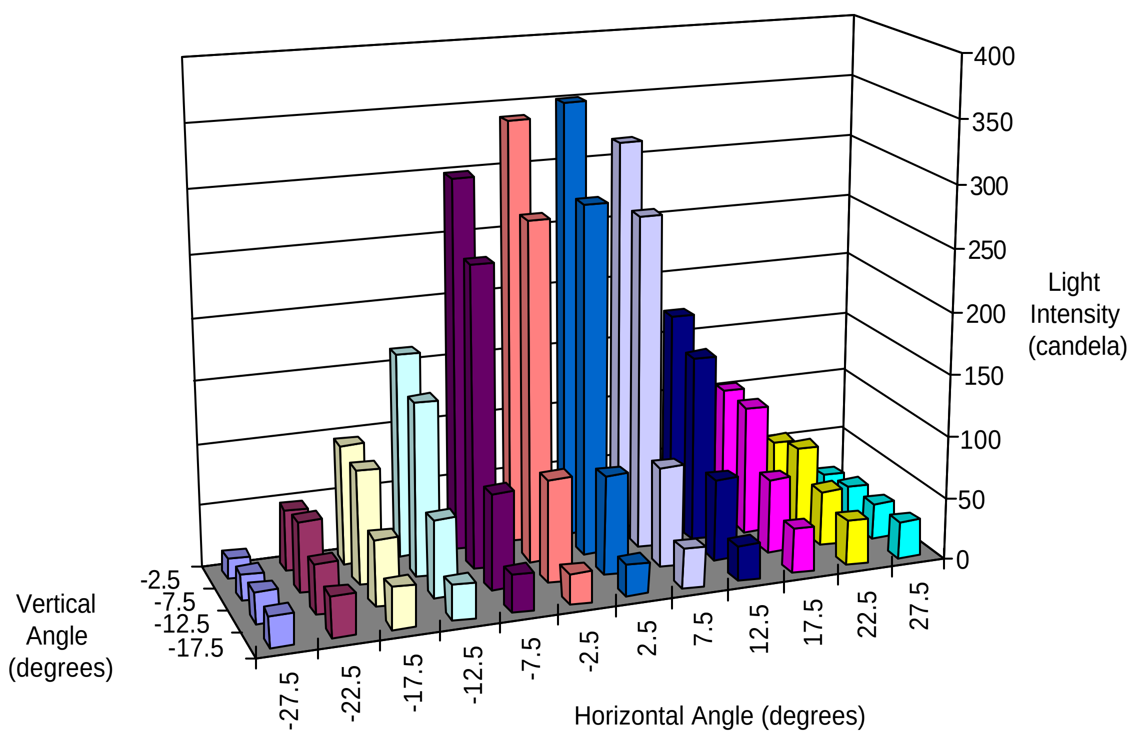

Figure A6.5.4b Output from WPS #6 (Red) signal, 10.5 volts, all elements on, ITE test.

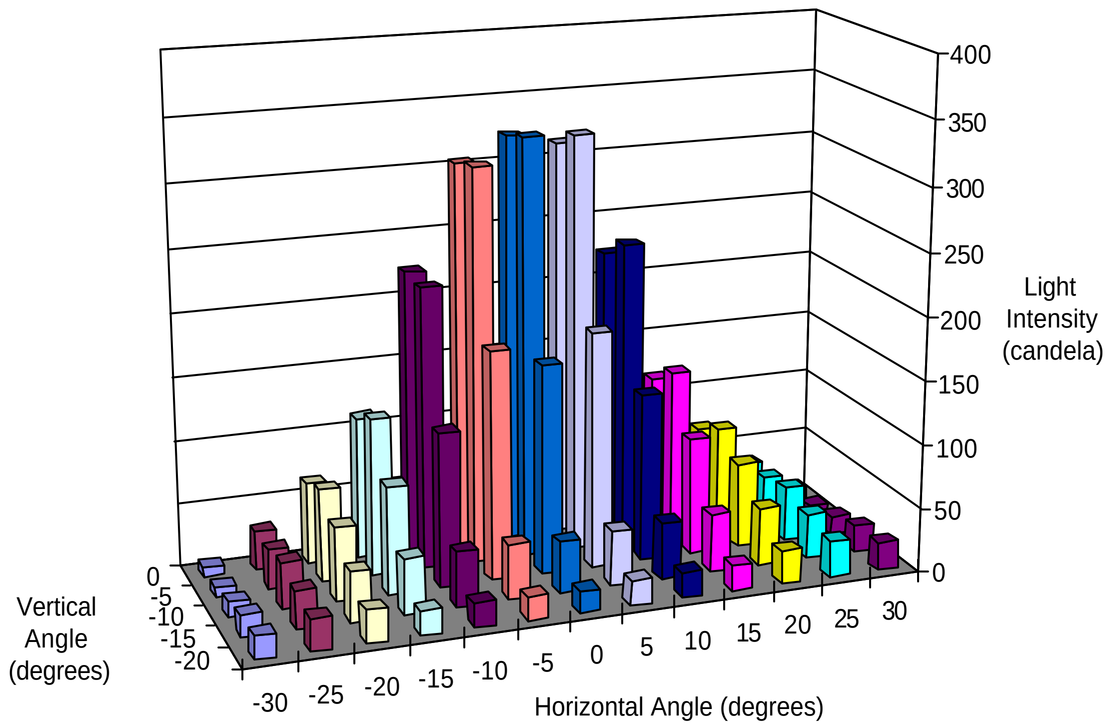

Figure A6.5.5a Output from WPS #6 (Red) signal, 12.0 volts, all elements on, TC test.

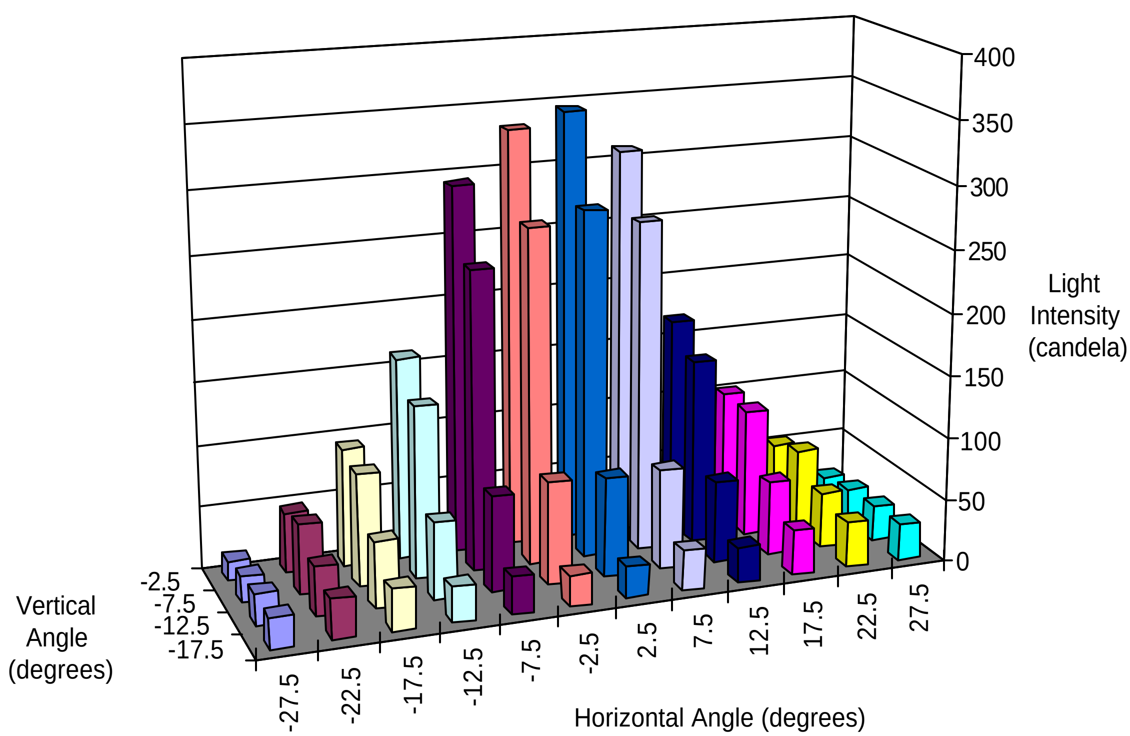

Figure A6.5.5b Output from WPS #6 (Red) signal, 12.0 volts, all elements on, ITE test.

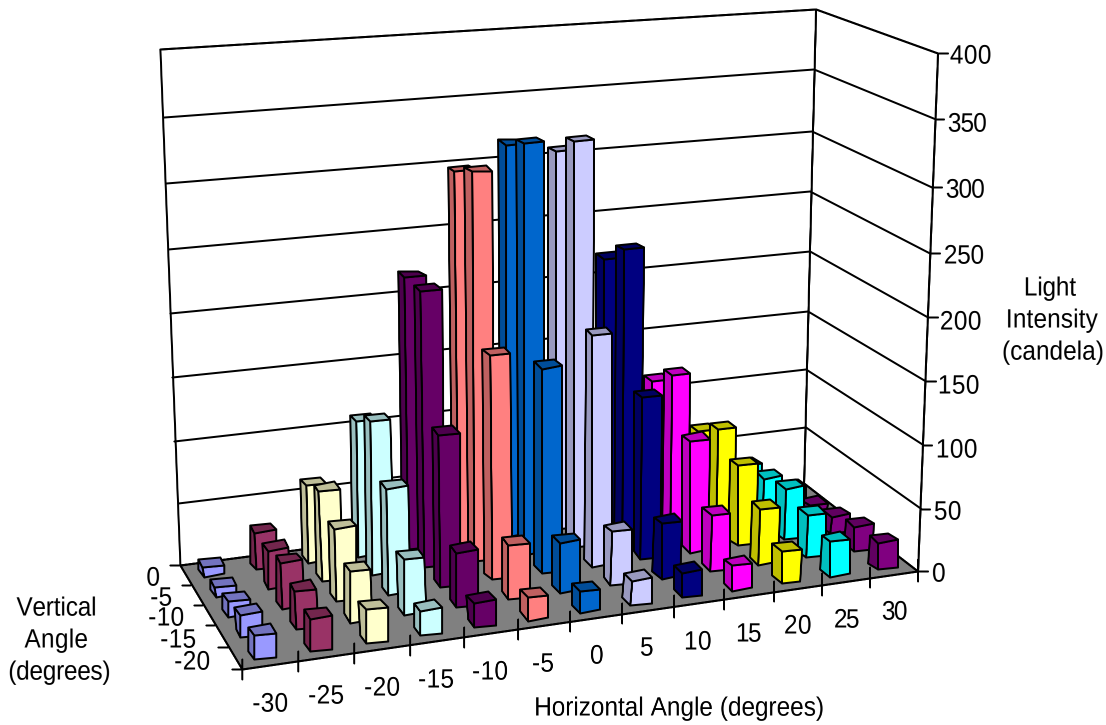

Figure A6.5.6a Output from WPS #6 (Red) signal, 13.5 volts, all elements on, TC test.

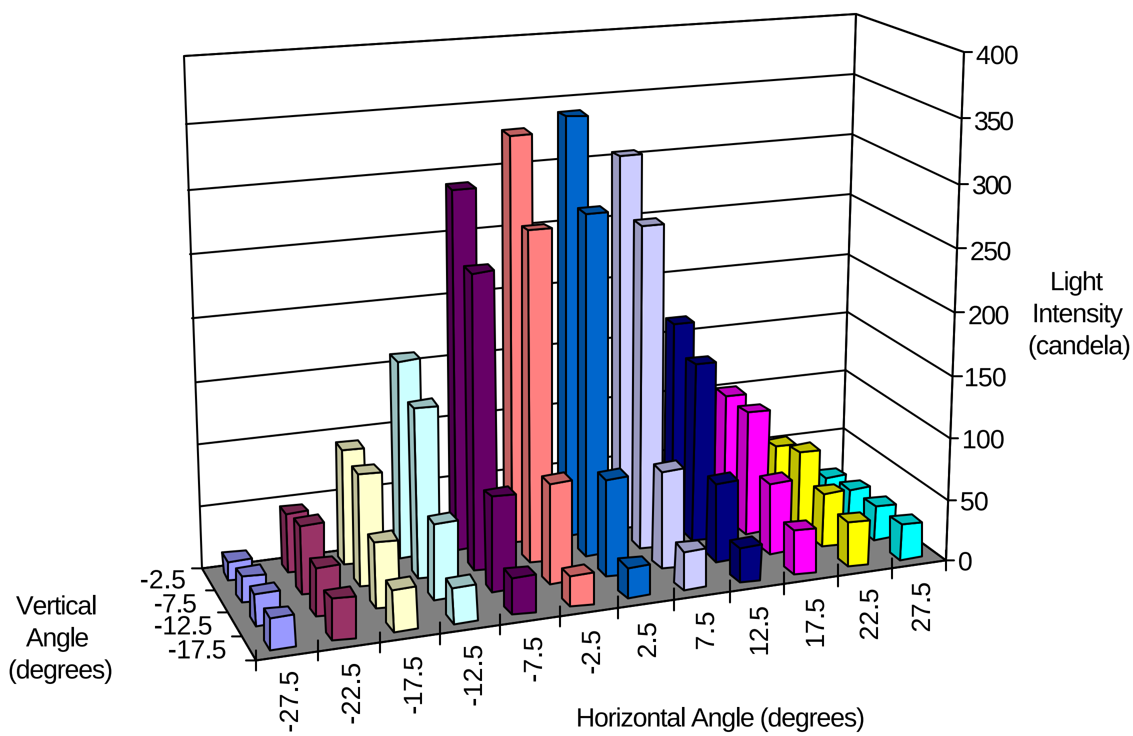

Figure A6.5.6b Output from WPS #6 (Red) signal, 13.5 volts, all elements on, ITE test.

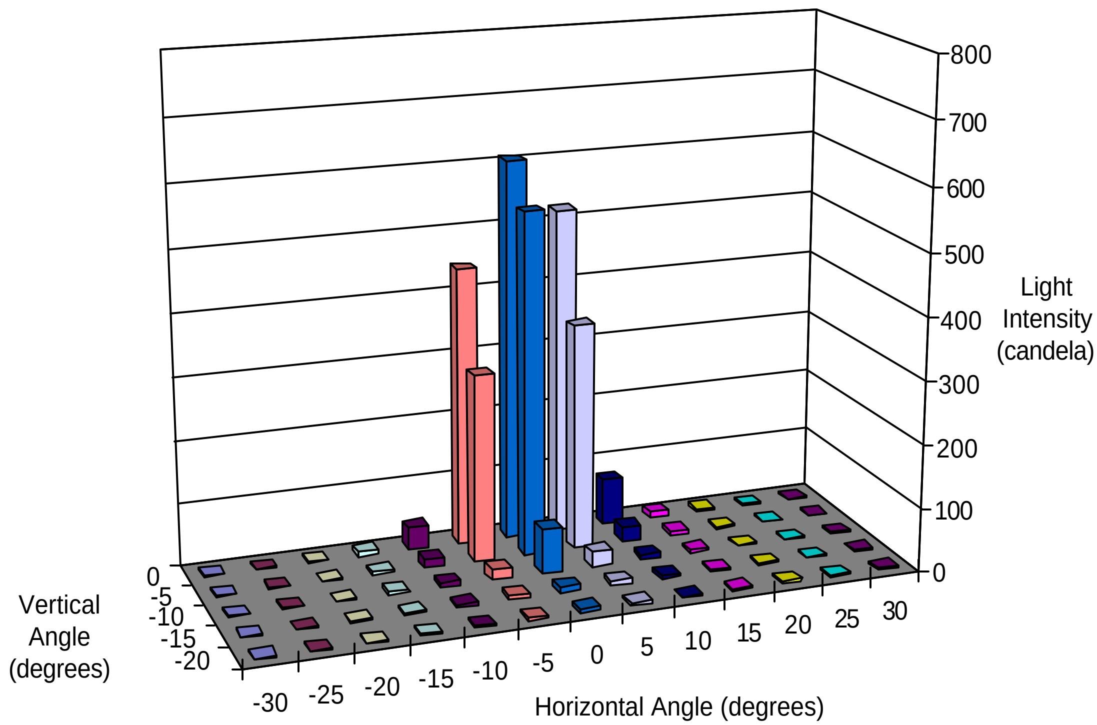

Figure A7.1.1a Output from WPS #7 (Red) signal, 10.0 volts, 32.0 ft, all elements on, TC test.

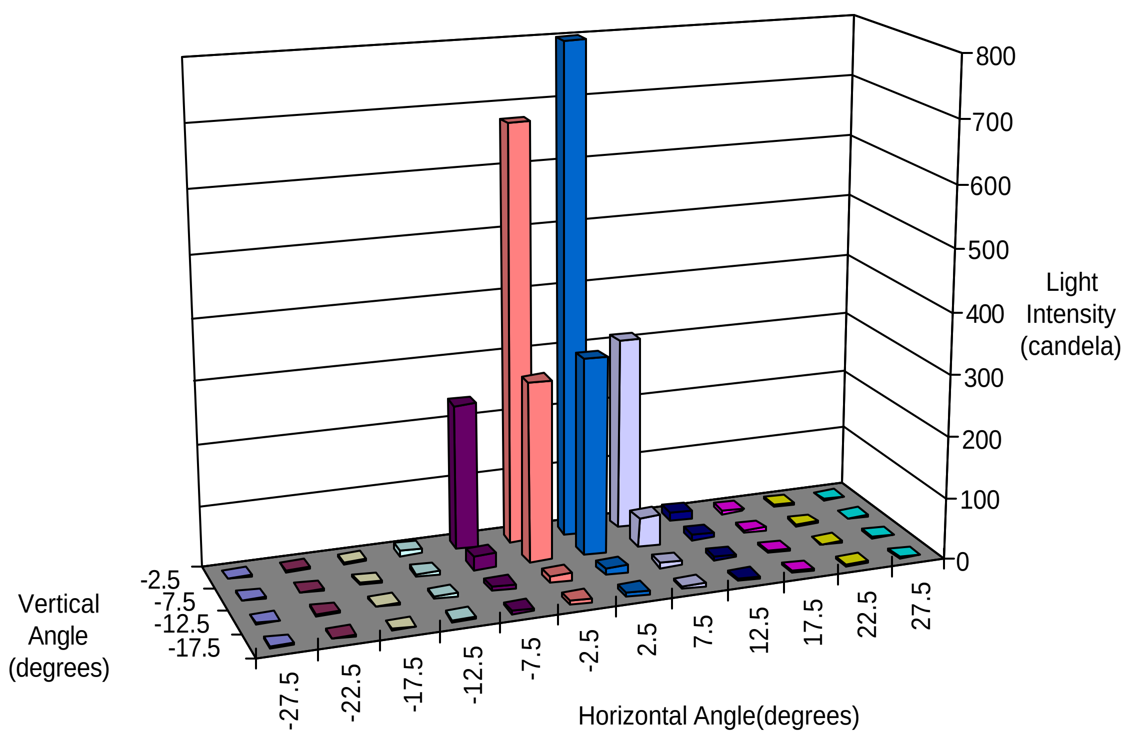

Figure A7.1.1b Output from WPS #7 (Red) signal, 10.0 volts, 32.0 ft, all elements on, ITE test.

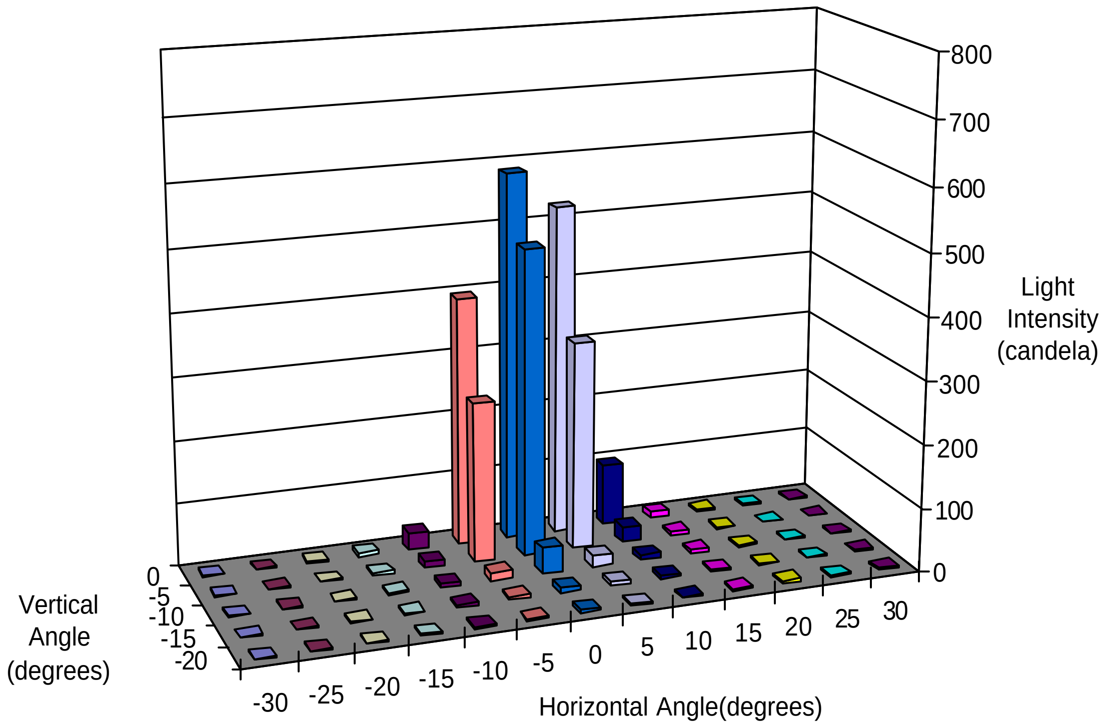

Figure A7.1.2a Output from WPS #7 (Red) signal, 10.0 volts, 34.0 ft, all elements on, TC test.

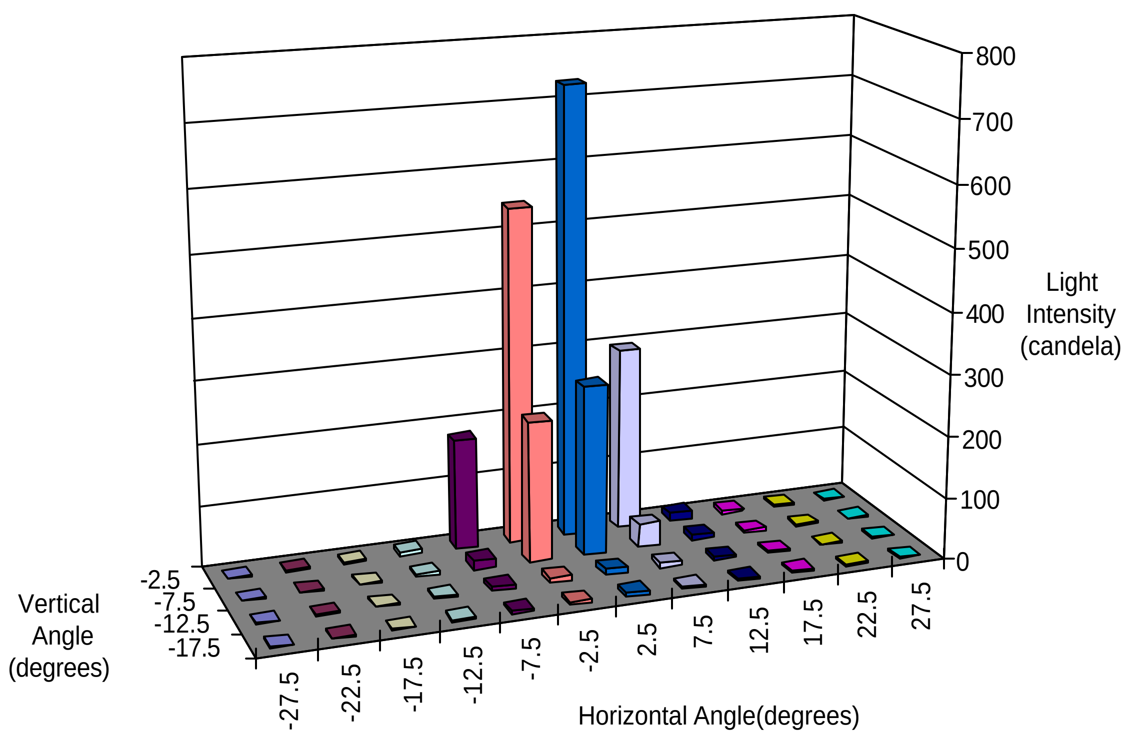

Figure A7.1.2b Output from WPS #7 (Red) signal, 10.0 volts, 34.0 ft, all elements on, ITE test.

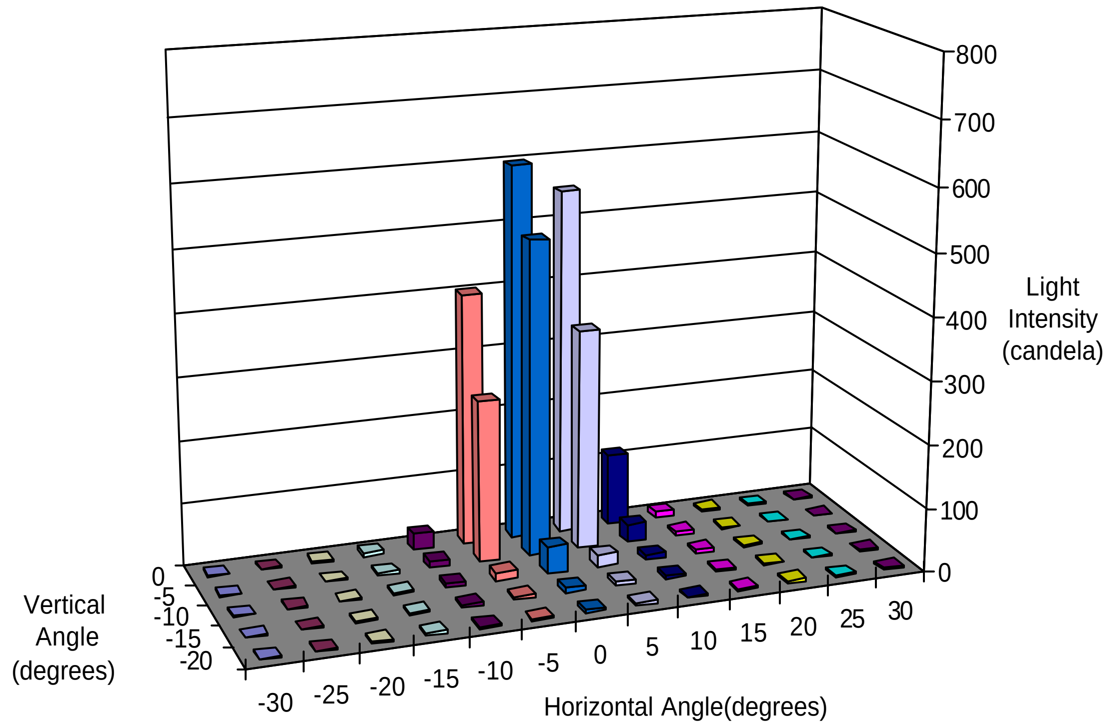

Figure A7.1.3a Output from WPS #7 (Red) signal, 10.0 volts, 36.0 ft, all elements on, TC test.

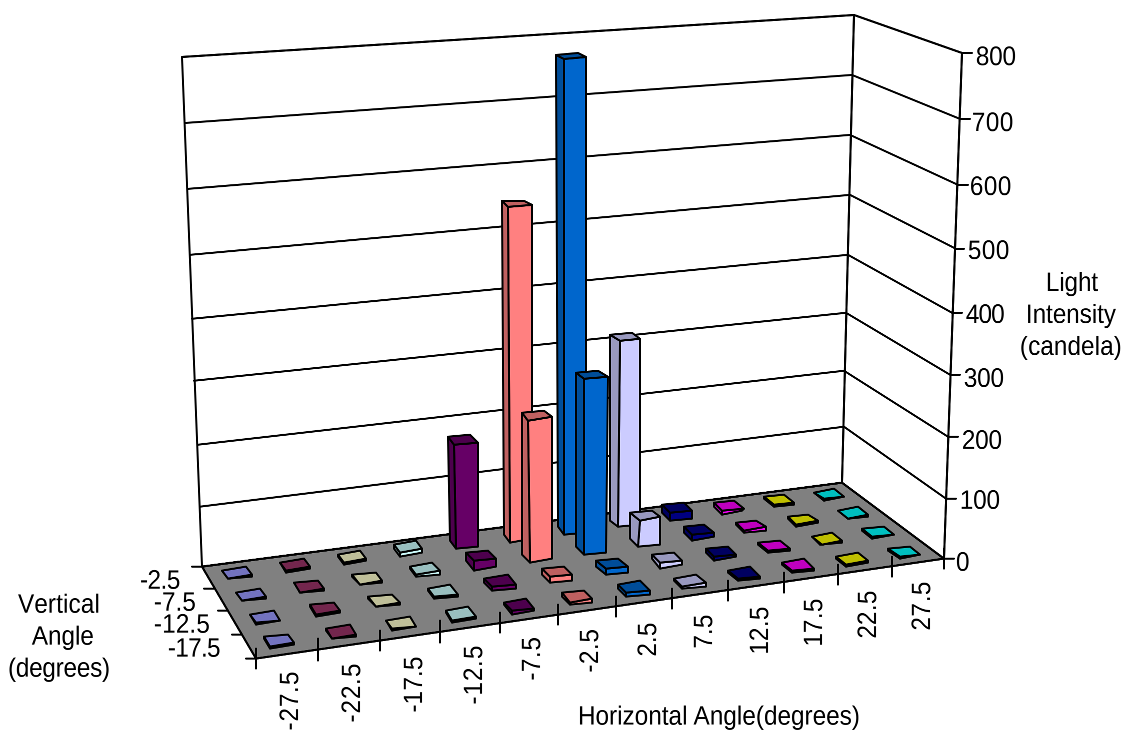

Figure A7.1.3b Output from WPS #7 (Red) signal, 10.0 volts, 36.0 ft, all elements on, ITE test.

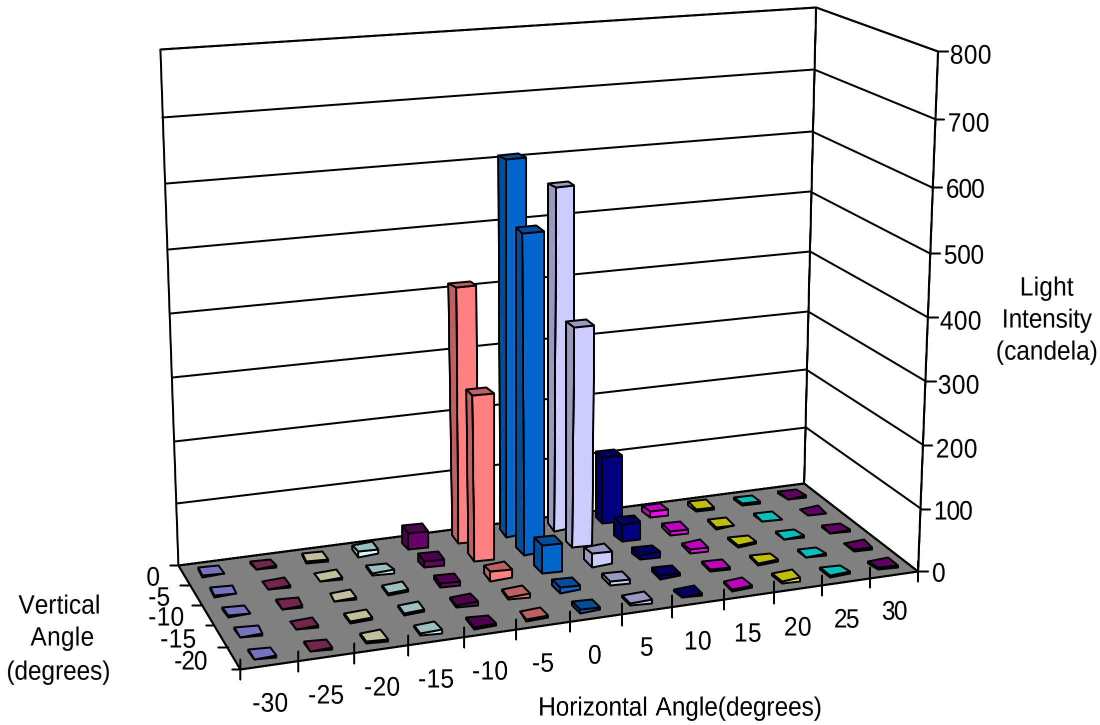

Figure A7.1.4a Output from WPS #7 (Red) signal, 10.0 volts, 38.0 ft, all elements on, TC test.

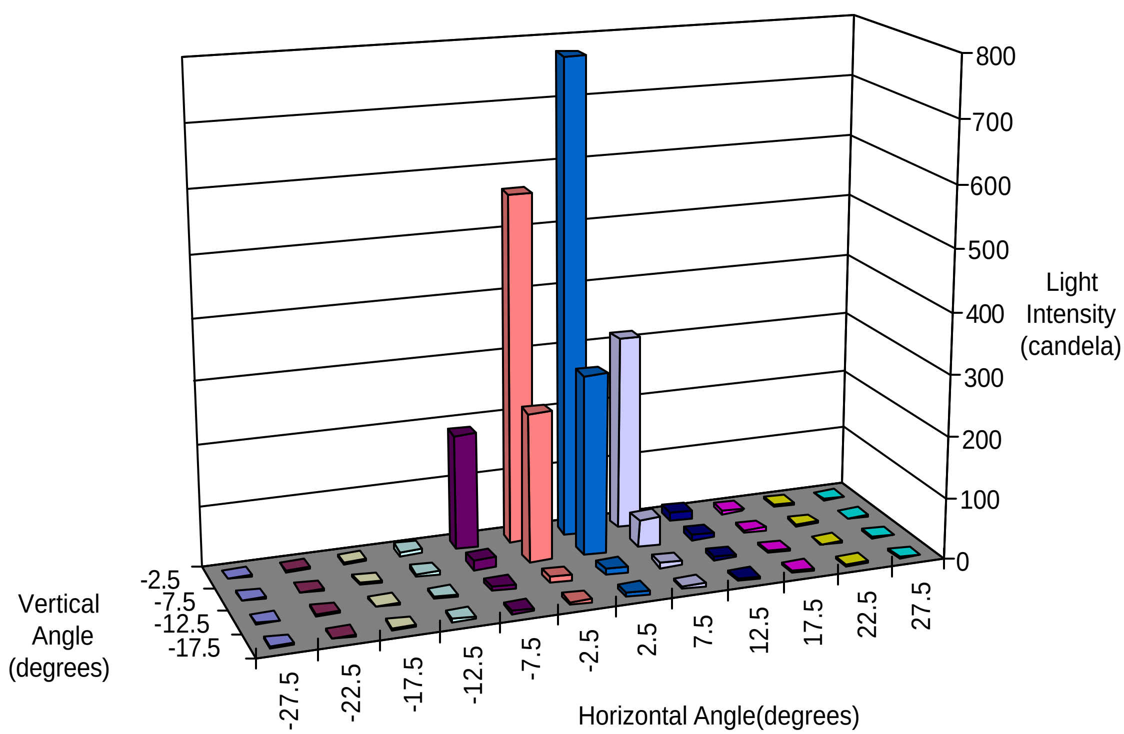

Figure A7.1.4b Output from WPS #7 (Red) signal, 10.0 volts, 38.0 ft, all elements on, ITE test.

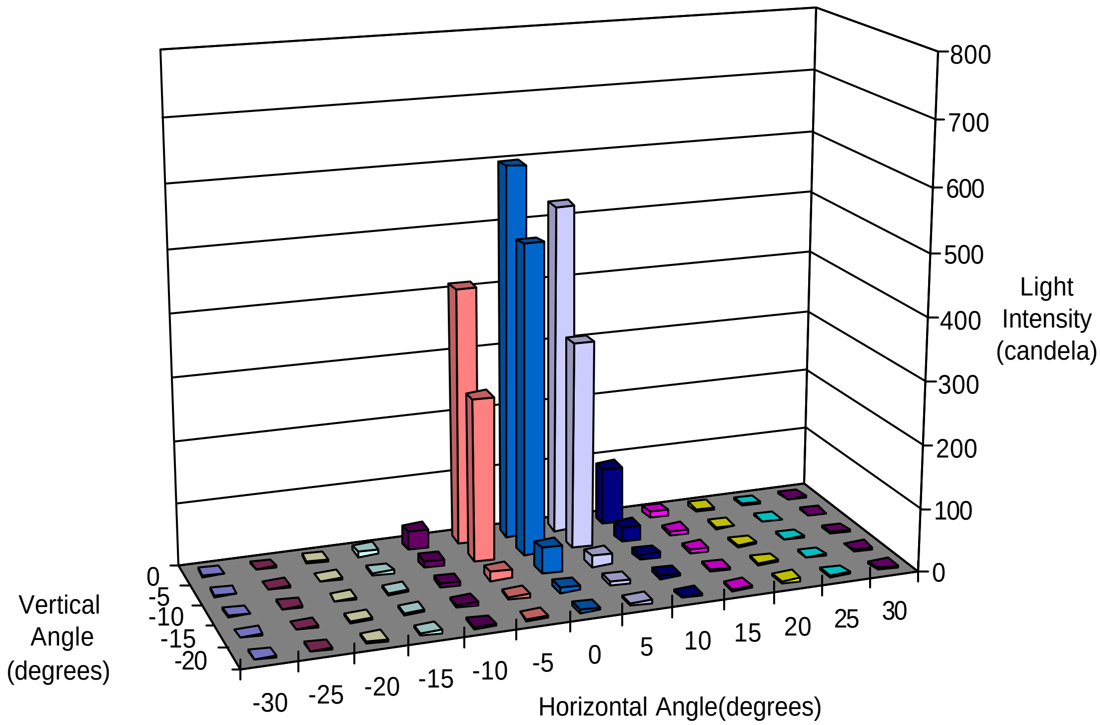

Figure A7.1.5a Output from WPS #7 (Red) signal, 10.0 volts, 40.0 ft, all elements on, TC test.

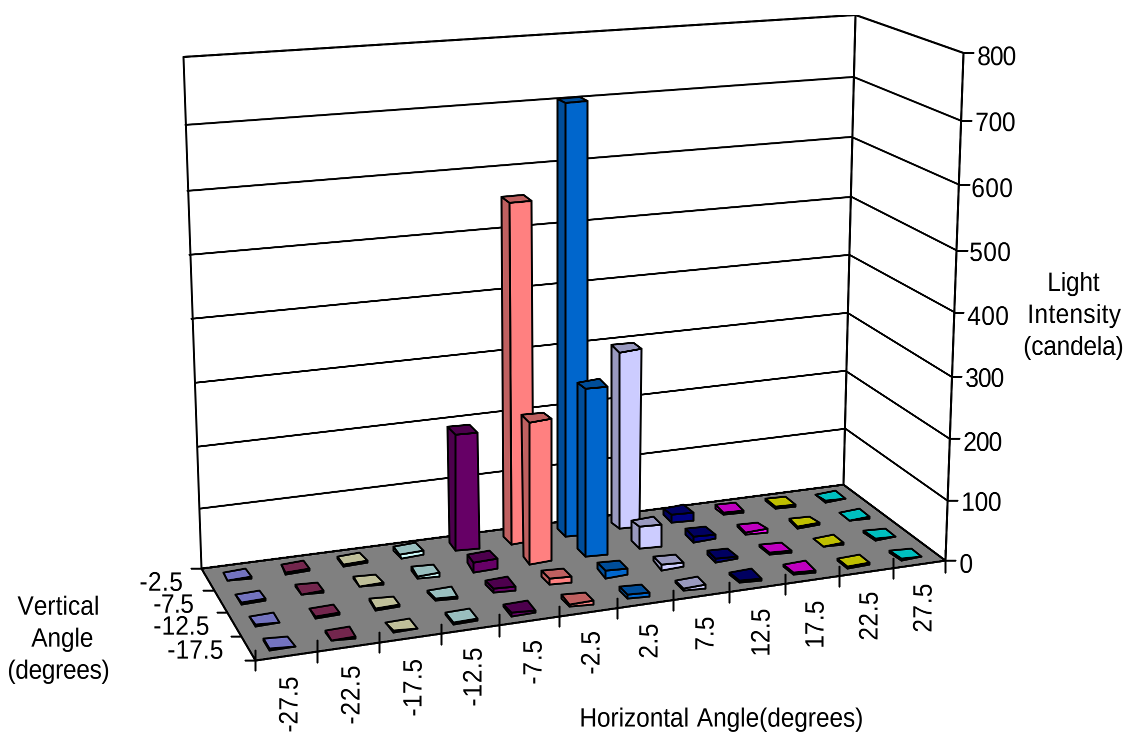

Figure A7.1.5b Output from WPS #7 (Red) signal, 10.0 volts, 40.0 ft, all elements on, ITE test.

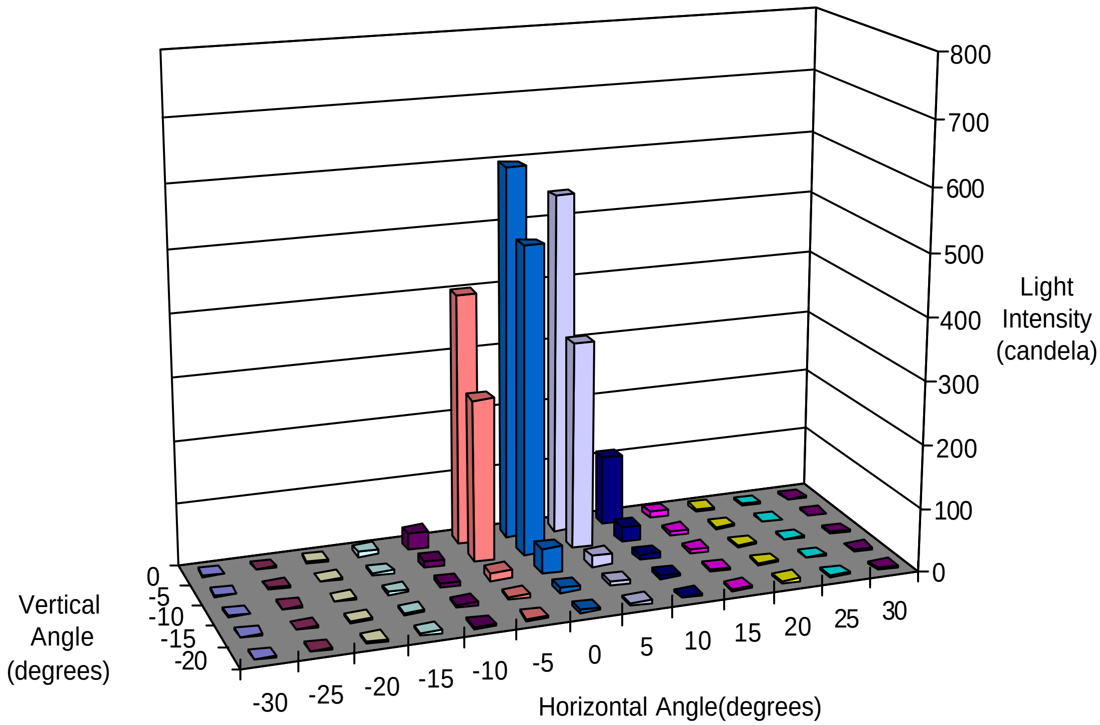

Figure A7.1.6a Output from WPS #7 (Red) signal, 10.0 volts, 42.0 ft, all elements on, TC test.

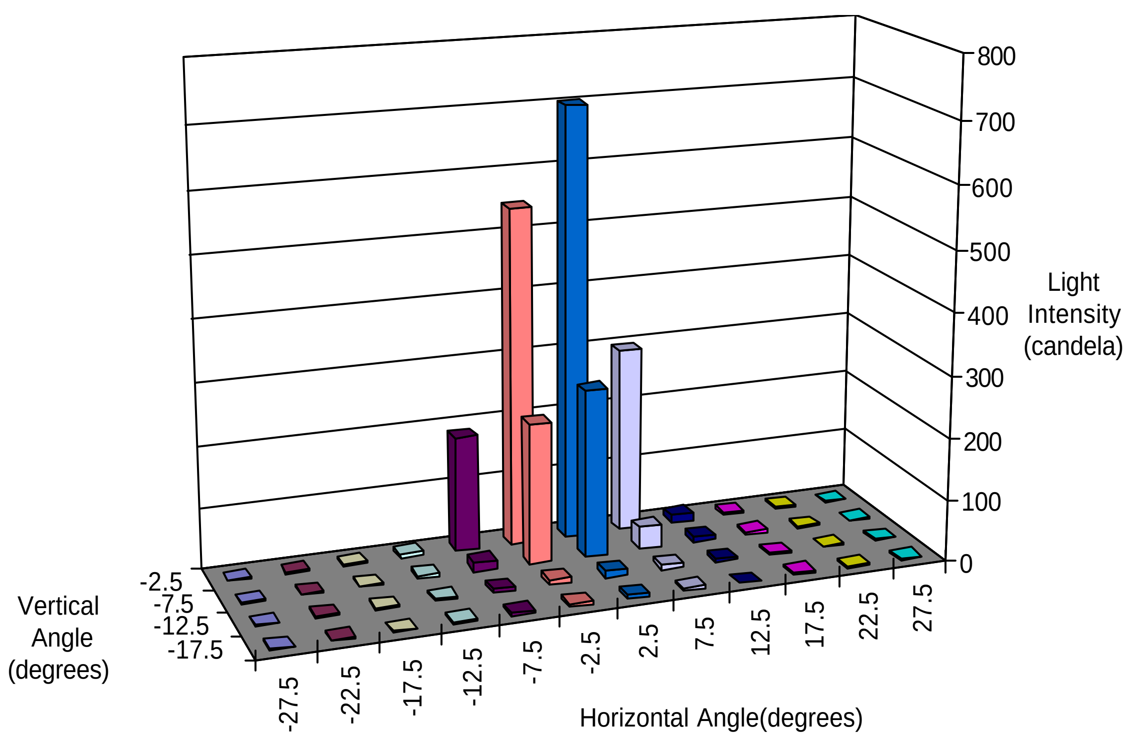

Figure A7.1.6b Output from WPS #7 (Red) signal, 10.0 volts, 42.0 ft, all elements on, ITE test.

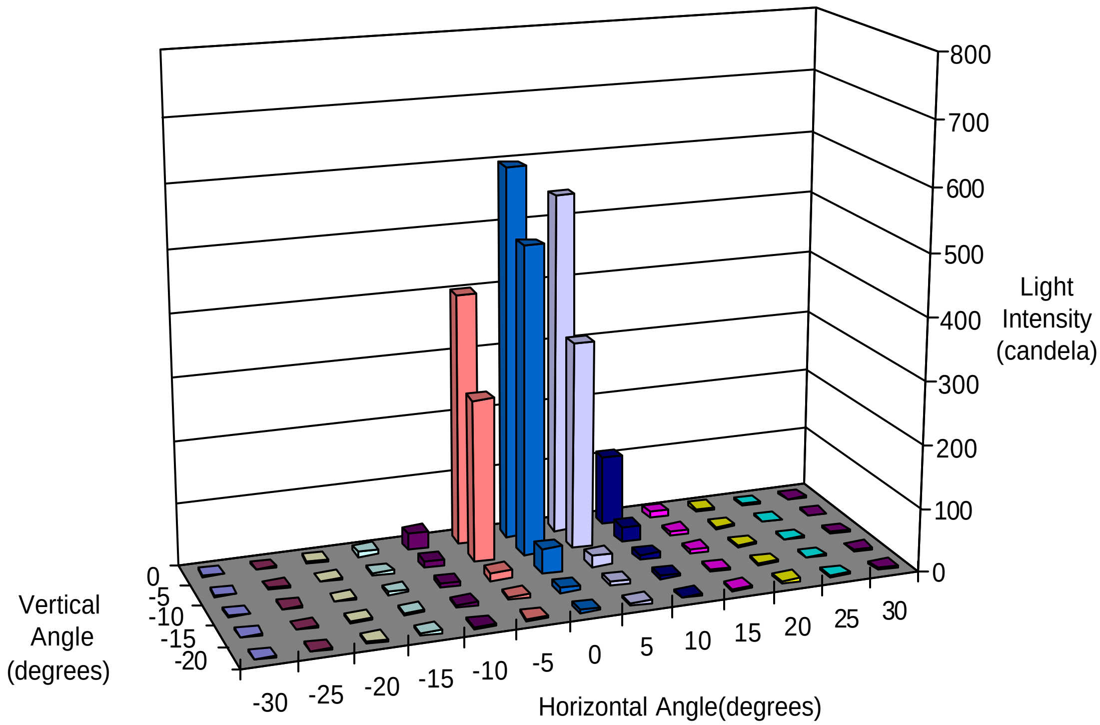

Figure A7.1.7a Output from WPS #7 (Red) signal, 10.0 volts, 44.0 ft, all elements on, TC test.

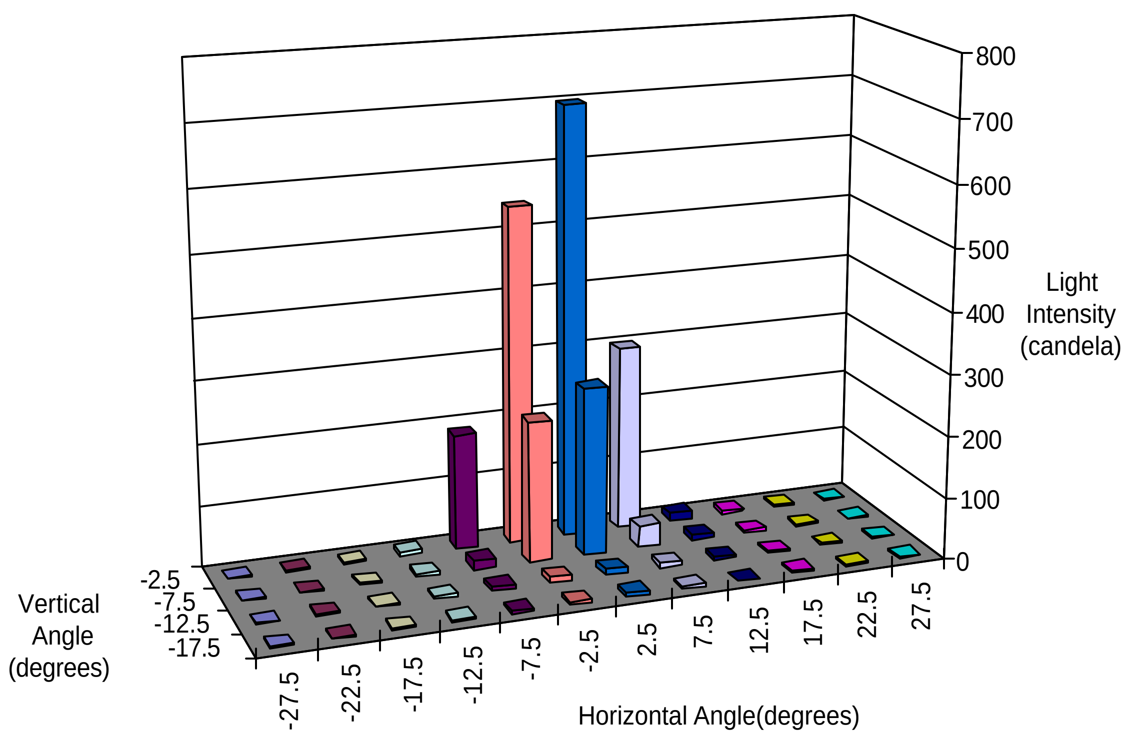

Figure A7.1.7b Output from WPS #7 (Red) signal, 10.0 volts, 44.0 ft, all elements on, ITE test

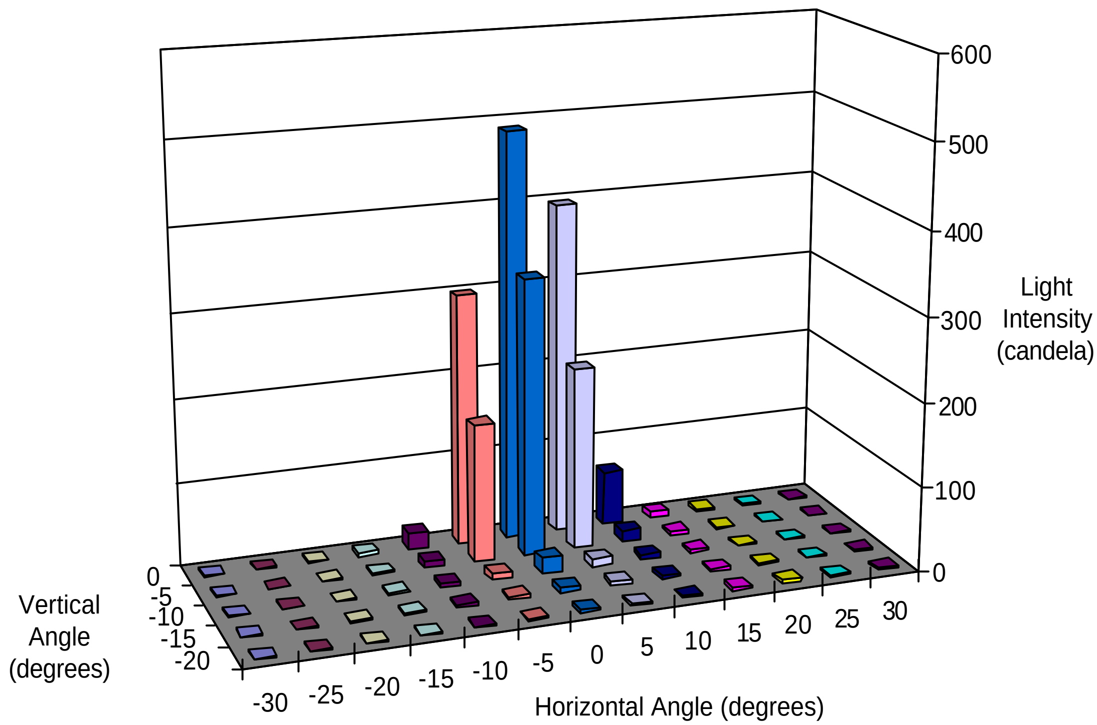

Figure A7.2.1a Output from WPS #7 (Red) signal, 10.0 volts, 32.0 ft, all elements on, TC test.

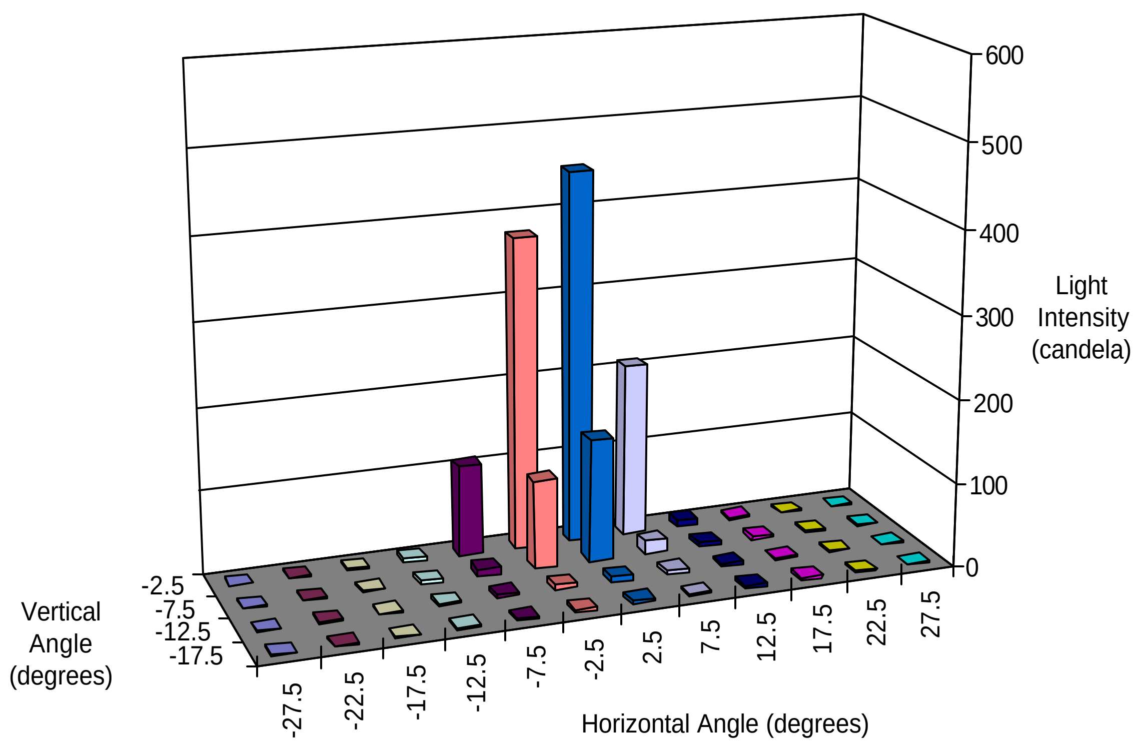

Figure A7.2.1b Output from WPS #7 (Red) signal, 10.0 volts, 32.0 ft, all elements on, ITE test.

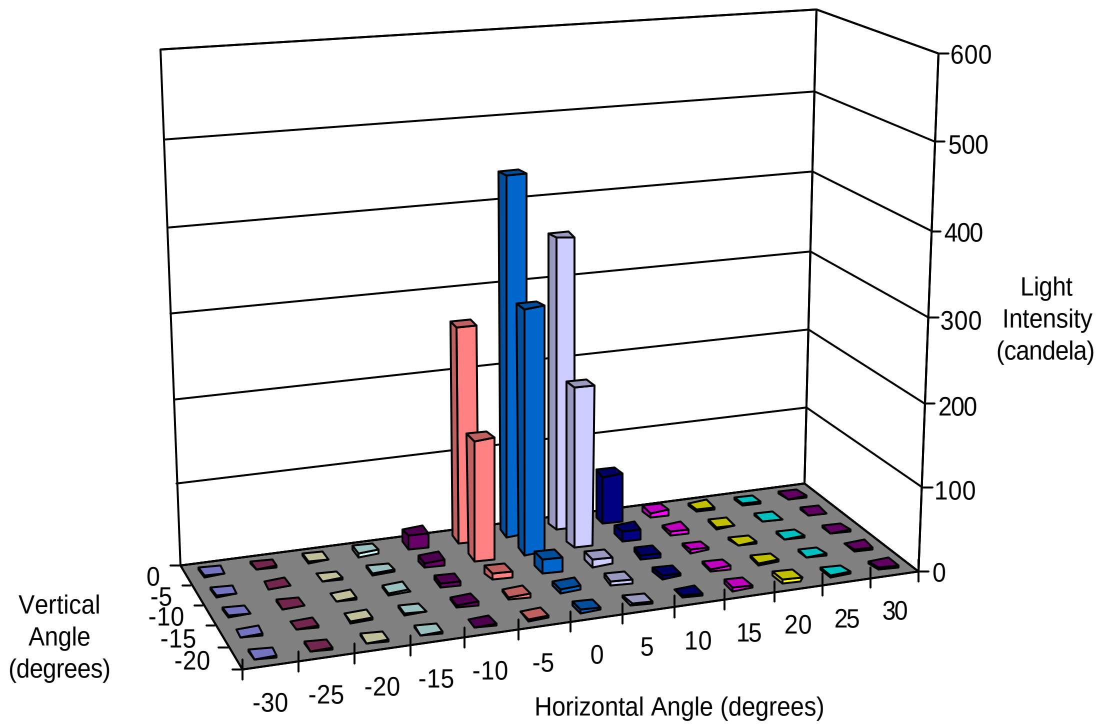

Figure A7.2.2a Output from WPS #7 (Red) signal, 10.0 volts, 34.0 ft, all elements on, TC test.

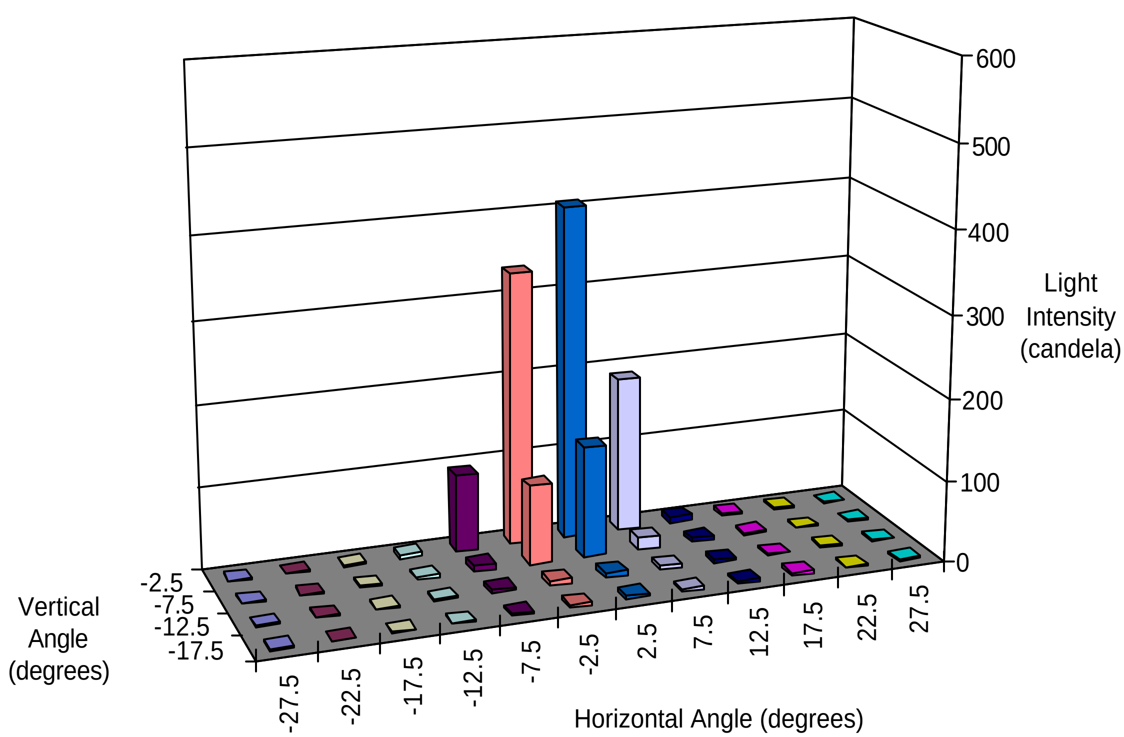

Figure A7.2.2b Output from WPS #7 (Red) signal, 10.0 volts, 34.0 ft, all elements on, ITE test.

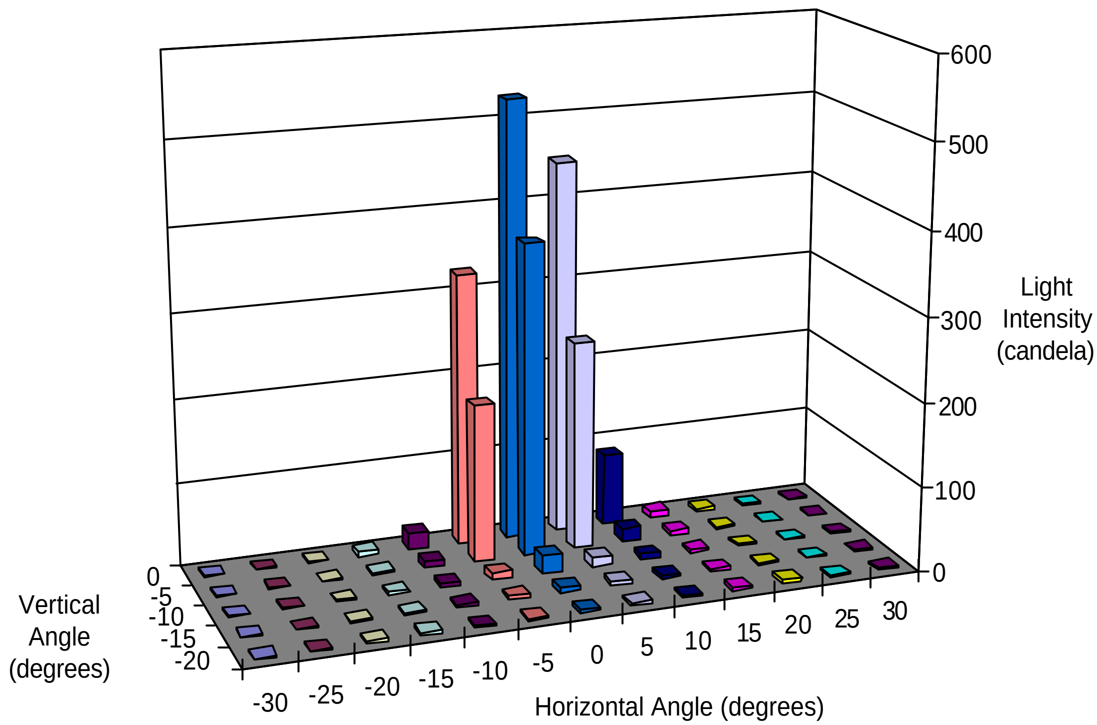

Figure A7.2.3a Output from WPS #7 (Red) signal, 10.0 volts, 36.0 ft, all elements on, TC test.

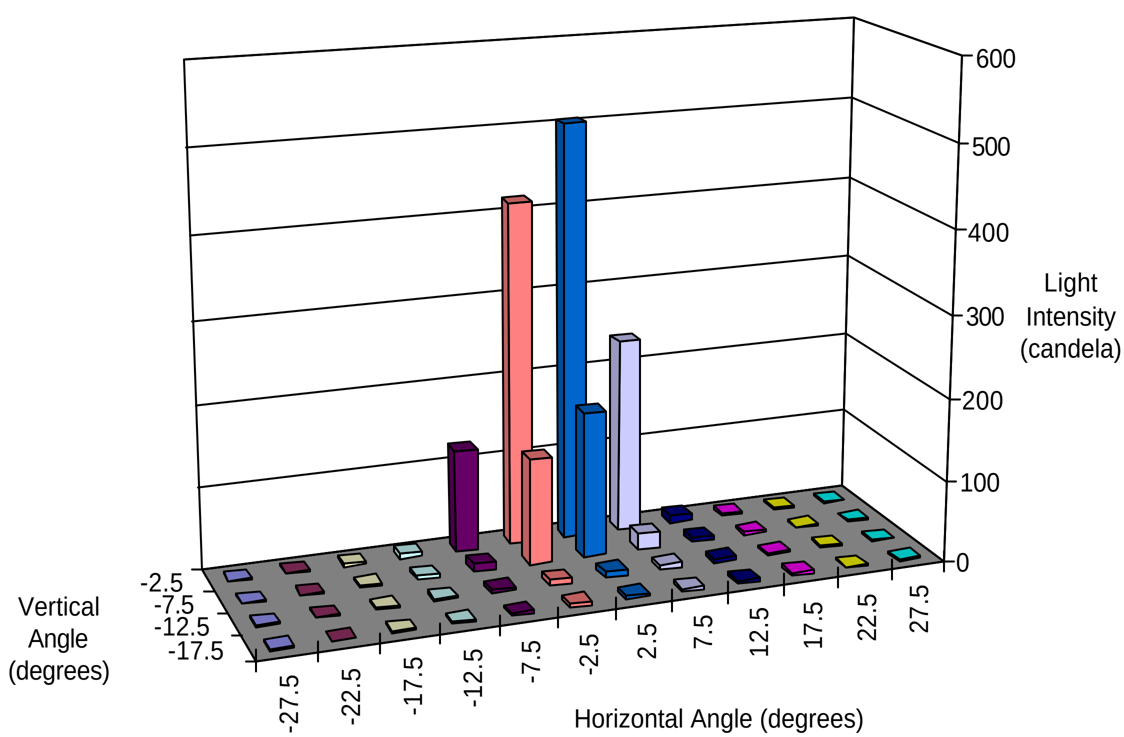

Figure A7.2.3b Output from WPS #7 (Red) signal, 10.0 volts, 36.0 ft, all elements on, ITE test.

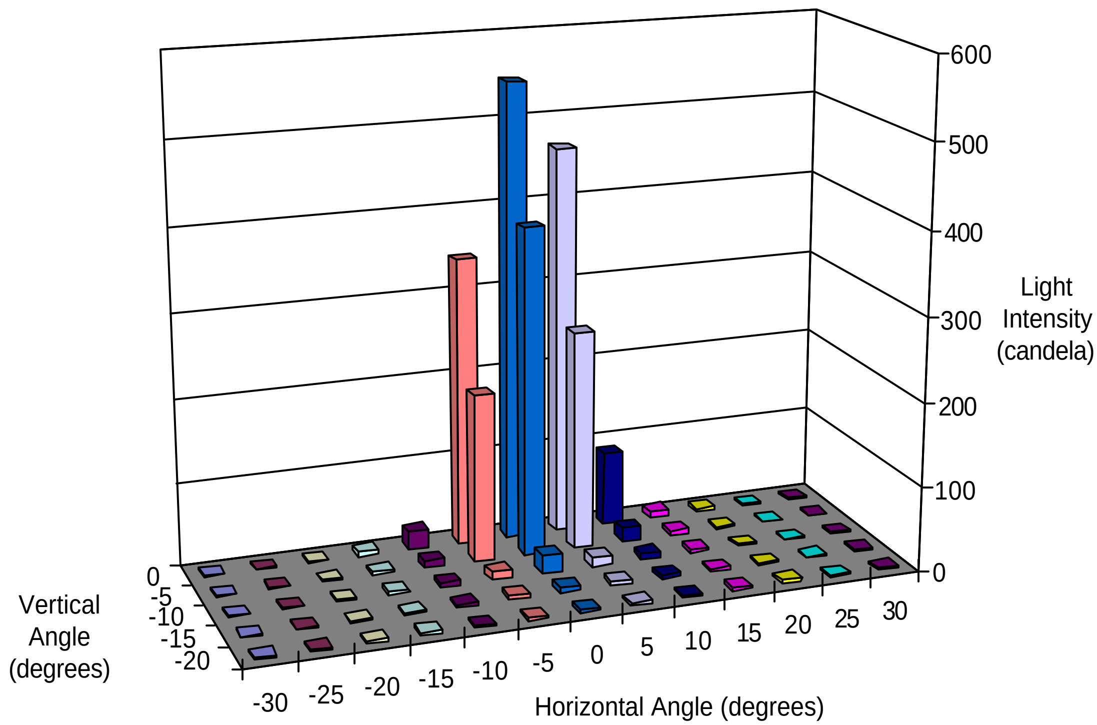

Figure A7.2.4a Output from WPS #7 (Red) signal, 10.0 volts, 38.0 ft, all elements on, TC test.

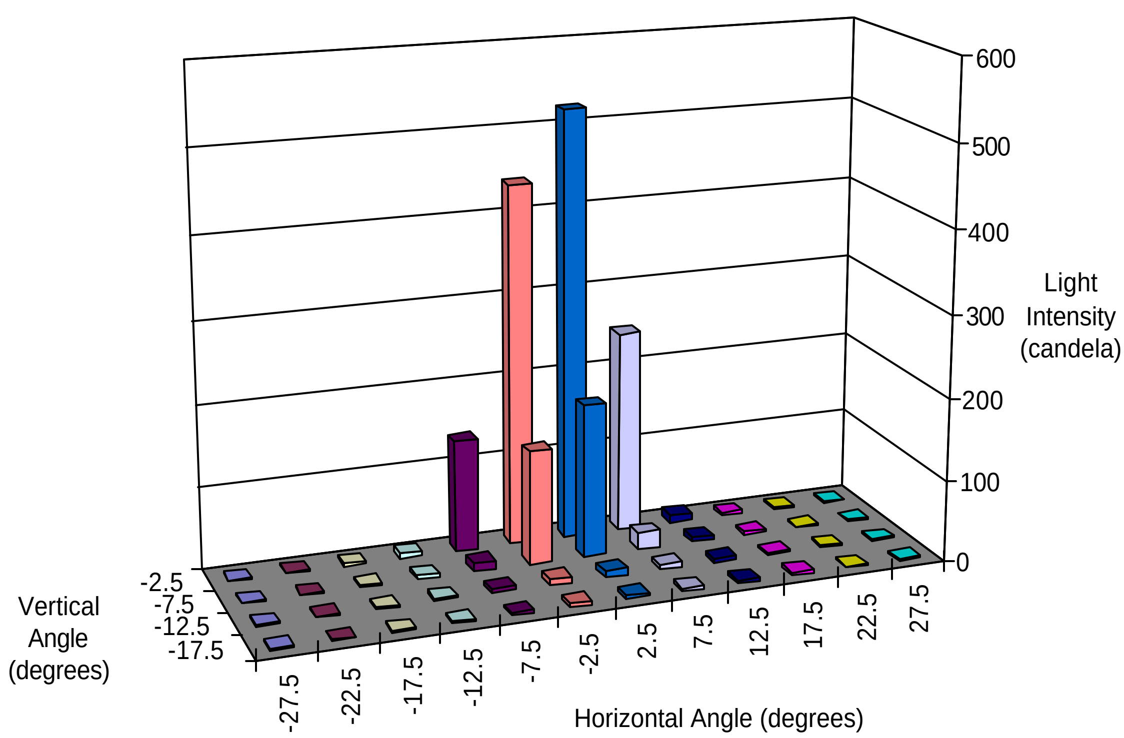

Figure A7.2.4b Output from WPS #7 (Red) signal, 10.0 volts, 38.0 ft, all elements on, ITE test.

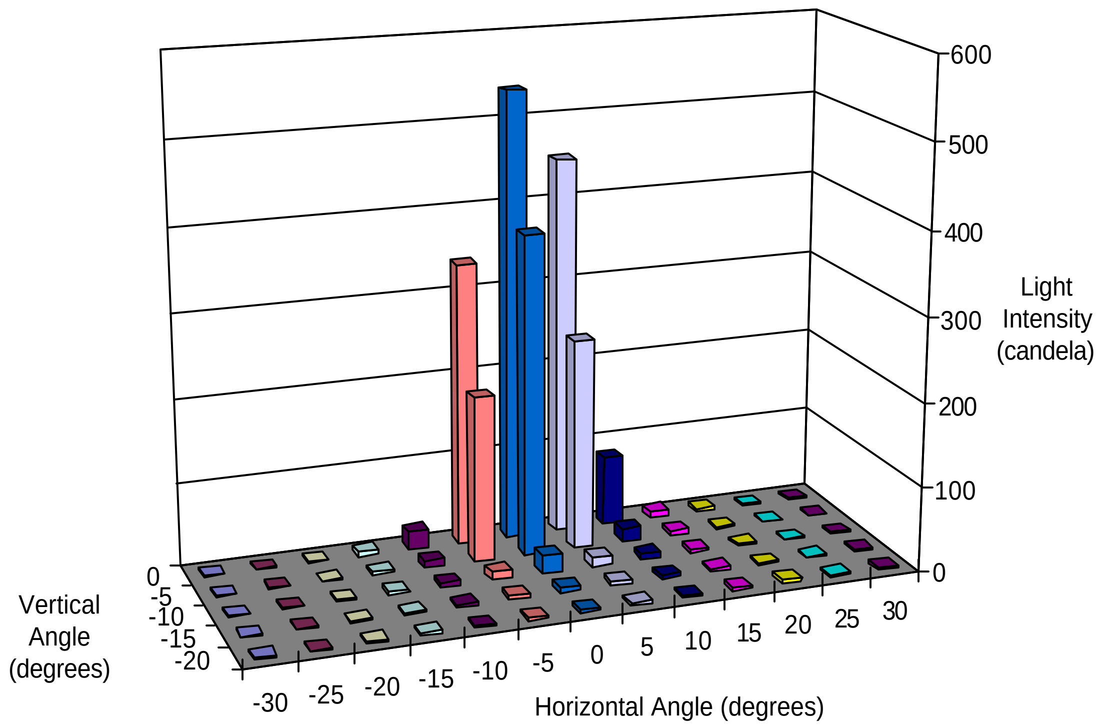

Figure A7.2.5a Output from WPS #7 (Red) signal, 10.0 volts, 40.0 ft, all elements on, TC test.

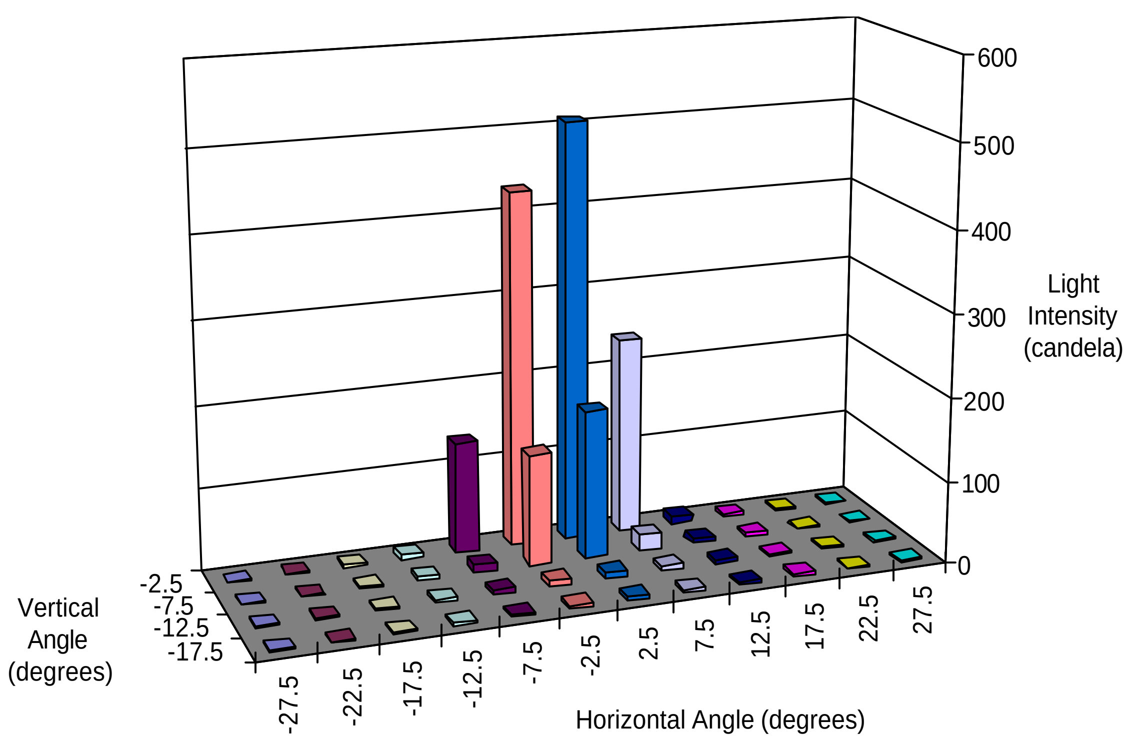

Figure A7.2.5b Output from WPS #7 (Red) signal, 10.0 volts, 40.0 ft, all elements on, ITE test.

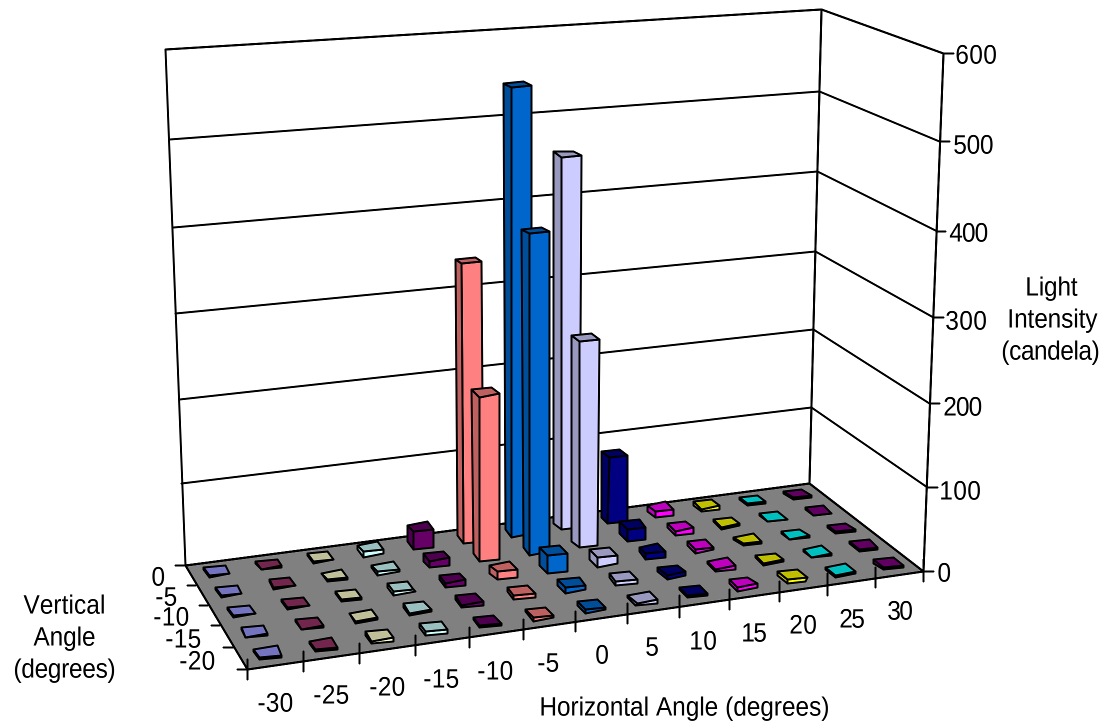

Figure A7.2.6a Output from WPS #7 (Red) signal, 10.0 volts, 42.0 ft, all elements on, TC test.

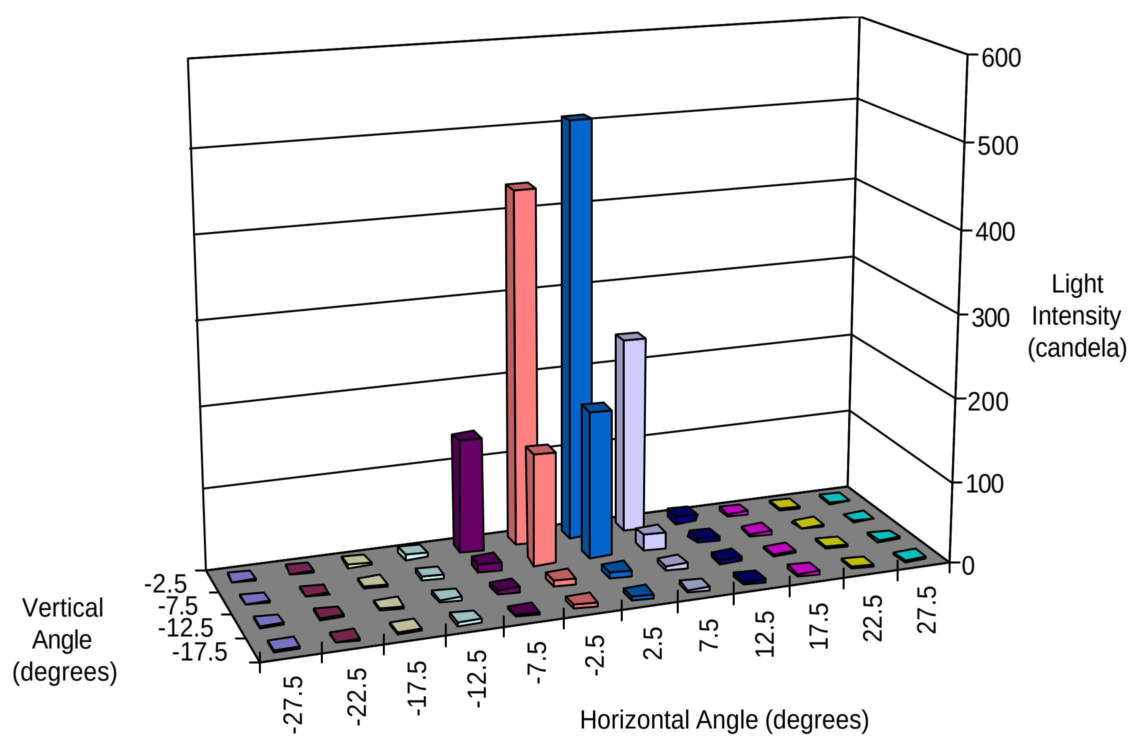

Figure A7.2.6b Output from WPS #7 (Red) signal, 10.0 volts, 42.0 ft, all elements on, ITE test.

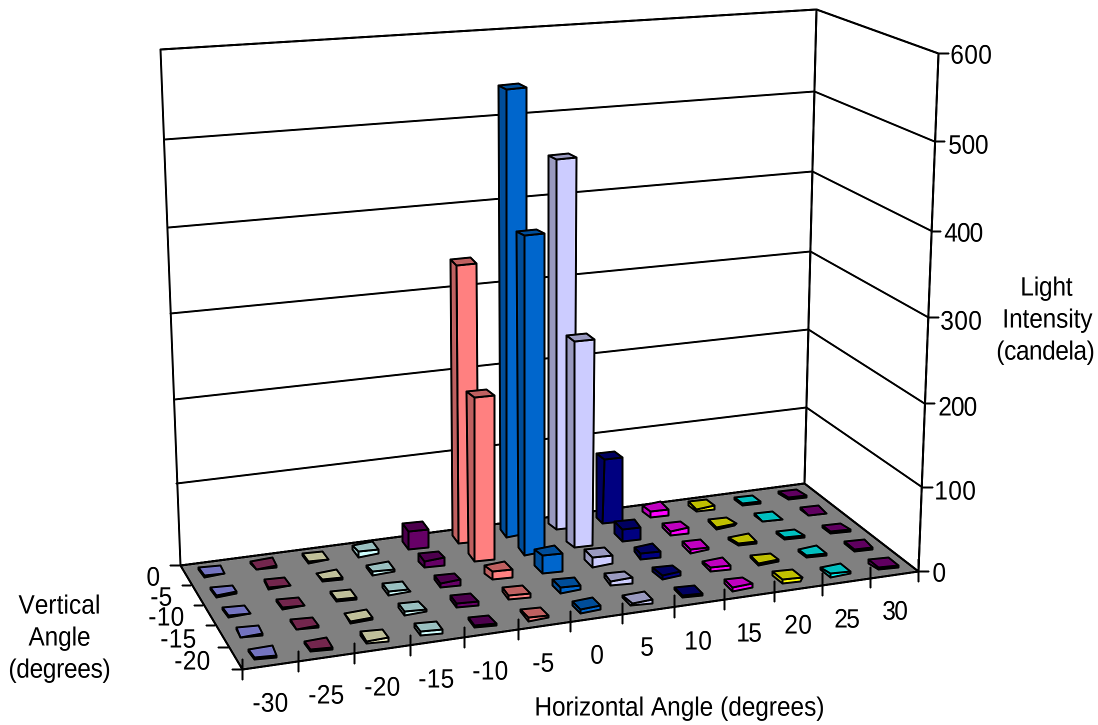

Figure A7.2.7a Output from WPS #7 (Red) signal, 10.0 volts, 44.0 ft, all elements on, TC test.

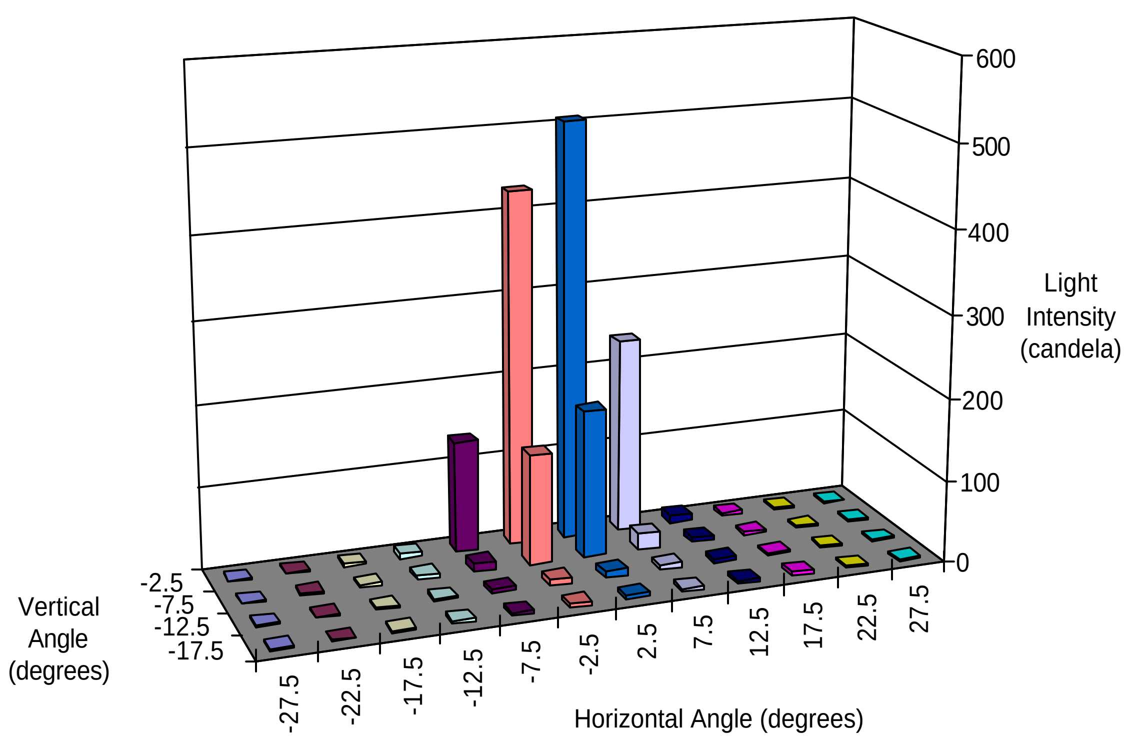

Figure A7.2.7b Output from WPS #7 (Red) signal, 10.0 volts, 44.0 ft, all elements on, ITE test.

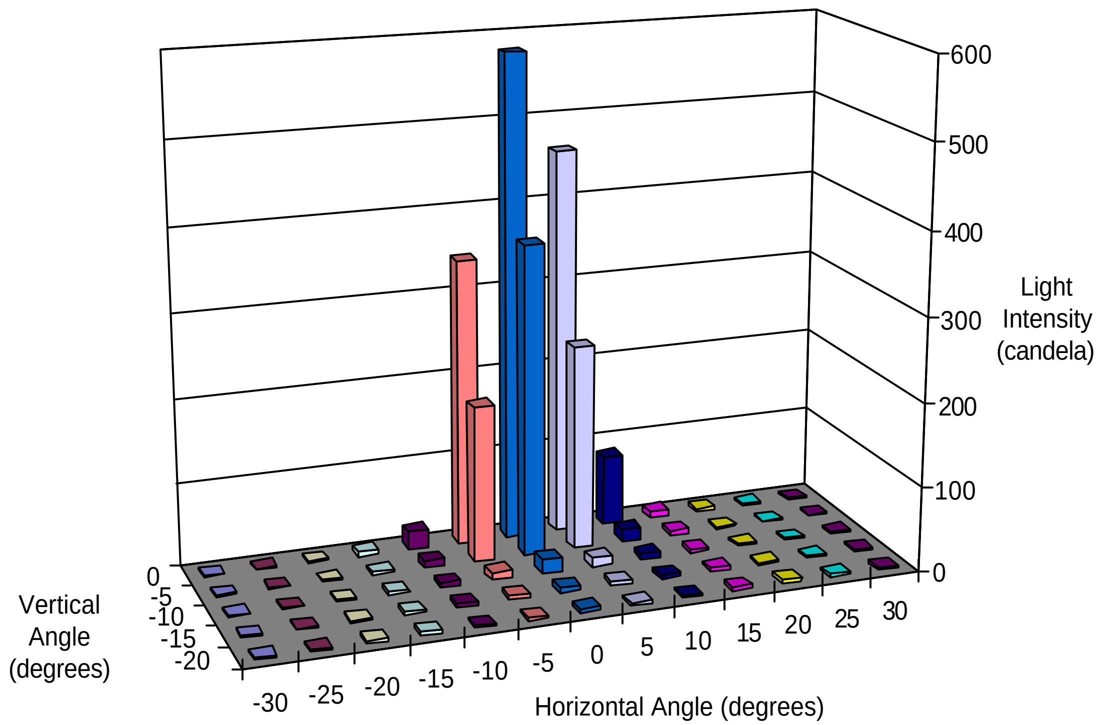

Figure A7.2.8a Output from WPS #7 (Red) signal, 10.0 volts, 46.0 ft, all elements on, TC test.

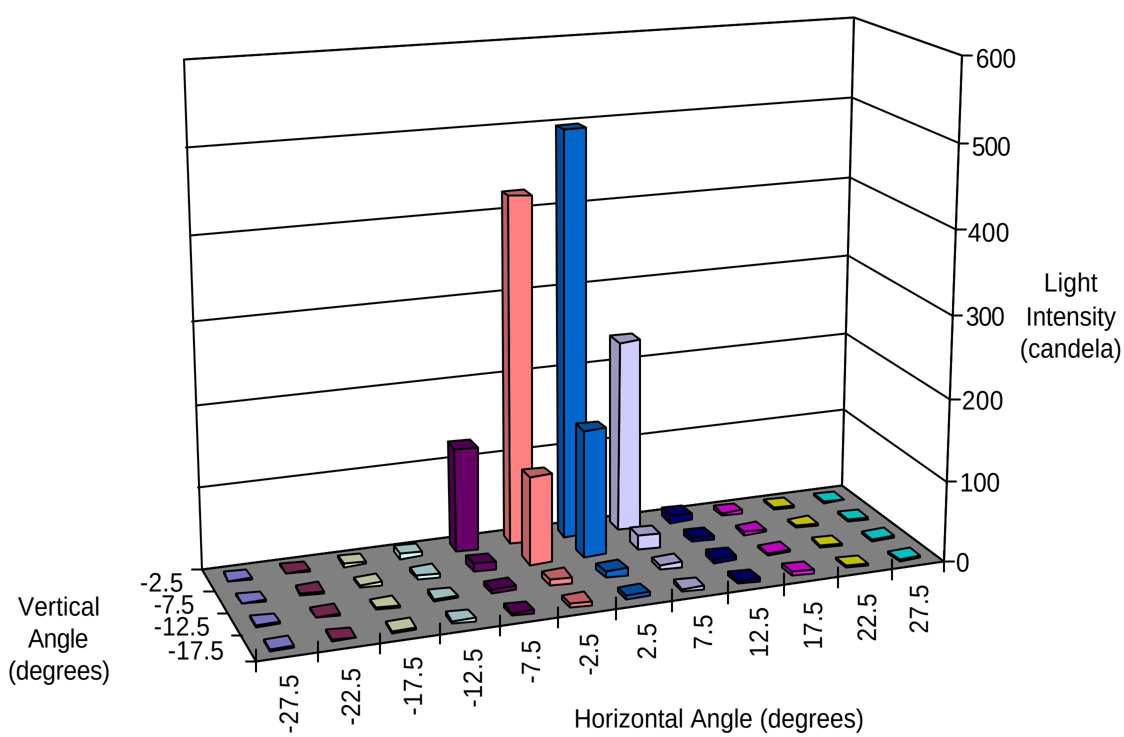

Figure A7.2.8b Output from WPS #7 (Red) signal, 10.0 volts, 46.0 ft, all elements on, ITE test.

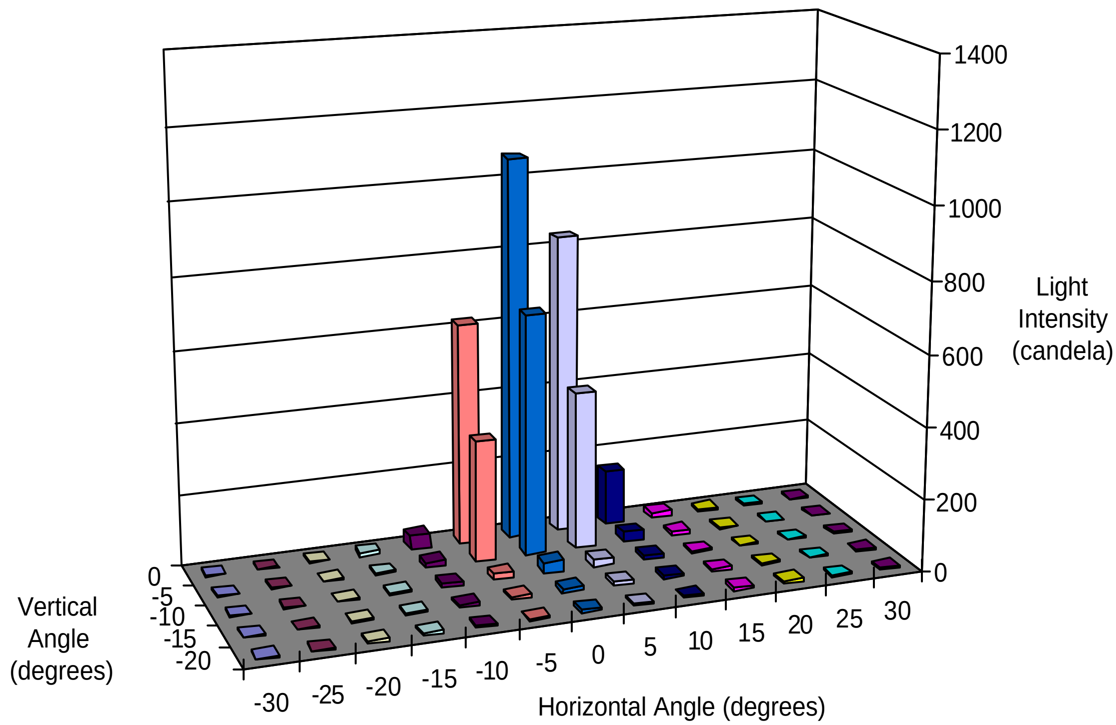

Figure A7.3.1a Output from WPS #7 (Red) signal, 10.0 volts, 46.0 ft, all elements on, TC test.

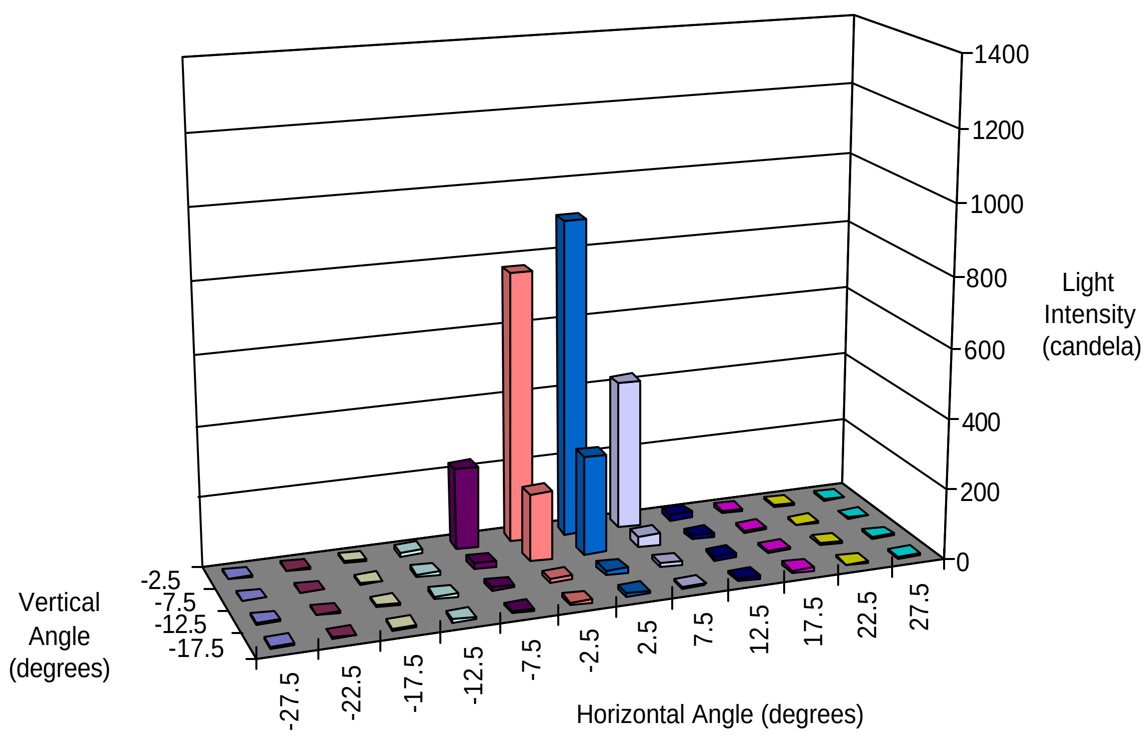

Figure A7.3.1b Output from WPS #7 (Red) signal, 10.0 volts, 46.0 ft, all elements on, ITE test.

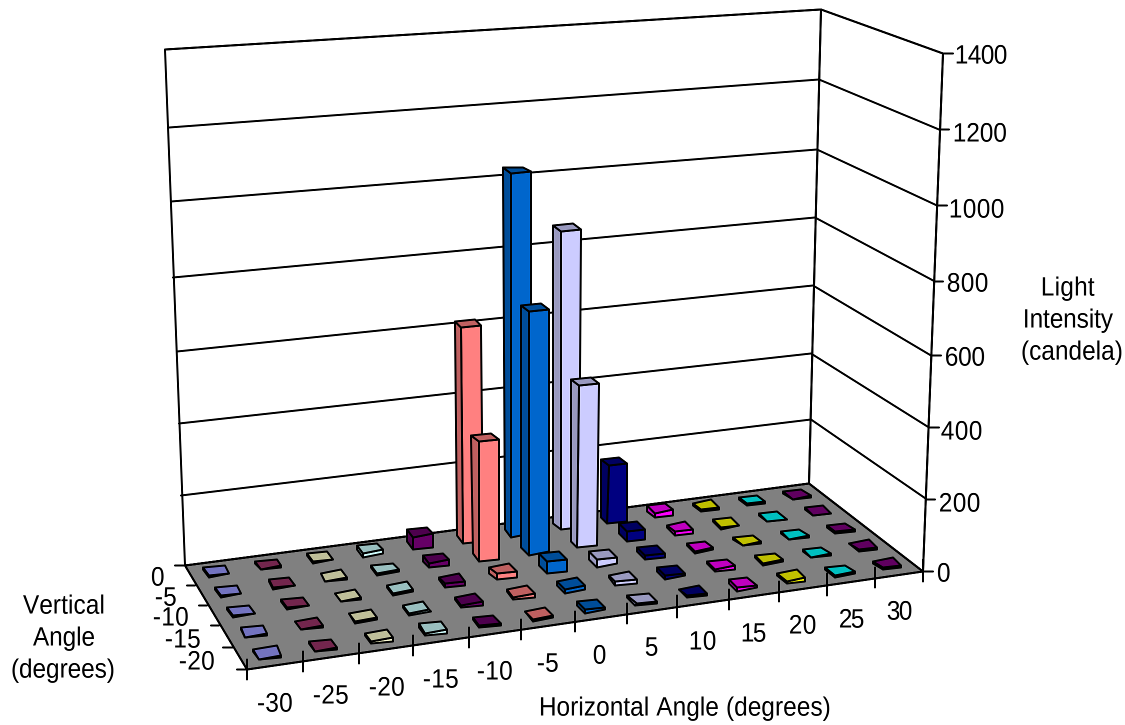

Figure A7.3.2a Output from WPS #7 (Red) signal, 10.0 volts, 44.0 ft, all elements on, TC test.

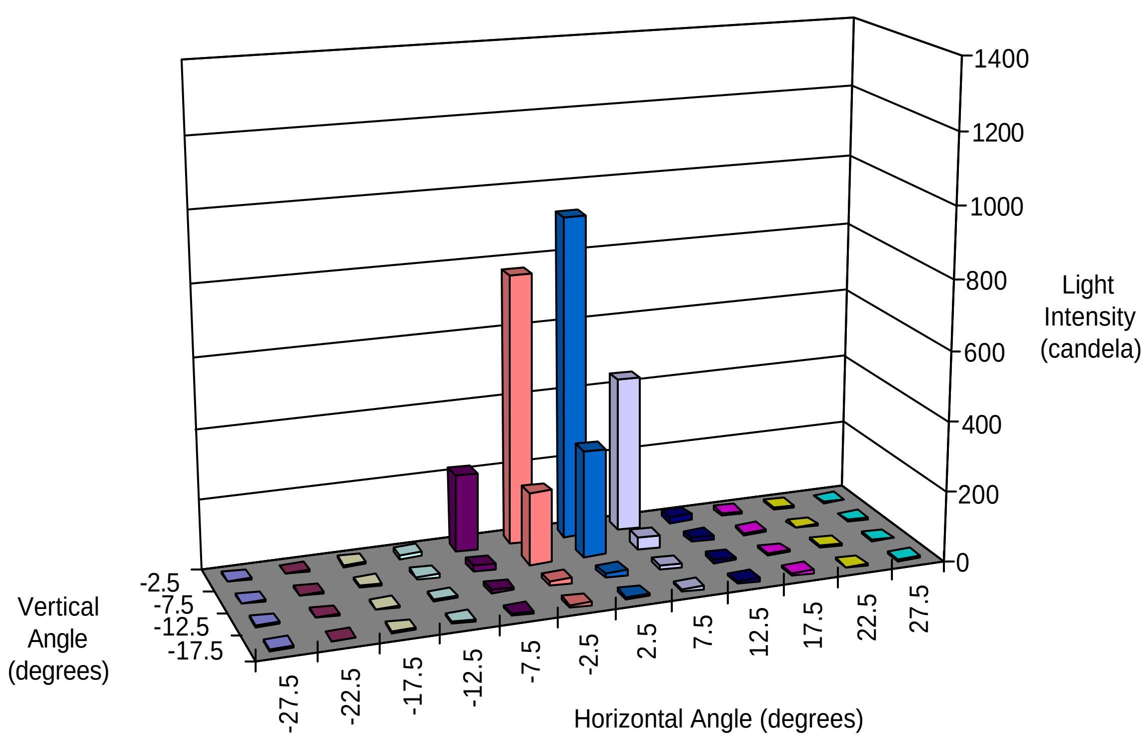

Figure A7.3.2b Output from WPS #7 (Red) signal, 10.0 volts, 44.0 ft, all elements on, ITE test.

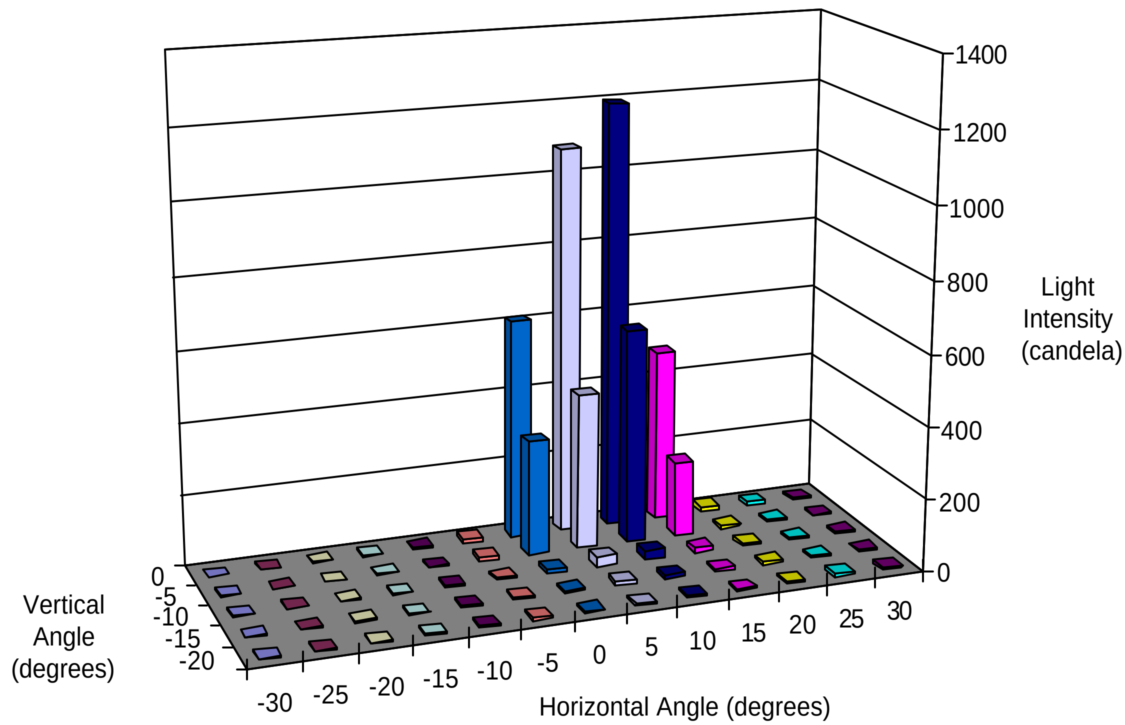

Figure A7.3.3a Output from WPS #7 (Red) signal, 10.0 volts, 42.0 ft, all elements on, TC test.

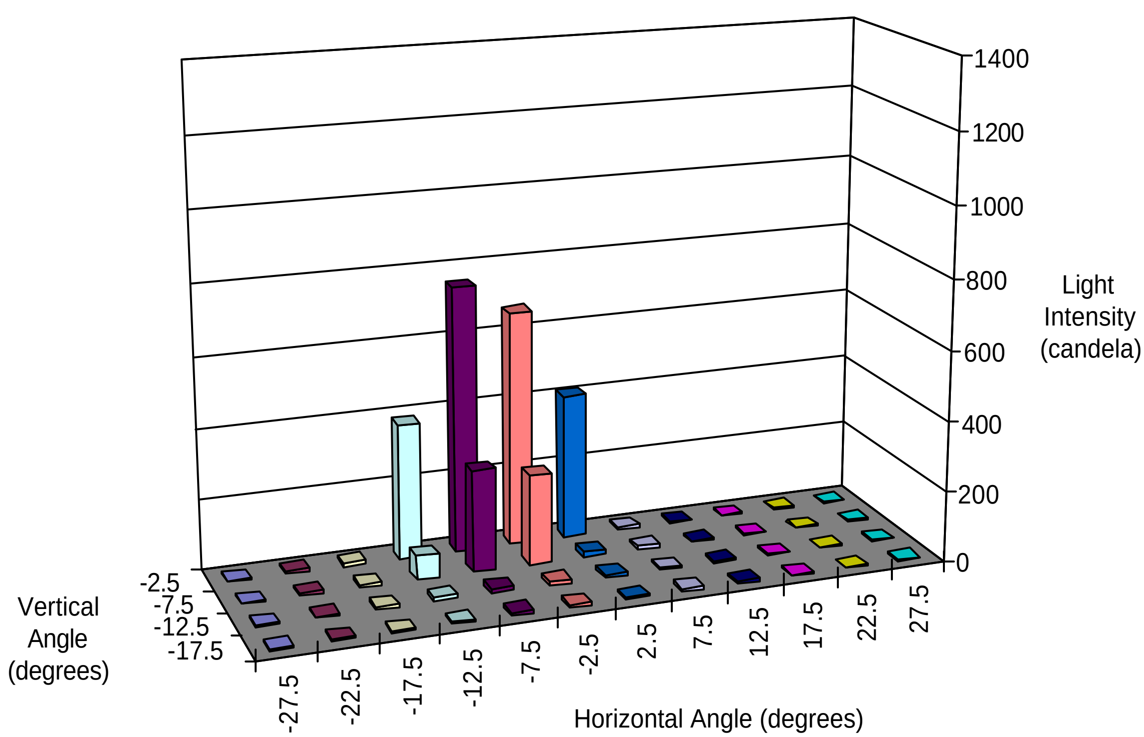

Figure A7.3.3b Output from WPS #7 (Red) signal, 10.0 volts, 42.0 ft, all elements on, ITE test.

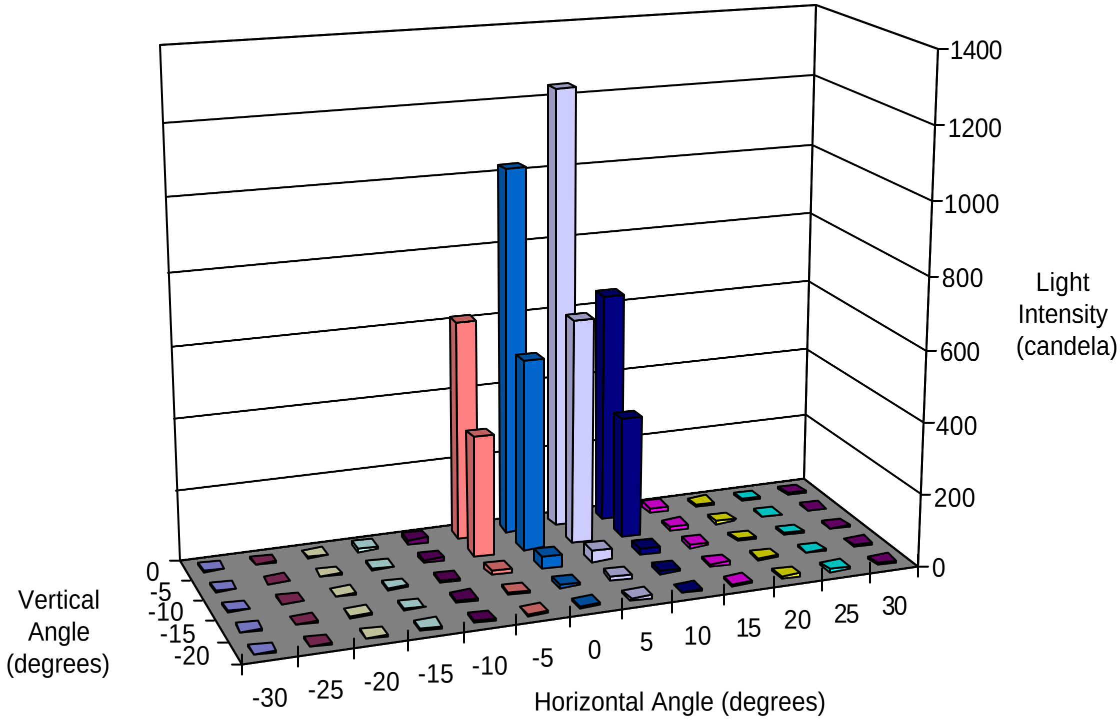

Figure A7.3.4a Output from WPS #7 (Red) signal, 10.0 volts, 40.0 ft, all elements on, TC test.

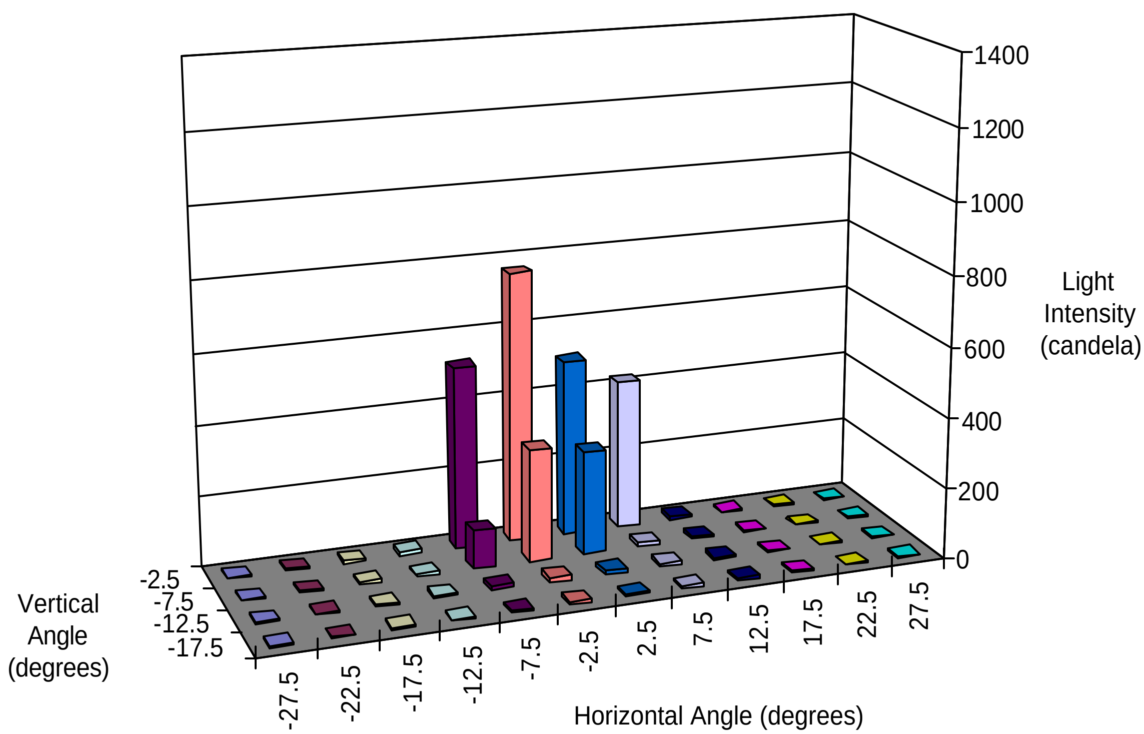

Figure A7.3.4b Output from WPS #7 (Red) signal, 10.0 volts, 40.0 ft, all elements on, ITE test.

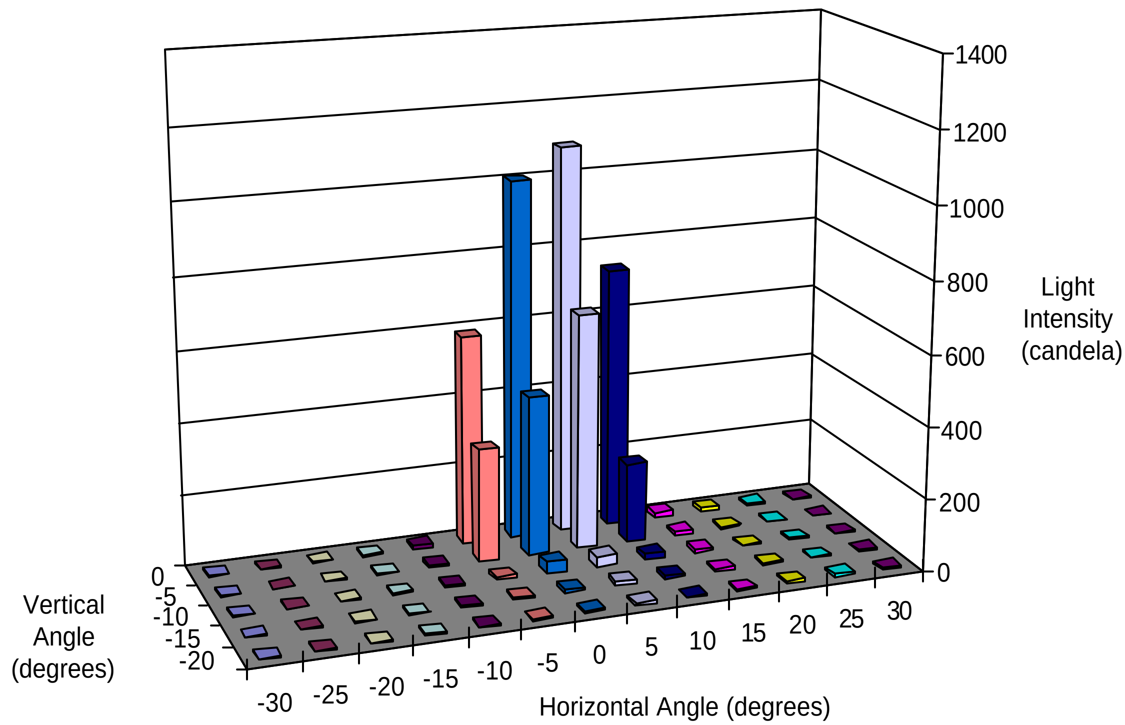

Figure A7.3.5a Output from WPS #7 (Red) signal, 10.0 volts, 38.0 ft, all elements on, TC test.

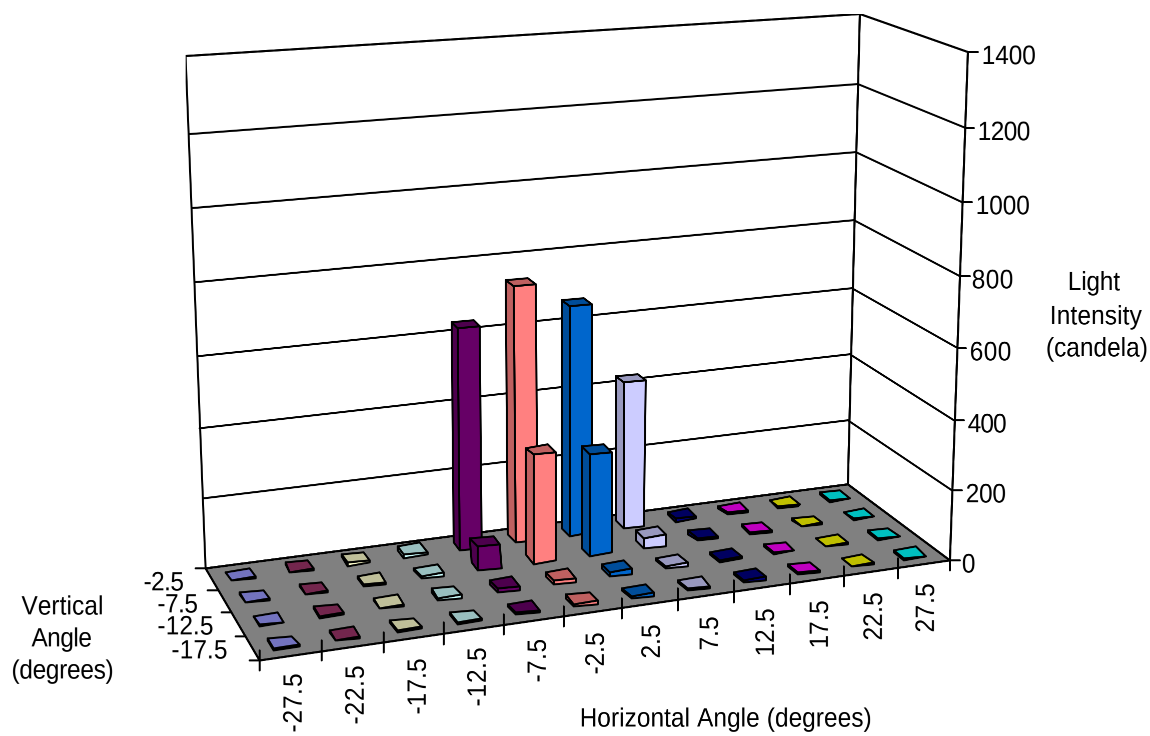

Figure A7.3.5b Output from WPS #7 (Red) signal, 10.0 volts, 38.0 ft, all elements on, ITE test.

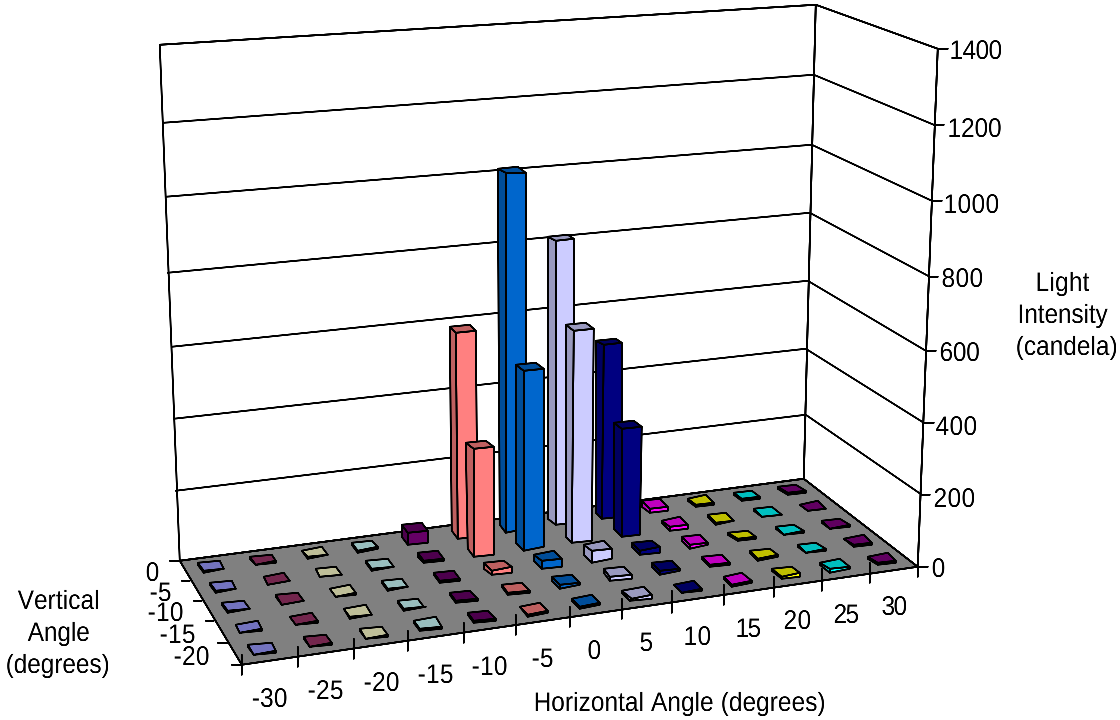

Figure A7.3.6a Output from WPS #7 (Red) signal, 10.0 volts, 36.0 ft, all elements on, TC test.

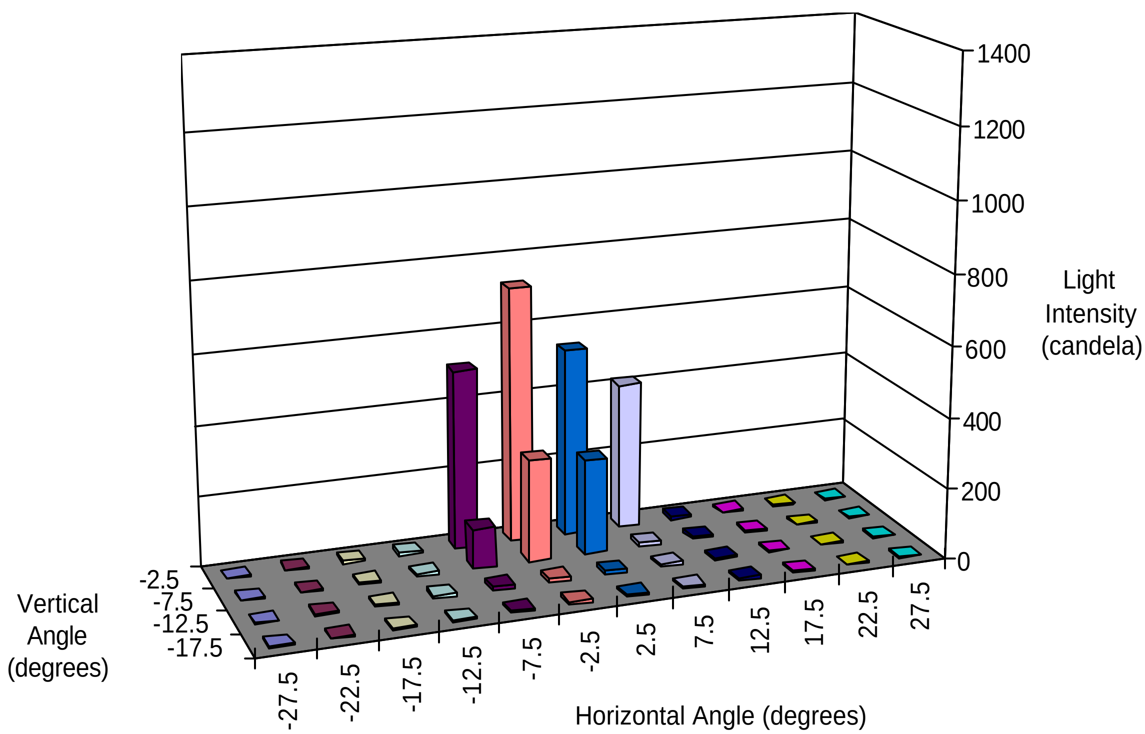

Figure A7.3.6b Output from WPS #7 (Red) signal, 10.0 volts, 36.0 ft, all elements on, ITE test.

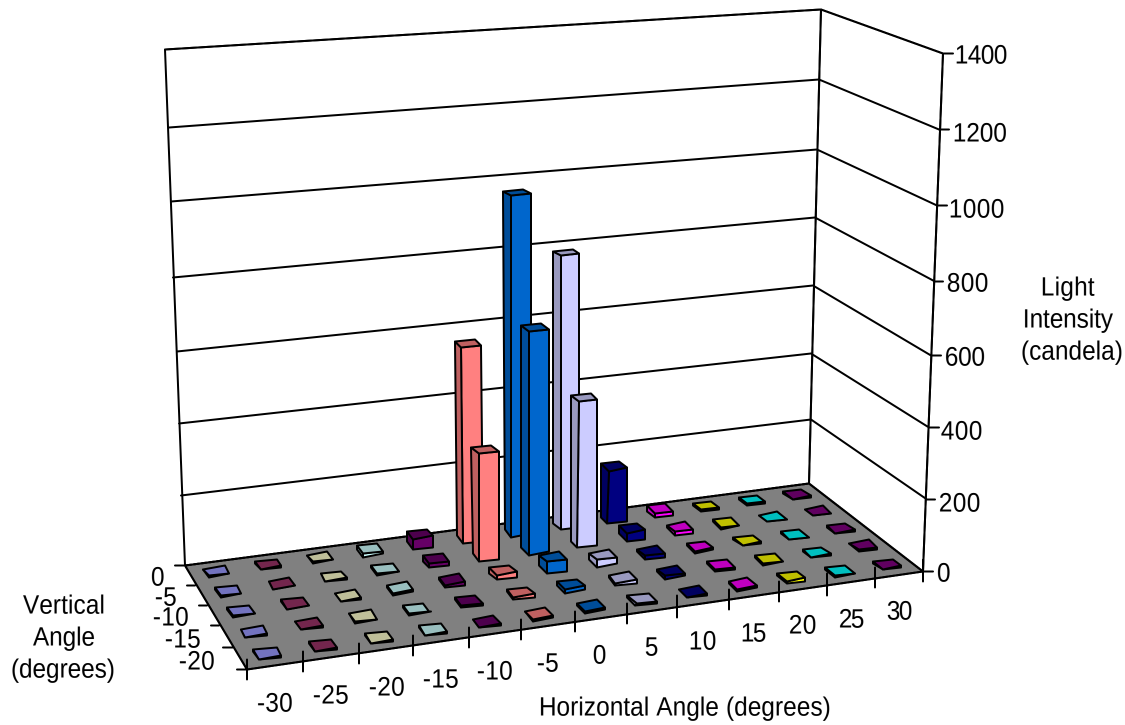

Figure A7.3.7a Output from WPS #7 (Red) signal, 10.0 volts, 34.0 ft, all elements on, TC test.

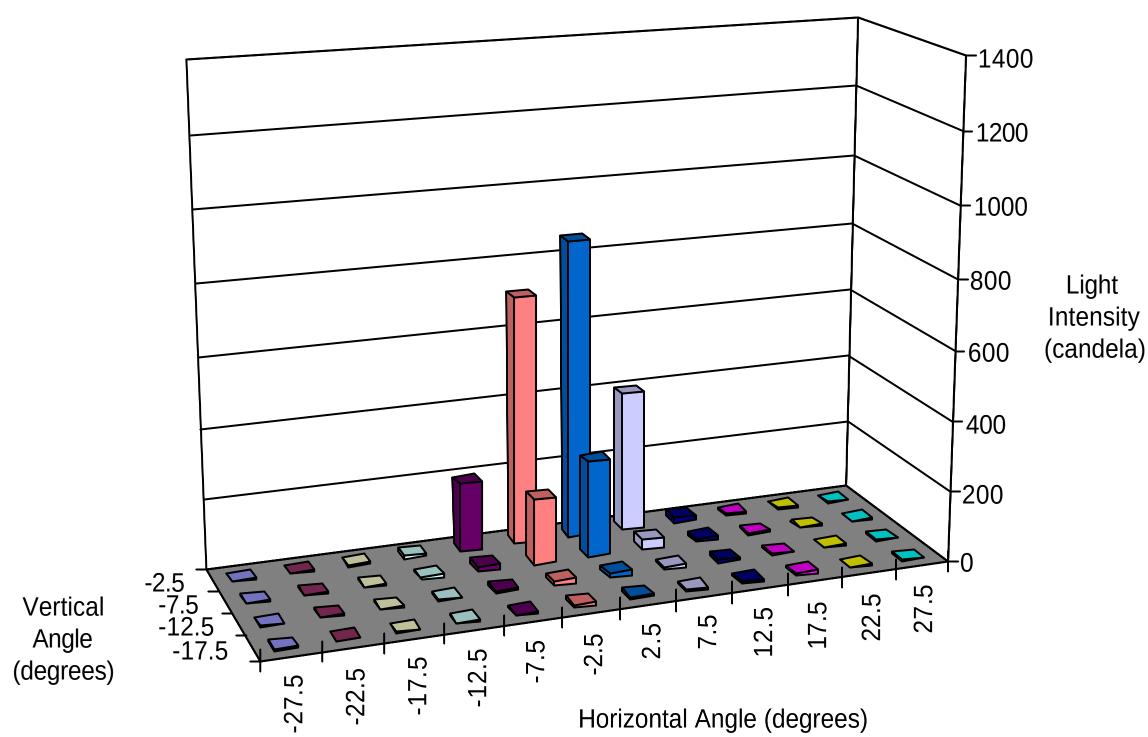

Figure A7.3.7b Output from WPS #7 (Red) signal, 10.0 volts, 34.0 ft, all elements on, ITE test.

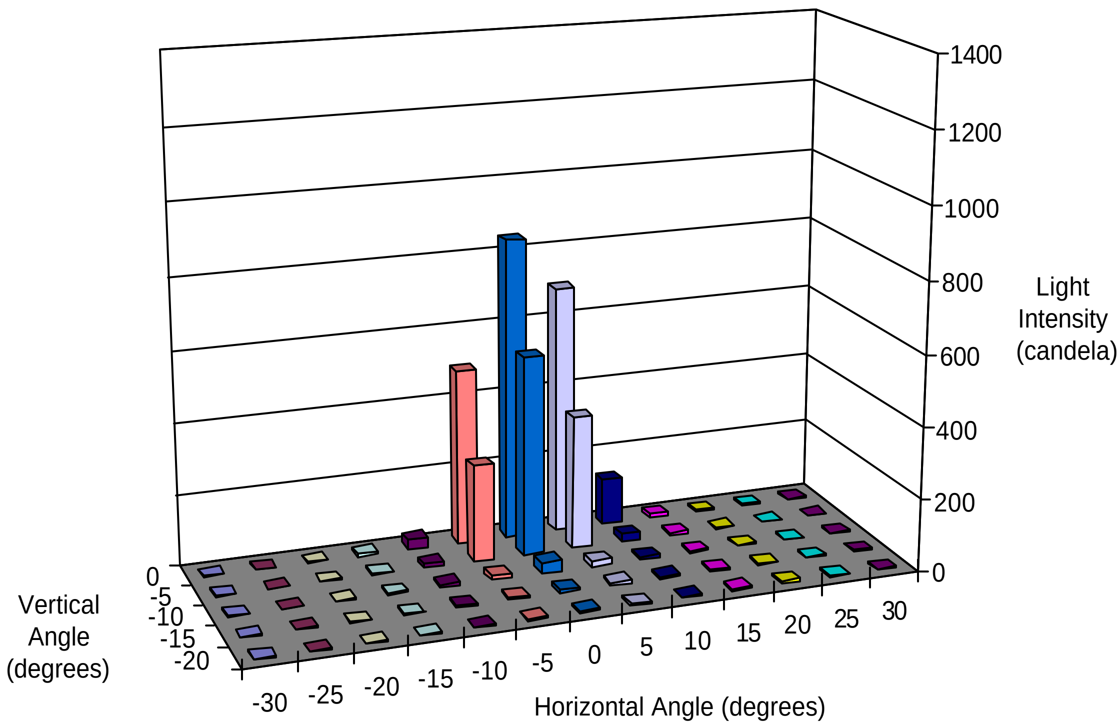

Figure A7.3.8a Output from WPS #7 (Red) signal, 10.0 volts, 32.0 ft, all elements on, TC test.

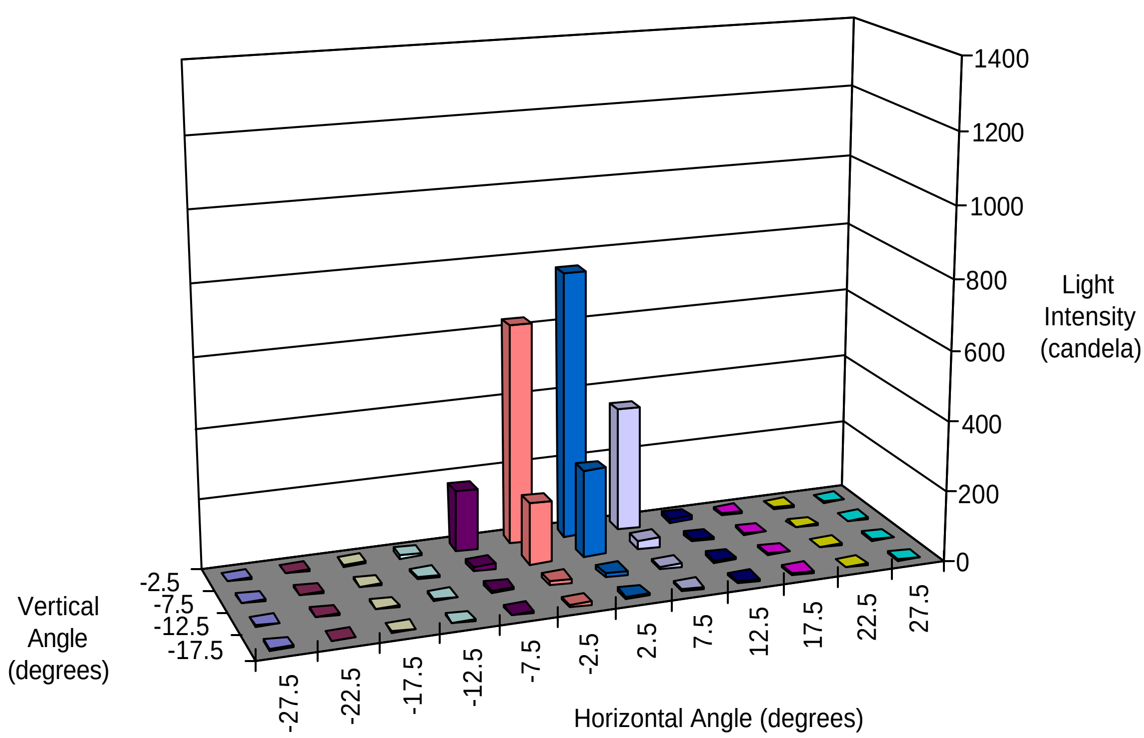

Figure A7.3.8b Output from WPS #7 (Red) signal, 10.0 volts, 32.0 ft, all elements on, ITE test.

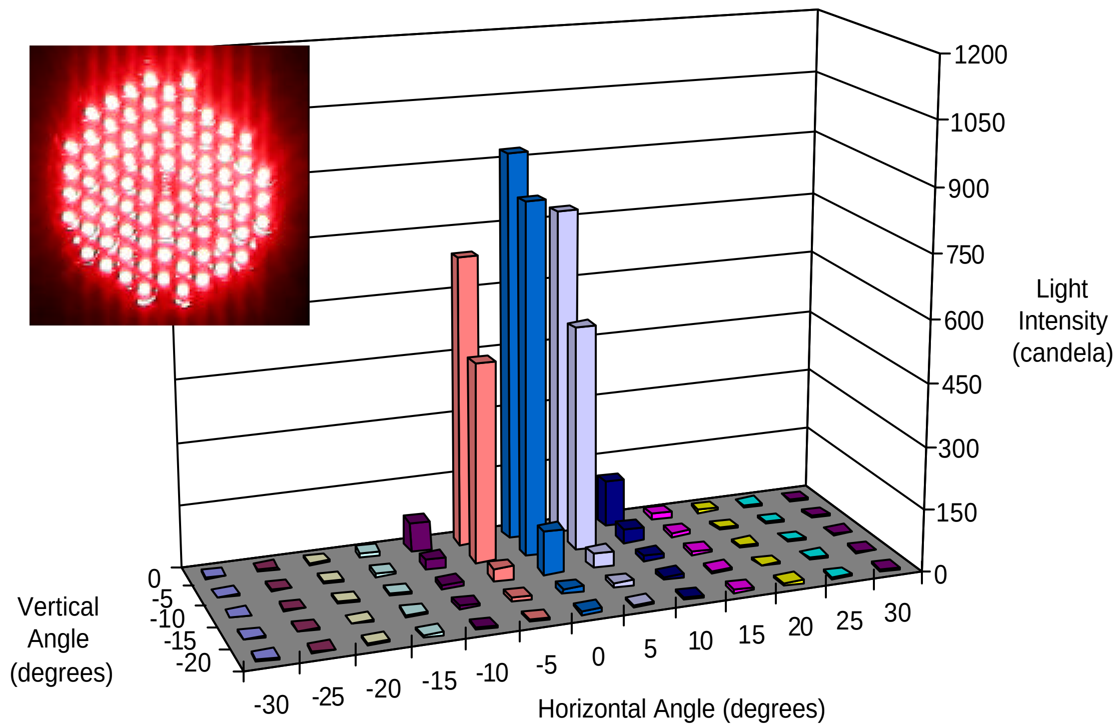

Figure A7.4.1a Output from WPS #7 (Red) signal, 10.0 volts, 84 elements (95% on), TC test.

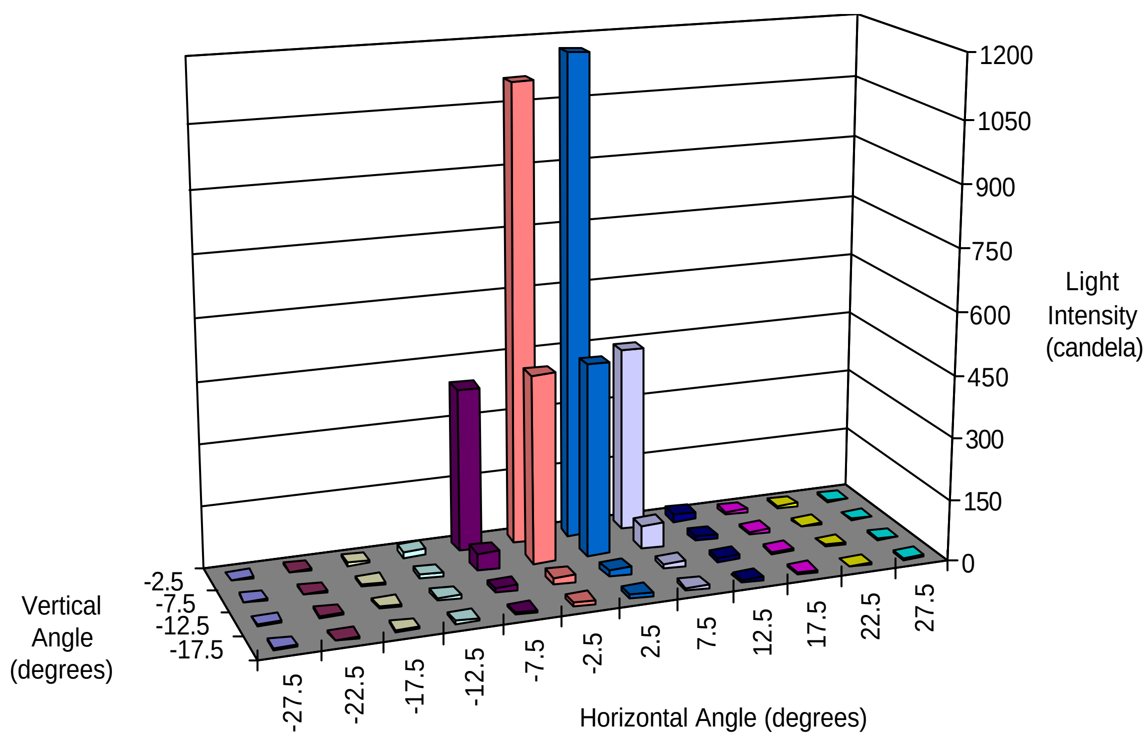

Figure A7.4.1b Output from WPS #7 (Red) signal, 10.0 volts, 84 elements (95% on), ITE test.

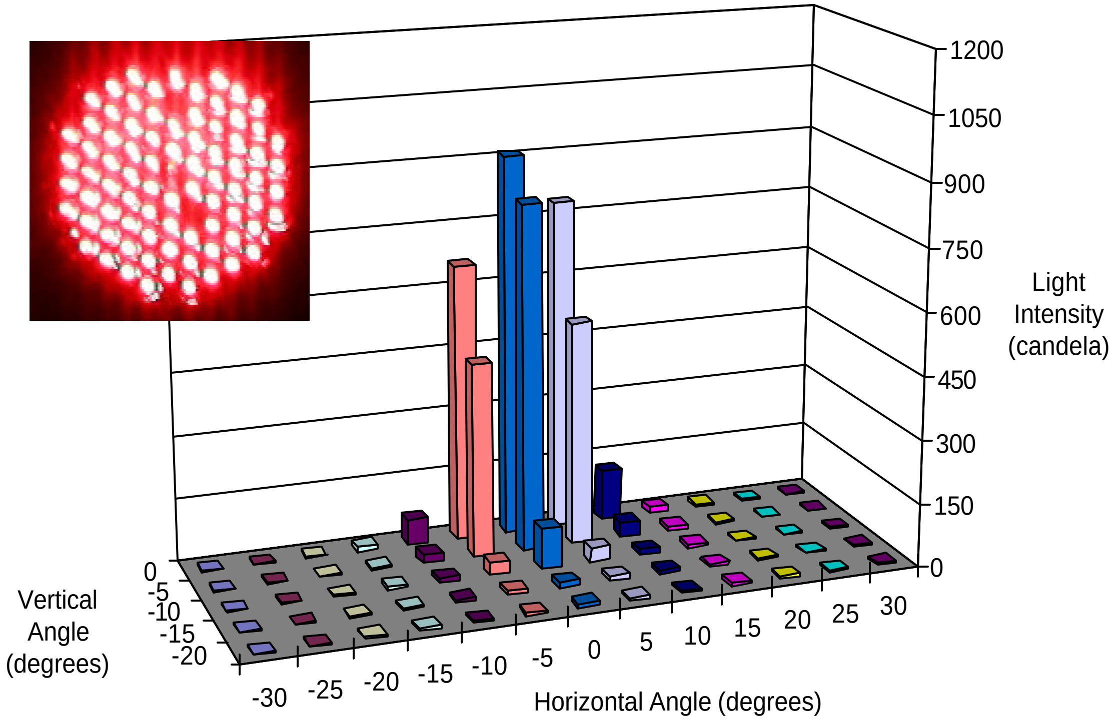

Figure A7.4.2a Output from WPS #7 (Red) signal, 10.0 volts, 84 elements (95% on), TC test.

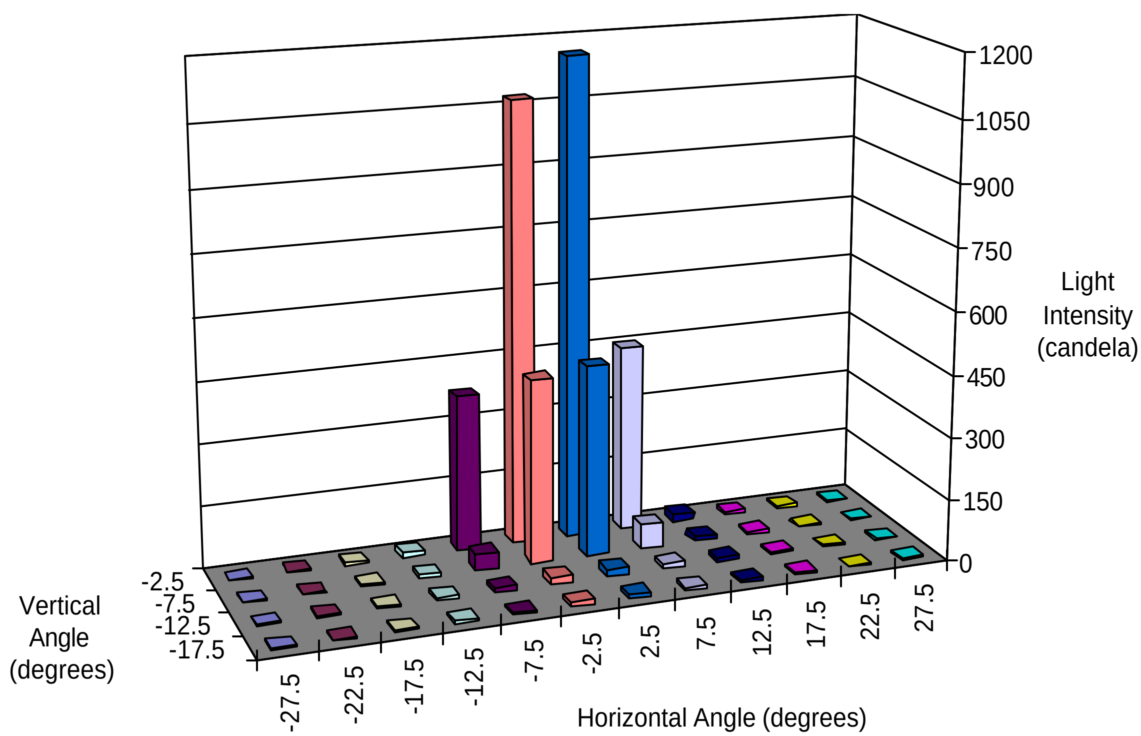

Figure A7.4.2b Output from WPS #7 (Red) signal, 10.0 volts, 84 elements (95% on), ITE test.

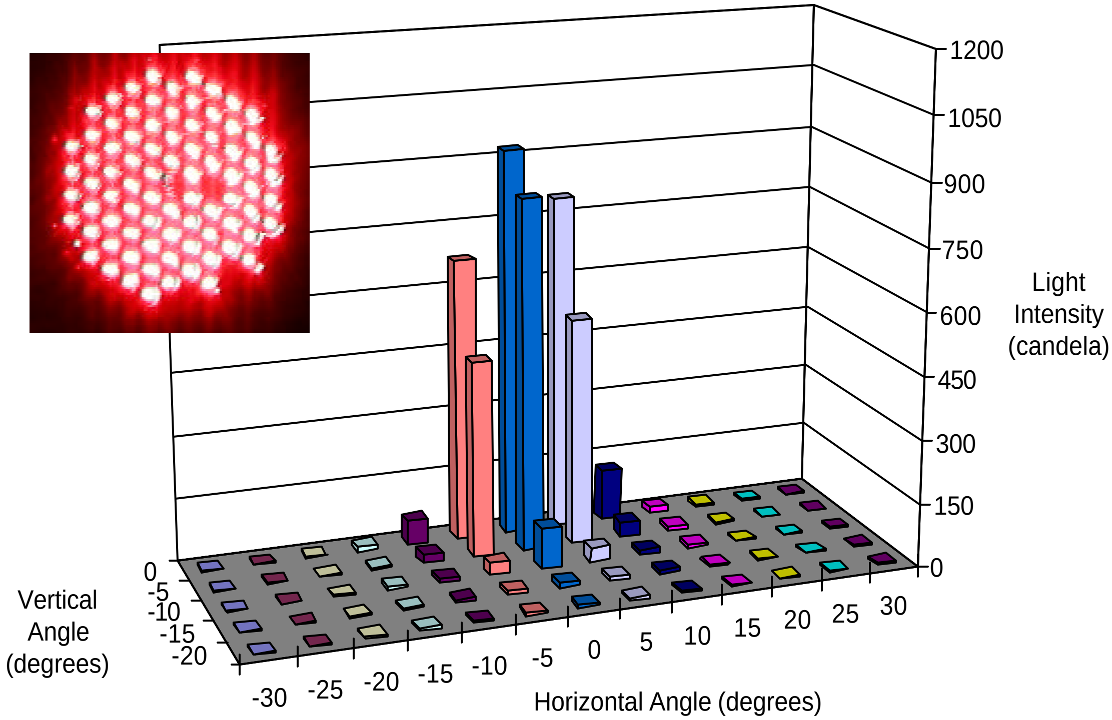

Figure A7.4.3a Output from WPS #7 (Red) signal, 10.0 volts, 84 elements (95% on), TC test.

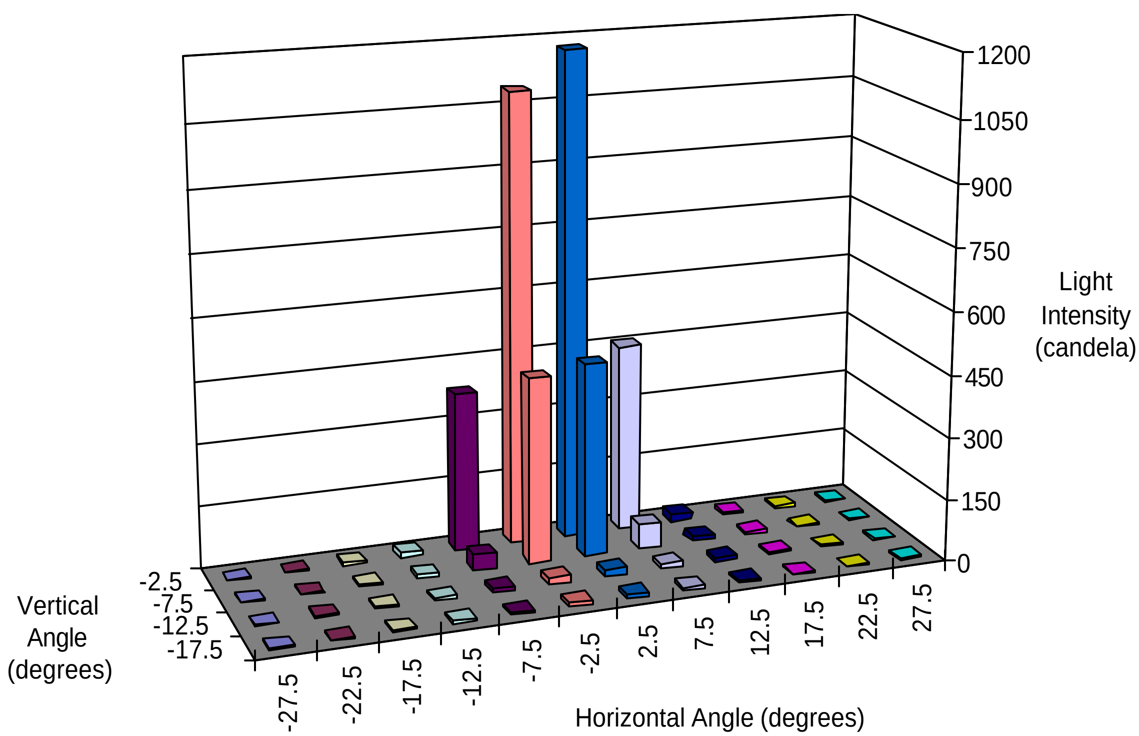

Figure A7.4.3b Output from WPS #7 (Red) signal, 10.0 volts, 84 elements (95% on), ITE test.

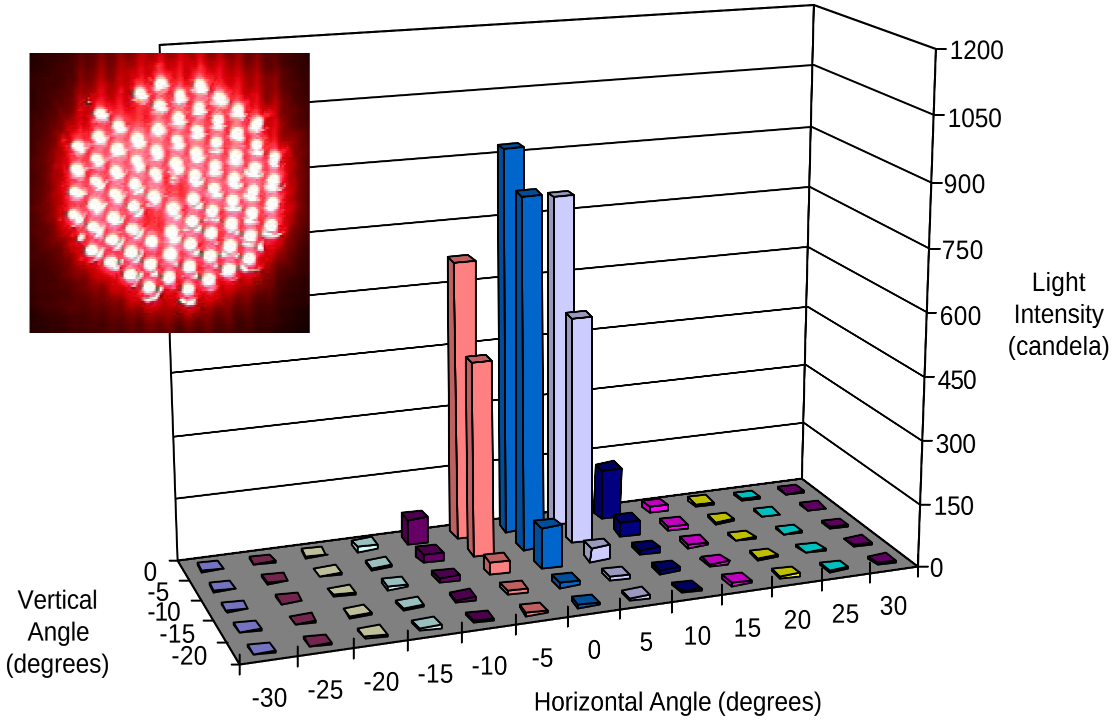

Figure A7.4.4a Output from WPS #7 (Red) signal, 10.0 volts, 84 elements (95% on), TC test.

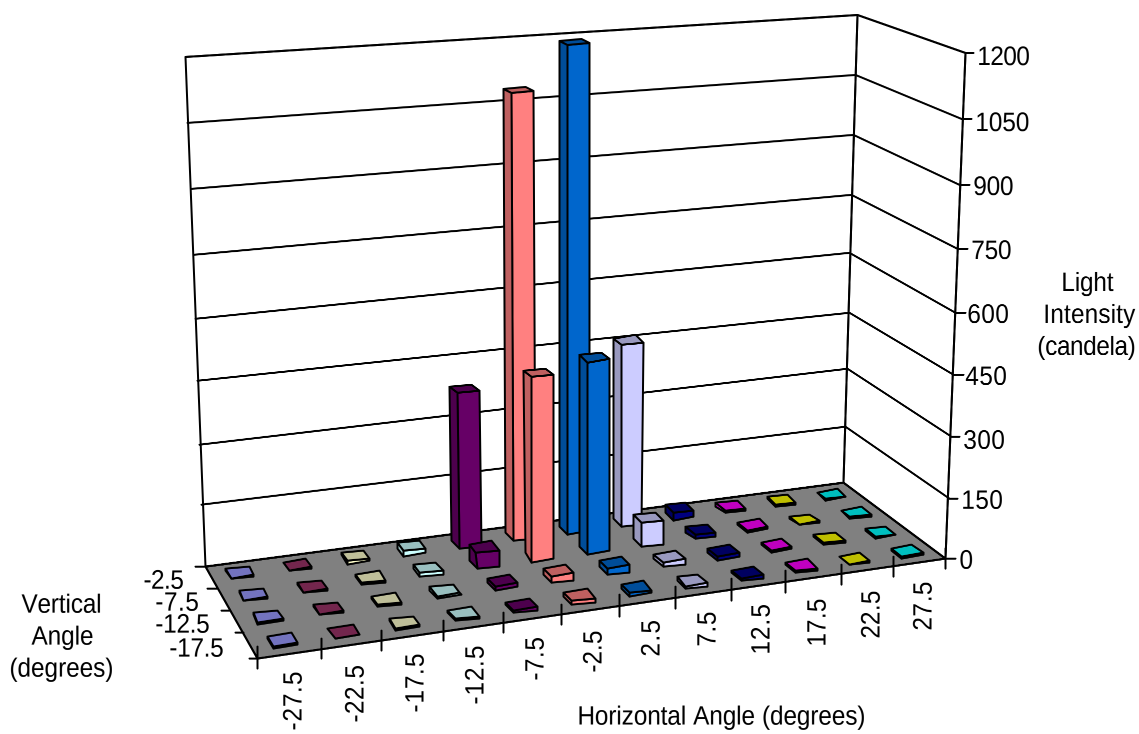

Figure A7.4.4b Output from WPS #7 (Red) signal, 10.0 volts, 84 elements (95% on), ITE test.

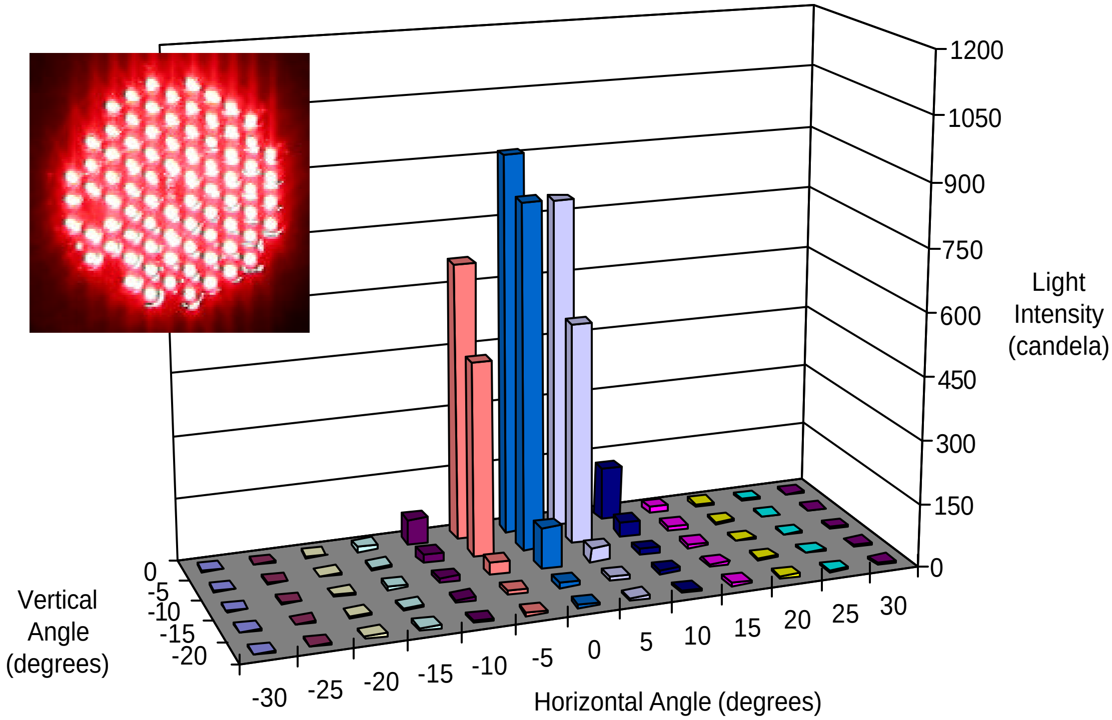

Figure A7.4.5a Output from WPS #7 (Red) signal, 10.0 volts, 84 elements (95% on), TC test.

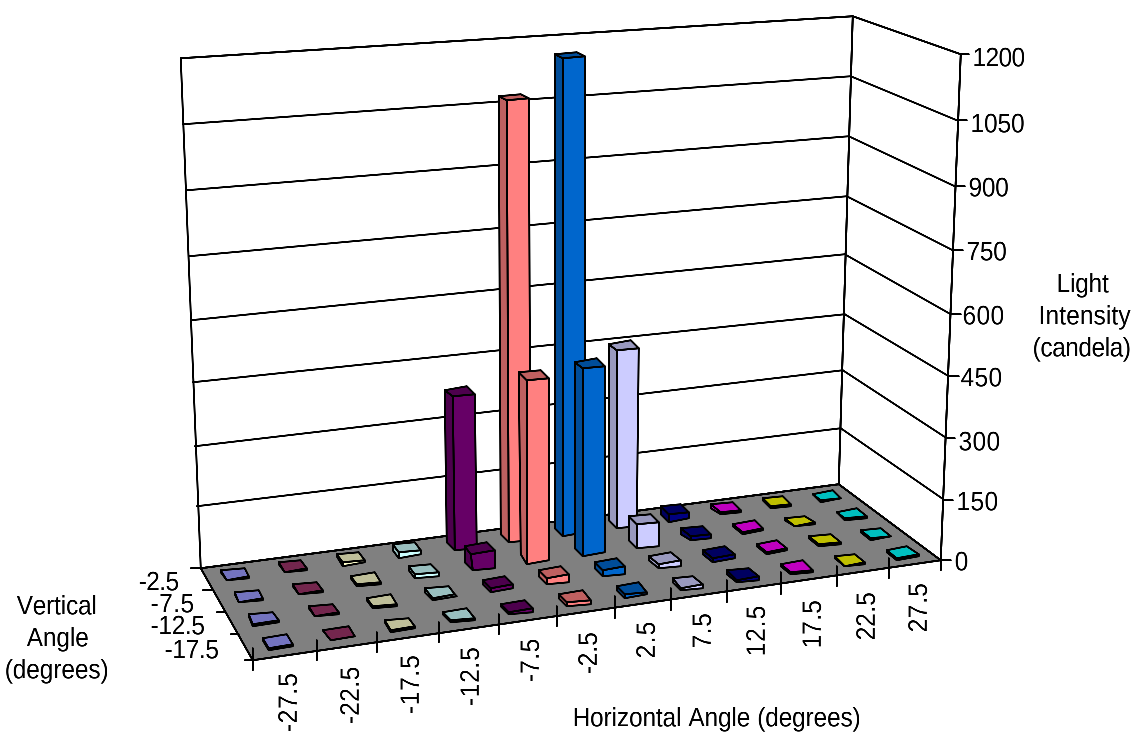

Figure A7.4.5b Output from WPS #7 (Red) signal, 10.0 volts, 84 elements (95% on), ITE test.

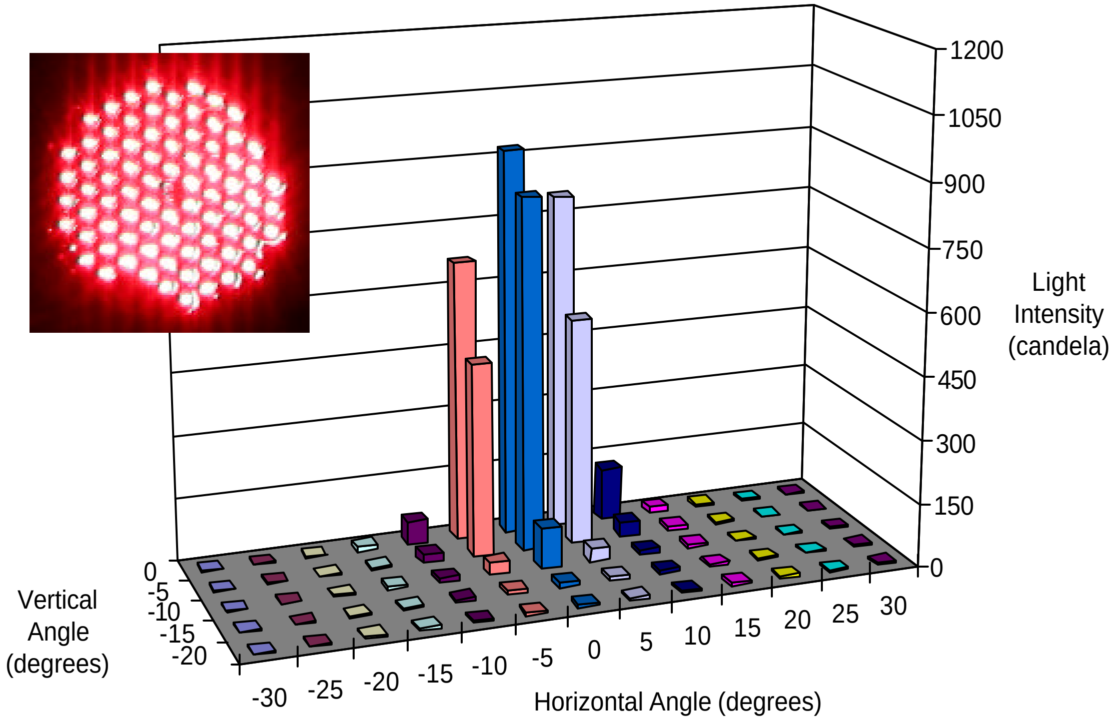

Figure A7.4.6a Output from WPS #7 (Red) signal, 10.0 volts, 84 elements (95% on), TC test.

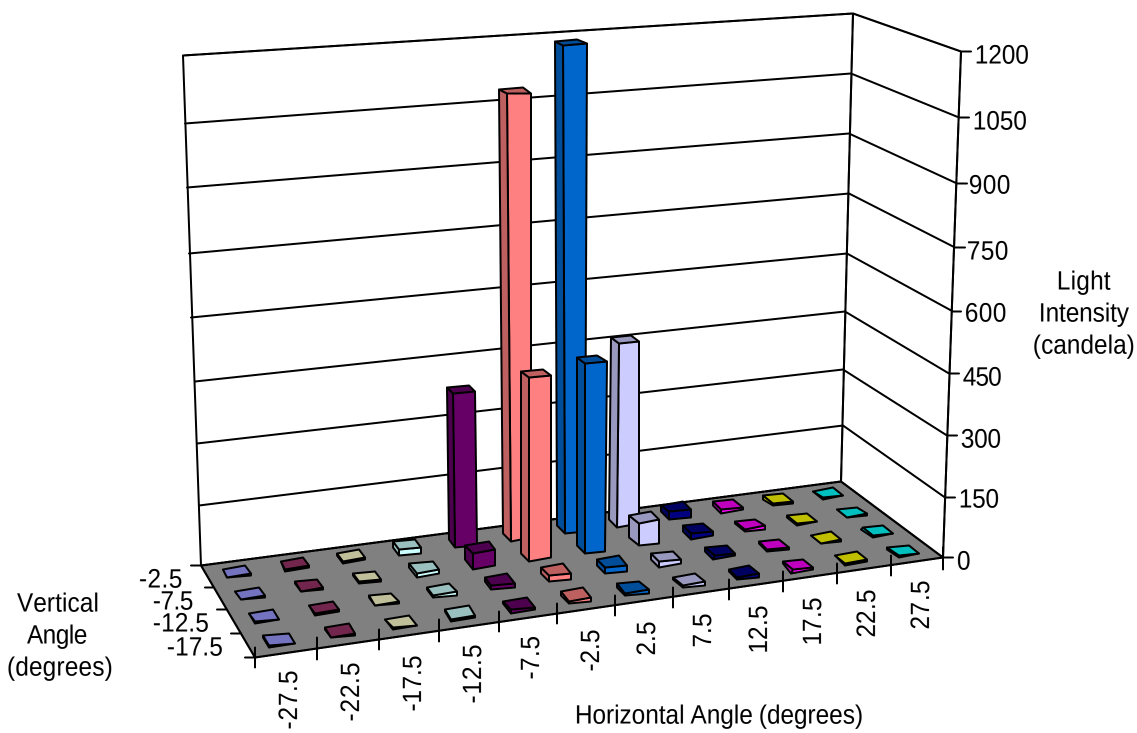

Figure A7.4.6b Output from WPS #7 (Red) signal, 10.0 volts, 84 elements (95% on), ITE test.

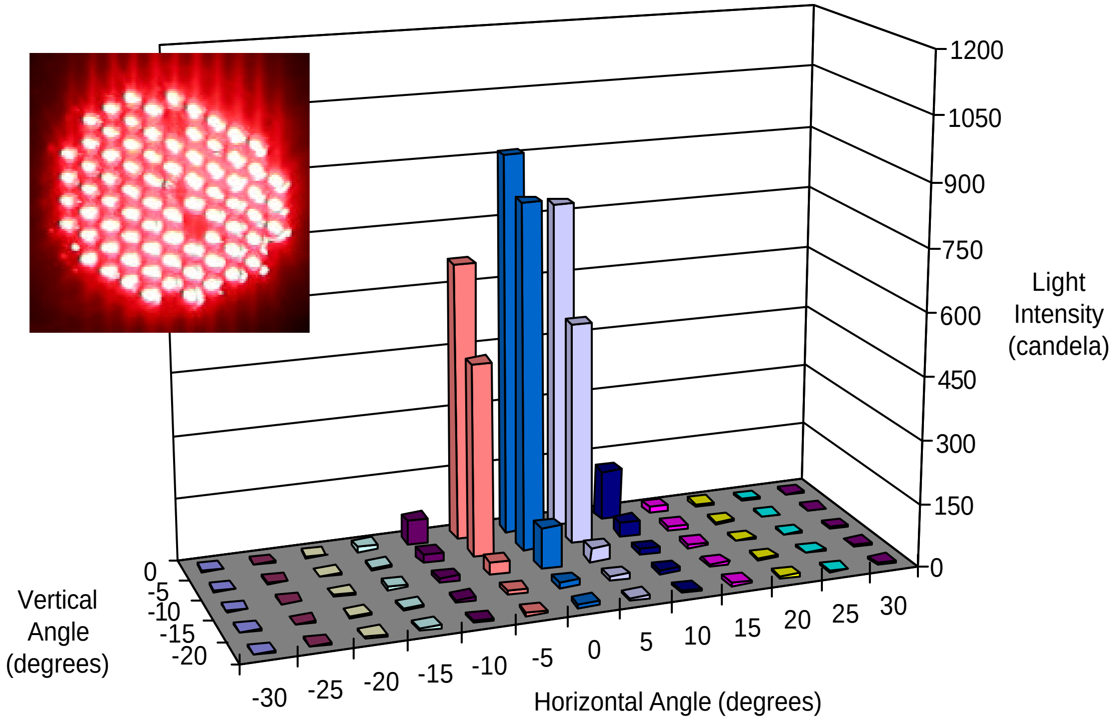

Figure A7.4.7a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90% on), TC test.

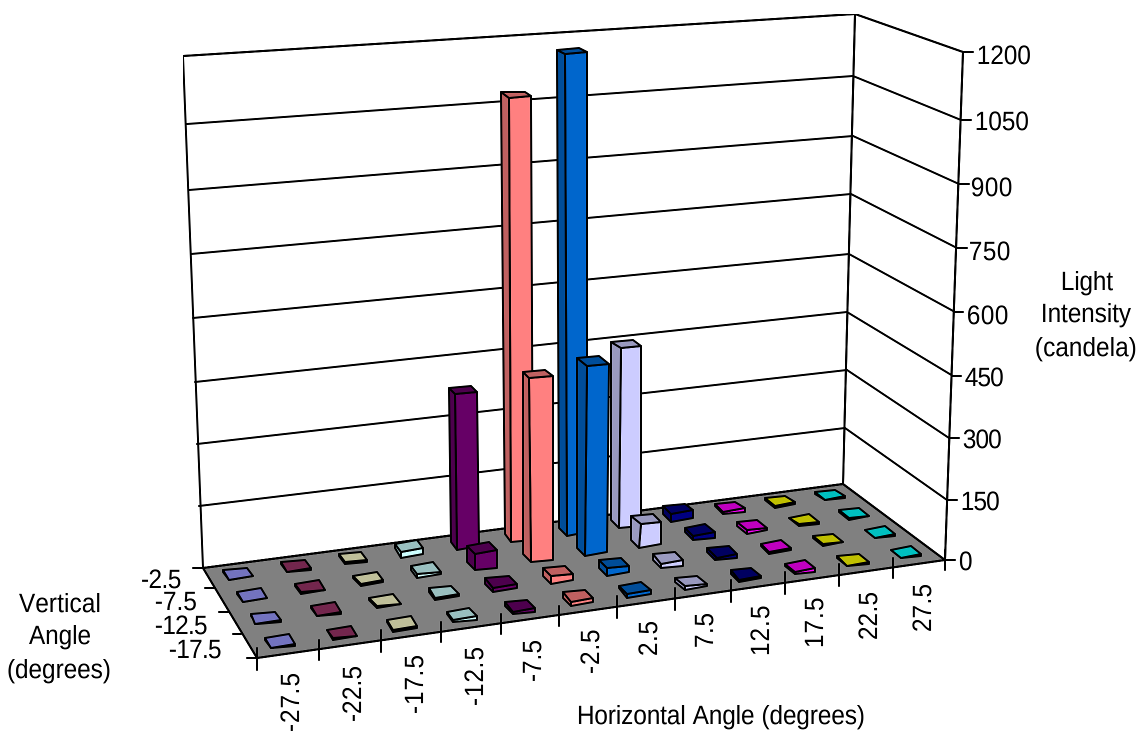

Figure A7.4.7b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90% on), ITE test.

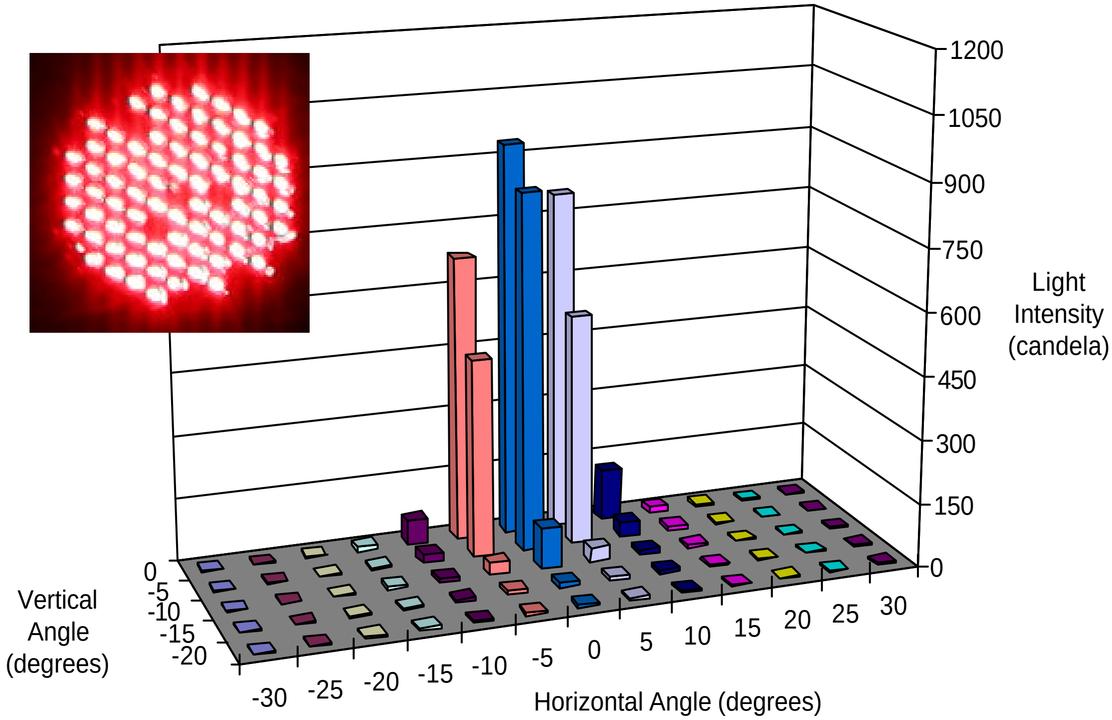

Figure A7.4.8a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90% on), TC test.

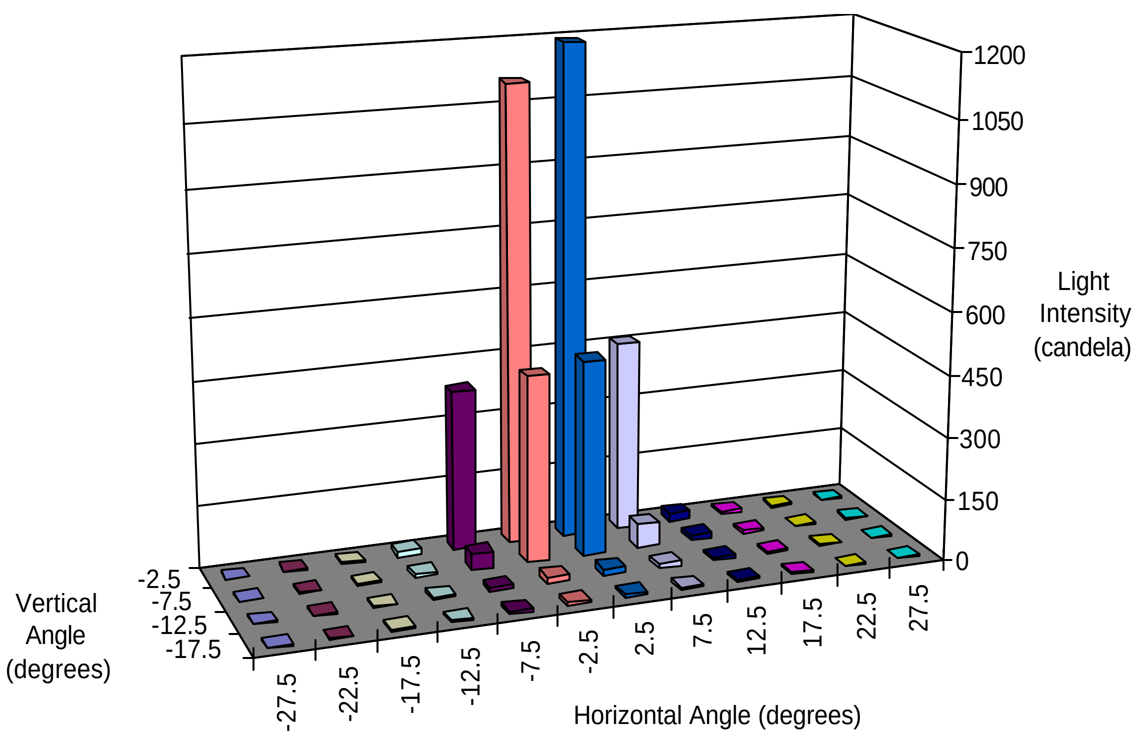

Figure A7.4.8b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90% on), ITE test.

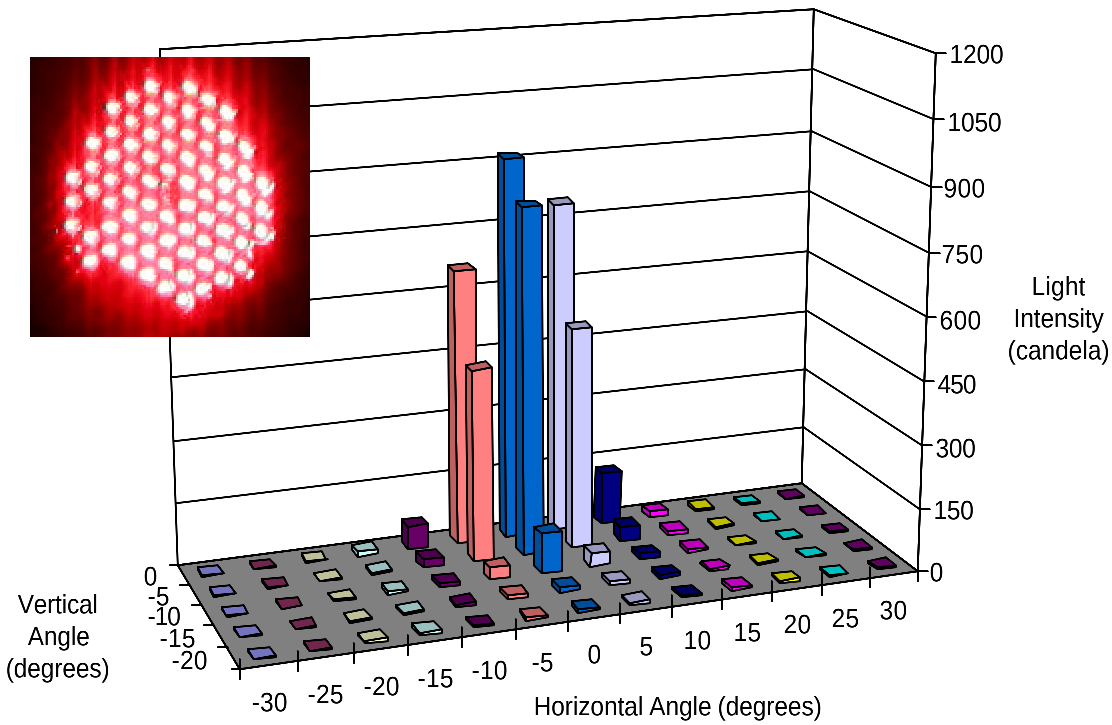

Figure A7.4.9a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90% on), TC test.

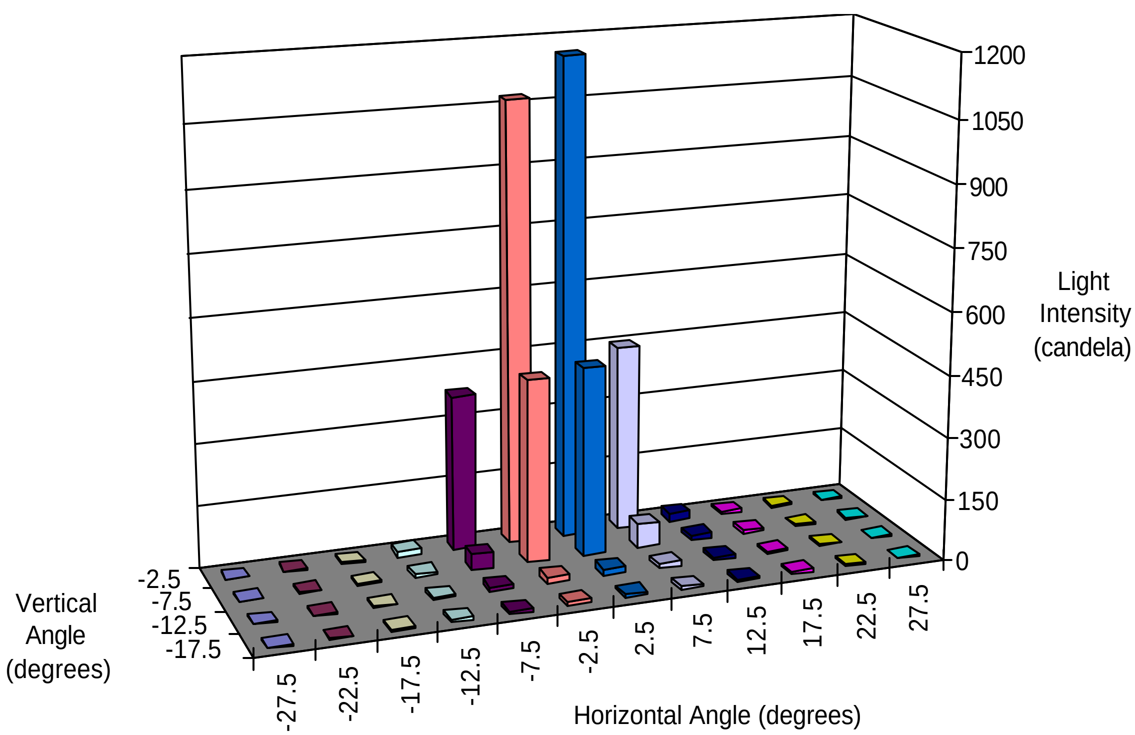

Figure A7.4.9b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90% on), ITE test.

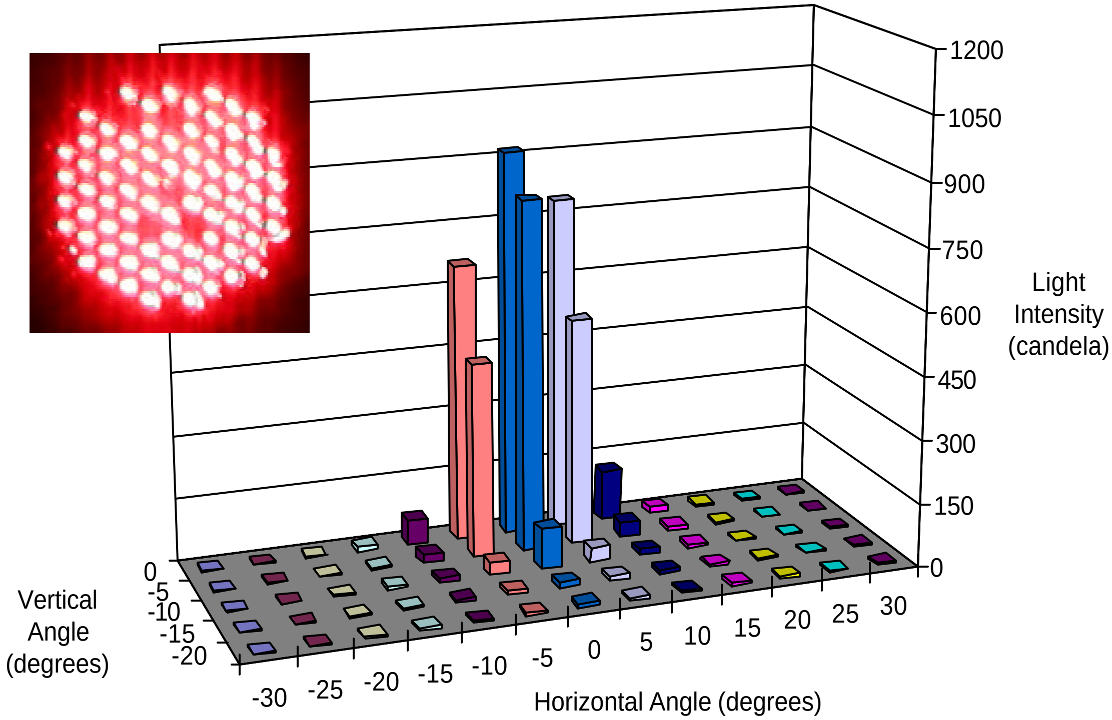

Figure A7.4.10a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90% on), TC test.

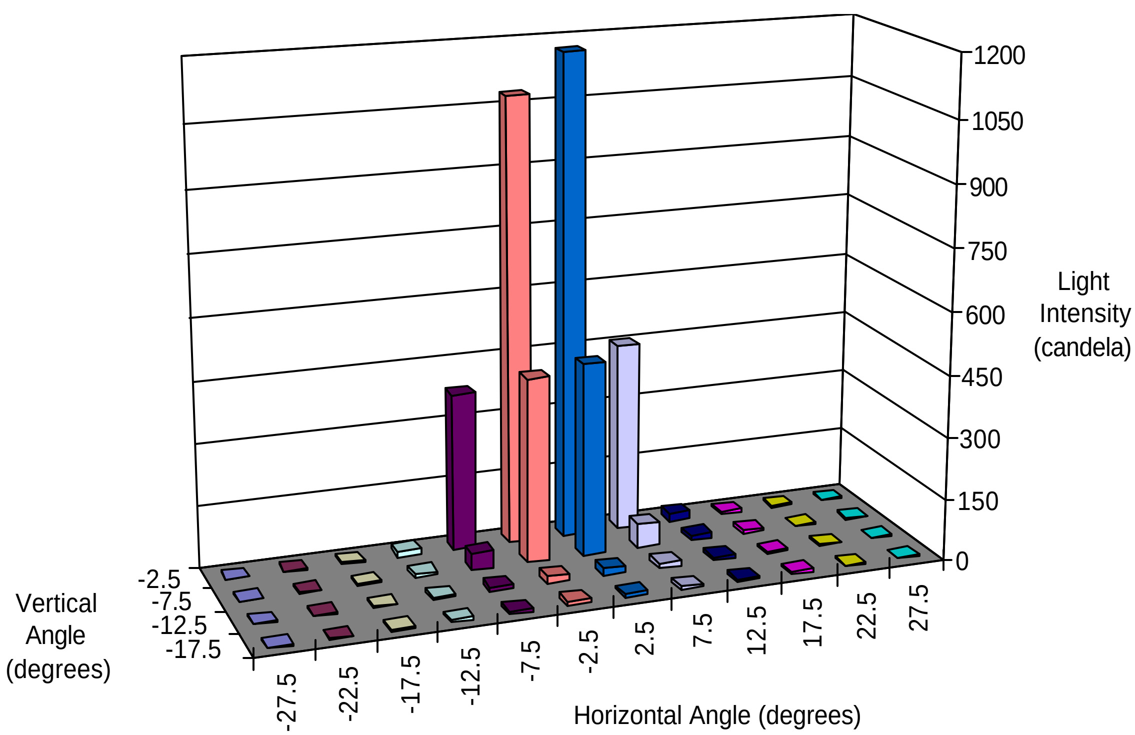

Figure A7.4.10b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90% on), ITE test.

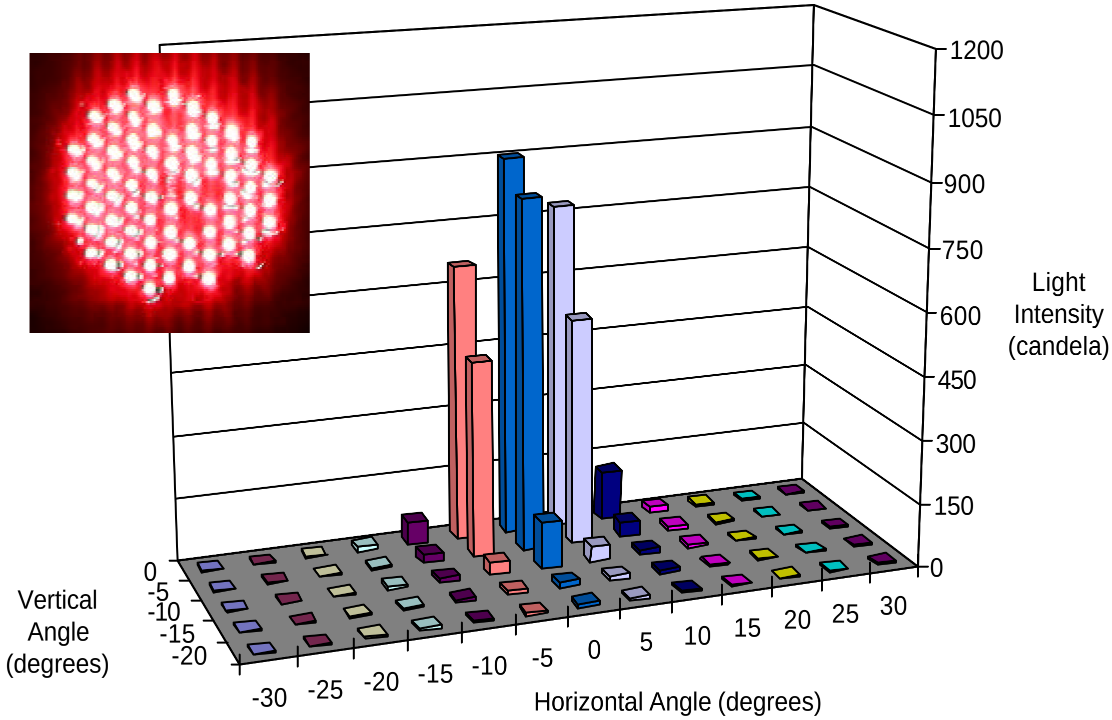

Figure A7.4.11a Output from WPS #7 (Red) signal, 10.0 volts, 76 elements (86% on), TC test.

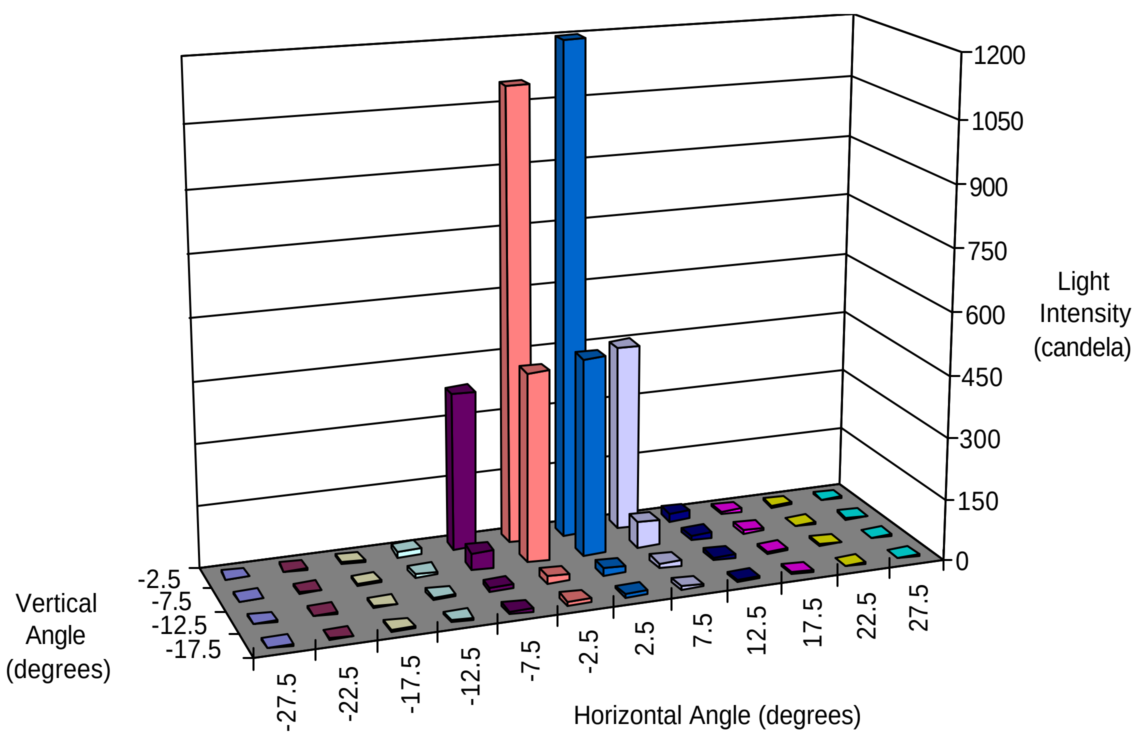

Figure A7.4.11b Output from WPS #7 (Red) signal, 10.0 volts, 76 elements (86% on), ITE test.

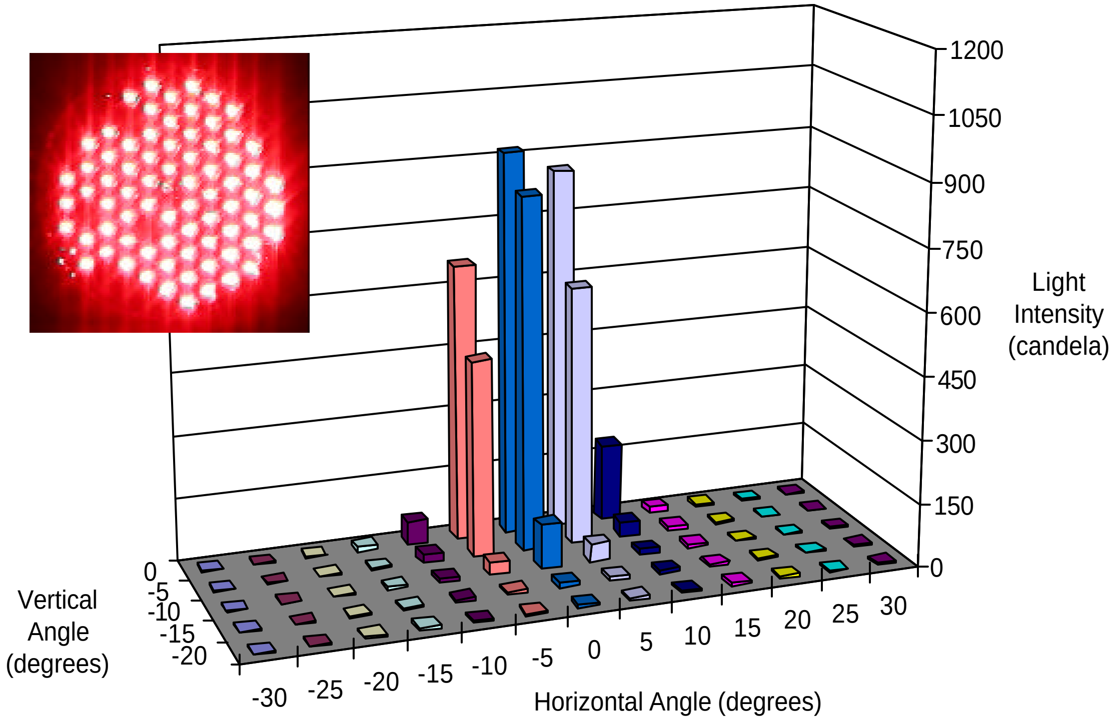

Figure A7.4.12a Output from WPS #7 (Red) signal, 10.0 volts, 76 elements (86% on), TC test.

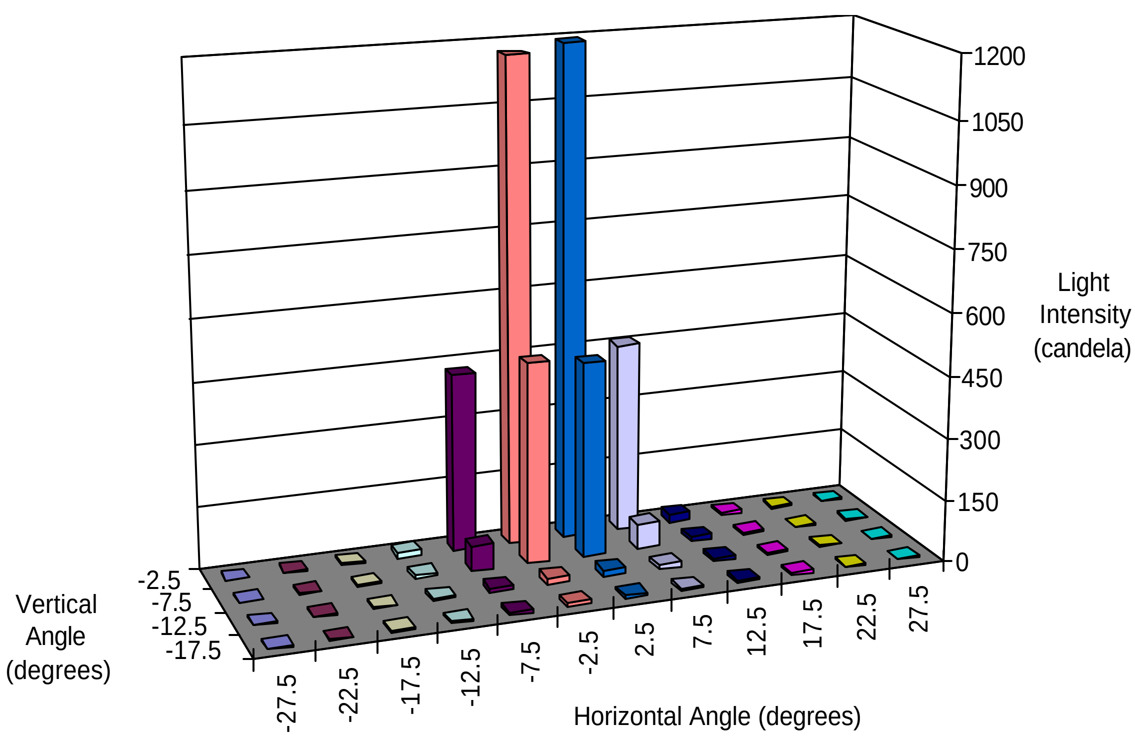

Figure A7.4.12b Output from WPS #7 (Red) signal, 10.0 volts, 76 elements (86% on), ITE test.

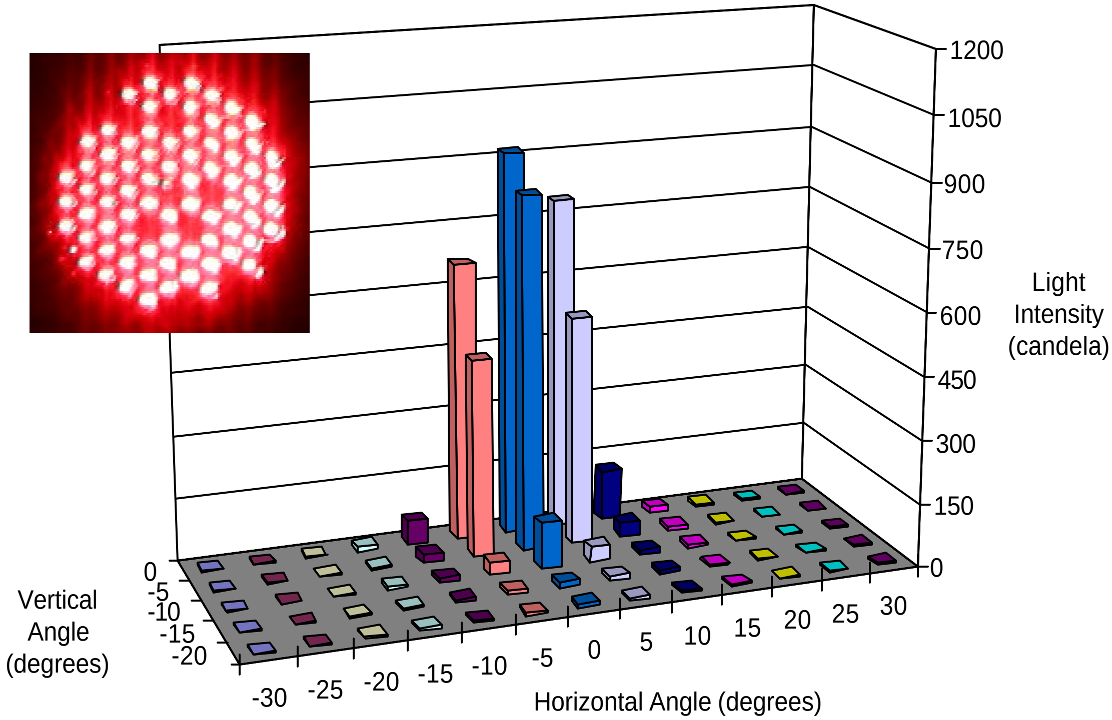

Figure A7.4.13a Output from WPS #7 (Red) signal, 10.0 volts, 76 elements (86% on), TC test.

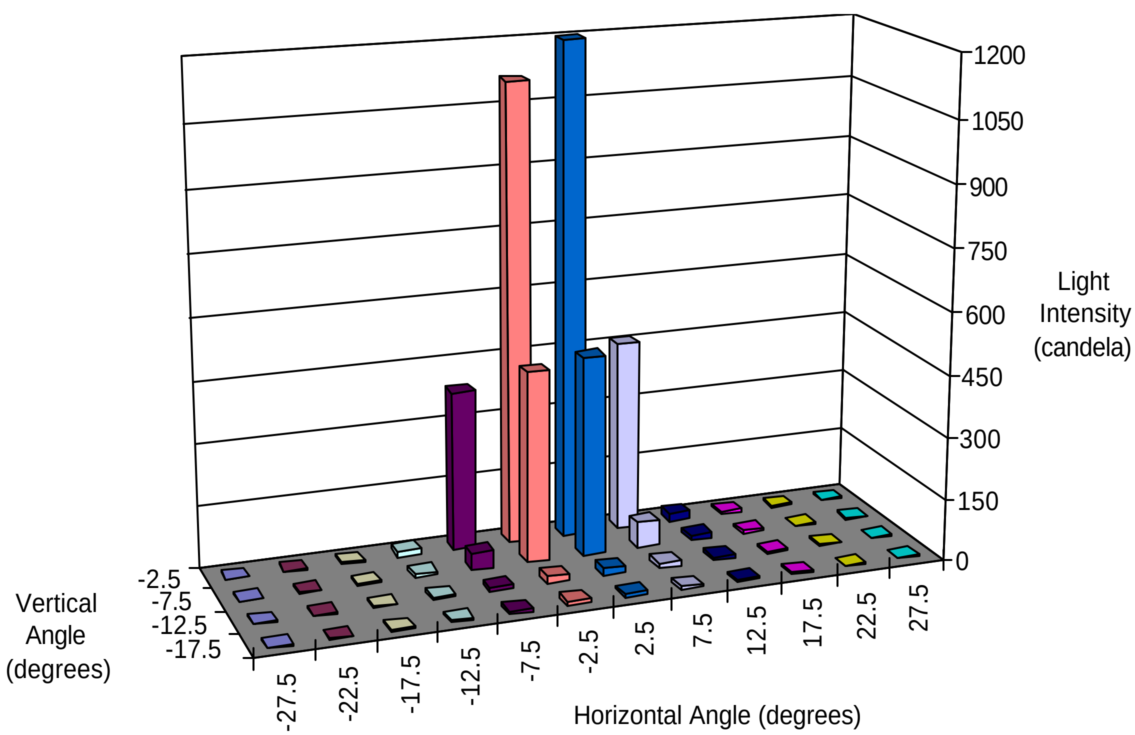

Figure A7.4.13b Output from WPS #7 (Red) signal, 10.0 volts, 76 elements (86% on), ITE test.

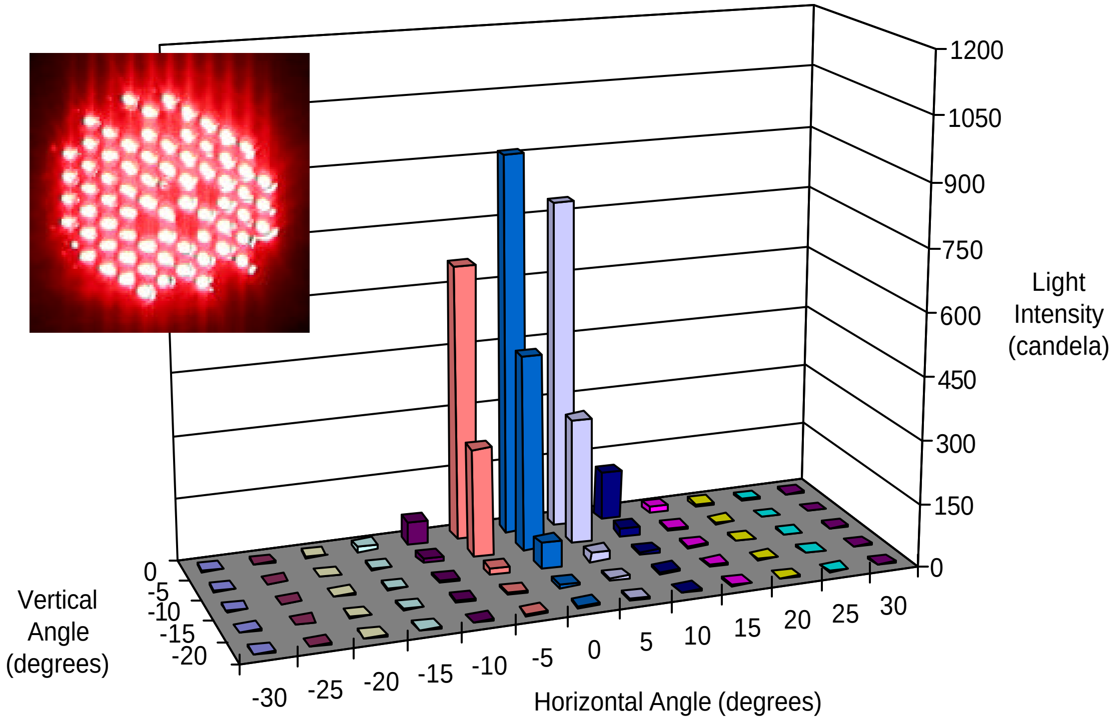

Figure A7.4.14a Output from WPS #7 (Red) signal, 10.0 volts, 72 elements (82% on), TC test.

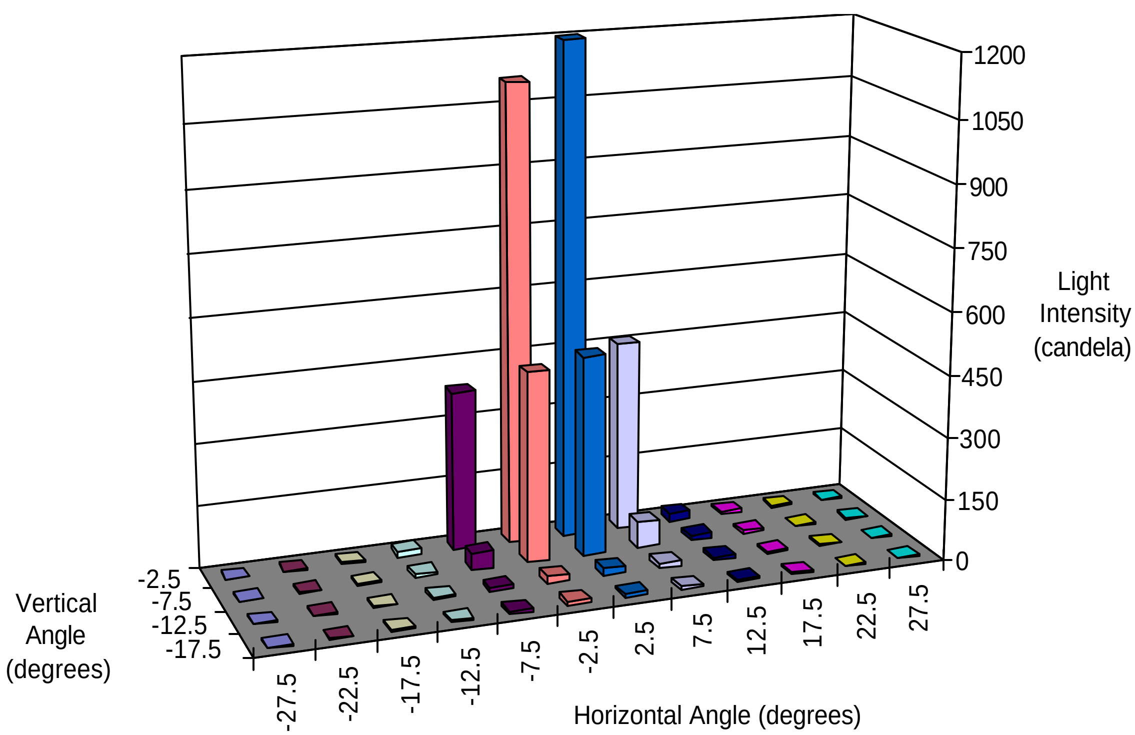

Figure A7.4.14b Output from WPS #7 (Red) signal, 10.0 volts, 72 elements (82% on), ITE test.

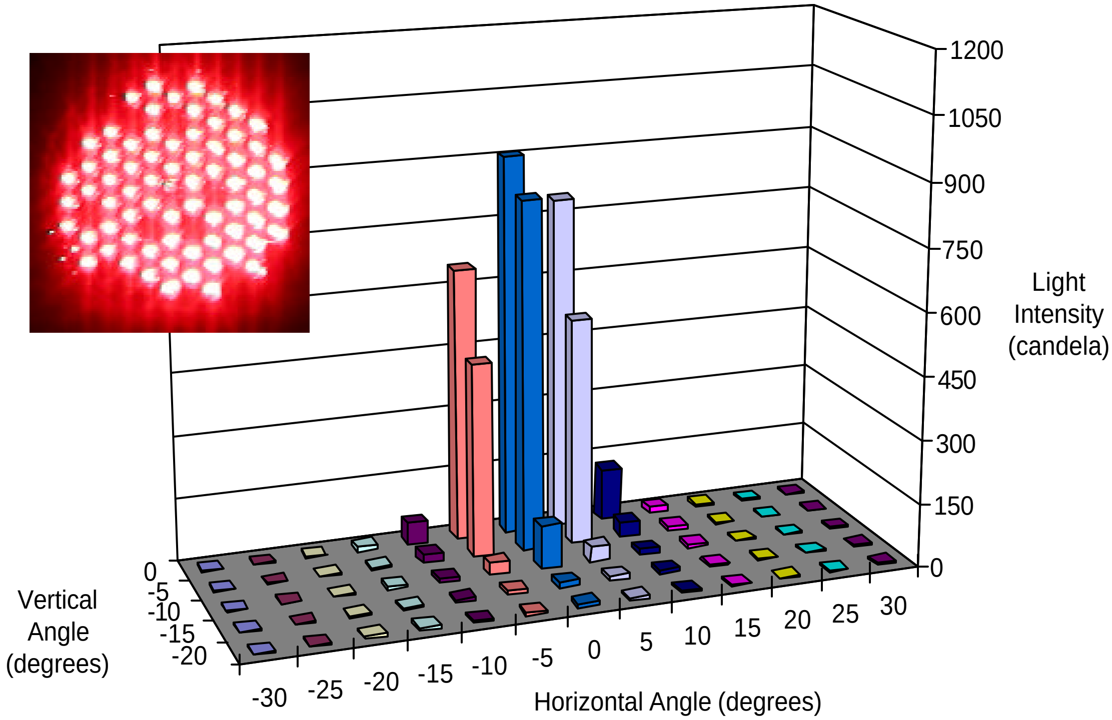

Figure A7.4.15a Output from WPS #7 (Red) signal, 10.0 volts, 72 elements (82% on), TC test.

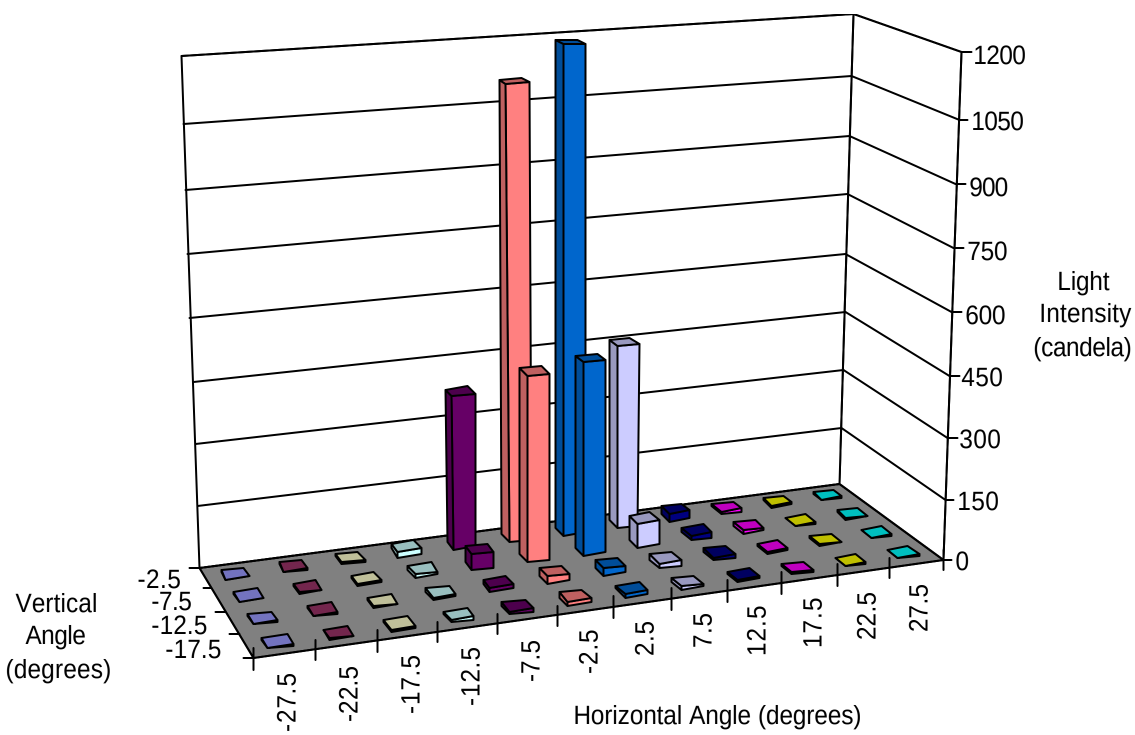

Figure A7.4.15b Output from WPS #7 (Red) signal, 10.0 volts, 72 elements (82% on), ITE test. .

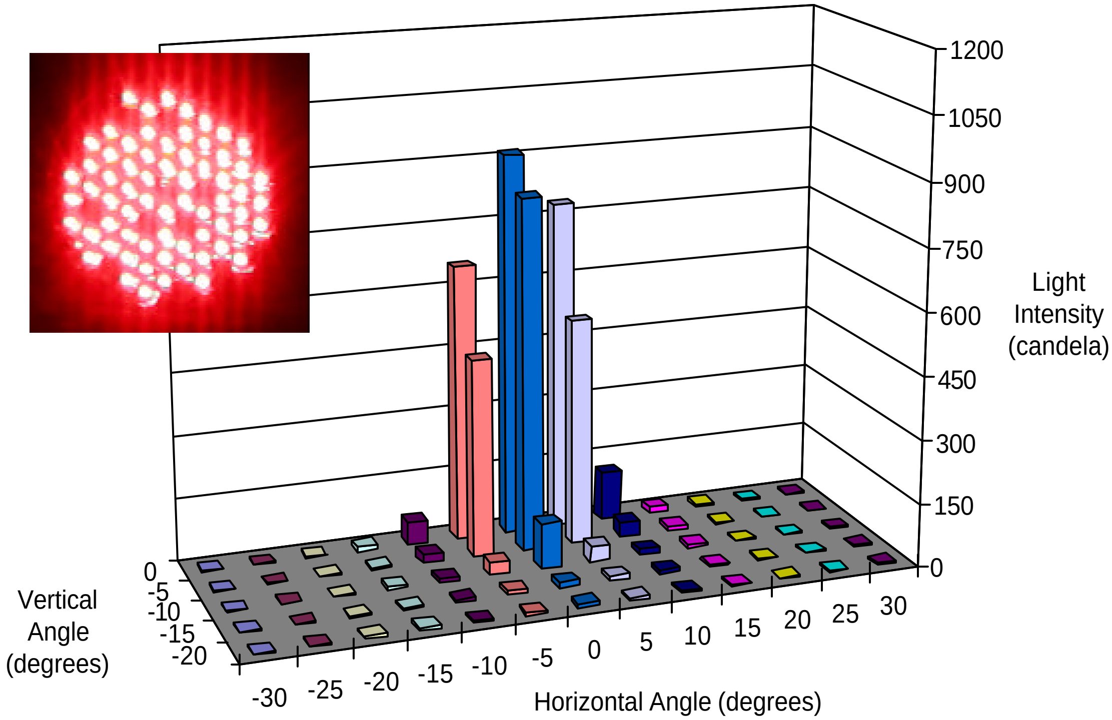

Figure A7.4.16a Output from WPS #7 (Red) signal, 10.0 volts, 68 elements (77% on), TC test.

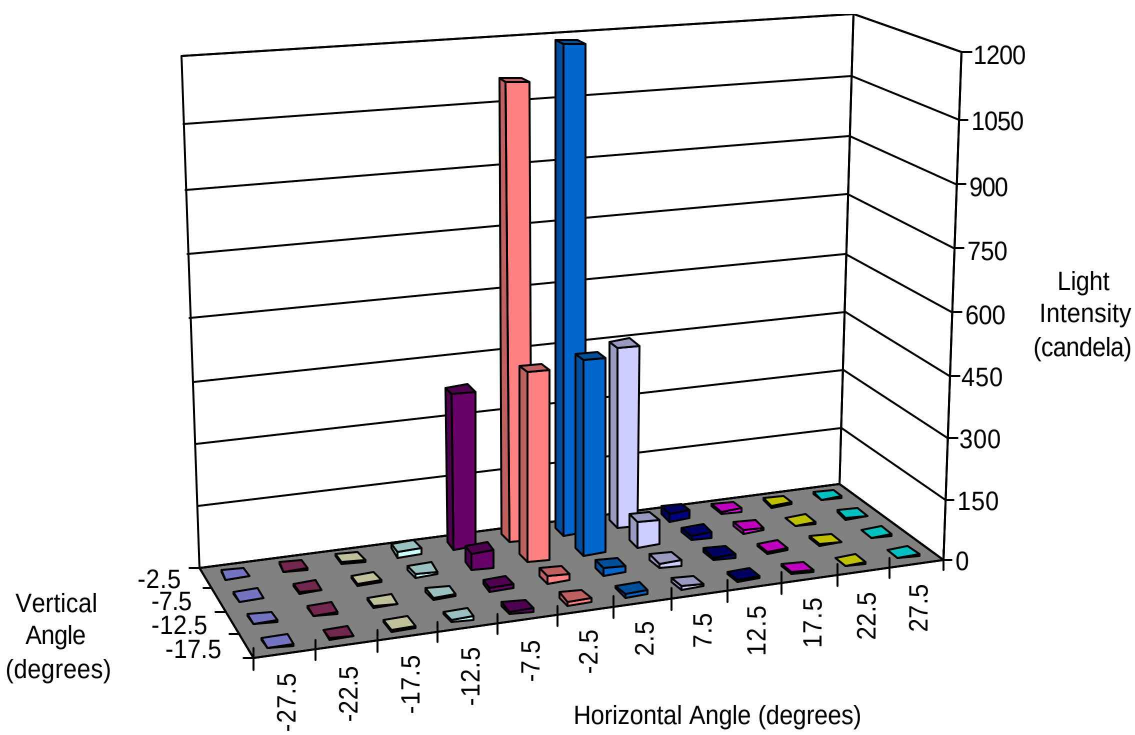

Figure A7.4.16b Output from WPS #7 (Red) signal, 10.0 volts, 68 elements (77% on), ITE test.

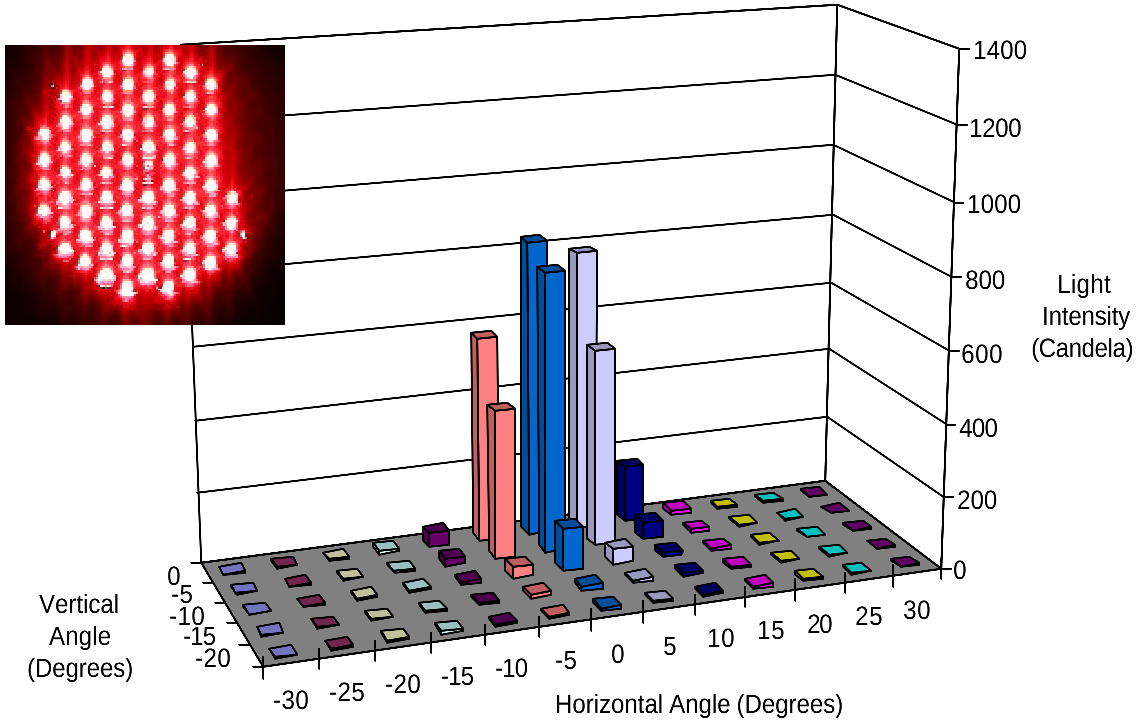

Figure A7.5.1a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

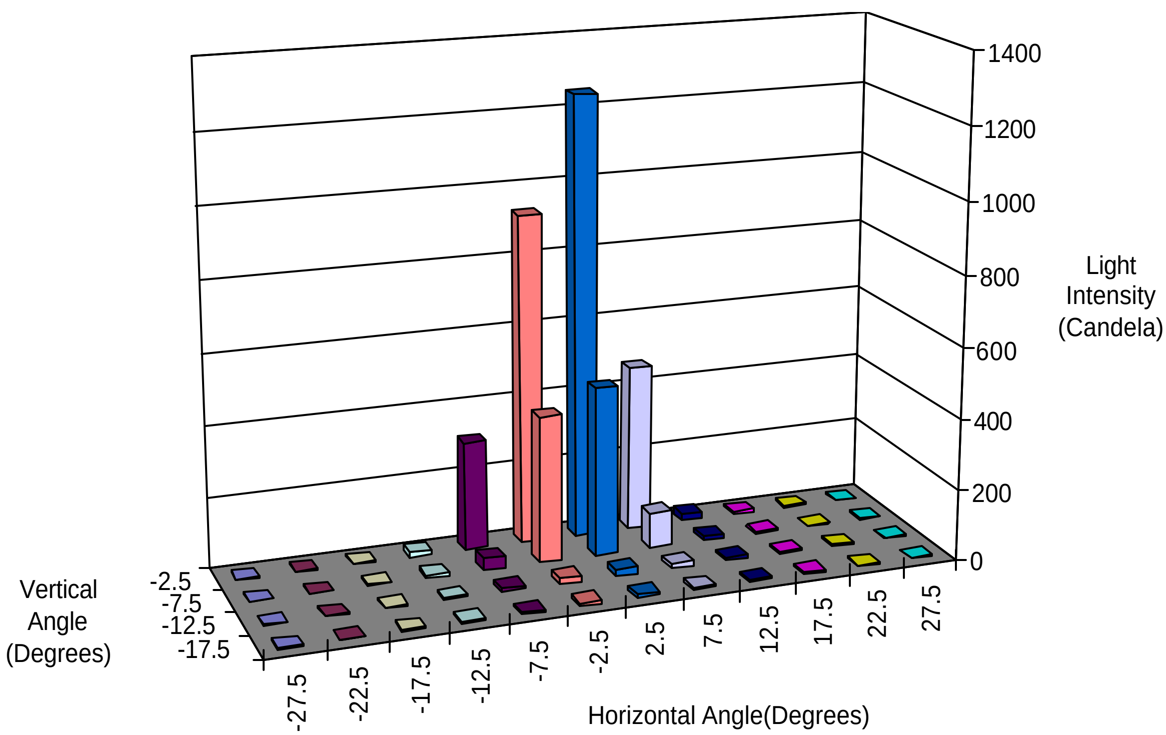

Figure A7.5.1b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

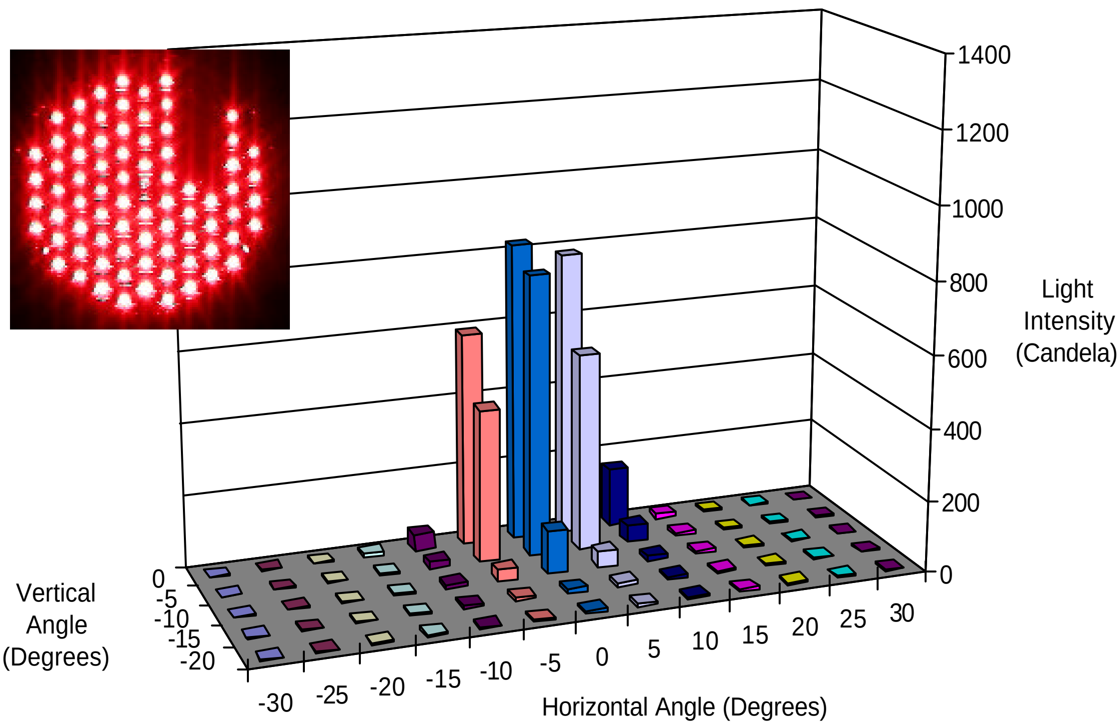

Figure A7.5.2a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

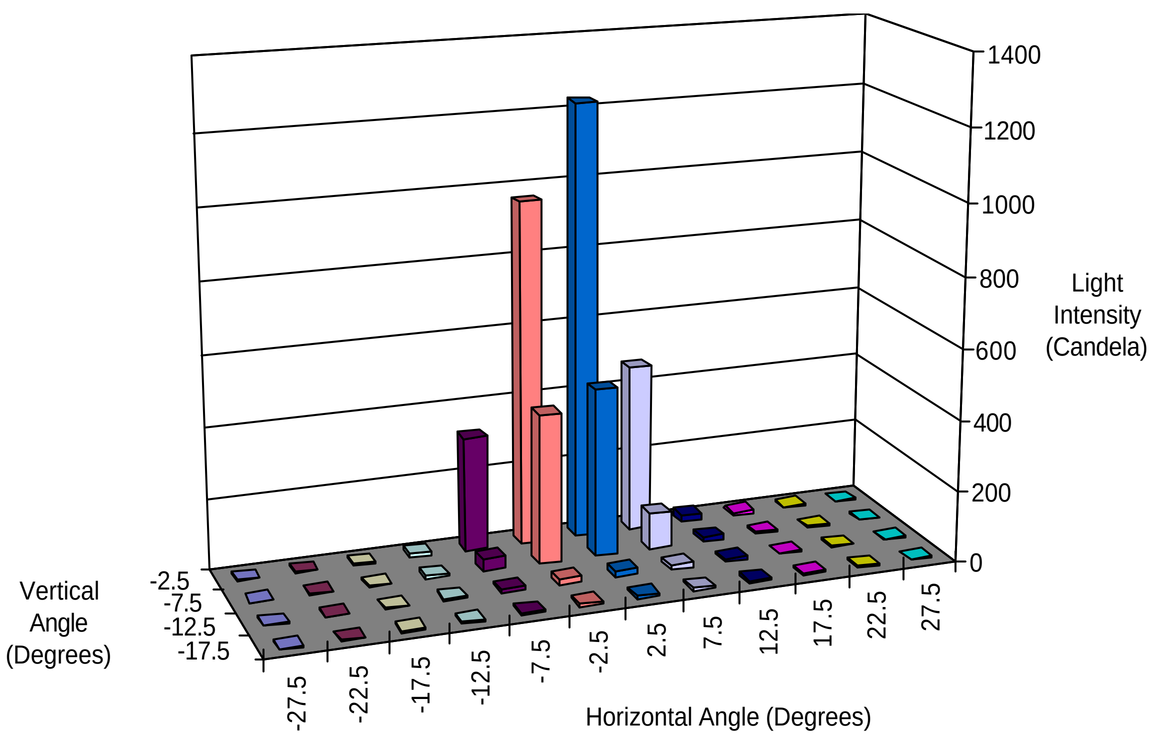

Figure A7.5.2b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

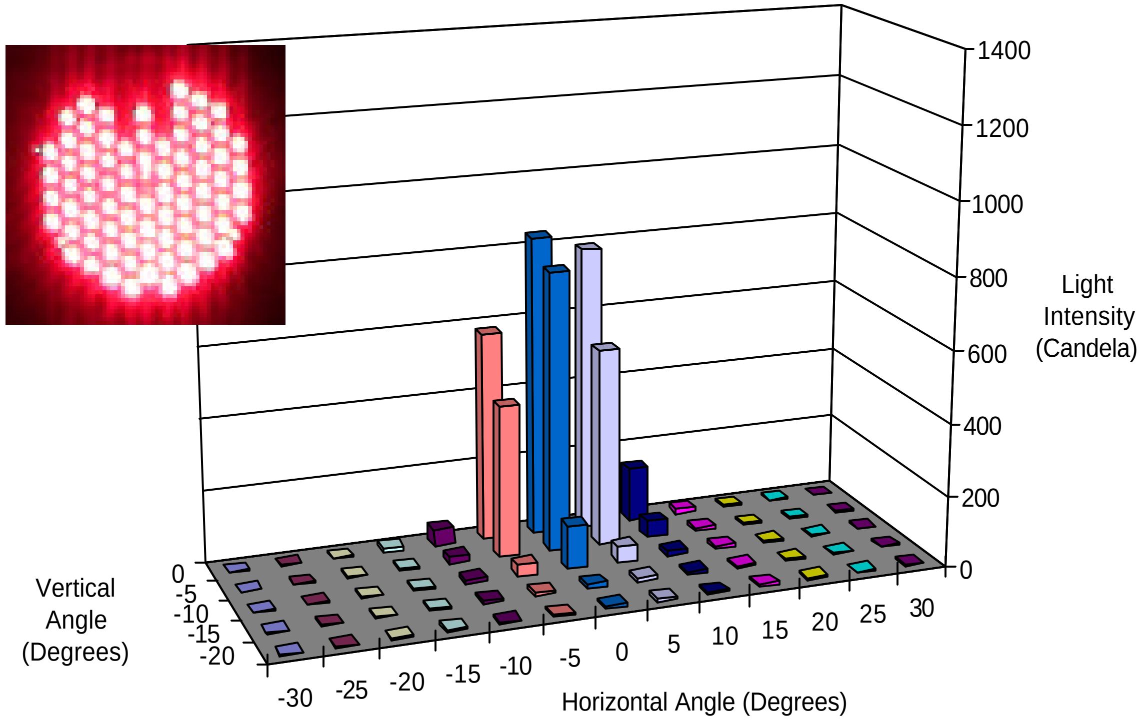

Figure A7.5.3a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

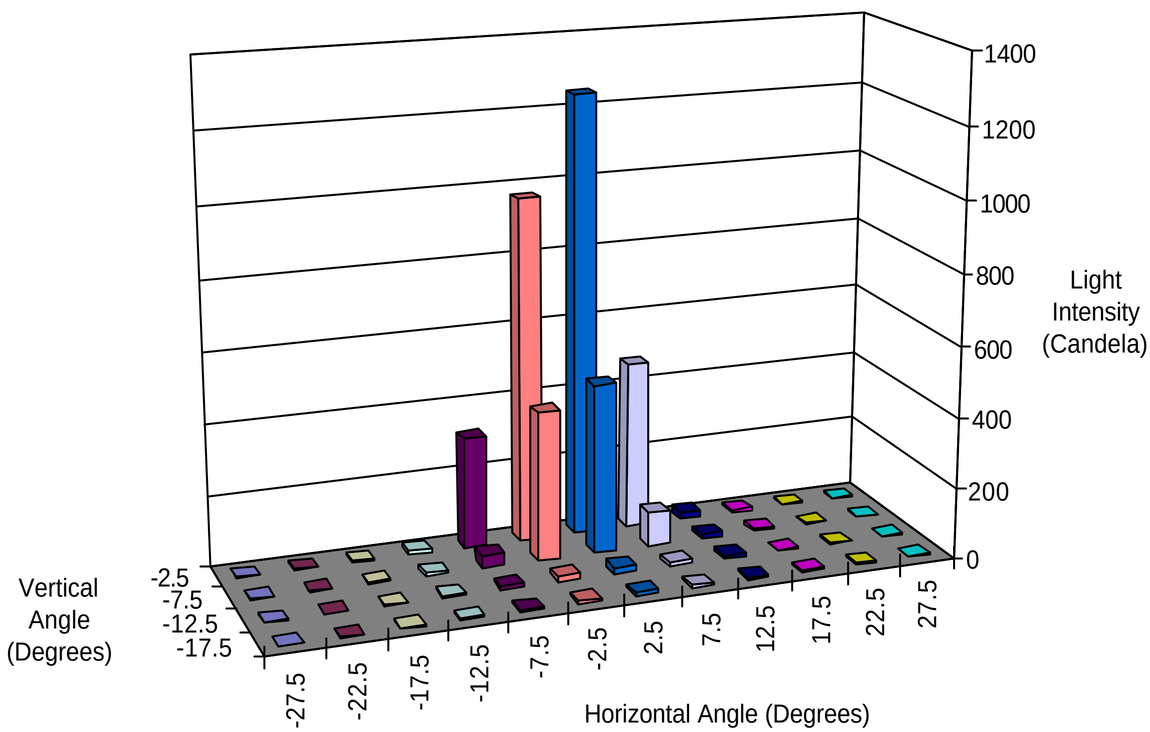

Figure A7.5.3b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

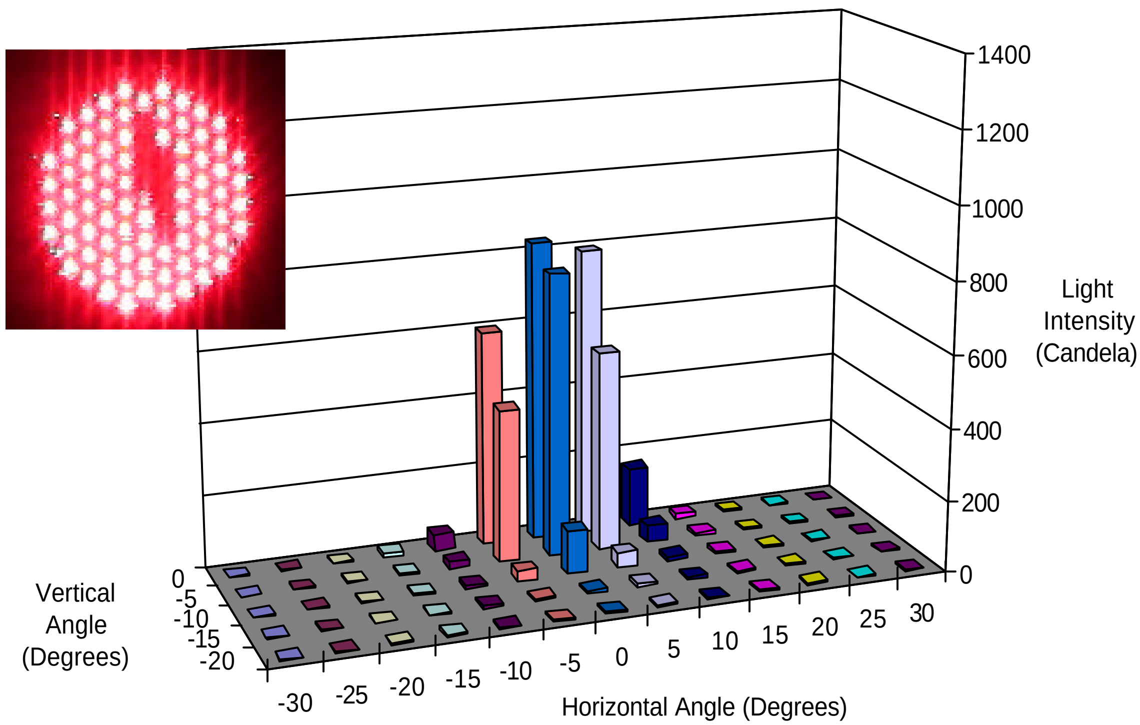

Figure A7.5.4a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

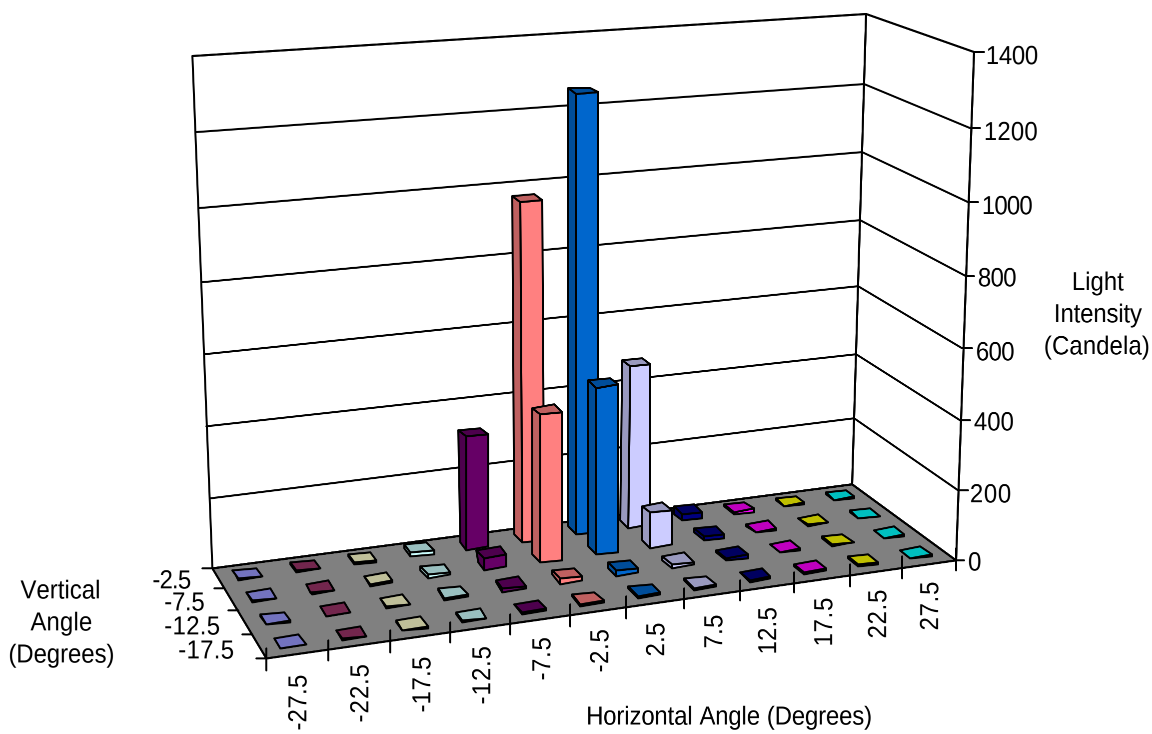

Figure A7.5.4b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

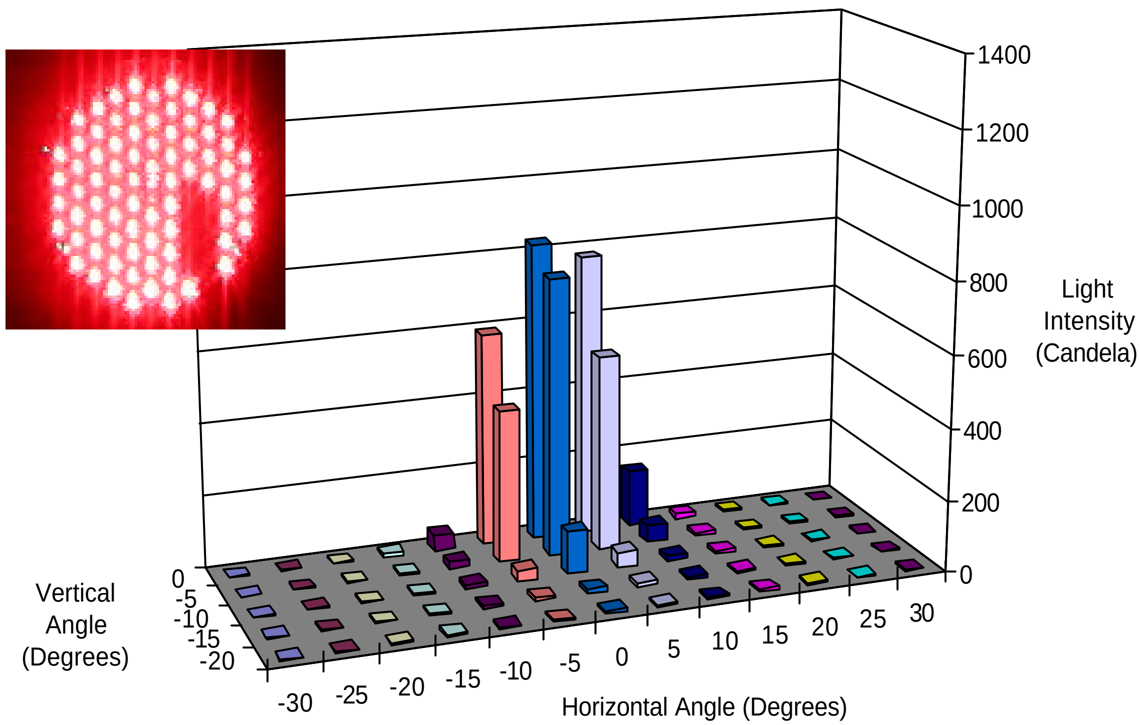

Figure A7.5.5a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

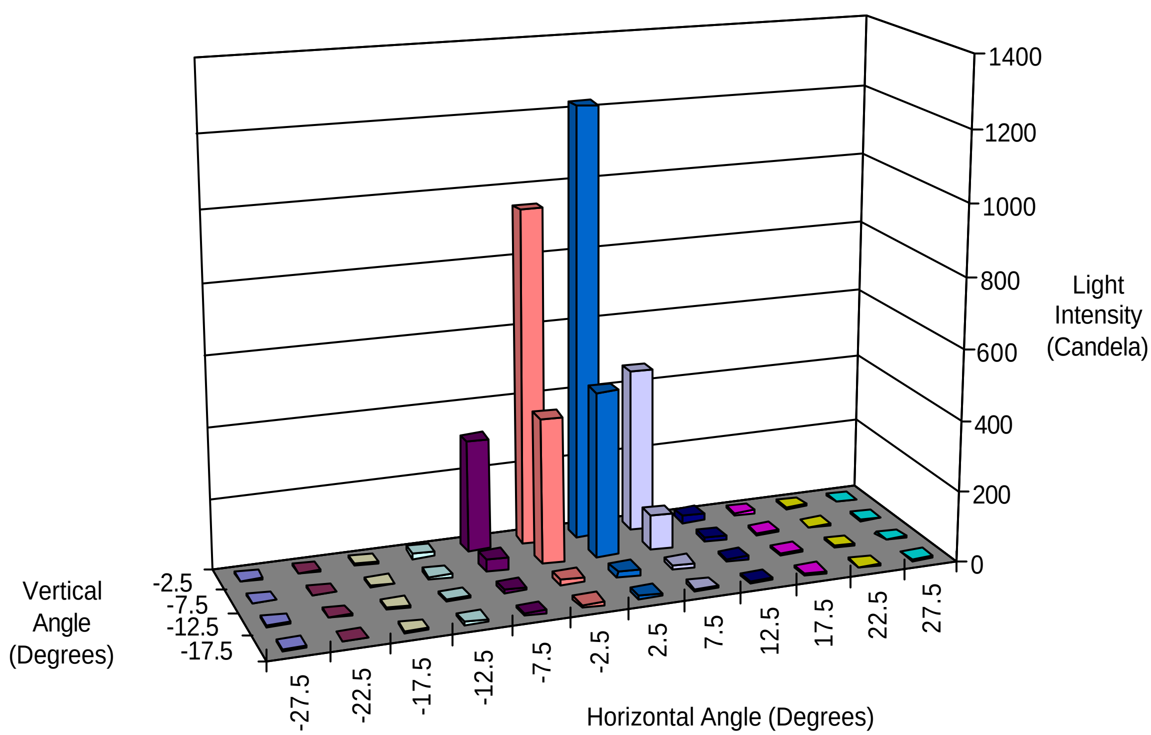

Figure A7.5.5b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

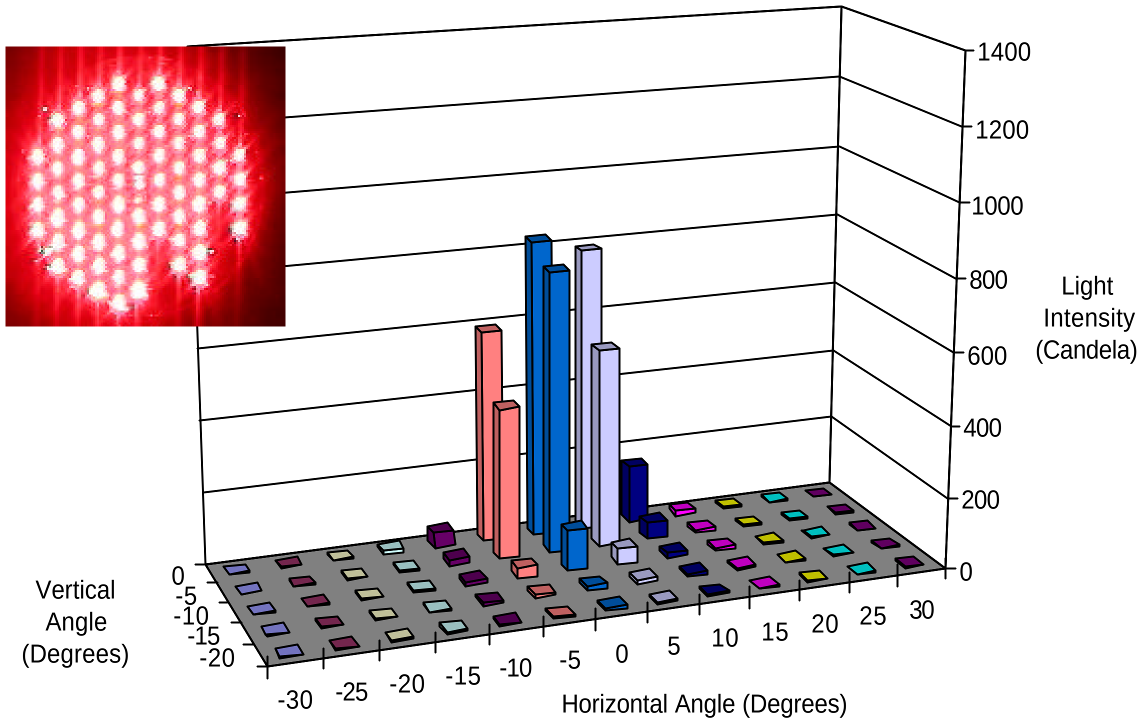

Figure A7.5.6a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

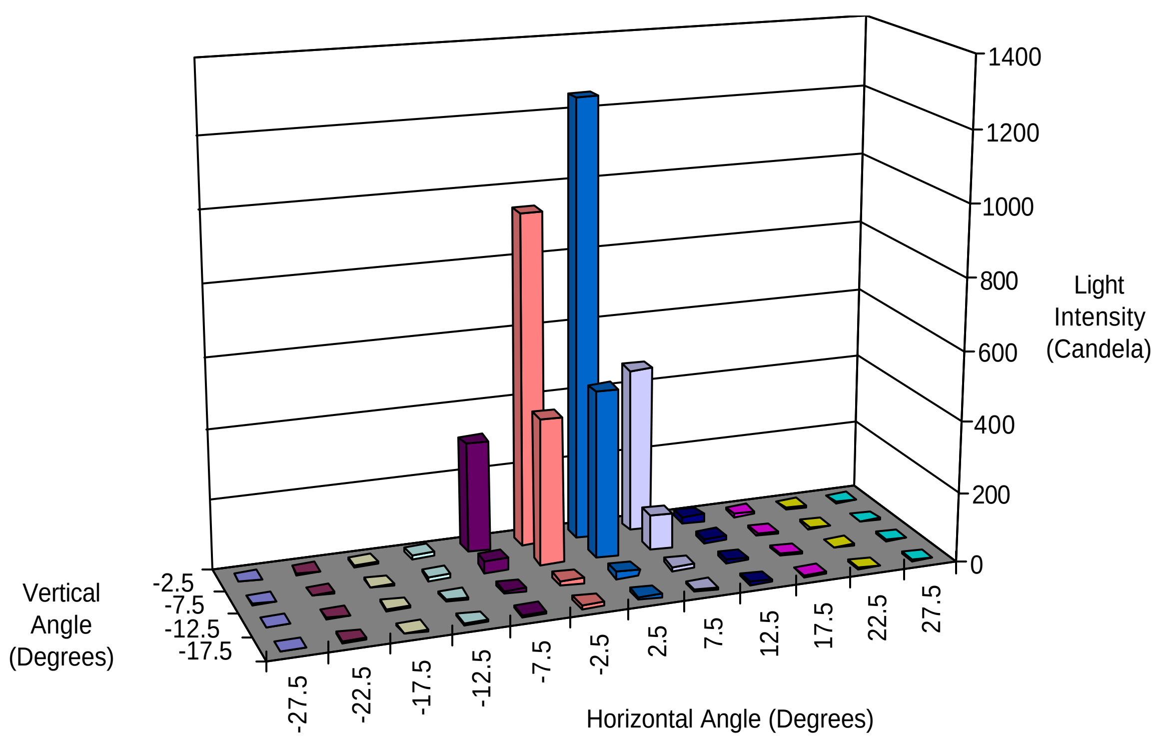

Figure A7.5.6b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

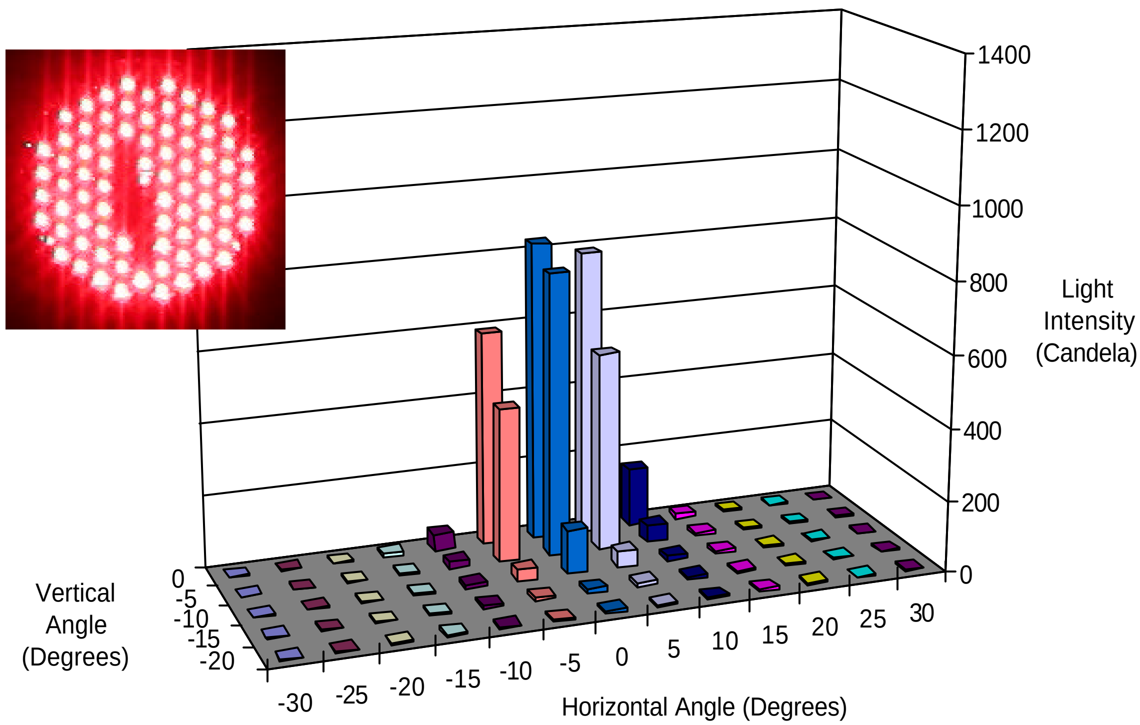

Figure A7.5.7a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

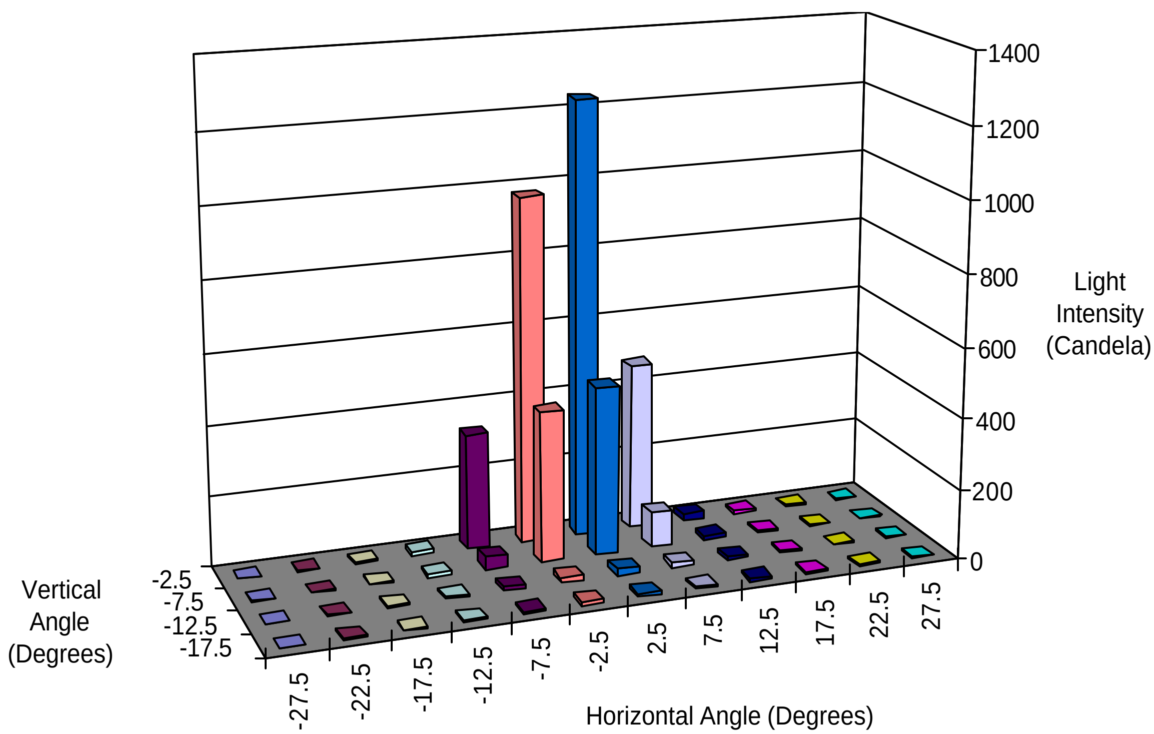

Figure A7.5.7b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

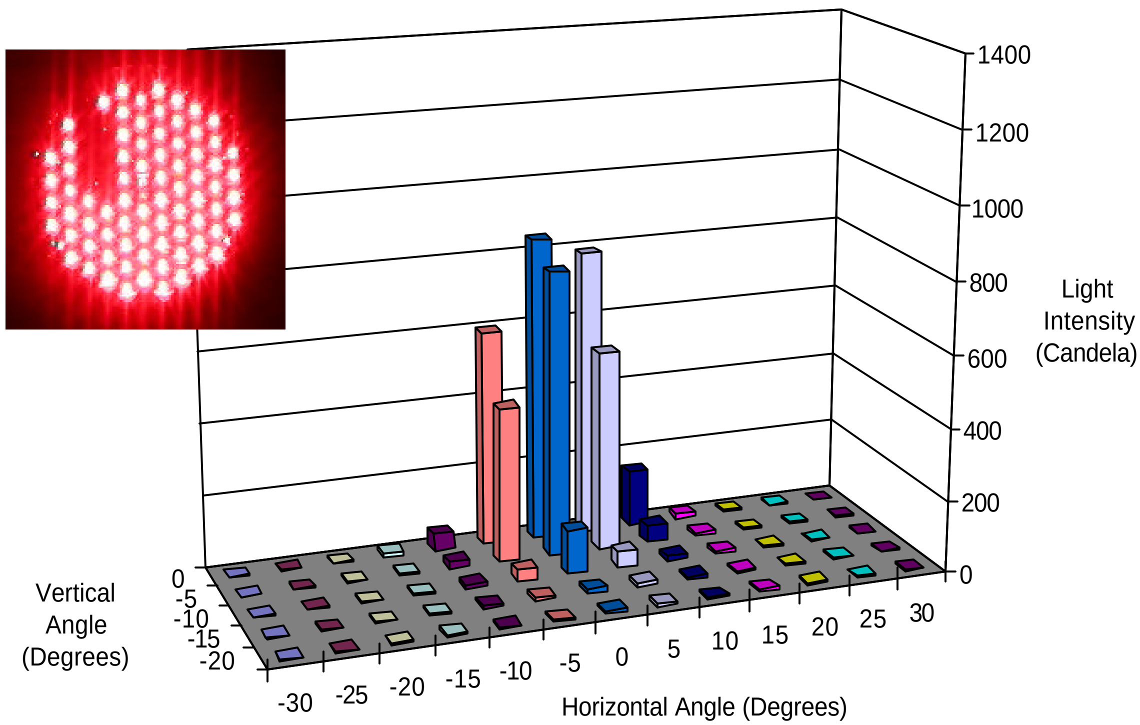

Figure A7.5.8a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

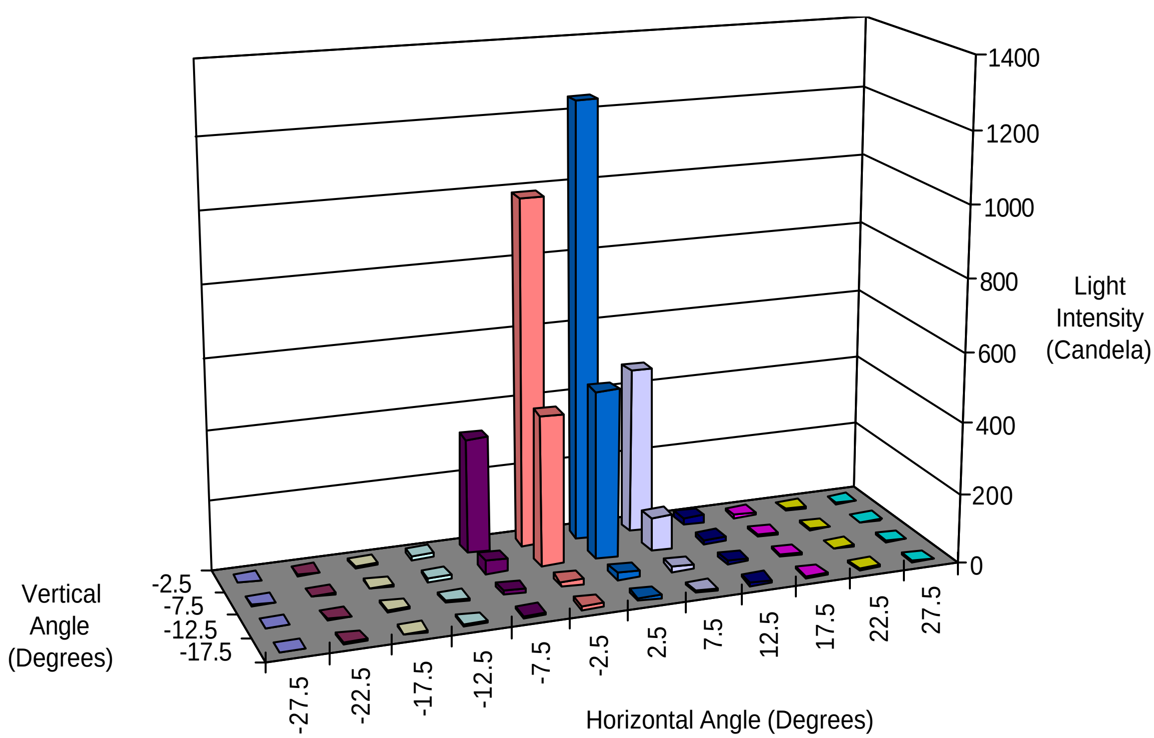

Figure A7.5.8b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

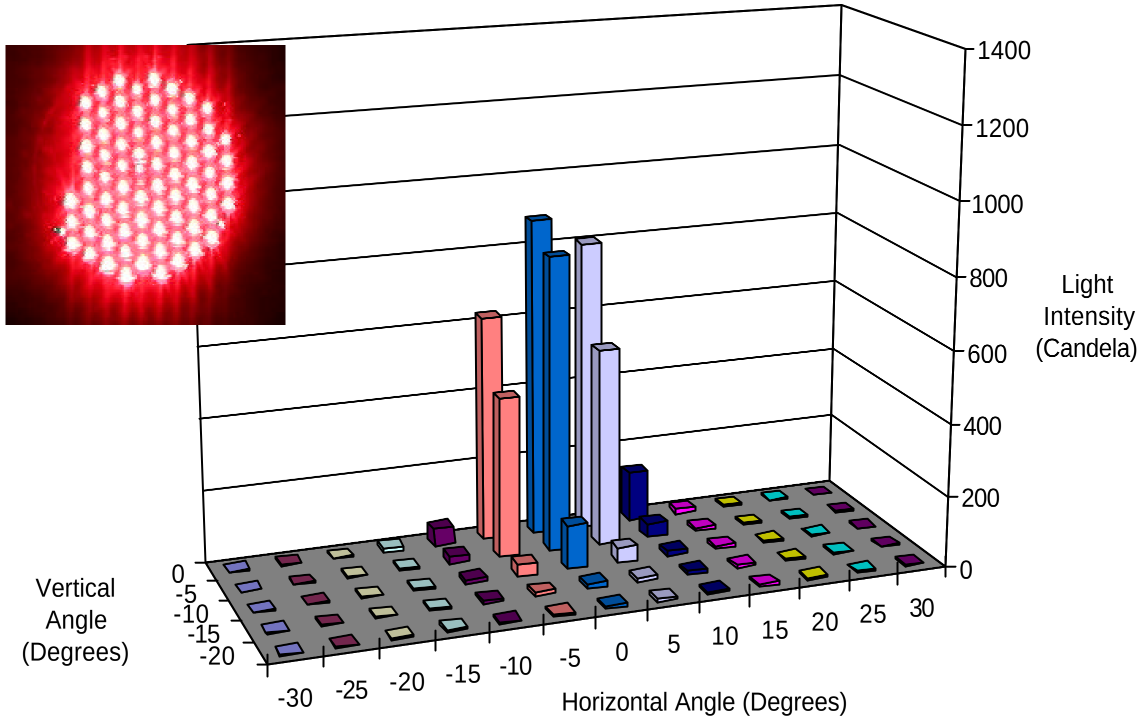

Figure A7.5.9a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

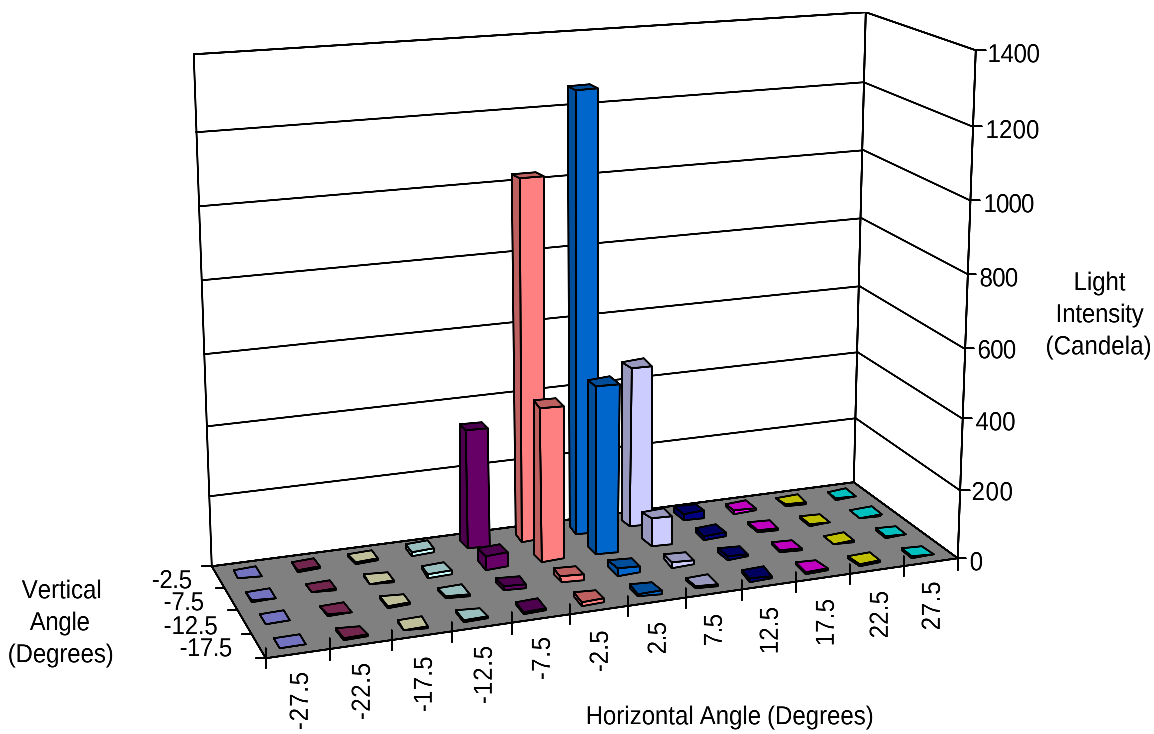

Figure A7.5.9b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

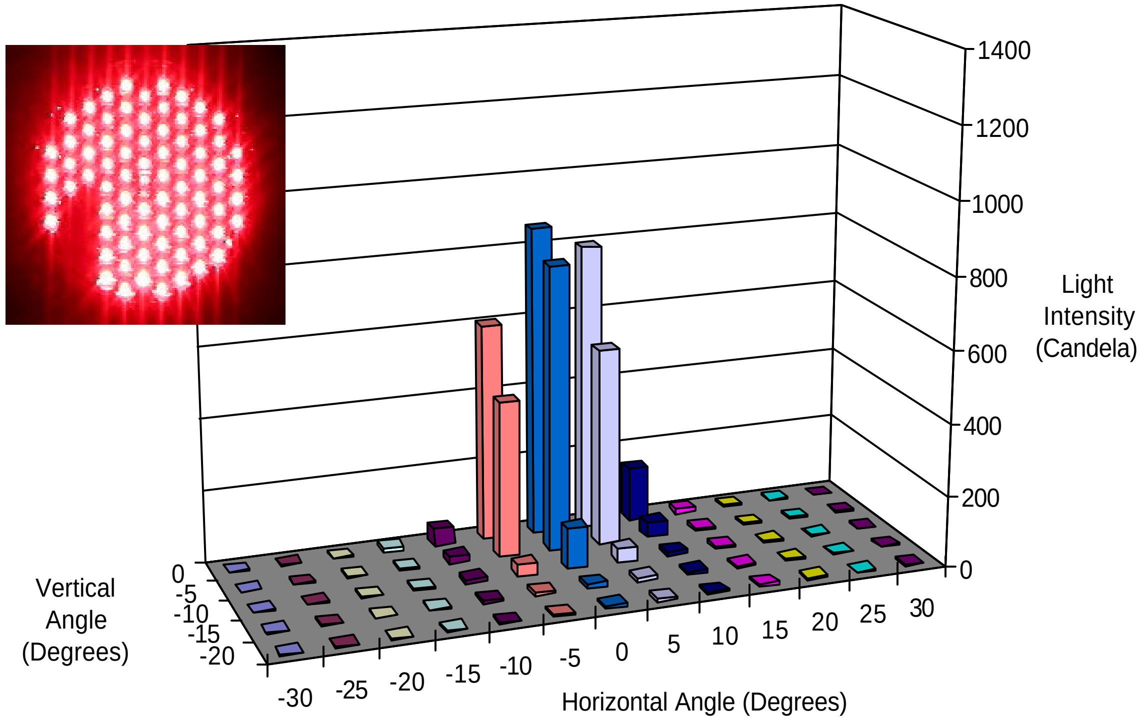

Figure A7.5.10a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

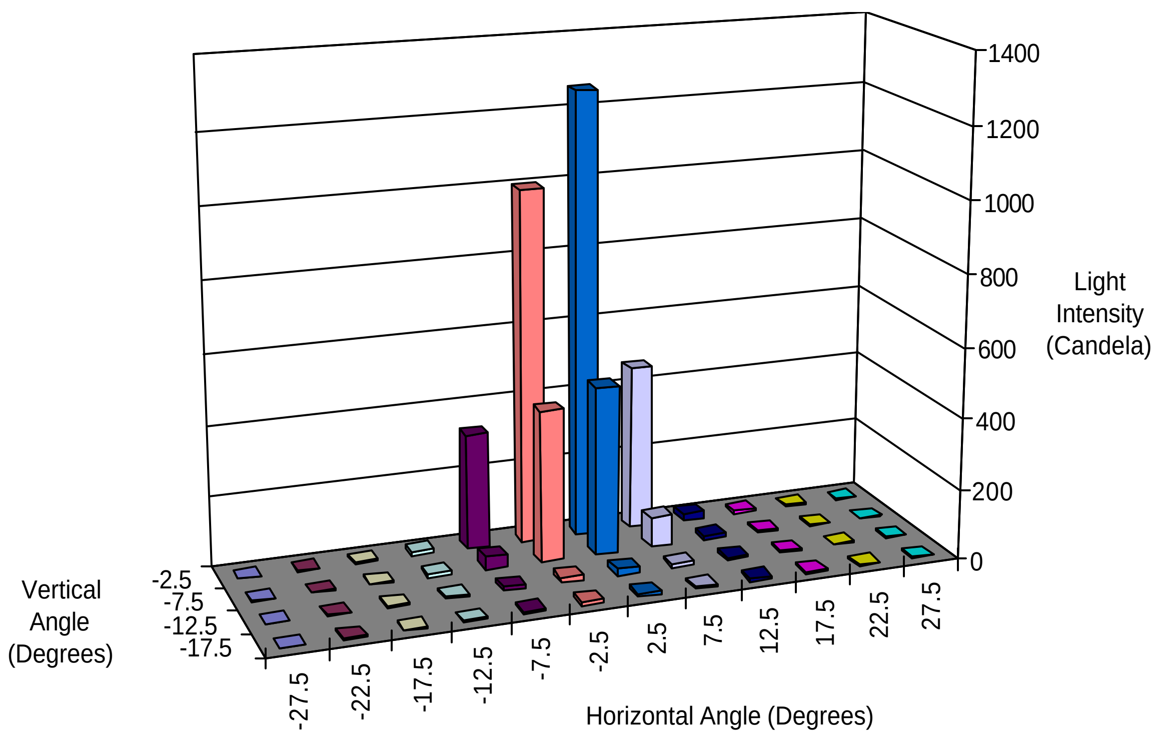

Figure A7.5.10b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

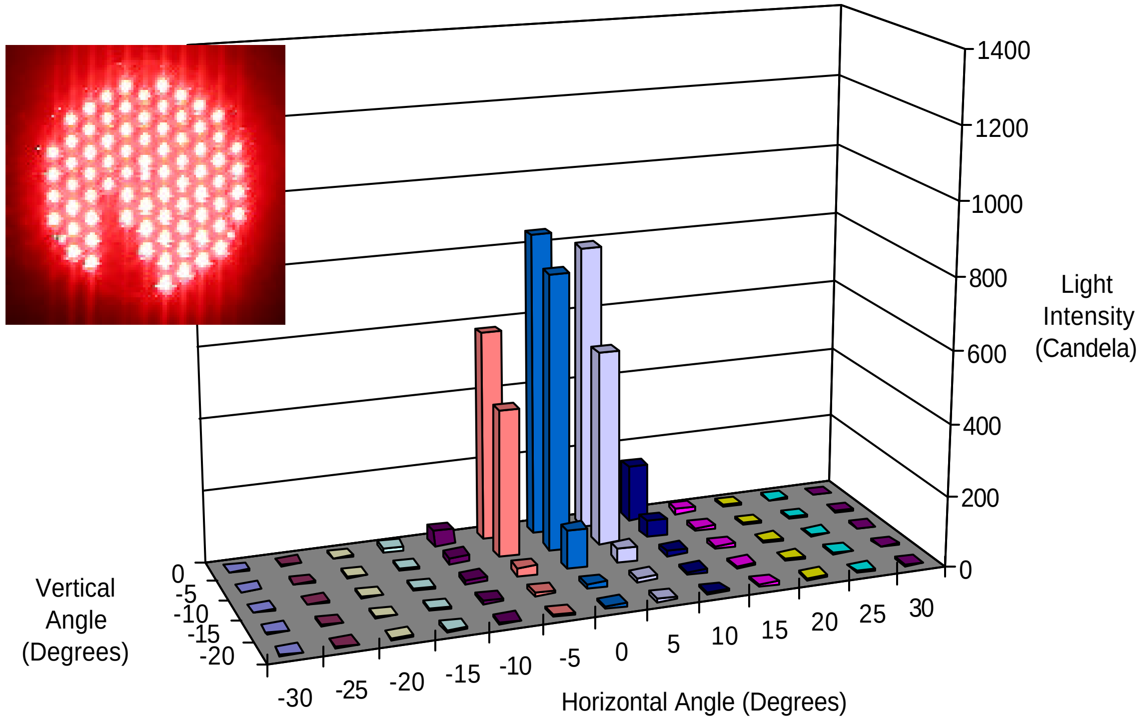

Figure A7.5.11a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

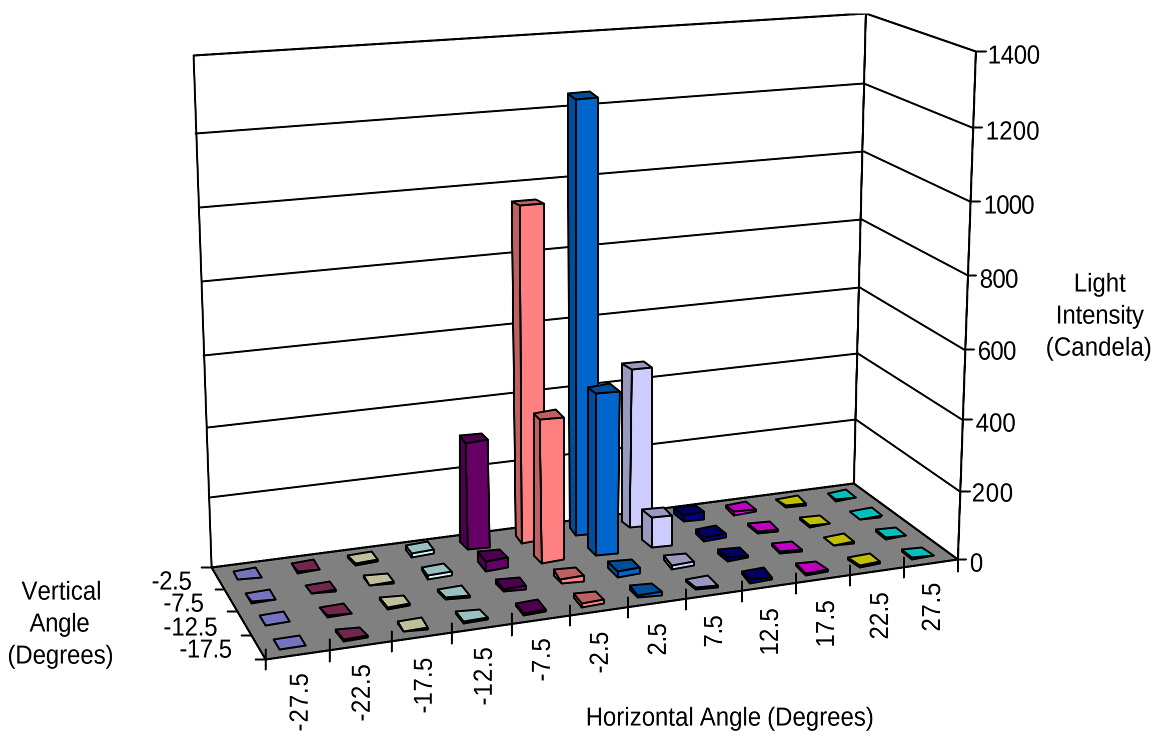

Figure A7.5.11b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

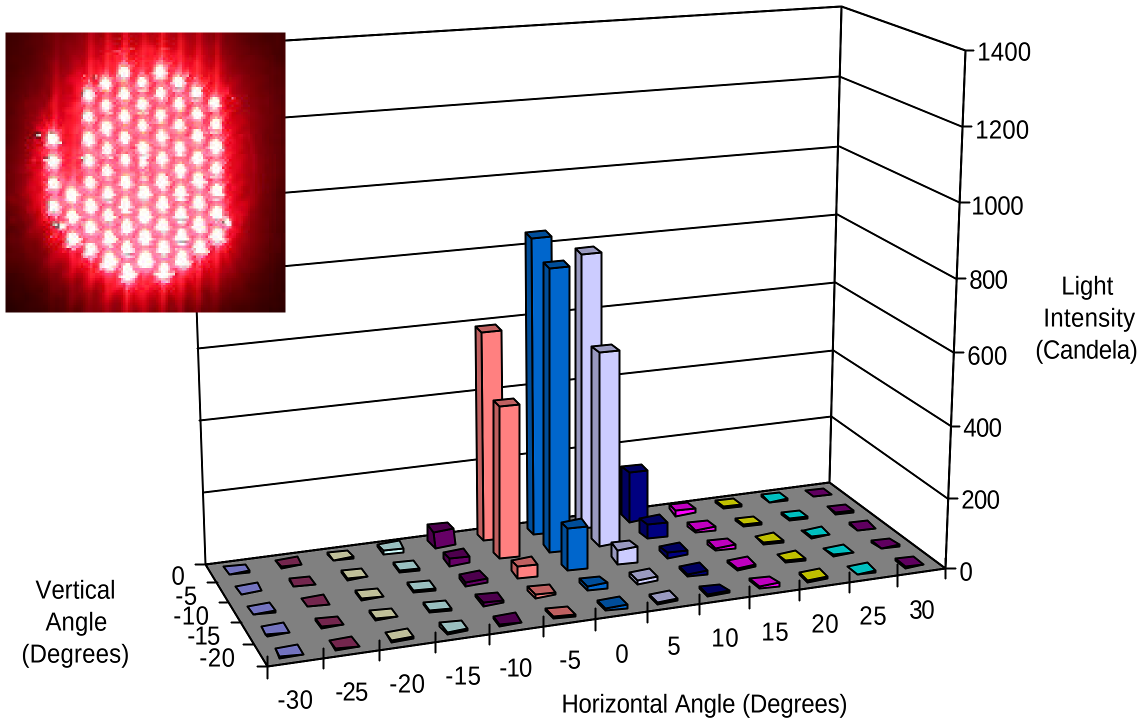

Figure A7.5.12a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

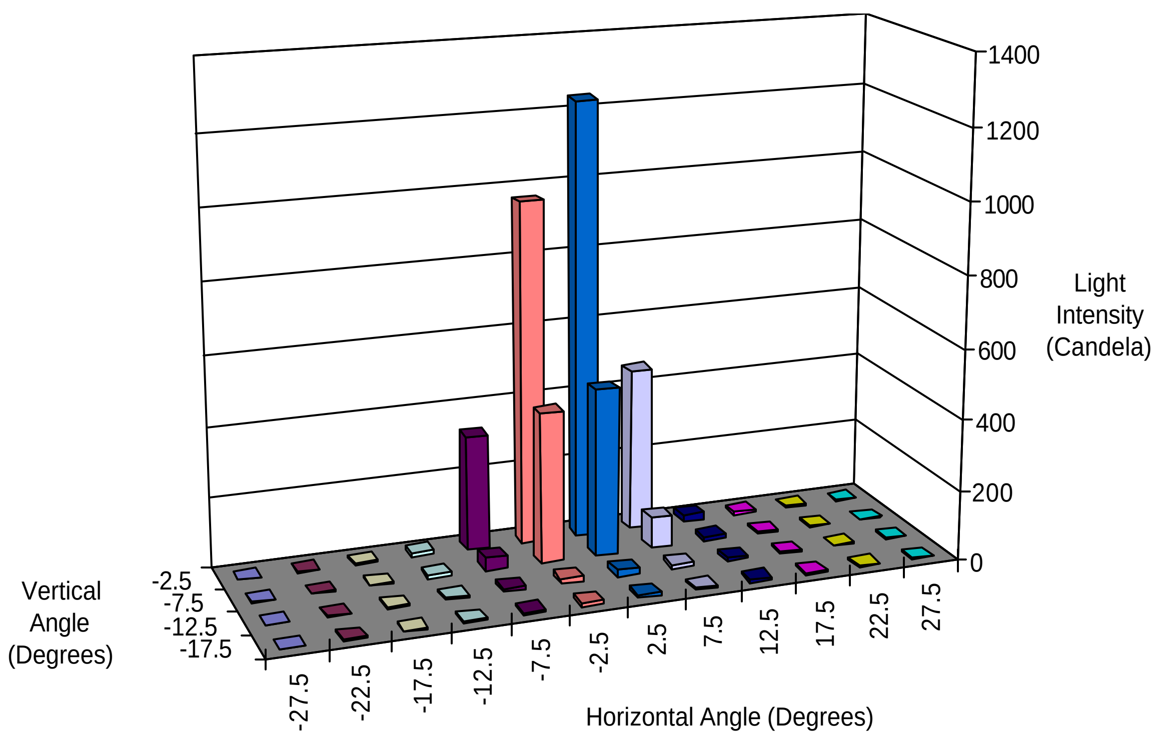

Figure A7.5.12b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

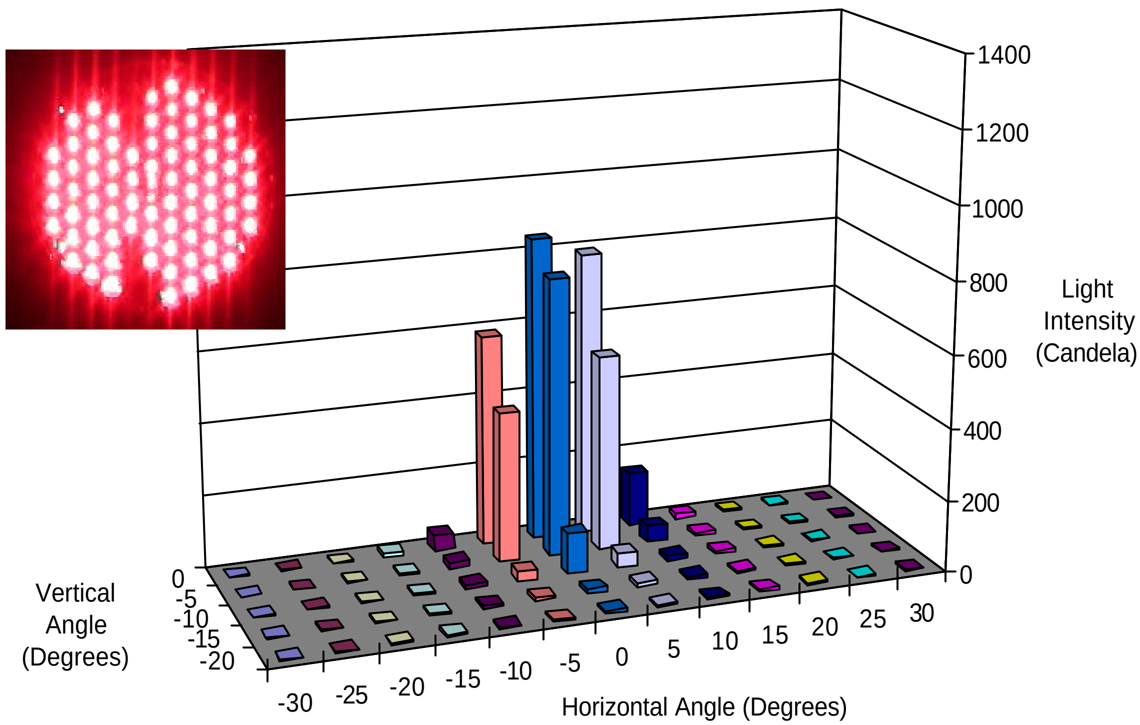

Figure A7.5.13a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

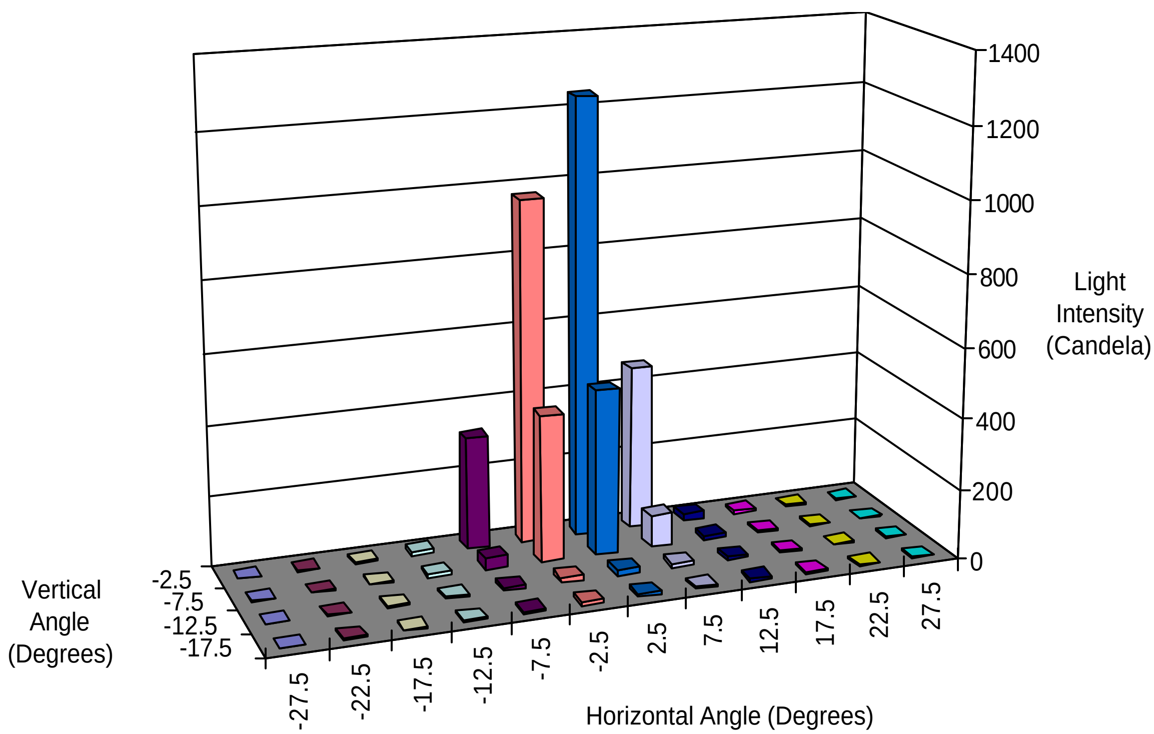

Figure A7.5.13b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

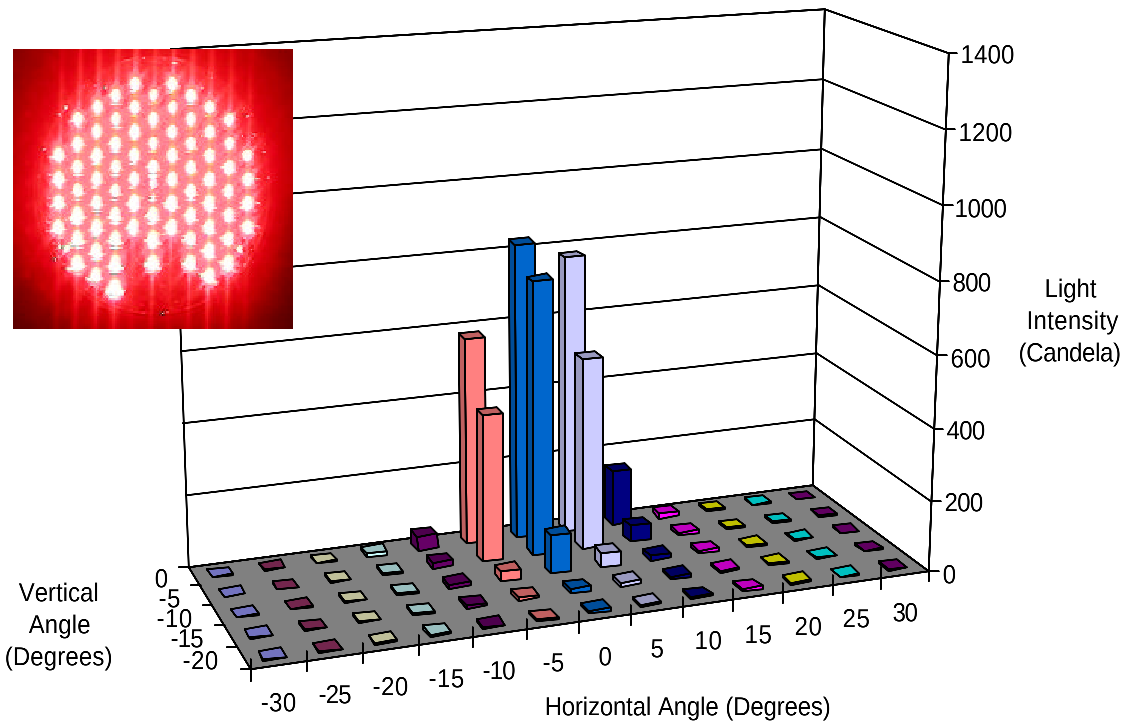

Figure A7.5.14a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

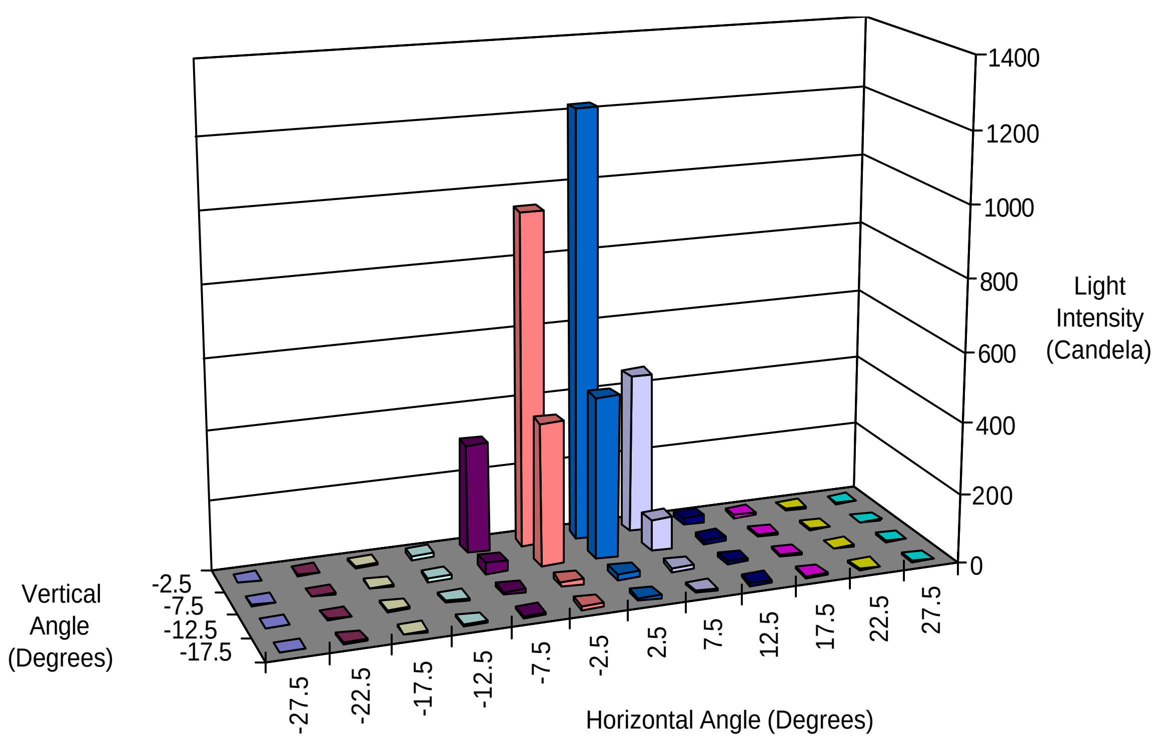

Figure A7.5.14b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

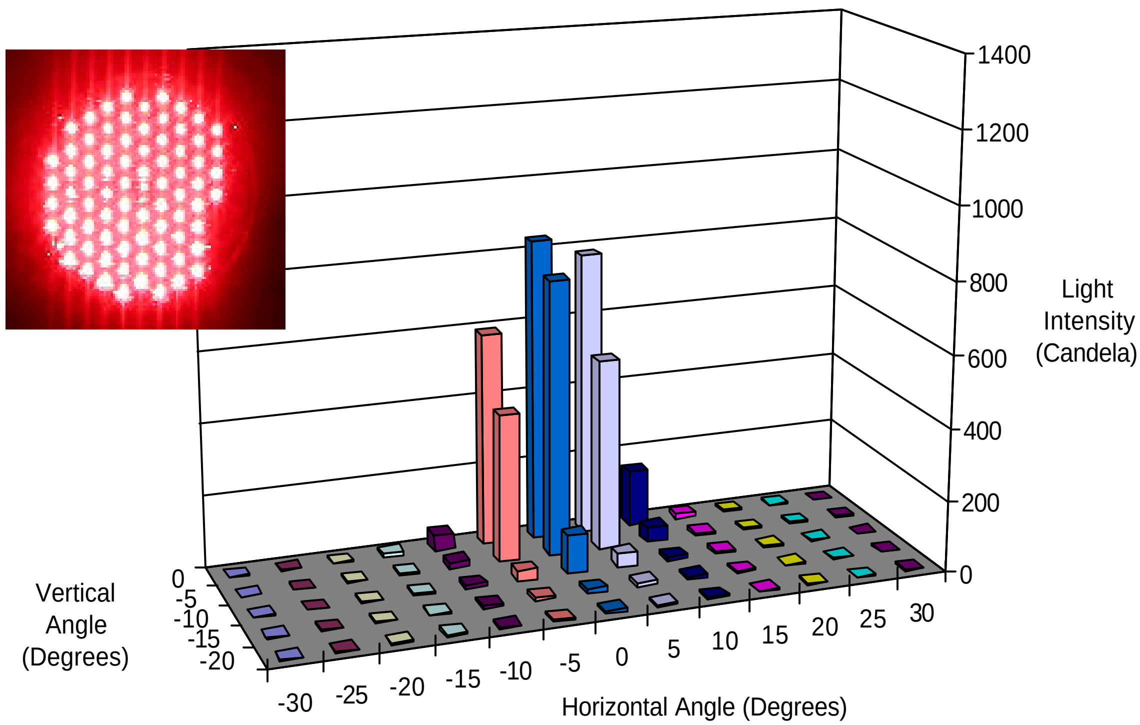

Figure A7.5.15a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

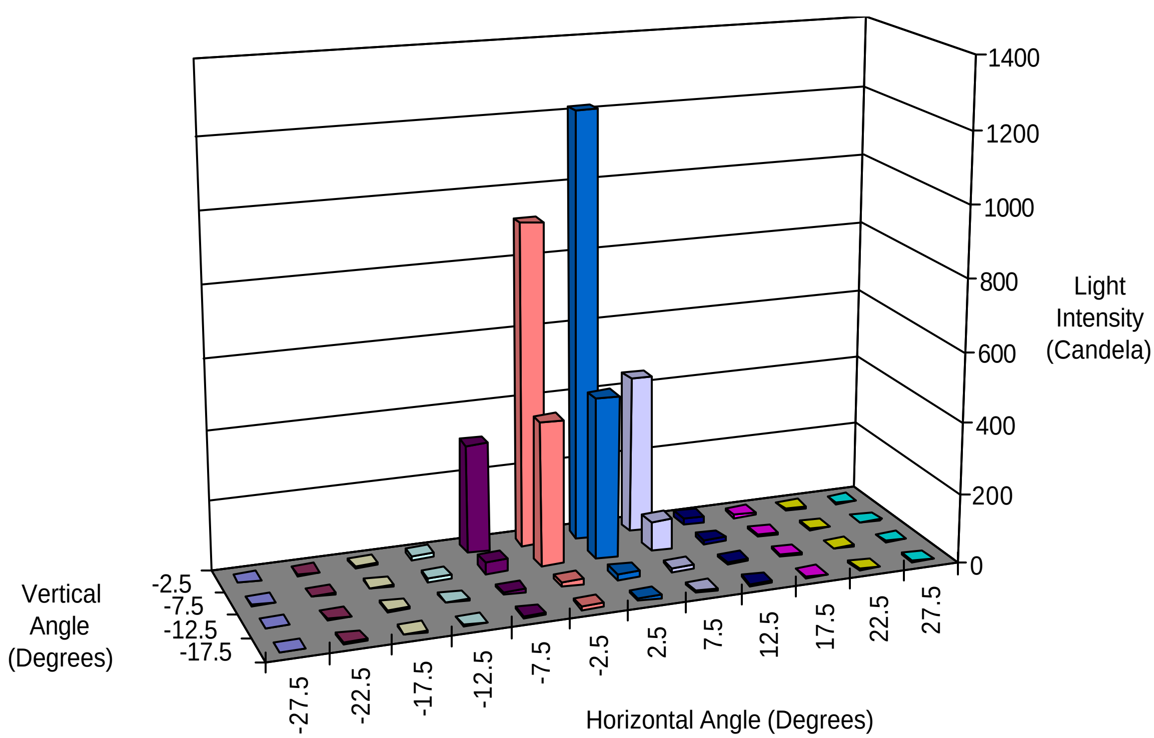

Figure A7.5.15b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

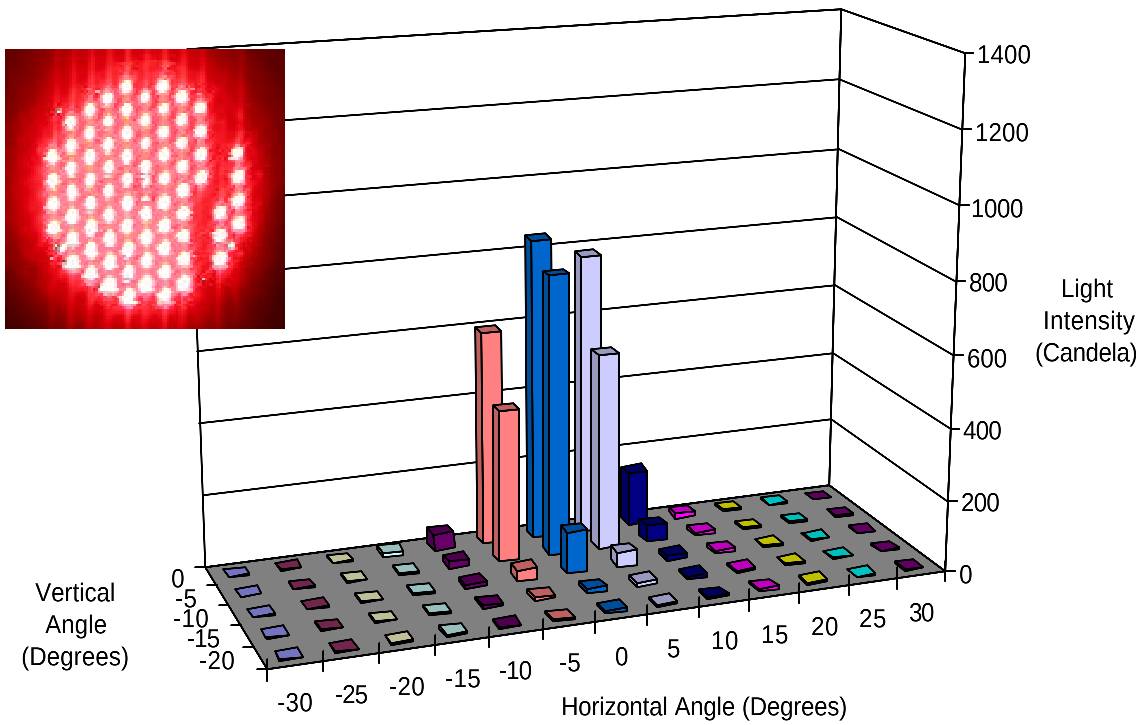

Figure A7.5.16a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

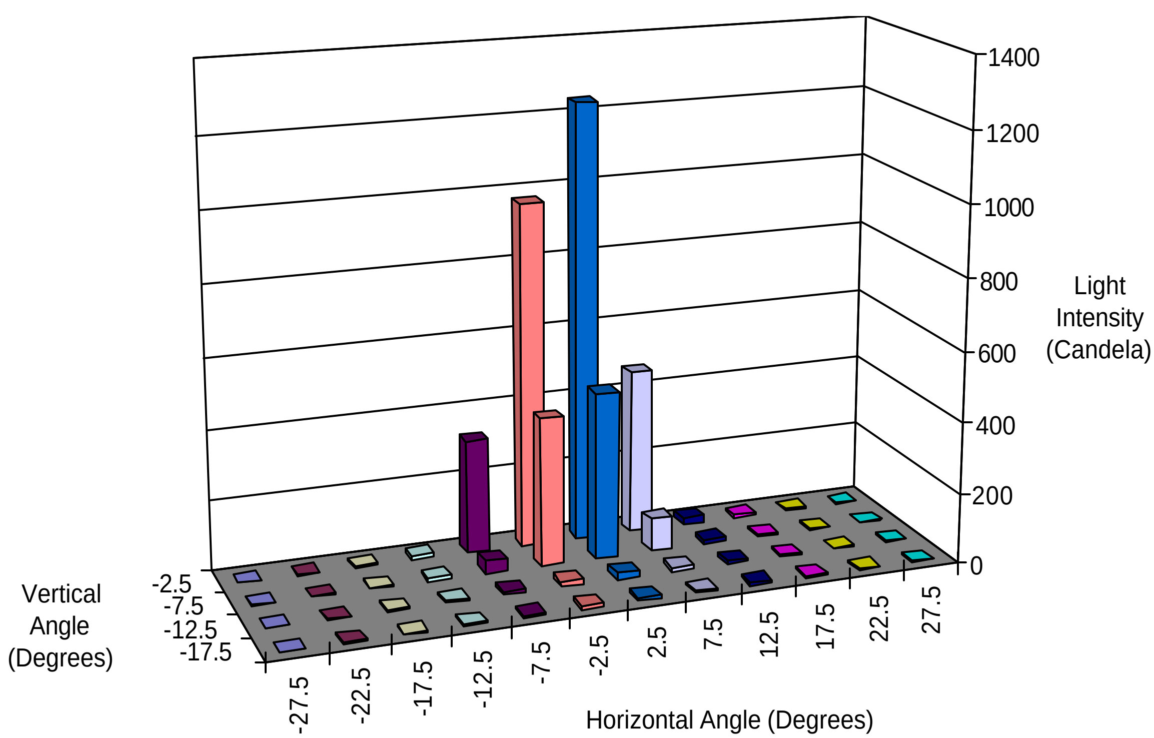

Figure A7.5.16b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

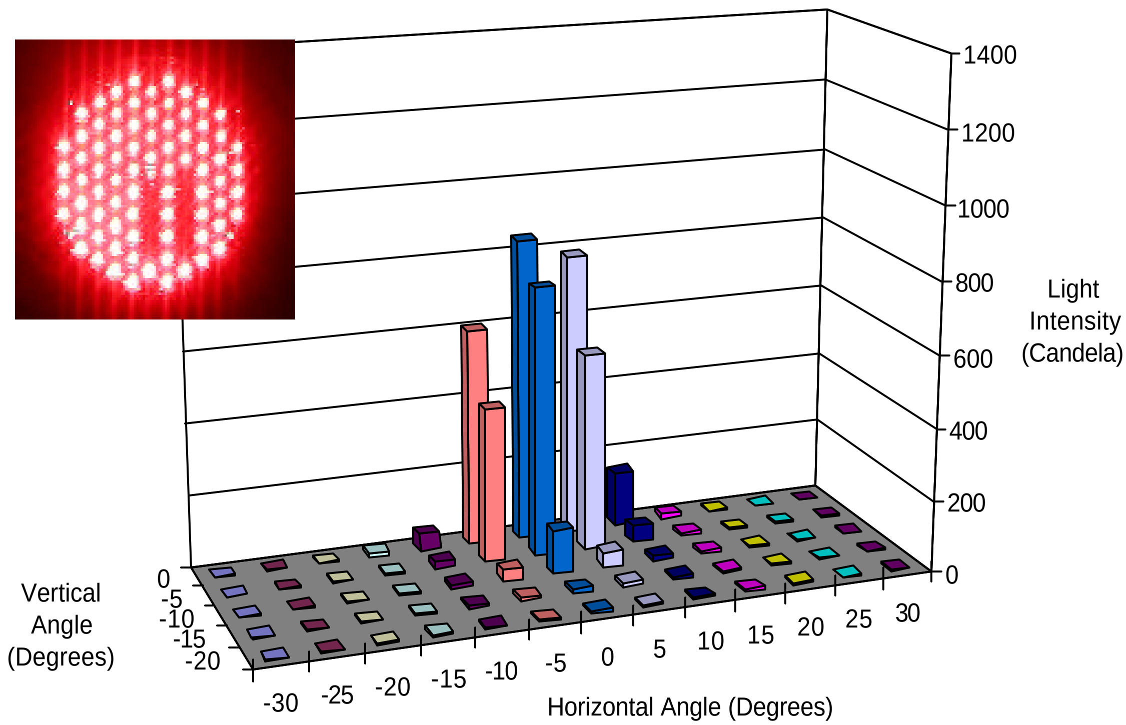

Figure A7.5.17a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

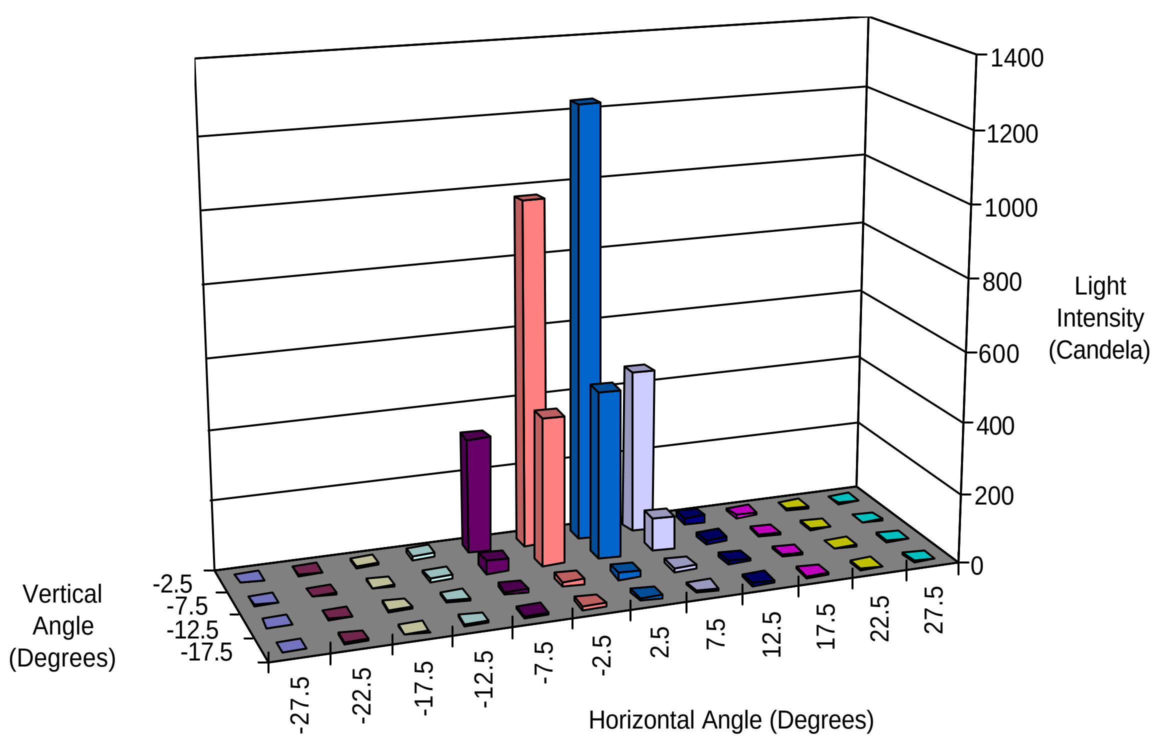

Figure A7.5.17b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

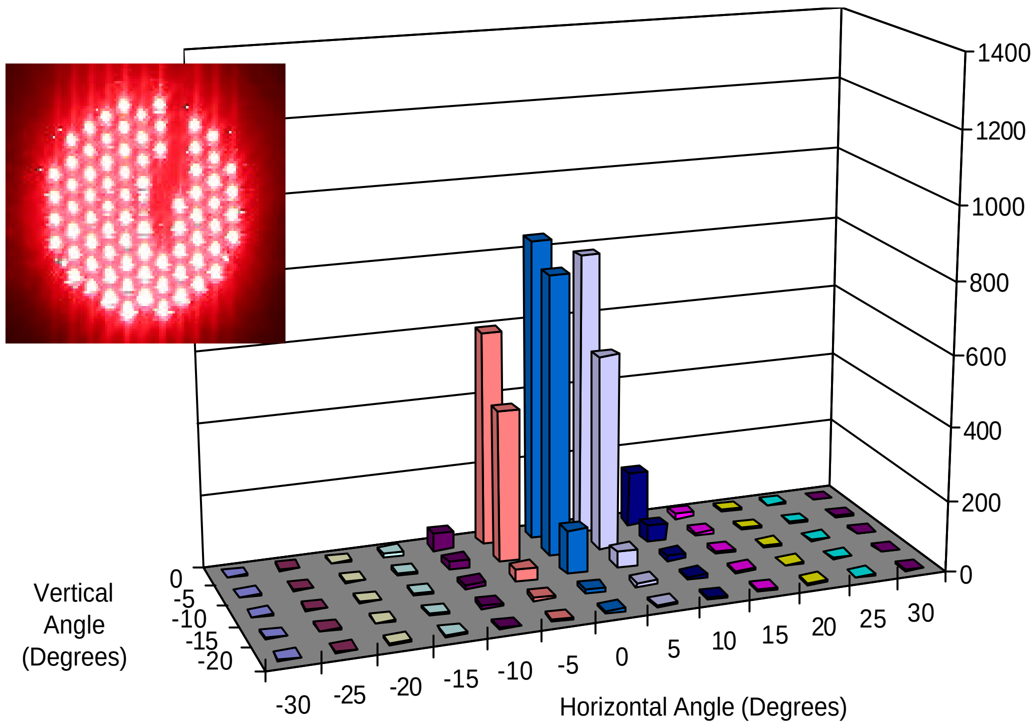

Figure A7.5.18a Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), TC test.

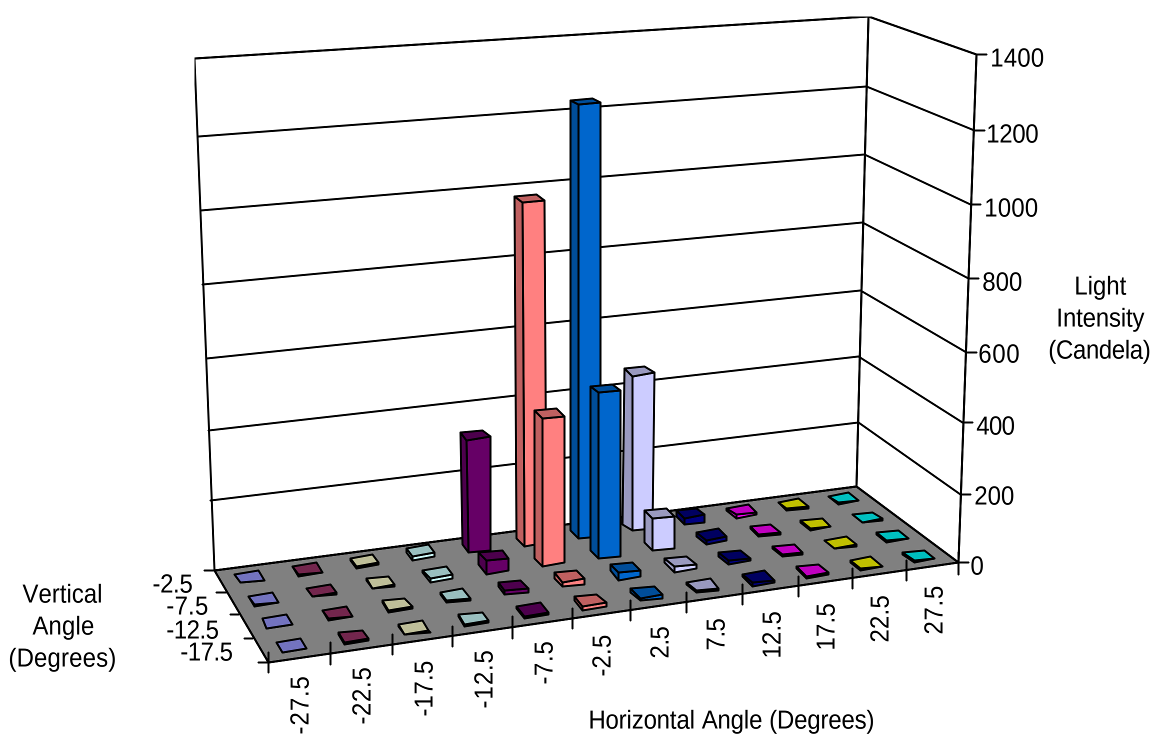

Figure A7.5.18b Output from WPS #7 (Red) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

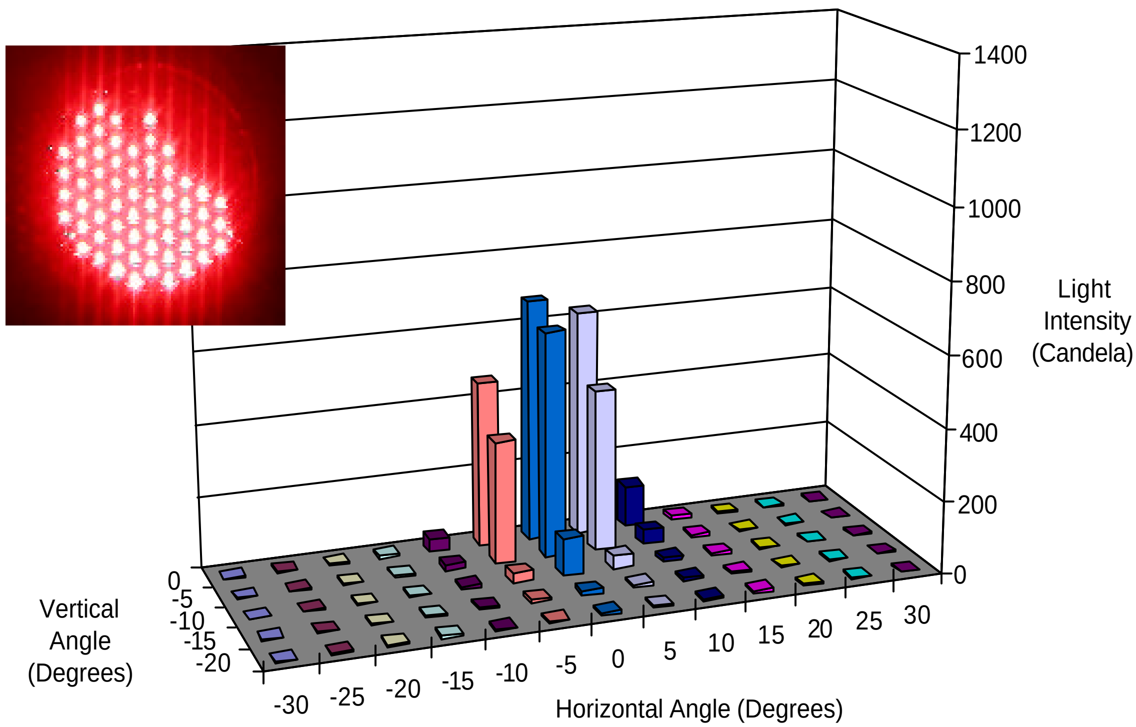

Figure A7.6.1a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

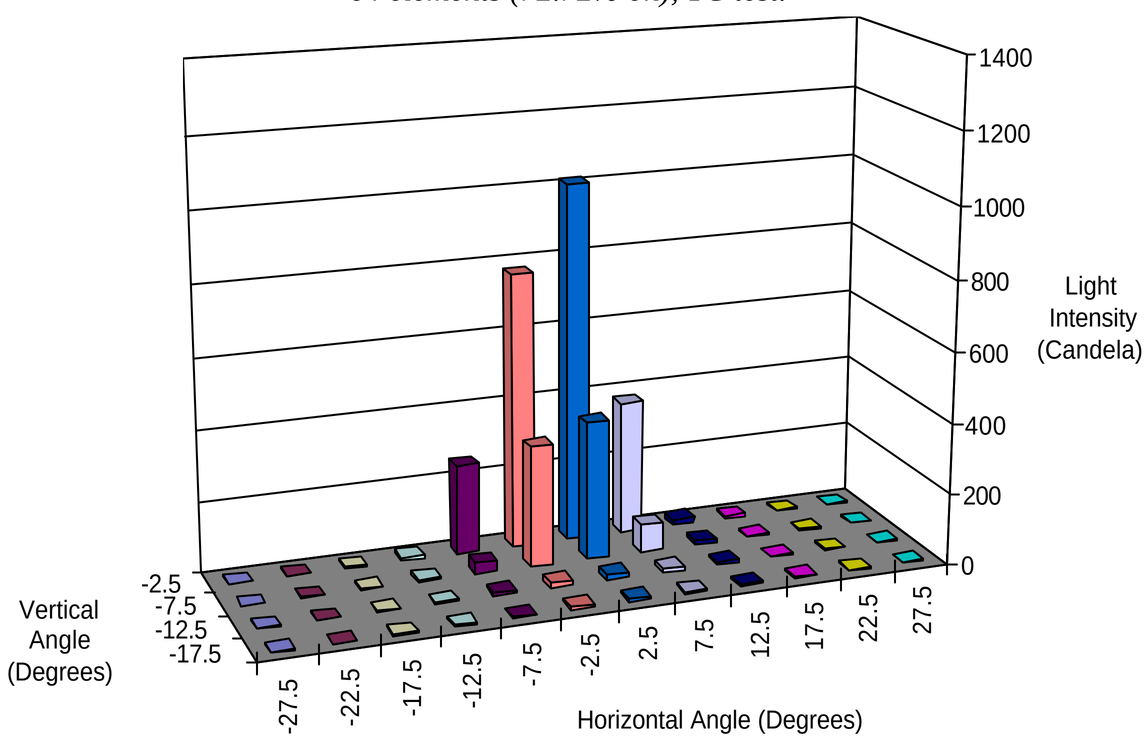

Figure A7.6.1b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

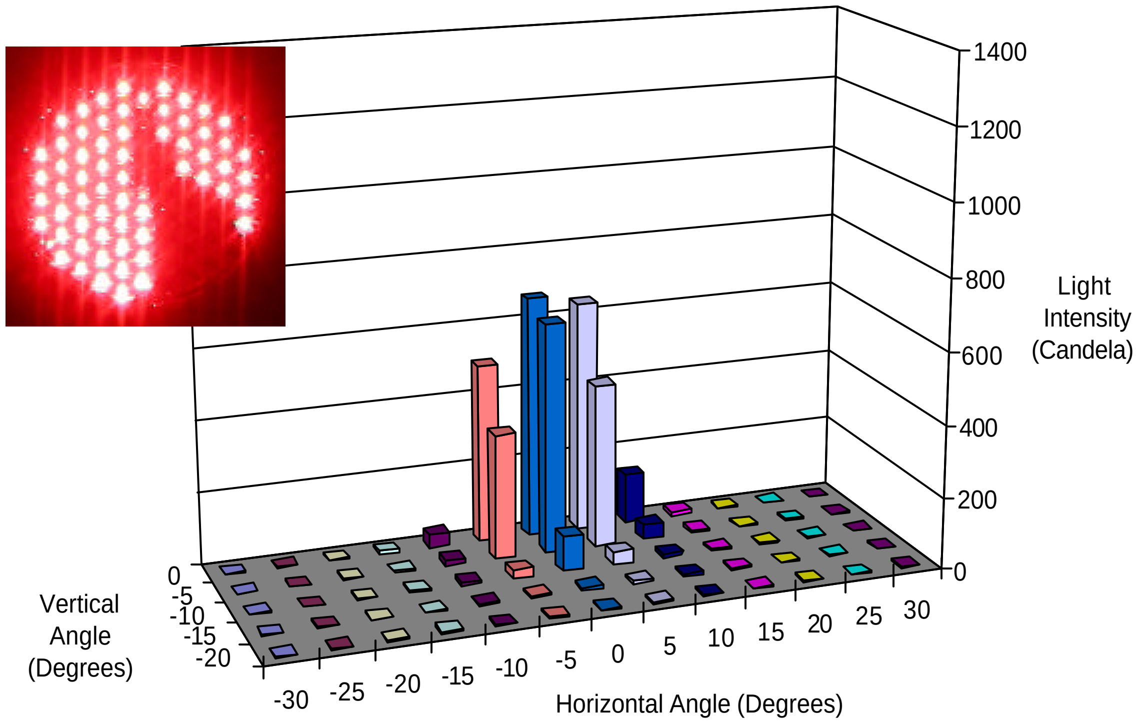

Figure A7.6.2a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

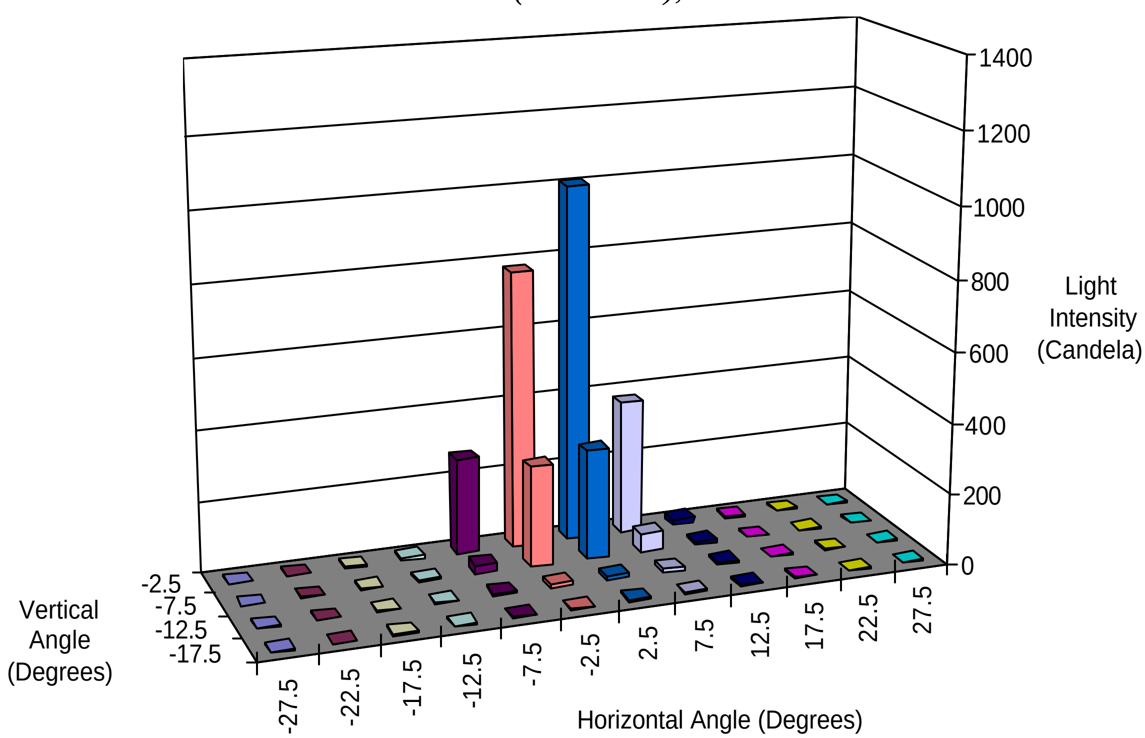

Figure A7.6.2b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

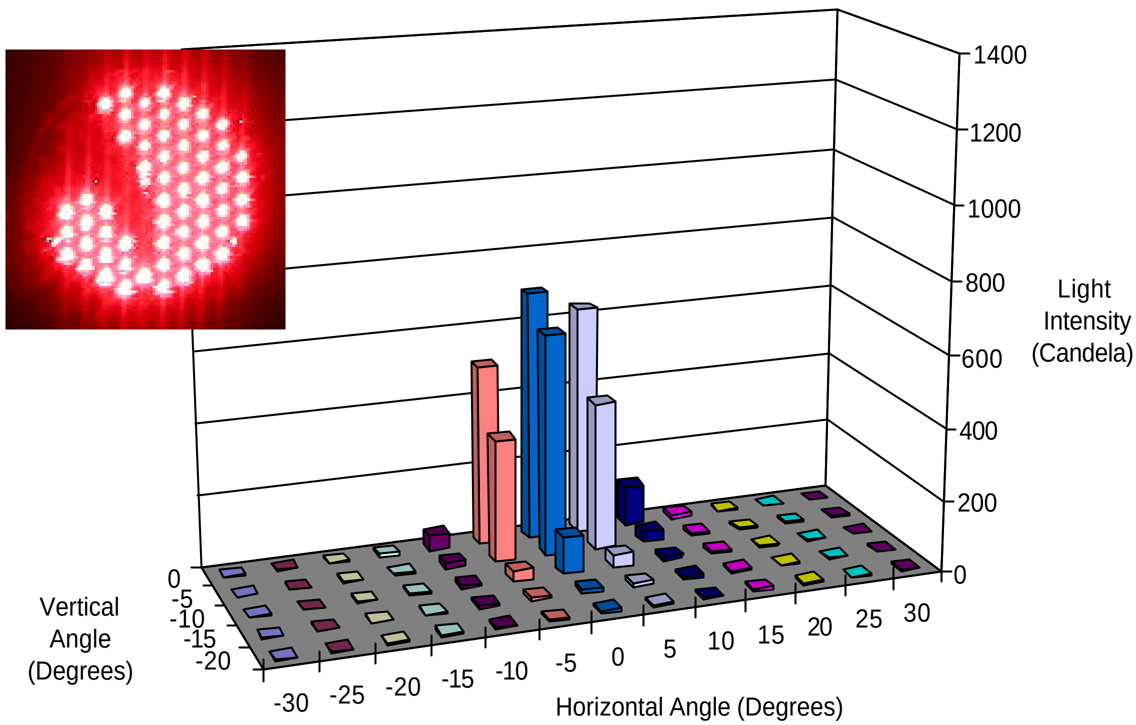

Figure A7.6.3a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

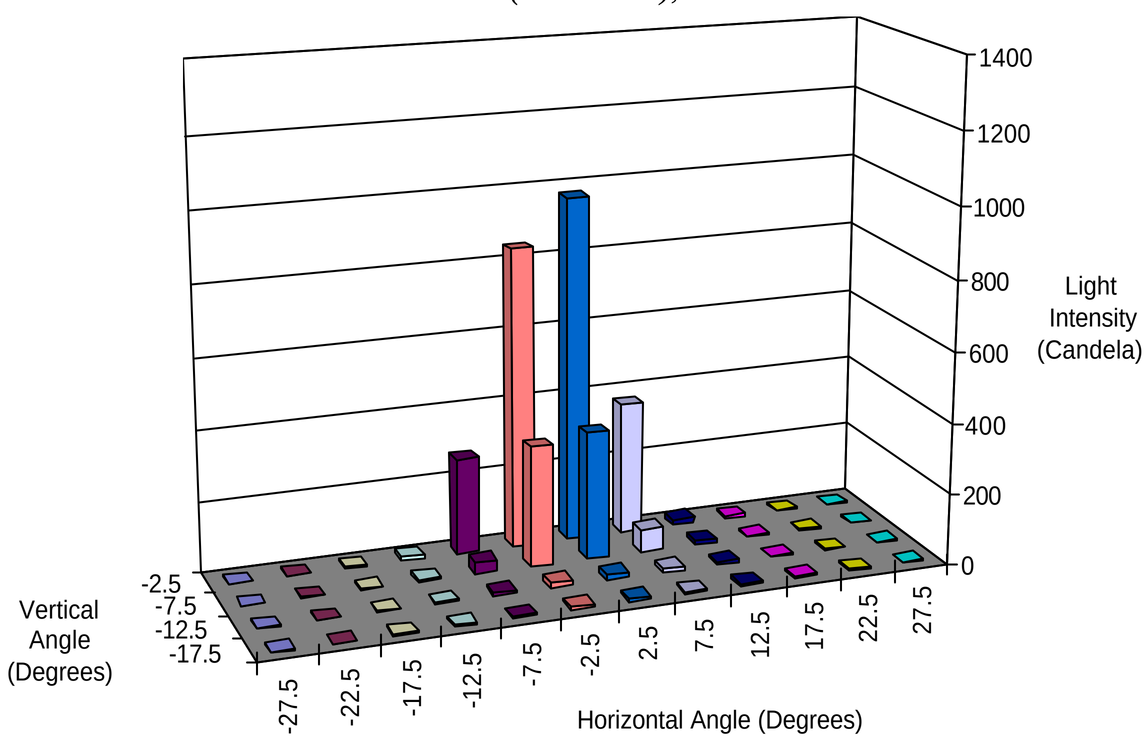

Figure A7.6.3b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

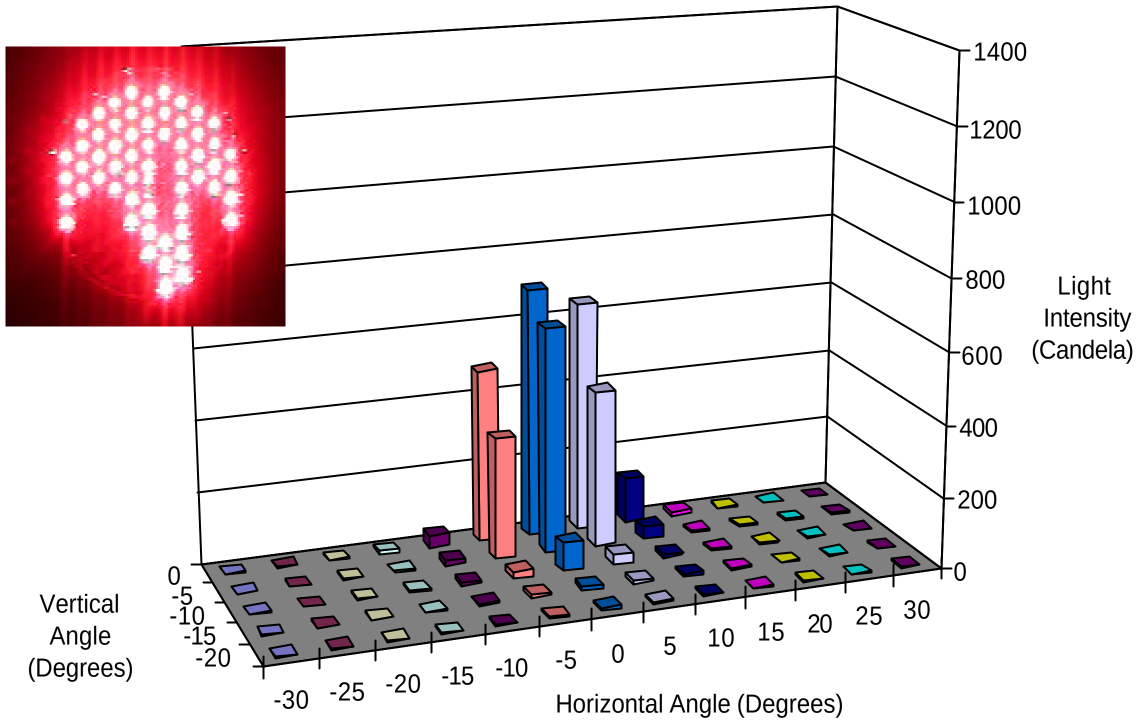

Figure A7.6.4a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

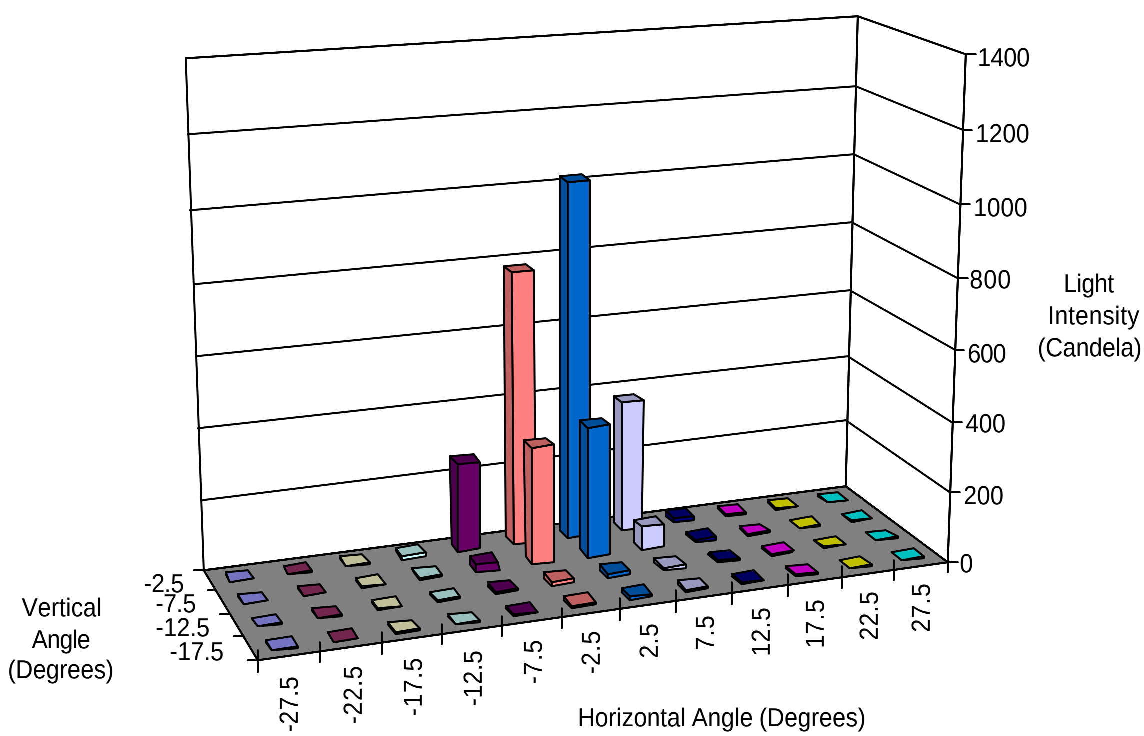

Figure A7.6.4b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

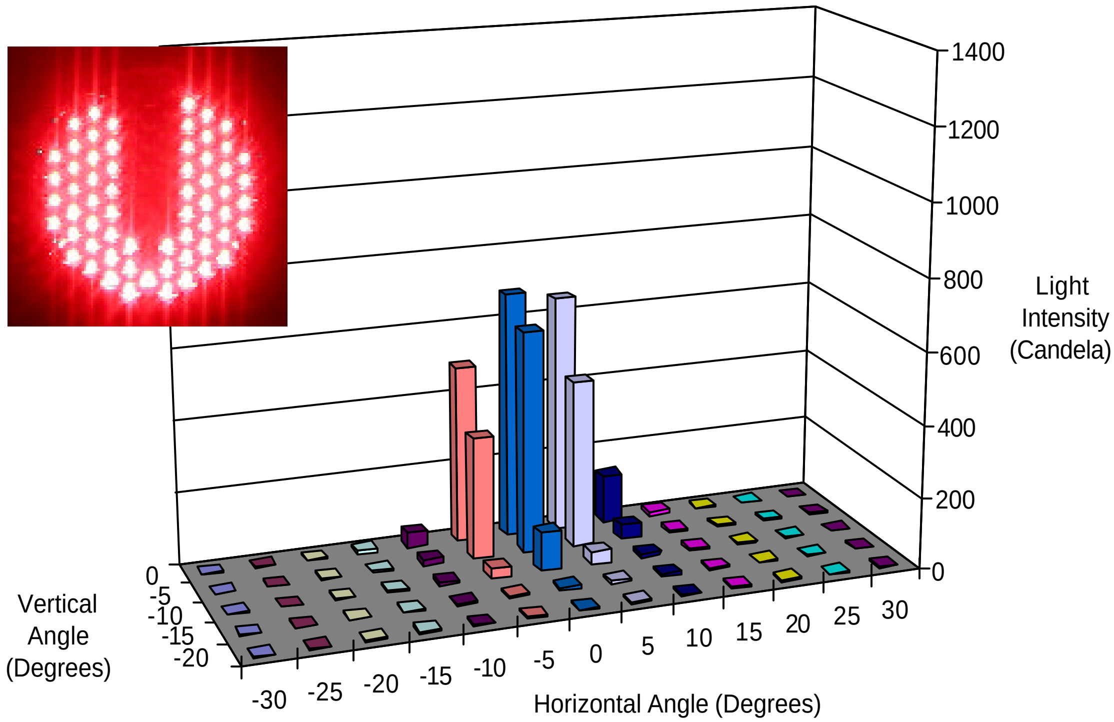

Figure A7.6.5a Output from WPS #7 (Red) signal, 10.0 volts,
64 elements (72.72% on), TC test.

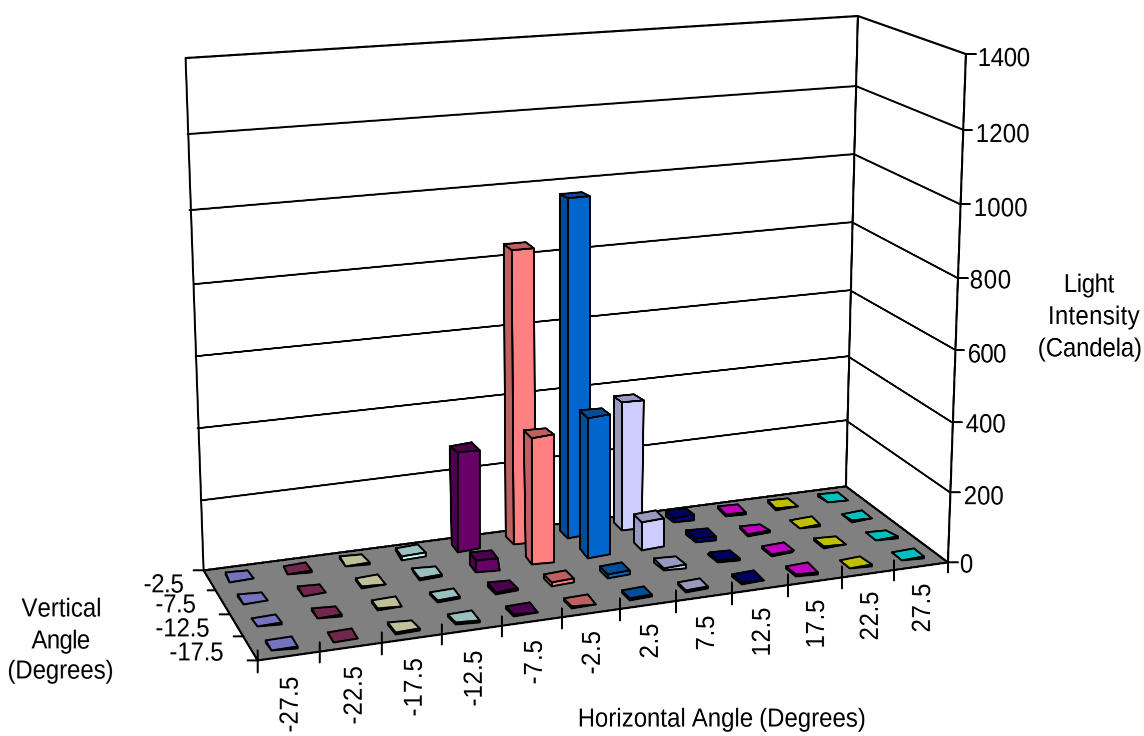

Figure A7.6.5b Output from WPS #7 (Red) signal, 10.0 volts,
64 elements (72.72% on), ITE test.

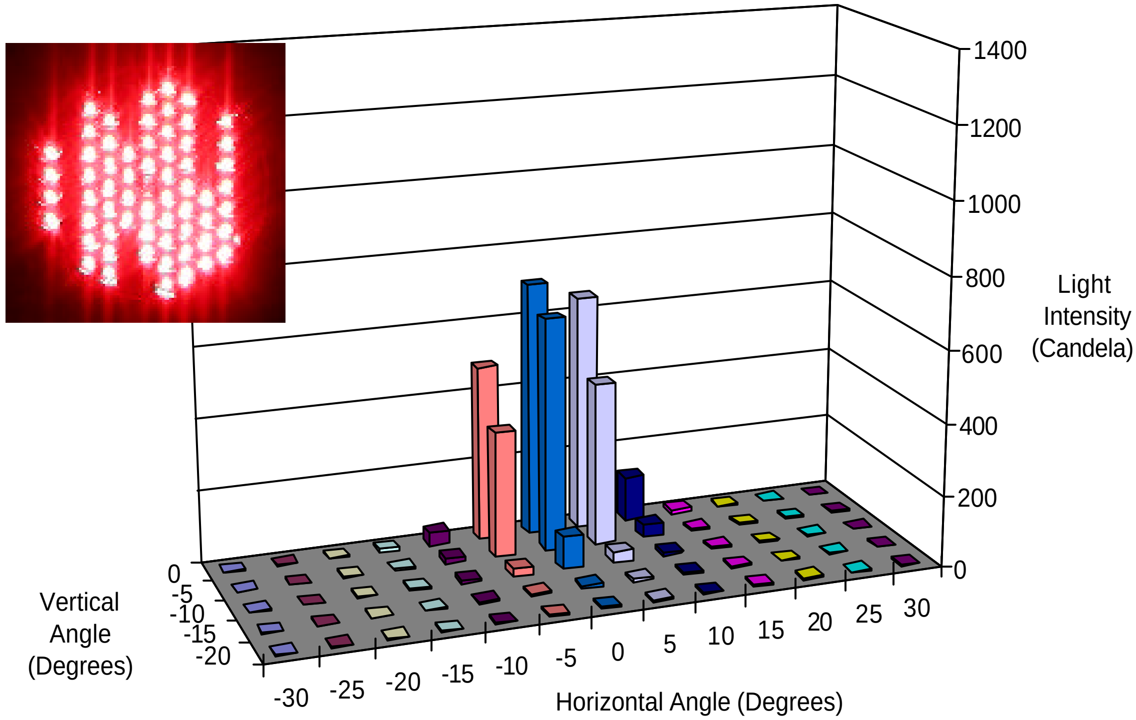

Figure A7.6.6a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

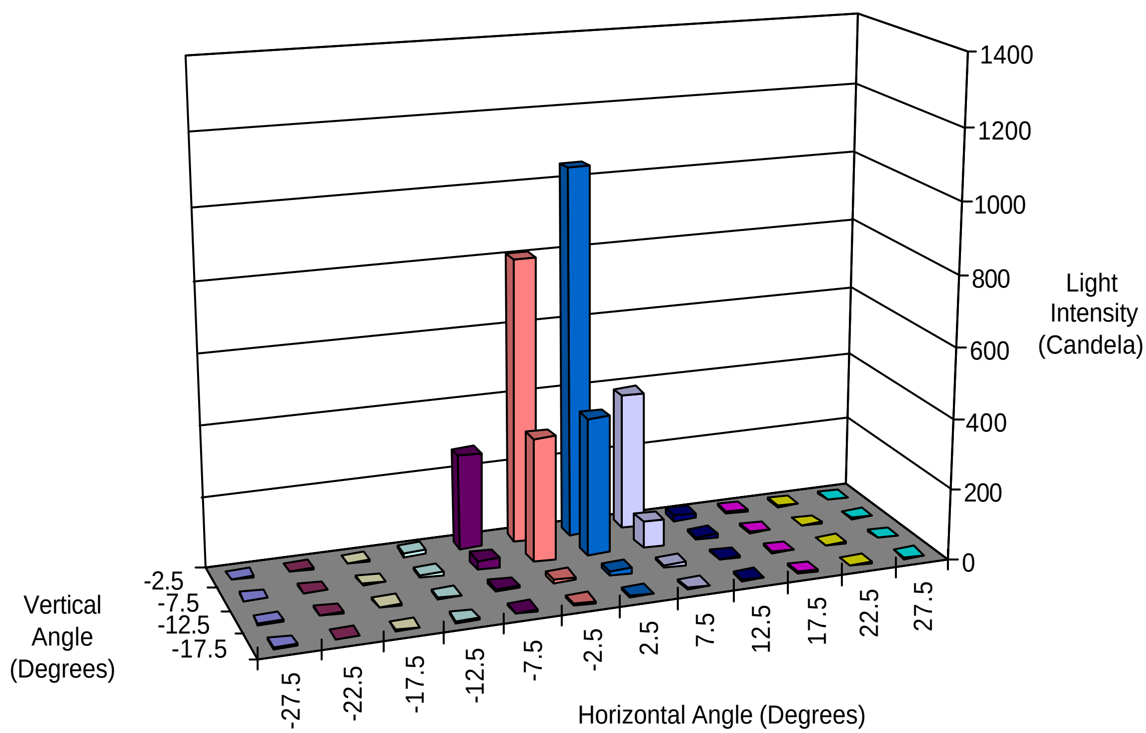

Figure A7.6.6b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

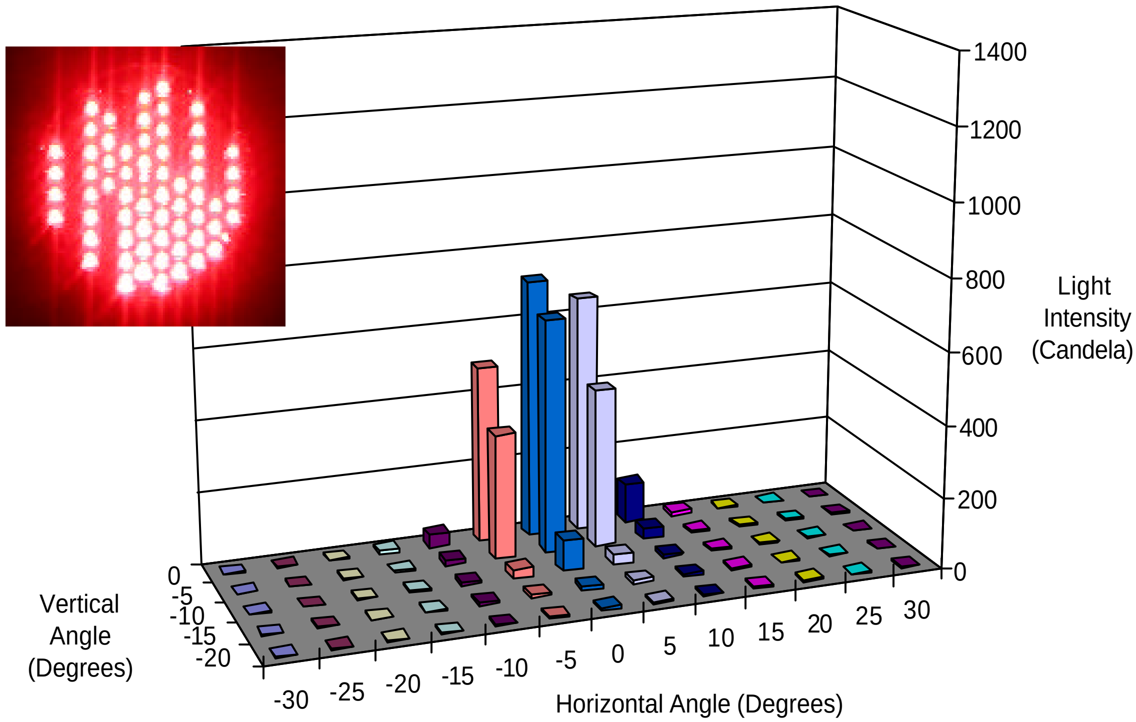

Figure A7.6.7a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

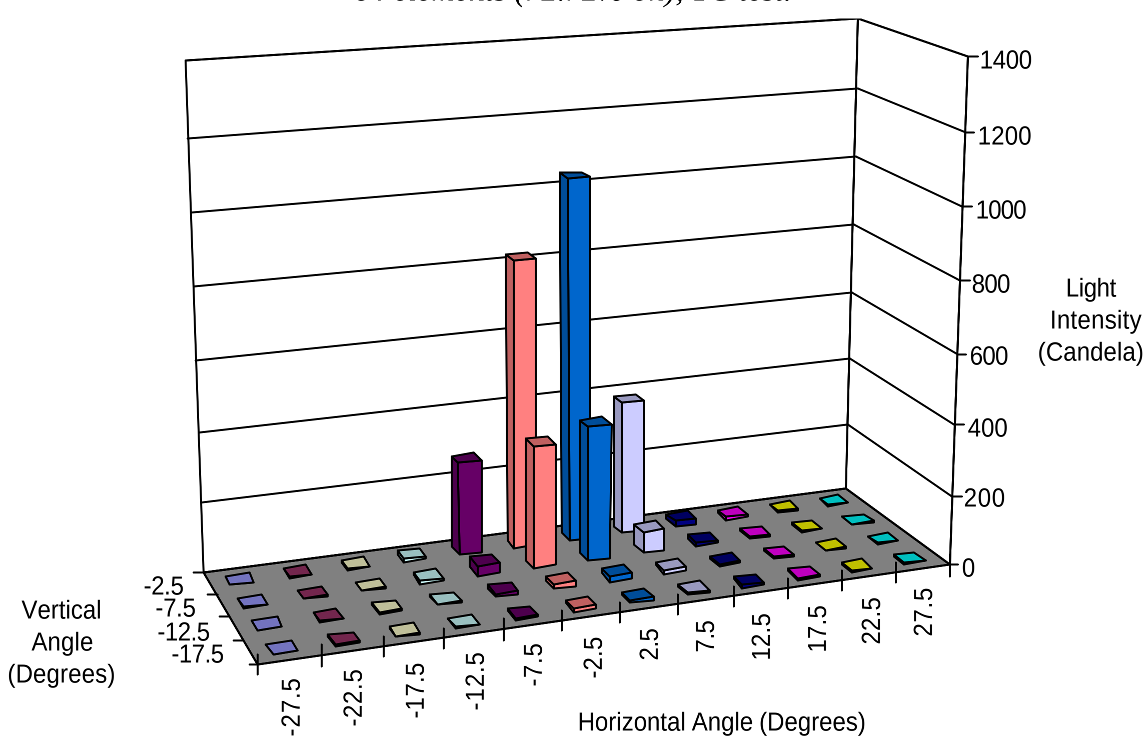

Figure A7.6.7b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

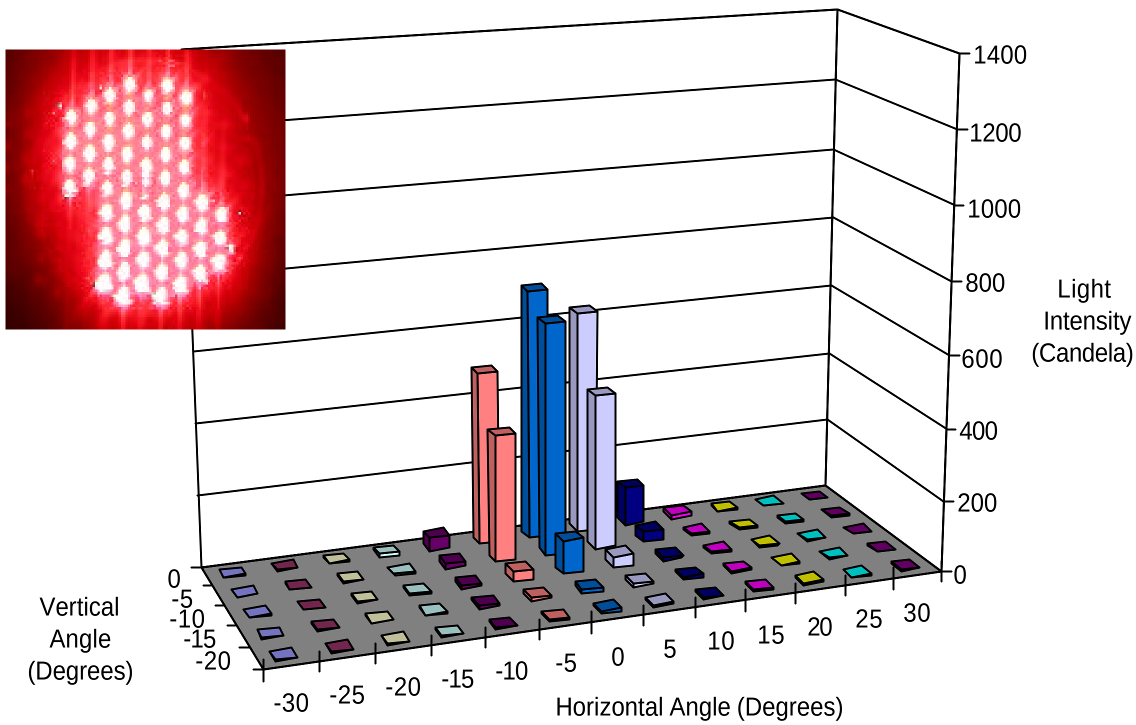

Figure A7.6.8a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

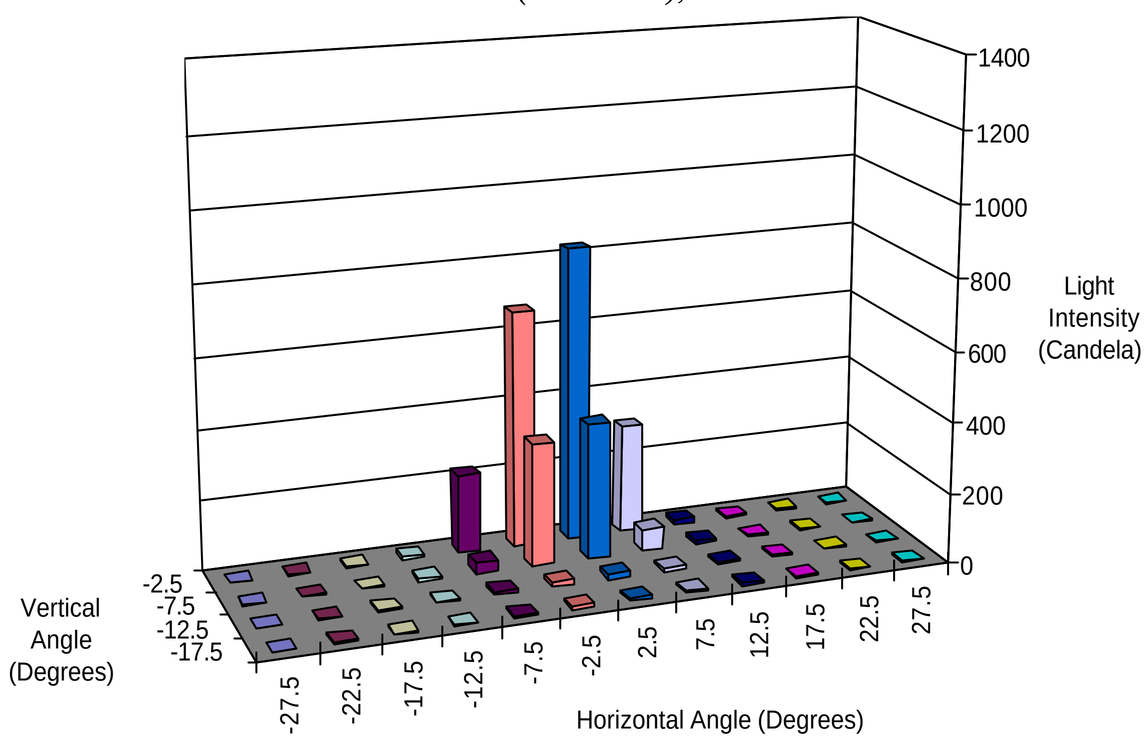

Figure A7.6.8b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

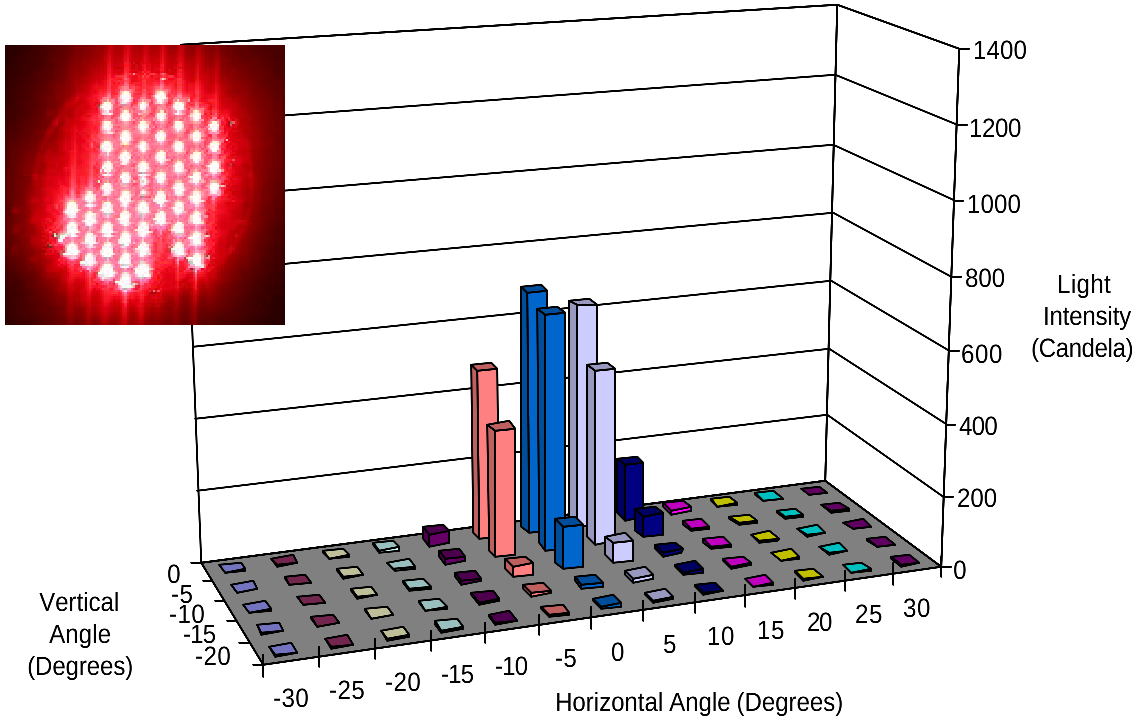

Figure A7.6.9a Output from WPS #7 (Red) signal, 10.0 volts,
64 elements (72.72% on), TC test.

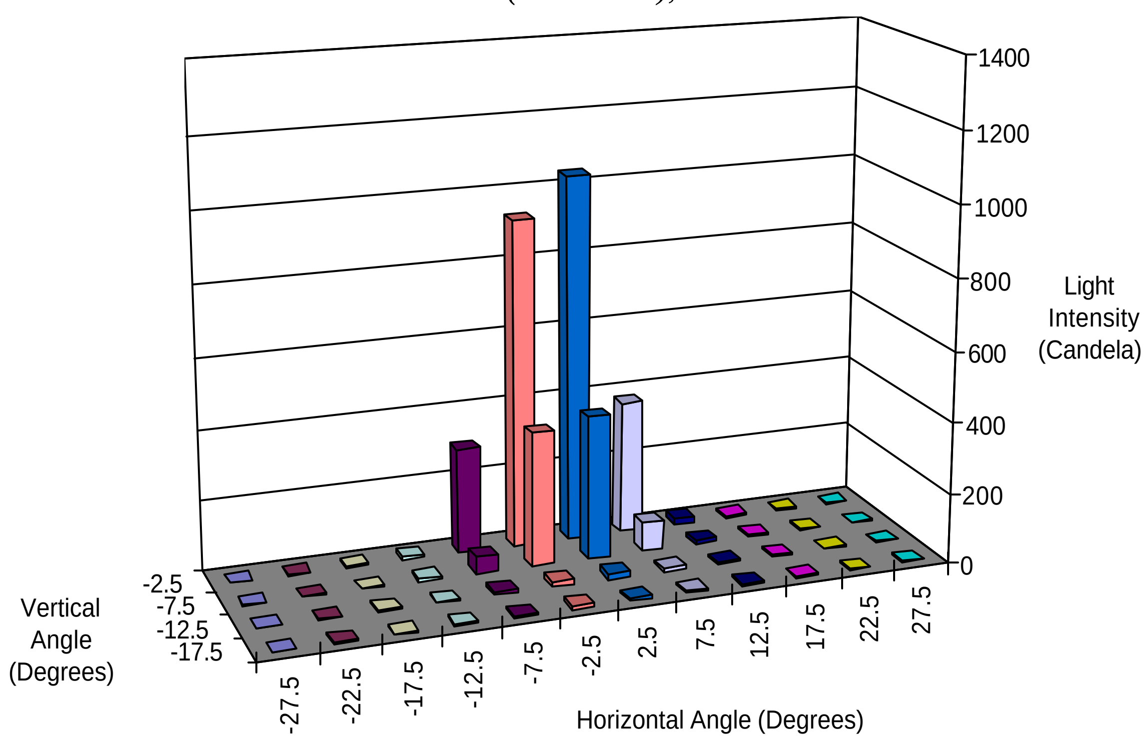

Figure A7.6.9b Output from WPS #7 (Red) signal, 10.0 volts,
64 elements (72.72% on), ITE test.

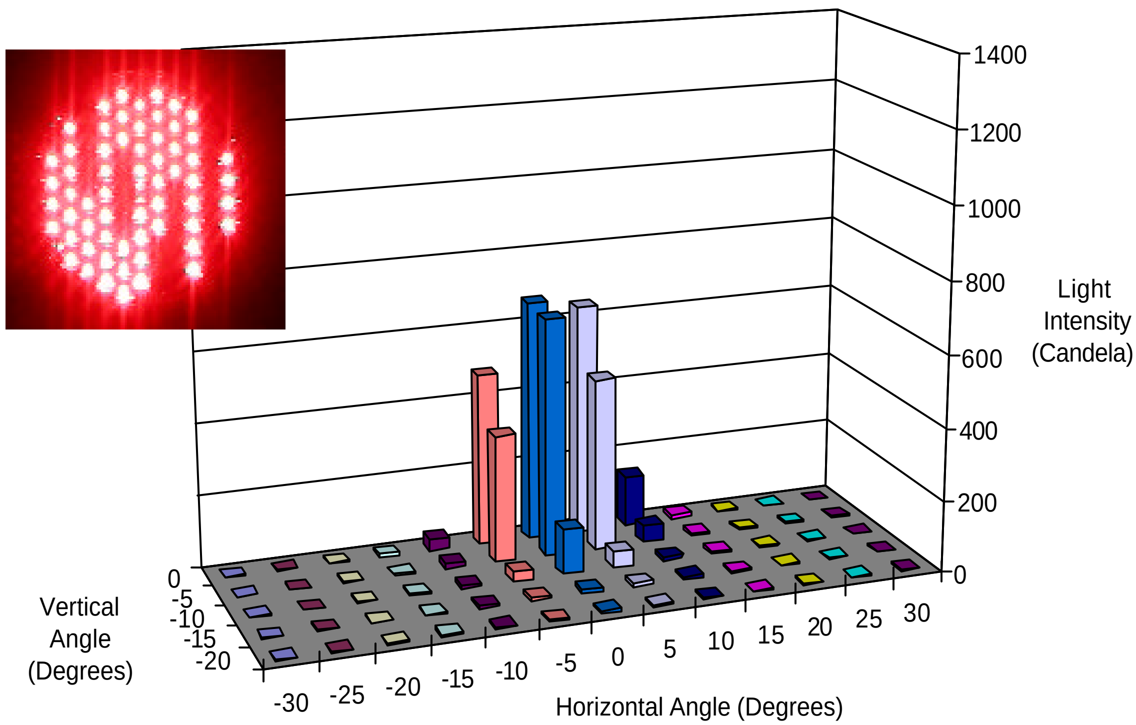

Figure A7.6.10a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

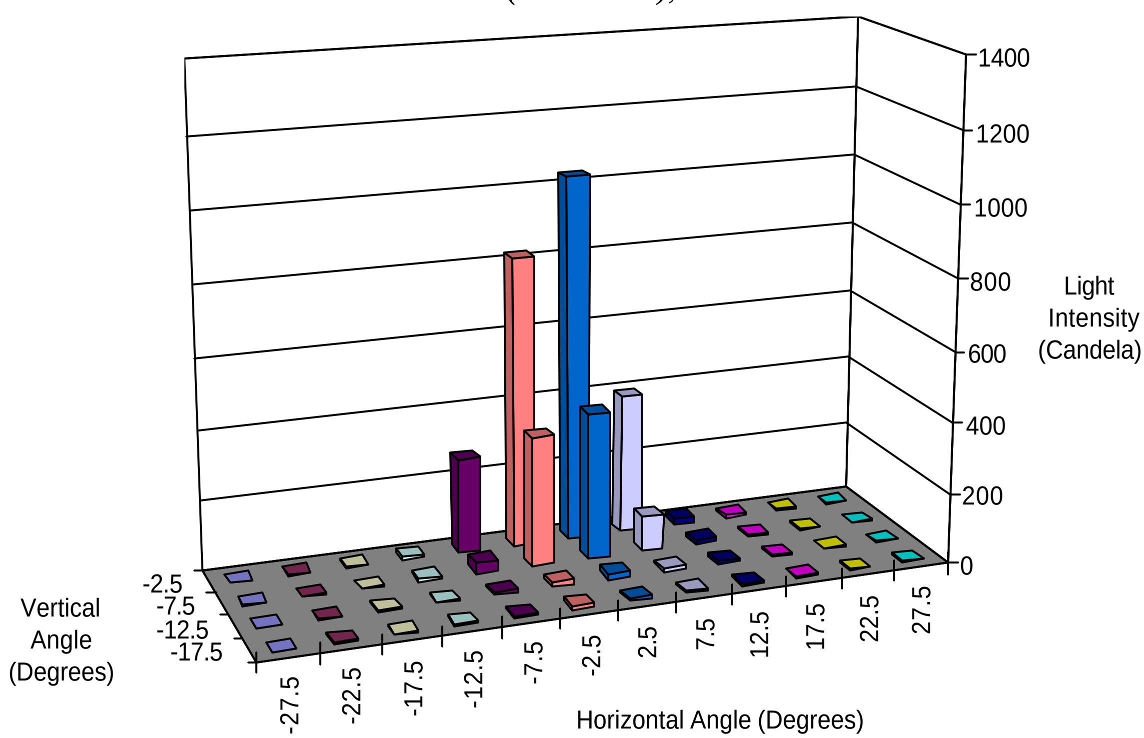

Figure A7.6.10b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

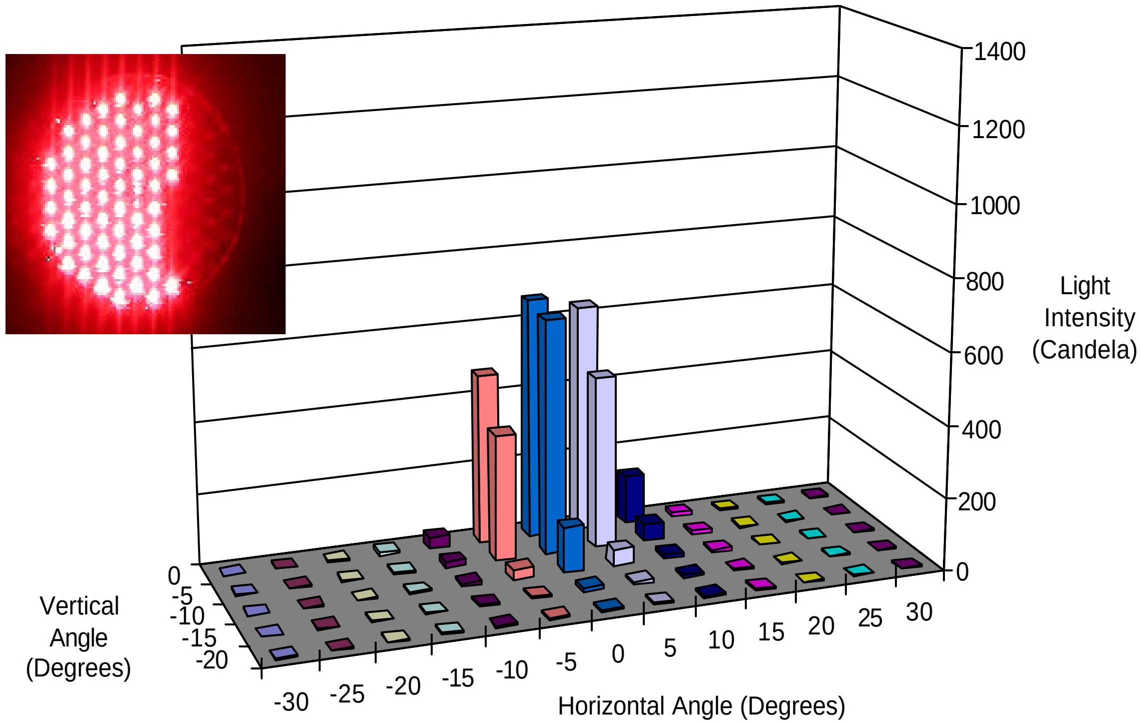

Figure A7.6.11a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

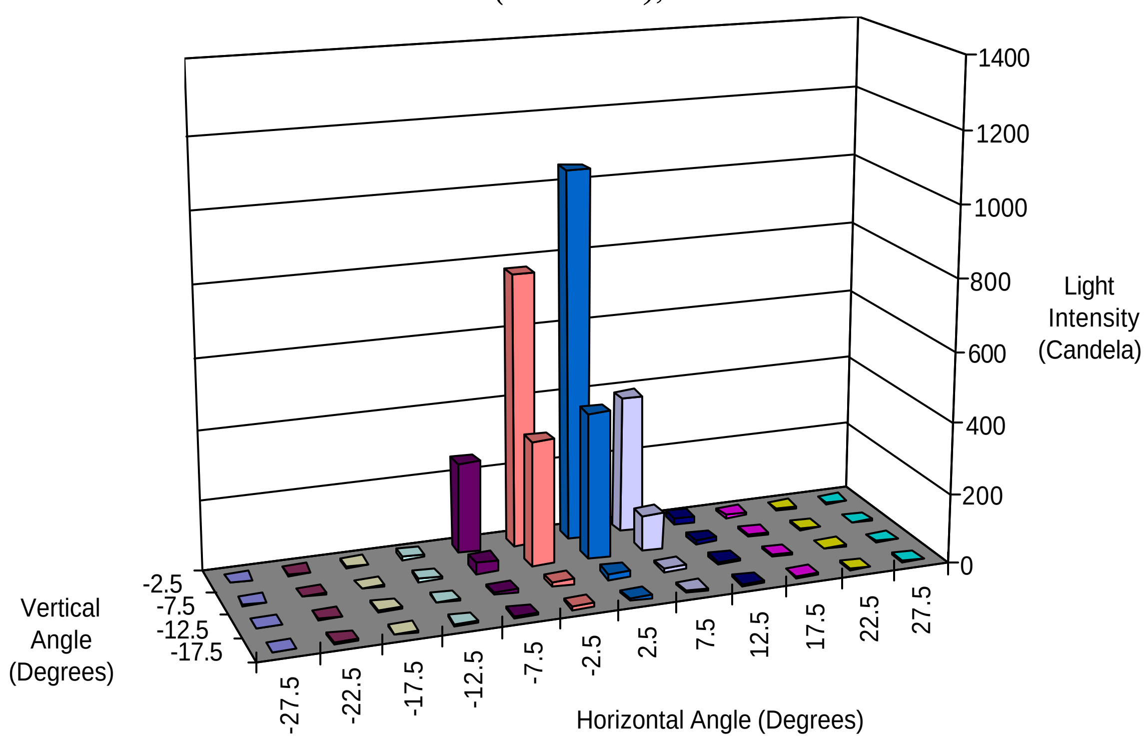

Figure A7.6.11b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

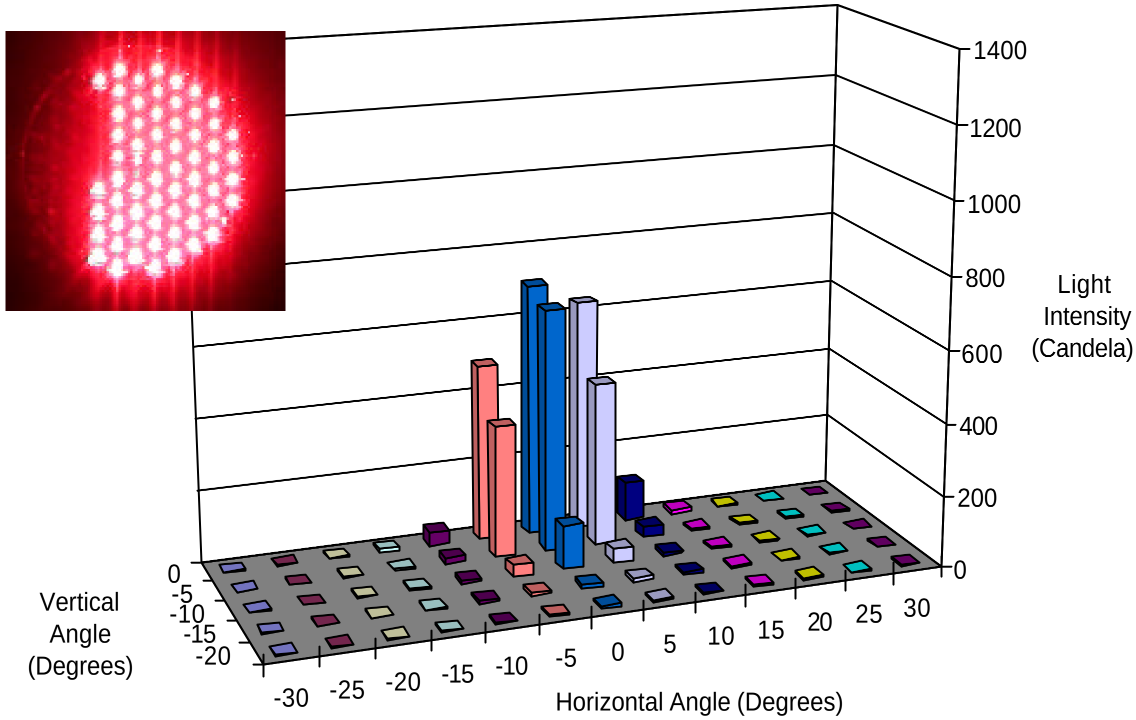

Figure A7.6.12a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

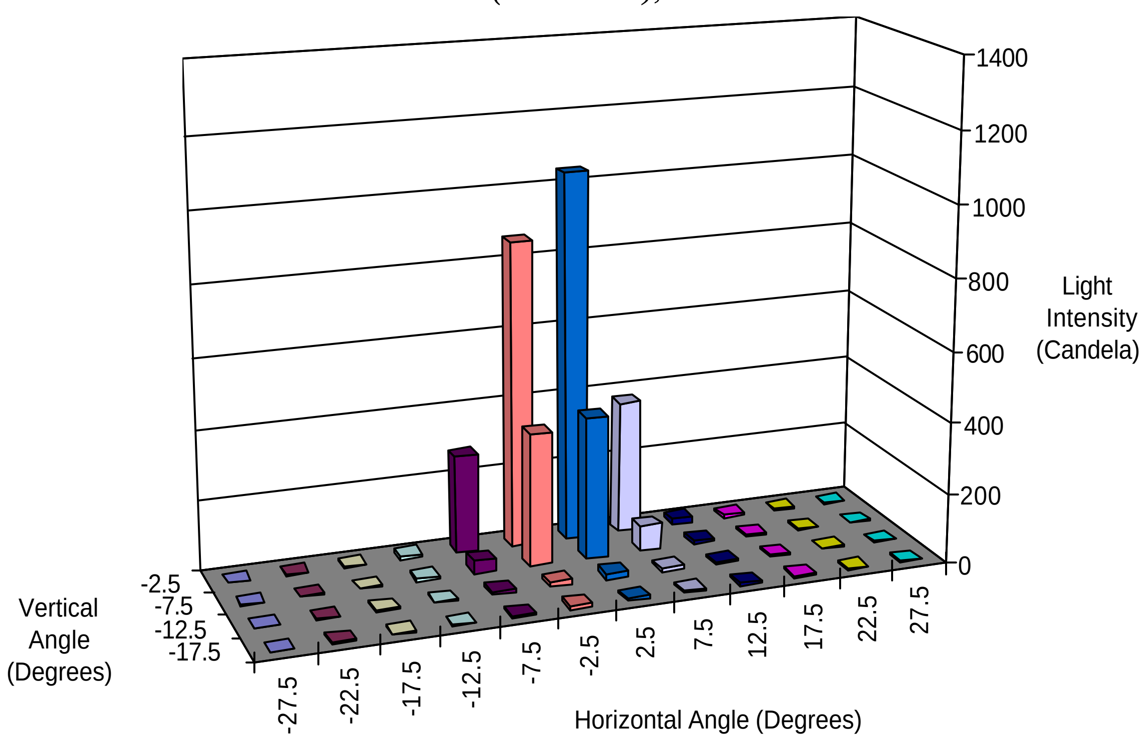

Figure A7.6.12b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

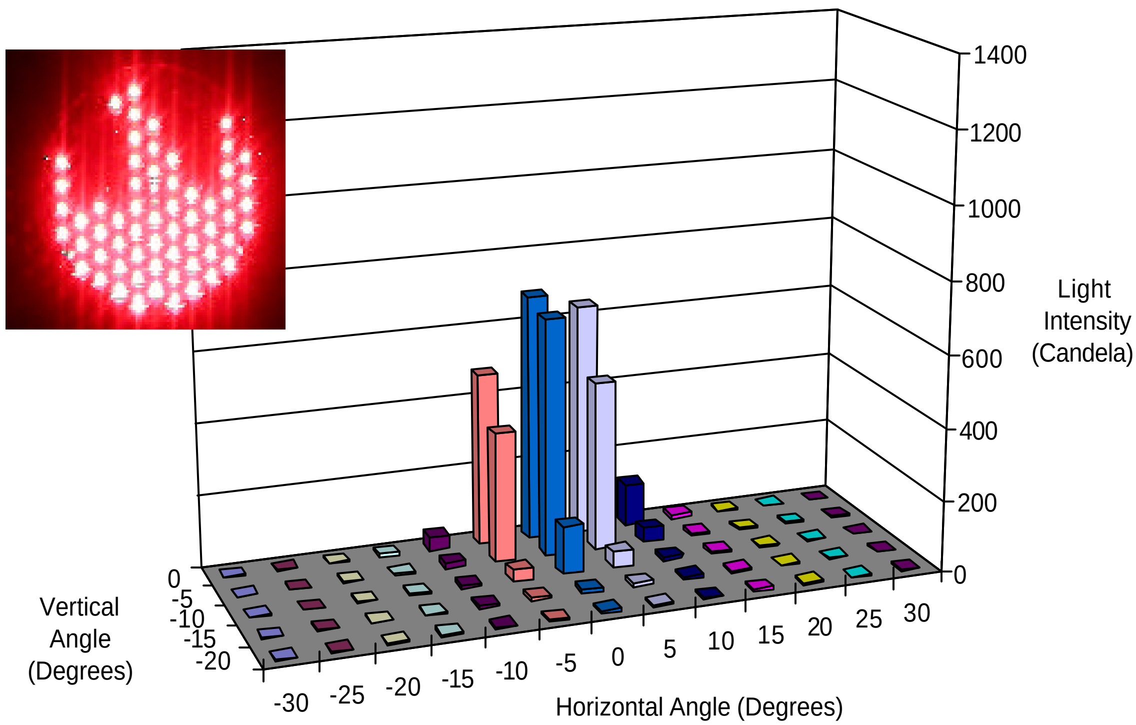

Figure A7.6.13a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

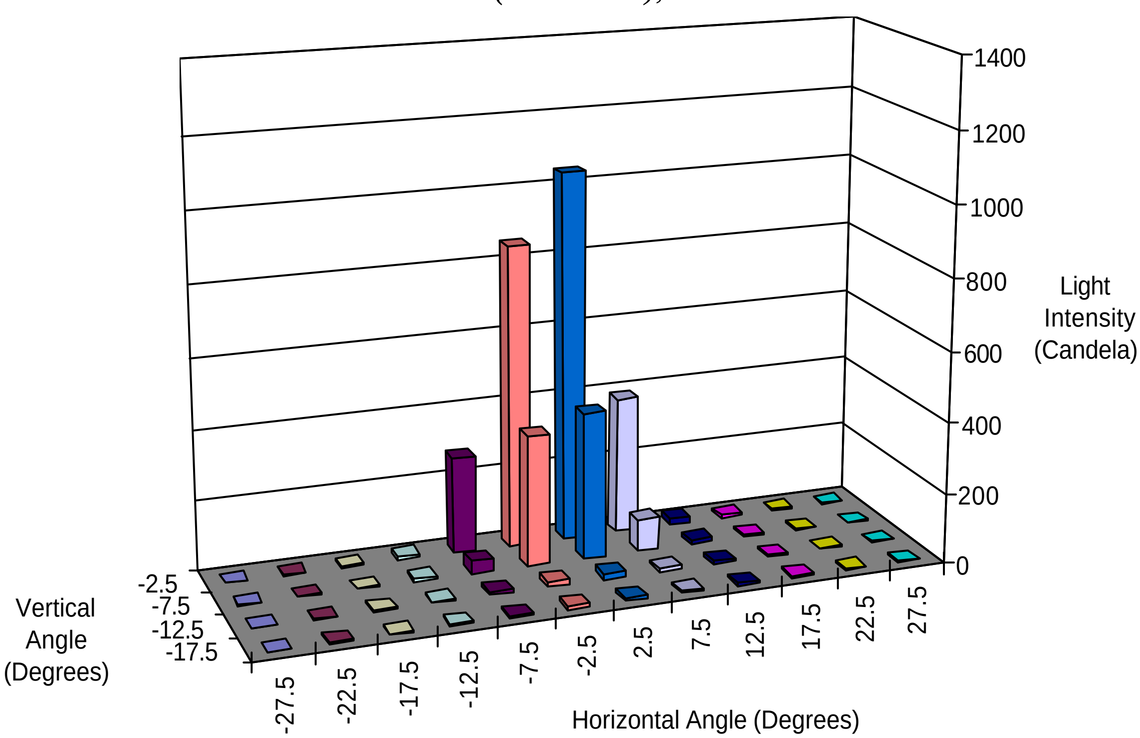

Figure A7.6.13b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

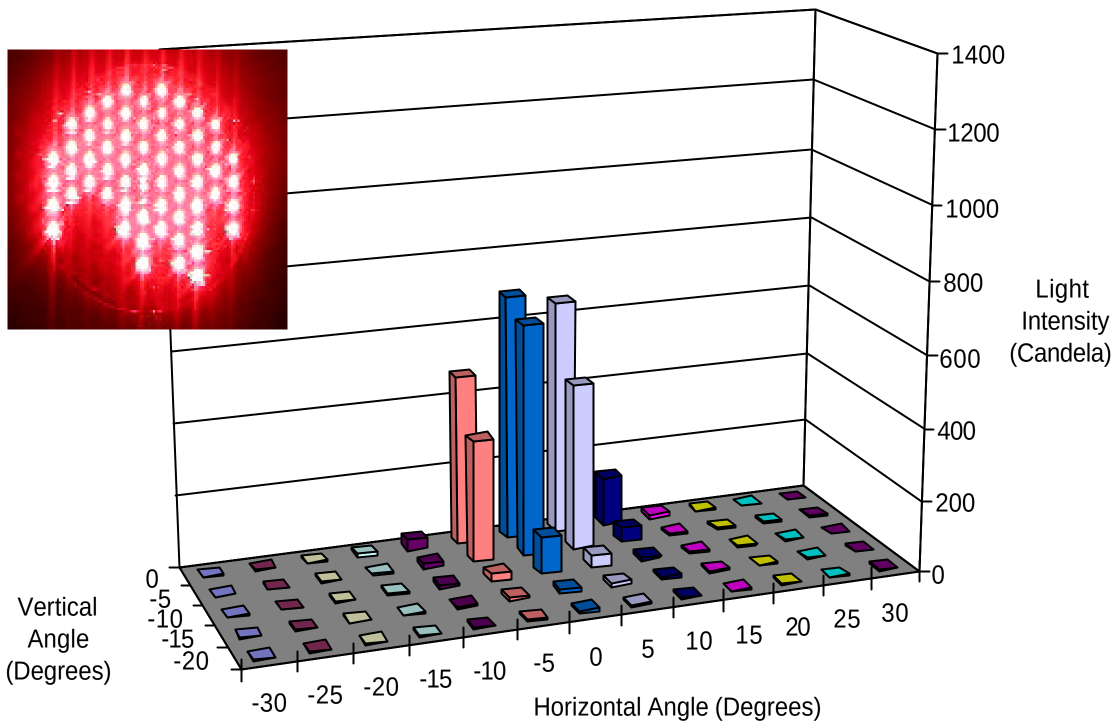

Figure A7.6.14a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

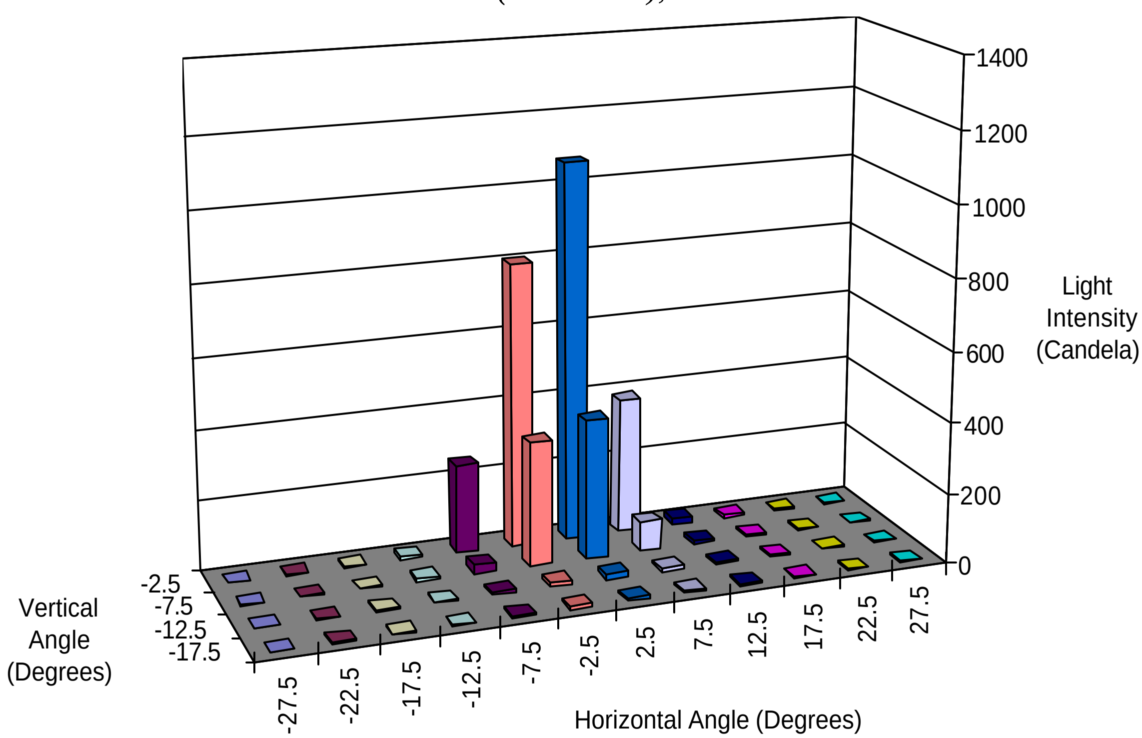

Figure A7.6.14b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

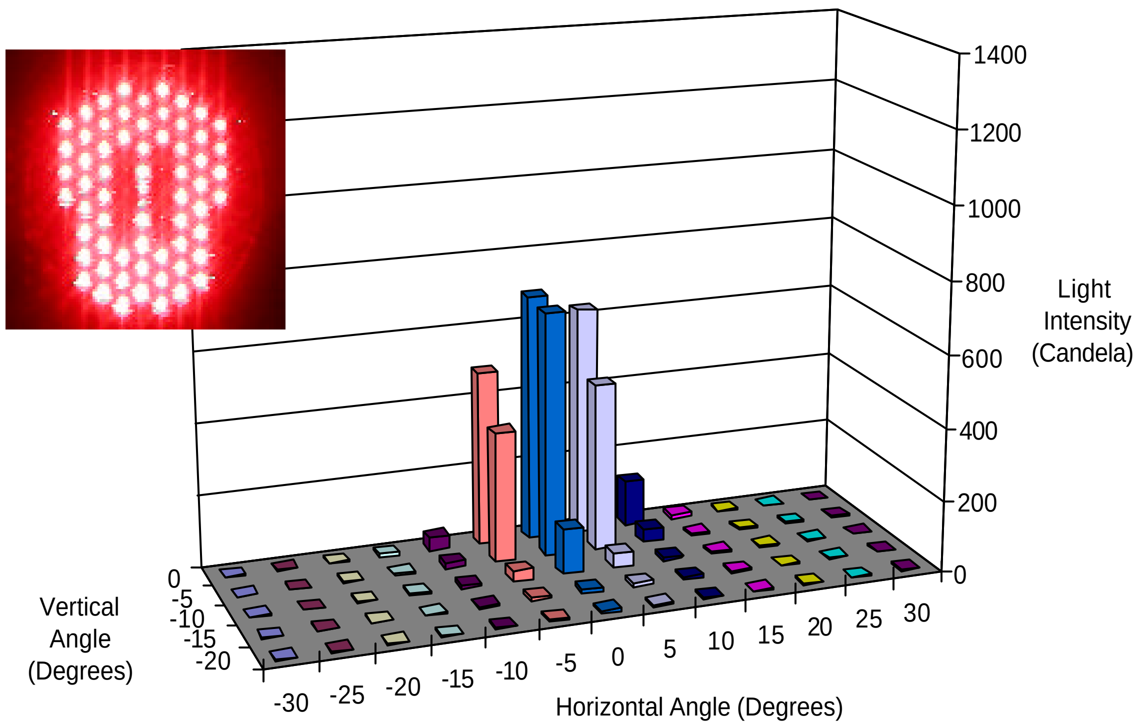

Figure A7.6.15a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

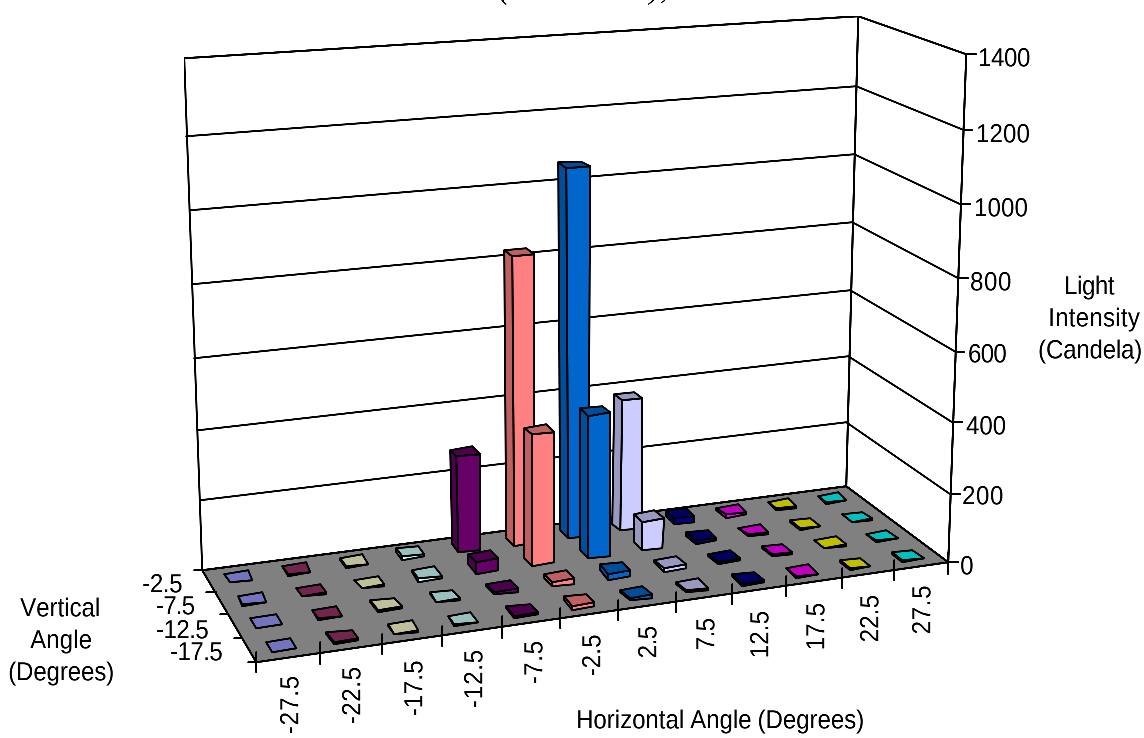

Figure A7.6.15b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

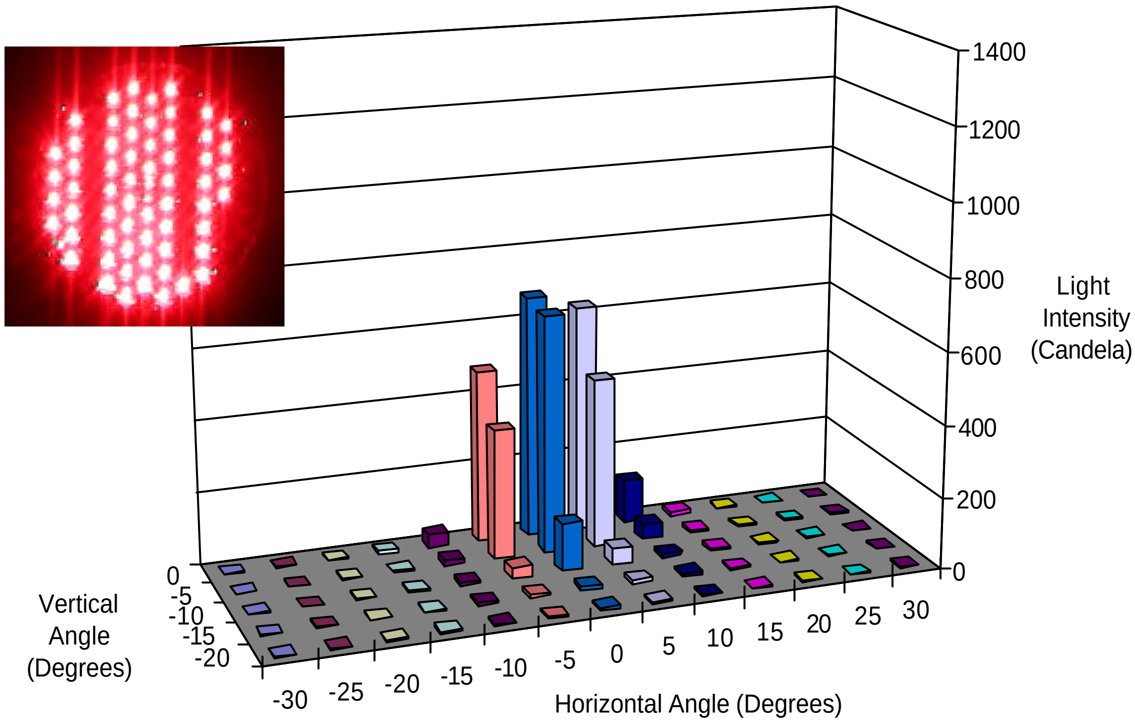

Figure A7.6.16a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

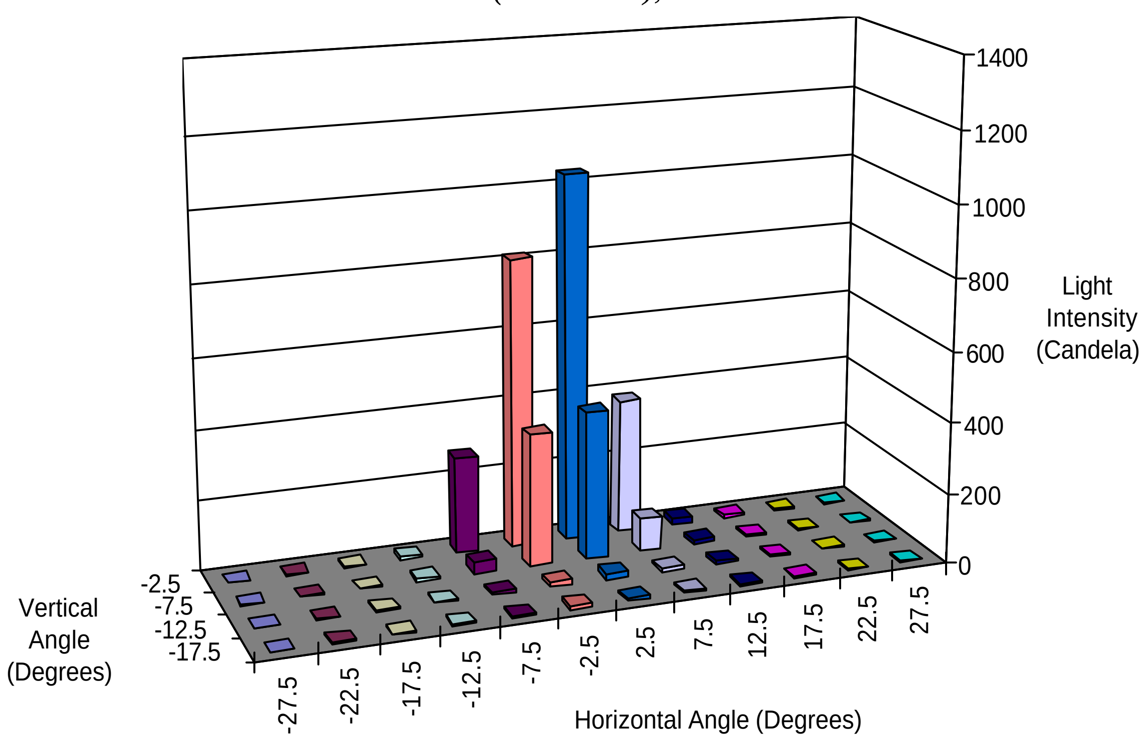

Figure A7.6.16b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

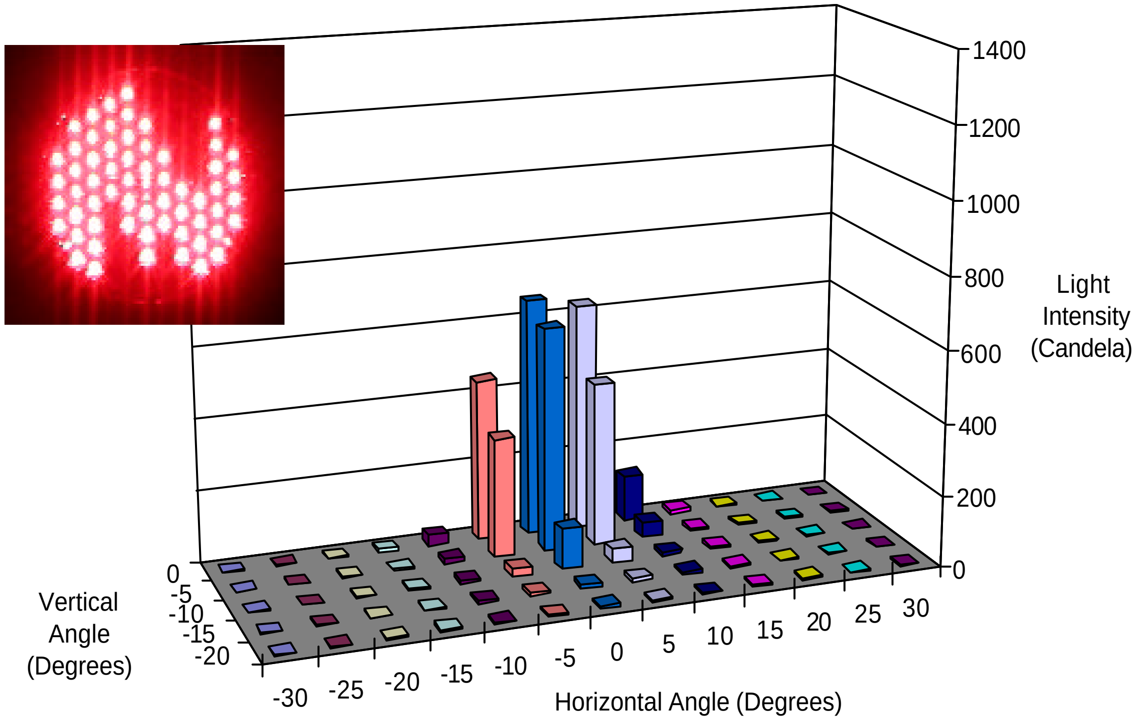

Figure A7.6.17a Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), TC test.

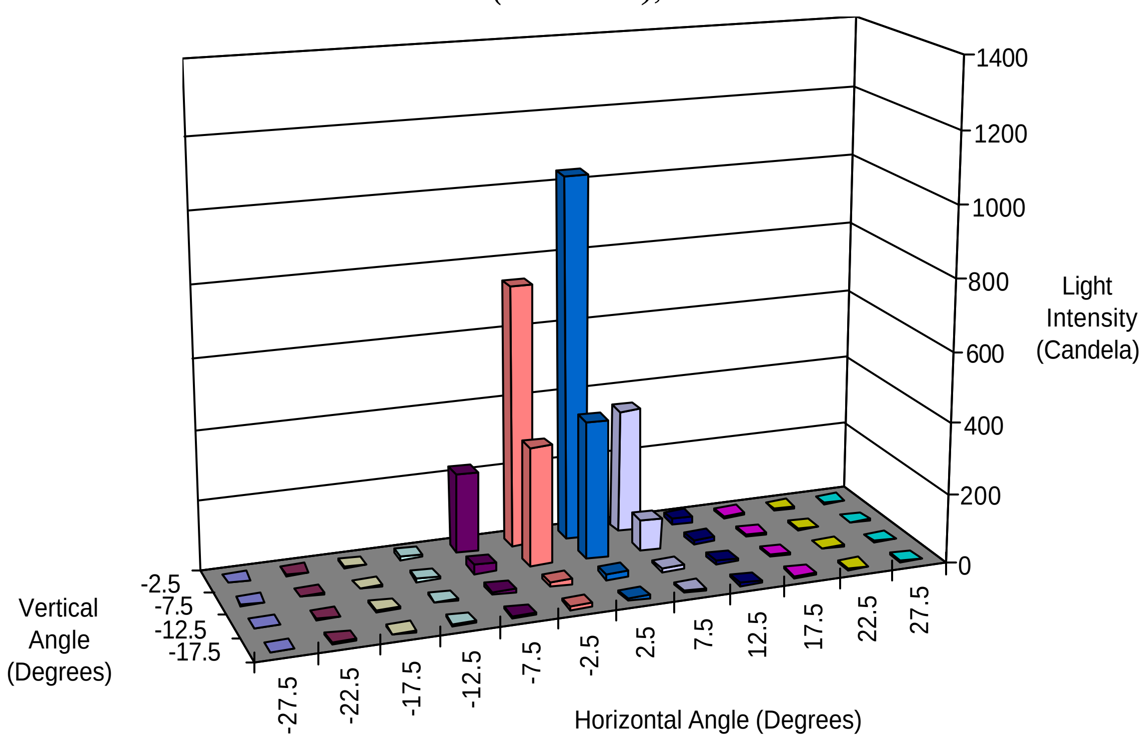

Figure A7.6.17b Output from WPS #7 (Red) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

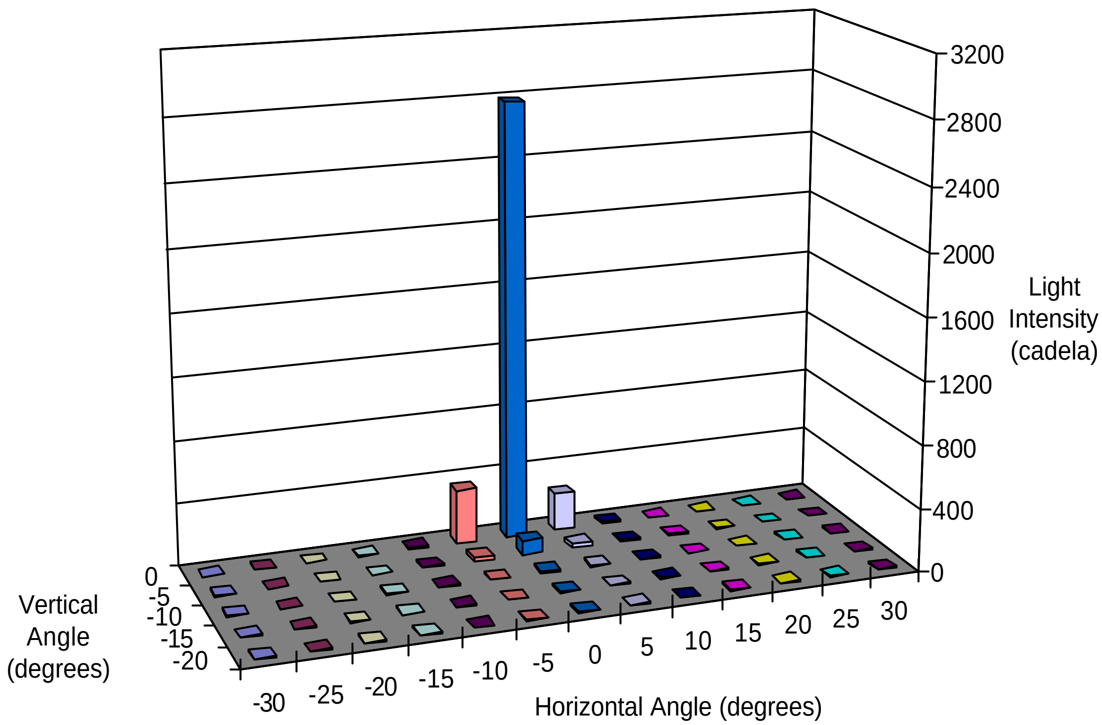

Figure A8.1.1a Output from WPS #8 (Yellow) signal, 10.0 volts, 37.0 ft, all elements on, TC test.

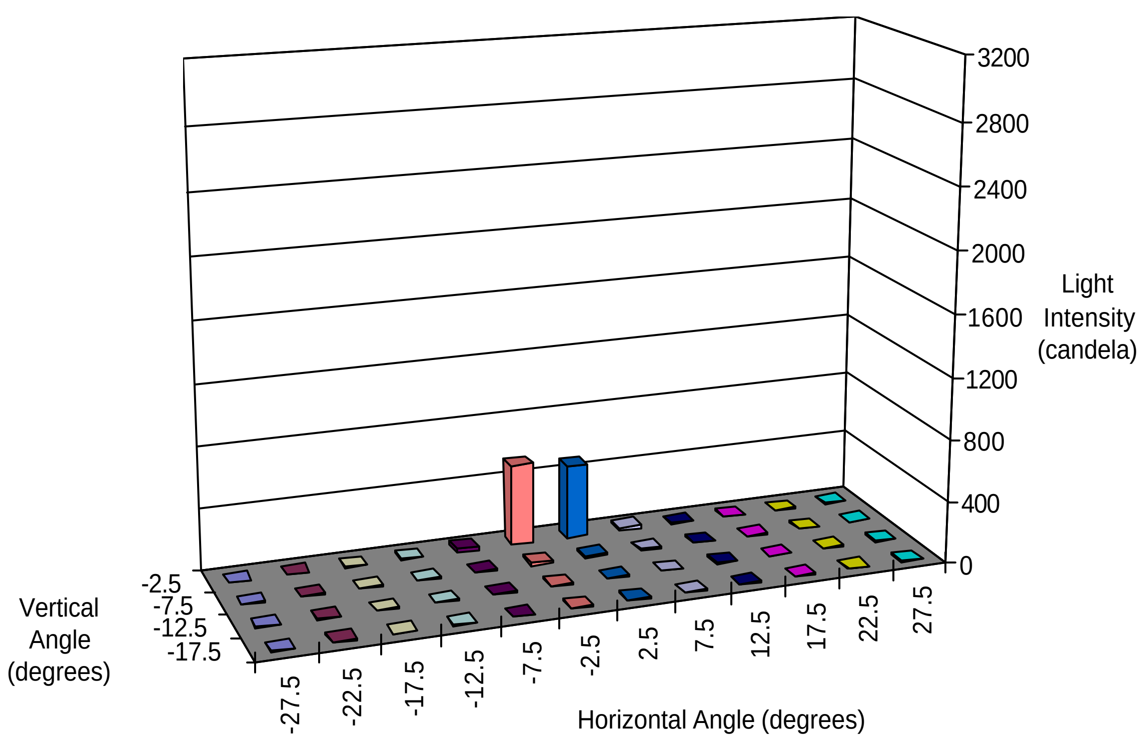

Figure A8.1.1b Output from WPS #8 (Yellow) signal, 10.0 volts, 37.0 ft, all elements on, ITE test.

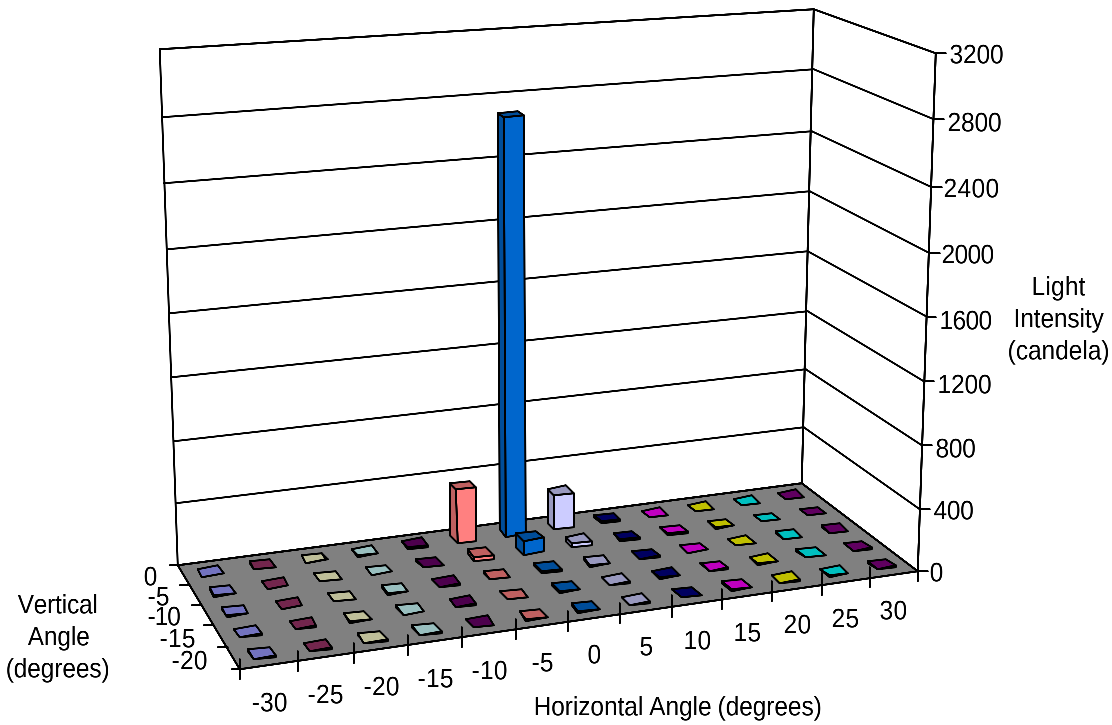

Figure A8.1.2a Output from WPS #8 (Yellow) signal, 10.0 volts, 38.0 ft, all elements on, TC test.

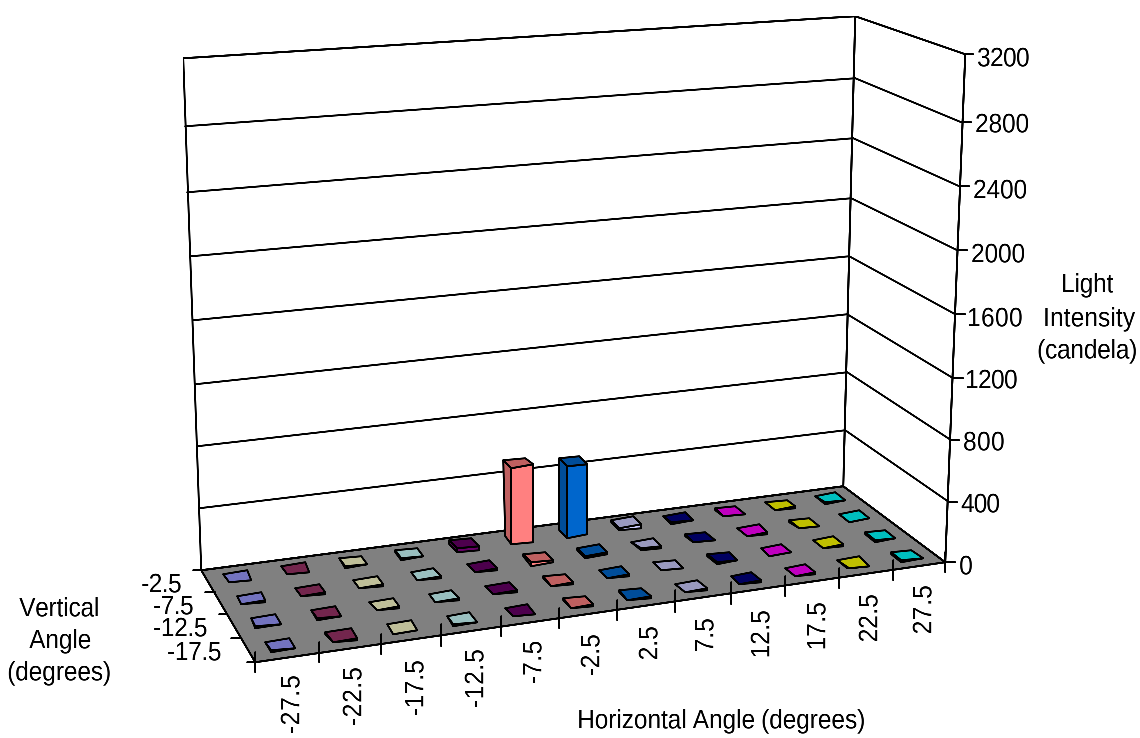

Figure A8.1.2b Output from WPS #8 (Yellow) signal, 10.0 volts, 38.0 ft, all elements on, ITE test.

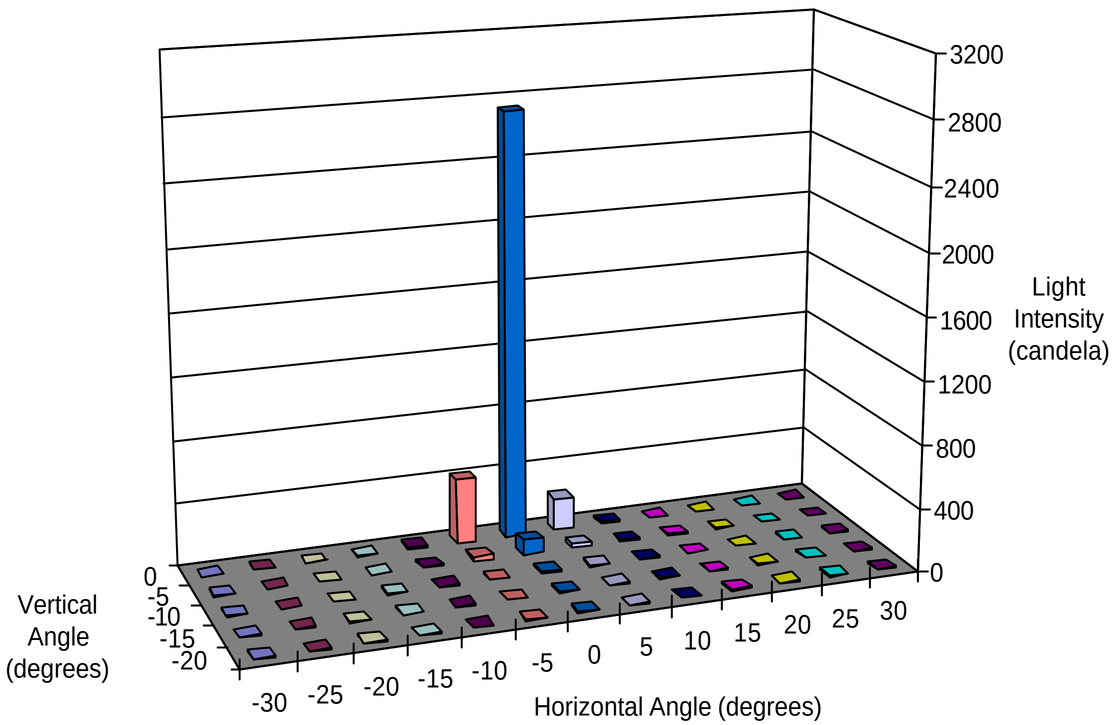

Figure A8.1.3a Output from WPS #8 (Yellow) signal, 10.0 volts, 40.0 ft, all elements on, TC test.

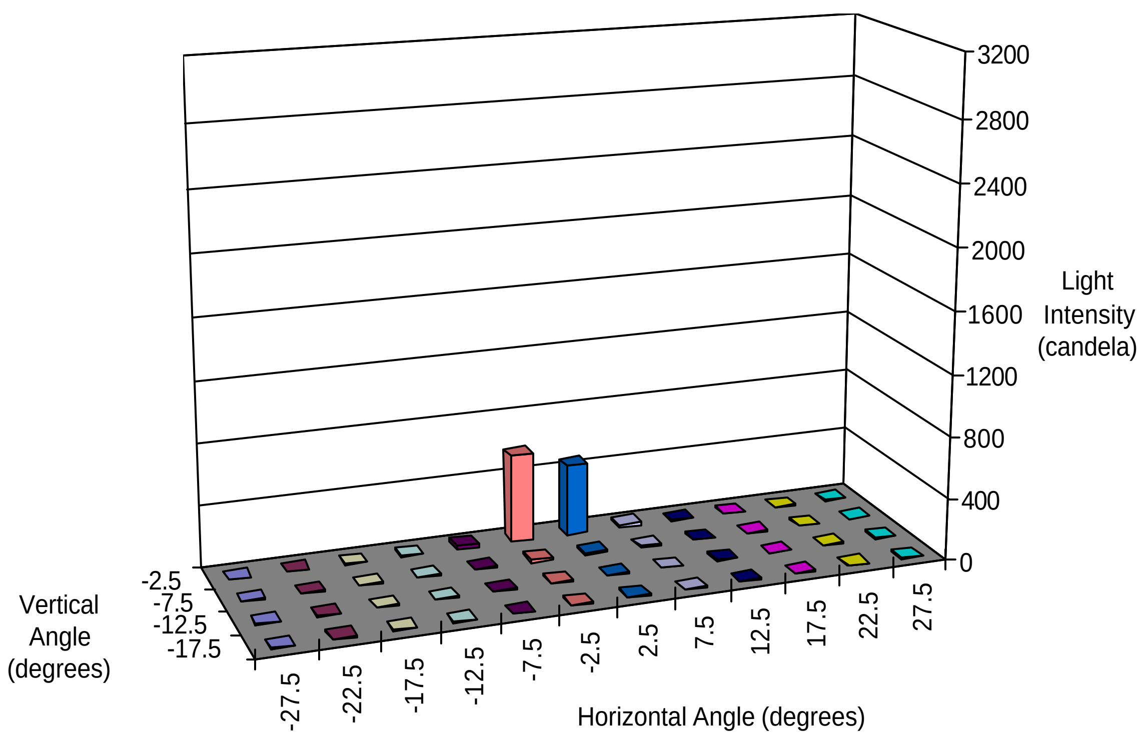

Figure A8.1.3b Output from WPS #8 (Yellow) signal, 10.0 volts, 40.0 ft, all elements on, ITE test.

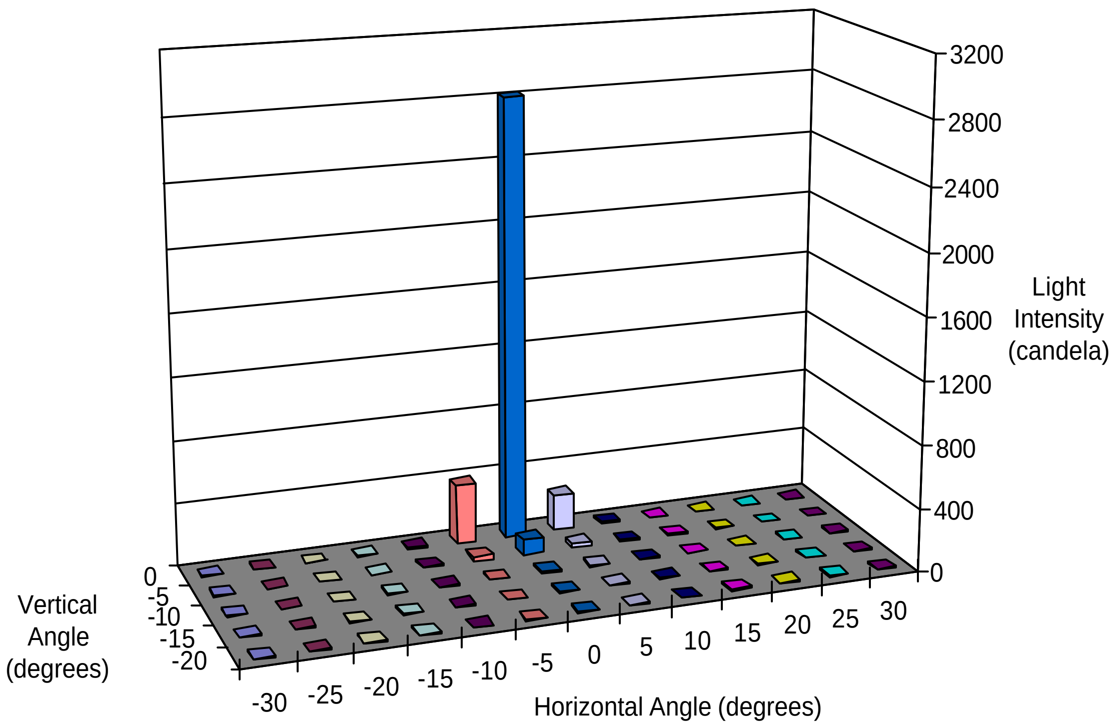

Figure A8.1.4a Output from WPS #8 (Yellow) signal, 10.0 volts, 42.0 ft, all elements on, TC test.

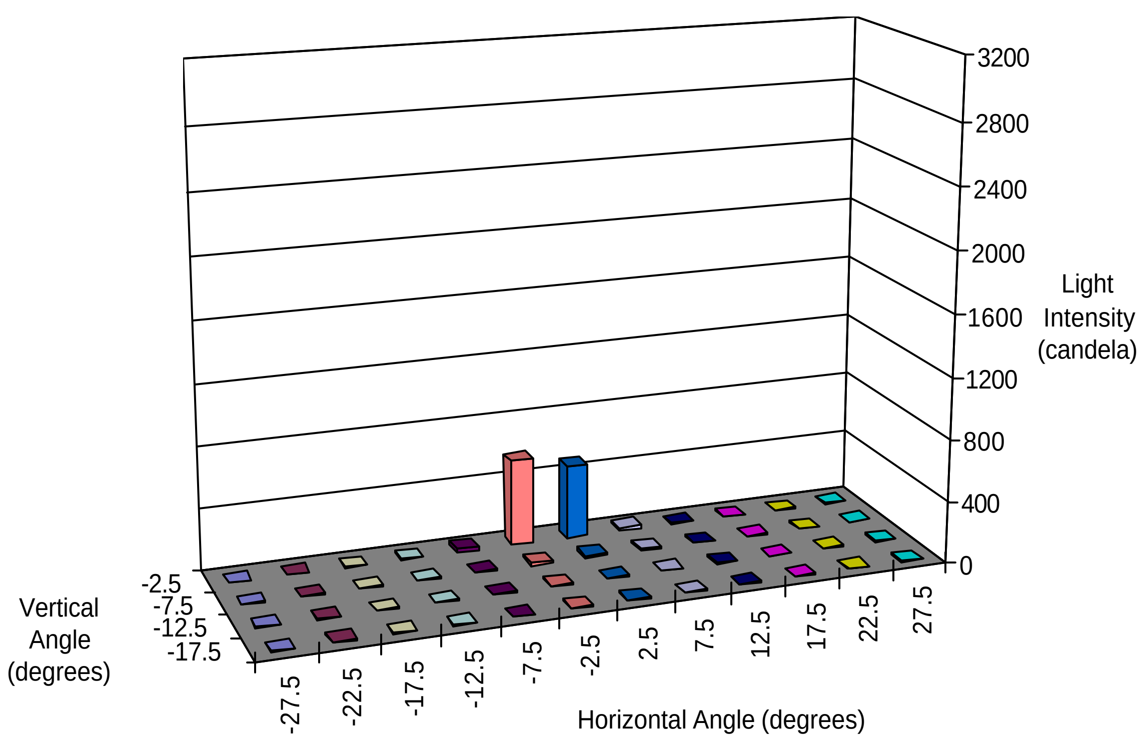

Figure A8.1.4b Output from WPS #8 (Yellow) signal, 10.0 volts, 42.0 ft, all elements on, ITE test.

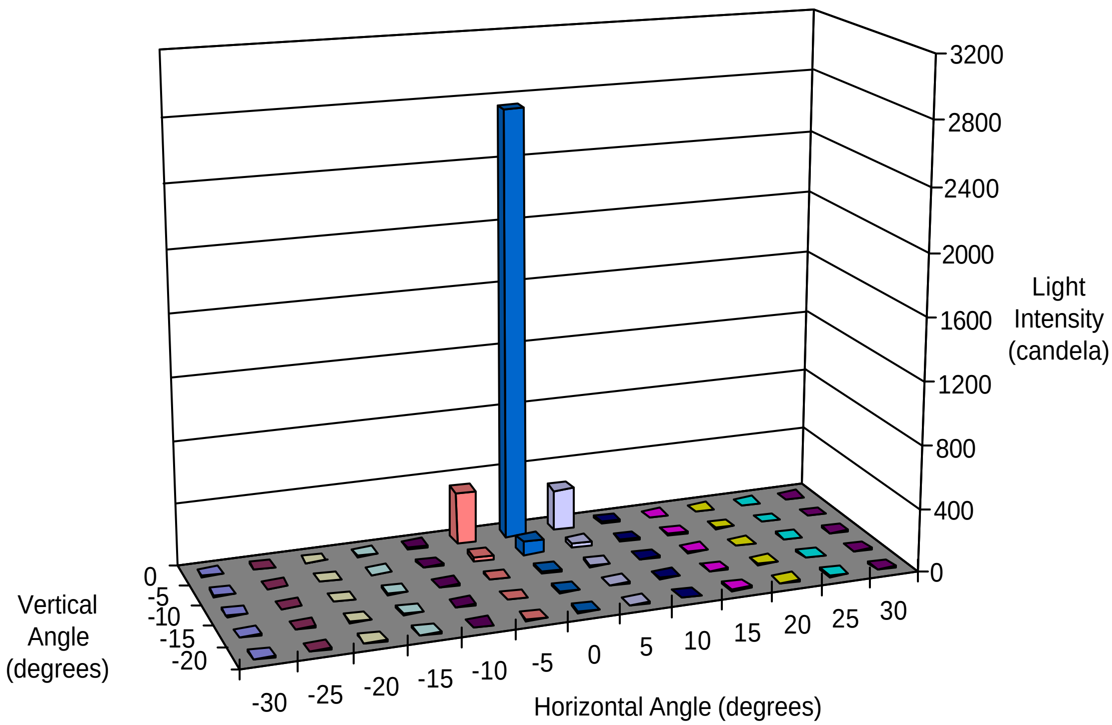

Figure A8.1.5a Output from WPS #8 (Yellow) signal, 10.0 volts, 44.0 ft, all elements on, TC test.

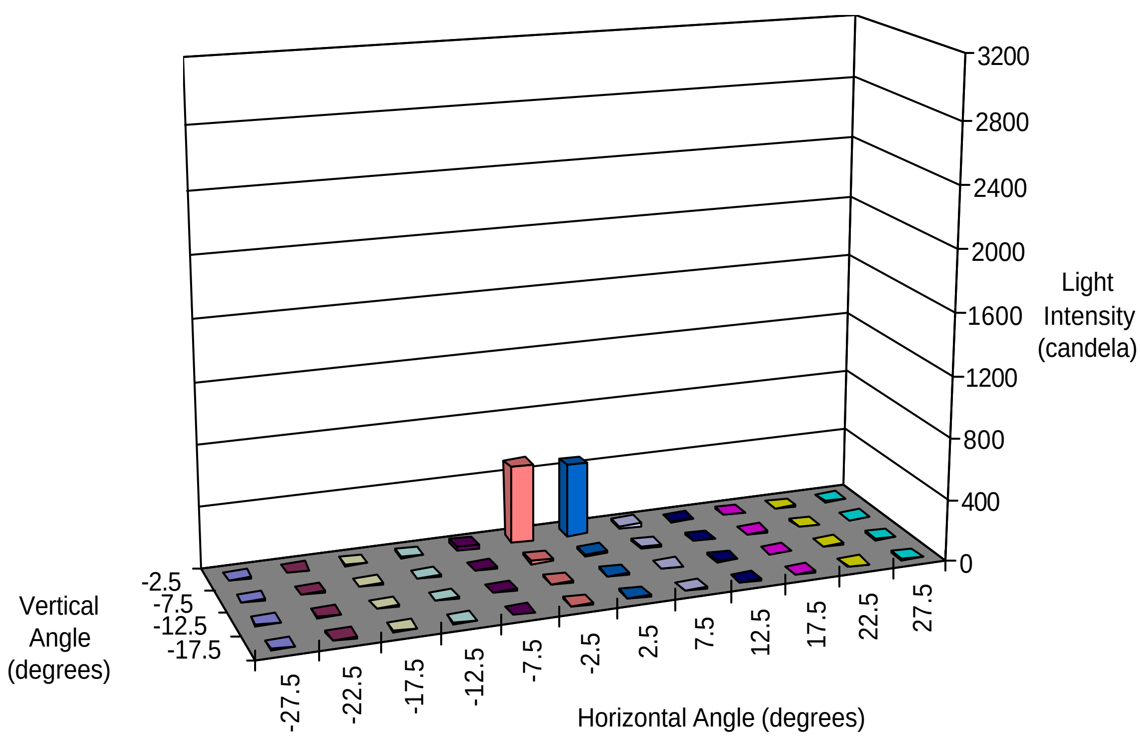

Figure A8.1.5b Output from WPS #8 (Yellow) signal, 10.0 volts, 44.0 ft, all elements on, ITE test.

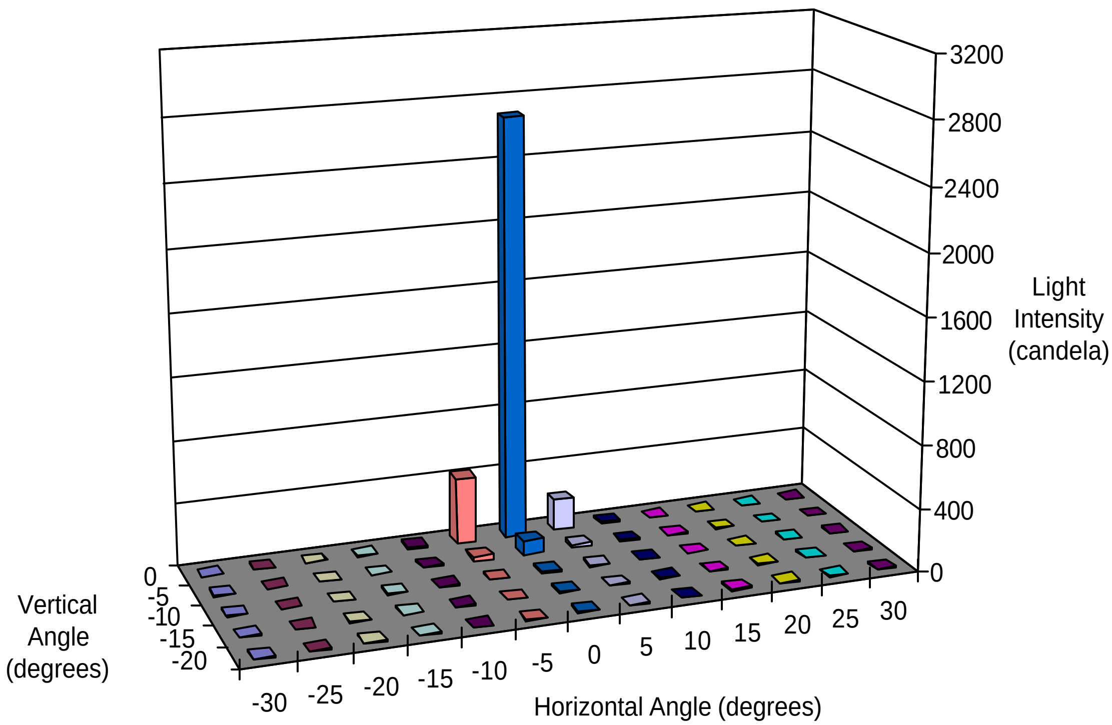

Figure A8.1.6a Output from WPS #8 (Yellow) signal, 10.0 volts, 36.0 ft, all elements on, TC test.

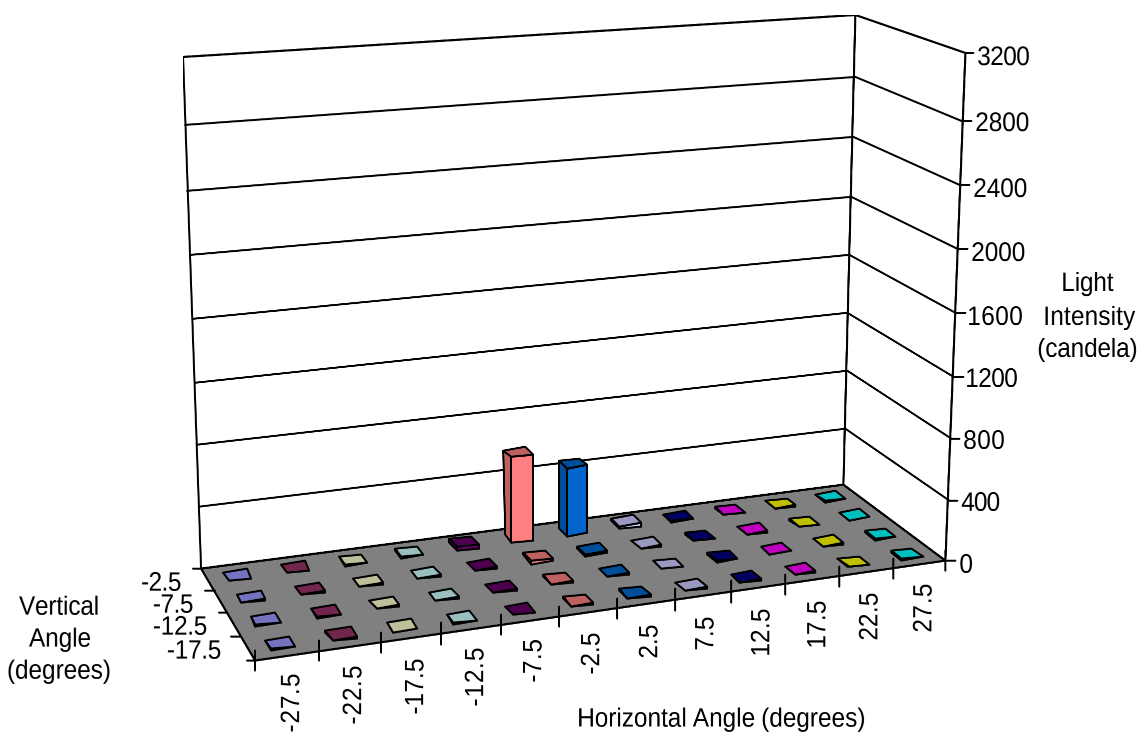

Figure A8.1.6b Output from WPS #8 (Yellow) signal, 10.0 volts, 36.0 ft, all elements on, ITE test.

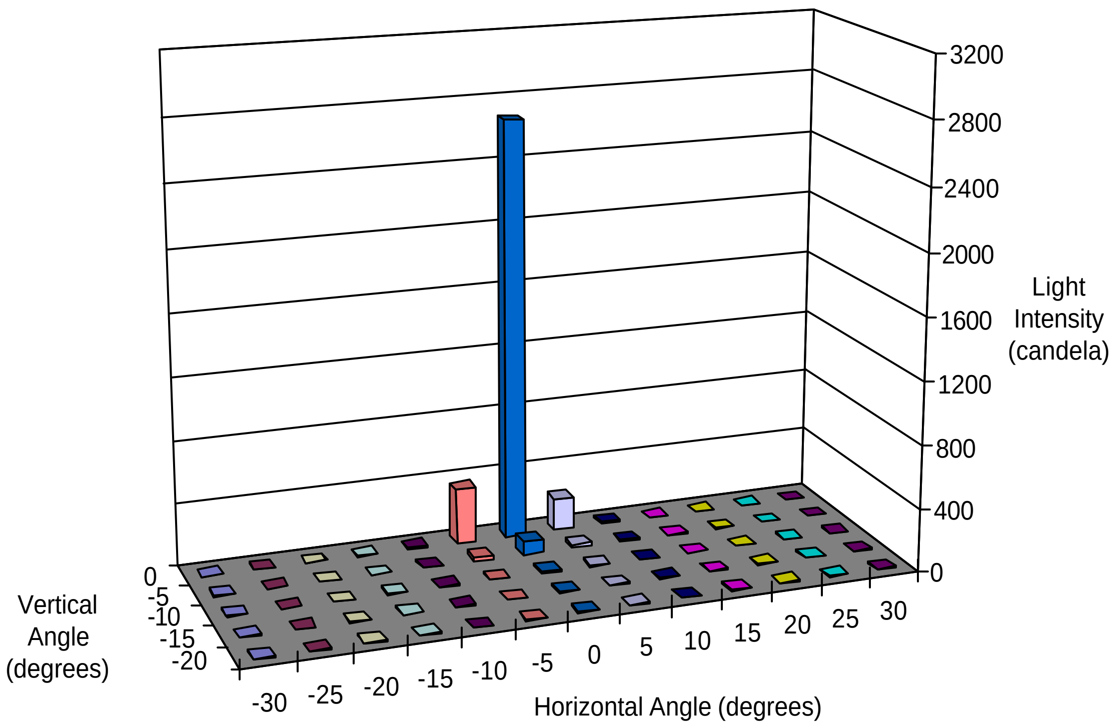

Figure A8.1.7a Output from WPS #8 (Yellow) signal, 10.0 volts, 34.0 ft, all elements on, TC test.

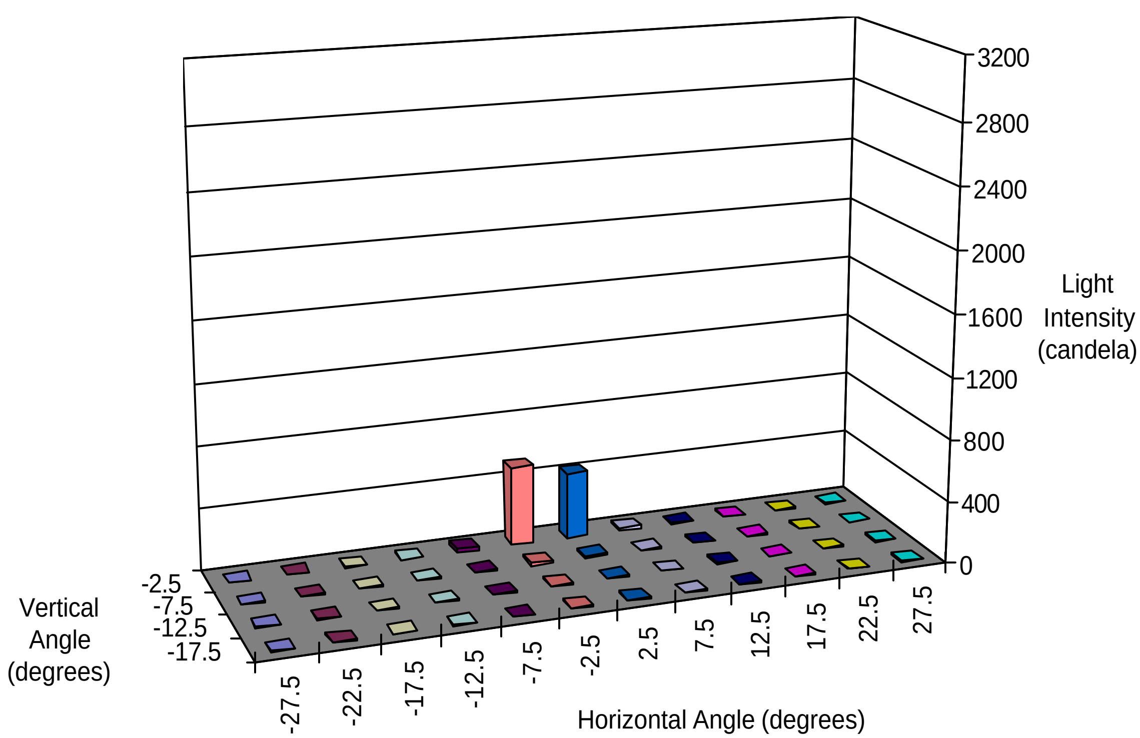

Figure A8.1.7b Output from WPS #8 (Yellow) signal, 10.0 volts, 34.0 ft, all elements on, ITE test.

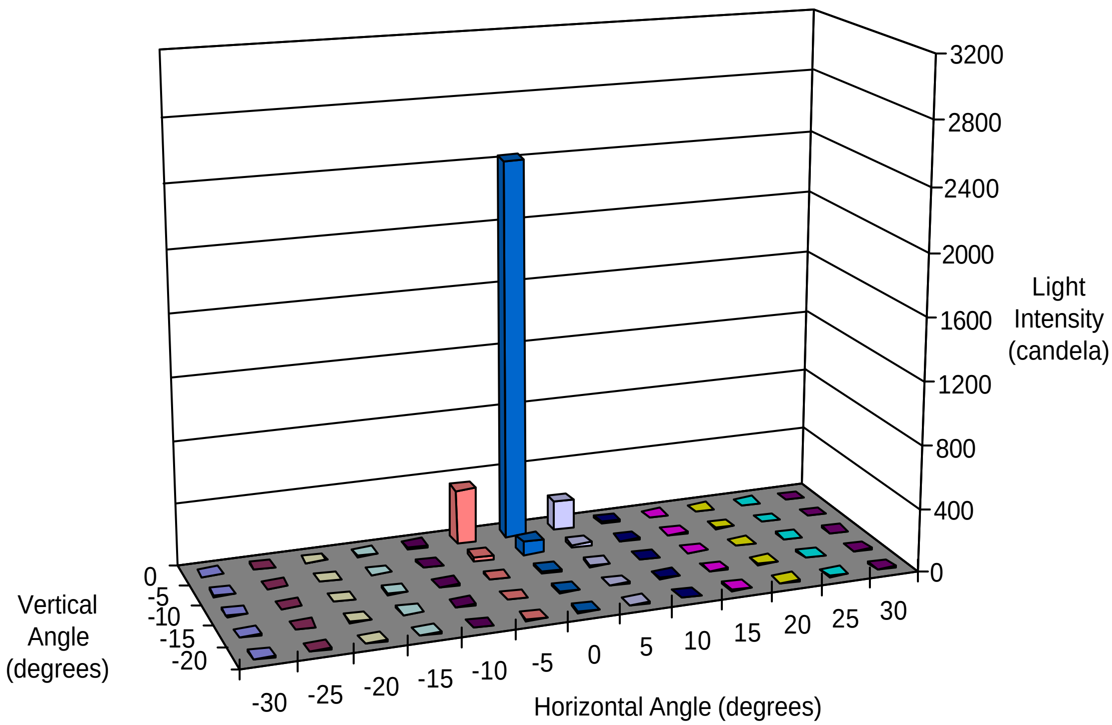

Figure A8.1.8a Output from WPS #8 (Yellow) signal, 10.0 volts, 32.0 ft, all elements on, TC test.

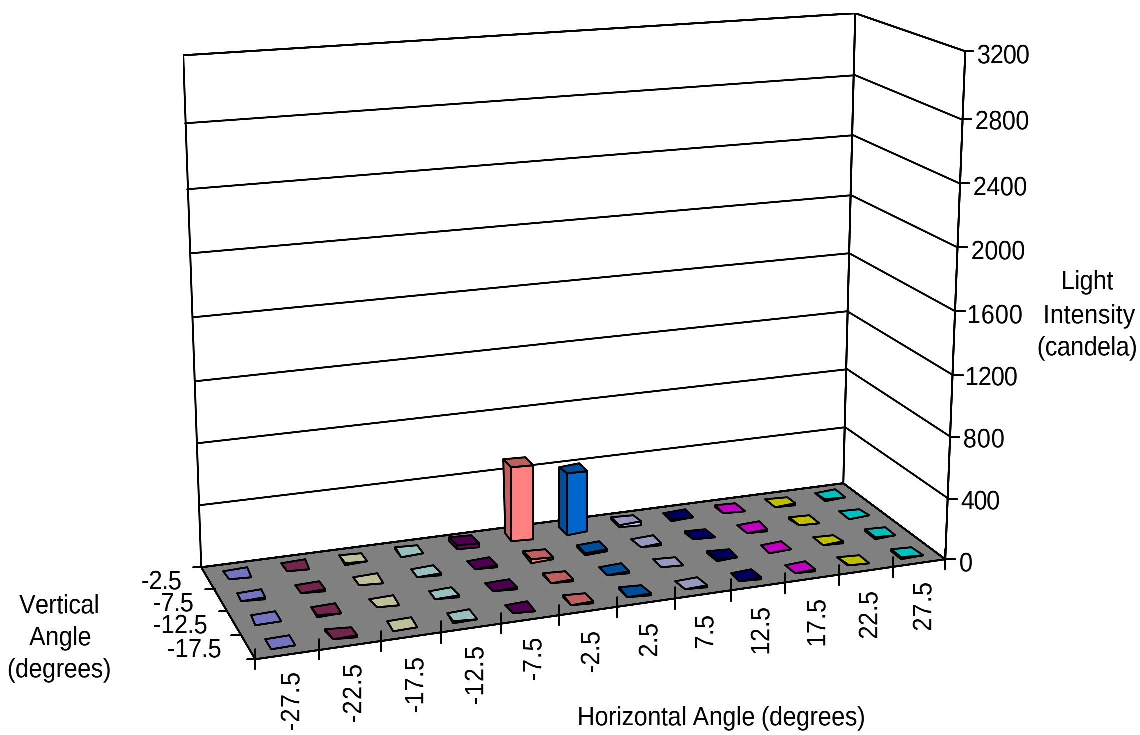

Figure A8.1.8b Output from WPS #8 (Yellow) signal, 10.0 volts, 32.0 ft, all elements on, ITE test.

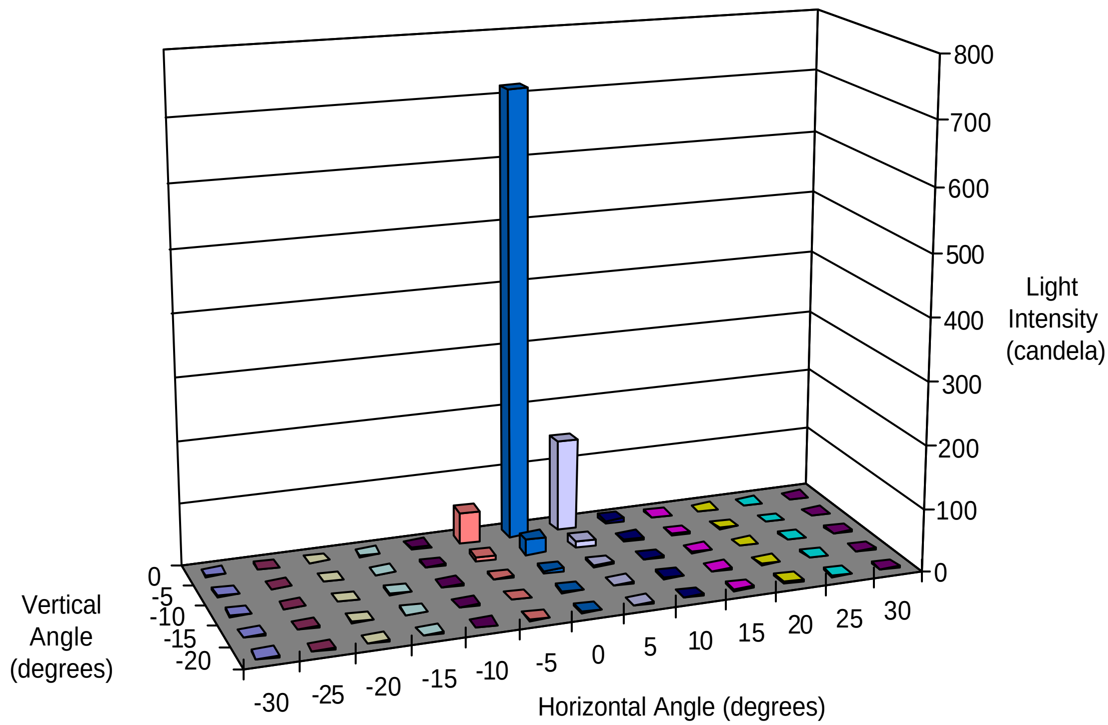

Figure A8.2.1a Output from WPS #8 (Yellow) signal, 10.0 volts, 32.0 ft, all elements on, TC test.

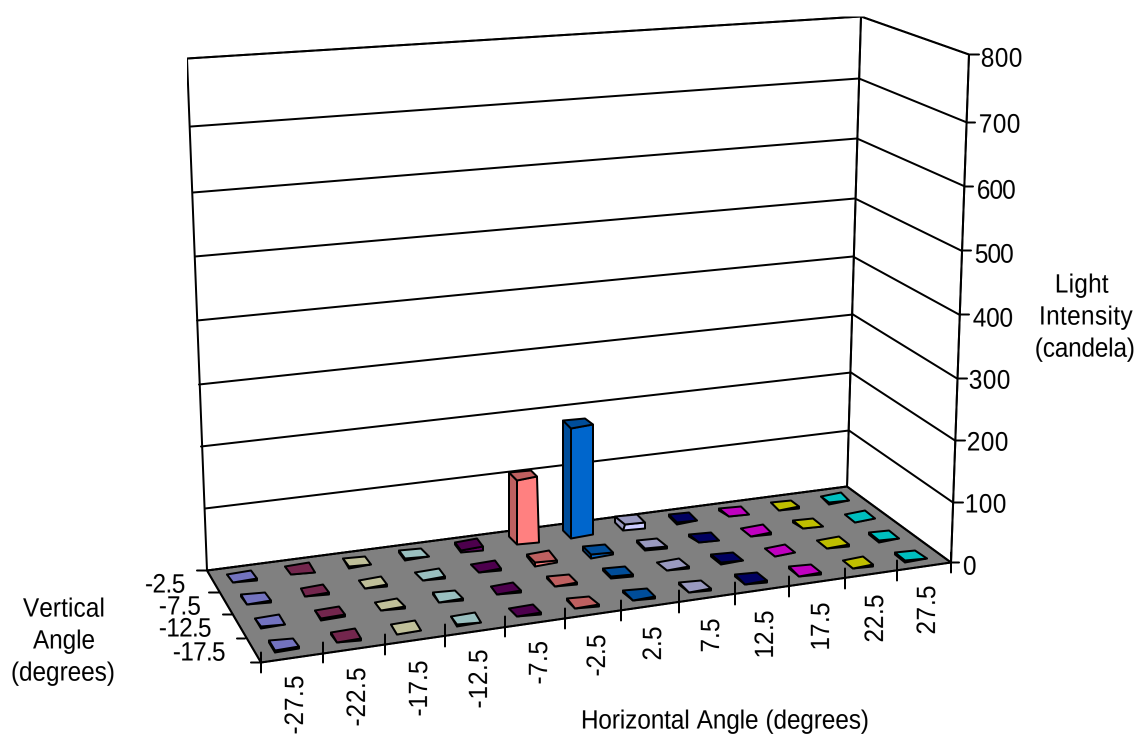

Figure A8.2.1b Output from WPS #8 (Yellow) signal, 10.0 volts, 32.0 ft, all elements on, ITE test.

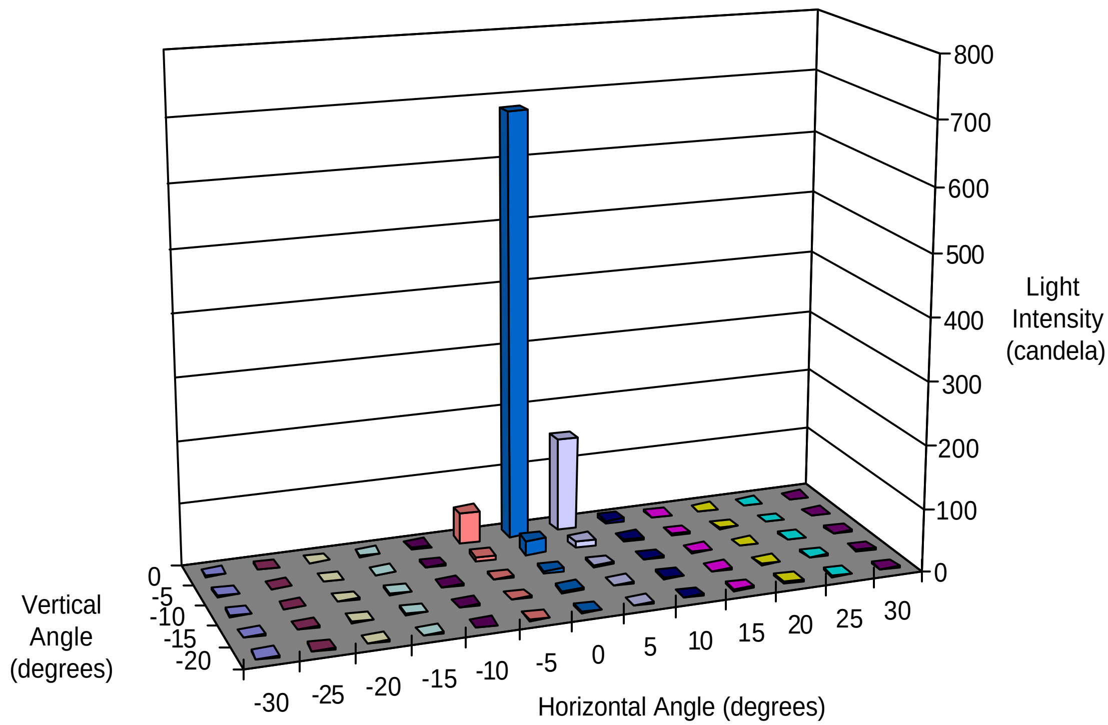

Figure A8.2.2a Output from WPS #8 (Yellow) signal, 10.0 volts, 34.0 ft, all elements on, TC test.

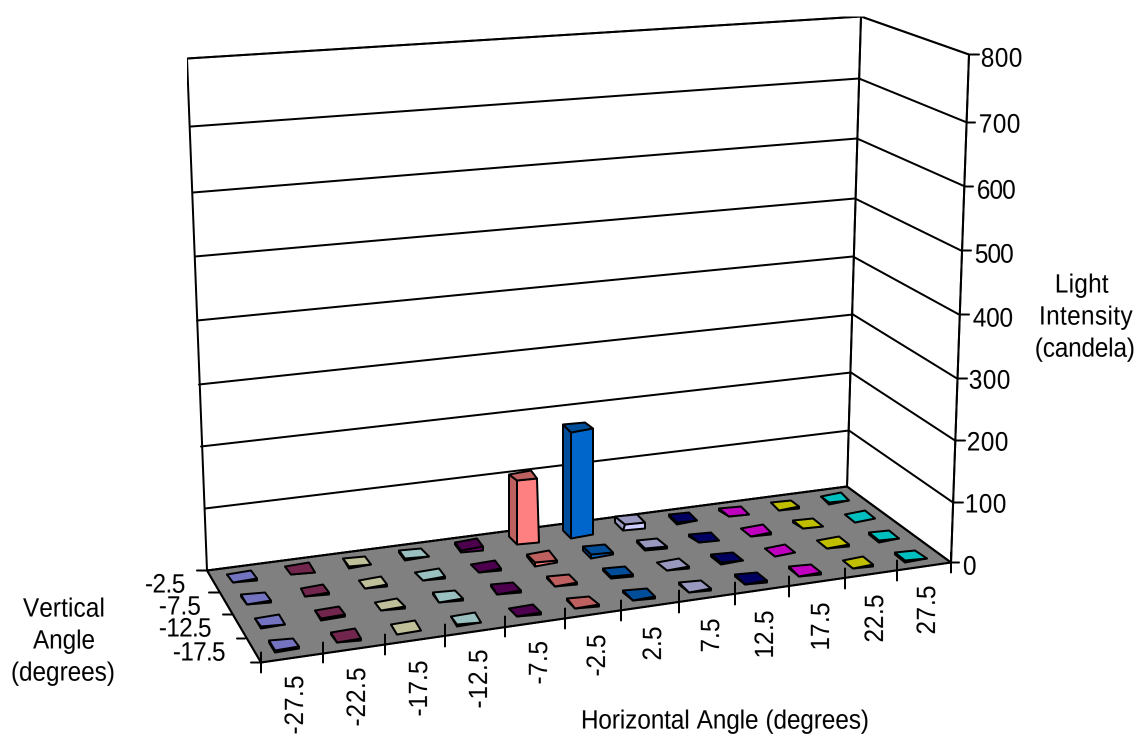

Figure A8.2.2b Output from WPS #8 (Yellow) signal, 10.0 volts, 34.0 ft, all elements on, ITE test.

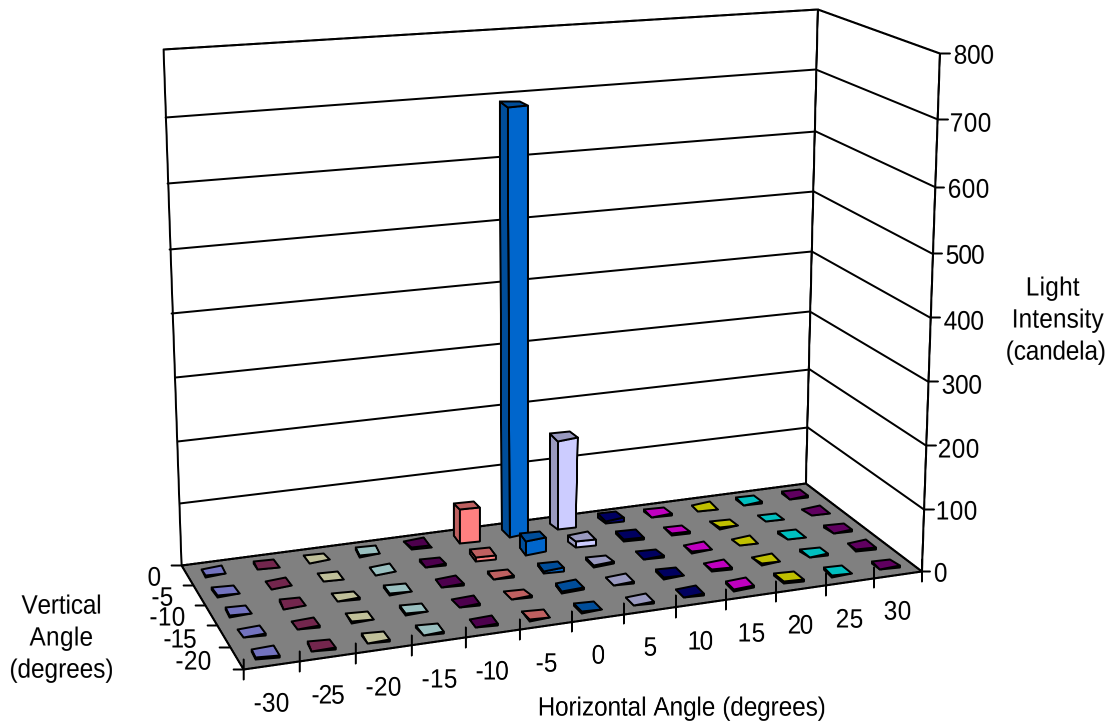

Figure A8.2.3a Output from WPS #8 (Yellow) signal, 10.0 volts, 36.0 ft, all elements on, TC test.

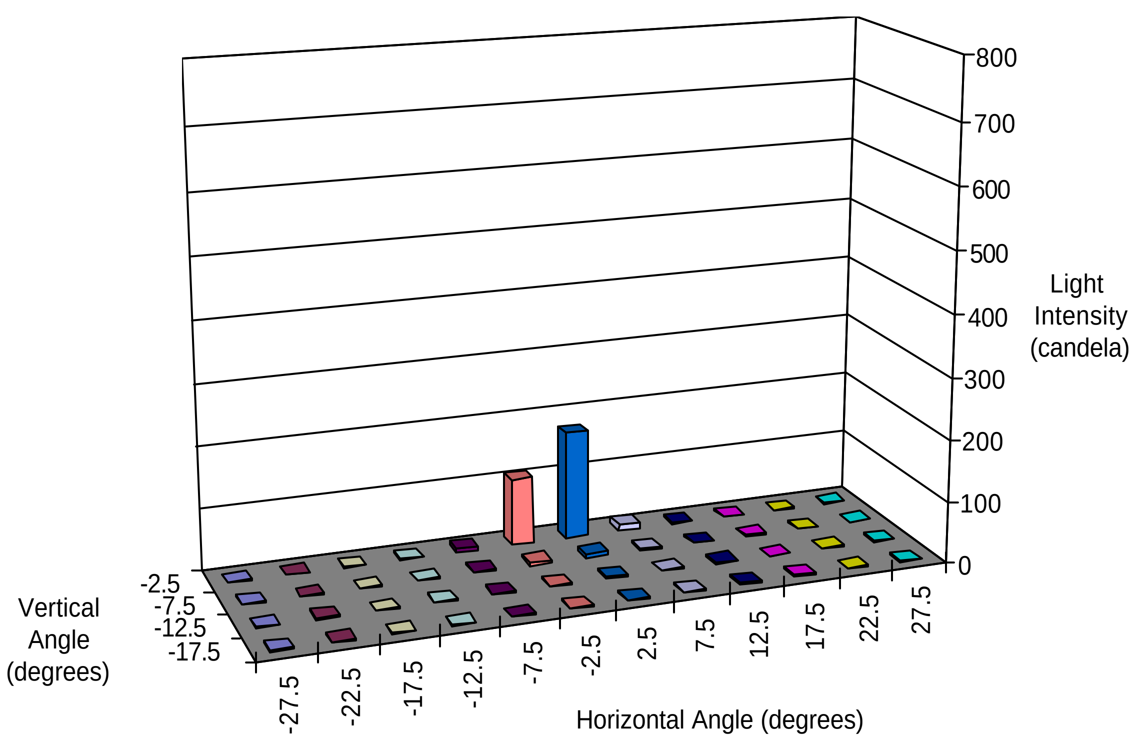

Figure A8.2.3b Output from WPS #8 (Yellow) signal, 10.0 volts, 36.0 ft, all elements on, ITE test.

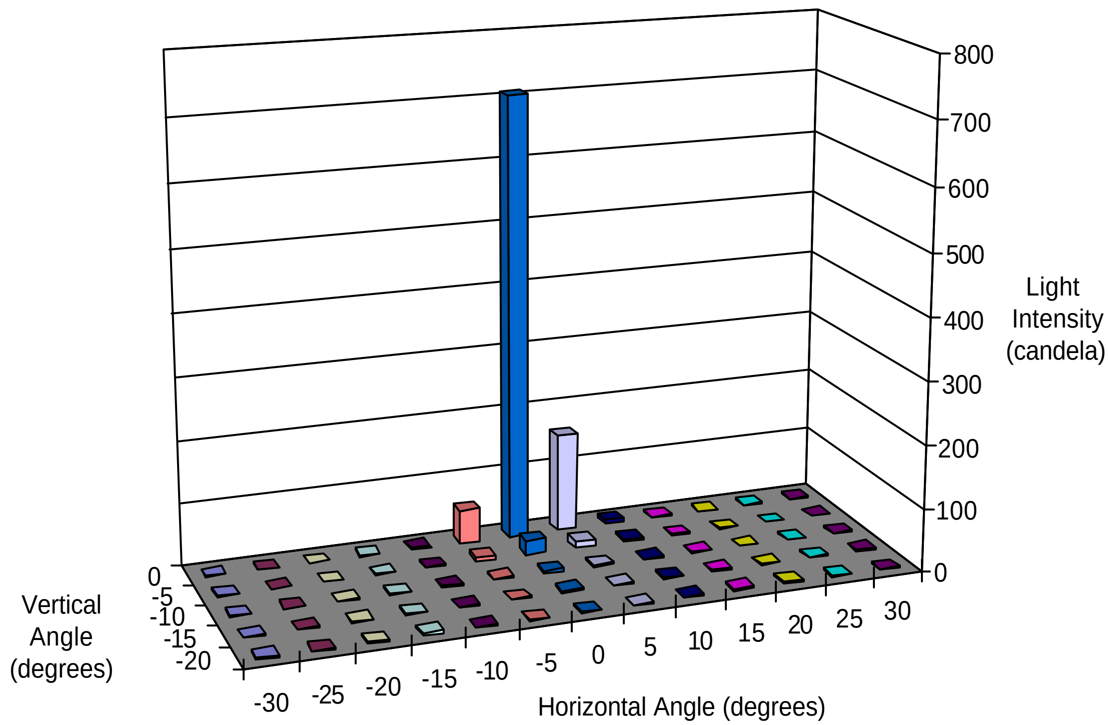

Figure A8.2.4a Output from WPS #8 (Yellow) signal, 10.0 volts, 38.0 ft, all elements on, TC test.

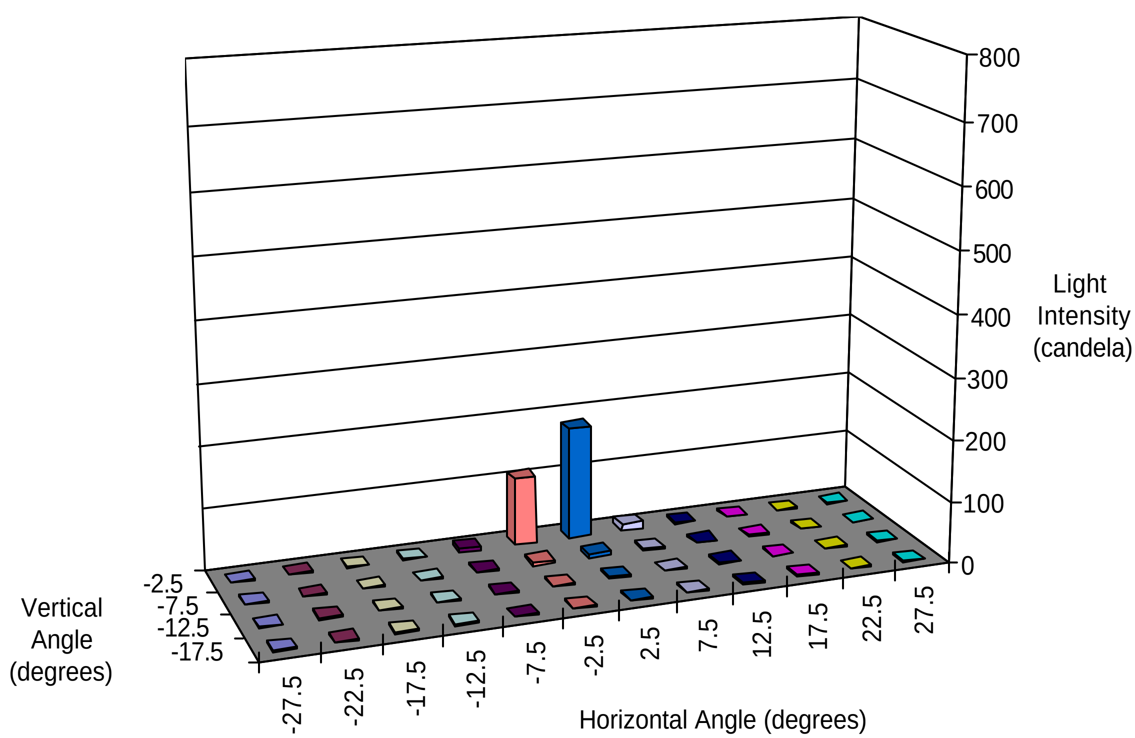

Figure A8.2.4b Output from WPS #8 (Yellow) signal, 10.0 volts, 38.0 ft, all elements on, ITE test.

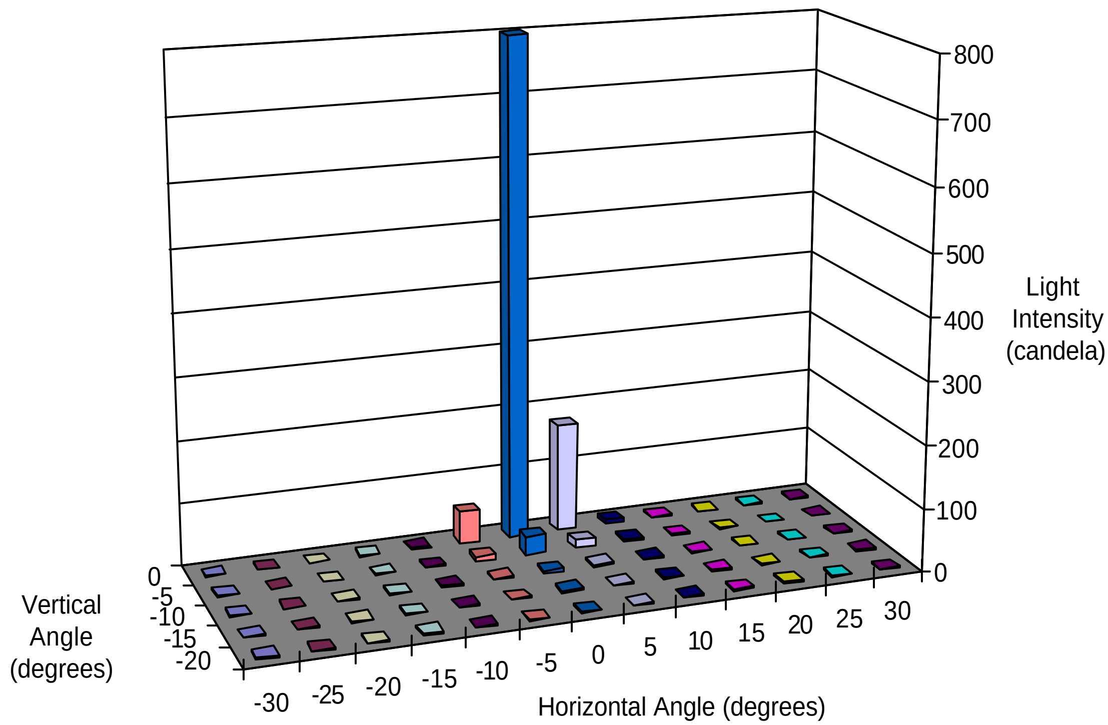

Figure A8.2.5a Output from WPS #8 (Yellow) signal, 10.0 volts, 40.0 ft, all elements on, TC test.

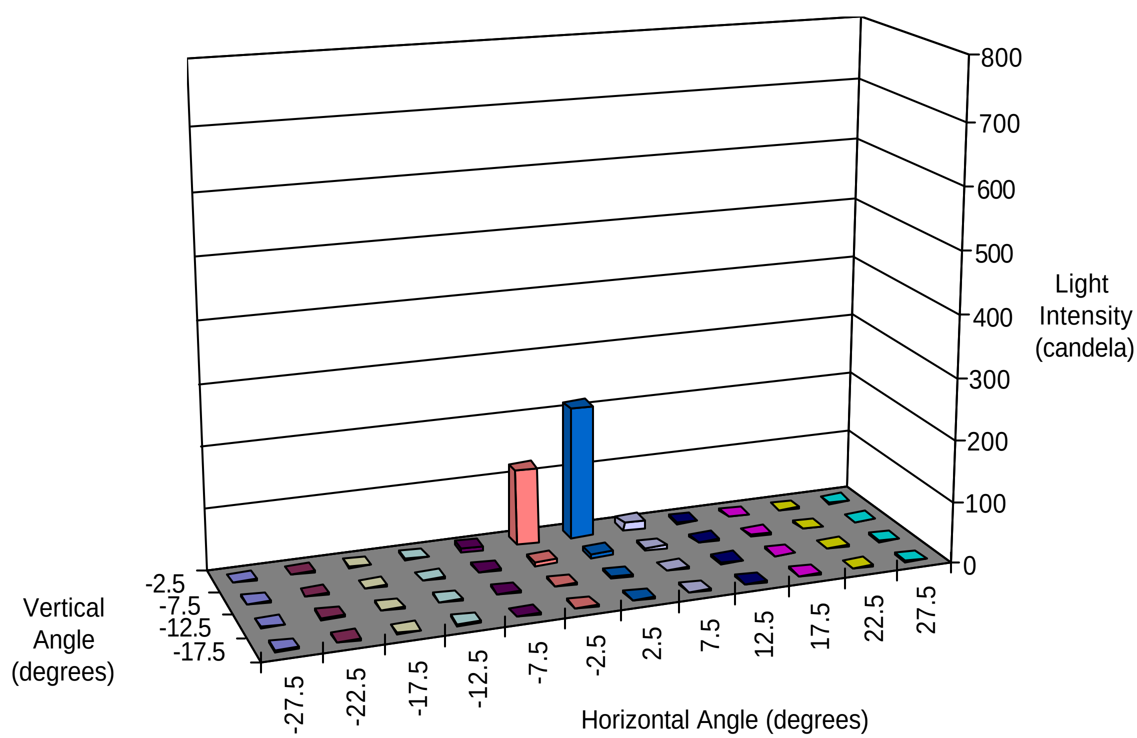

Figure A8.2.5b Output from WPS #8 (Yellow) signal, 10.0 volts, 40.0 ft, all elements on, ITE test.

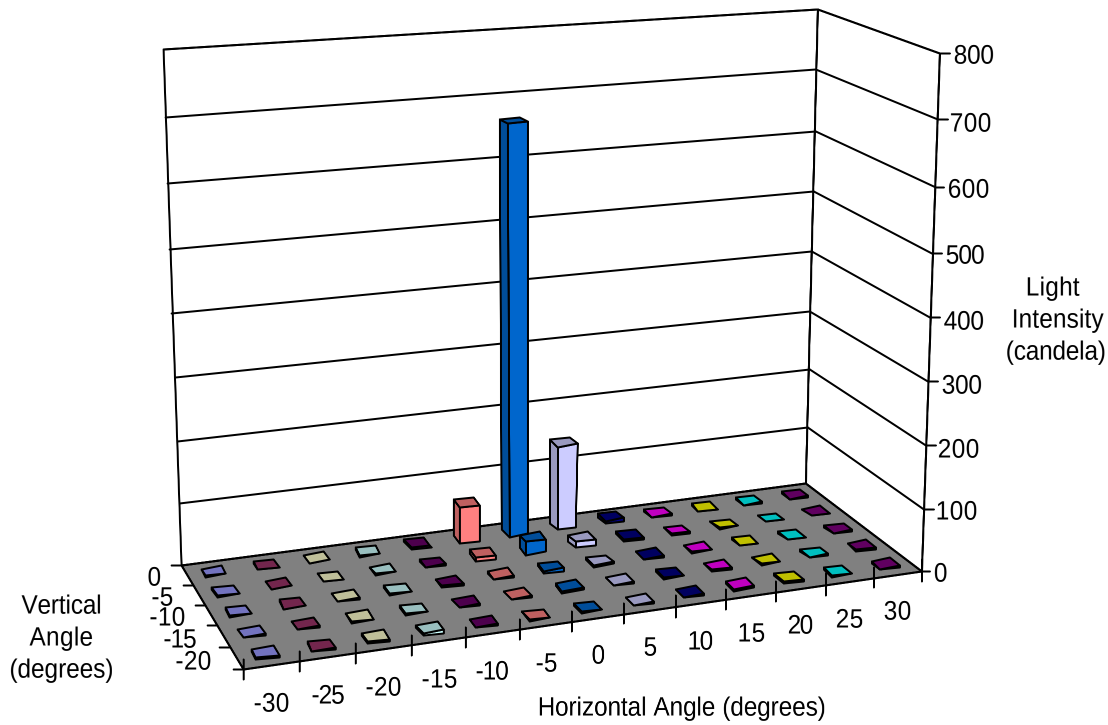

Figure A8.2.6a Output from WPS #8 (Yellow) signal, 10.0 volts, 42.0 ft, all elements on, TC test.

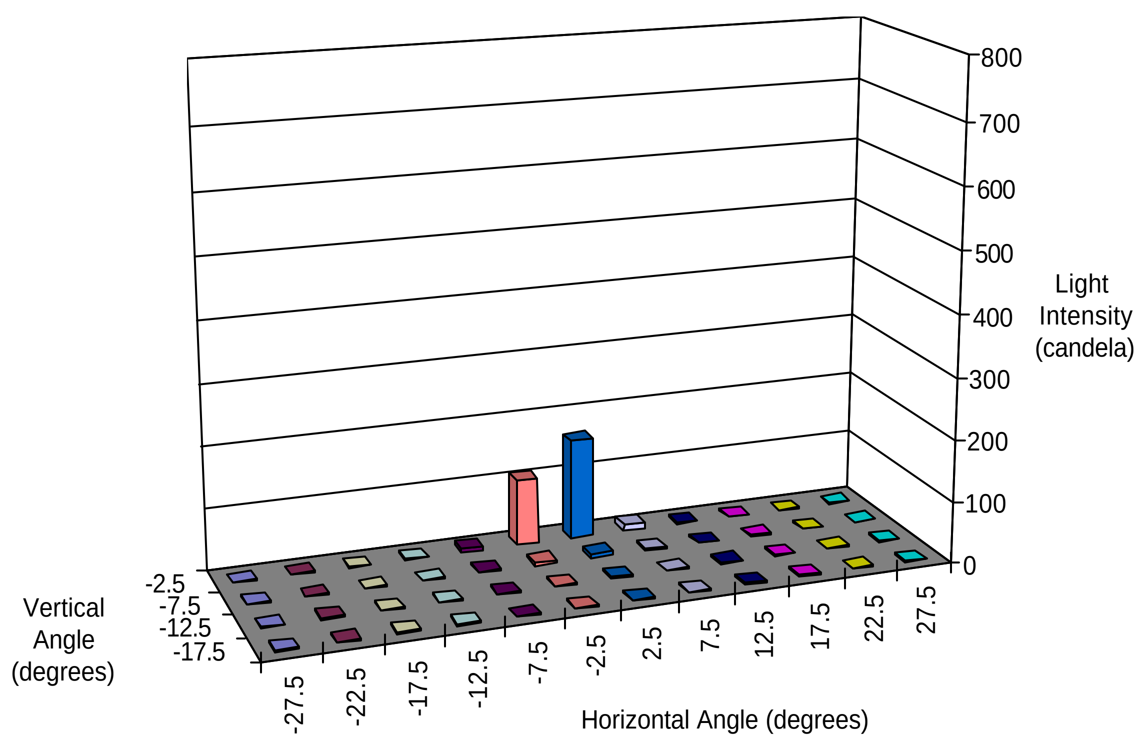

Figure A8.2.6b Output from WPS #8 (Yellow) signal, 10.0 volts, 42.0 ft, all elements on, ITE test.

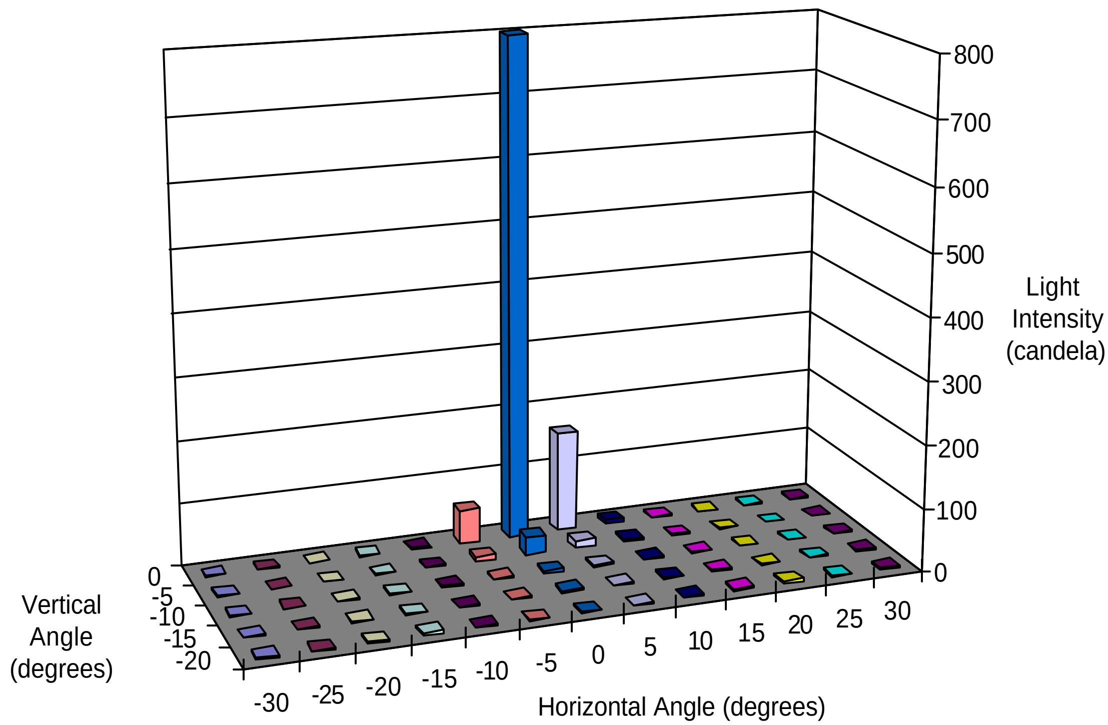

Figure A8.2.7a Output from WPS #8 (Yellow) signal, 10.0 volts, 44.0 ft, all elements on, TC test.

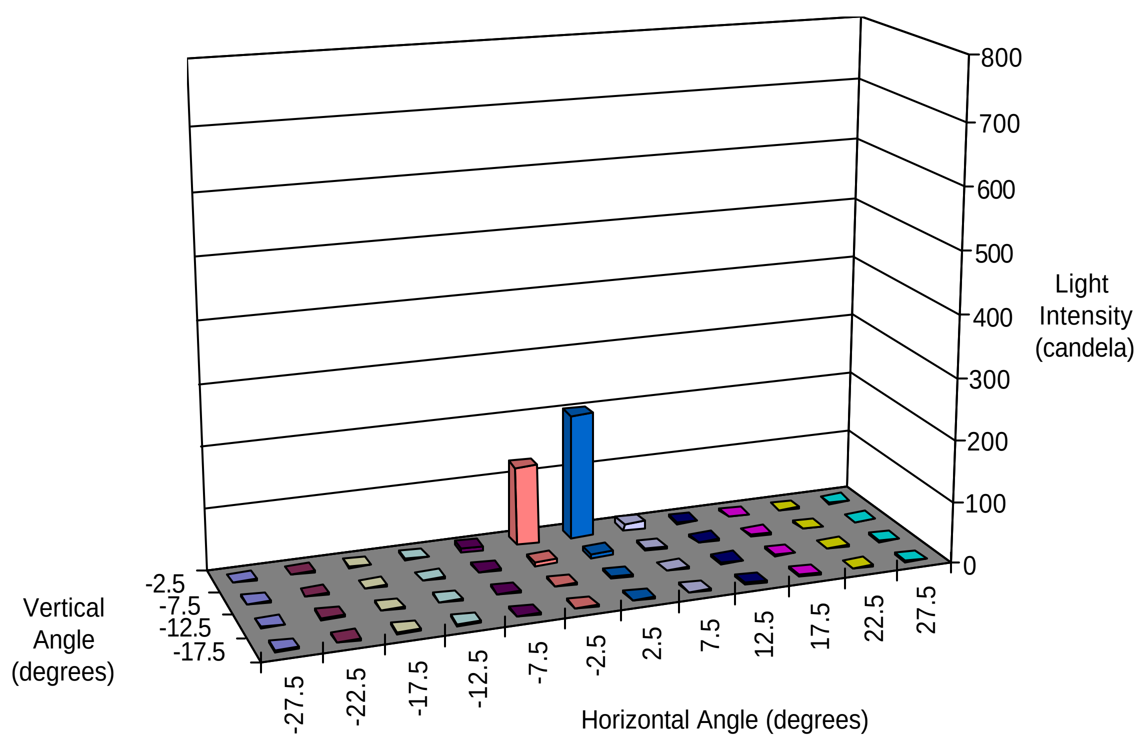

Figure A8.2.7b Output from WPS #8 (Yellow) signal, 10.0 volts, 44.0 ft, all elements on, ITE test.

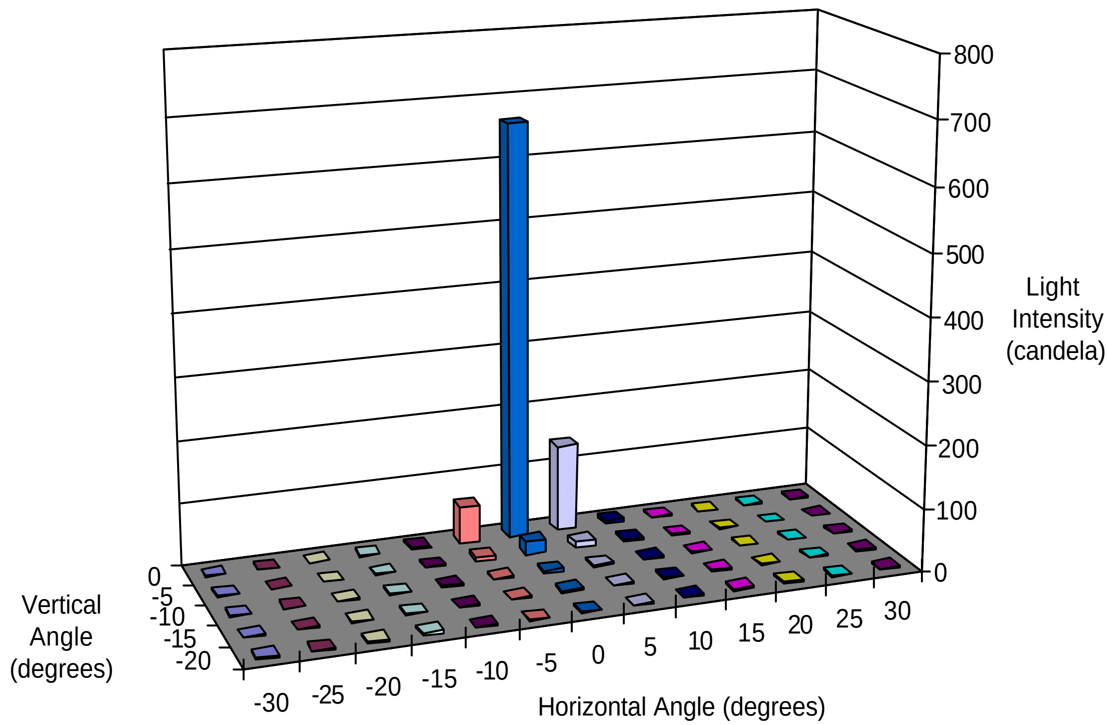

Figure A8.2.8a Output from WPS #8 (Yellow) signal, 10.0 volts, 46.0 ft, all elements on, TC test.

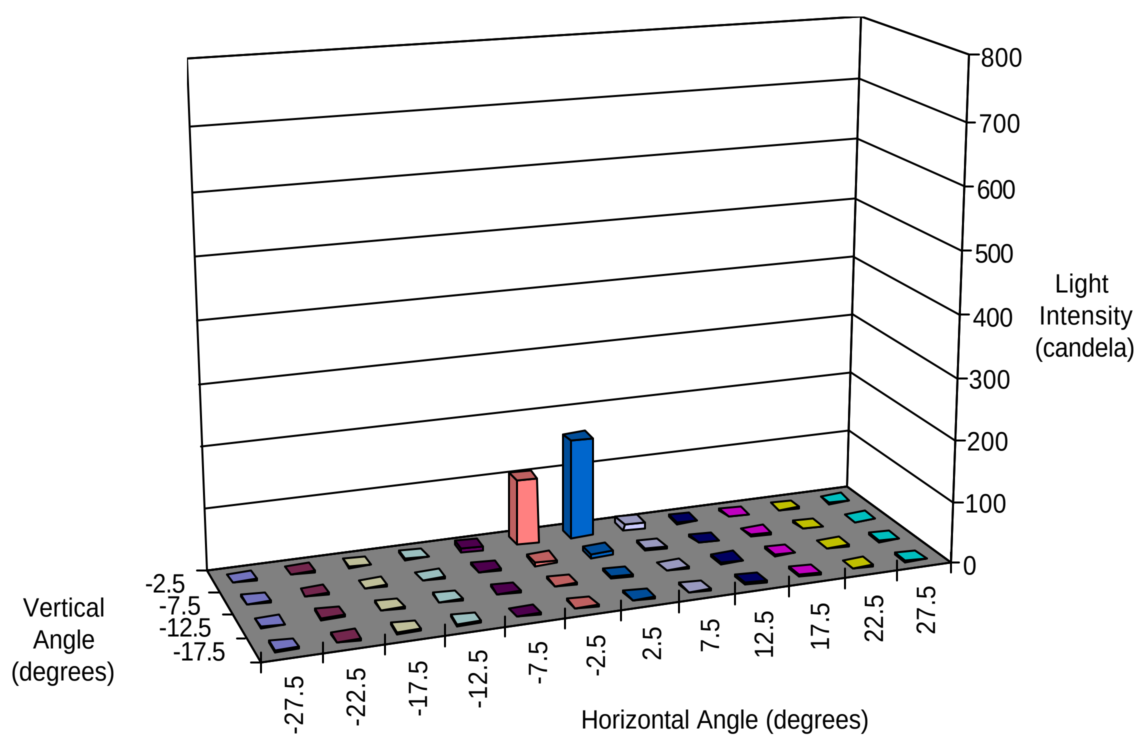

Figure A8.2.8b Output from WPS #8 (Yellow) signal, 10.0 volts, 46.0 ft, all elements on, ITE test.

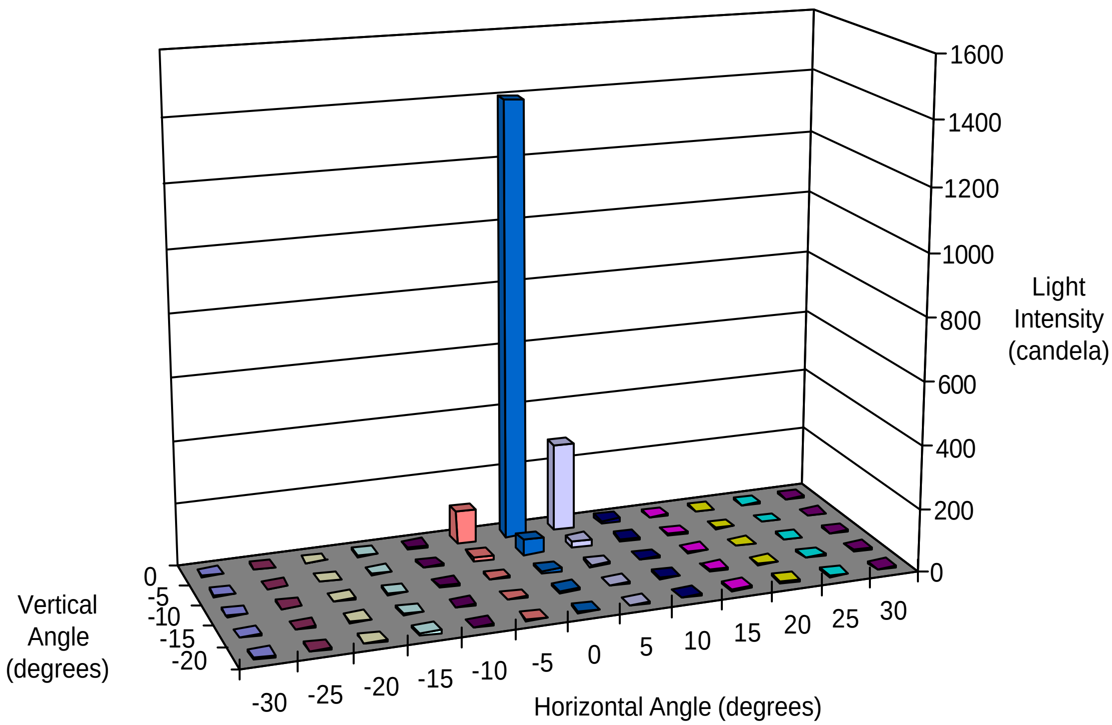

Figure A8.3.1a Output from WPS #8 (Yellow) signal, 10.0 volts, 46.0 ft, all elements on, TC test.

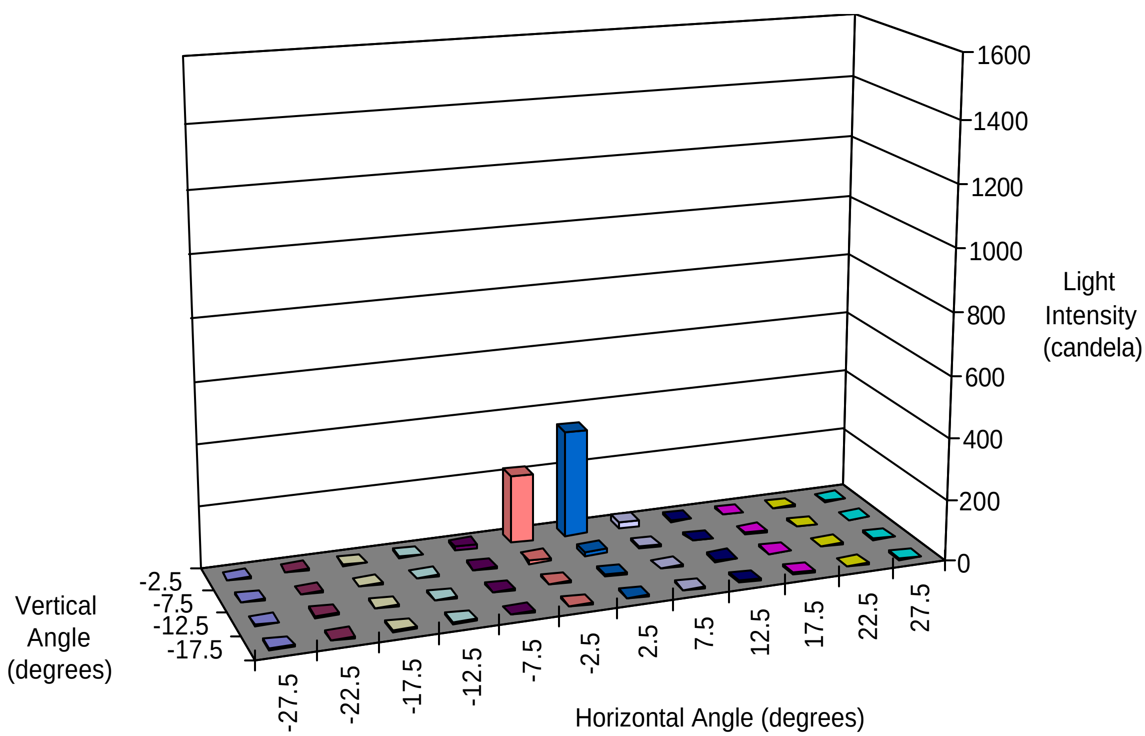

Figure A8.3.1b Output from WPS #8 (Yellow) signal, 10.0 volts, 46.0 ft, all elements on, ITE test.

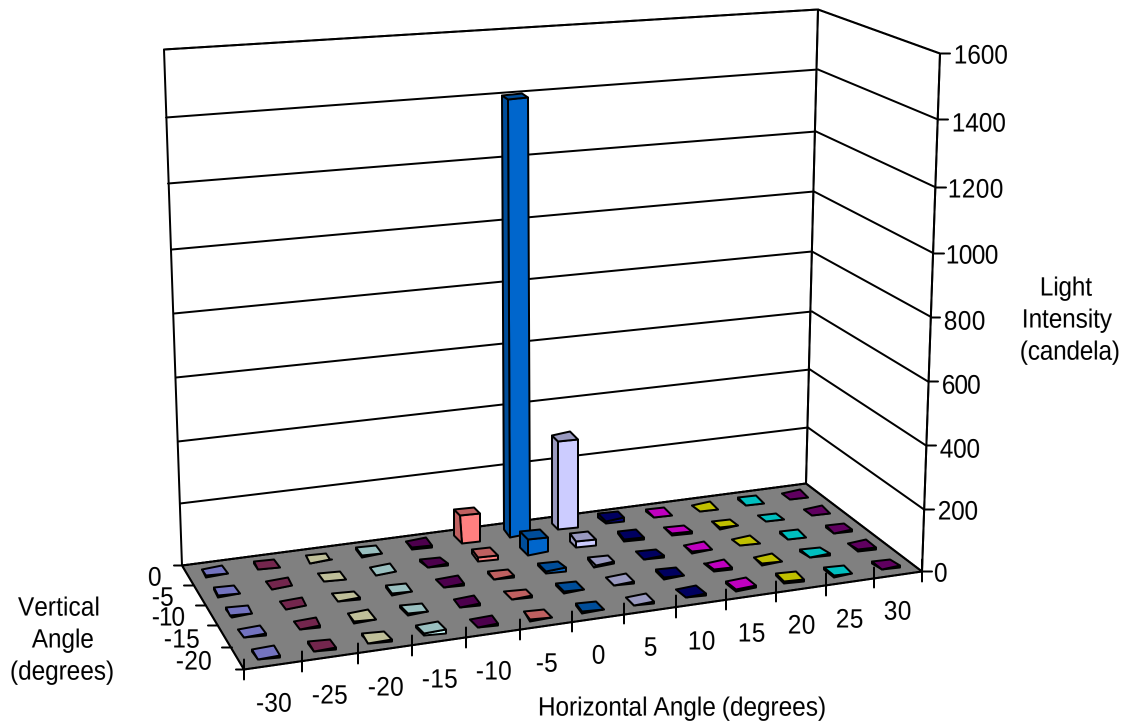

Figure A8.3.2a Output from WPS #8 (Yellow) signal, 10.0 volts, 44.0 ft, all elements on, TC test.

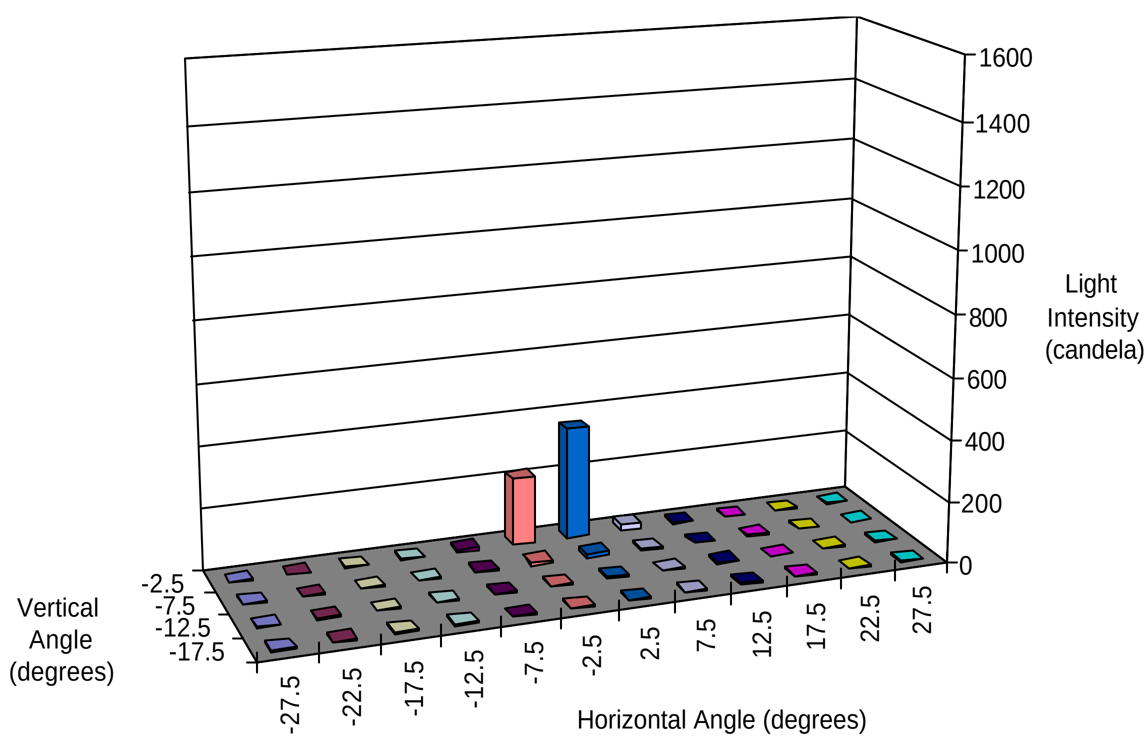

Figure A8.3.2b Output from WPS #8 (Yellow) signal, 10.0 volts, 44.0 ft, all elements on, ITE test.

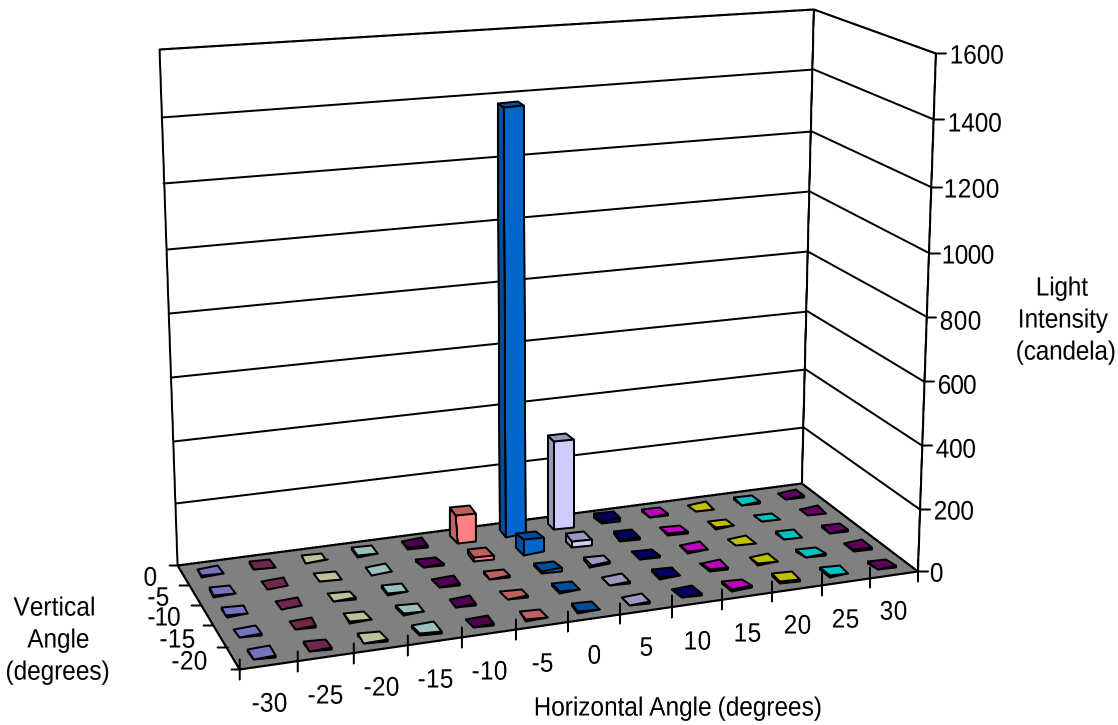

Figure A8.3.3a Output from WPS #8 (Yellow) signal, 10.0 volts, 42.0 ft, all elements on, TC test.

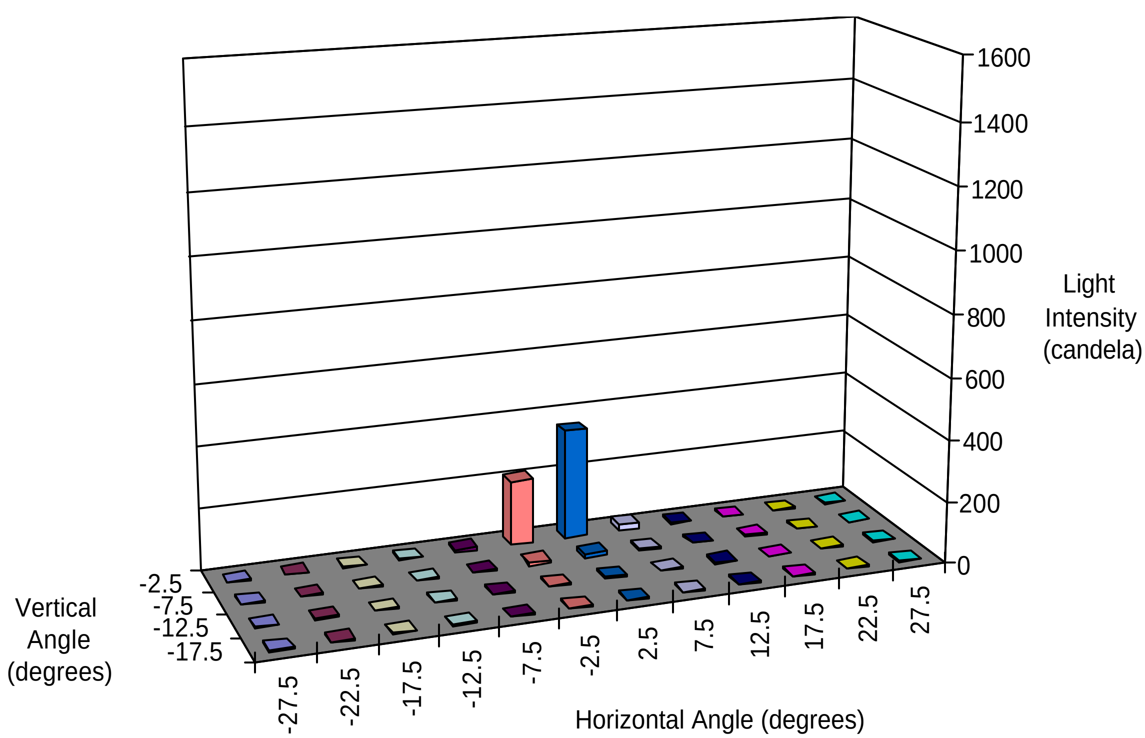

Figure A8.3.3b Output from WPS #8 (Yellow) signal, 10.0 volts, 42.0 ft, all elements on, ITE test.

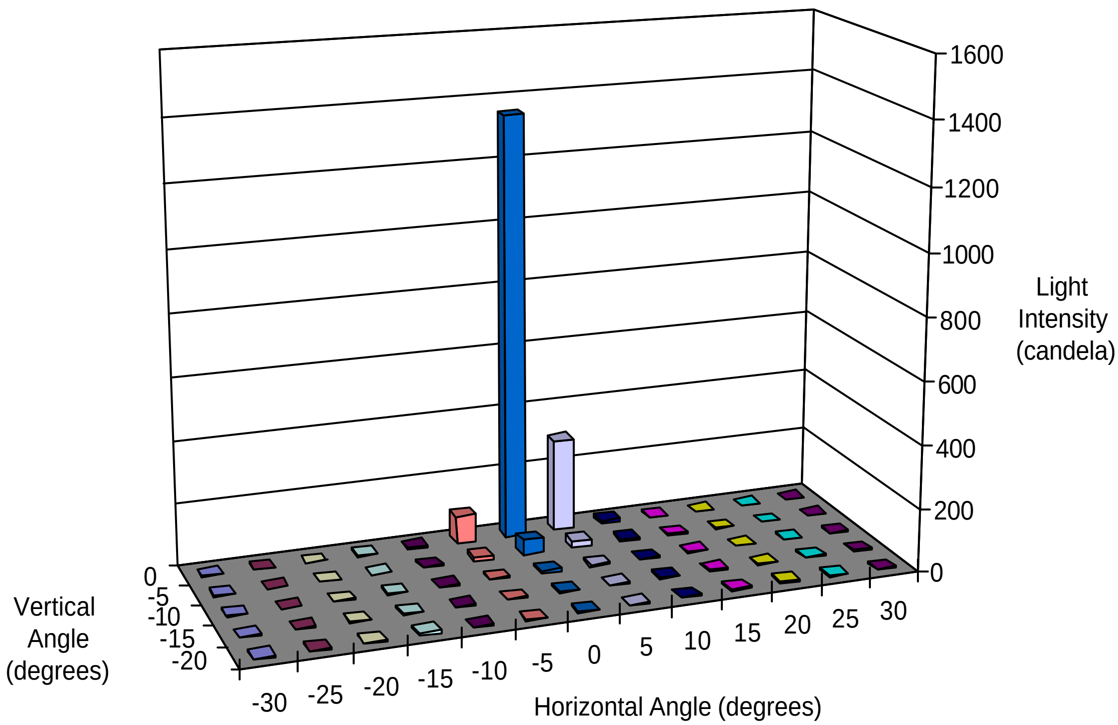

Figure A8.3.4a Output from WPS #8 (Yellow) signal, 10.0 volts, 40.0 ft, all elements on, TC test.

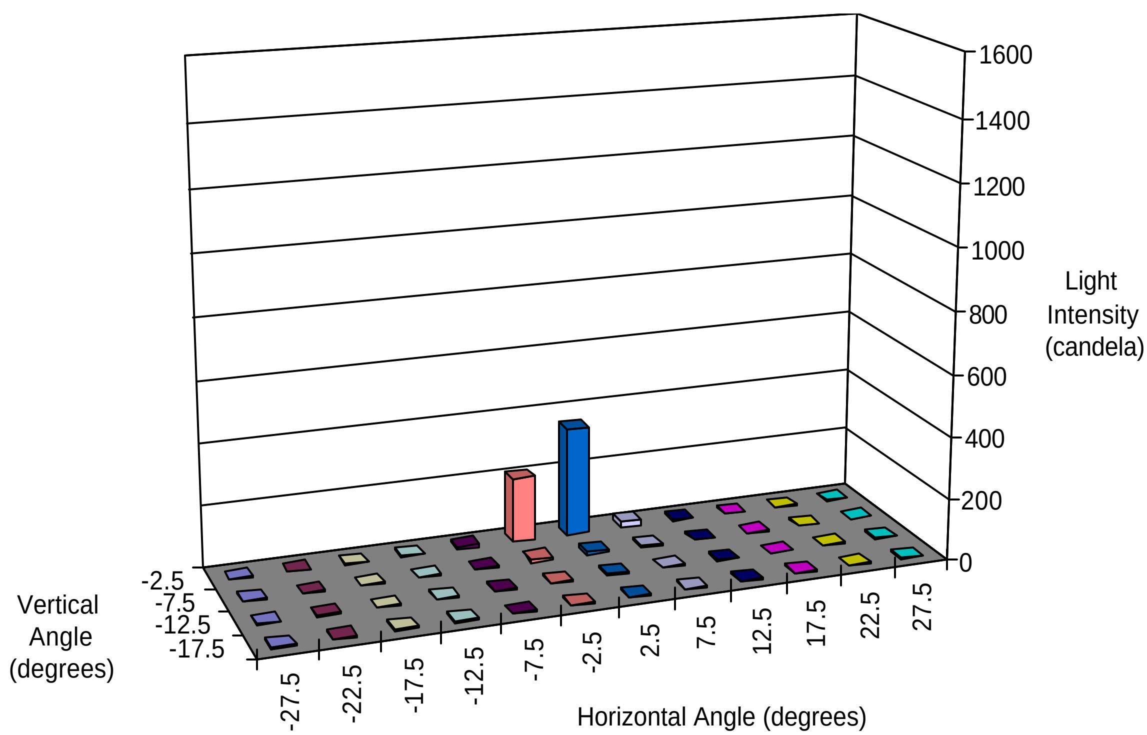

Figure A8.3.4b Output from WPS #8 (Yellow) signal, 10.0 volts, 40.0 ft, all elements on, ITE test.

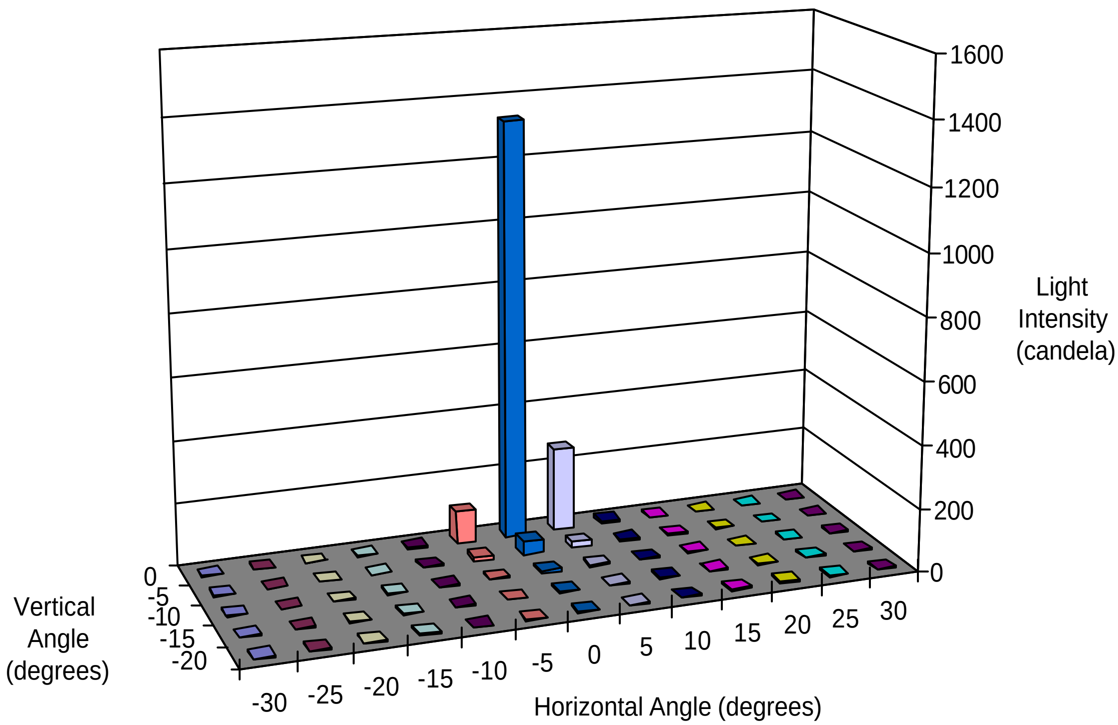

Figure A8.3.5a Output from WPS #8 (Yellow) signal, 10.0 volts, 38.0 ft, all elements on, TC test.

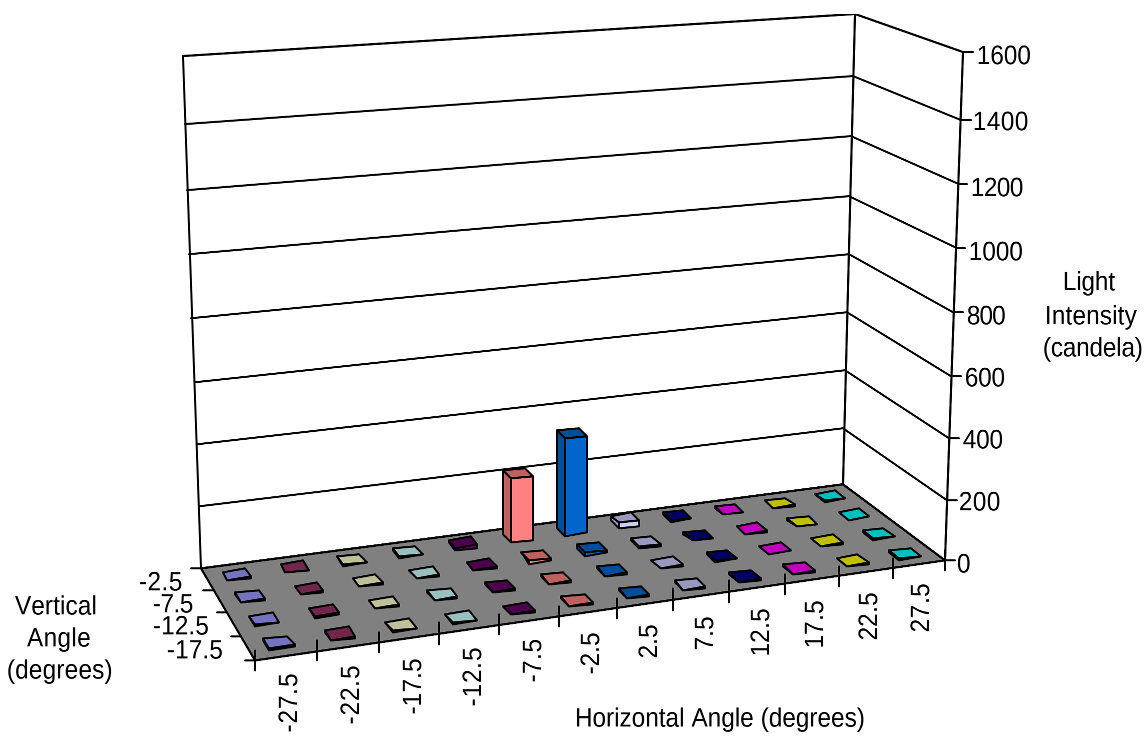

Figure A8.3.5b Output from WPS #8 (Yellow) signal, 10.0 volts, 38.0 ft, all elements on, ITE test.

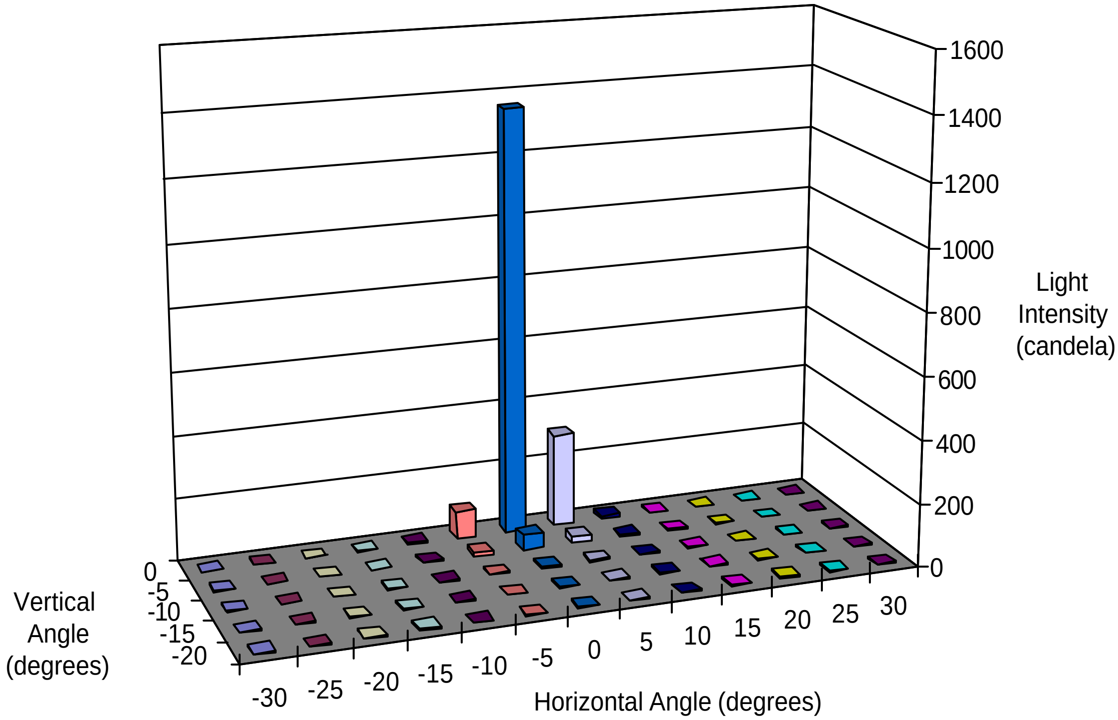

Figure A8.3.6a Output from WPS #8 (Yellow) signal, 10.0 volts, 36.0 ft, all elements on, TC test.

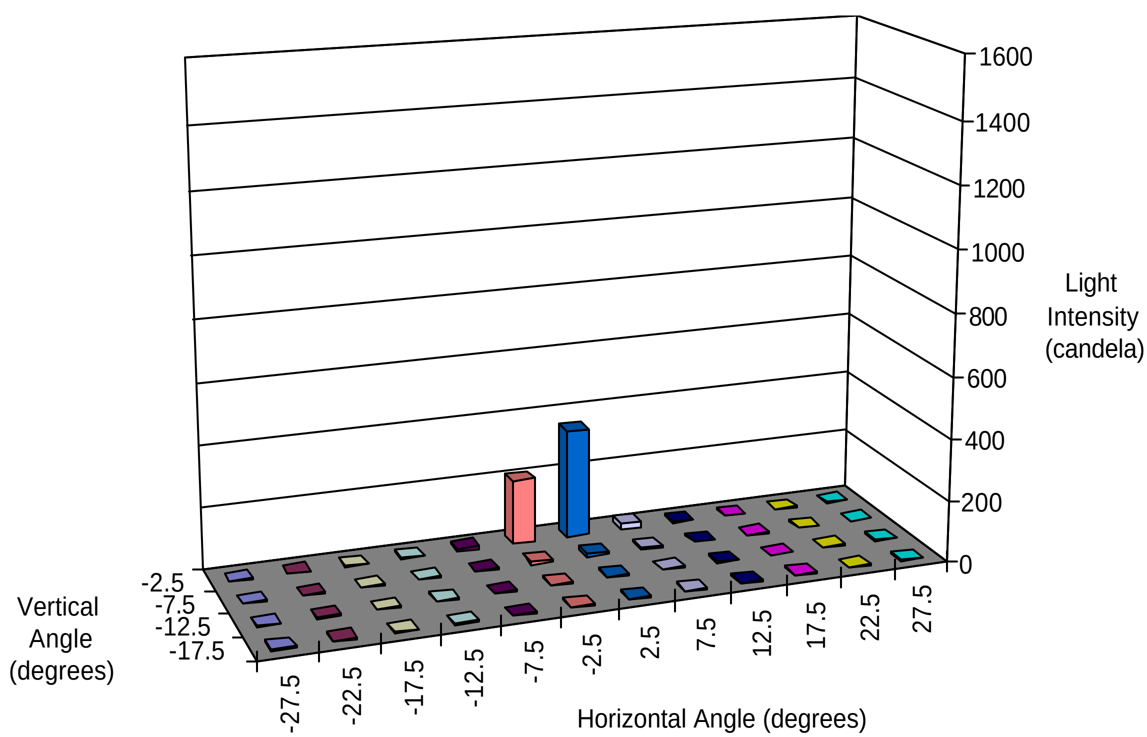

Figure A8.3.6b Output from WPS #8 (Yellow) signal, 10.0 volts, 36.0 ft, all elements on, ITE test.

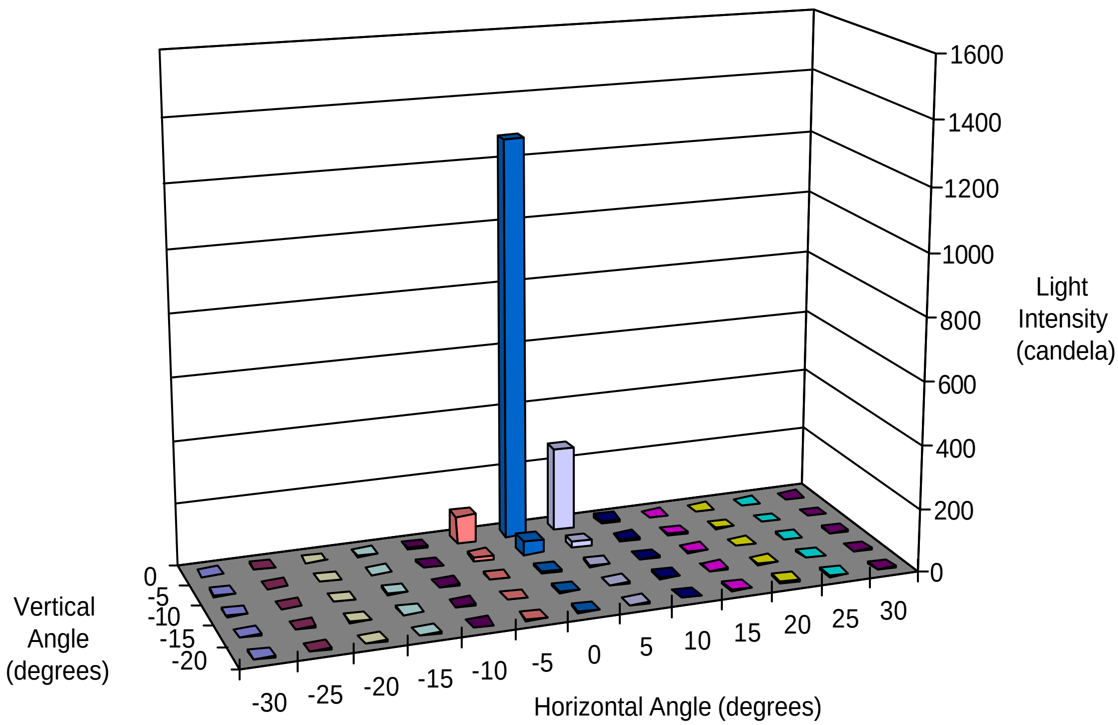

Figure A8.3.7a Output from WPS #8 (Yellow) signal, 10.0 volts, 34.0 ft, all elements on, TC test.

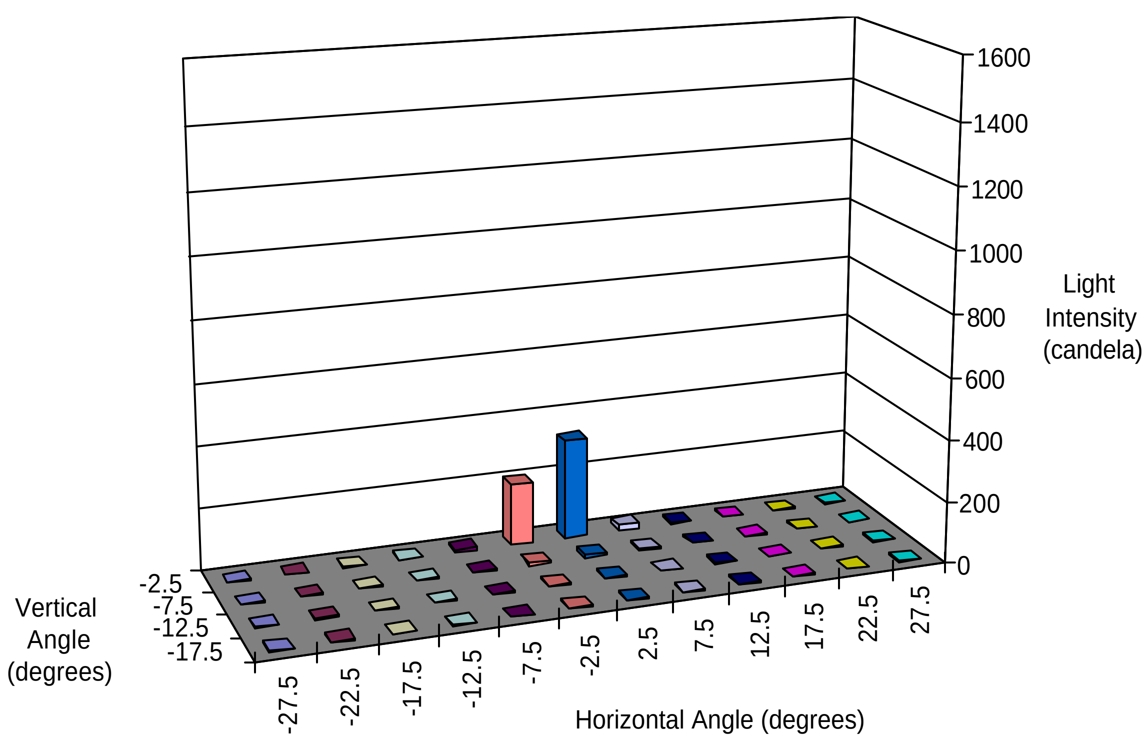

Figure A8.3.7b Output from WPS #8 (Yellow) signal, 10.0 volts, 34.0 ft, all elements on, ITE test.

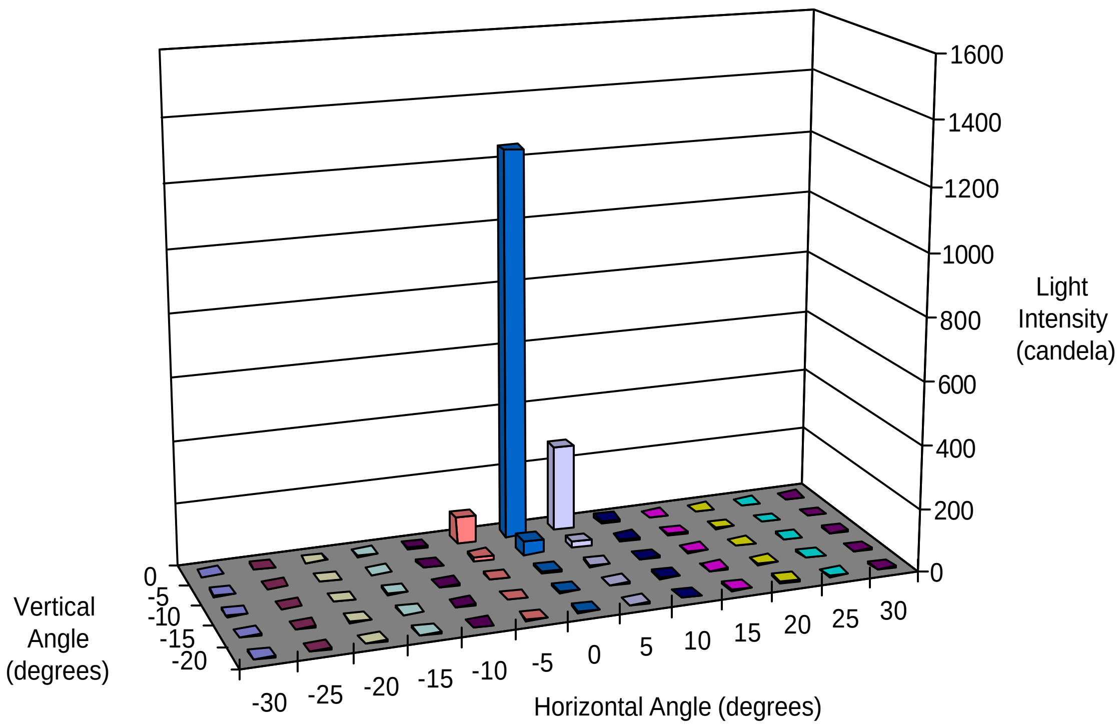

Figure A8.3.8a Output from WPS #8 (Yellow) signal, 10.0 volts, 32.0 ft, all elements on, TC test.

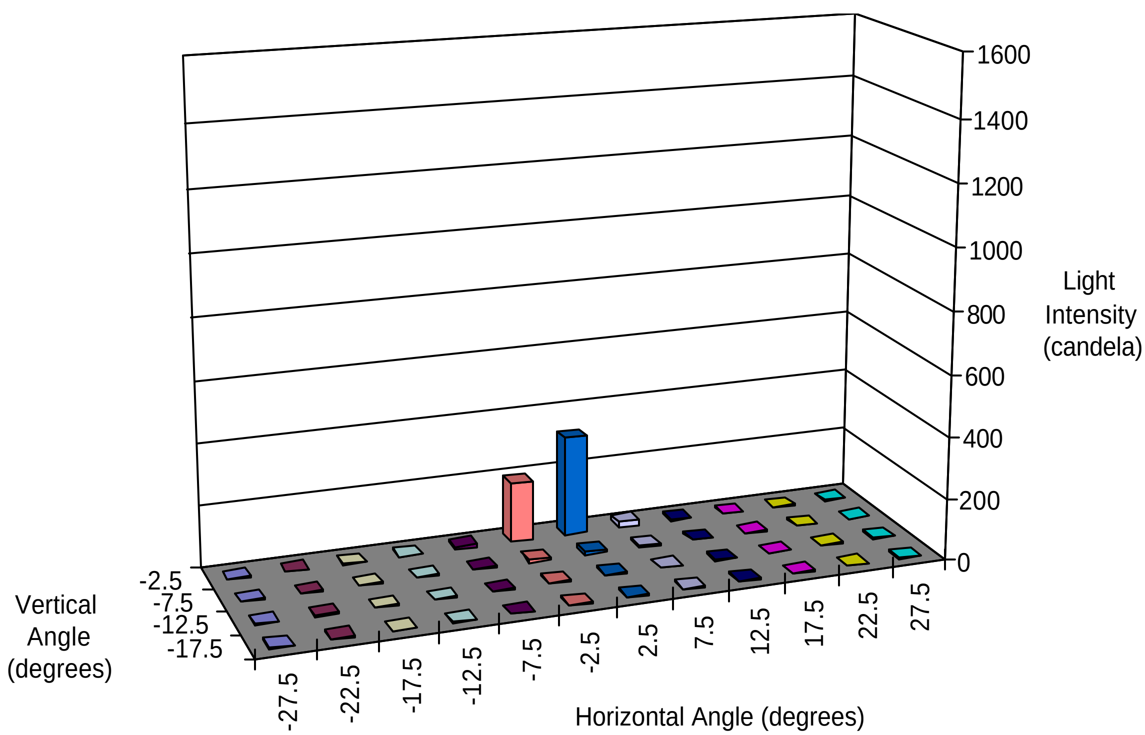

Figure A8.3.8b Output from WPS #8 (Yellow) signal, 10.0 volts, 32.0 ft, all elements on, ITE test.

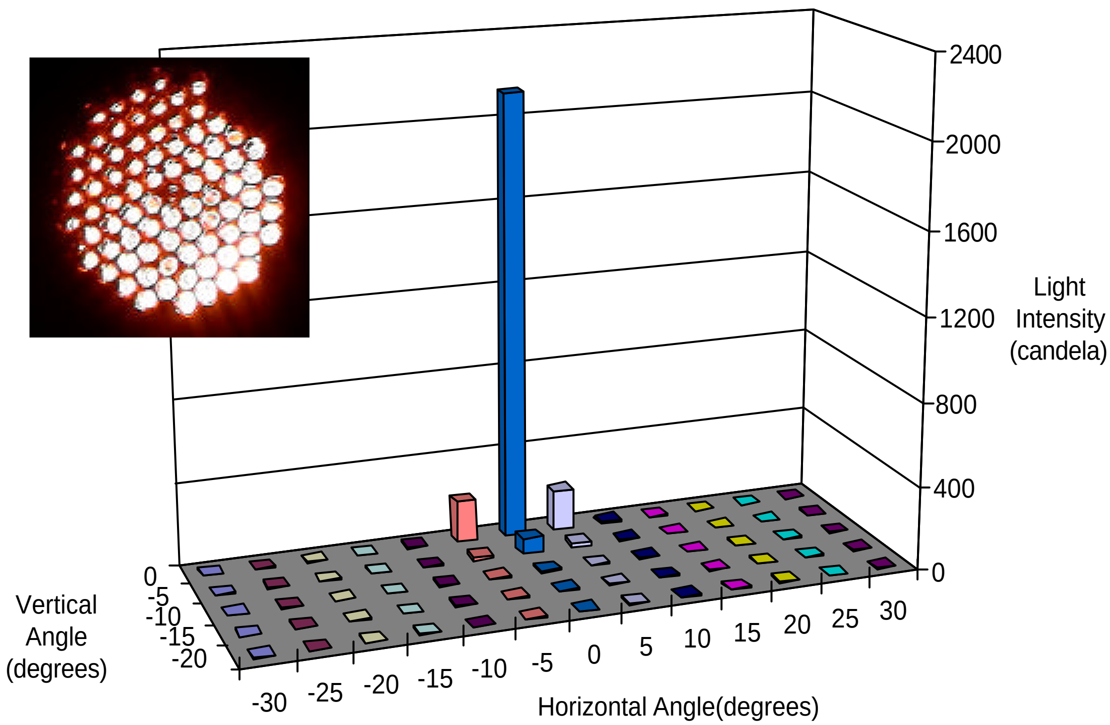

Figure A8.4.1a Output from WPS #8 (Yellow) signal, 10.0 volts, 84 elements (95% on), TC test.

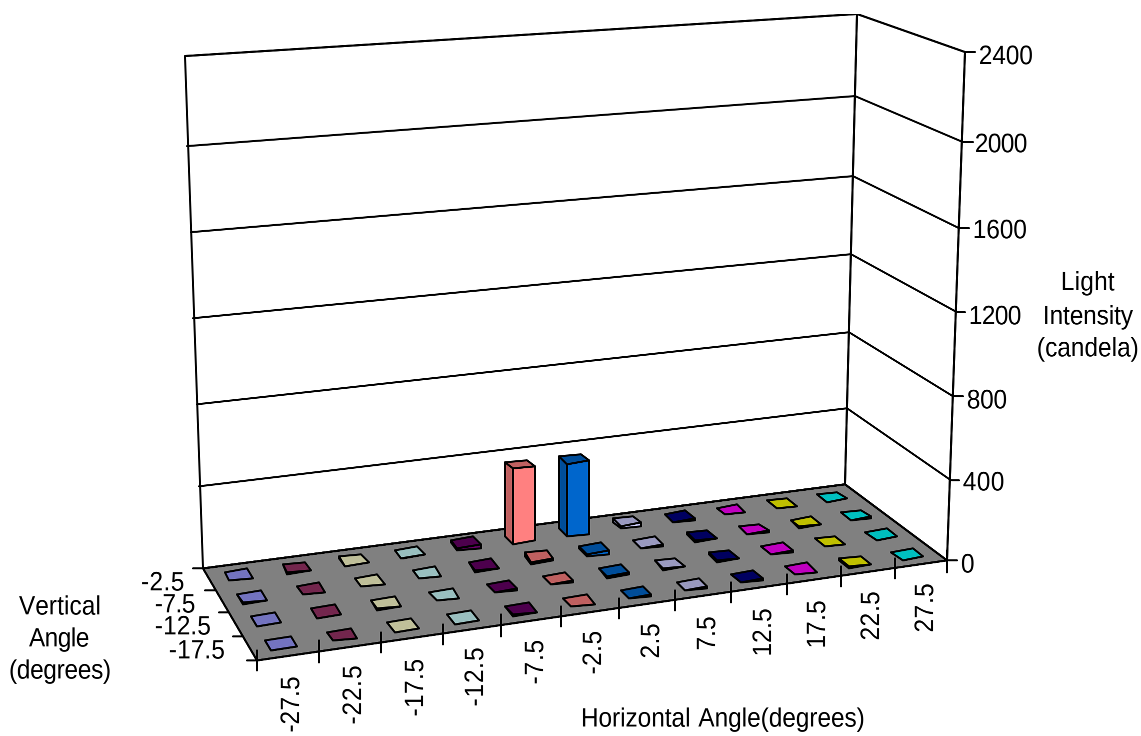

Figure A8.4.1b Output from WPS #8 (Yellow) signal, 10.0 volts, 84 elements (95% on), ITE test.

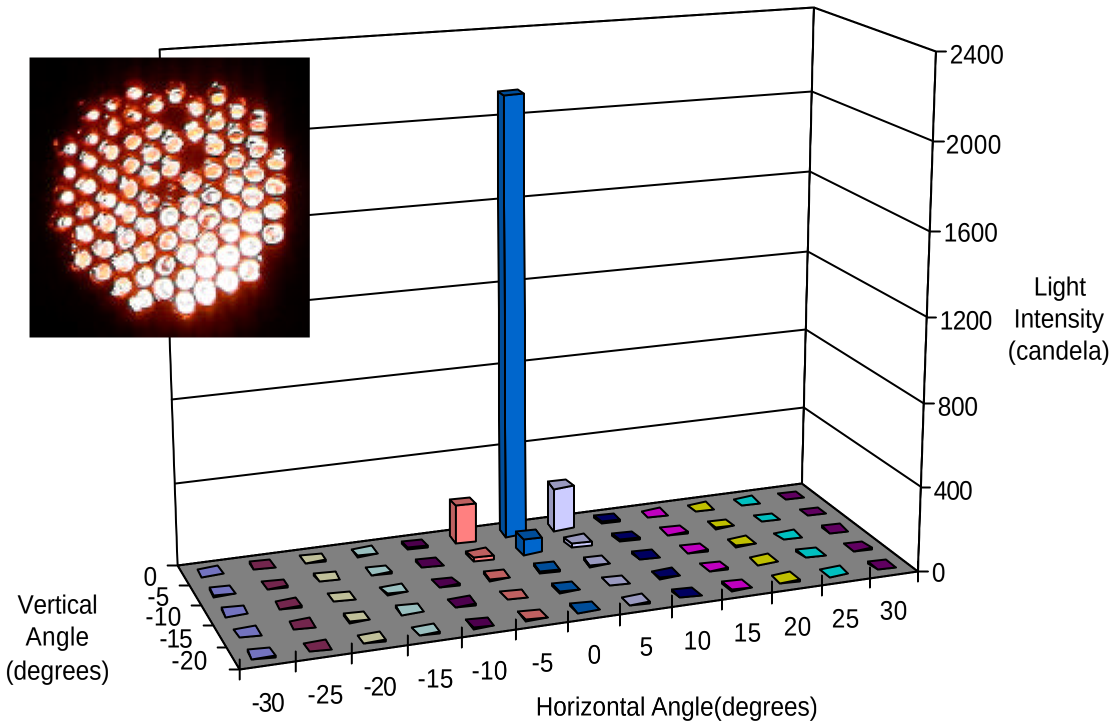

Figure A8.4.2a Output from WPS #8 (Yellow) signal, 10.0 volts, 84 elements (95% on), TC test.

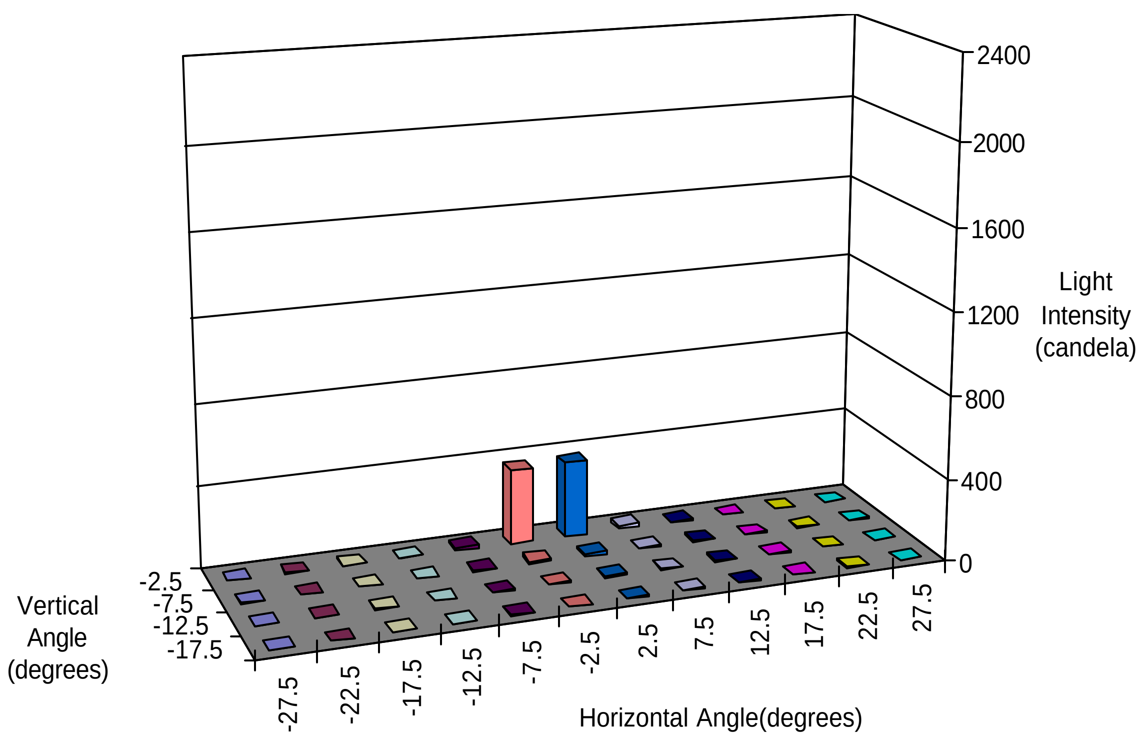

Figure A8.4.2b Output from WPS #8 (Yellow) signal, 10.0 volts, 84 elements (95% on), ITE test.

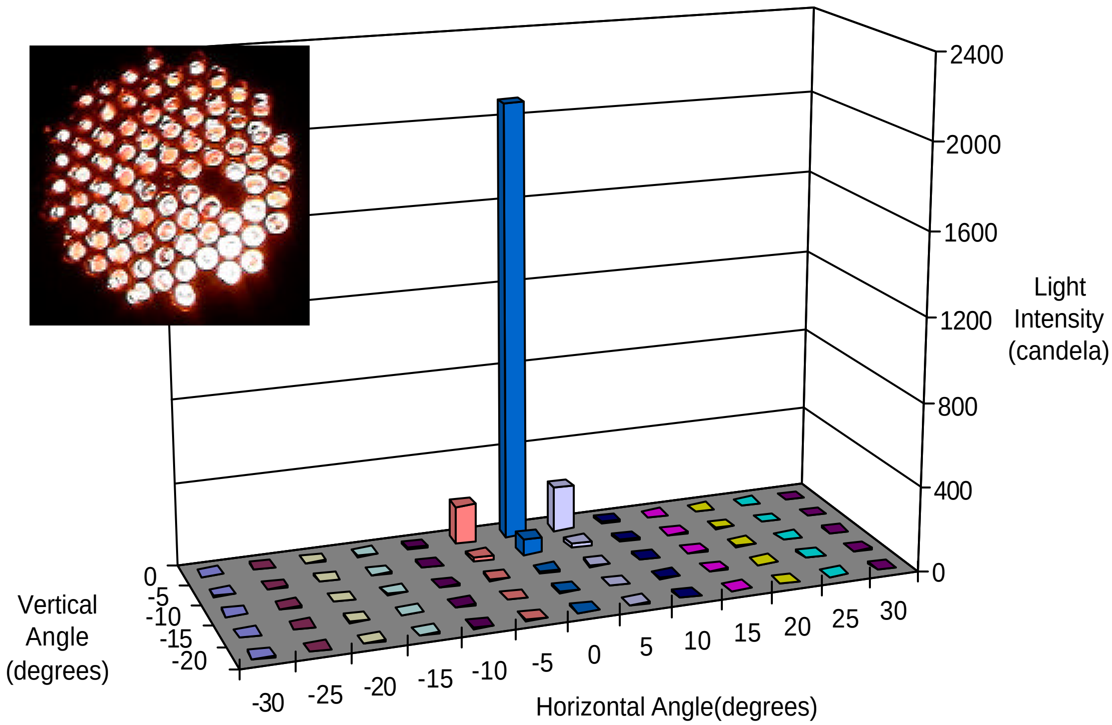

Figure A8.4.3a Output from WPS #8 (Yellow) signal, 10.0 volts, 84 elements (95% on), TC test.

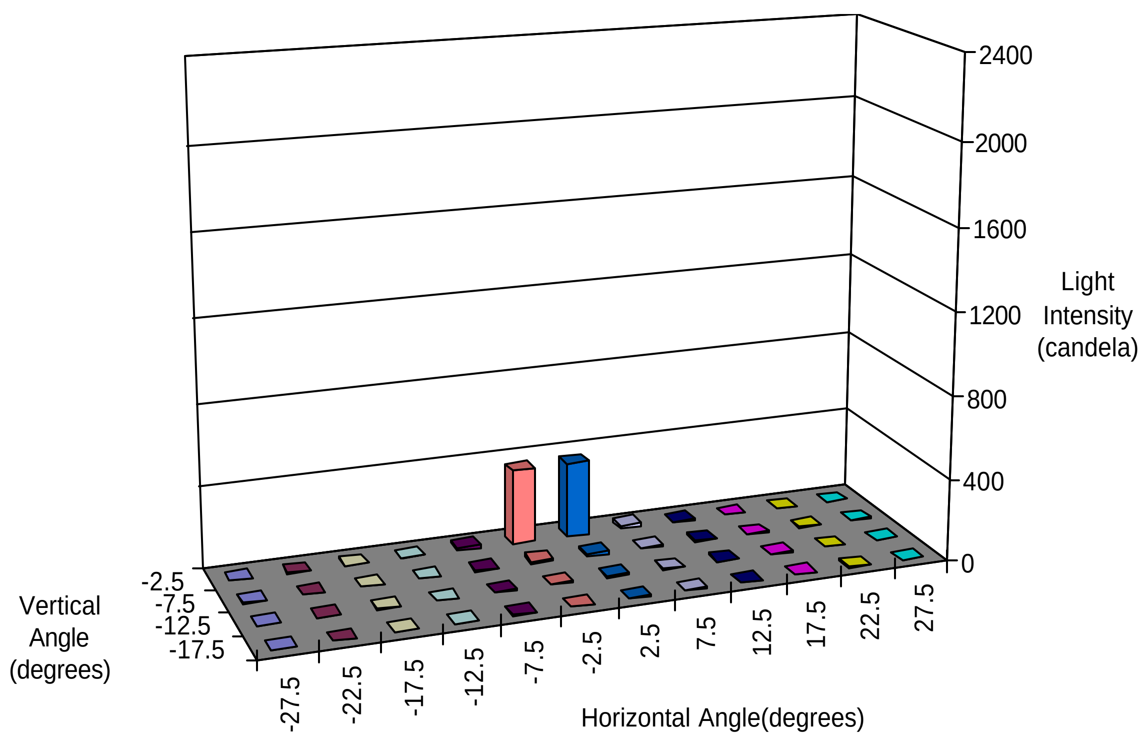

Figure A8.4.3b Output from WPS #8 (Yellow) signal, 10.0 volts, 84 elements (95% on), ITE test.

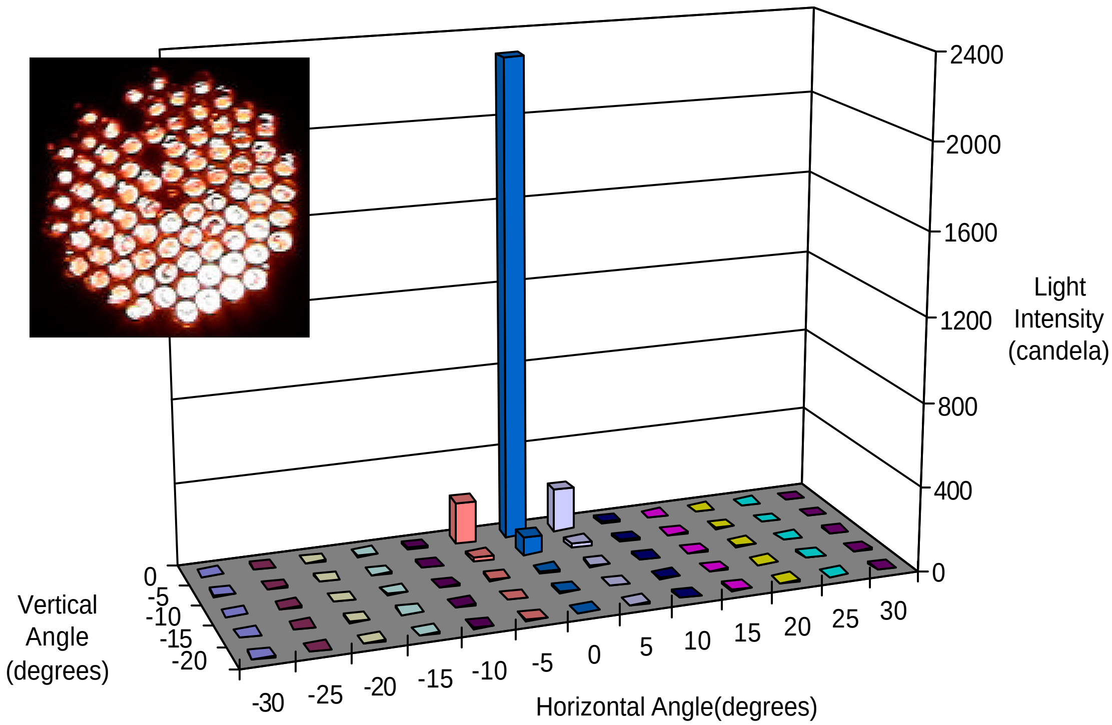

Figure A8.4.4a Output from WPS #8 (Yellow) signal, 10.0 volts, 84 elements (95% on), TC test.

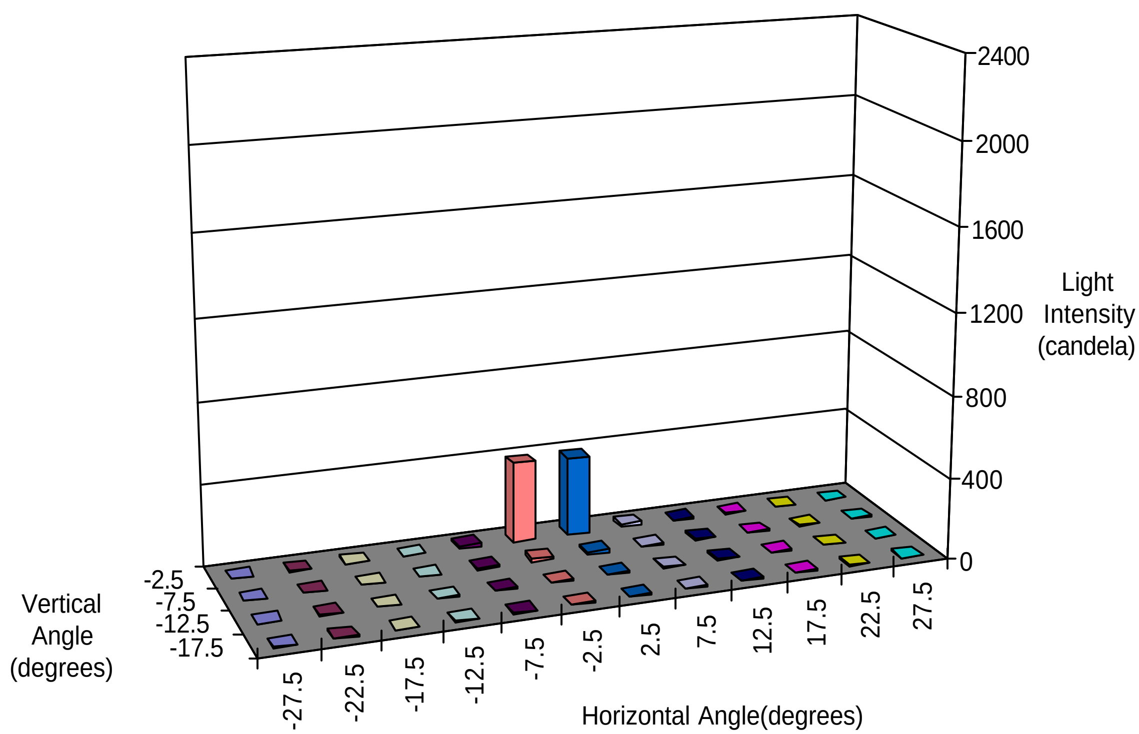

Figure A8.4.4b Output from WPS #8 (Yellow) signal, 10.0 volts, 84 elements (95% on), ITE test.

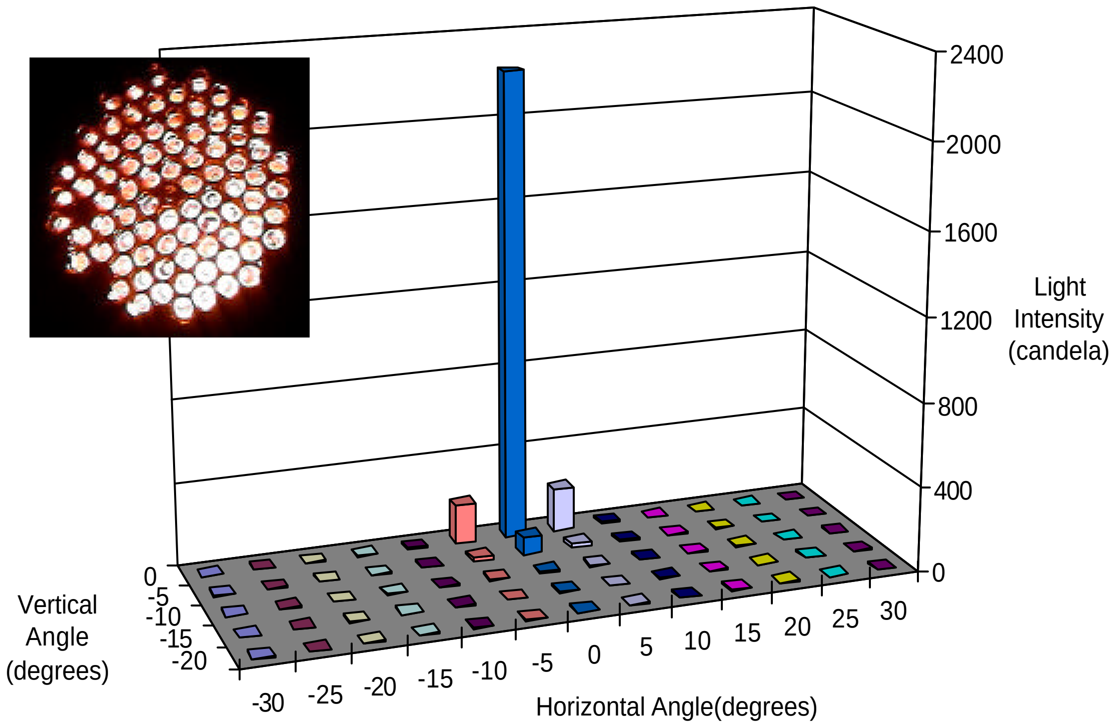

Figure A8.4.5a Output from WPS #8 (Yellow) signal, 10.0 volts, 84 elements (95% on), TC test.

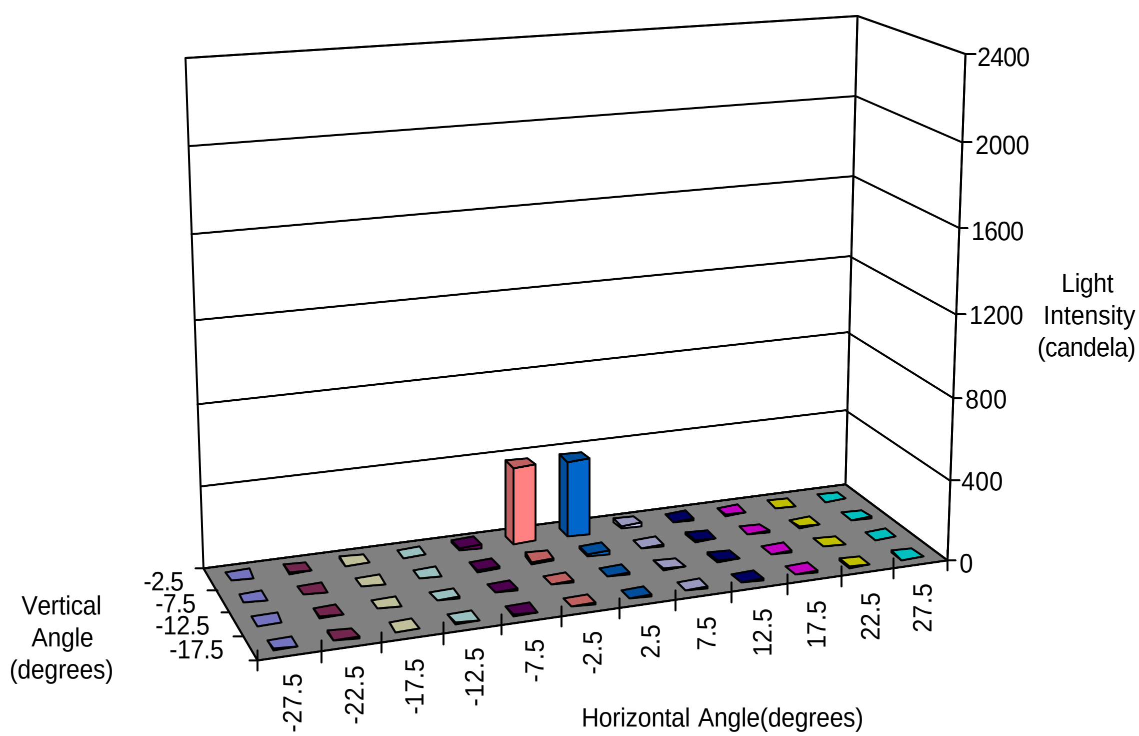

Figure A8.4.5b Output from WPS #8 (Yellow) signal, 10.0 volts, 84 elements (95% on), ITE test.

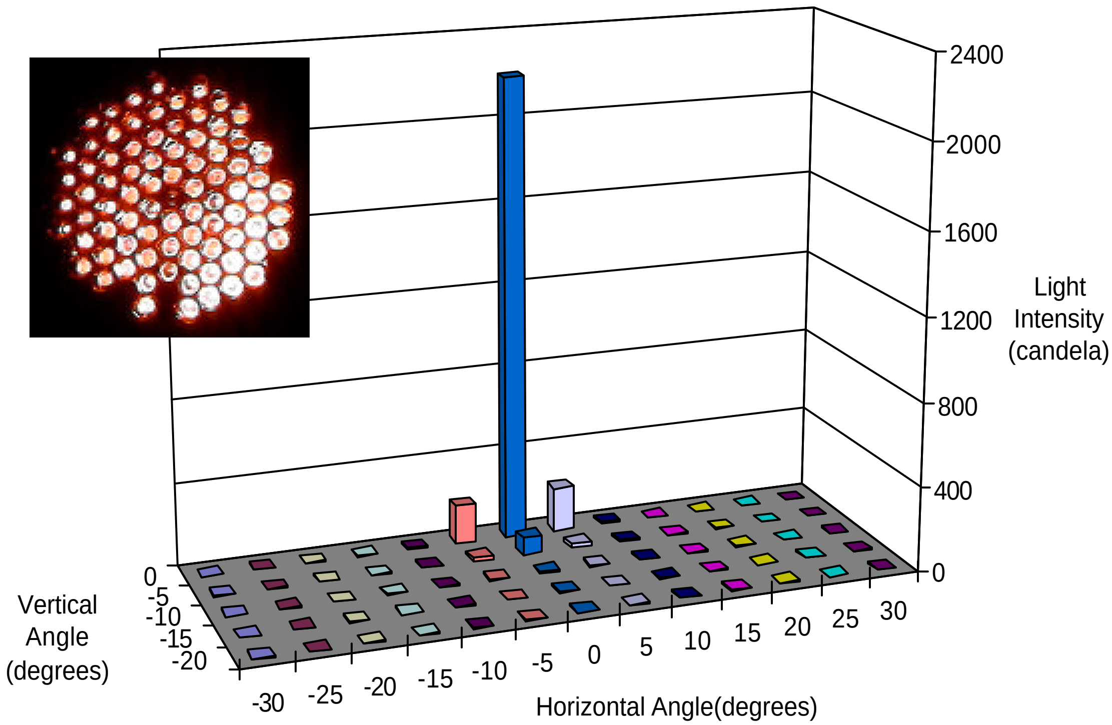

Figure A8.4.6a Output from WPS #8 (Yellow) signal, 10.0 volts, 84 elements (95% on), TC test.

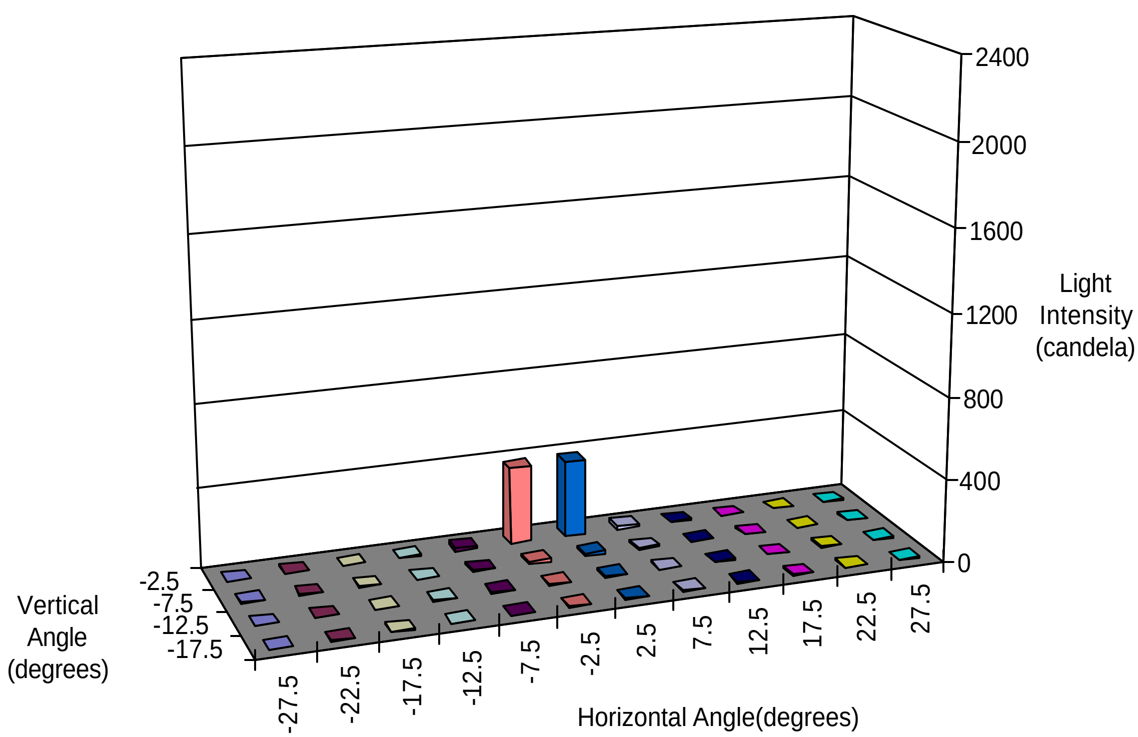

Figure A8.4.6b Output from WPS #8 (Yellow) signal, 10.0 volts, 84 elements (95% on), ITE test.

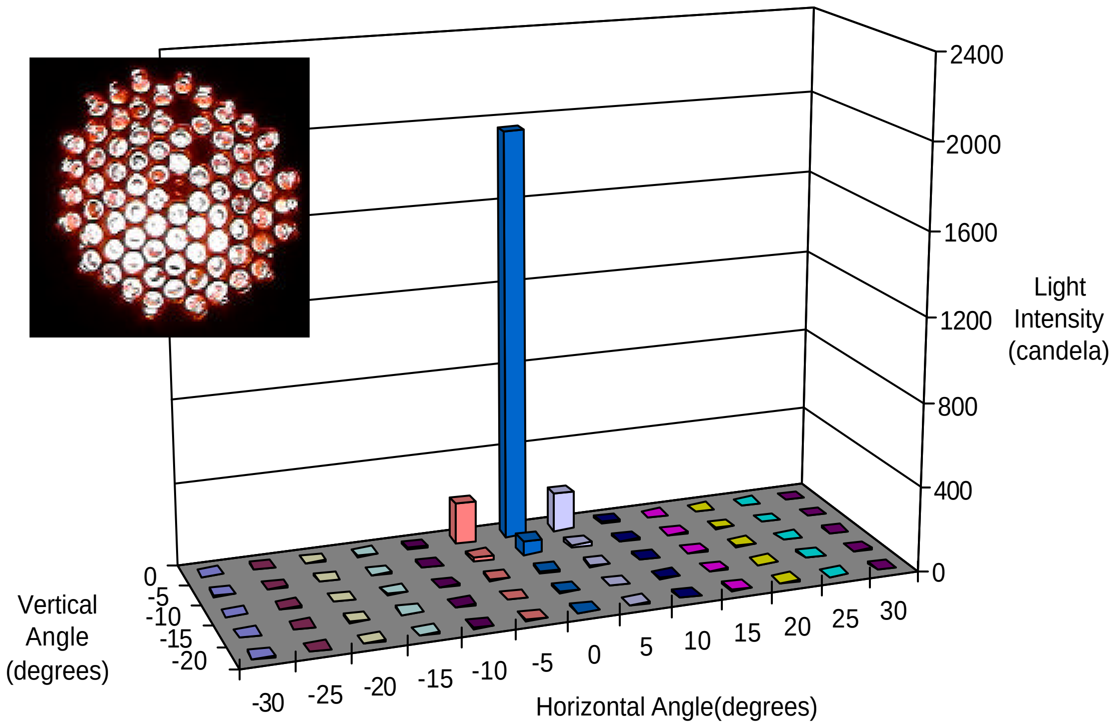

Figure A8.4.7a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (91% on), TC test.

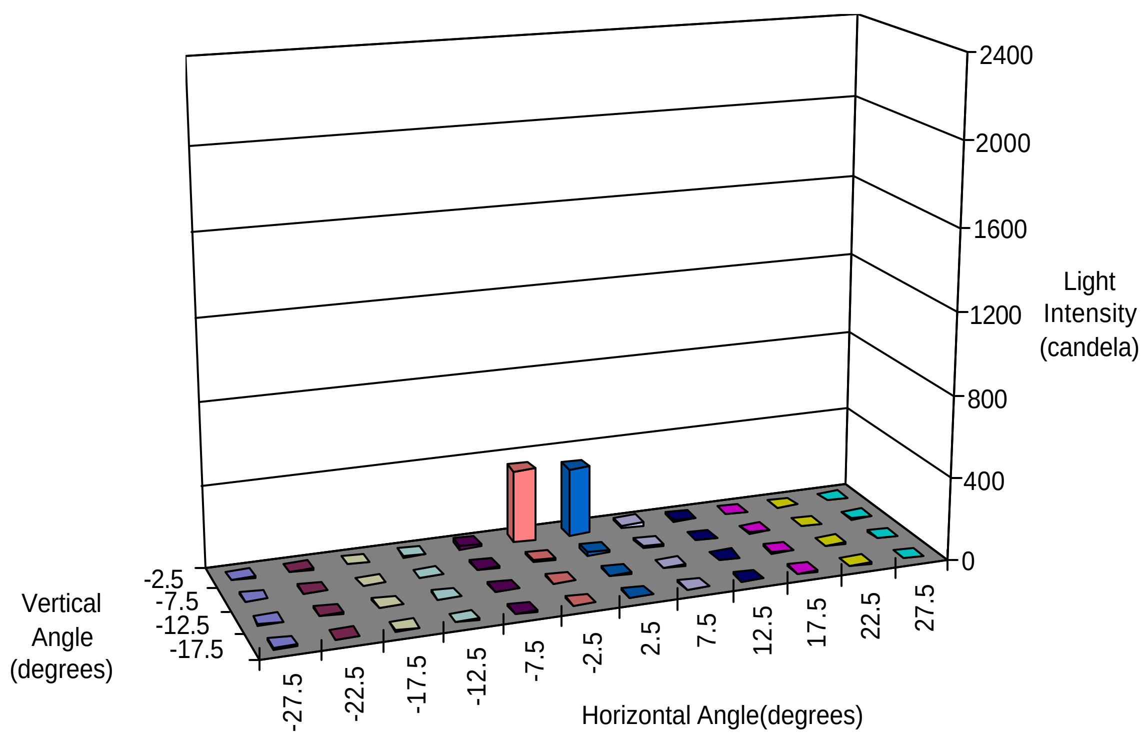

Figure A8.4.7b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (91% on), ITE test.

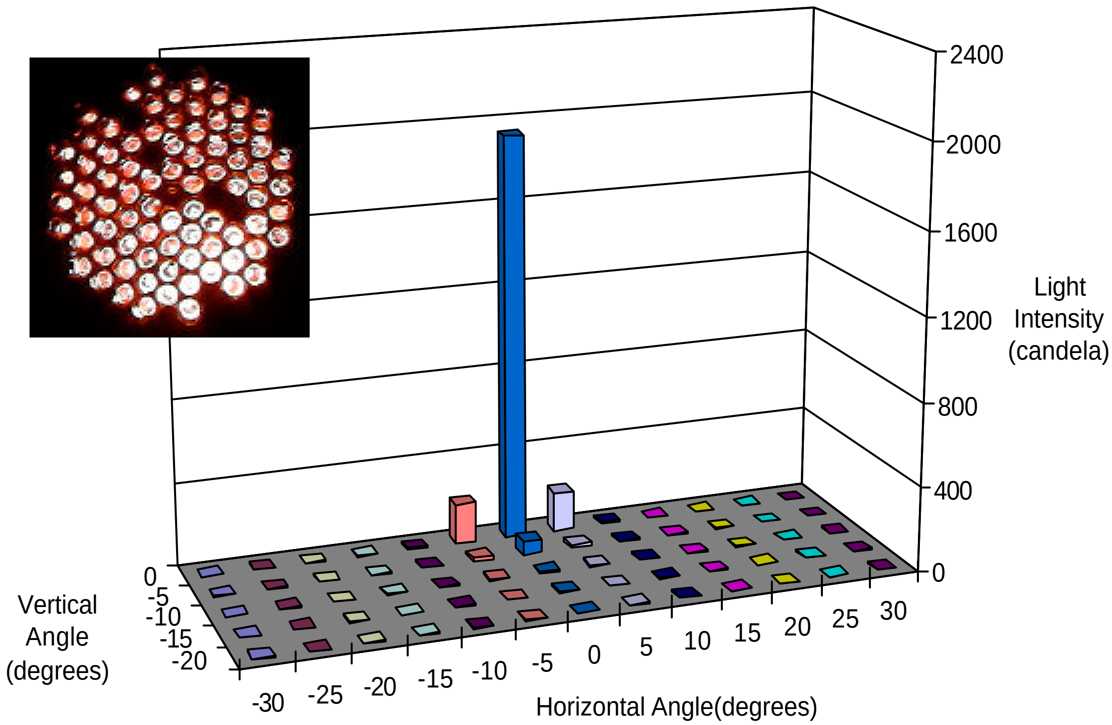

Figure A8.4.8a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (91% on), TC test.

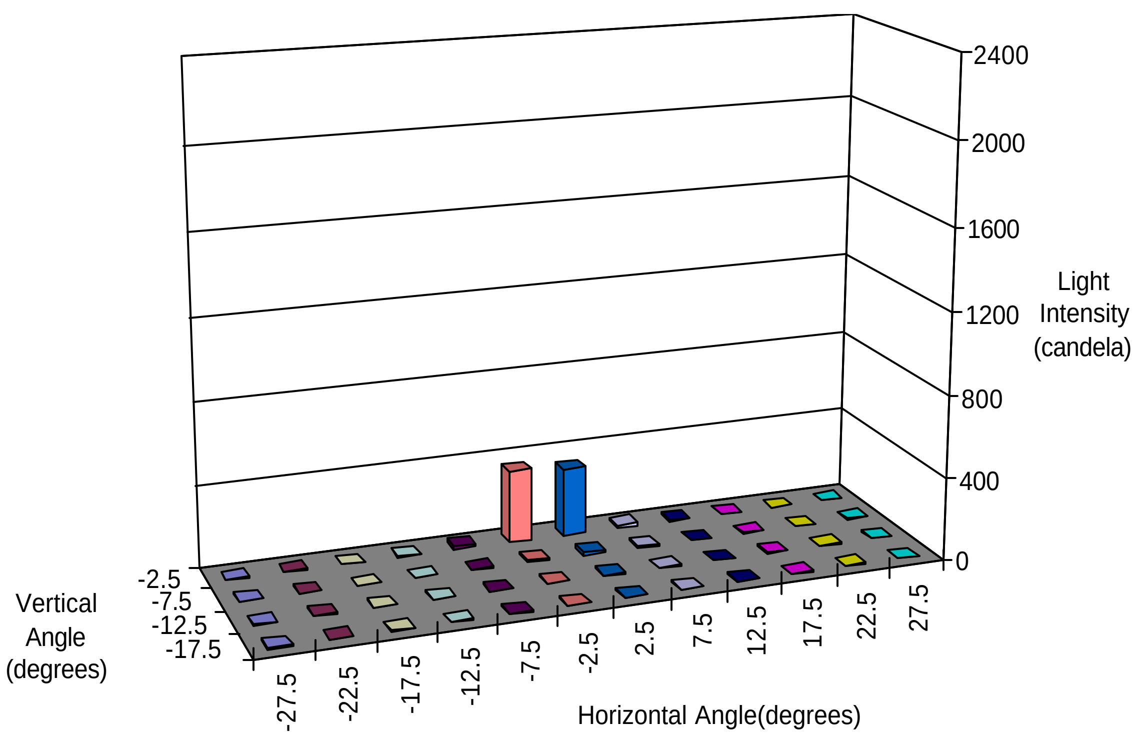

Figure A8.4.8b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (91% on), ITE test.

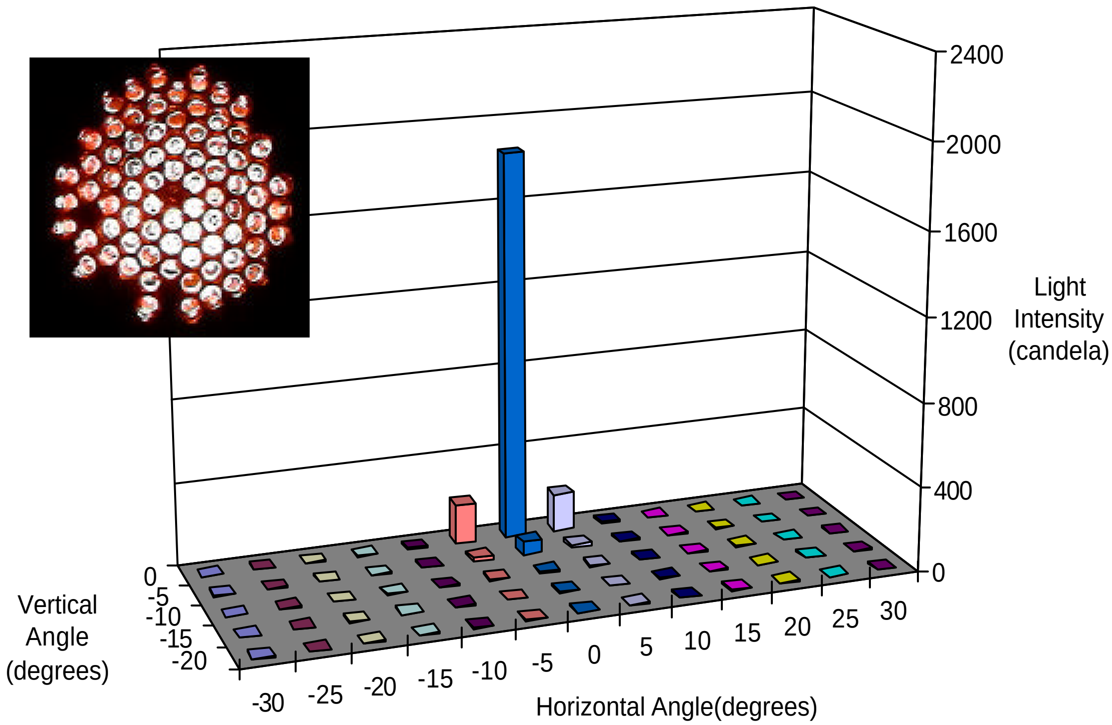

Figure A8.4.9a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (91% on), TC test.

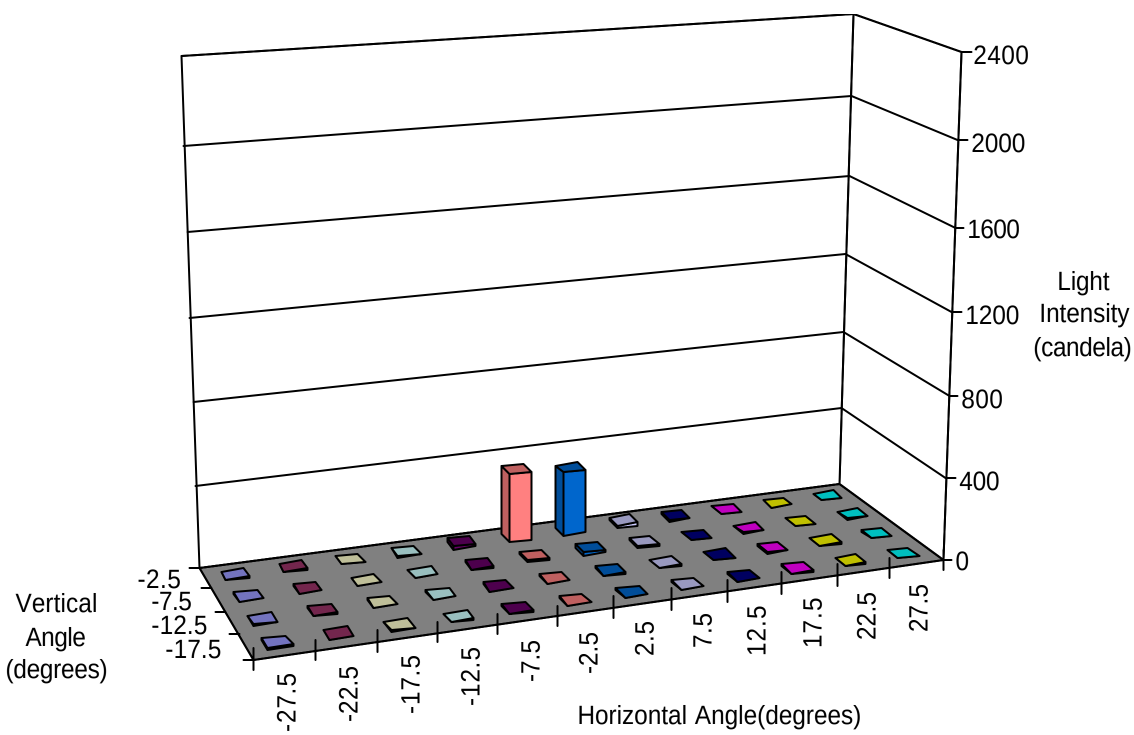

Figure A8.4.9b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (91% on), ITE test.

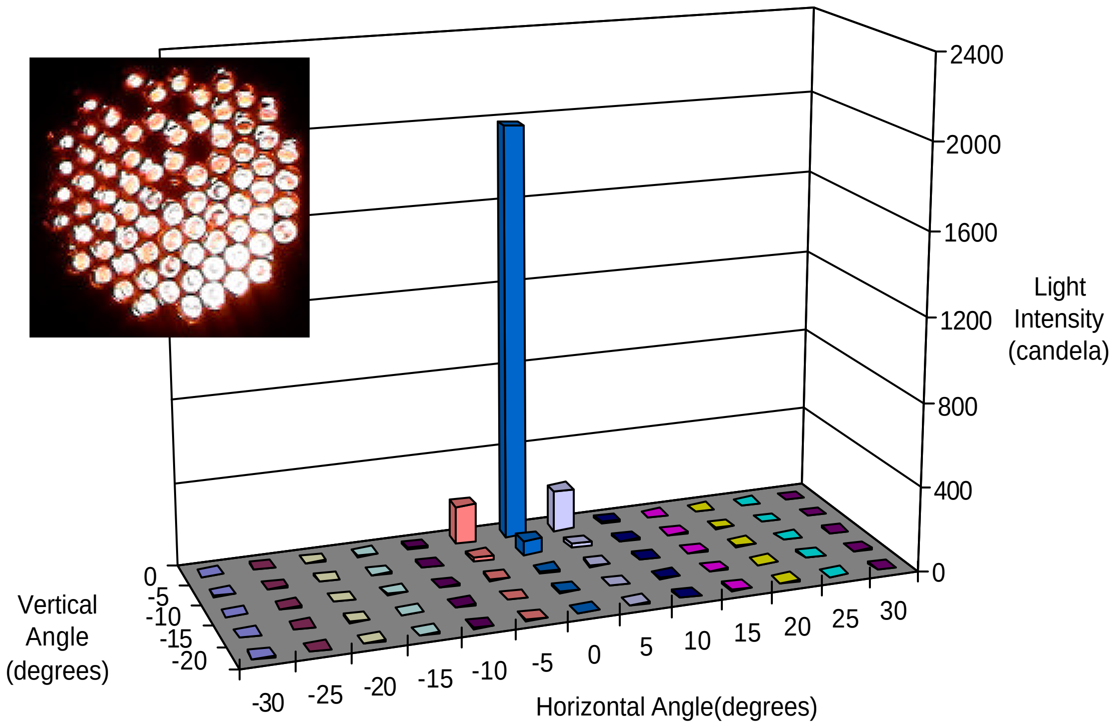

Figure A8.4.10a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (91% on), TC test.

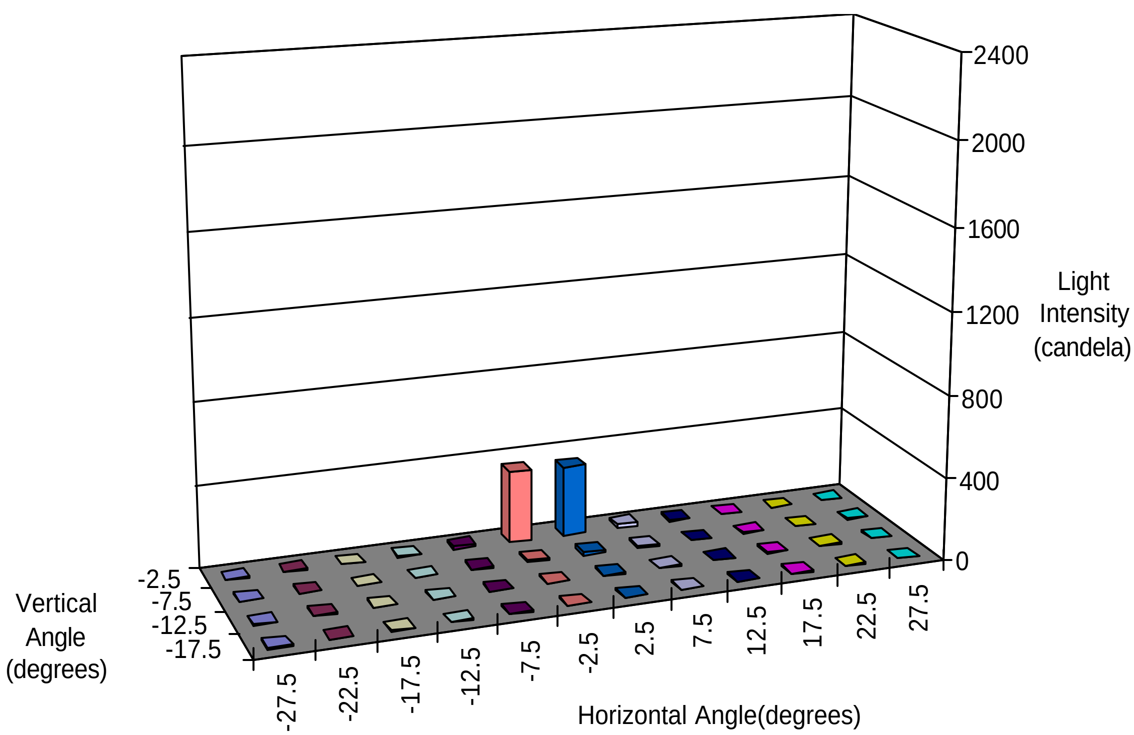

Figure A8.4.10b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (91% on), ITE test.

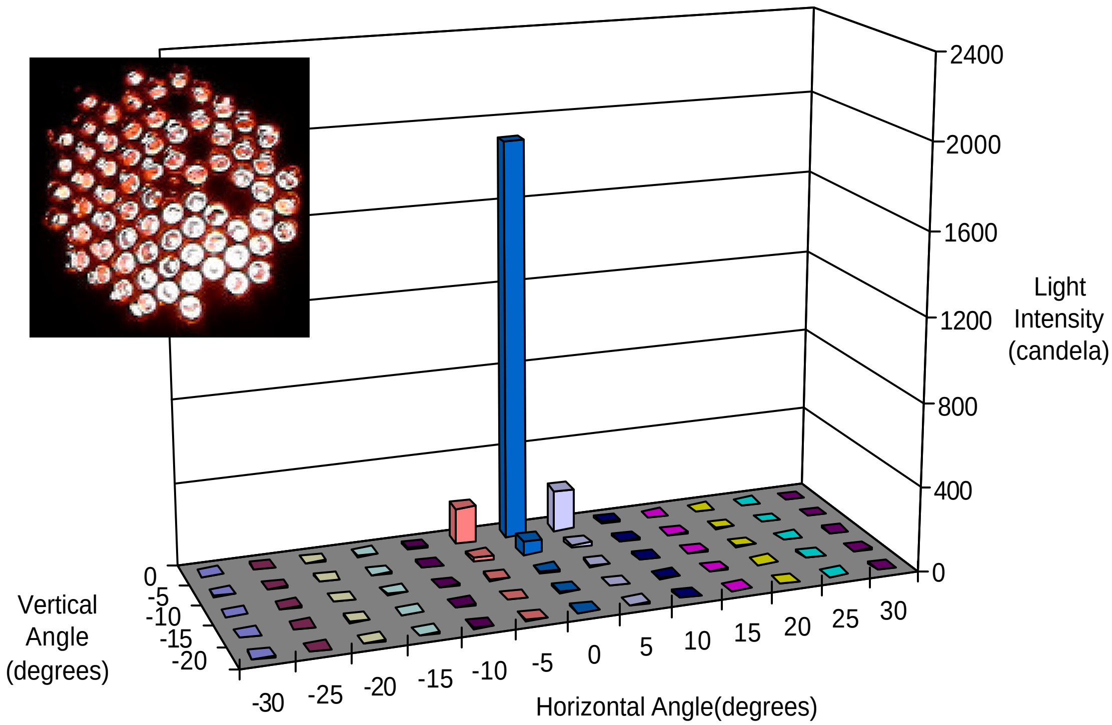

Figure A8.4.11a Output from WPS #8 (Yellow) signal, 10.0 volts, 76 elements (86% on), TC test.

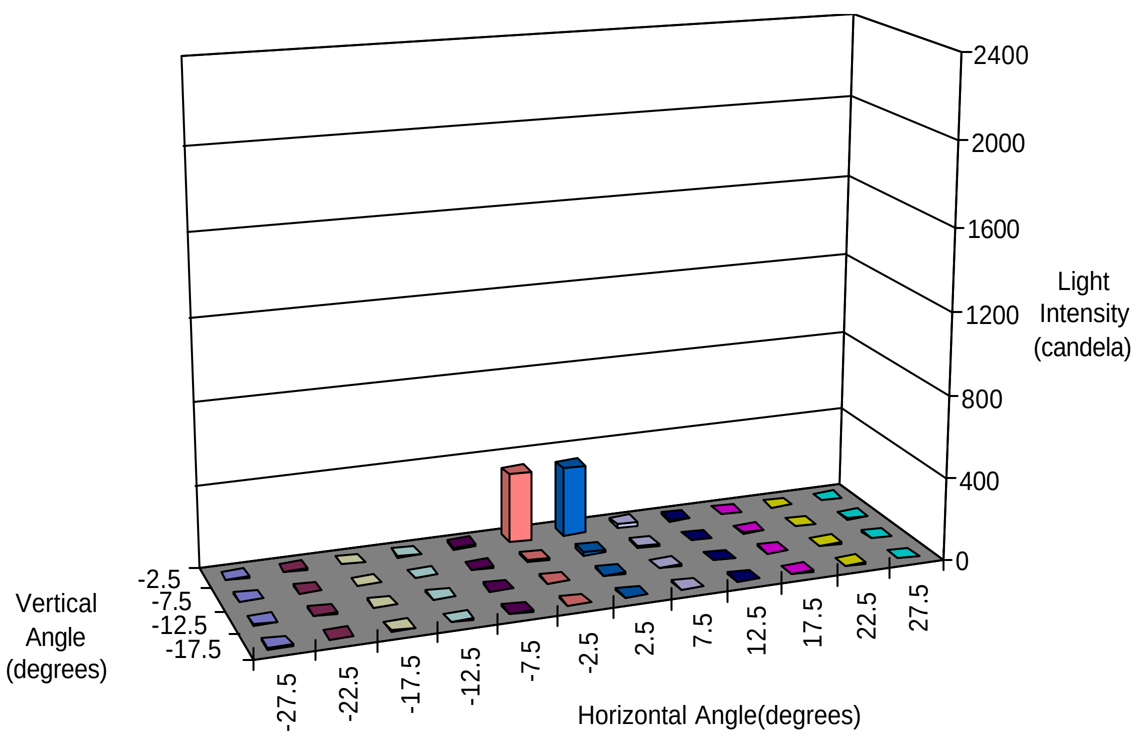

Figure A8.4.11b Output from WPS #8 (Yellow) signal, 10.0 volts, 76 elements (86% on), ITE test.

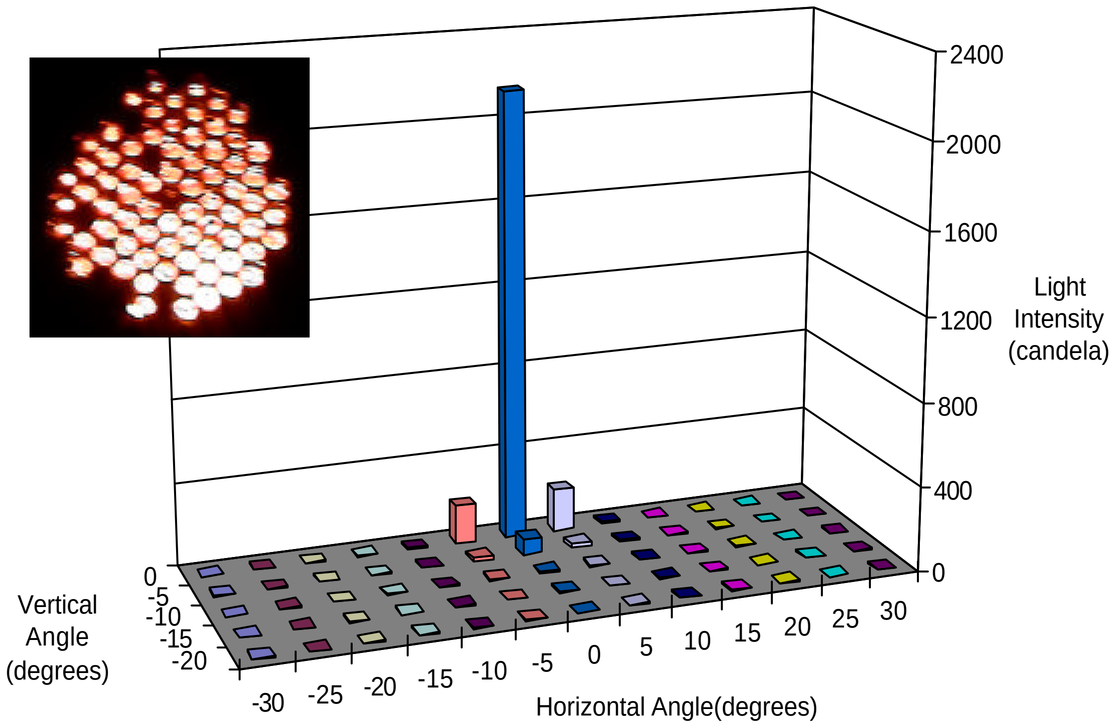

Figure A8.4.12a Output from WPS #8 (Yellow) signal, 10.0 volts, 76 elements (86% on), TC test.

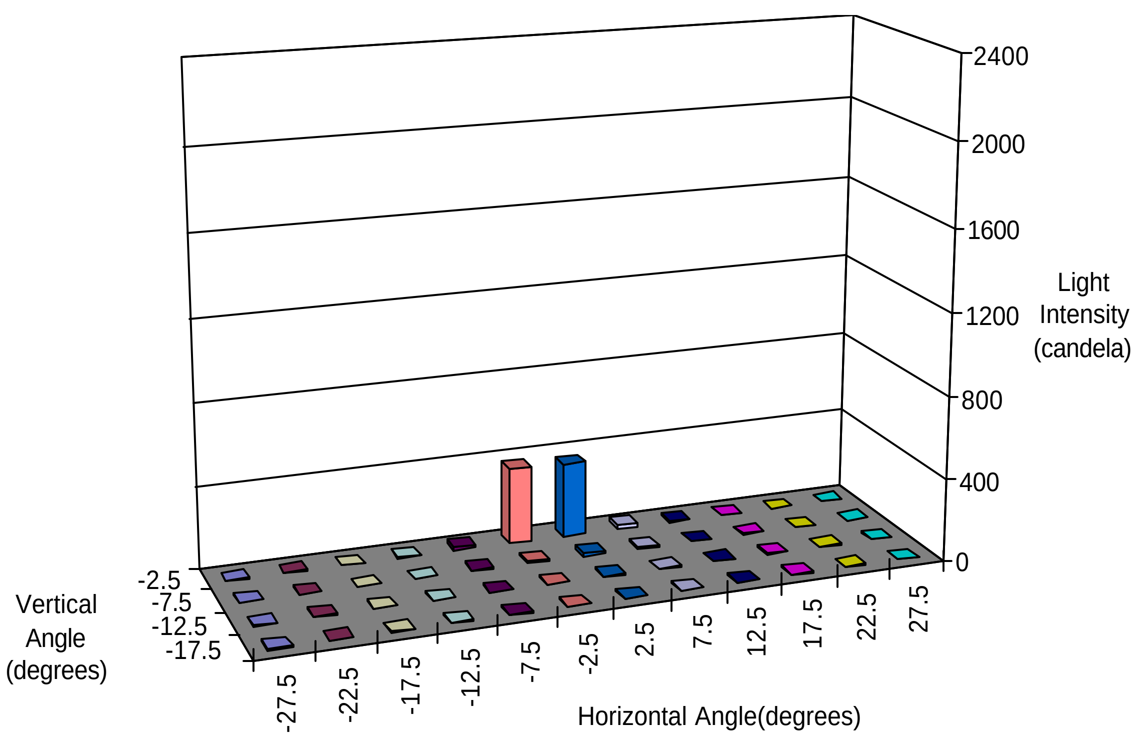

Figure A8.4.12b Output from WPS #8 (Yellow) signal, 10.0 volts, 76 elements (86% on), ITE test.

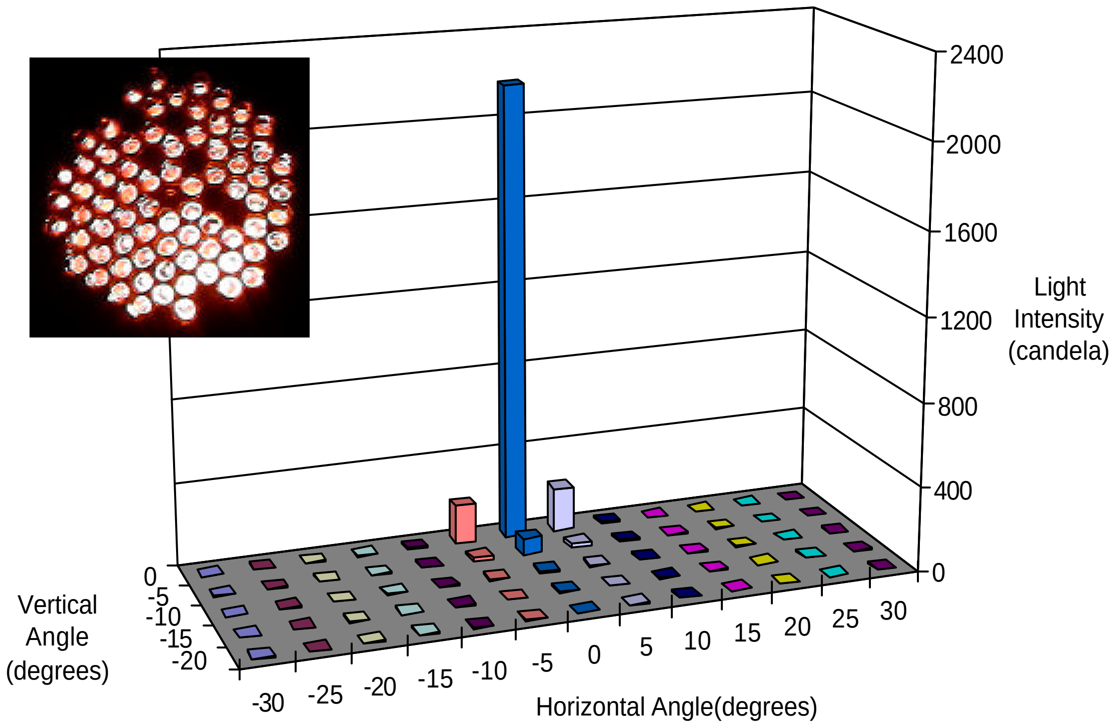

Figure A8.4.13a Output from WPS #8 (Yellow) signal, 10.0 volts, 76 elements (86% on), TC test.

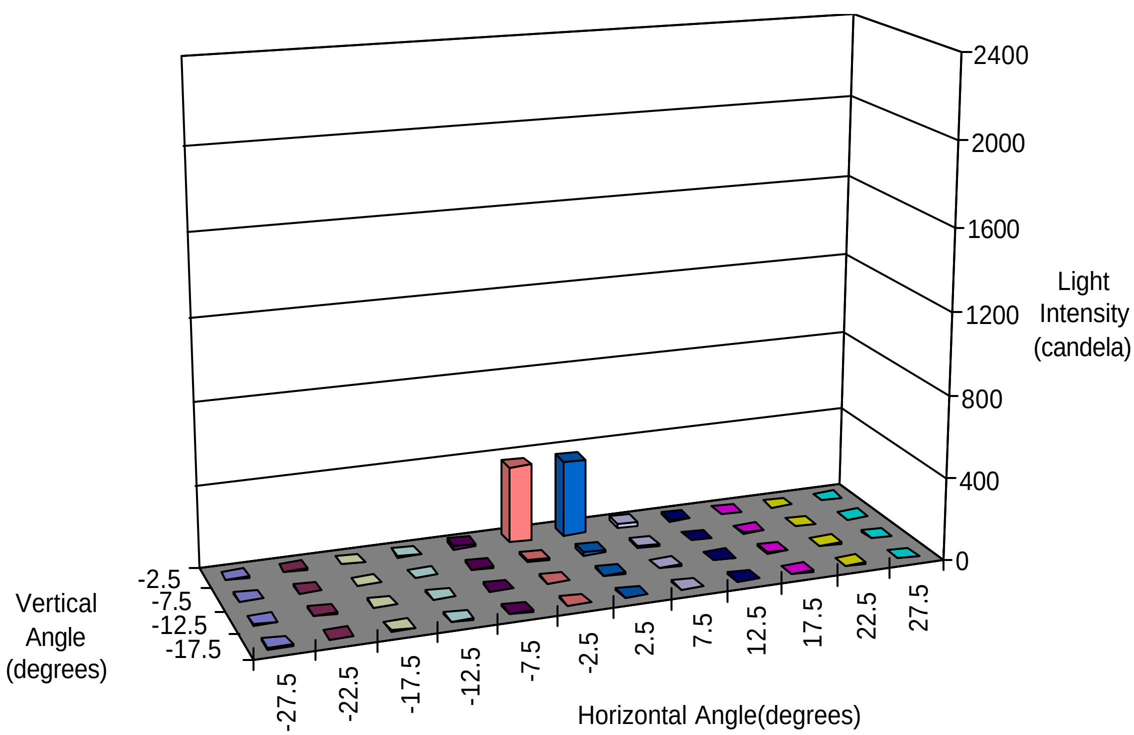

Figure A8.4.13b Output from WPS #8 (Yellow) signal, 10.0 volts, 76 elements (86% on), ITE test.

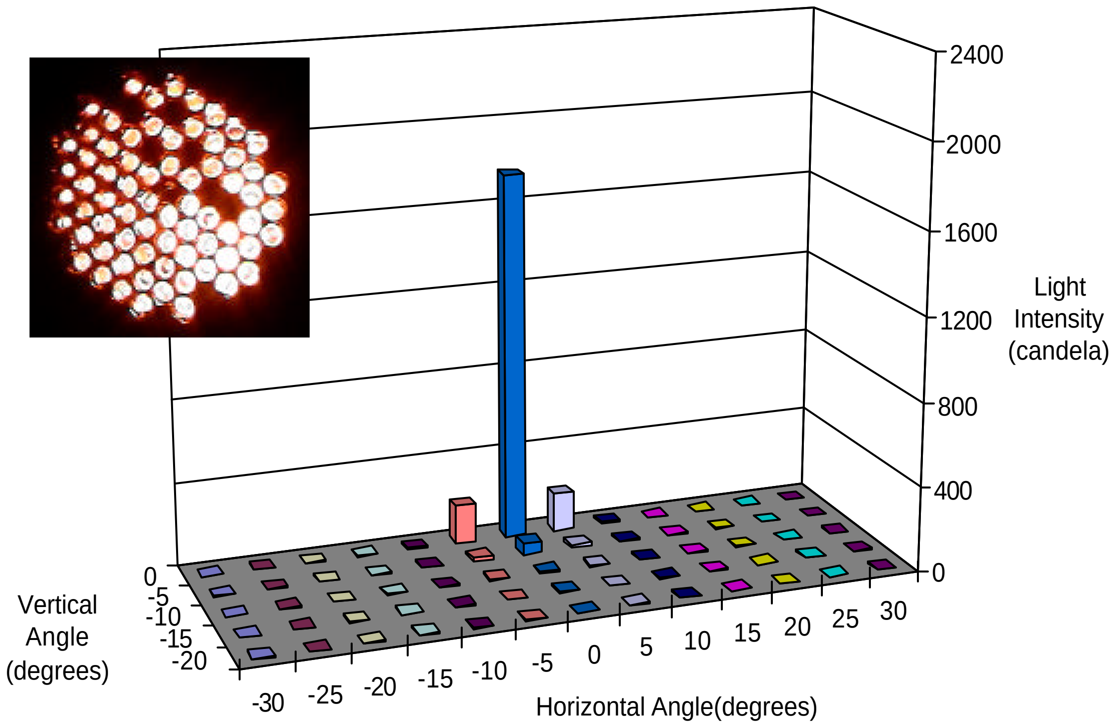

Figure A8.4.14a Output from WPS #8 (Yellow) signal, 10.0 volts, 72 elements (82% on), TC test.

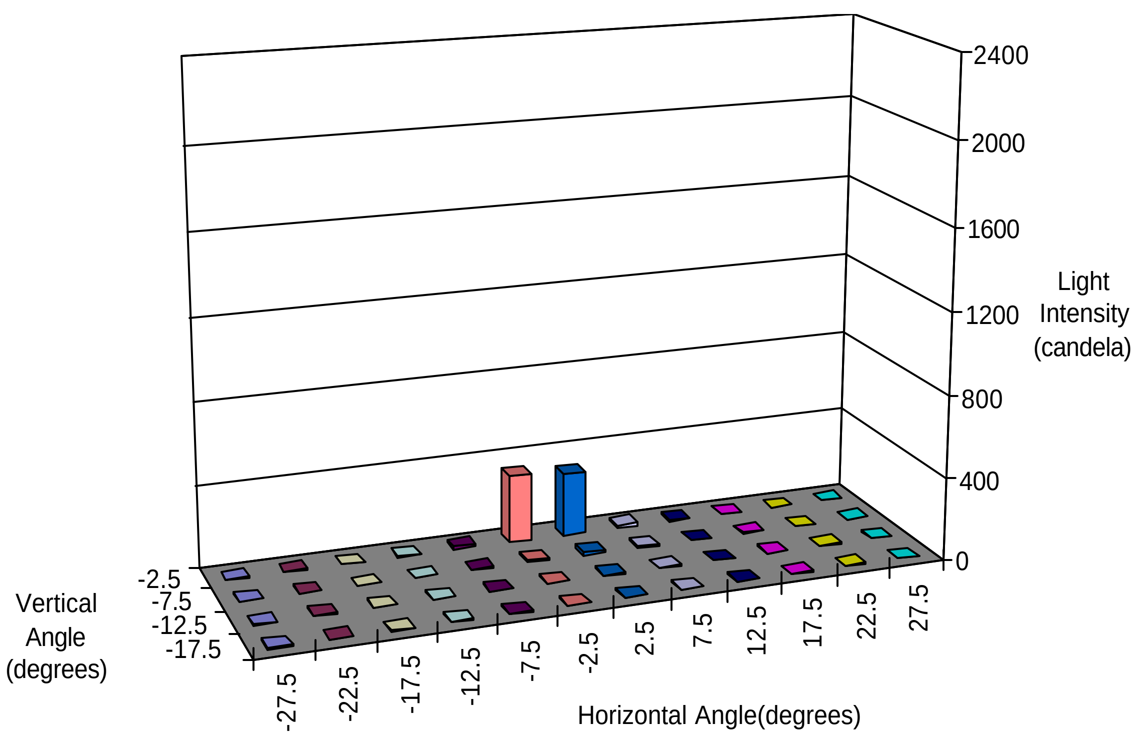

Figure A8.4.14b Output from WPS #8 (Yellow) signal, 10.0 volts, 72 elements (82% on), ITE test.

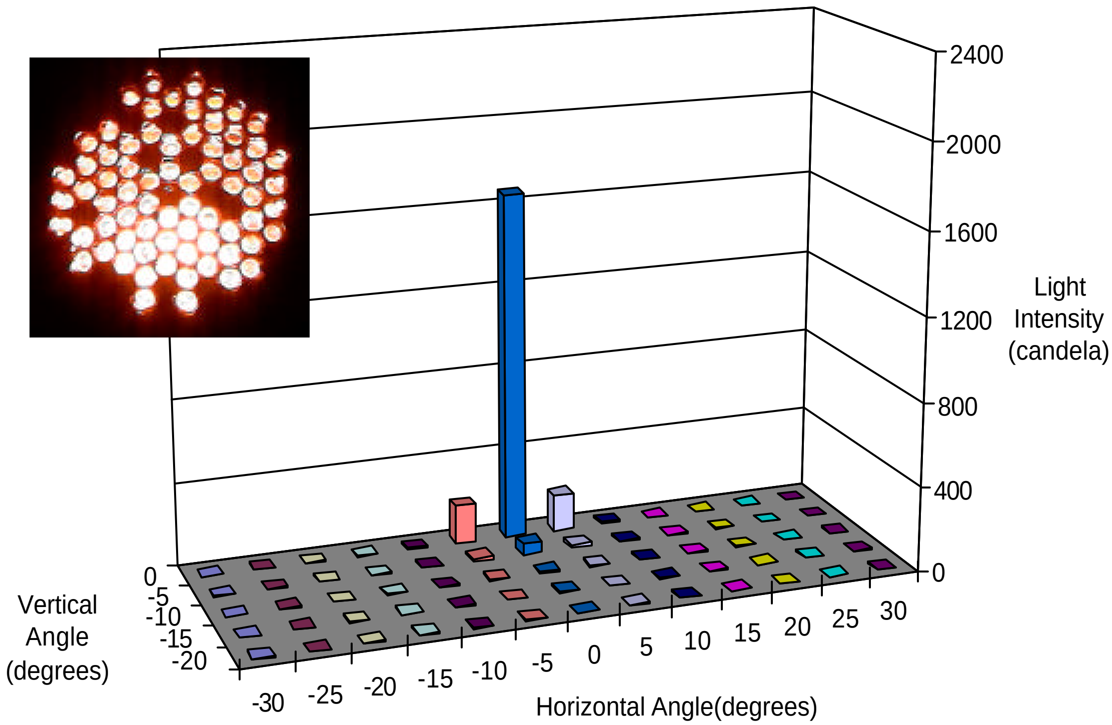

Figure A8.4.15a Output from WPS #8 (Yellow) signal, 10.0 volts, 72 elements (82% on), TC test.

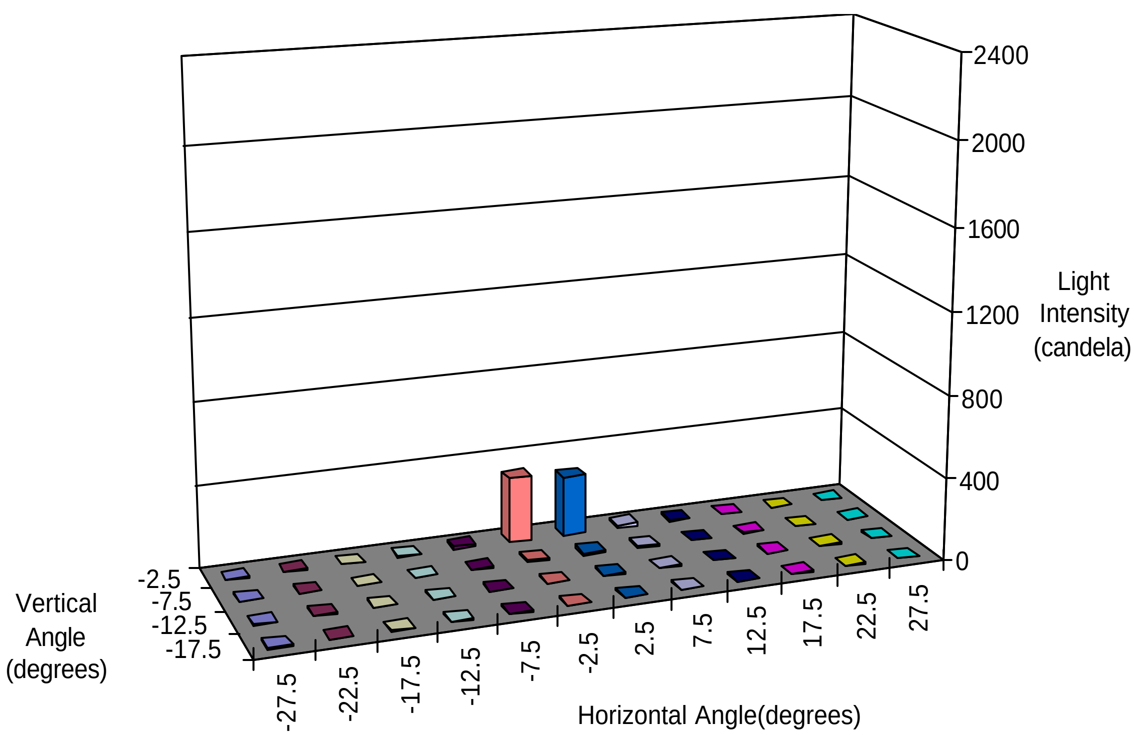

Figure A8.4.15b Output from WPS #8 (Yellow) signal, 10.0 volts, 72 elements (82% on), ITE test.

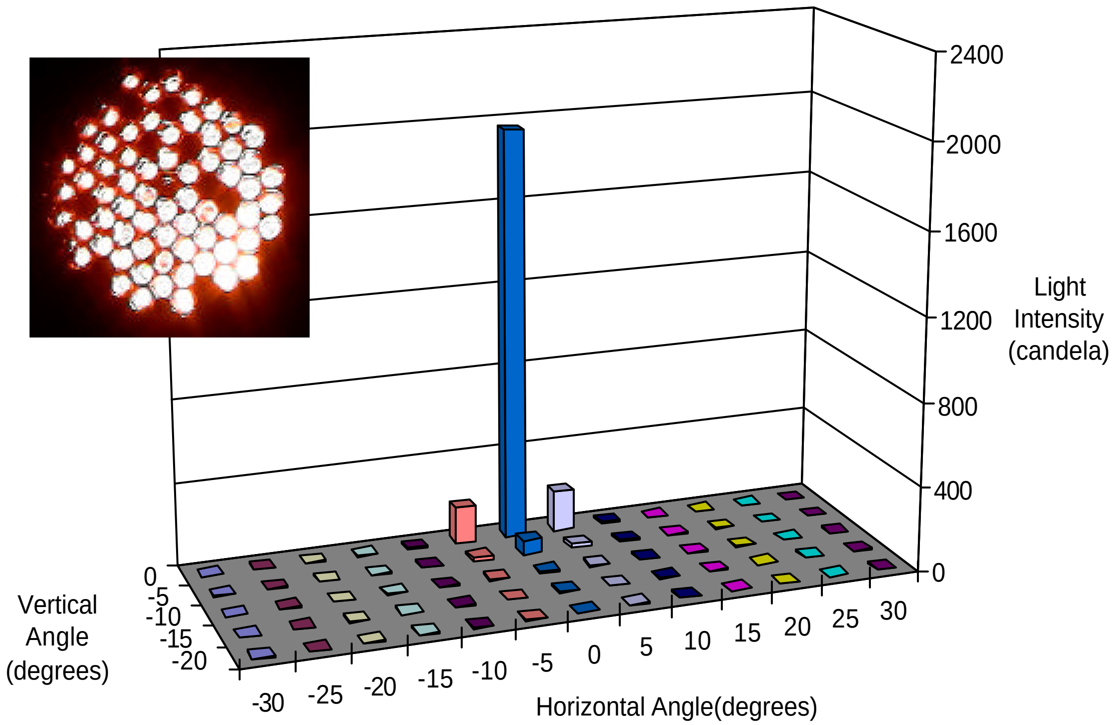

Figure A8.4.16a Output from WPS #8 (Yellow) signal, 10.0 volts, 68 elements (77% on), TC test.

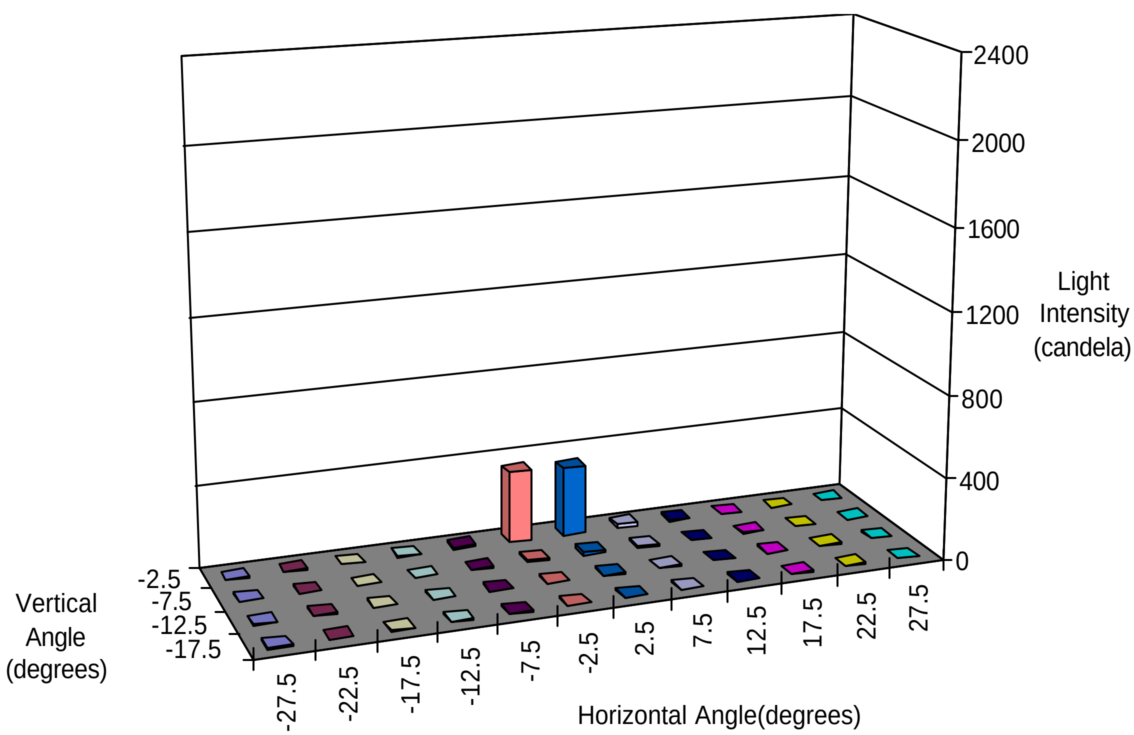

Figure A8.4.16b Output from WPS #8 (Yellow) signal, 10.0 volts, 68 elements (77% on), ITE test.

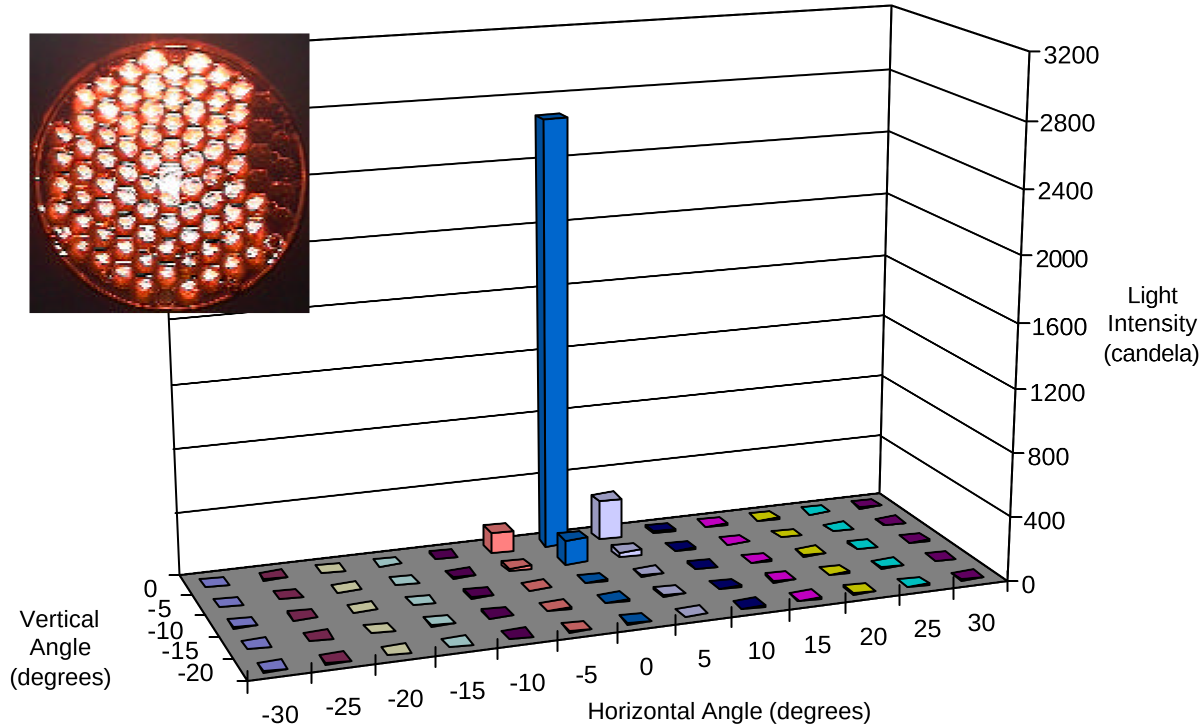

Figure A8.5.1a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

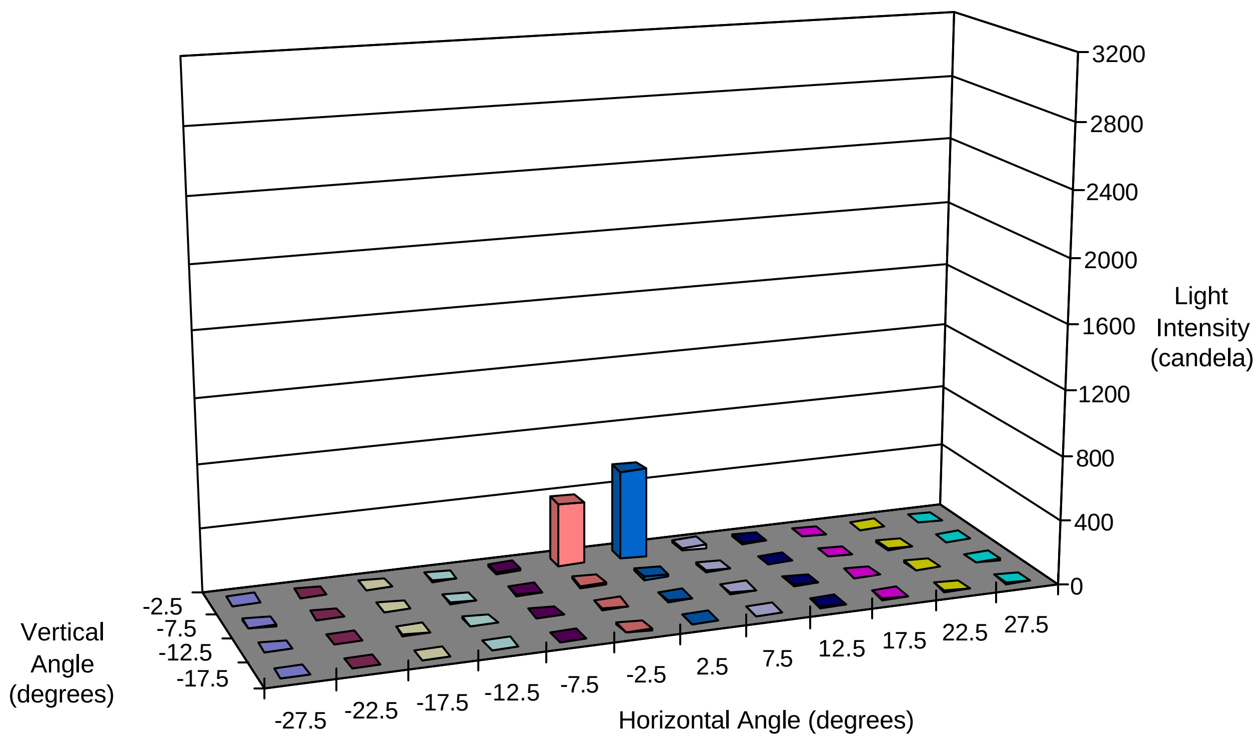

Figure A8.5.1b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

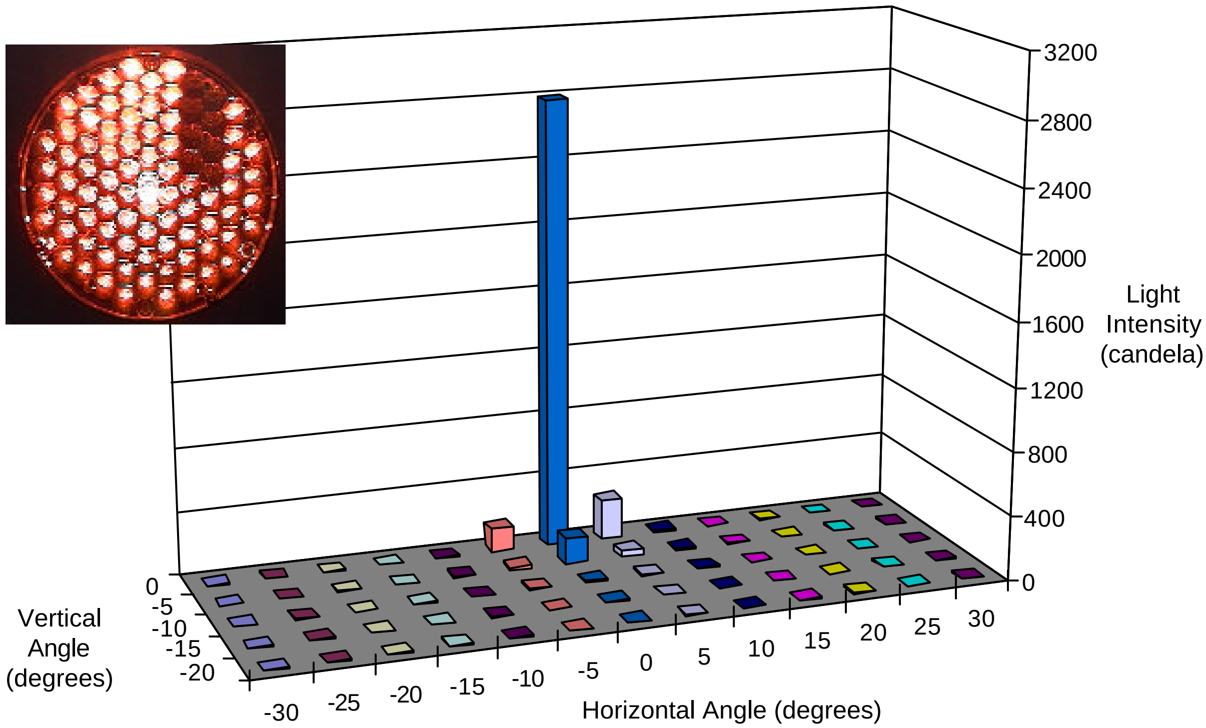

Figure A8.5.2a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

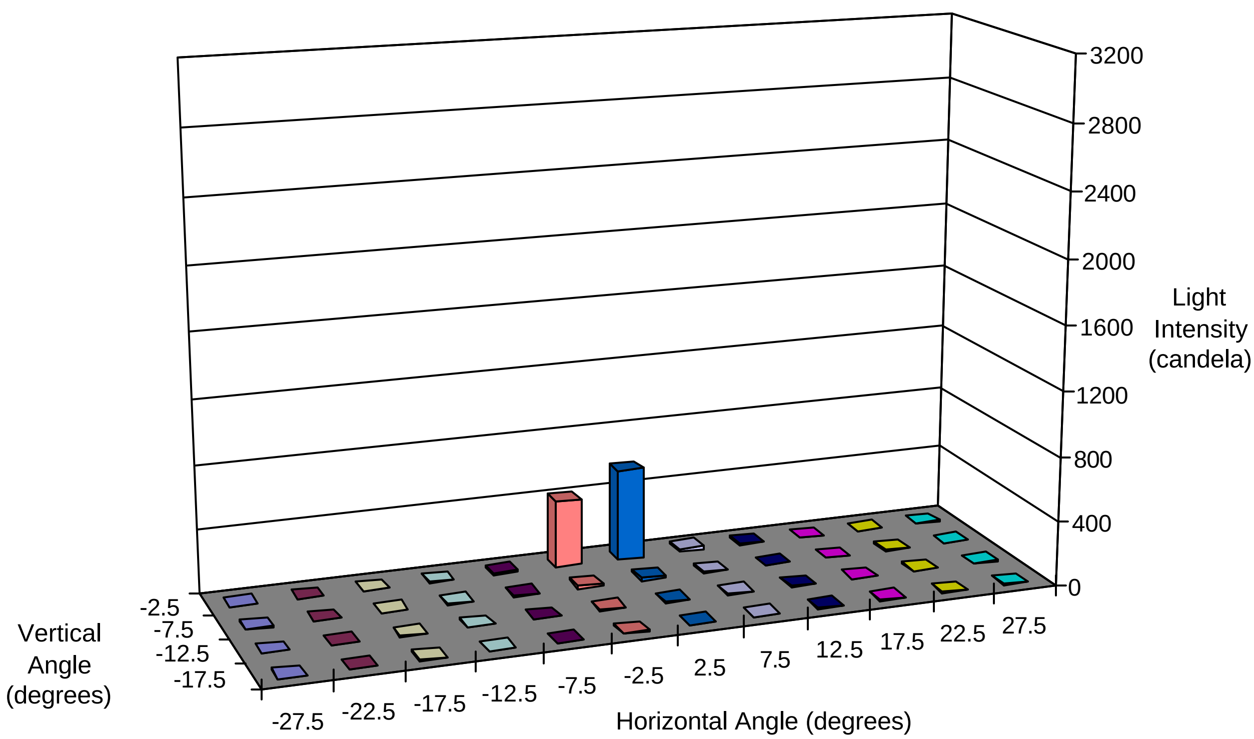

Figure A8.5.2b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

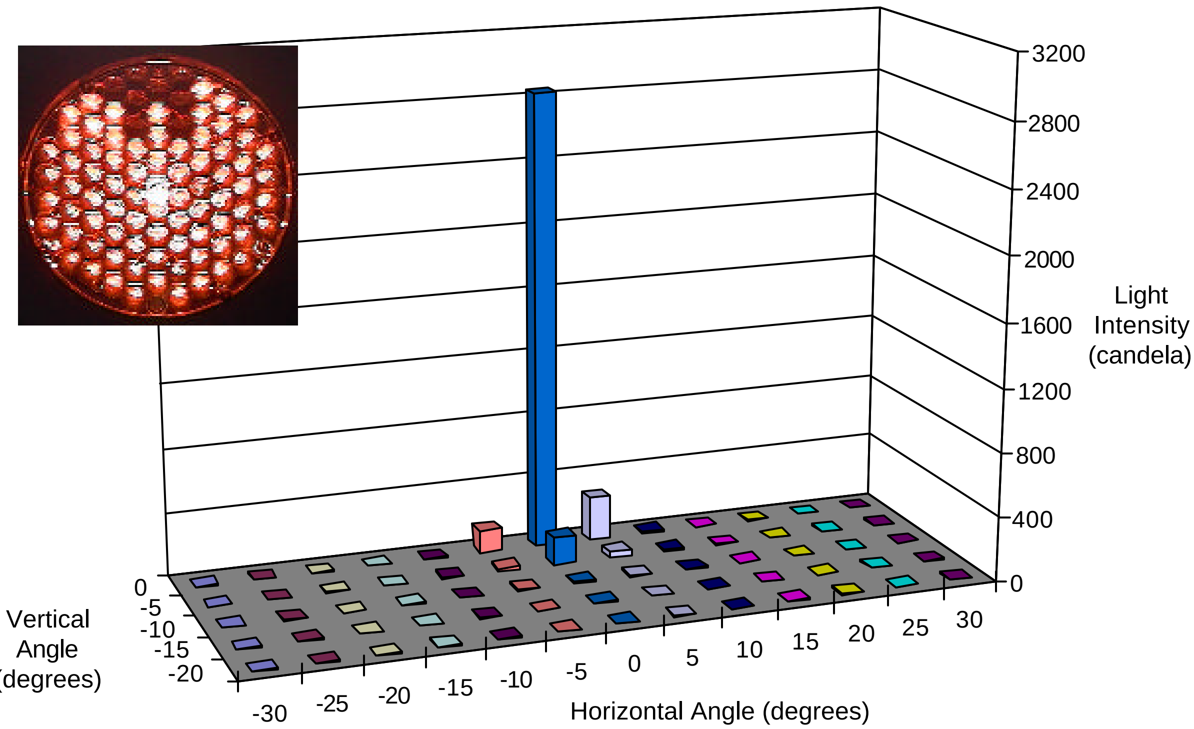

Figure A8.5.3a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

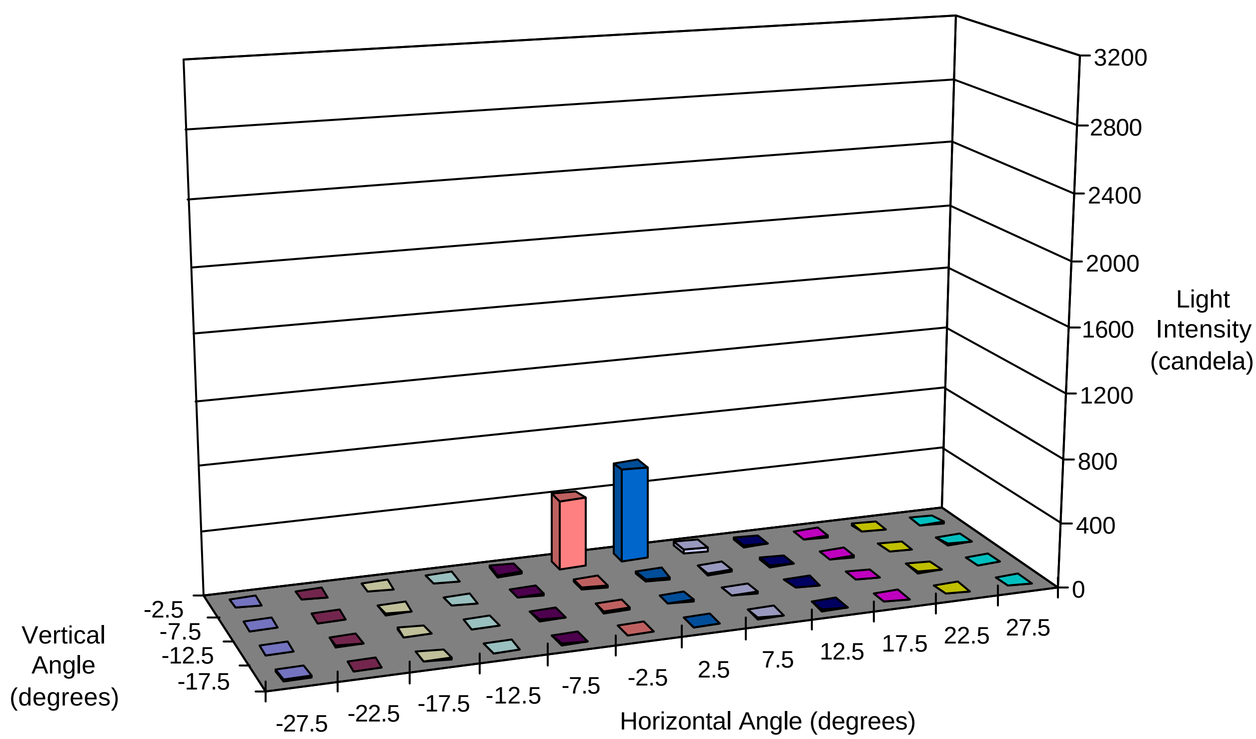

Figure A8.5.3b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

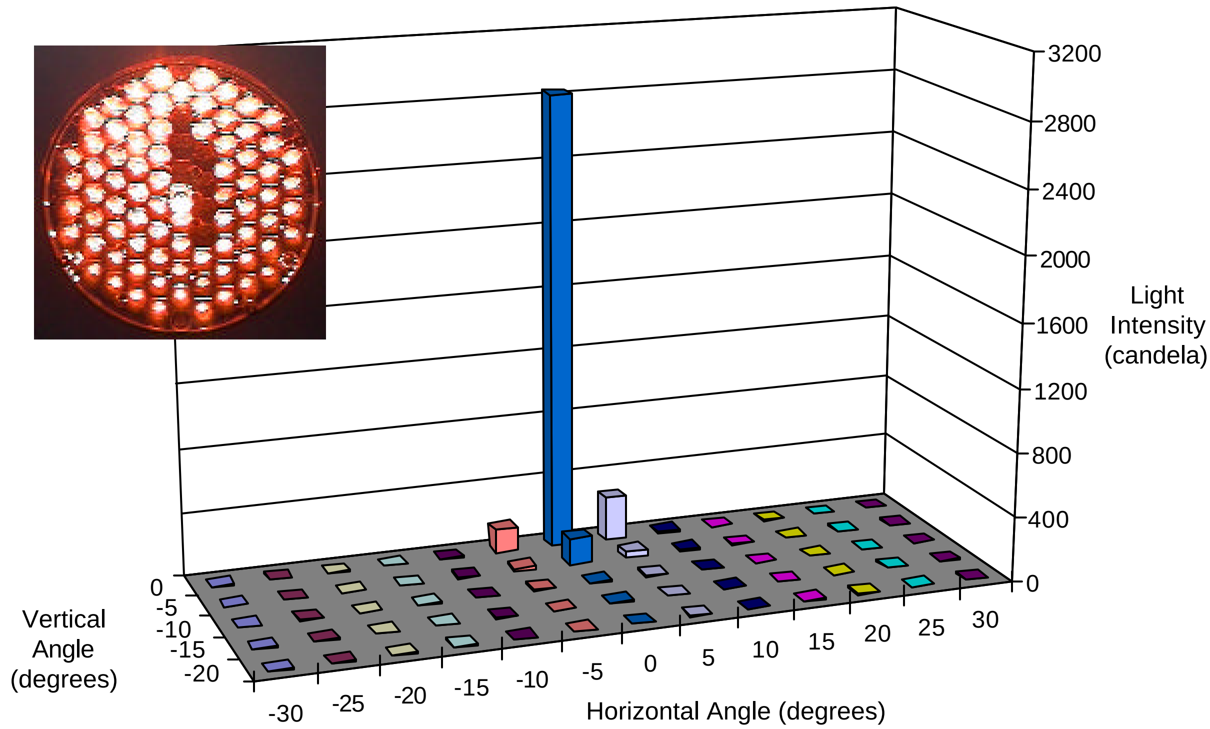

Figure A8.5.4a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

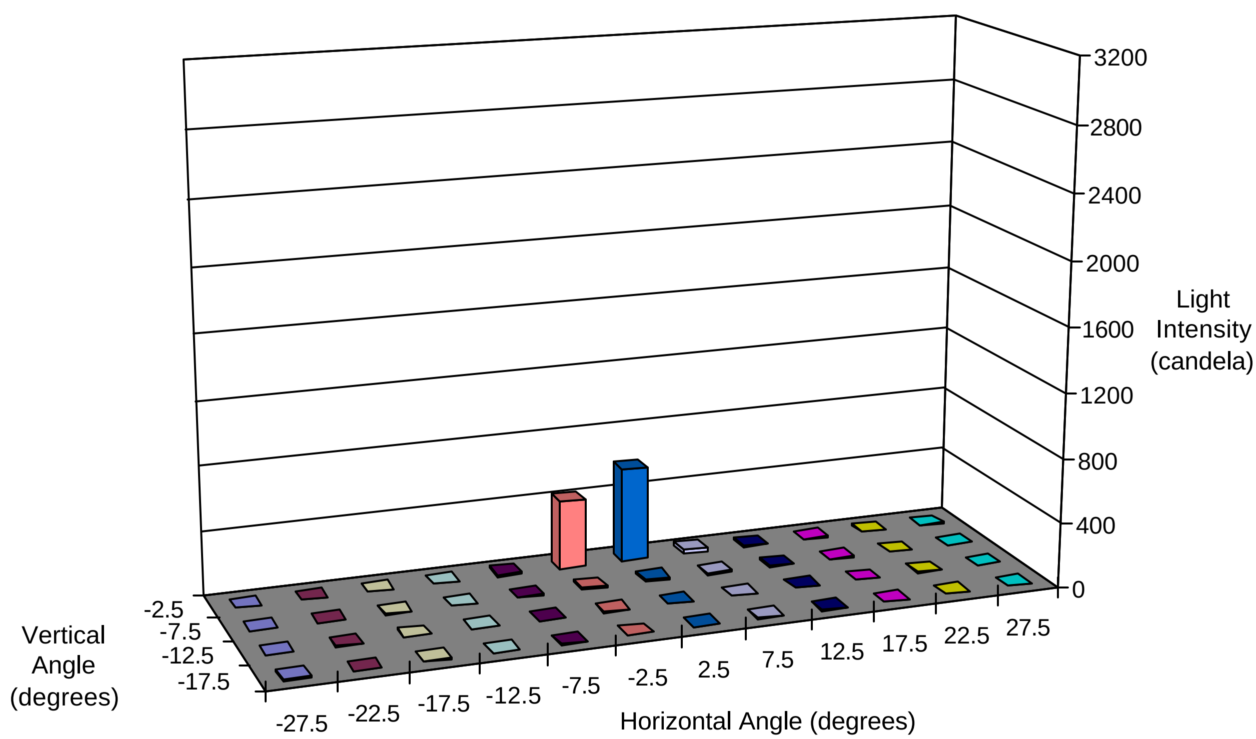

Figure A8.5.4b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

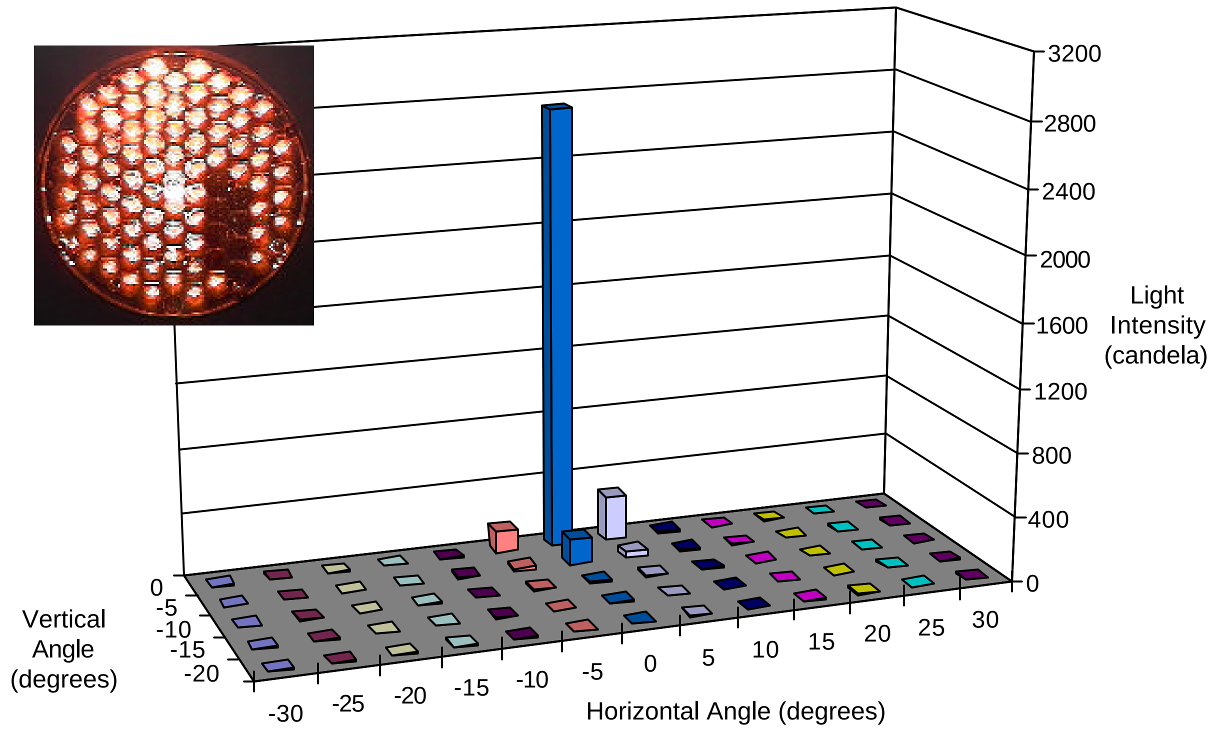

Figure A8.5.5a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

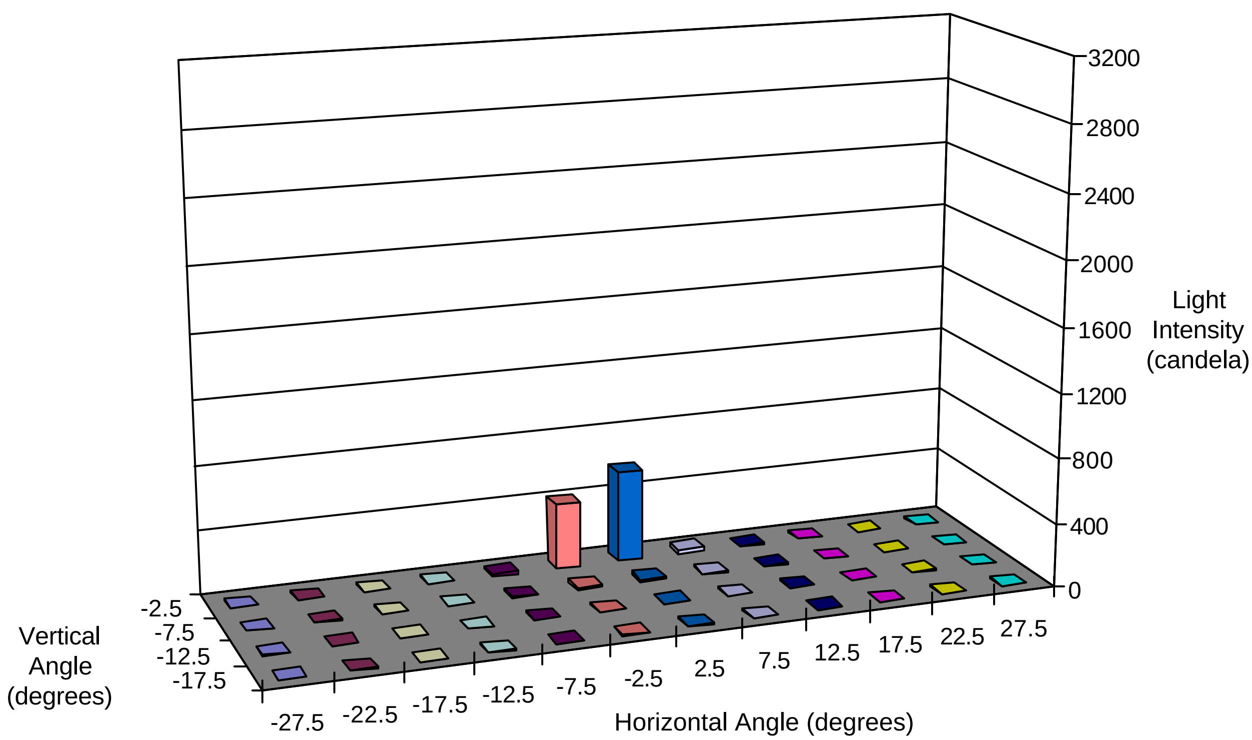

Figure A8.5.5b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

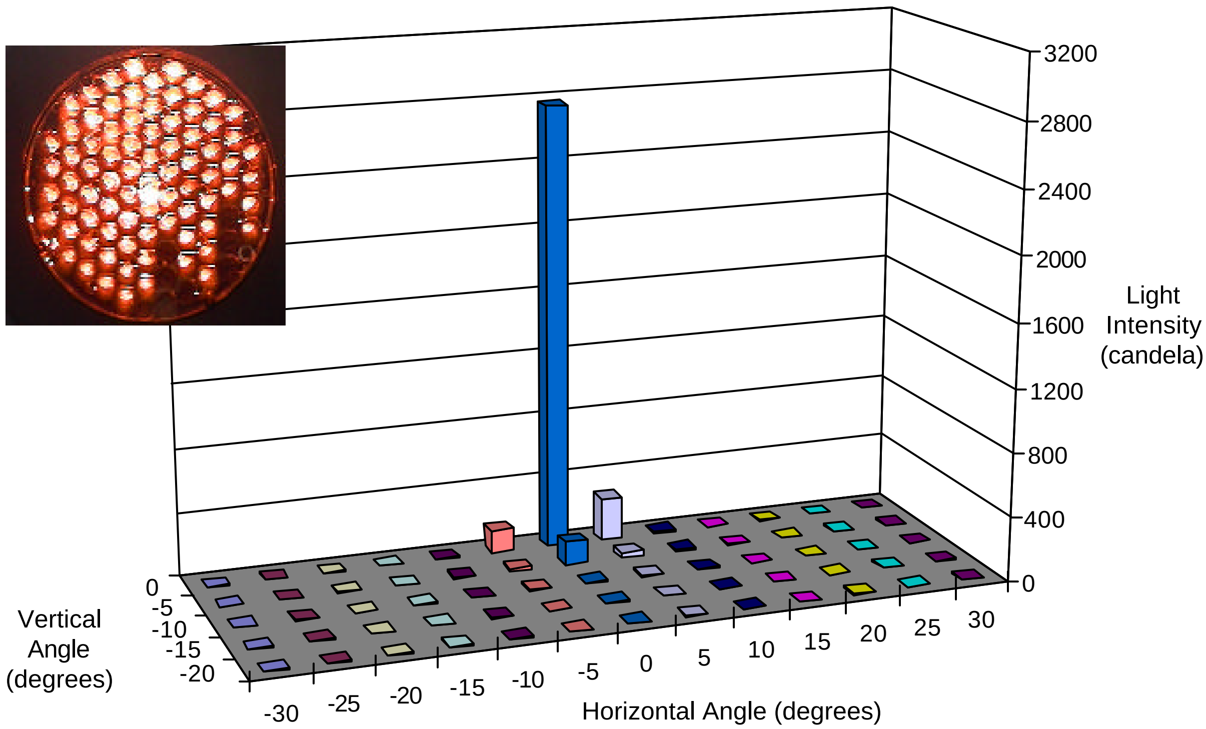

Figure A8.5.6a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

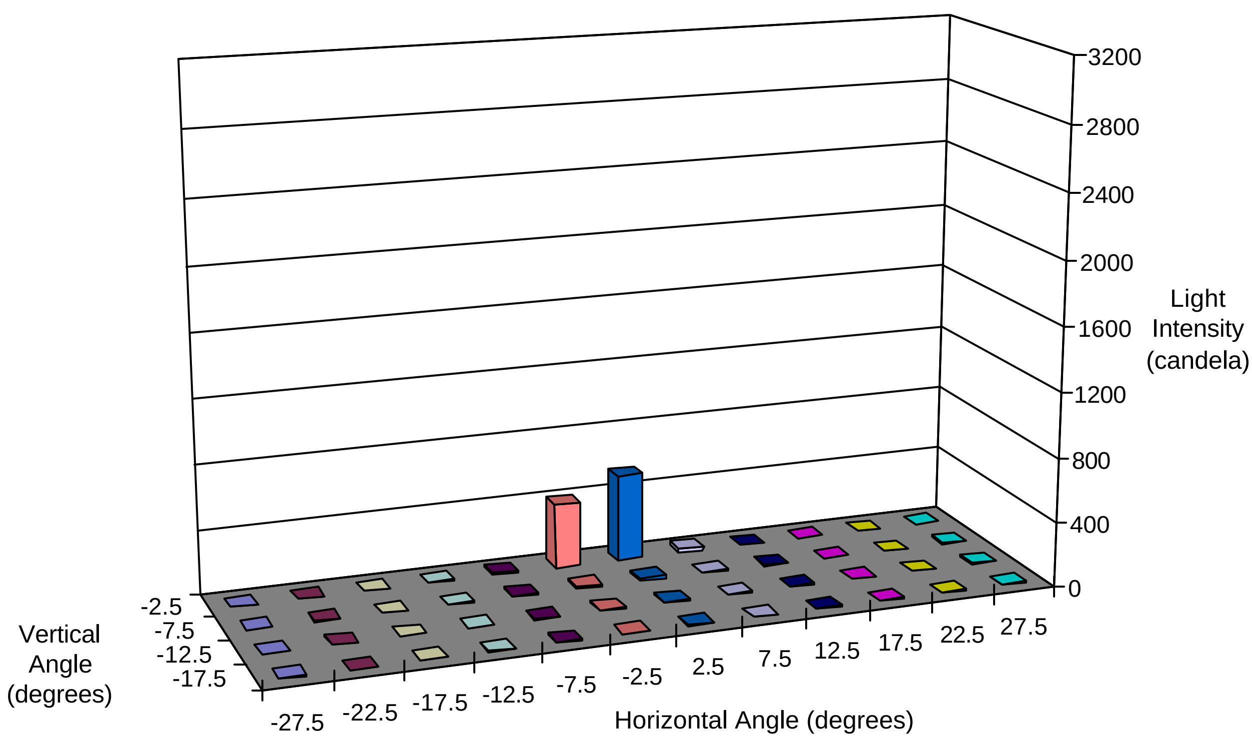

Figure A8.5.6b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

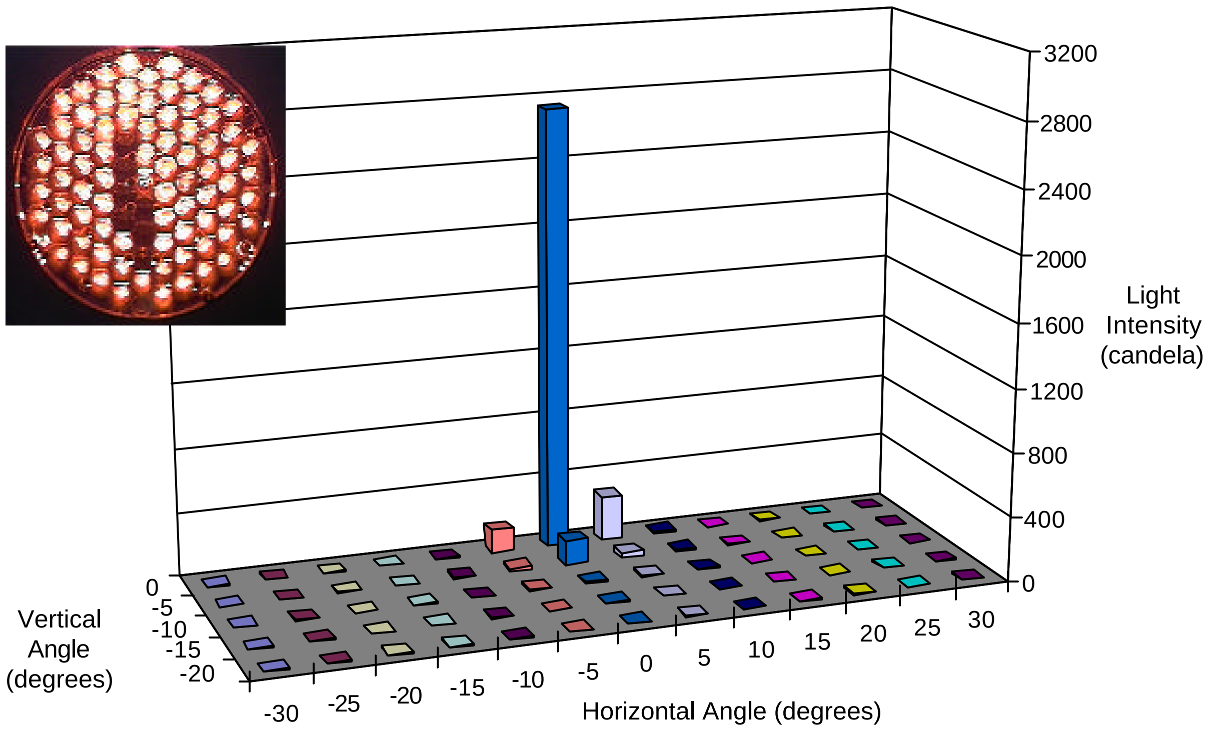

Figure A8.5.7a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

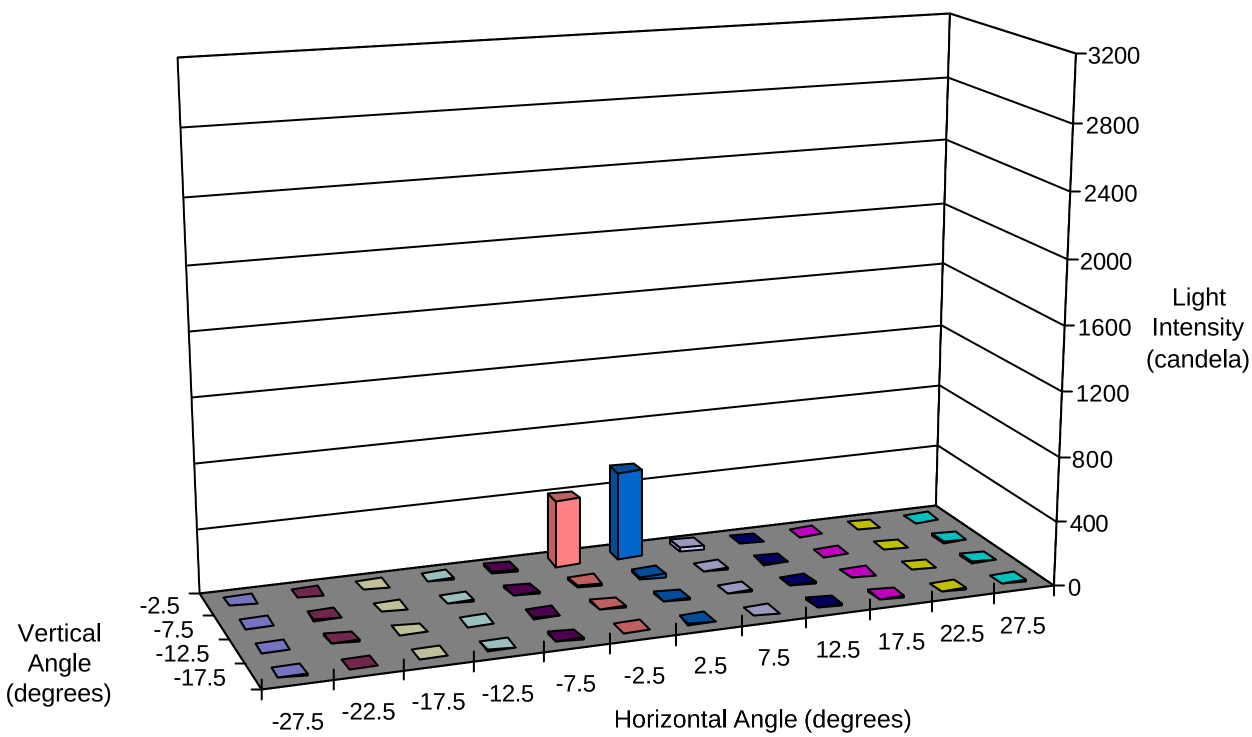

Figure A8.5.7b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

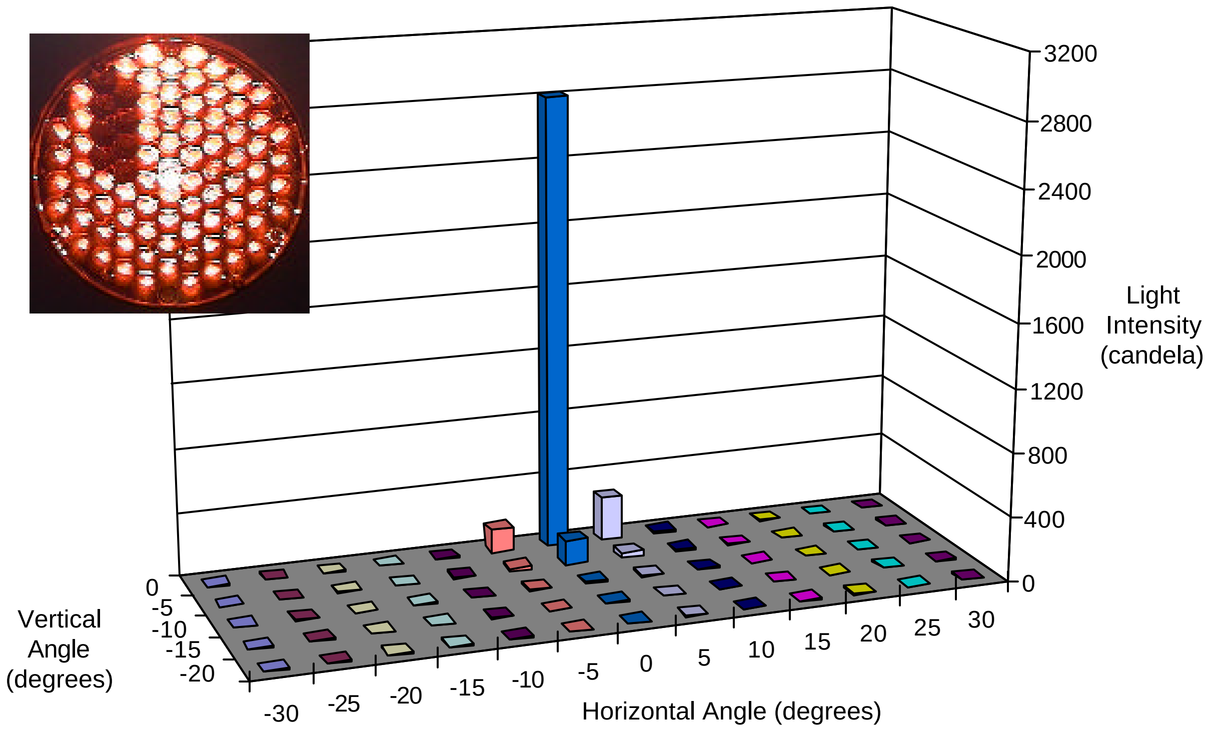

Figure A8.5.8a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

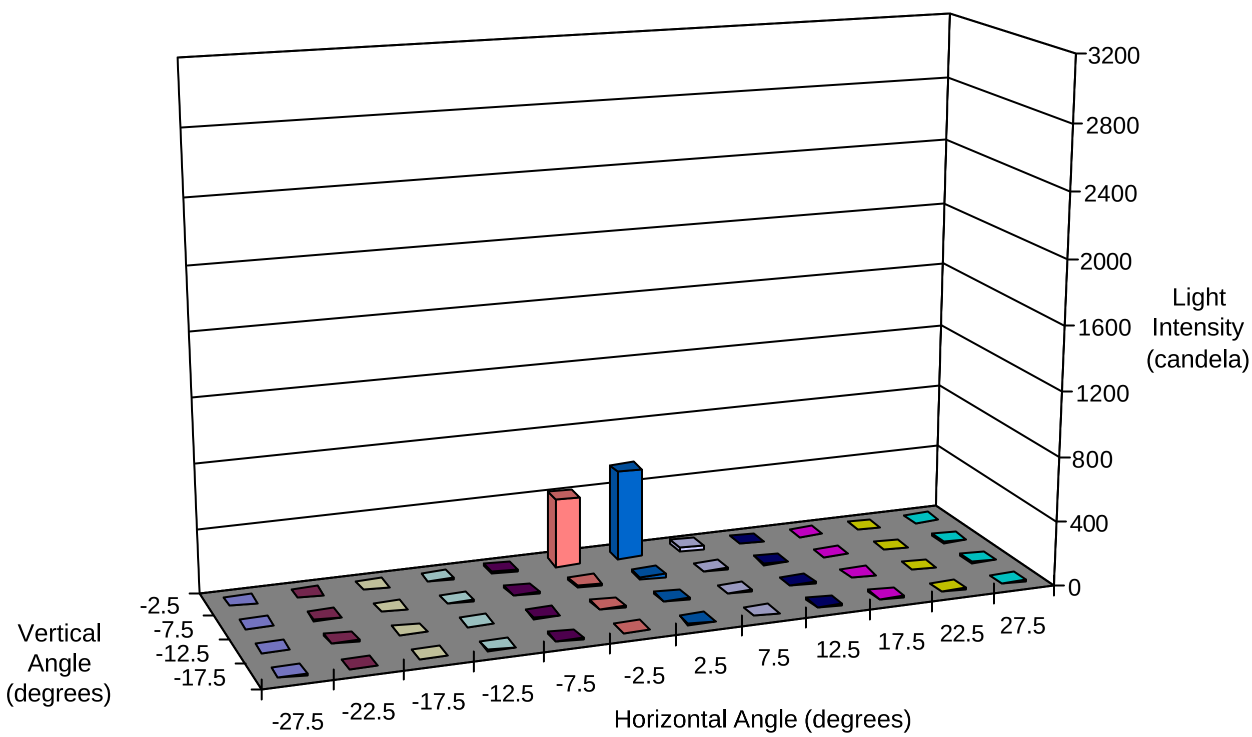

Figure A8.5.8b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

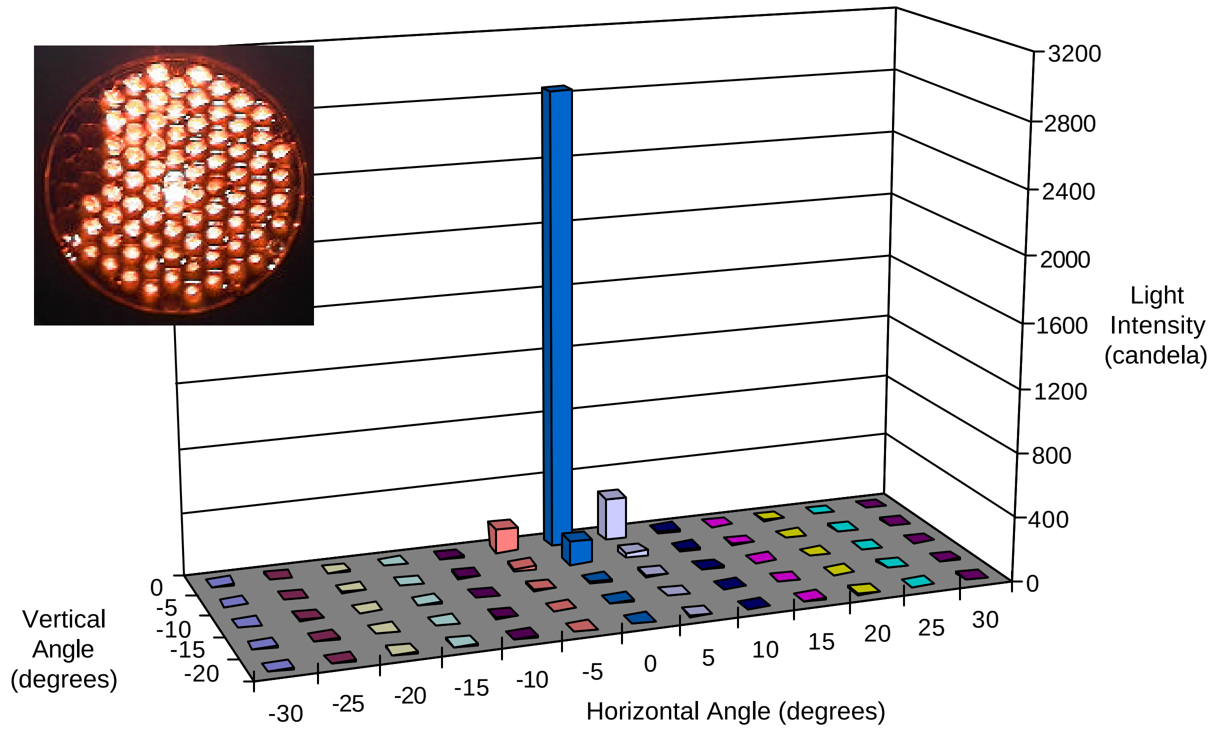

Figure A8.5.9a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

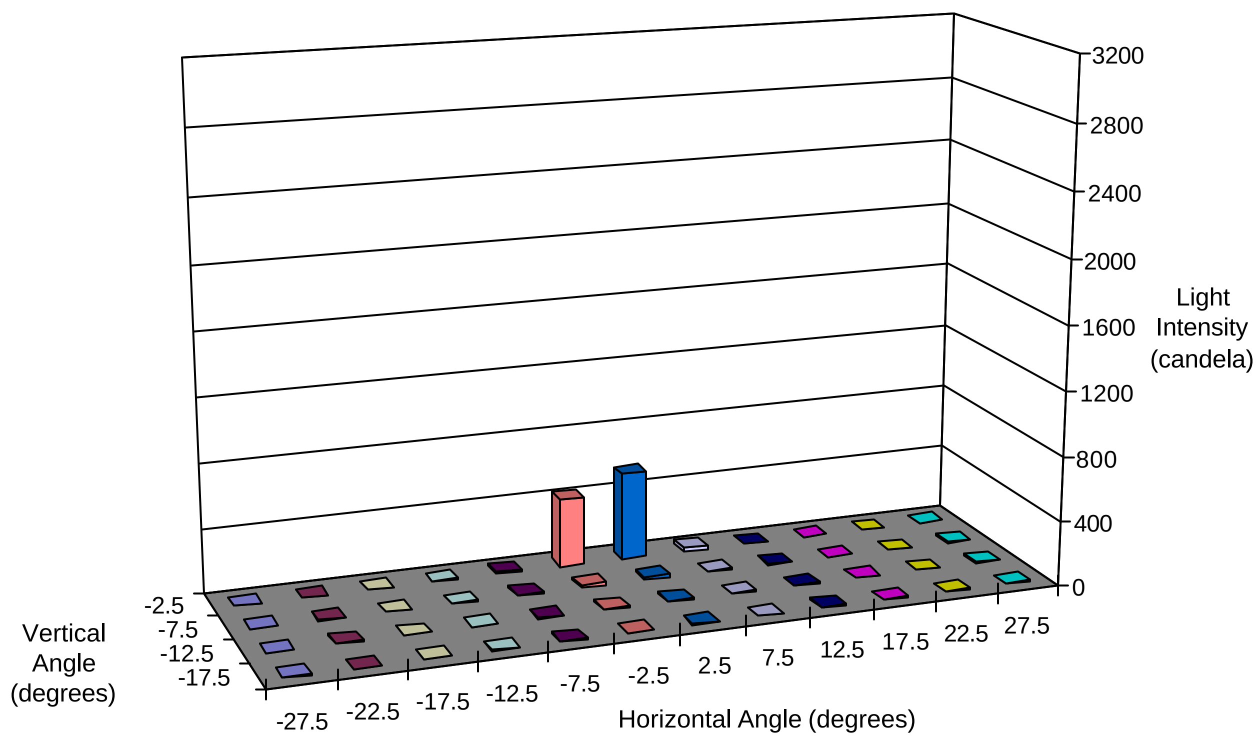

Figure A8.5.9b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

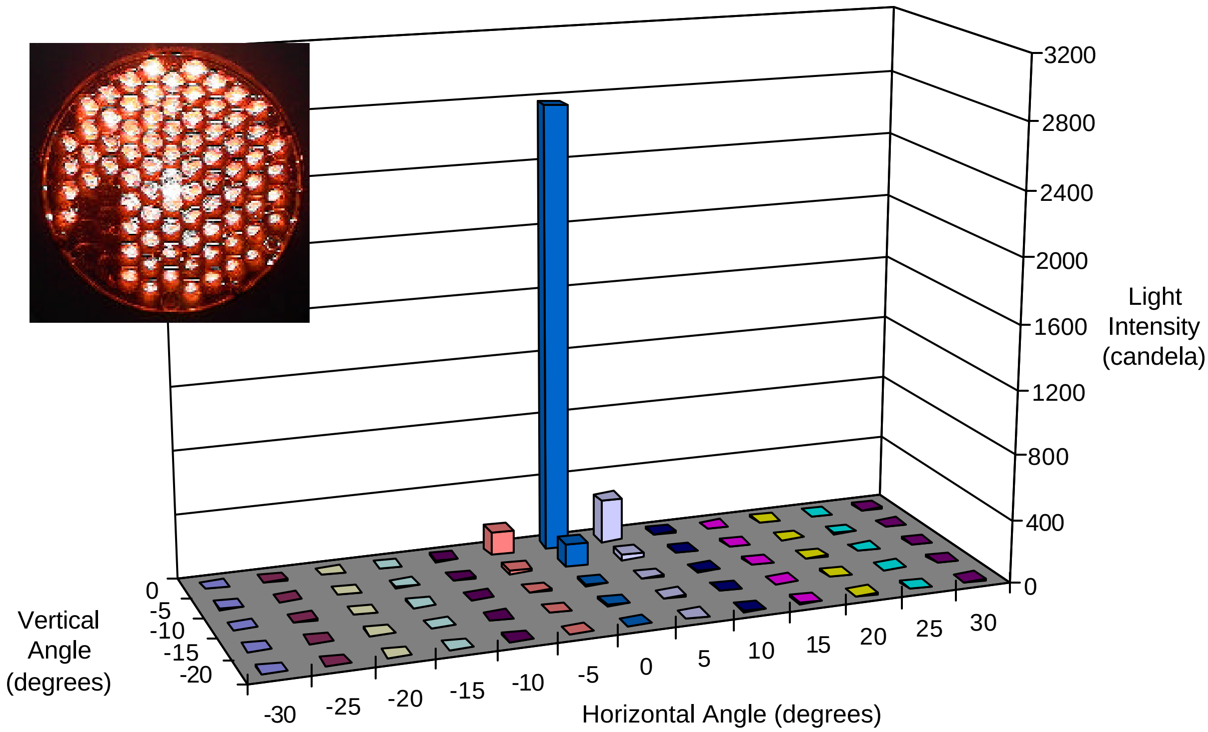

Figure A8.5.10a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

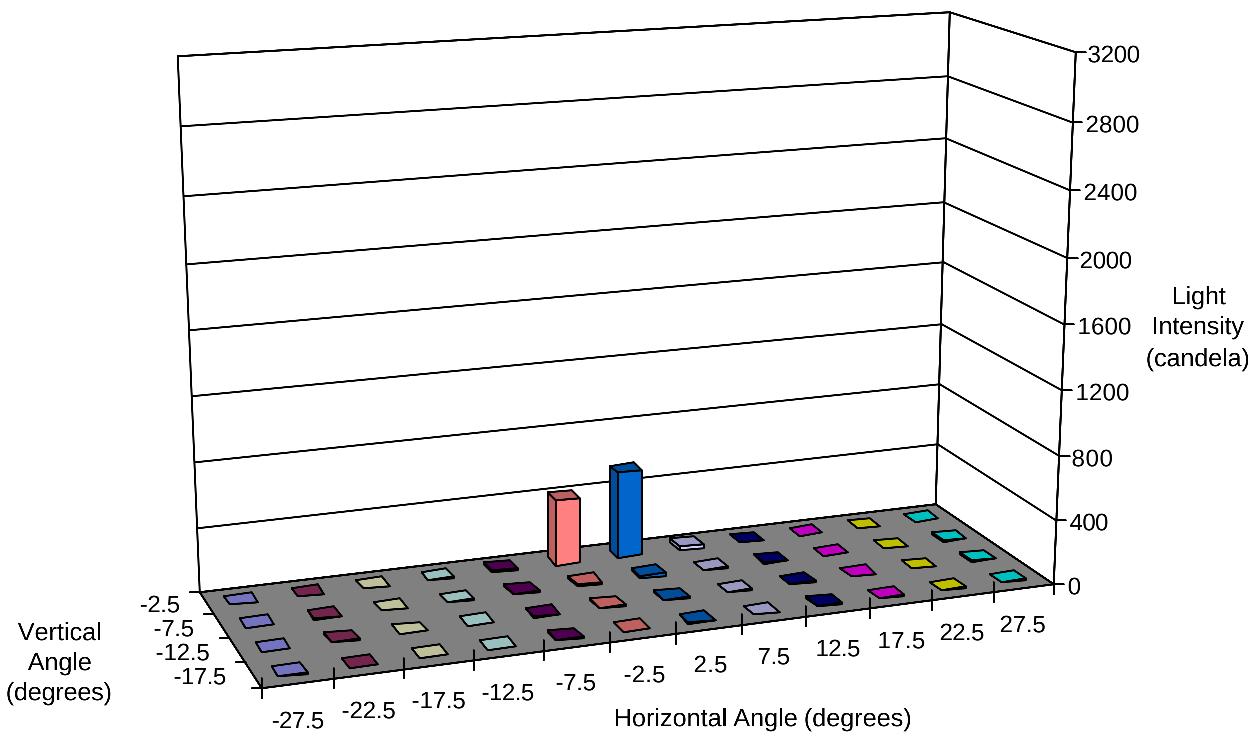

Figure A8.5.10b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

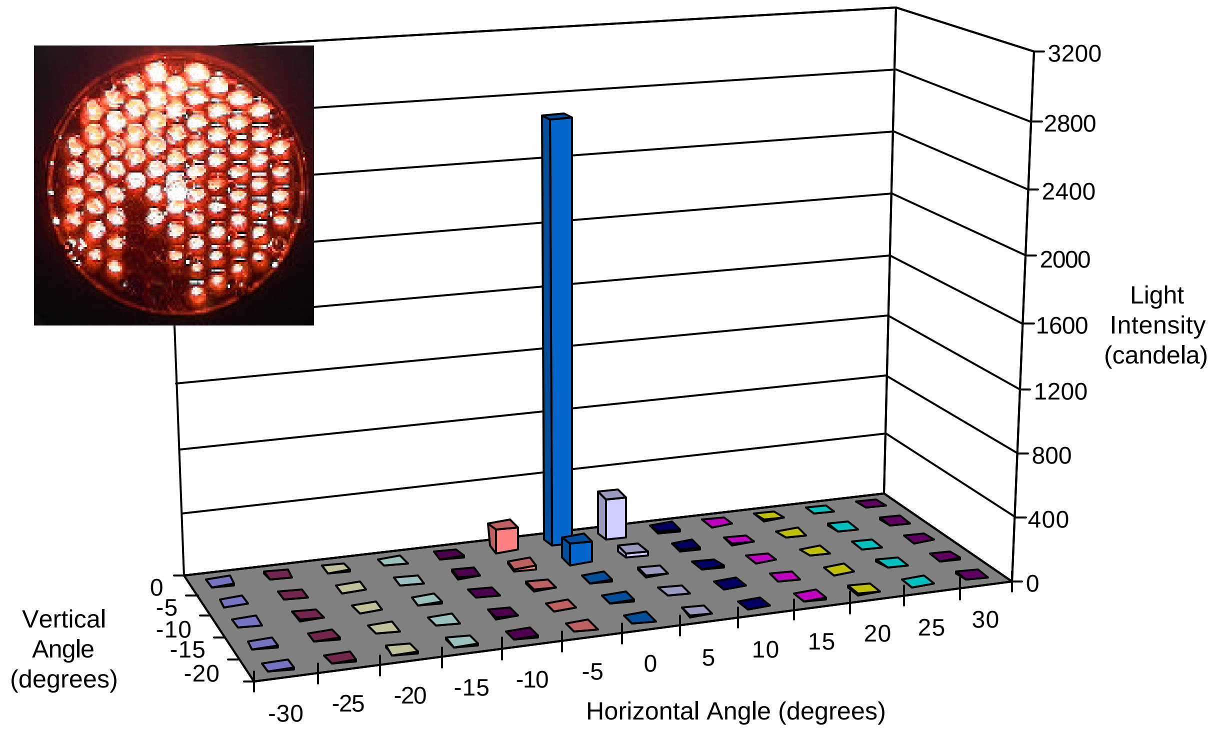

Figure A8.5.11a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

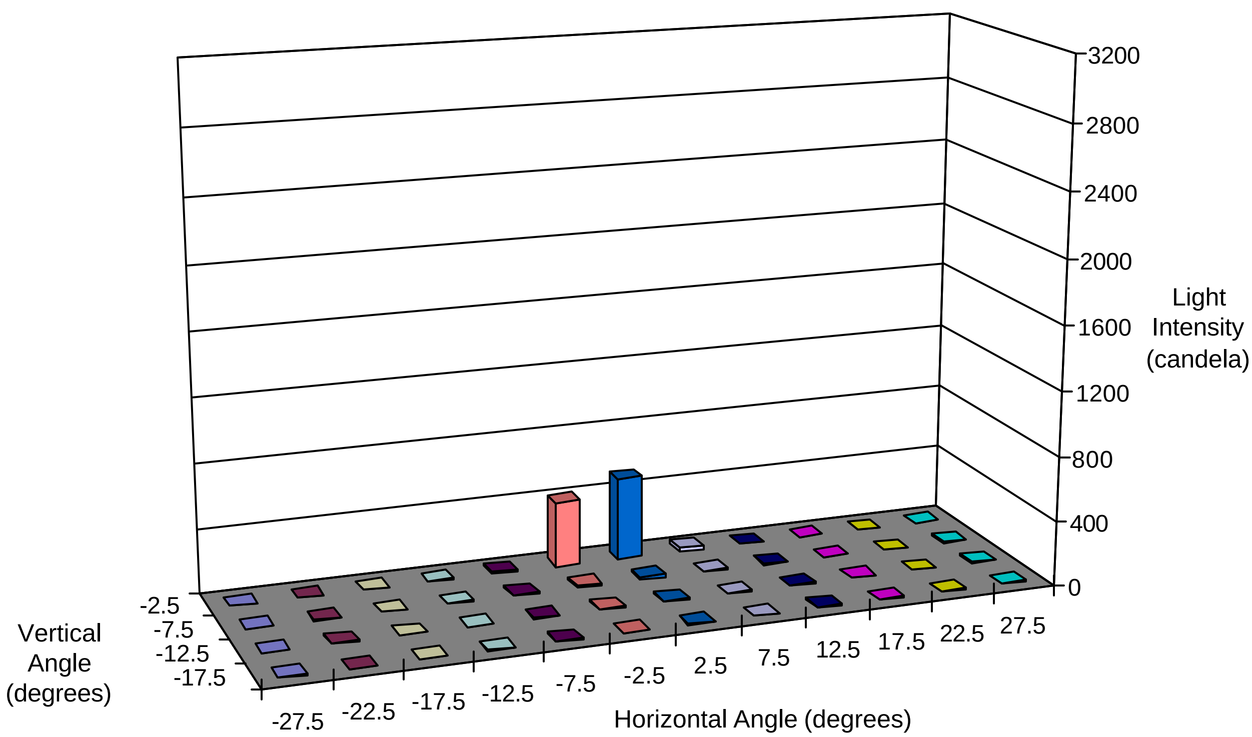

Figure A8.5.11b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

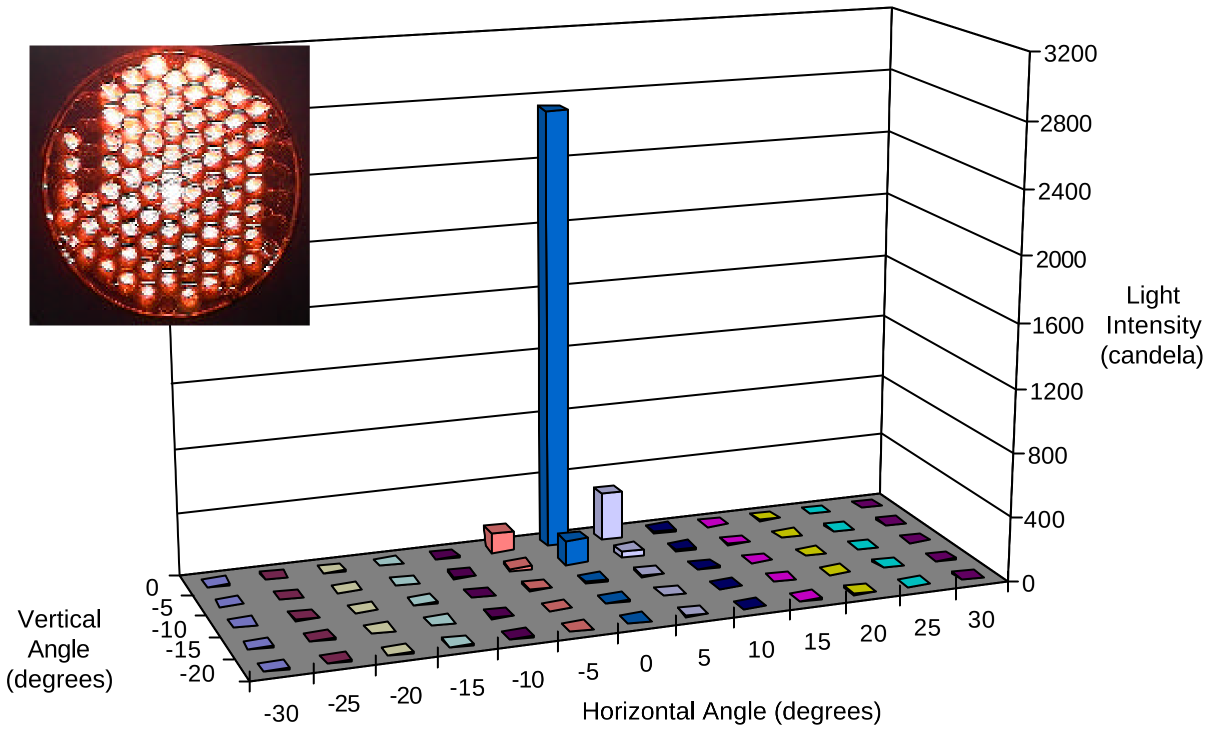

Figure A8.5.12a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

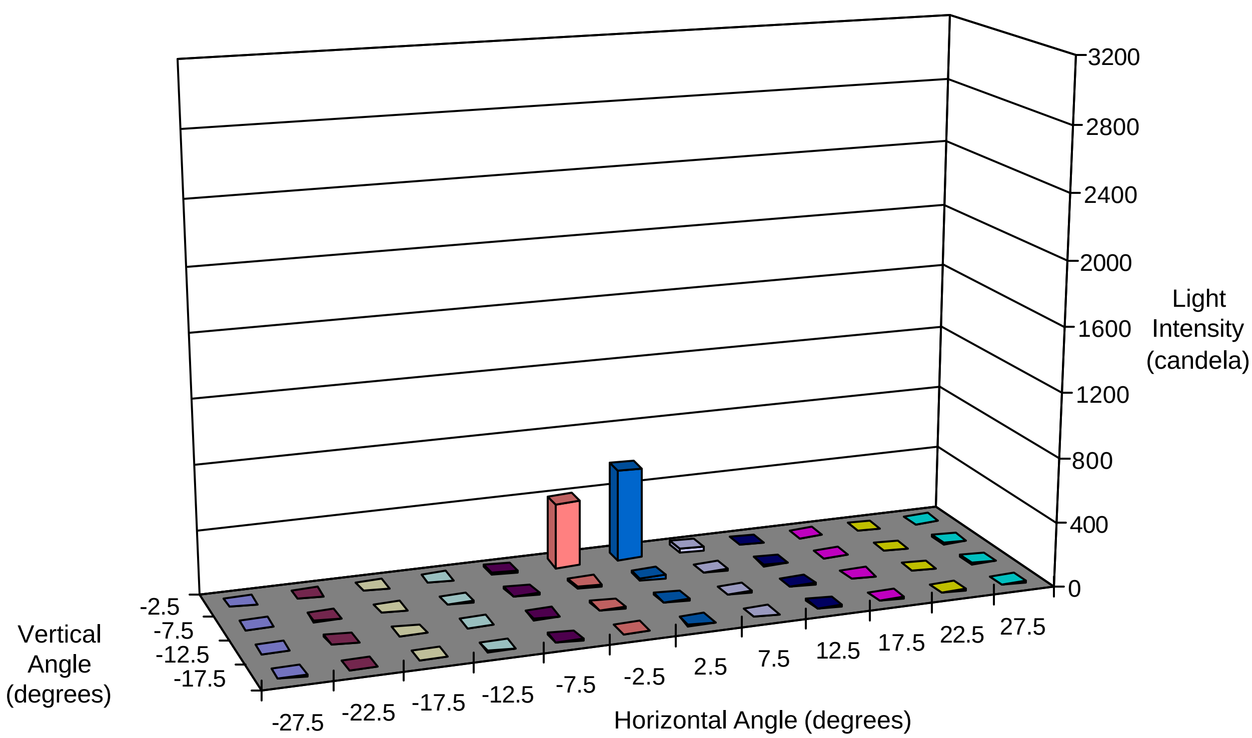

Figure A8.5.12b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

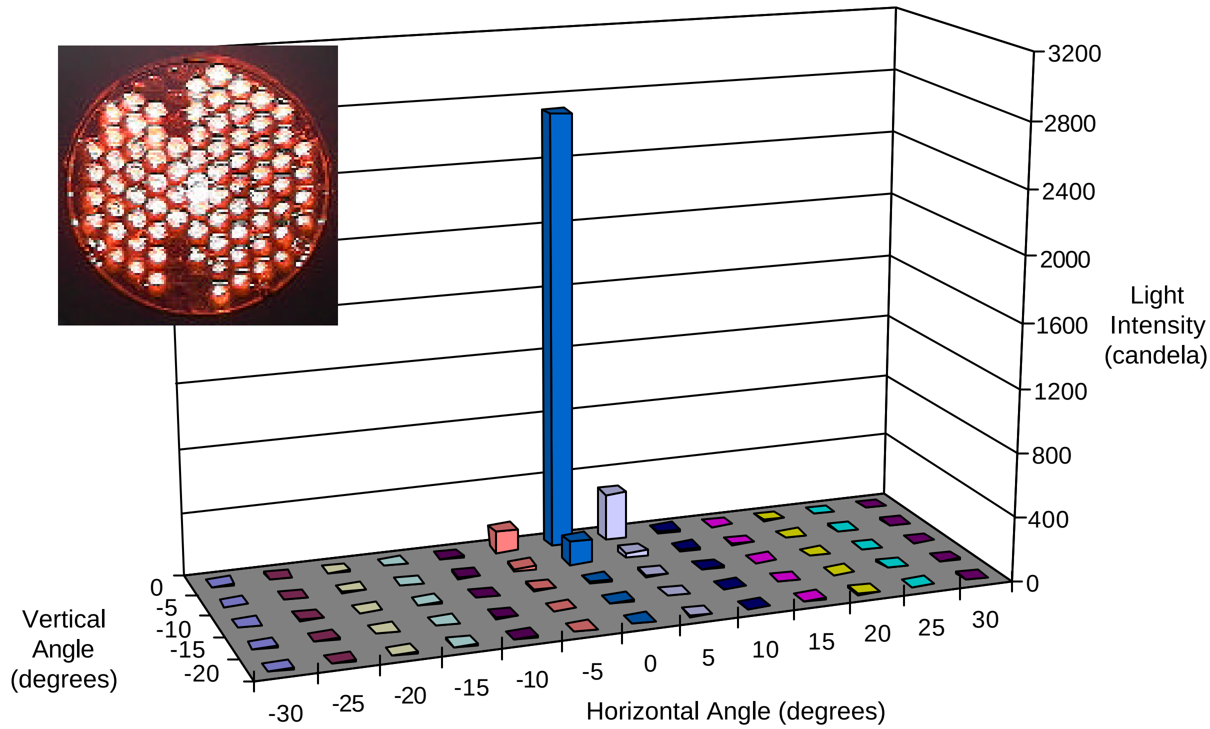

Figure A8.5.13a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

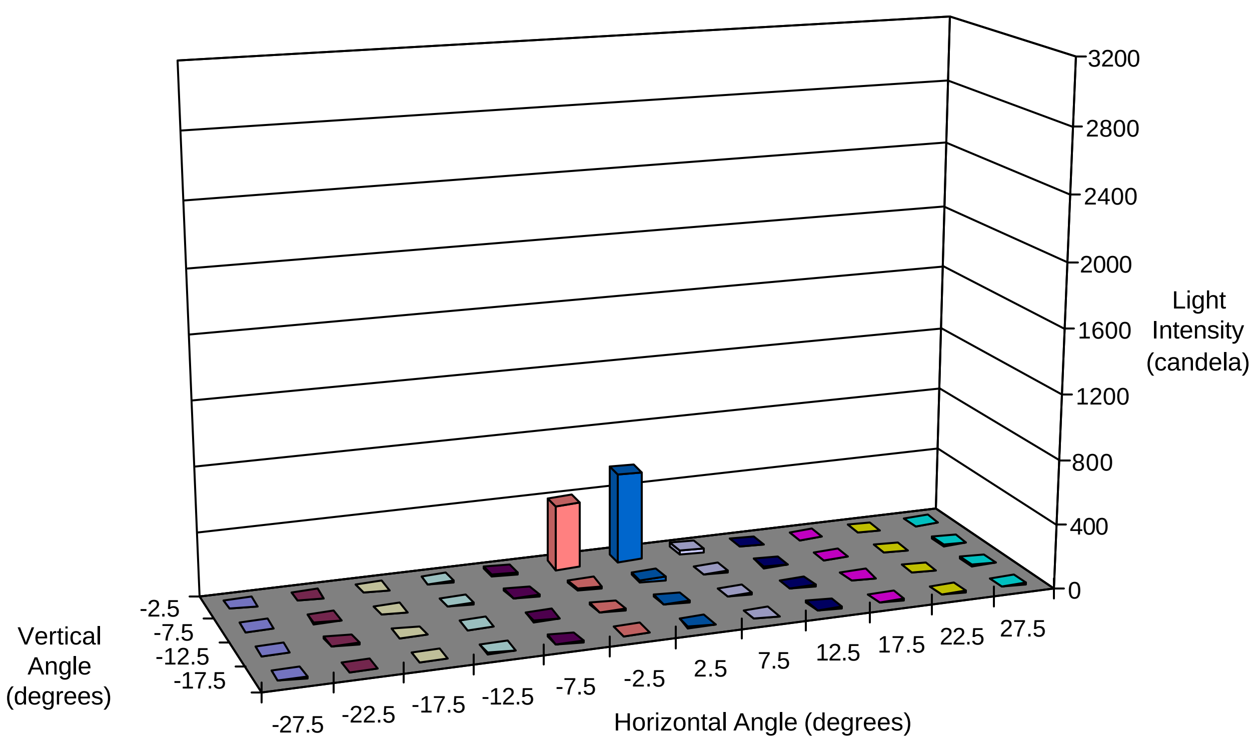

Figure A8.5.13b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

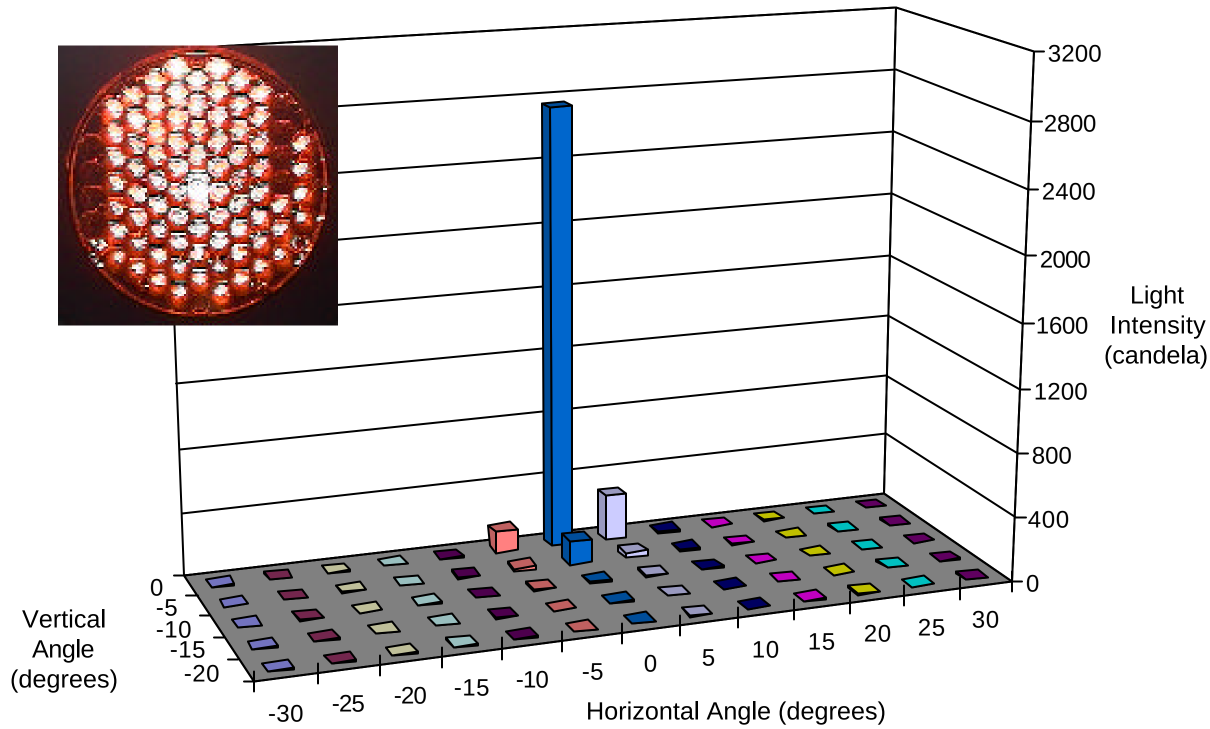

Figure A8.5.14a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

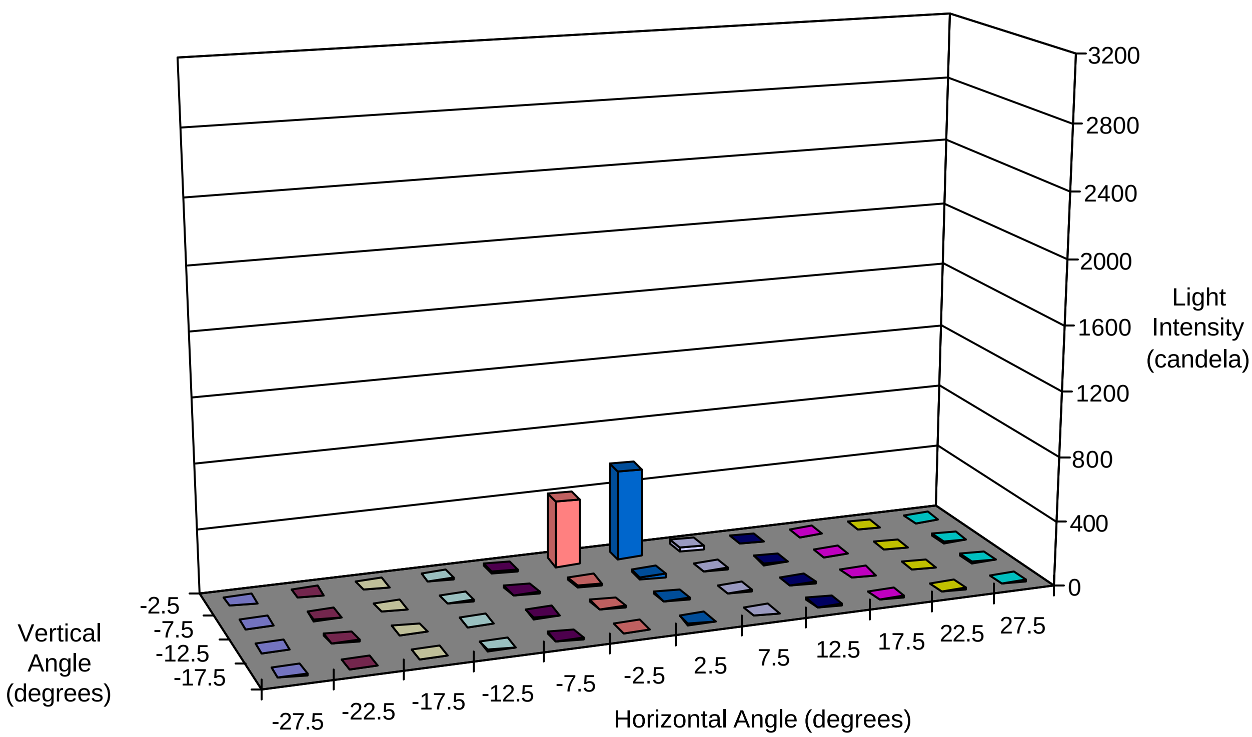

Figure A8.5.14b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

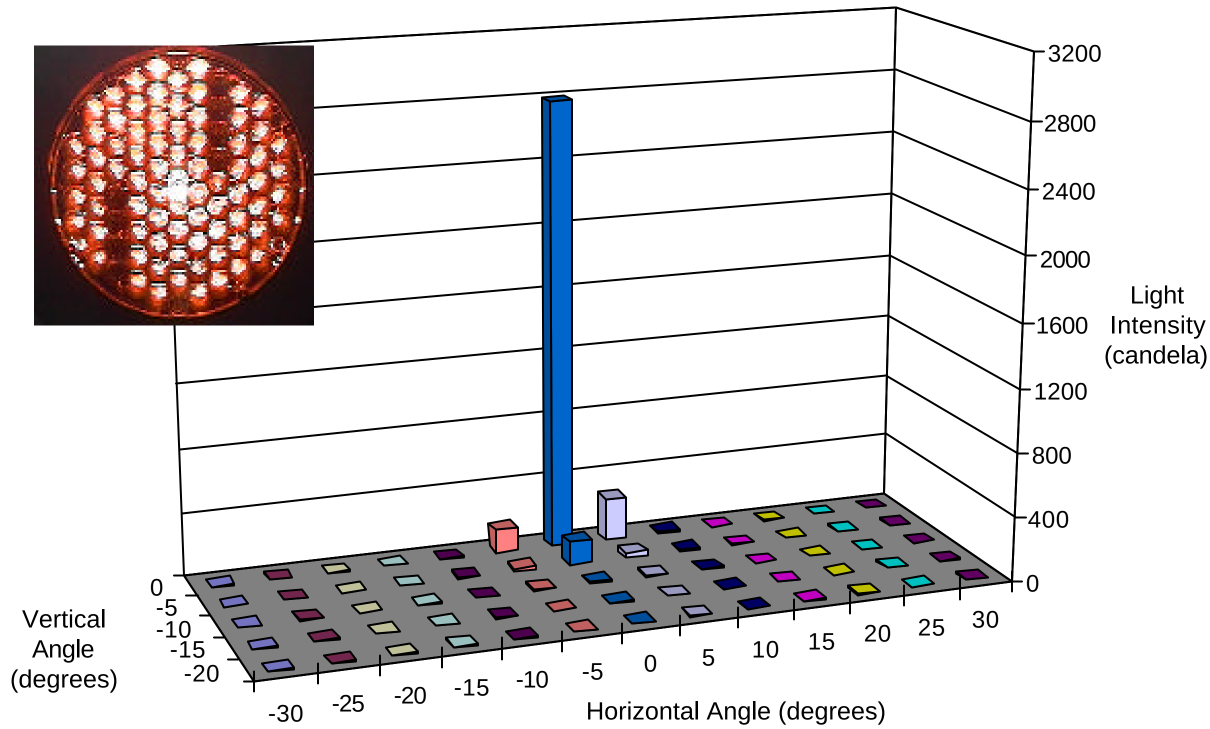

Figure A8.5.15a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

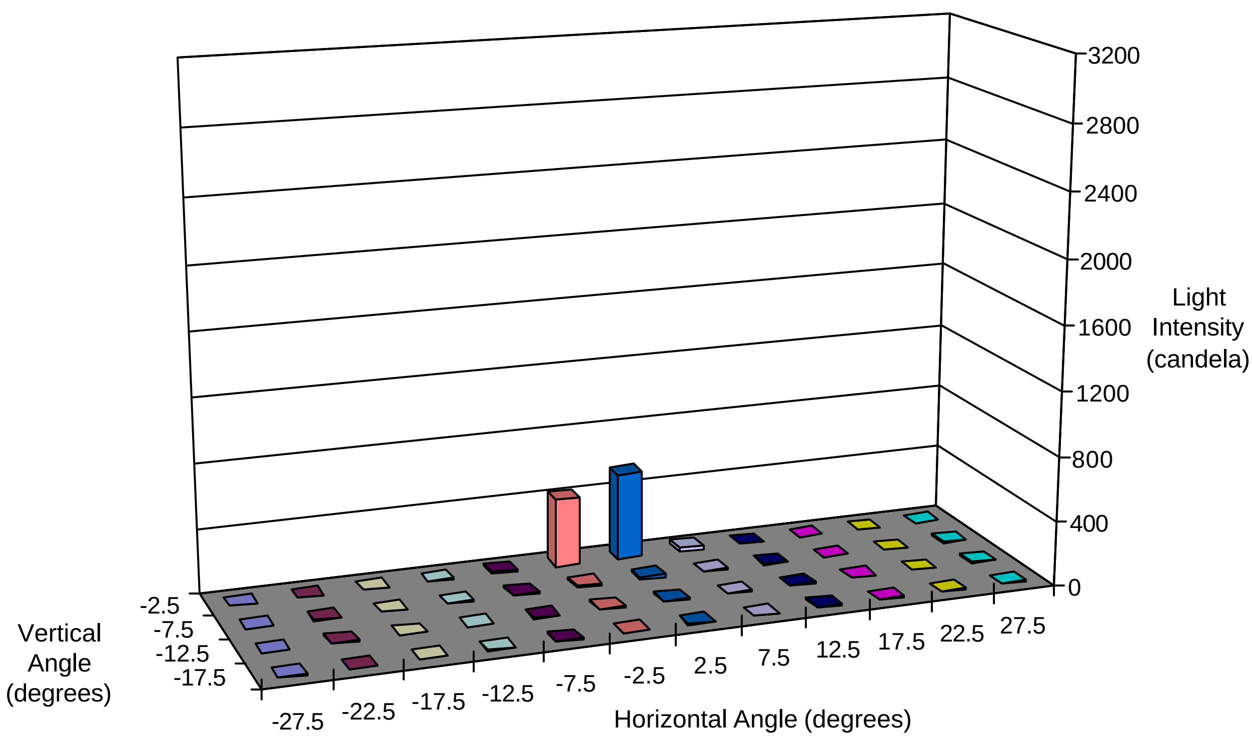

Figure A8.5.15b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

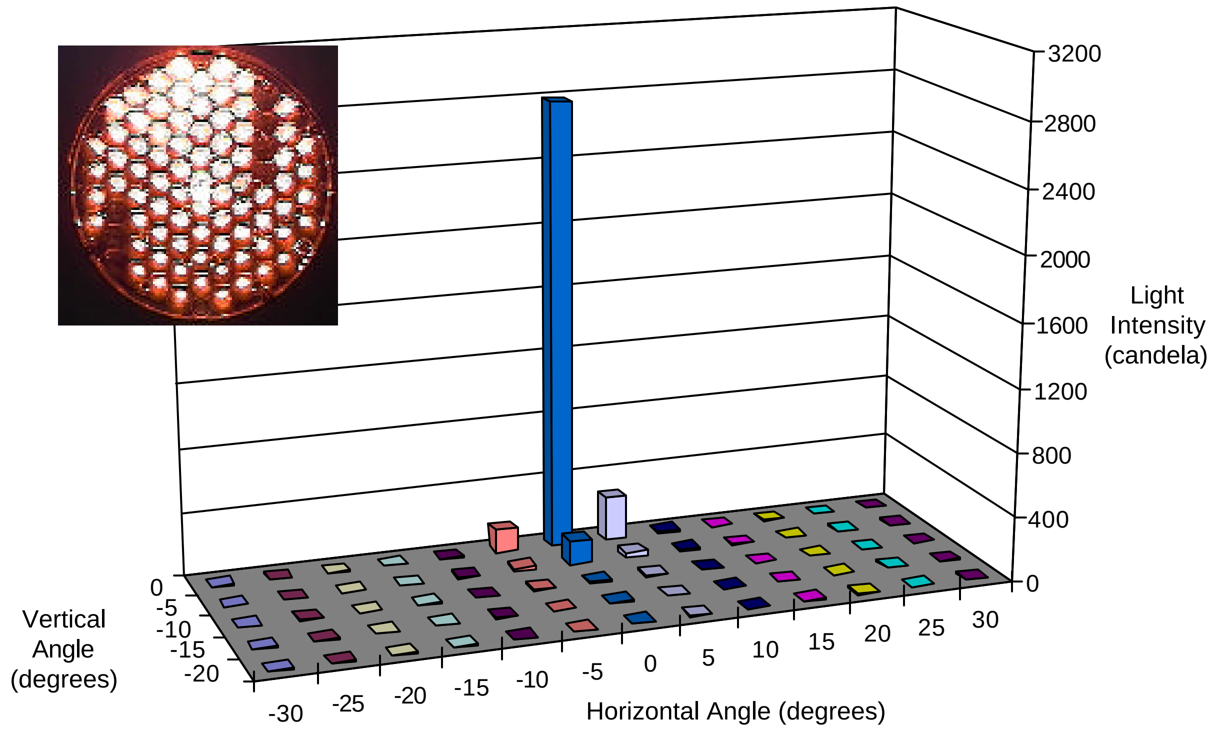

Figure A8.5.16a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

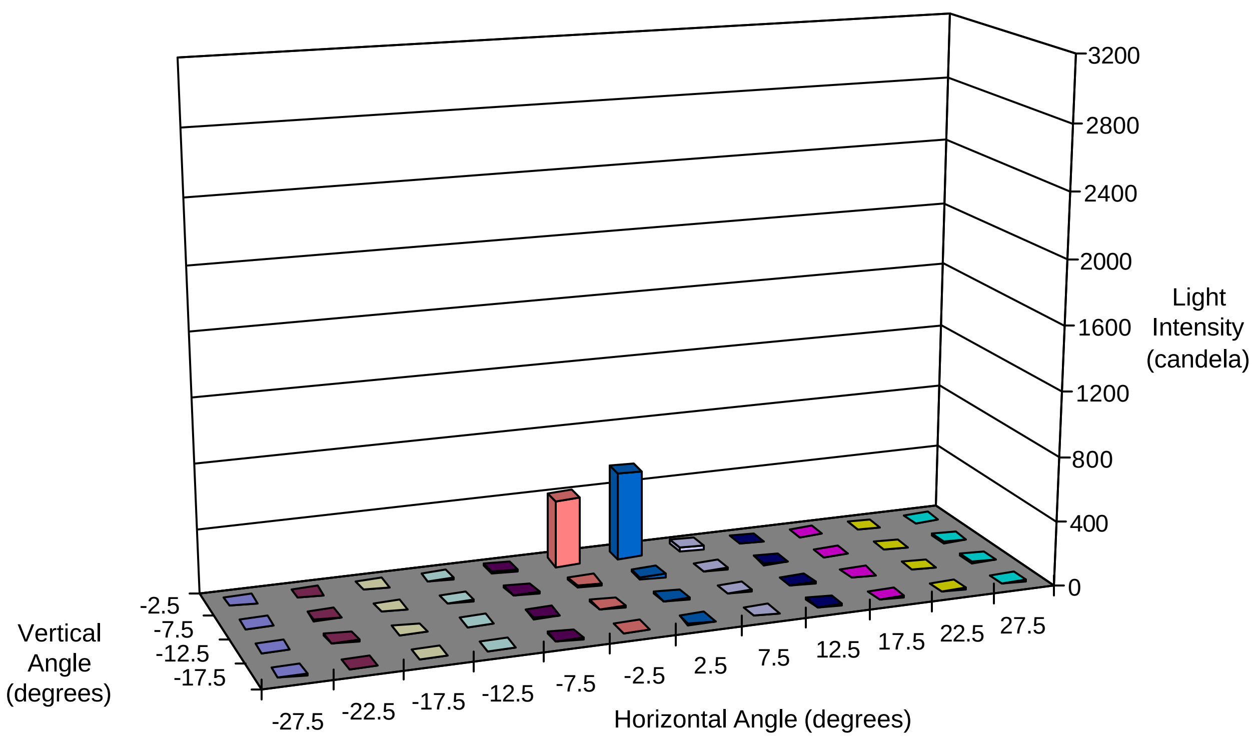

Figure A8.5.16b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

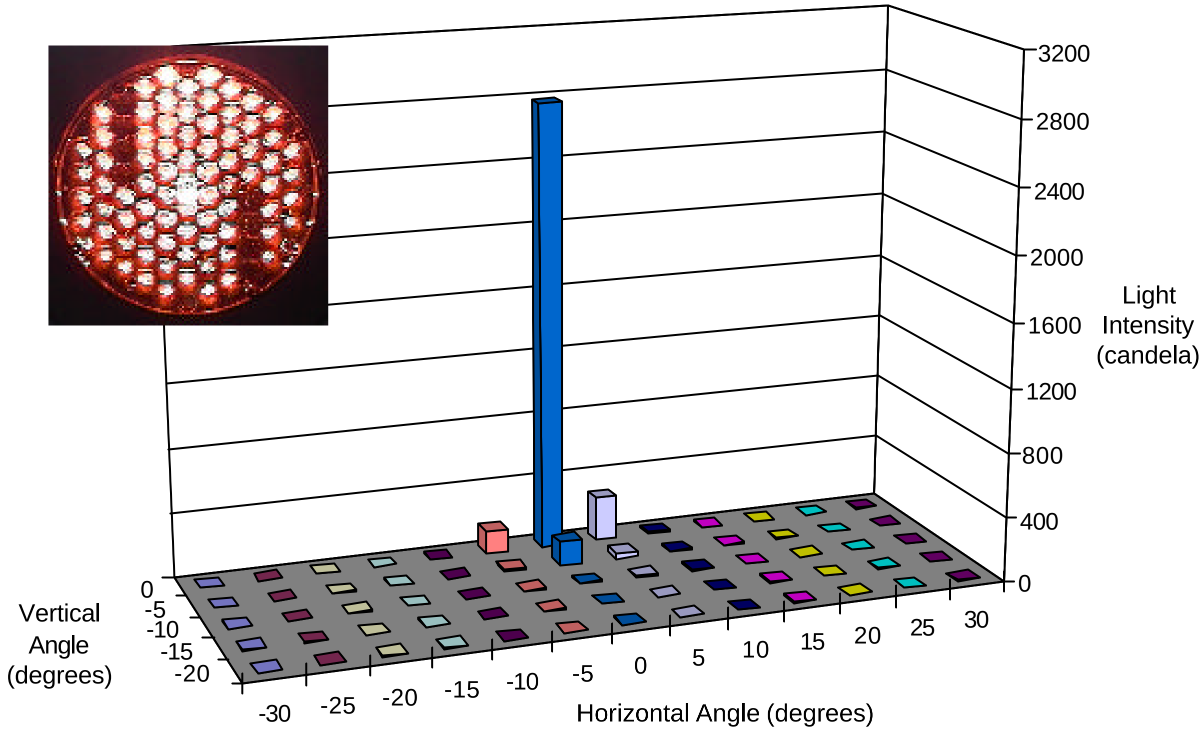

Figure A8.5.17a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

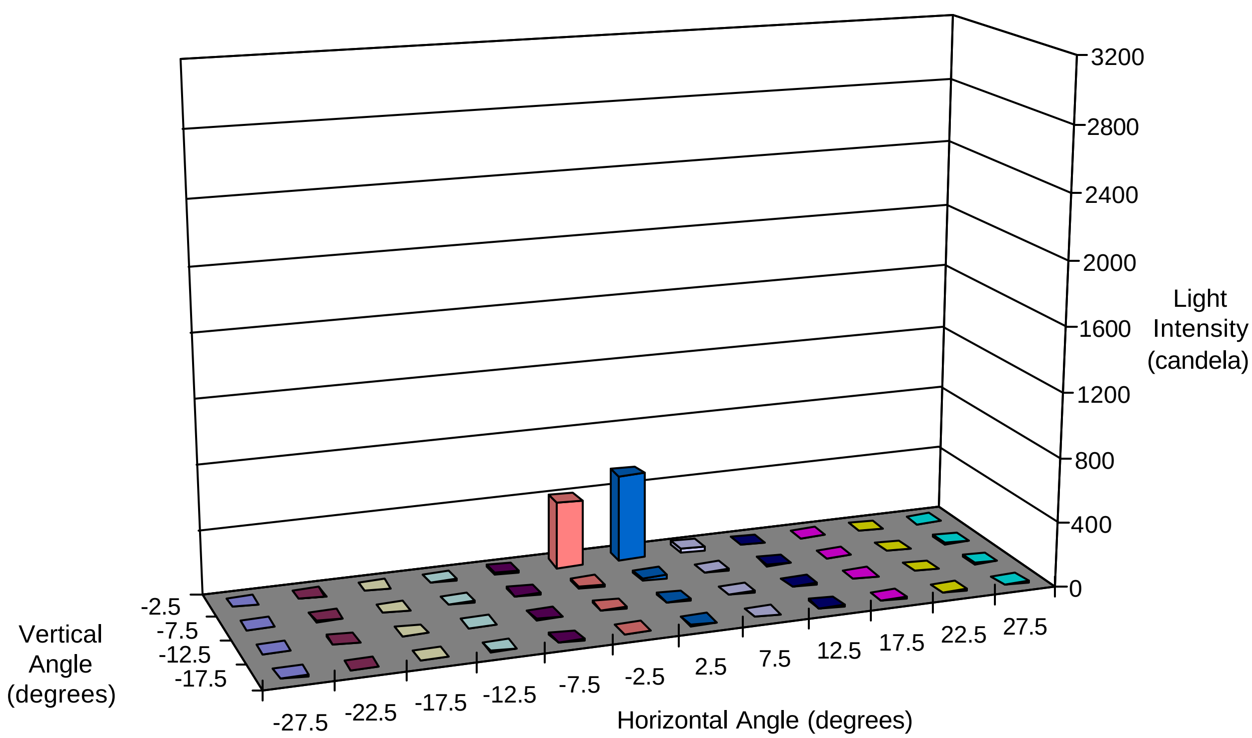

Figure A8.5.17b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

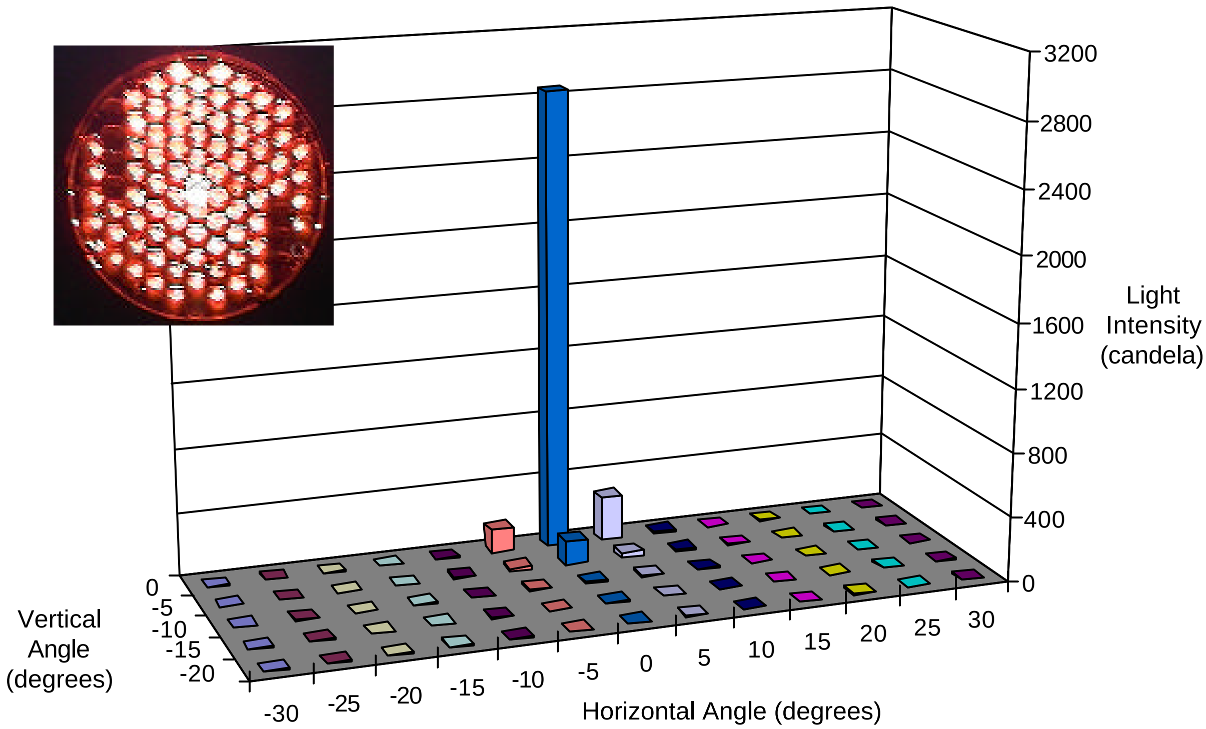

Figure A8.5.18a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

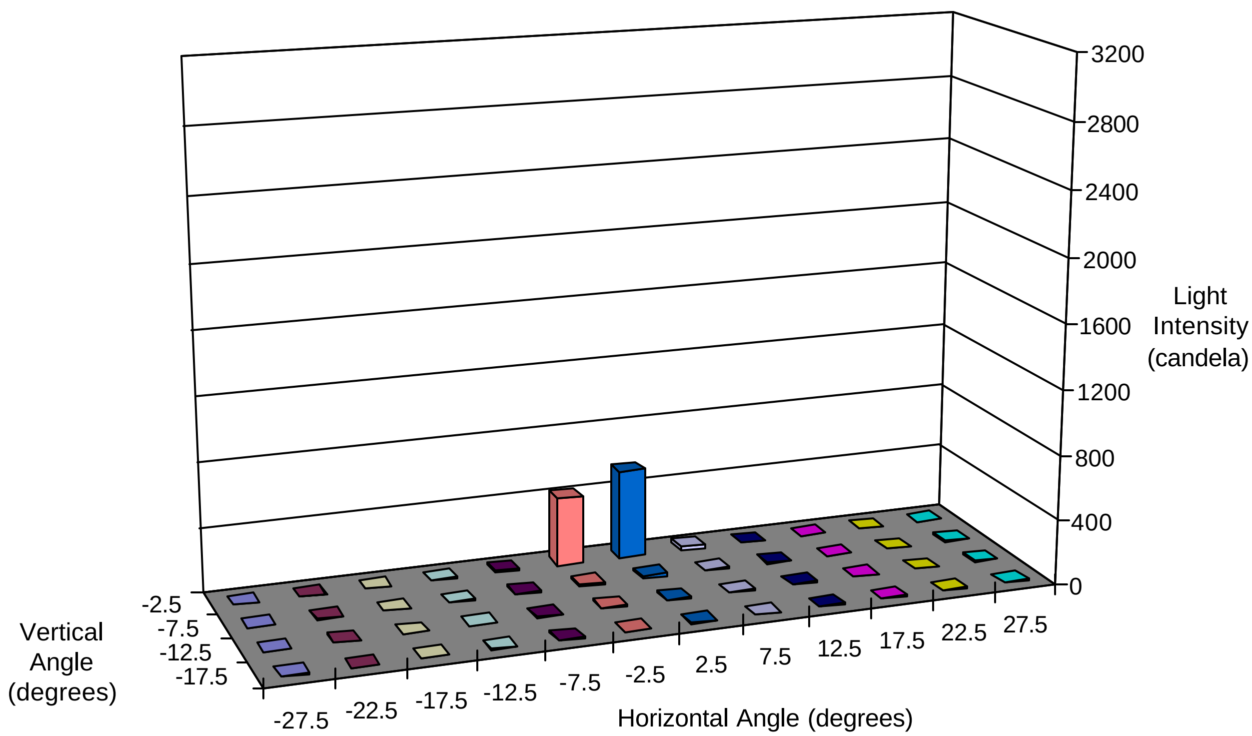

Figure A8.5.18b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

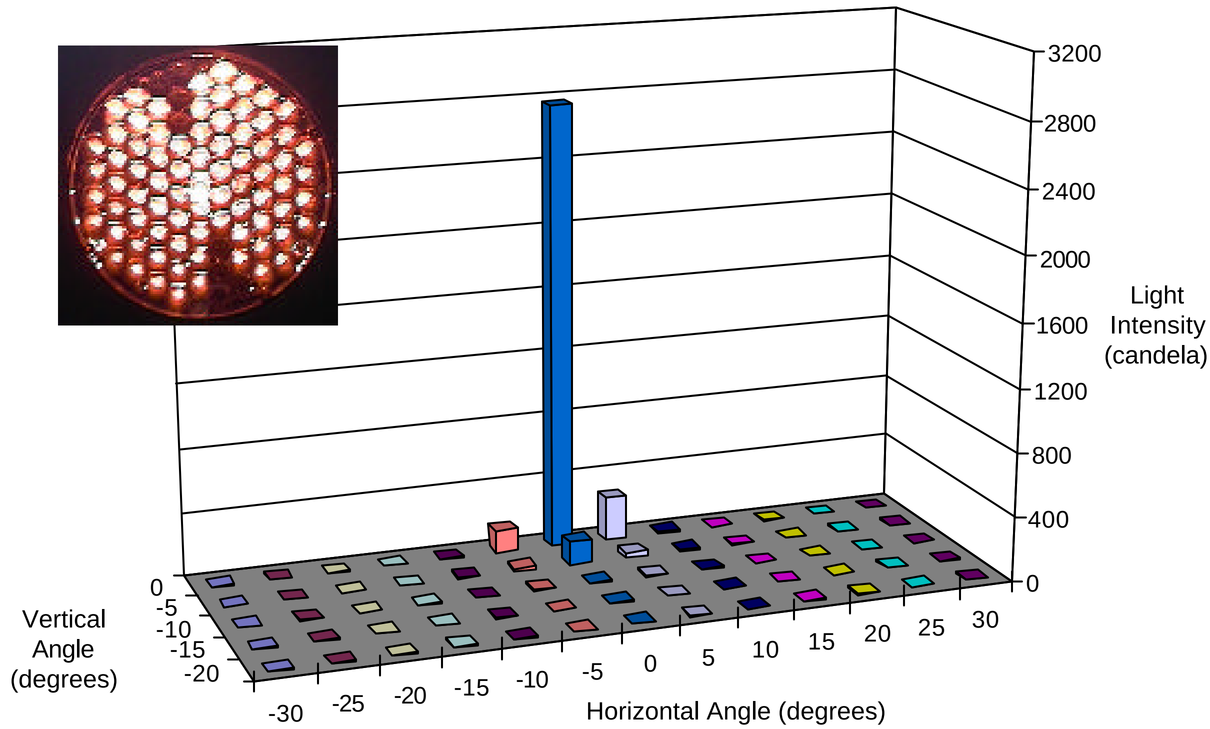

Figure A8.5.19a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

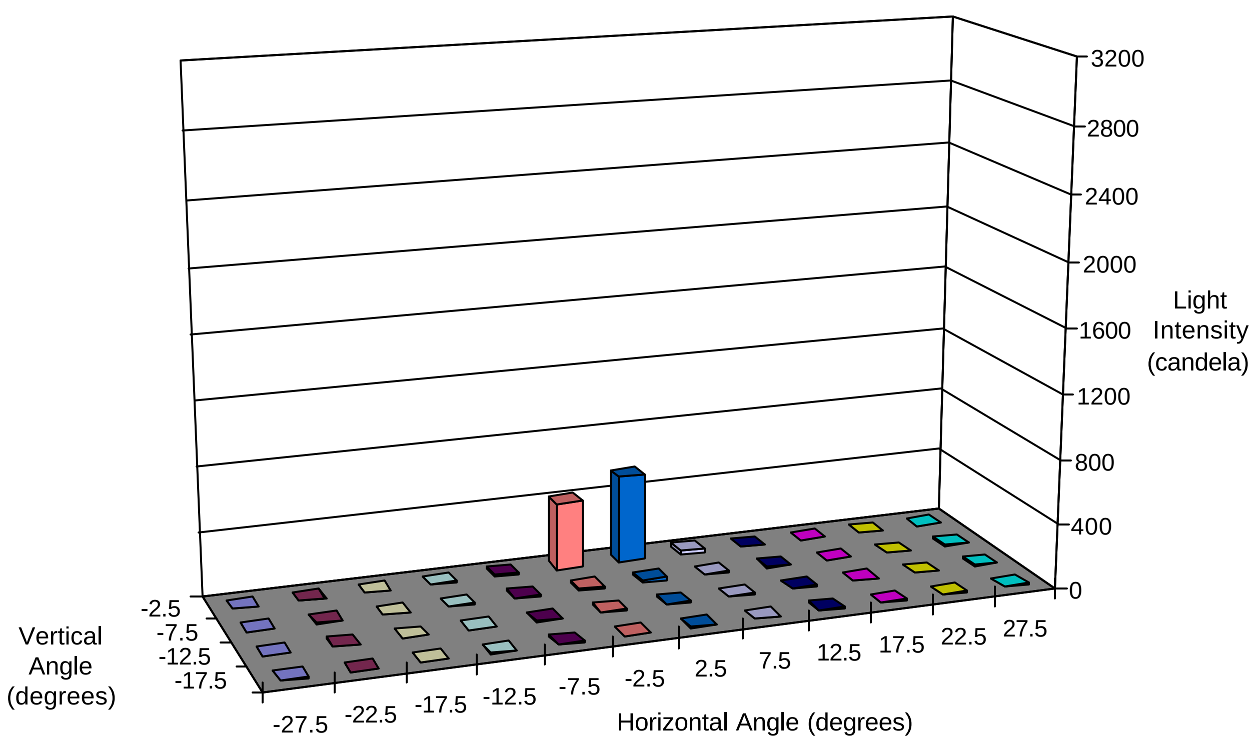

Figure A8.5.19b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

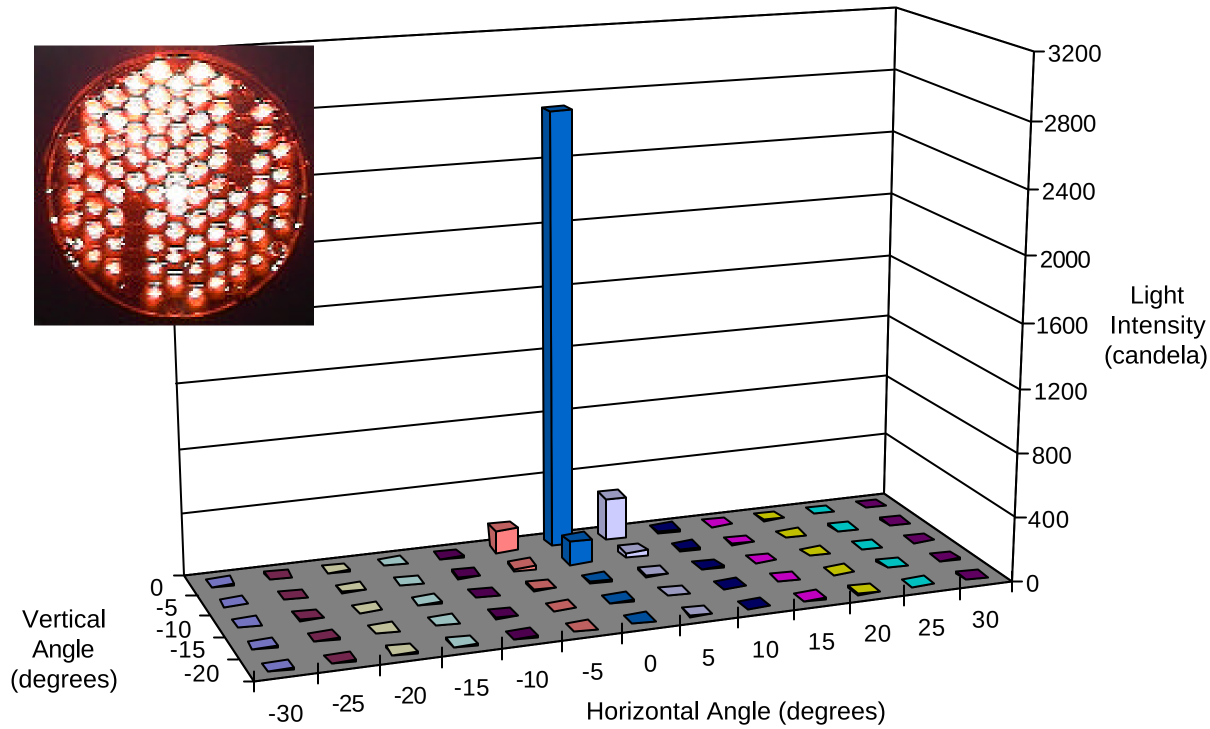

Figure A8.5.20a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

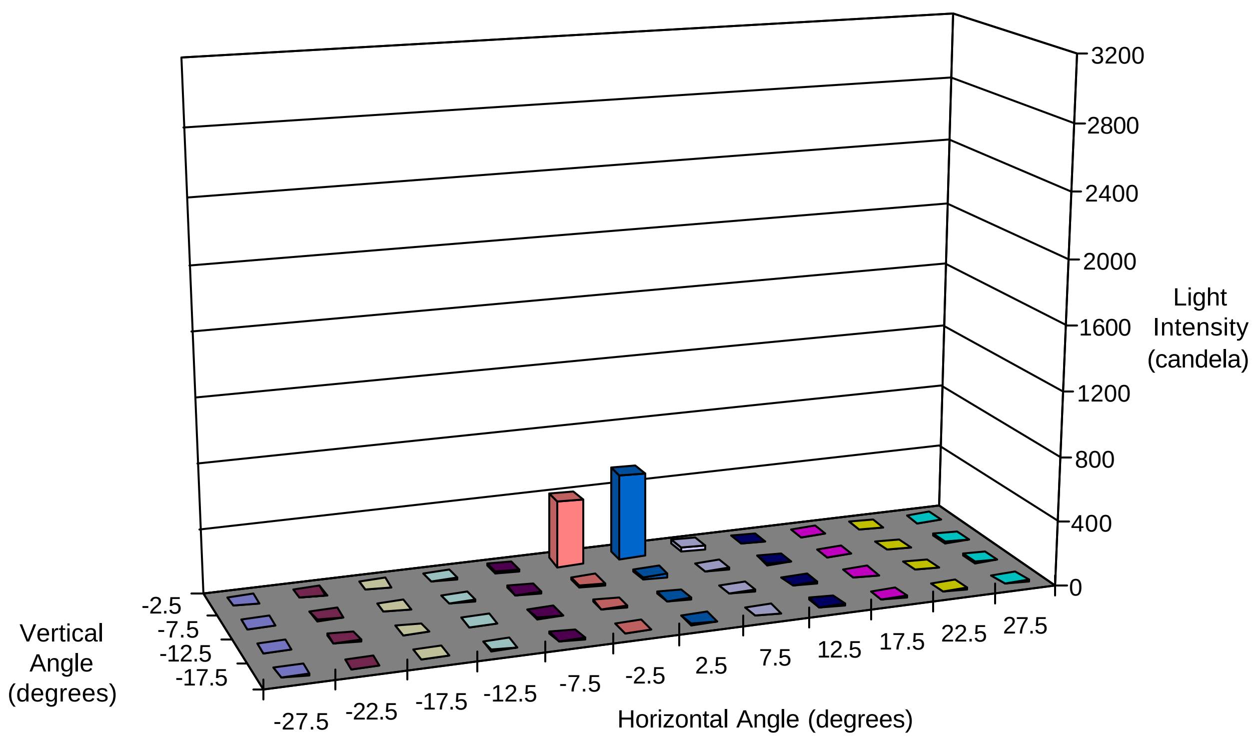

Figure A8.5.20b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

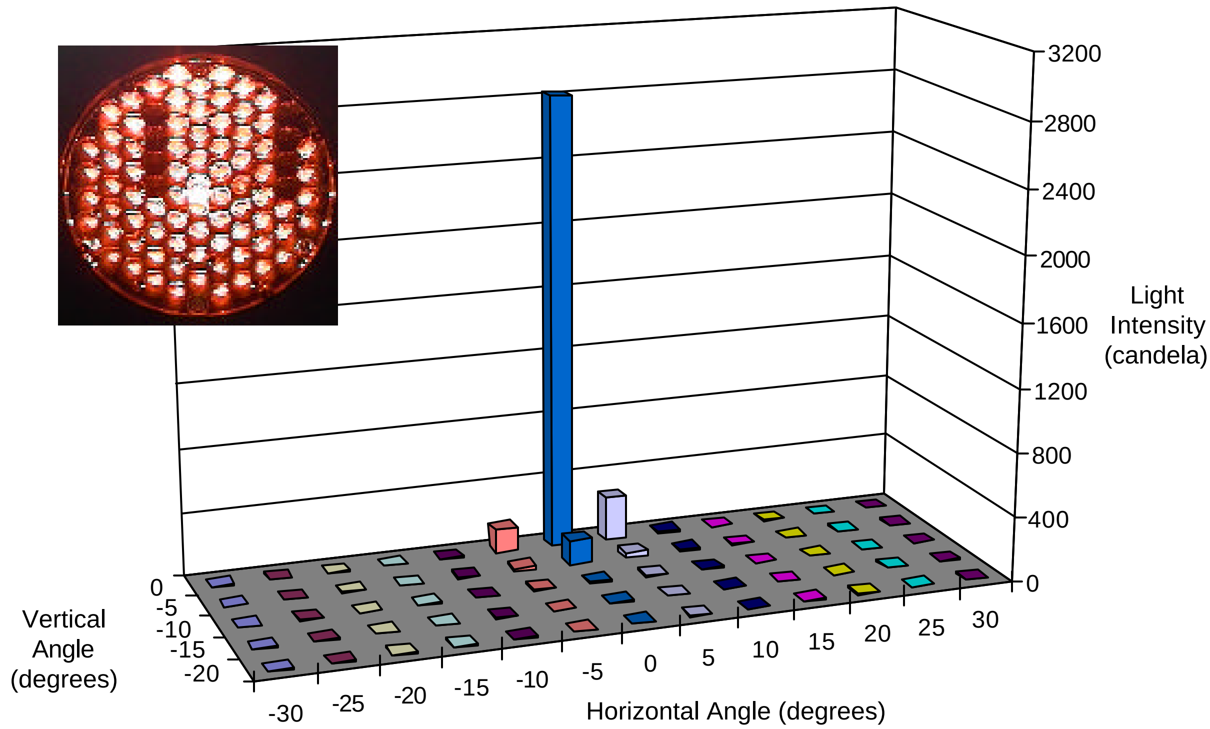

Figure A8.5.21a Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), TC test.

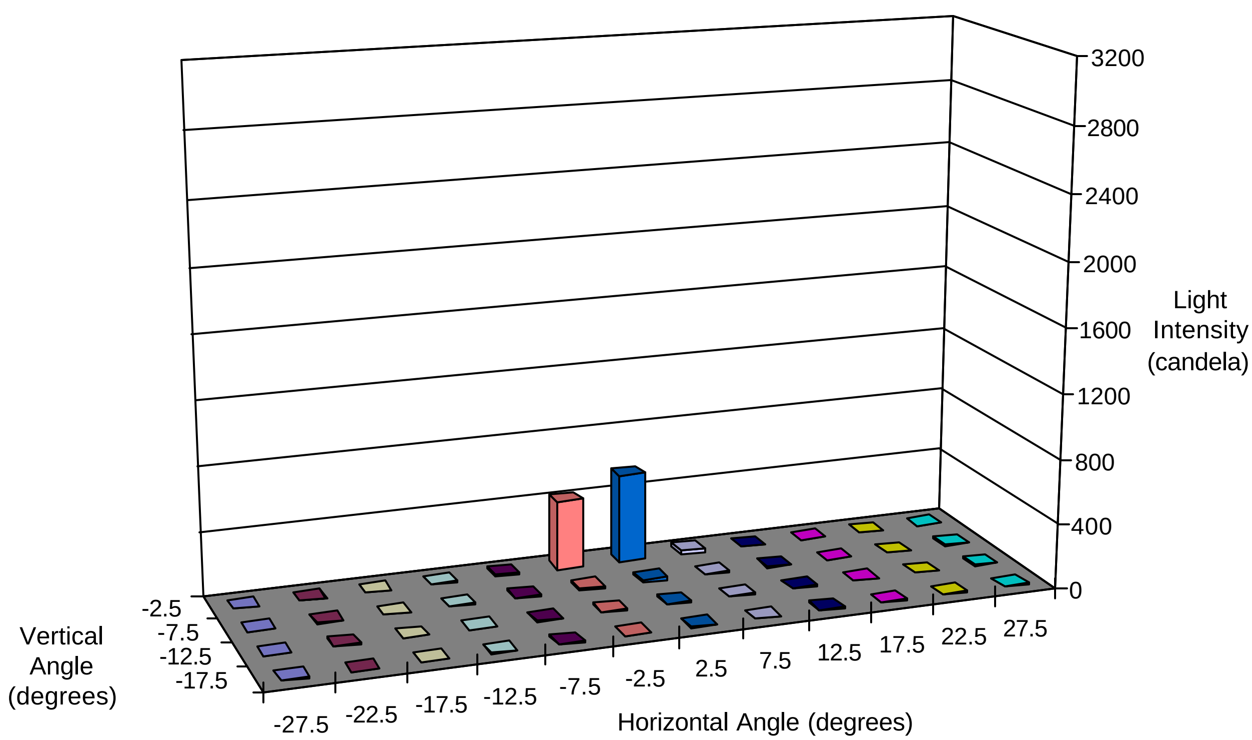

Figure A8.5.21b Output from WPS #8 (Yellow) signal, 10.0 volts, 80 elements (90.9% on), ITE test.

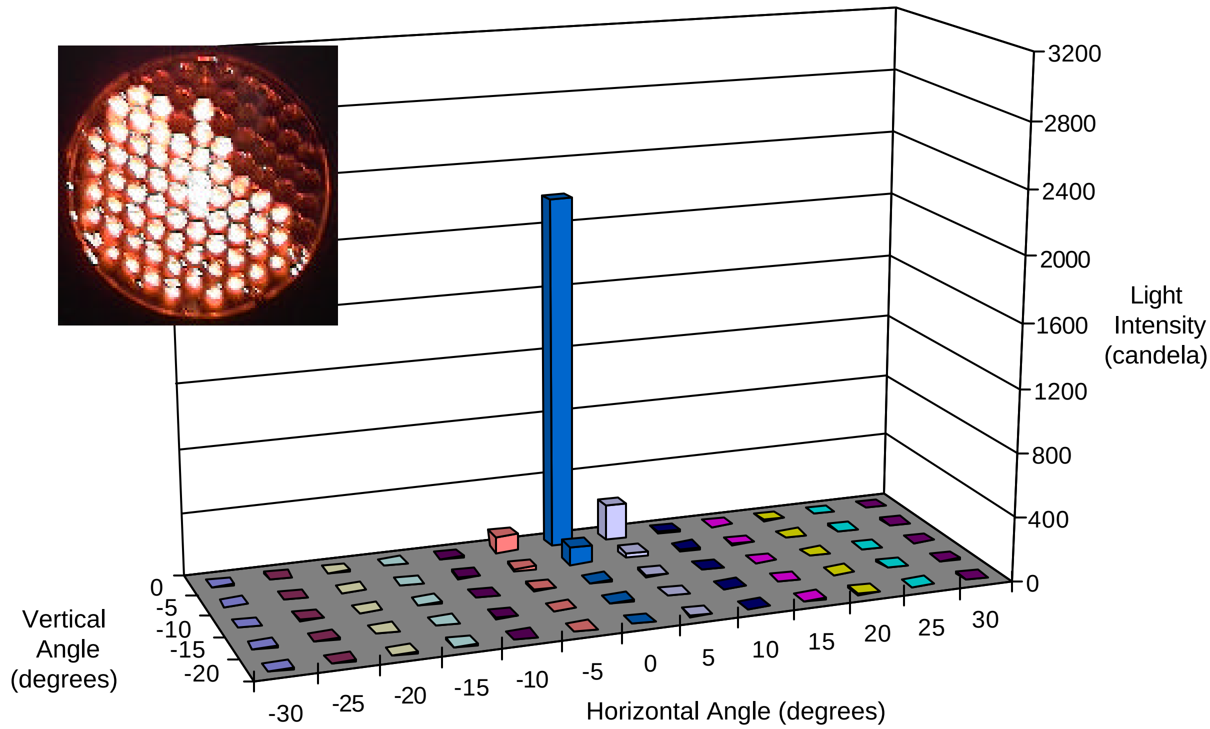

Figure A8.6.1a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

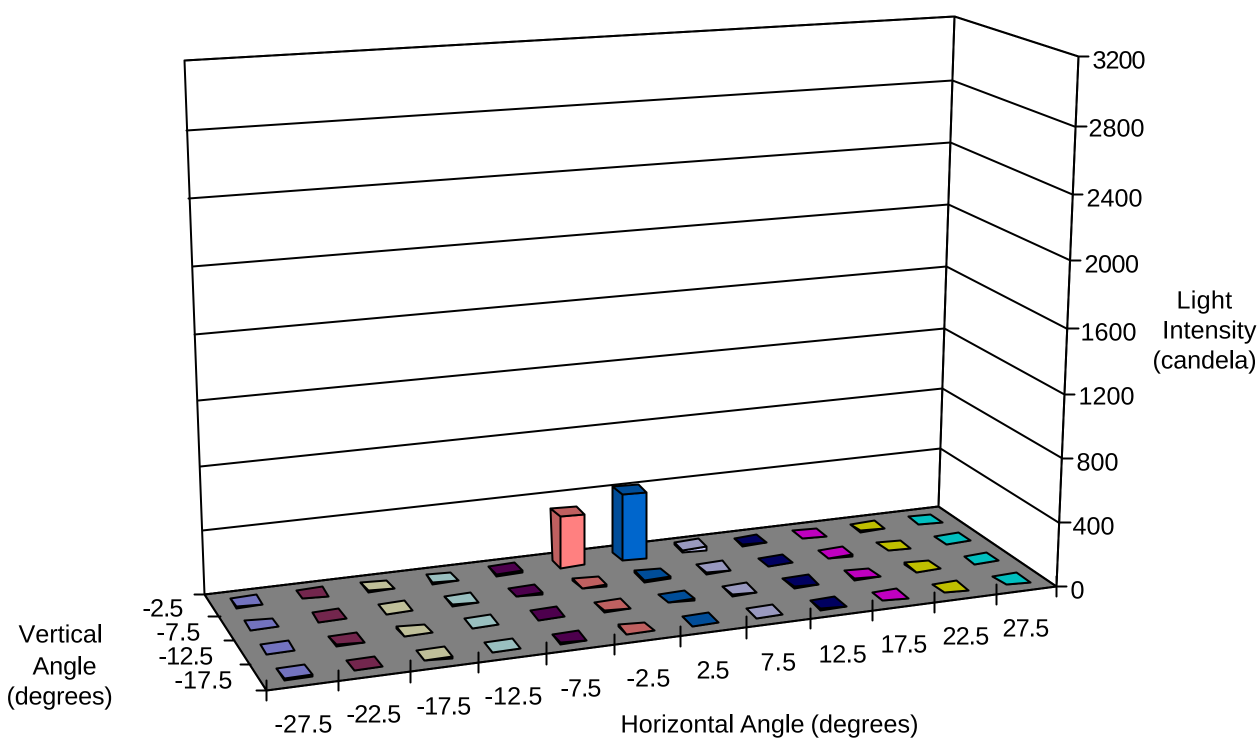

Figure A8.6.1b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

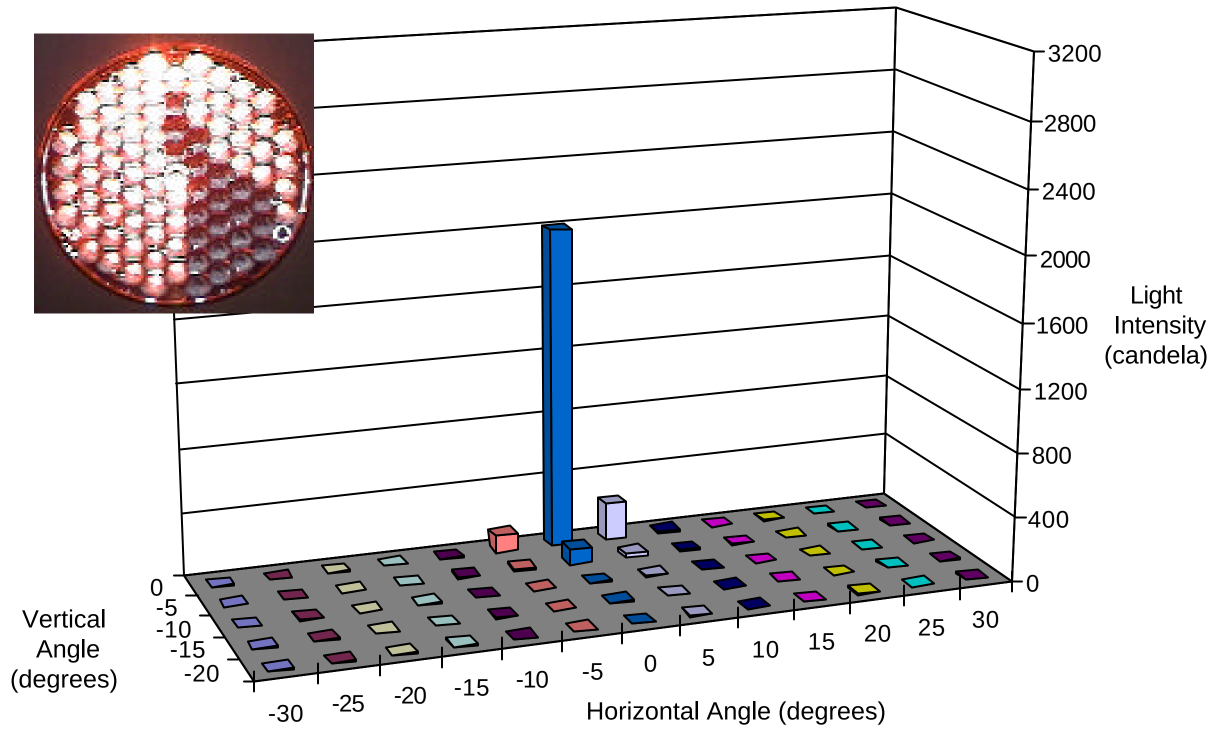

Figure A8.6.2a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

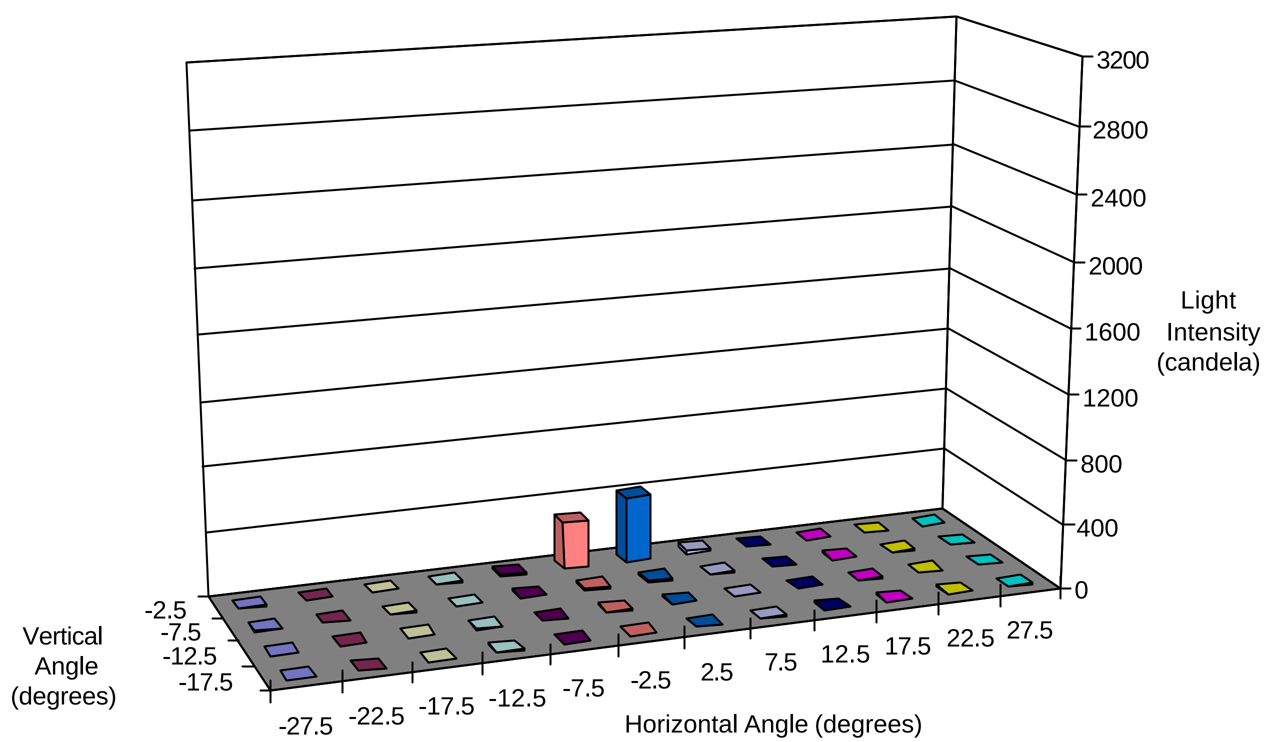

Figure A8.6.2b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

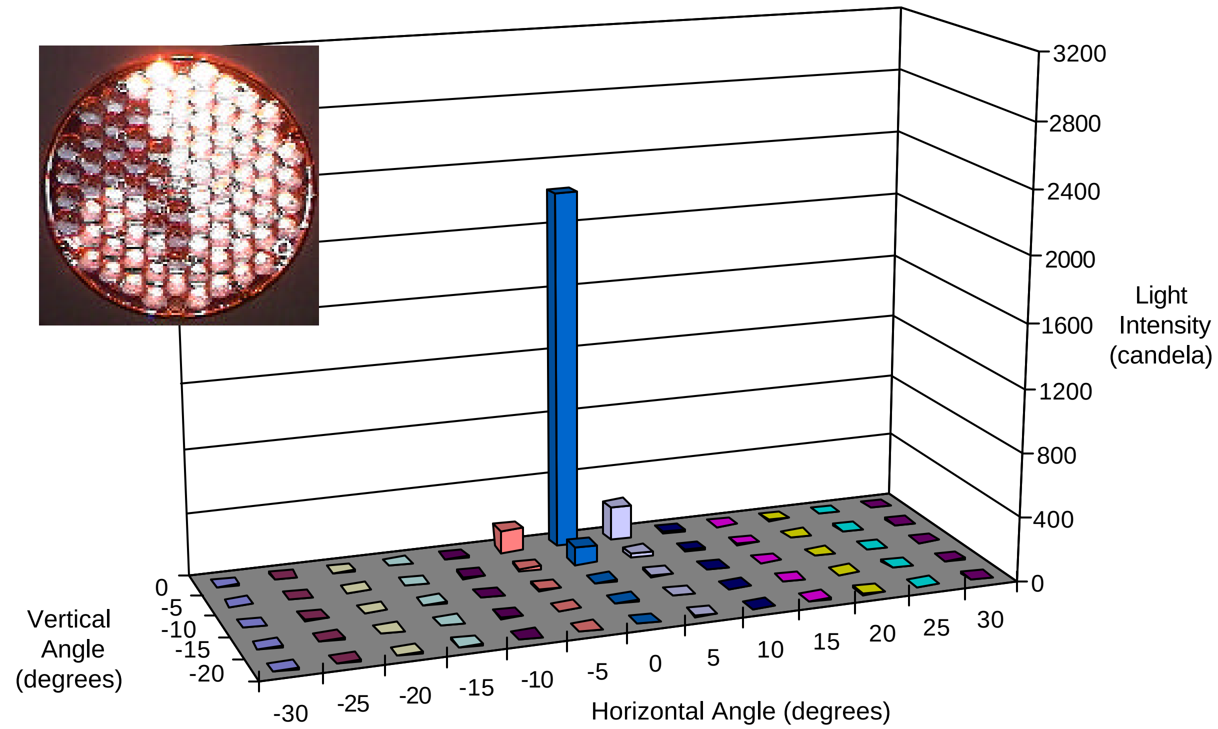

Figure A8.6.3a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

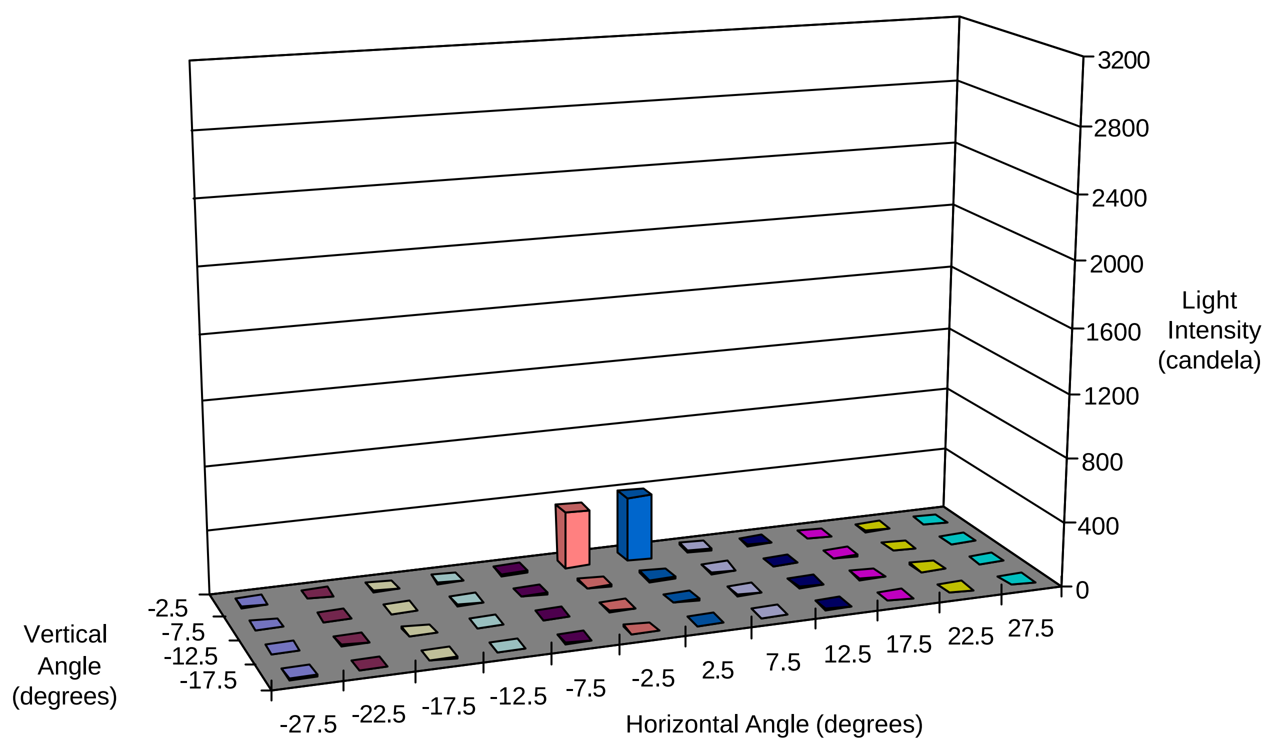

Figure A8.6.3b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

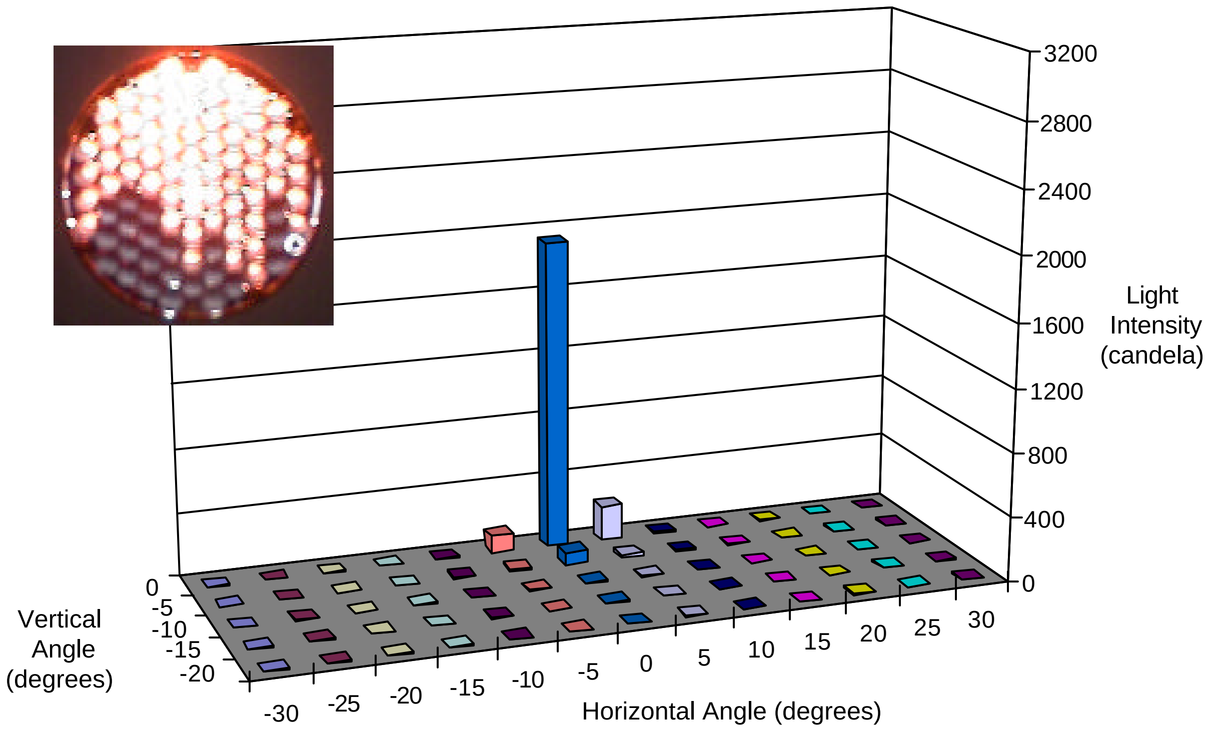

Figure A8.6.4a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

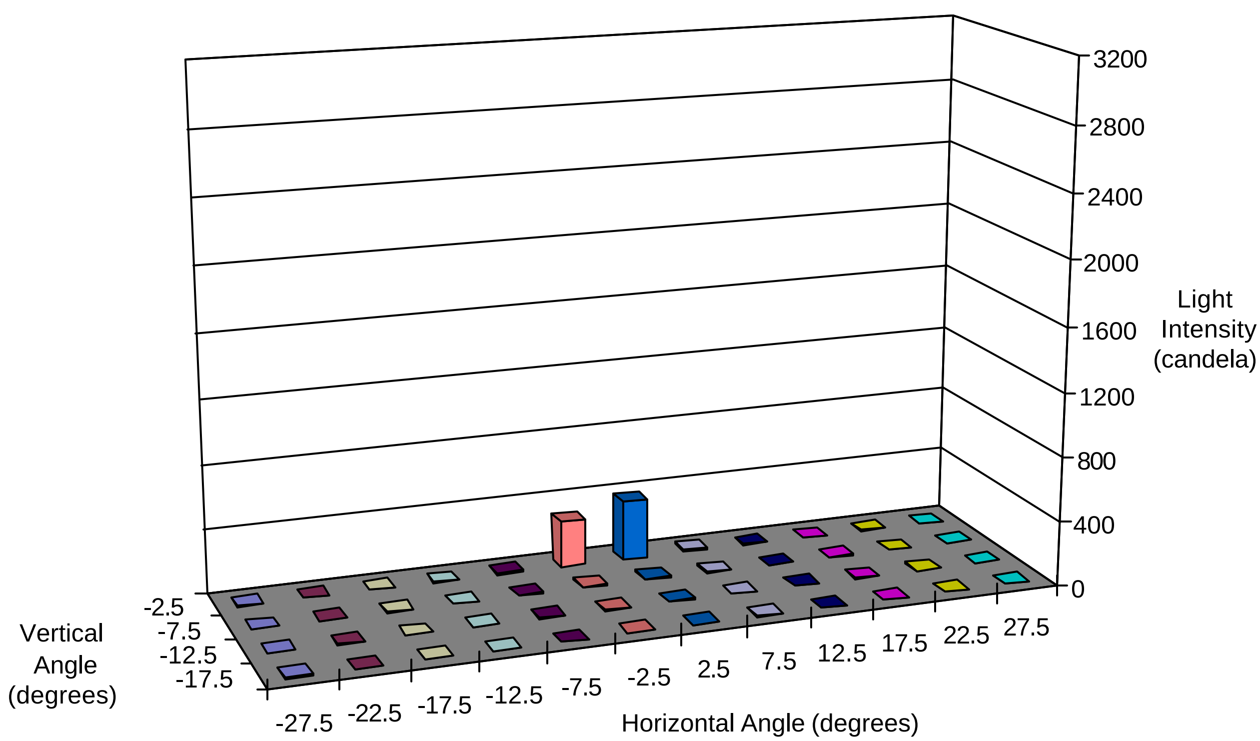

Figure A8.6.4b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

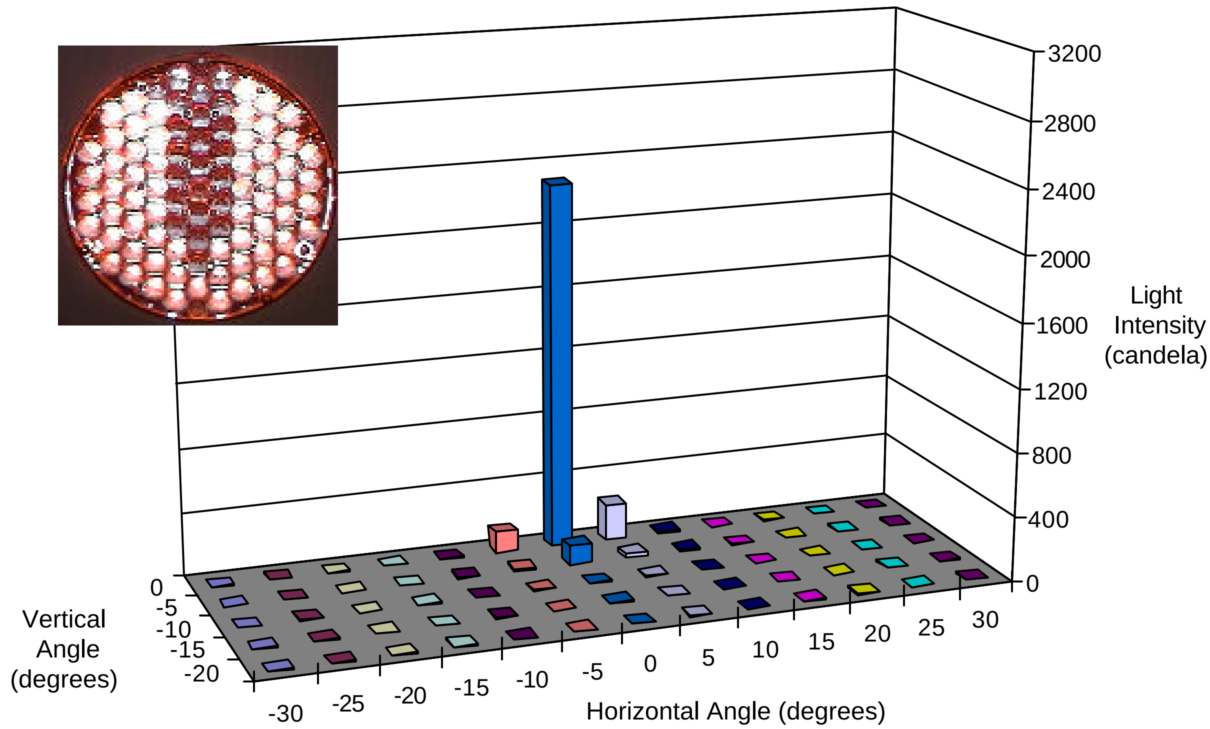

Figure A8.6.5a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

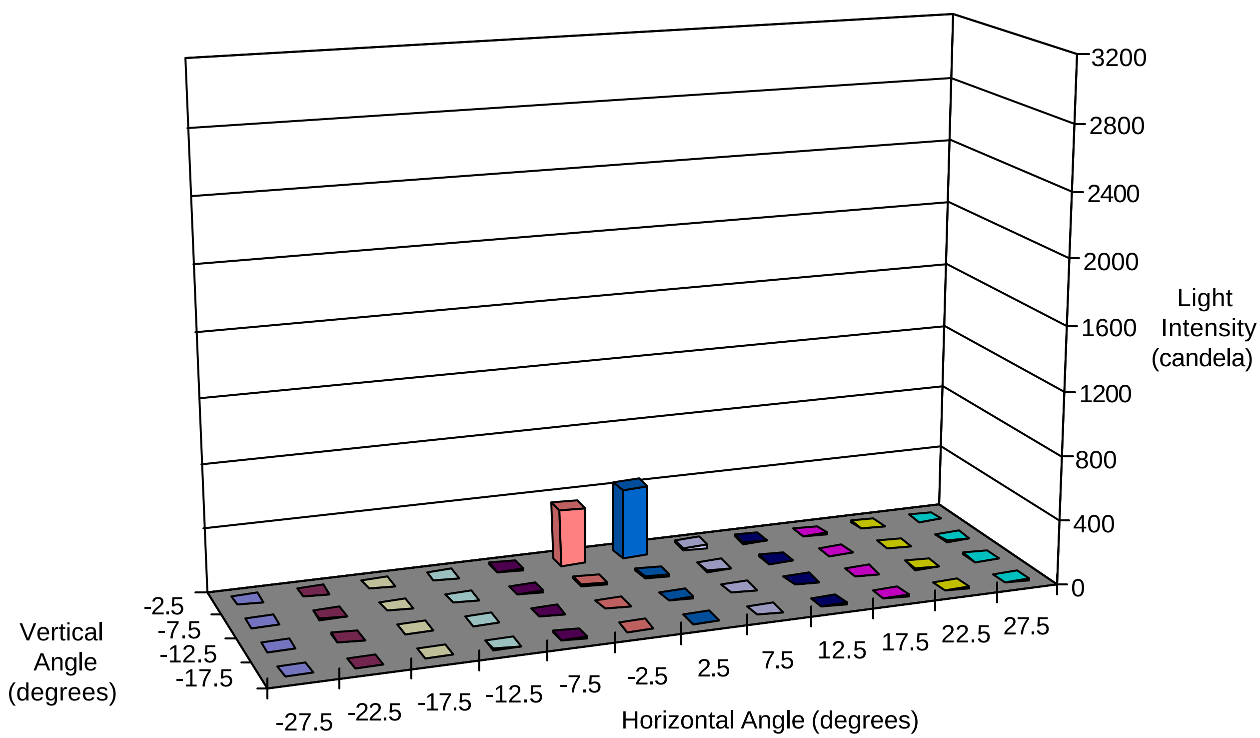

Figure A8.6.5b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

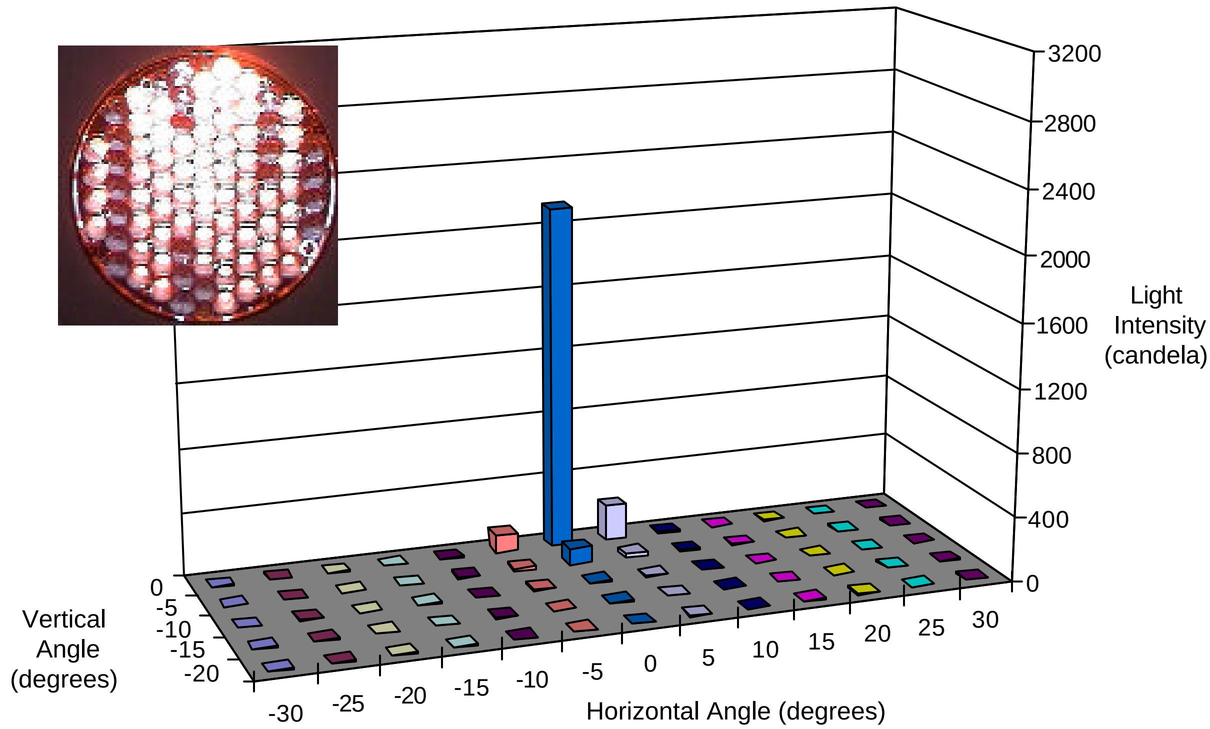

Figure A8.6.6a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

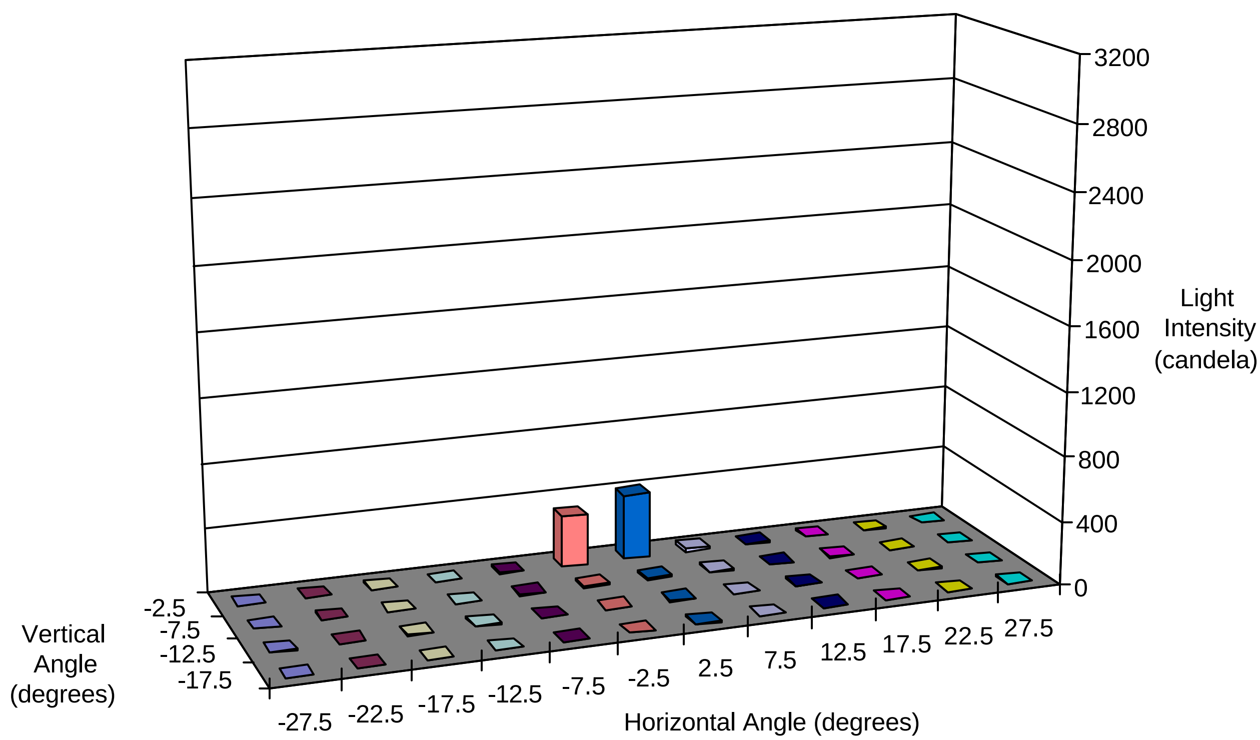

Figure A8.6.6b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

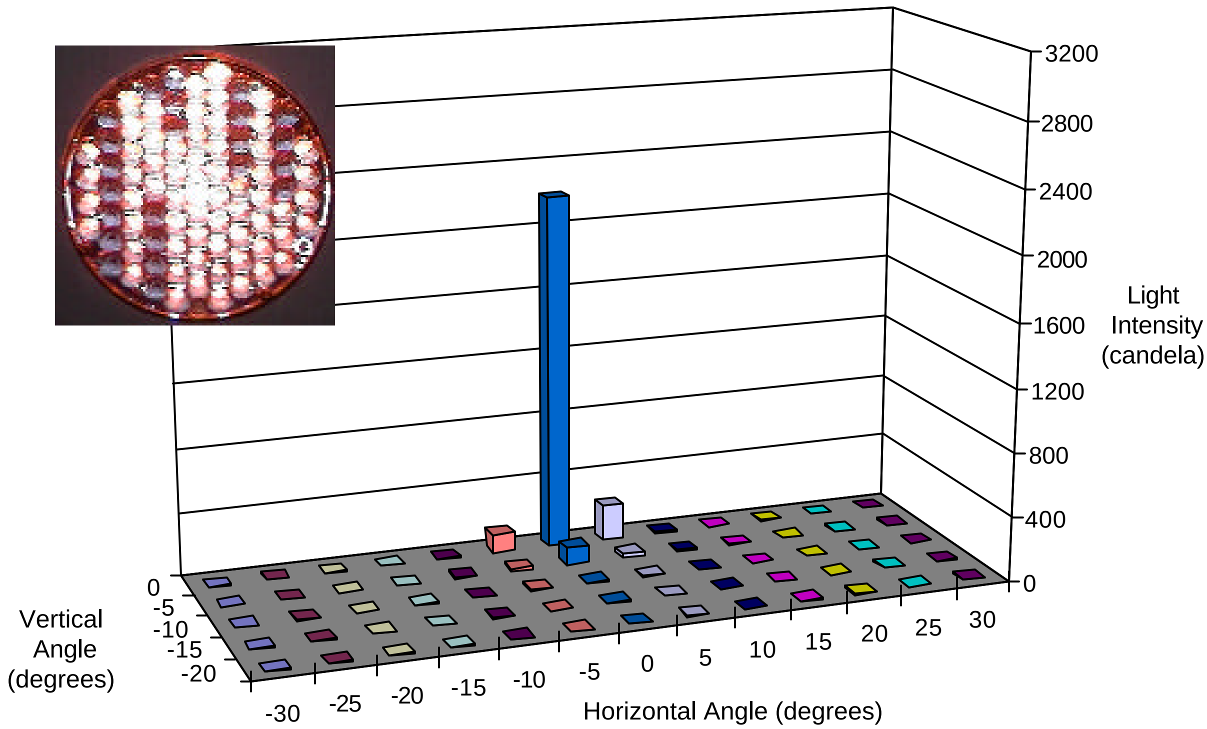

Figure A8.6.7a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

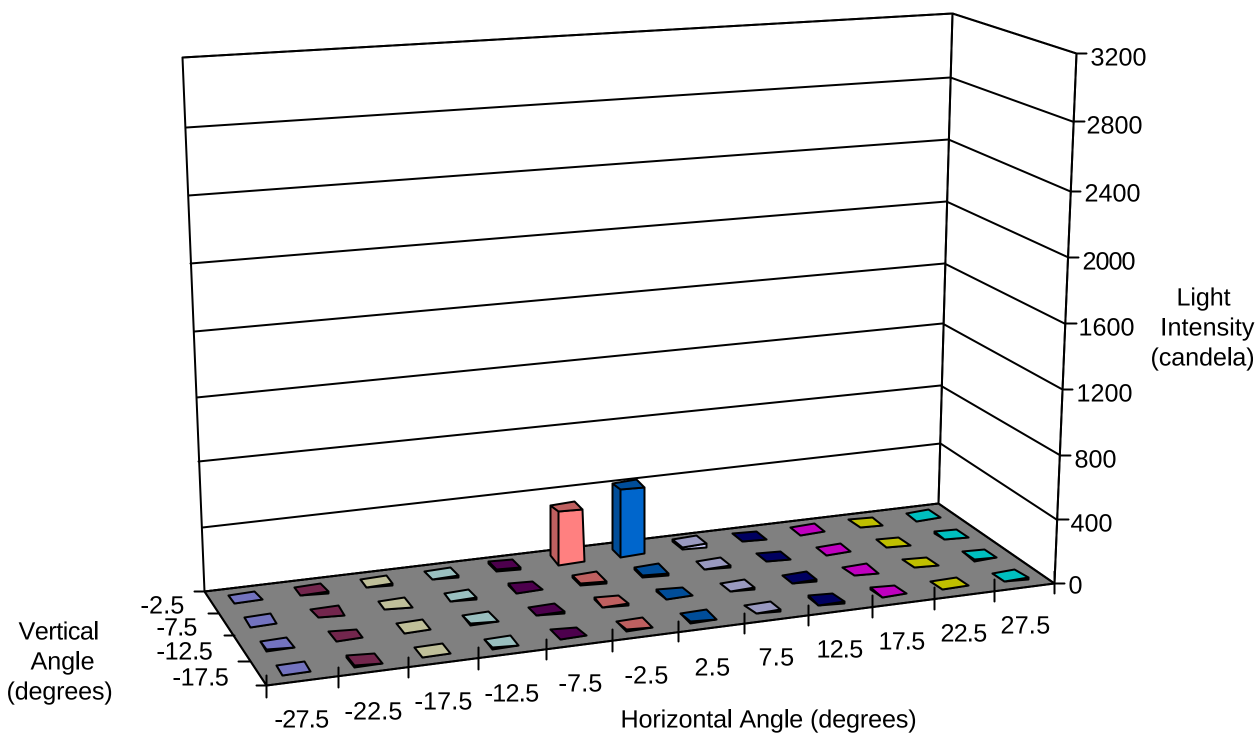

Figure A8.6.7b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

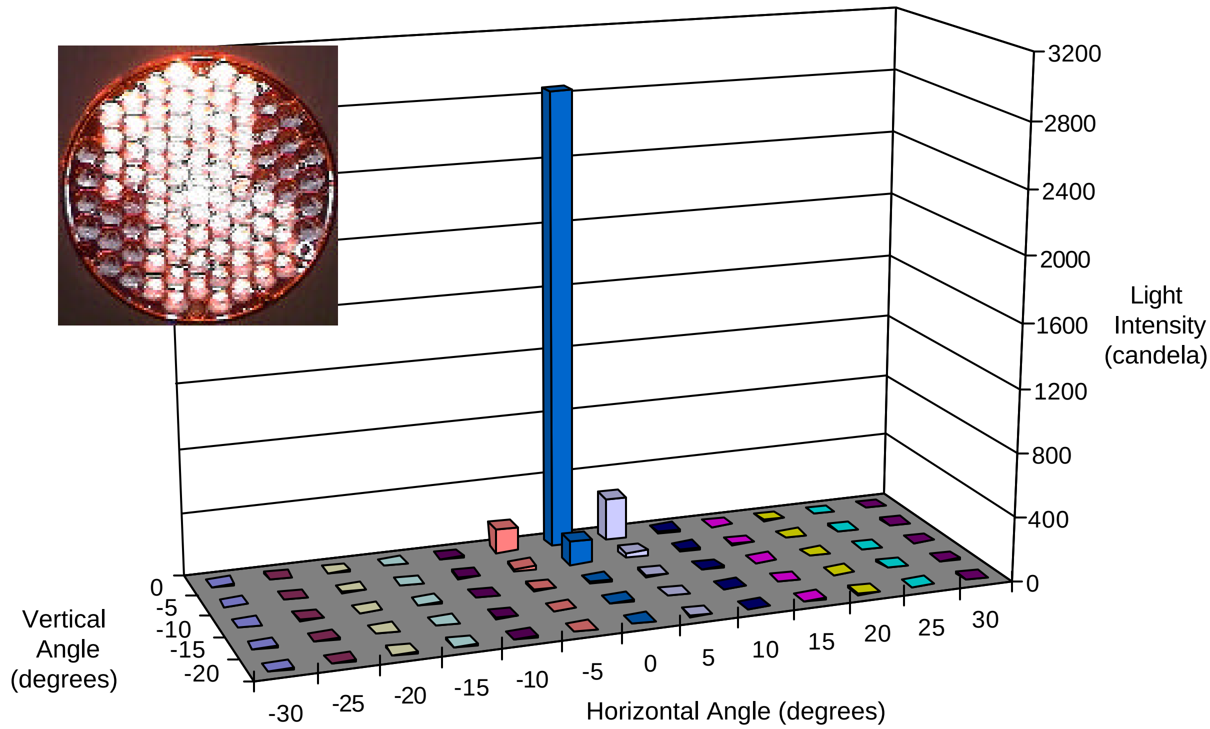

Figure A8.6.8a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

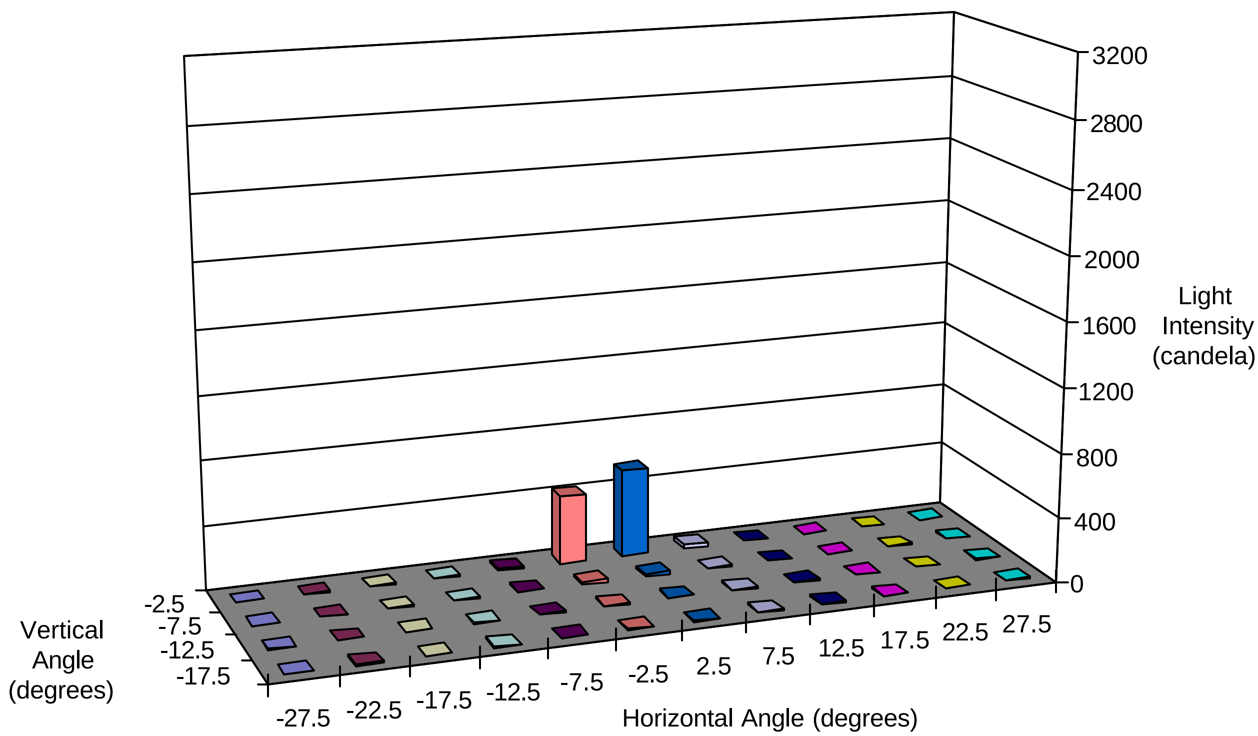

Figure A8.6.8b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

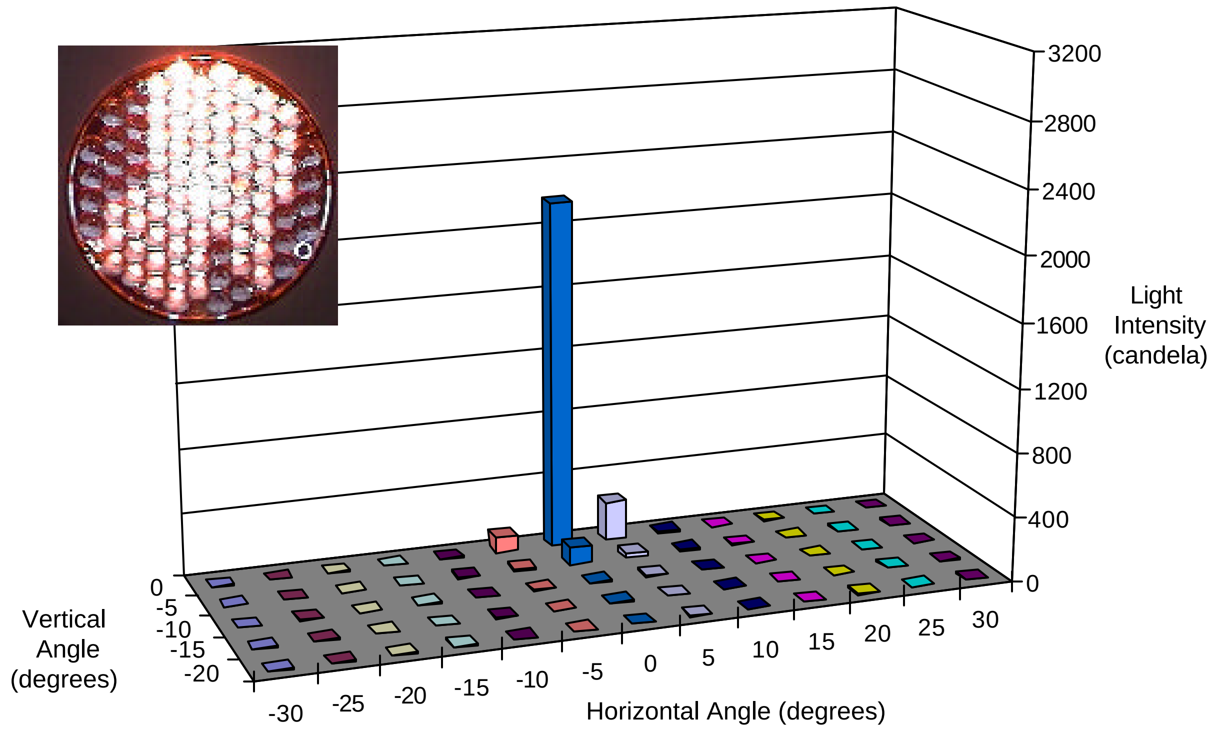

Figure A8.6.9a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

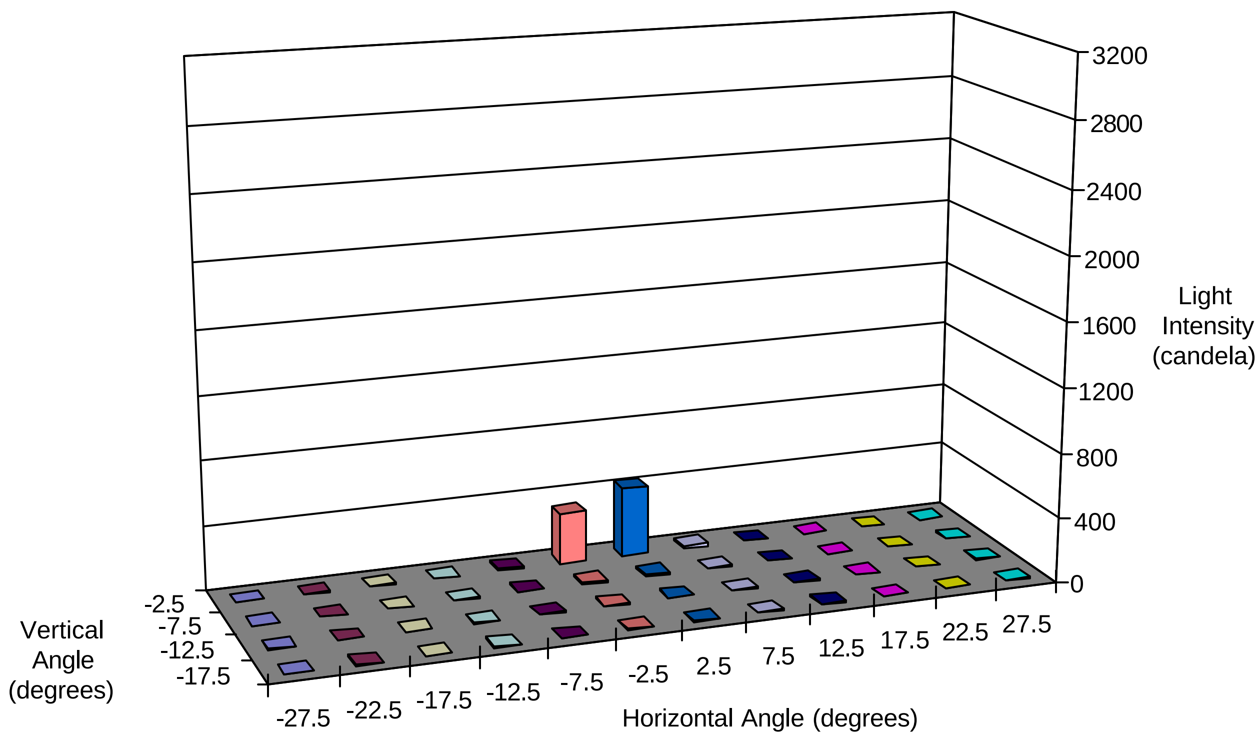

Figure A8.6.9b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

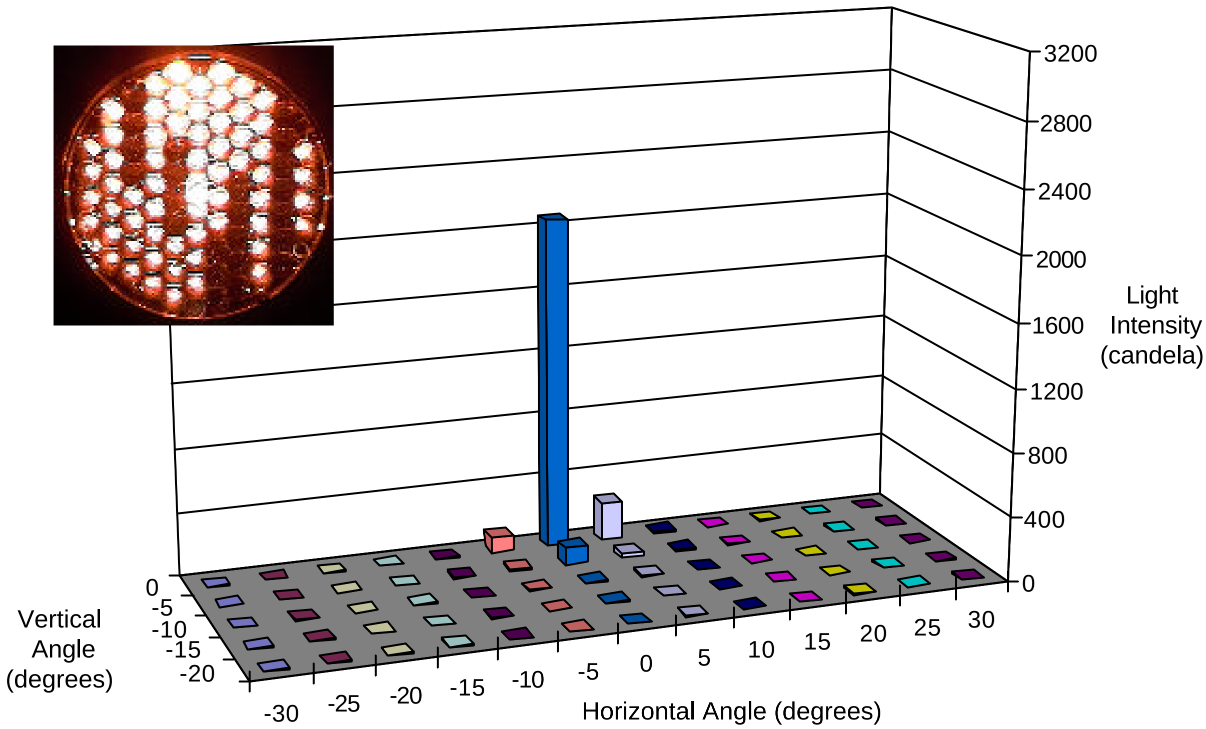

Figure A8.6.10a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

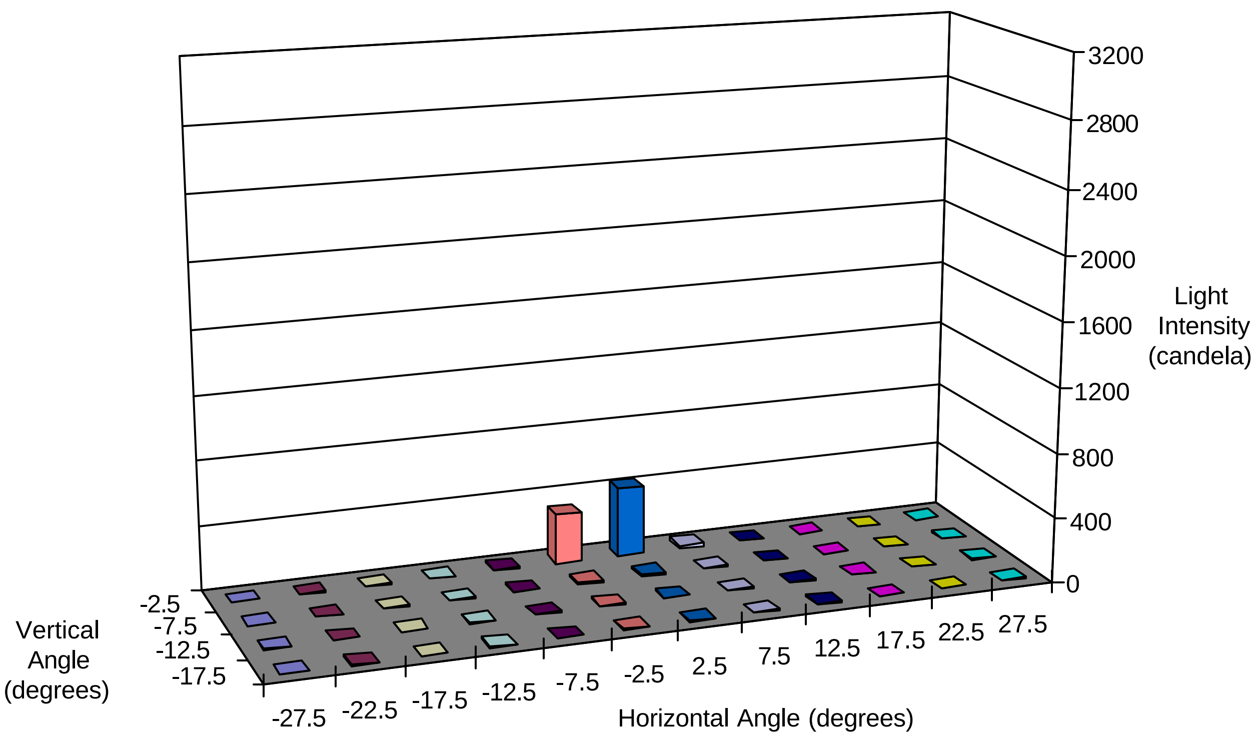

Figure A8.6.10b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

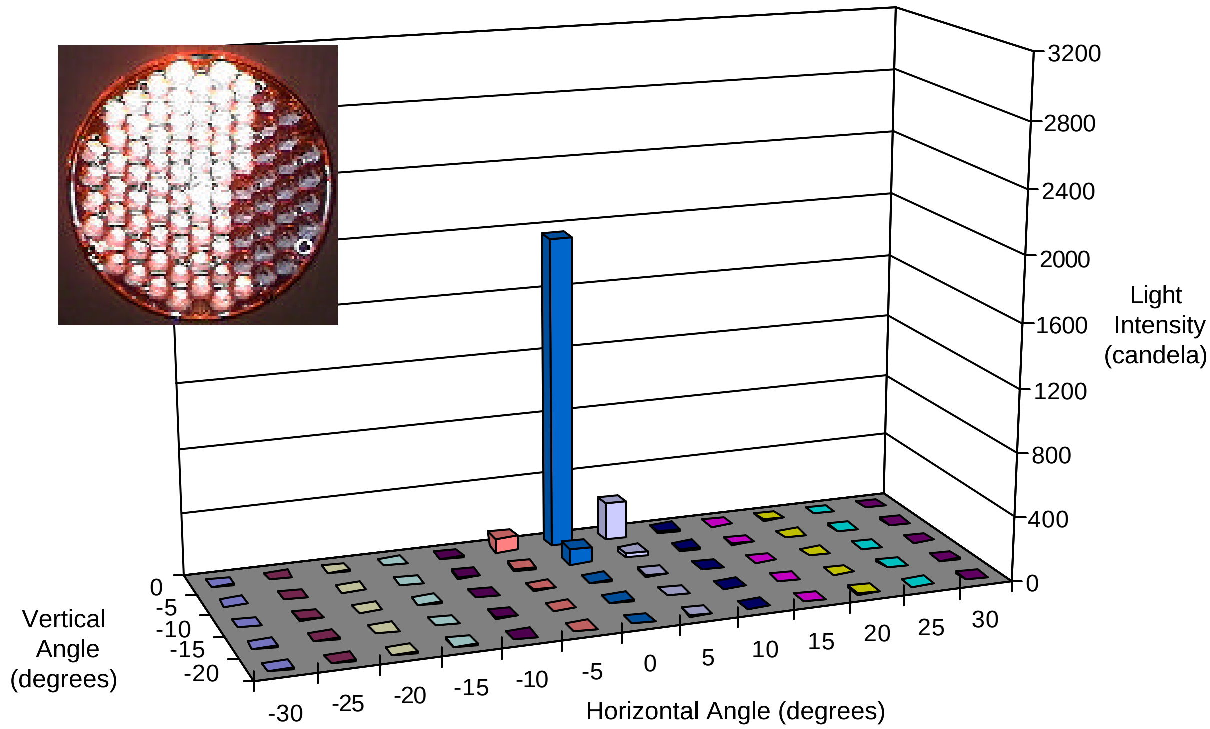

Figure A8.6.11a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

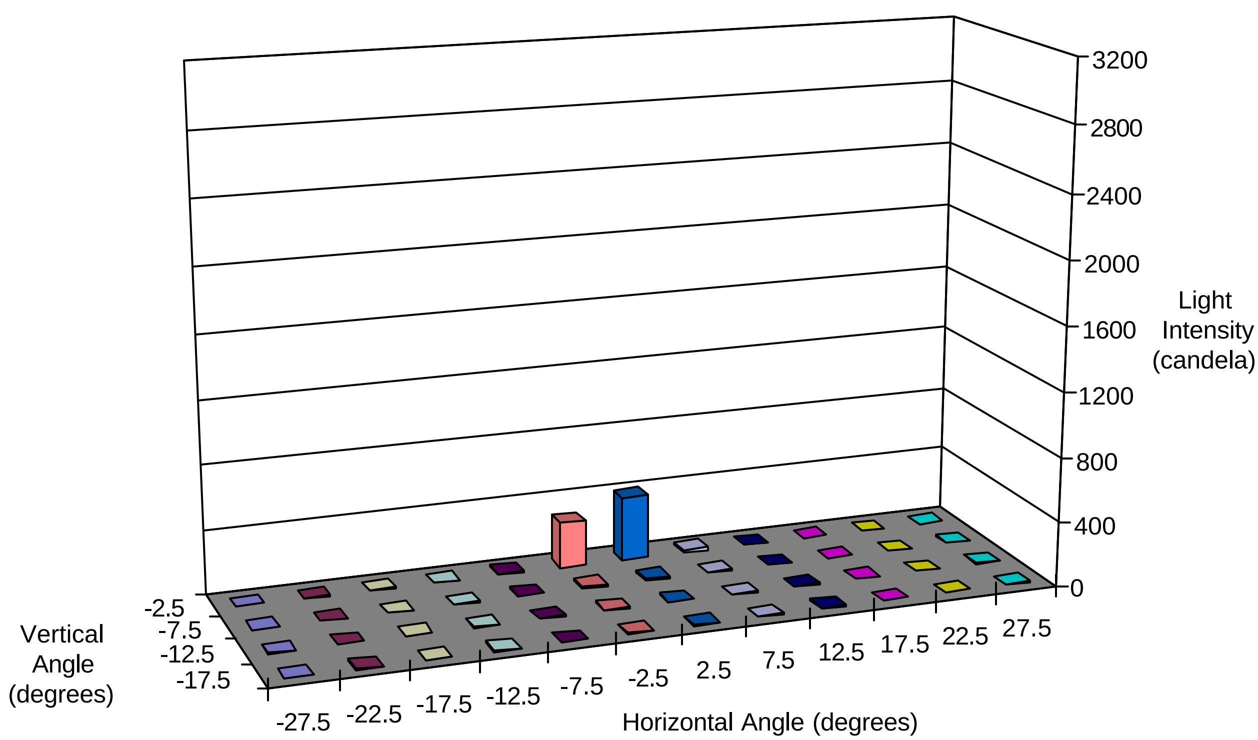

Figure A8.6.11b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

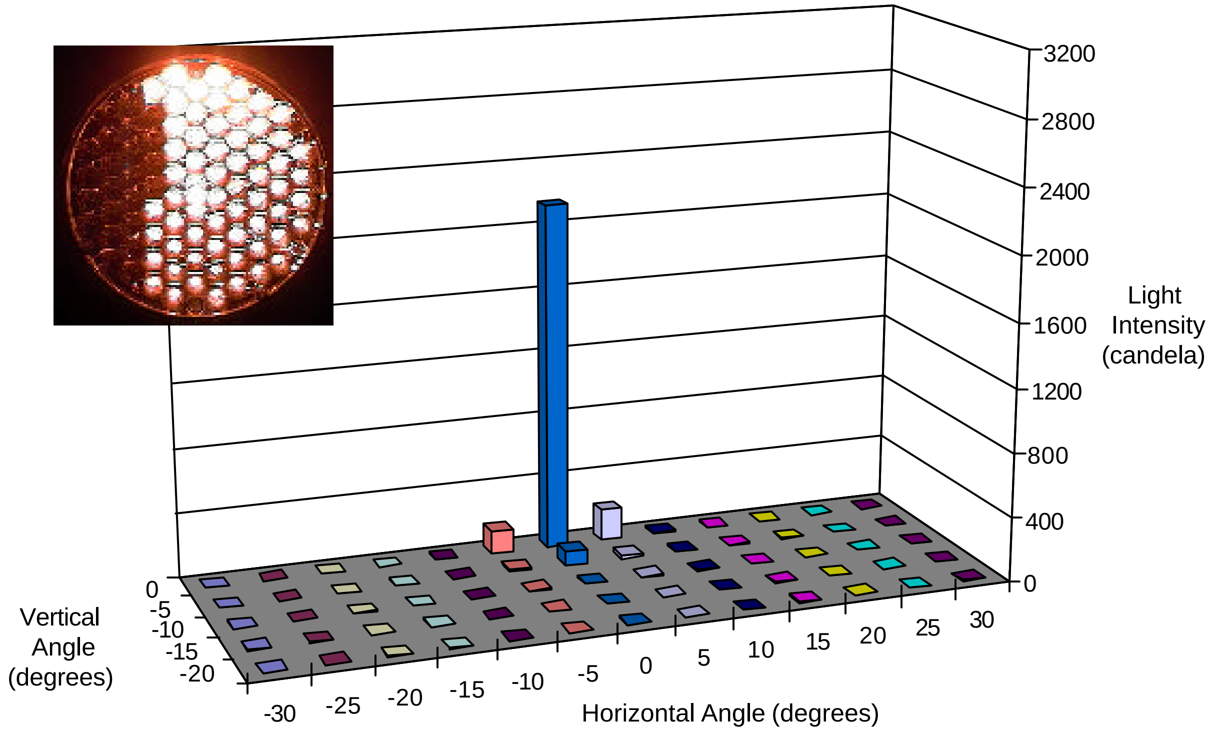

Figure A8.6.12a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

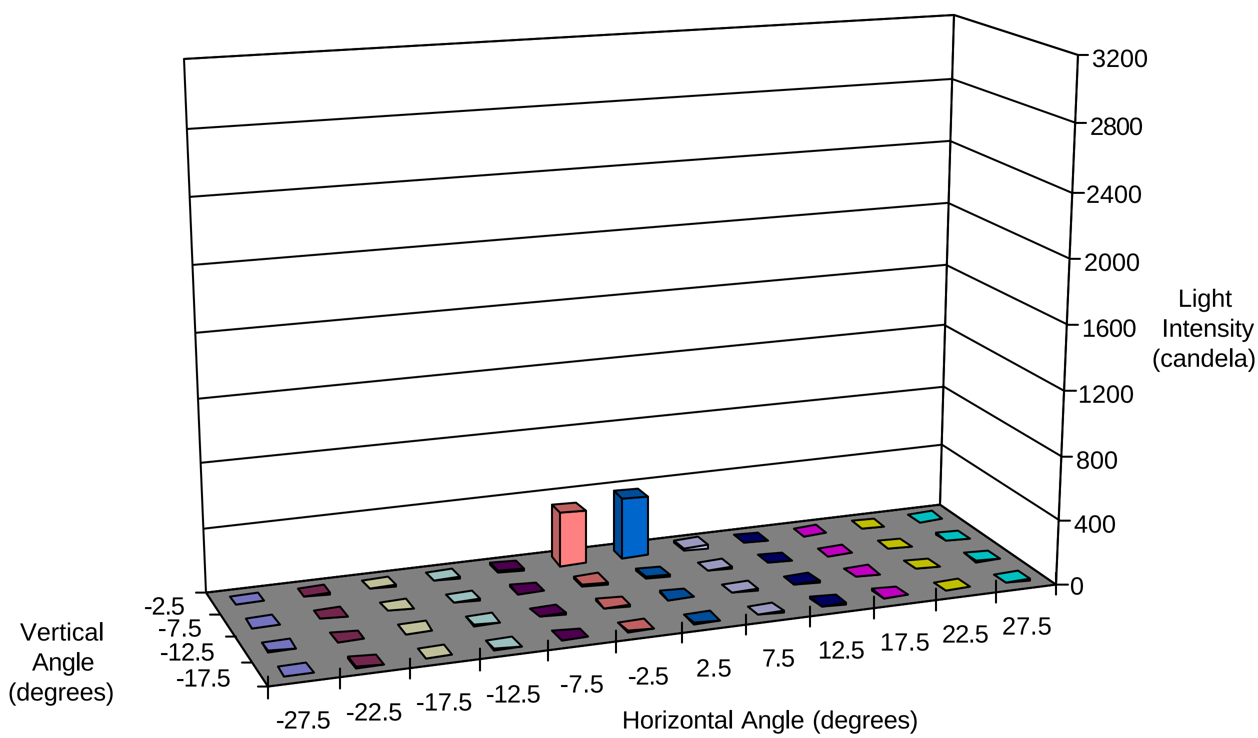

Figure A8.6.12b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

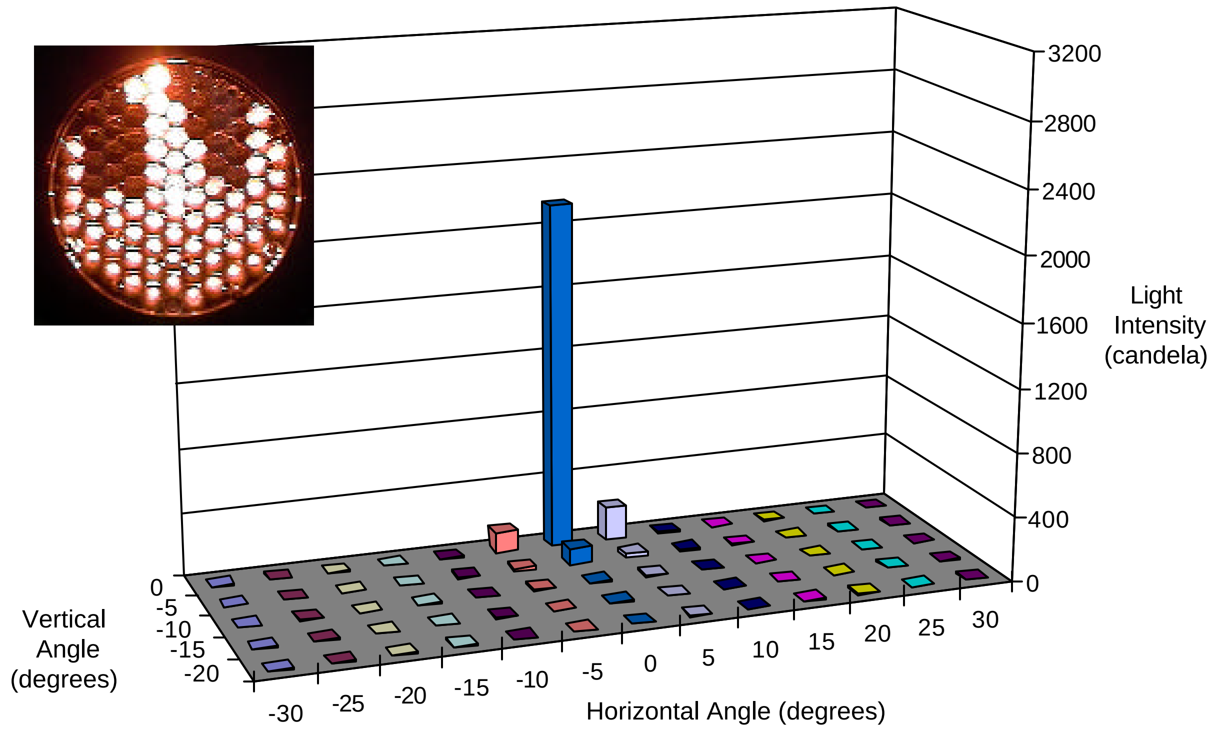

Figure A8.6.13a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

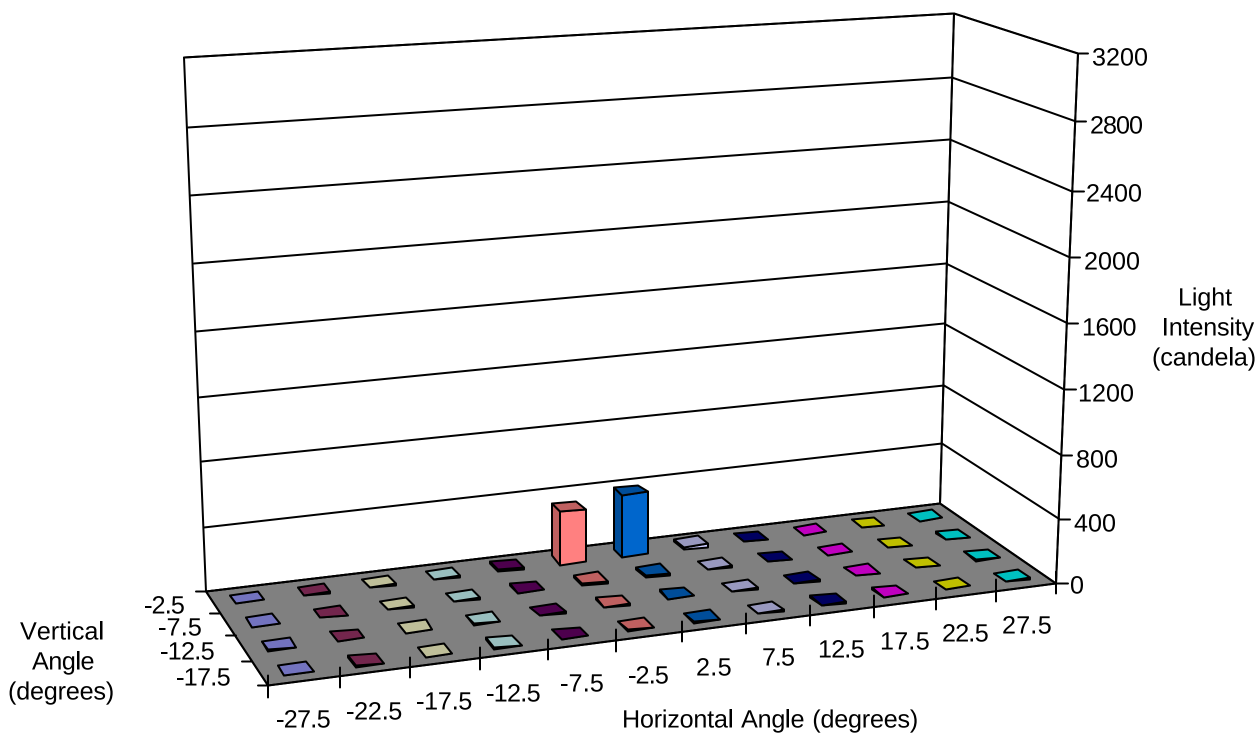

Figure A8.6.13b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

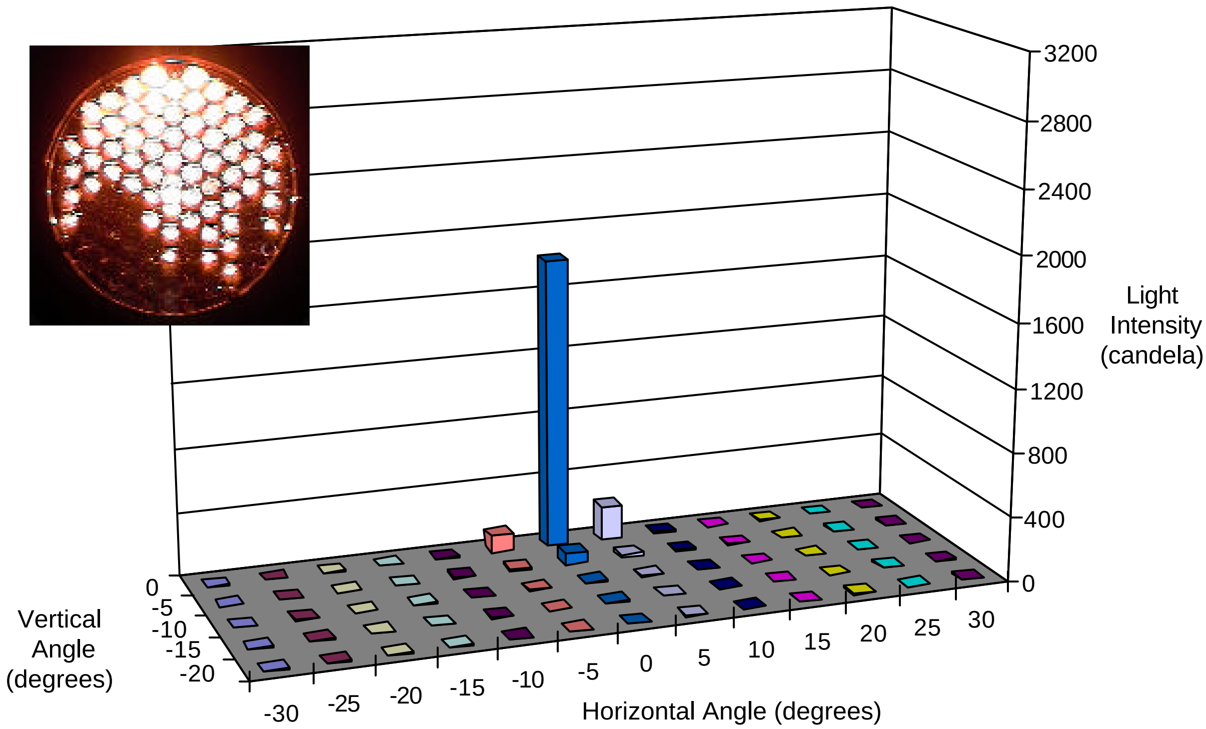

Figure A8.6.14a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

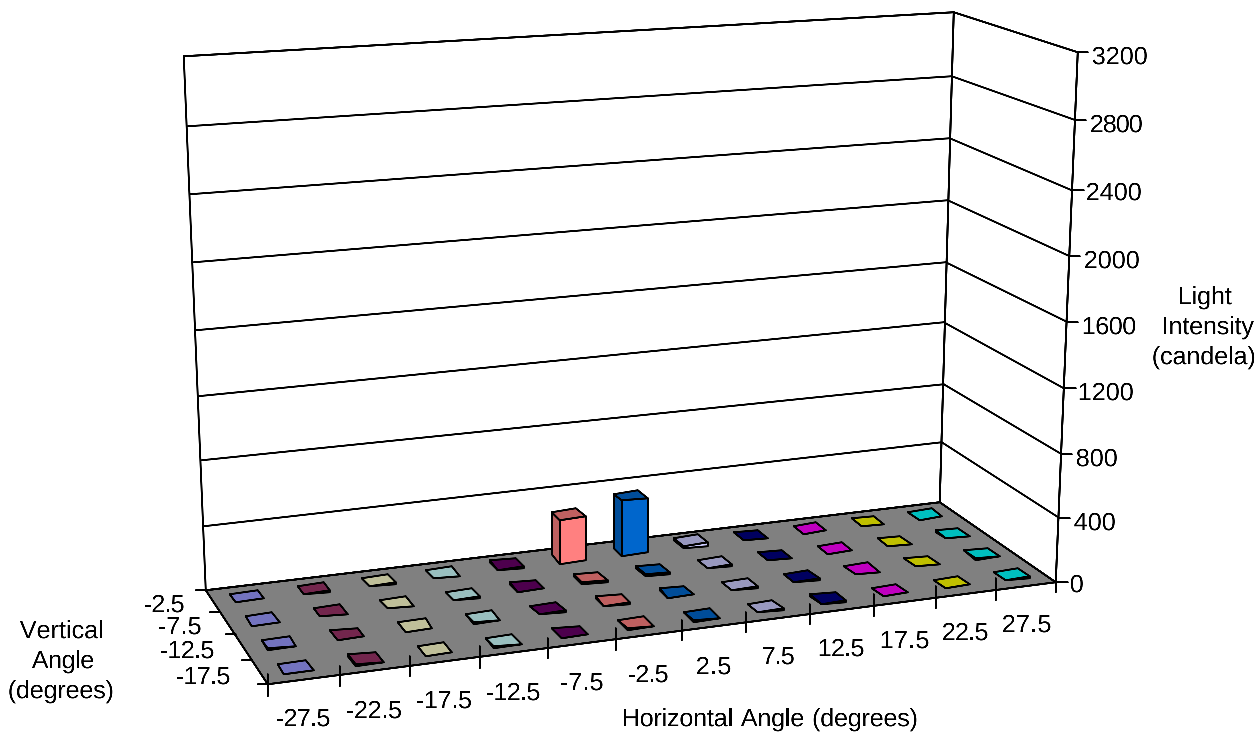

Figure A8.6.14b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

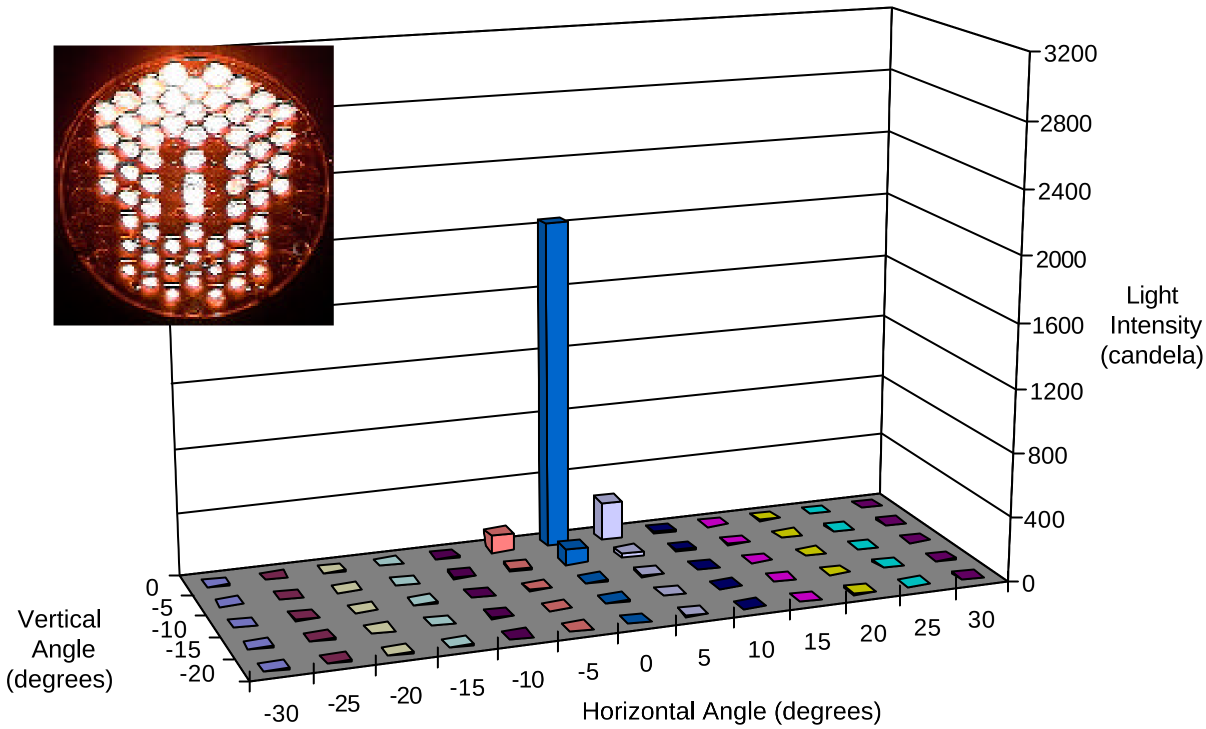

Figure A8.6.15a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

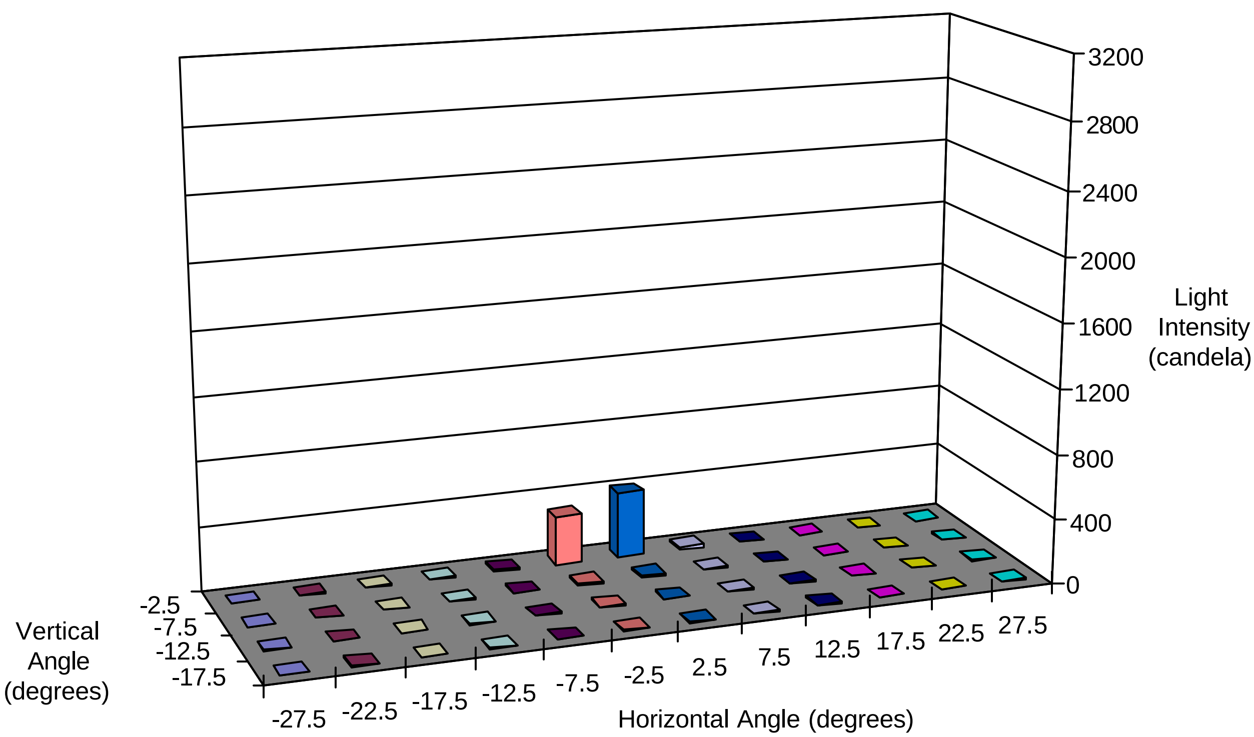

Figure A8.6.15b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

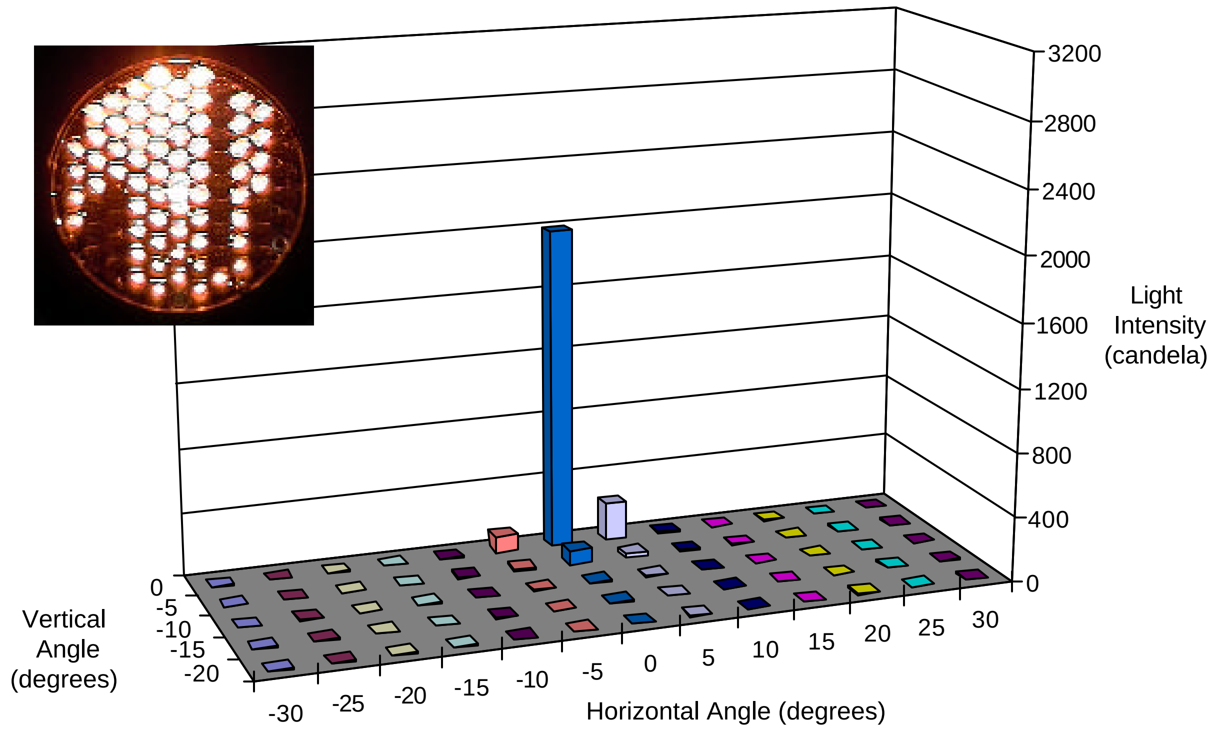

Figure A8.6.16a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

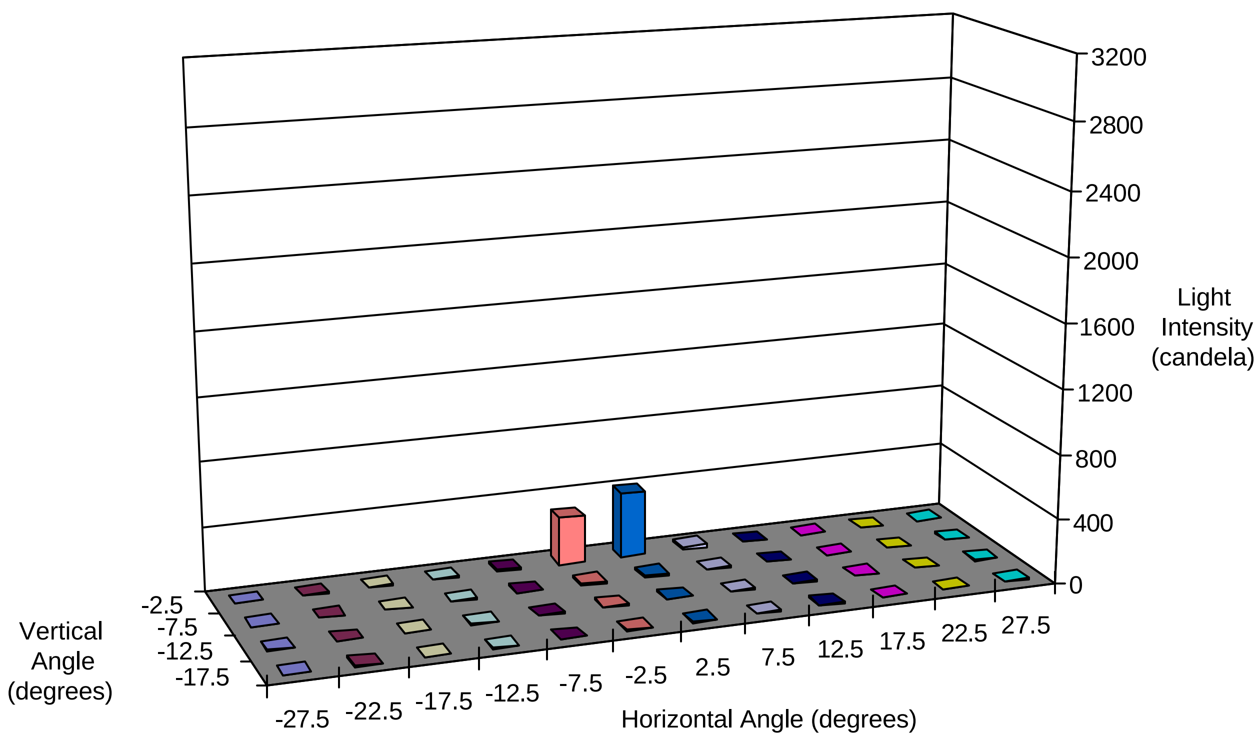

Figure A8.6.16b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

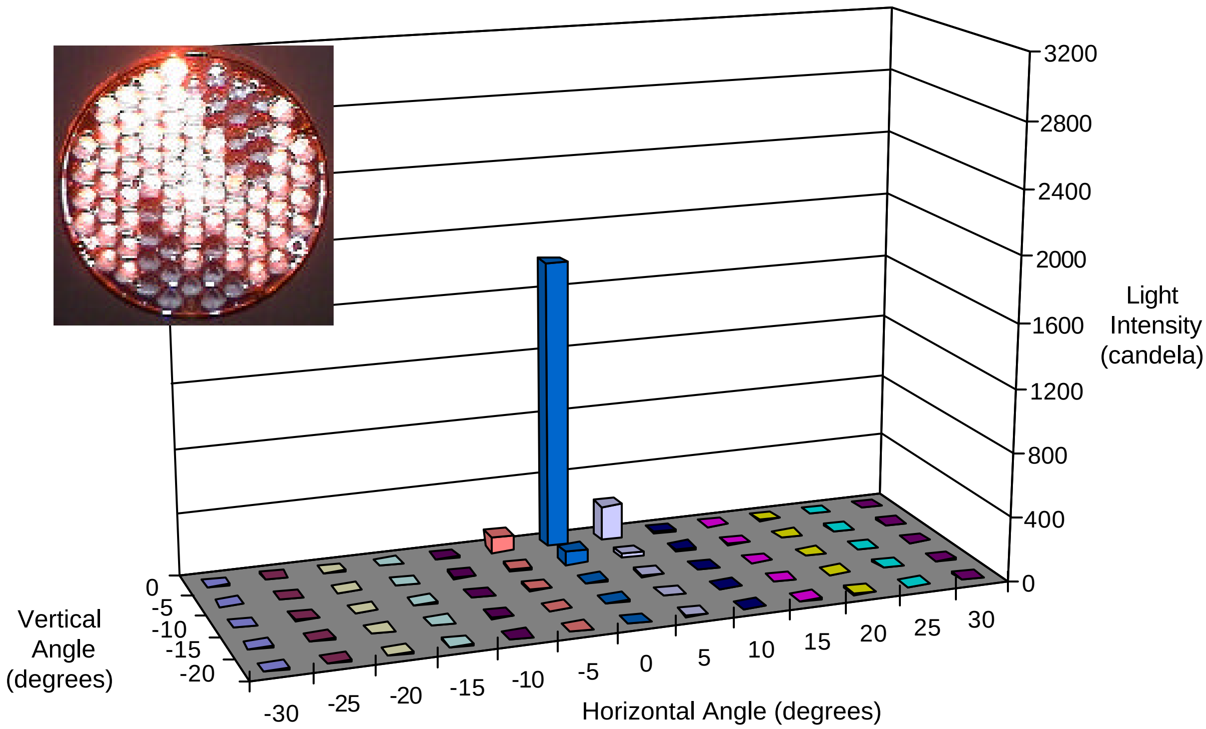

Figure A8.6.17a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

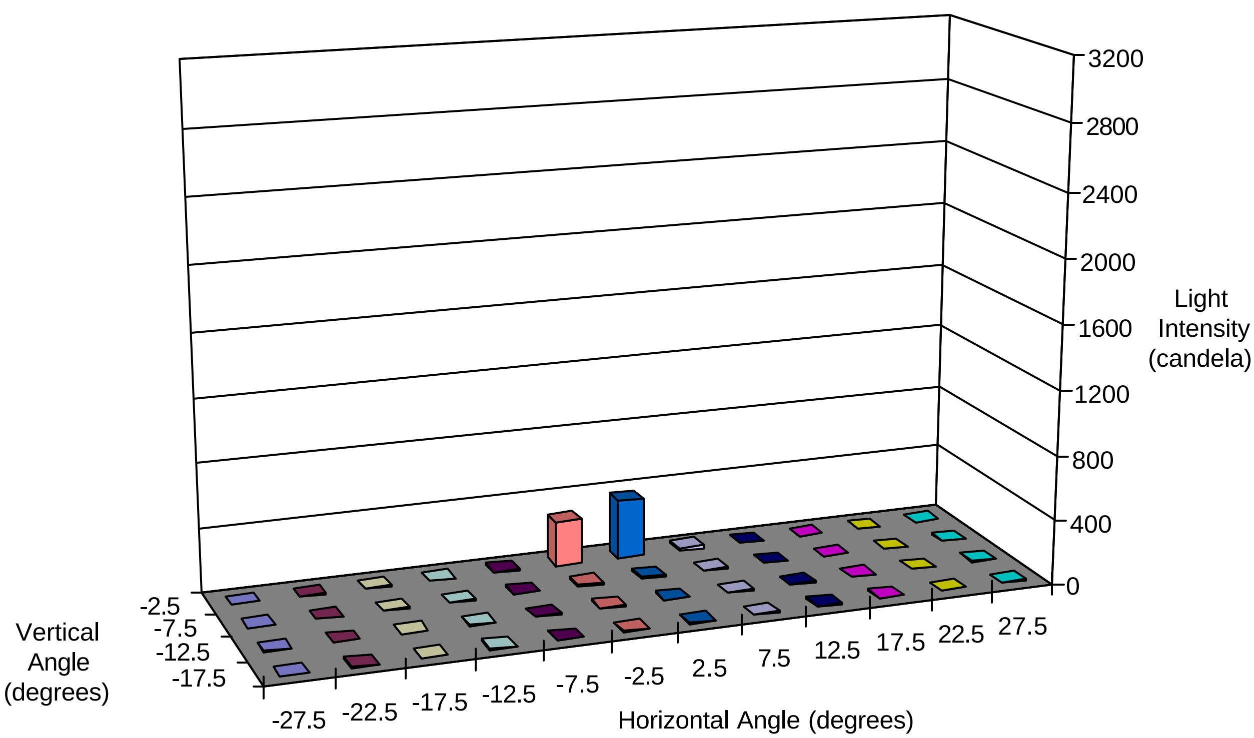

Figure A8.6.17b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

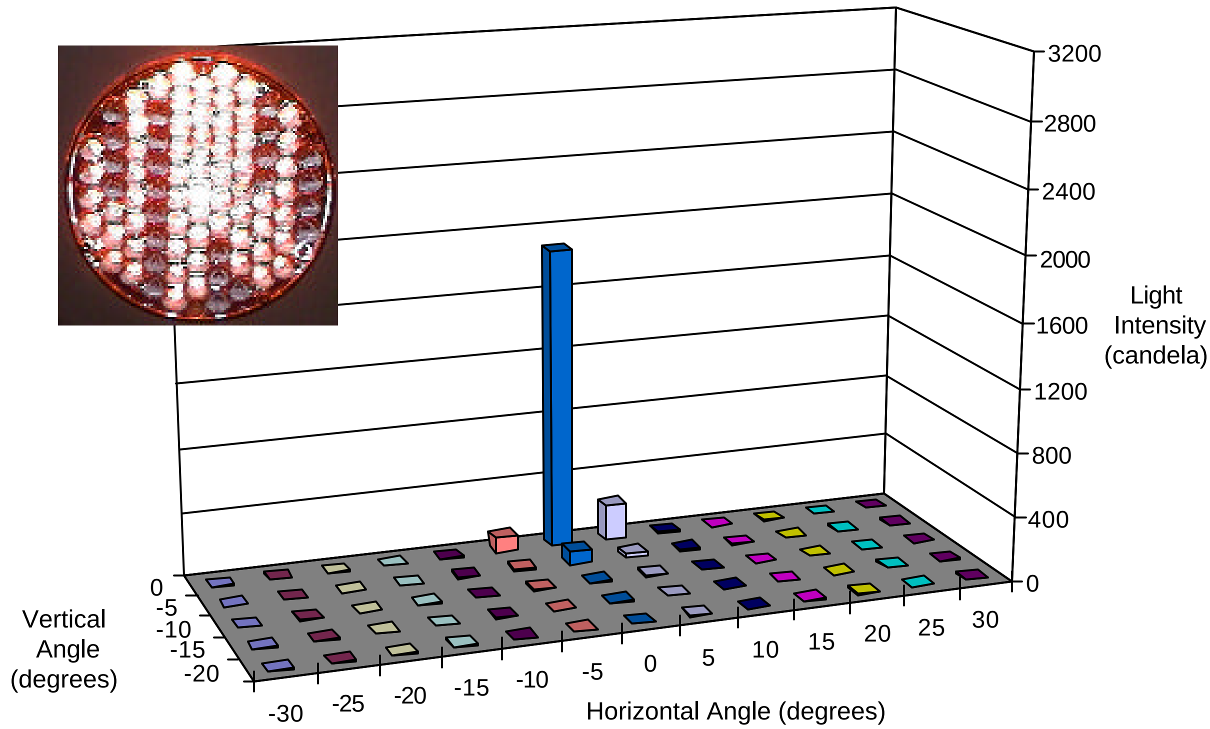

Figure A8.6.18a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

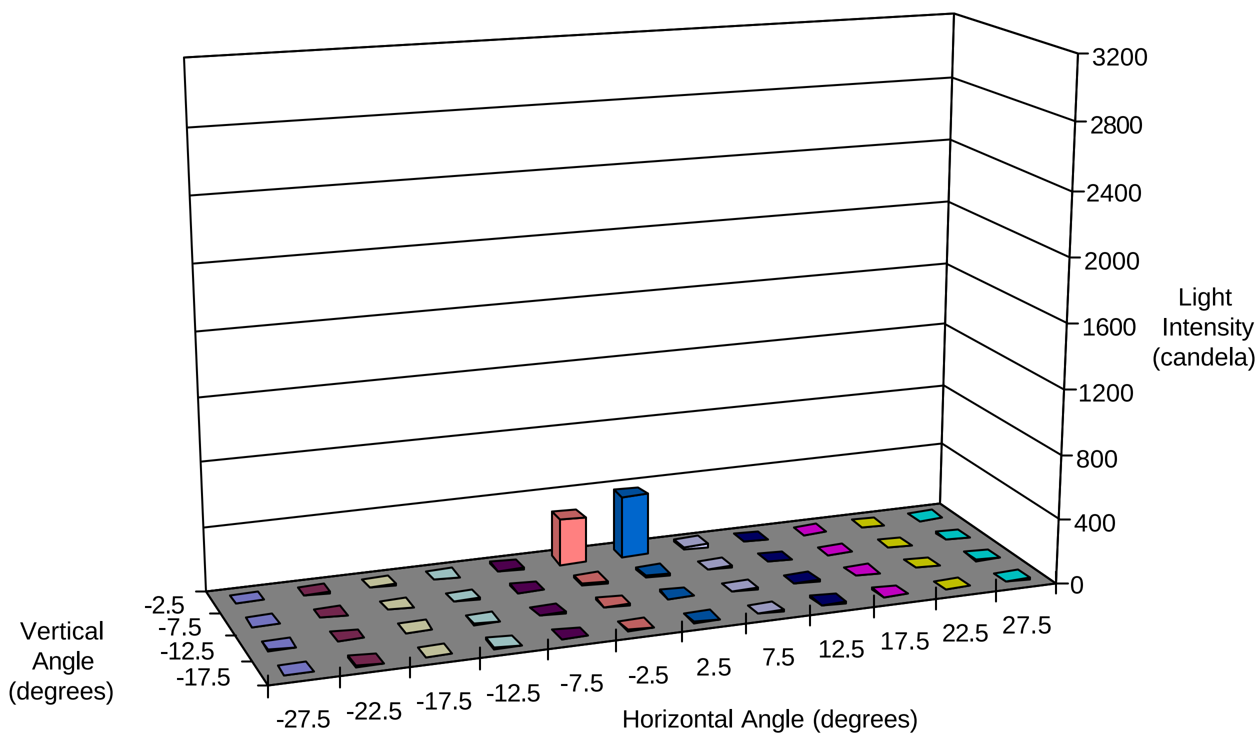

Figure A8.6.18b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

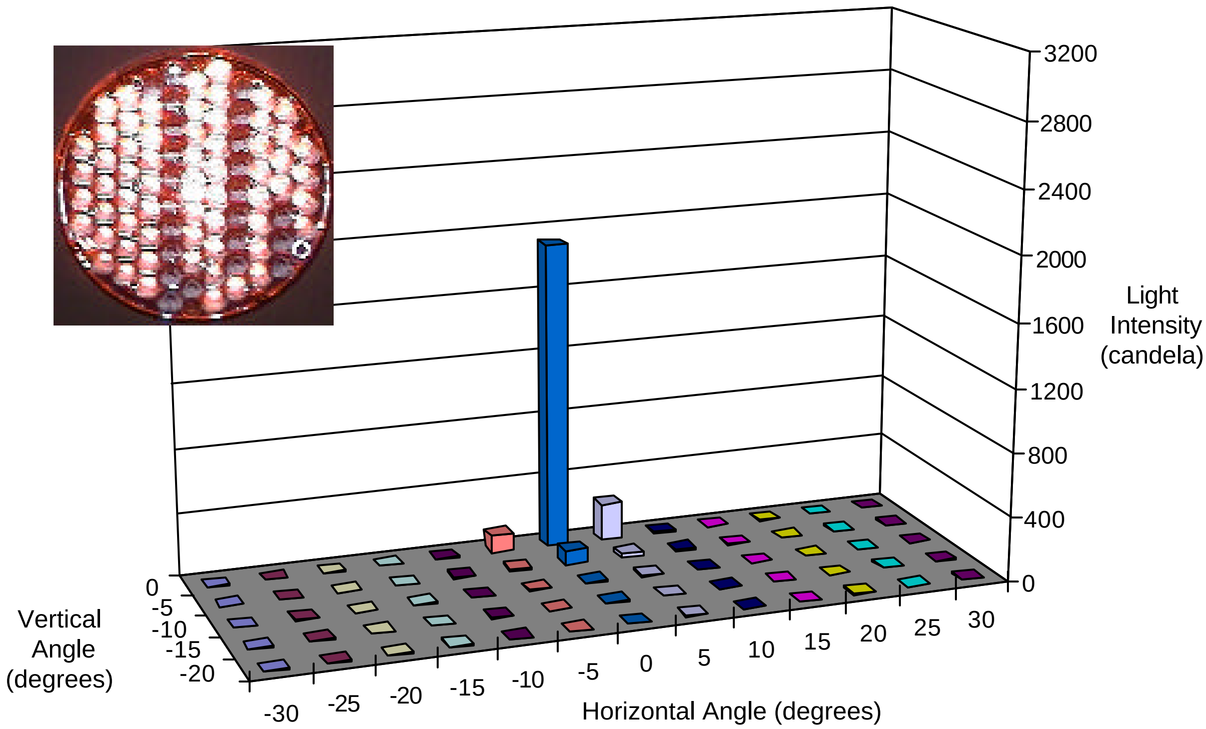

Figure A8.6.19a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

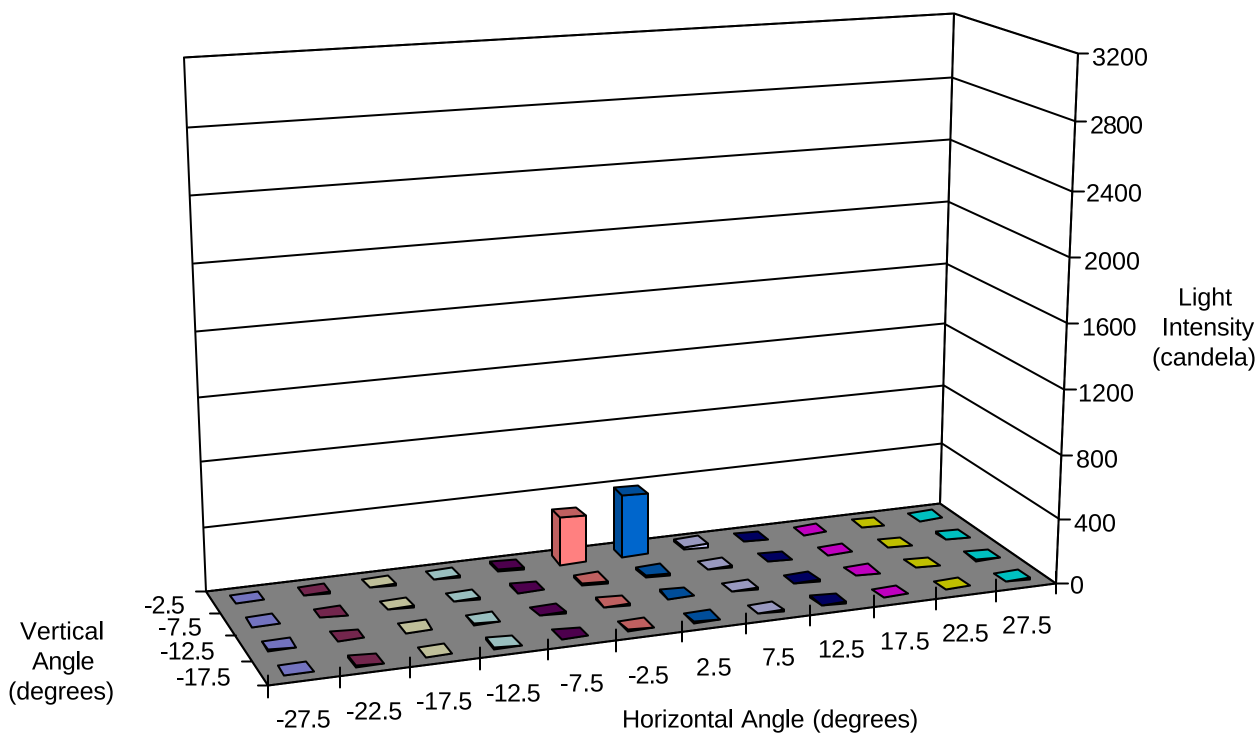

Figure A8.6.19b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

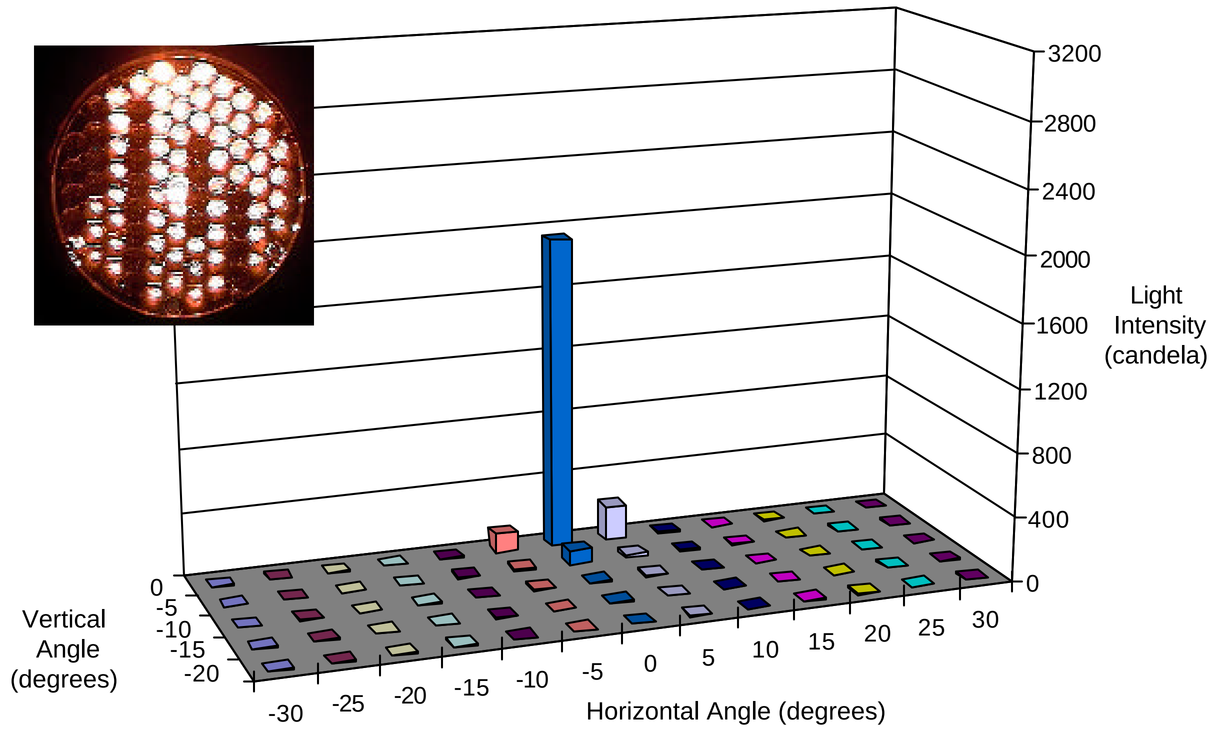

Figure A8.6.20a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

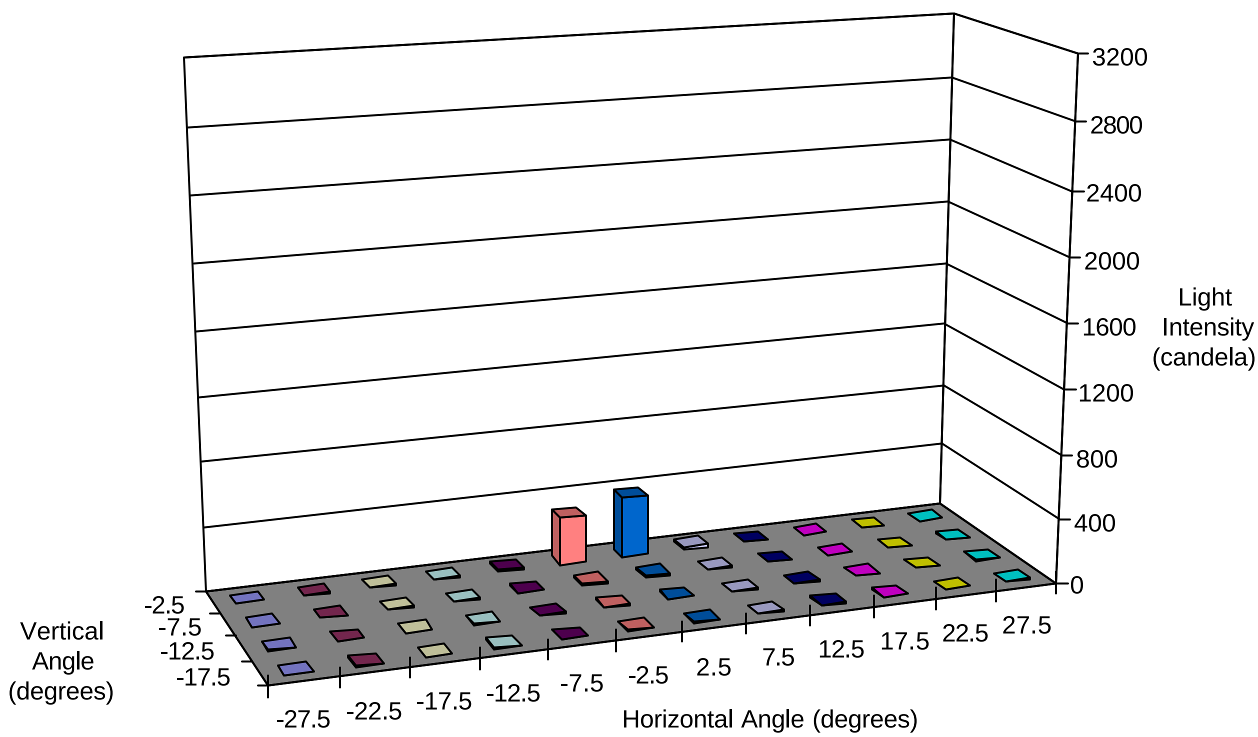

Figure A8.6.20b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

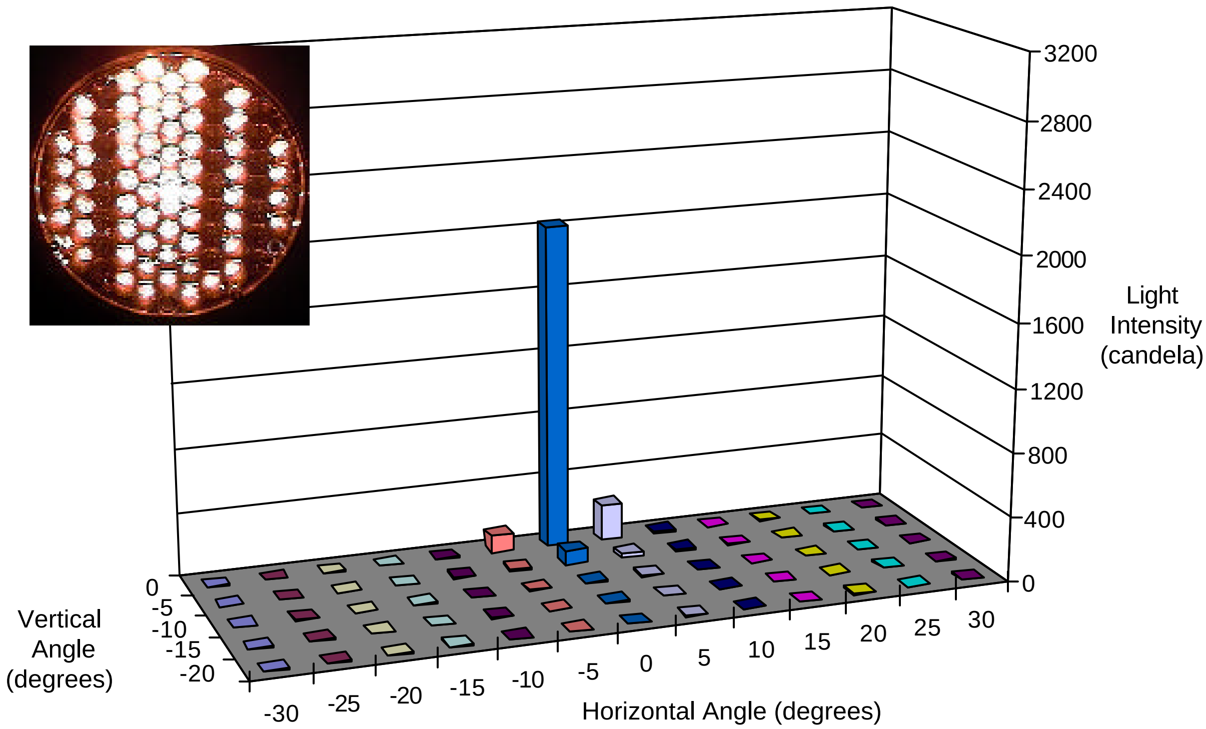

Figure A8.6.21a Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), TC test.

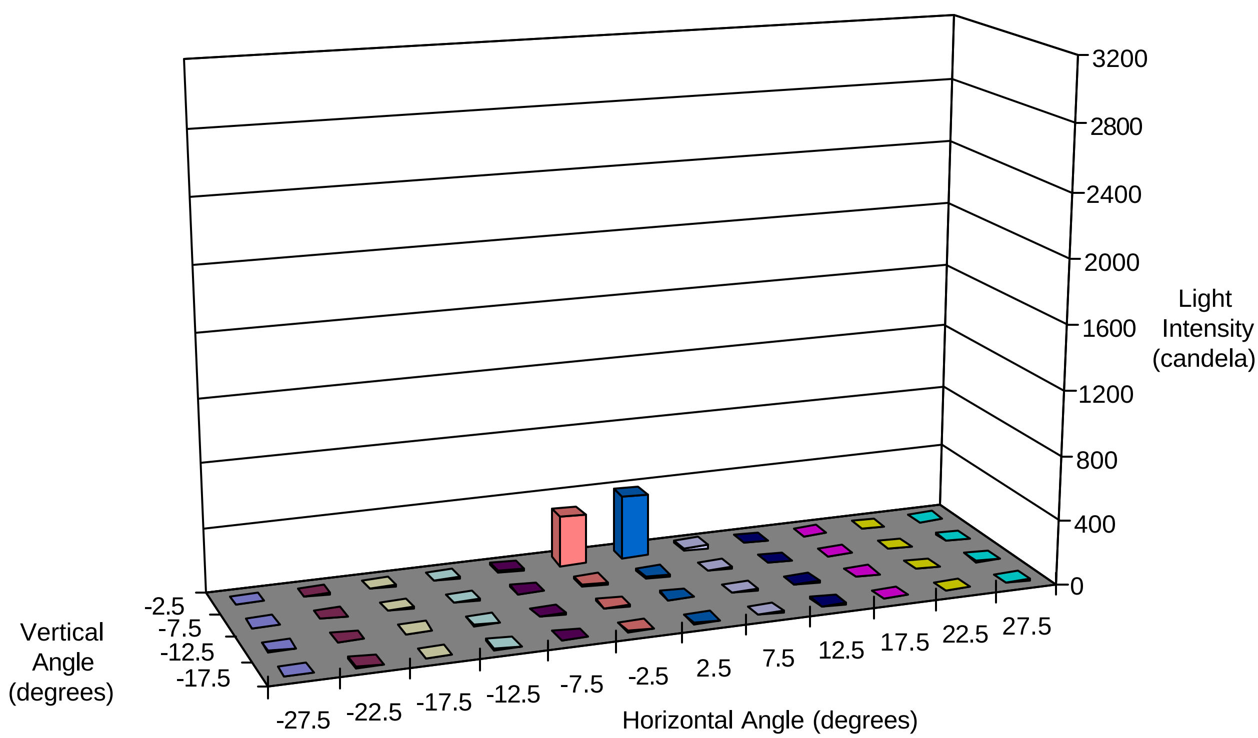

Figure A8.6.21b Output from WPS #8 (Yellow) signal, 10.0 volts, 64 elements (72.72% on), ITE test.

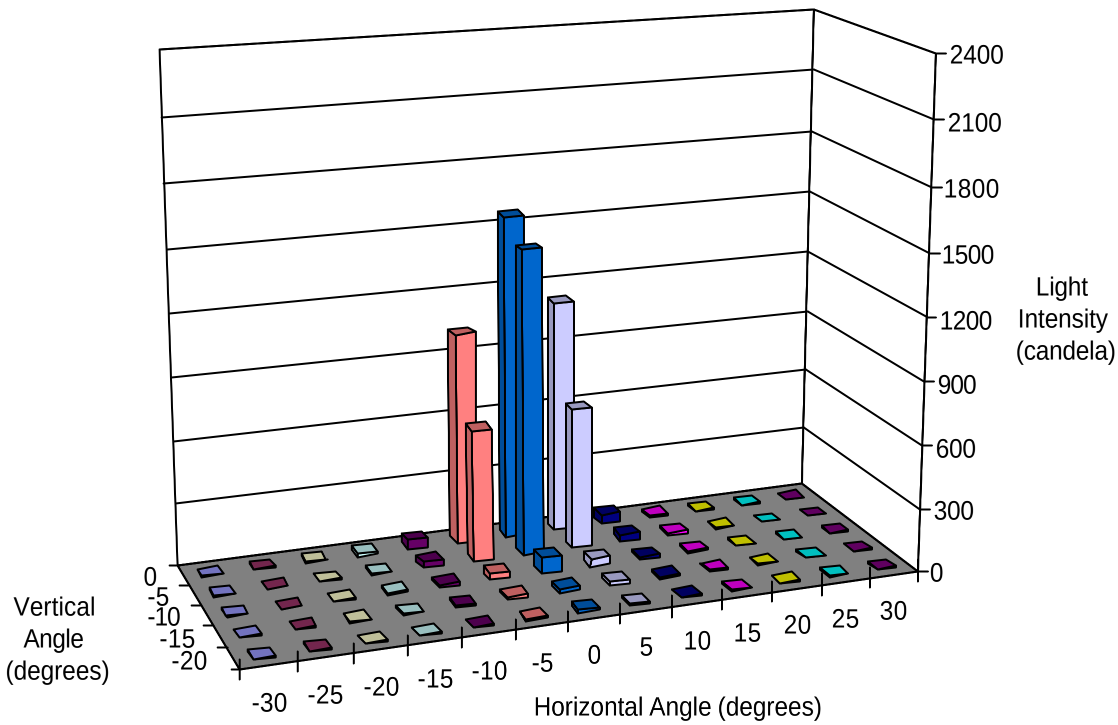

Figure A9.1.1a Output from WPS #9 (Green) signal, 10.0 volts, 38.0 ft, all elements on, TC test.

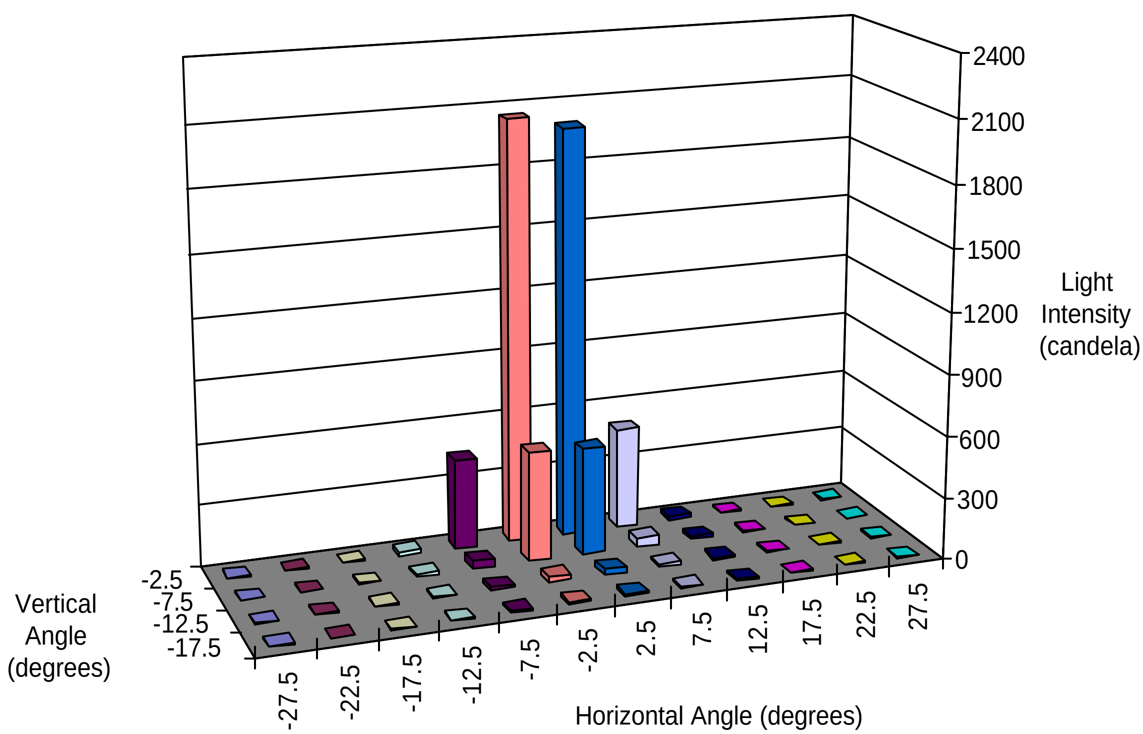

Figure A9.1.1b Output from WPS #9 (Green) signal, 10.0 volts, 38.0 ft, all elements on, ITE test.

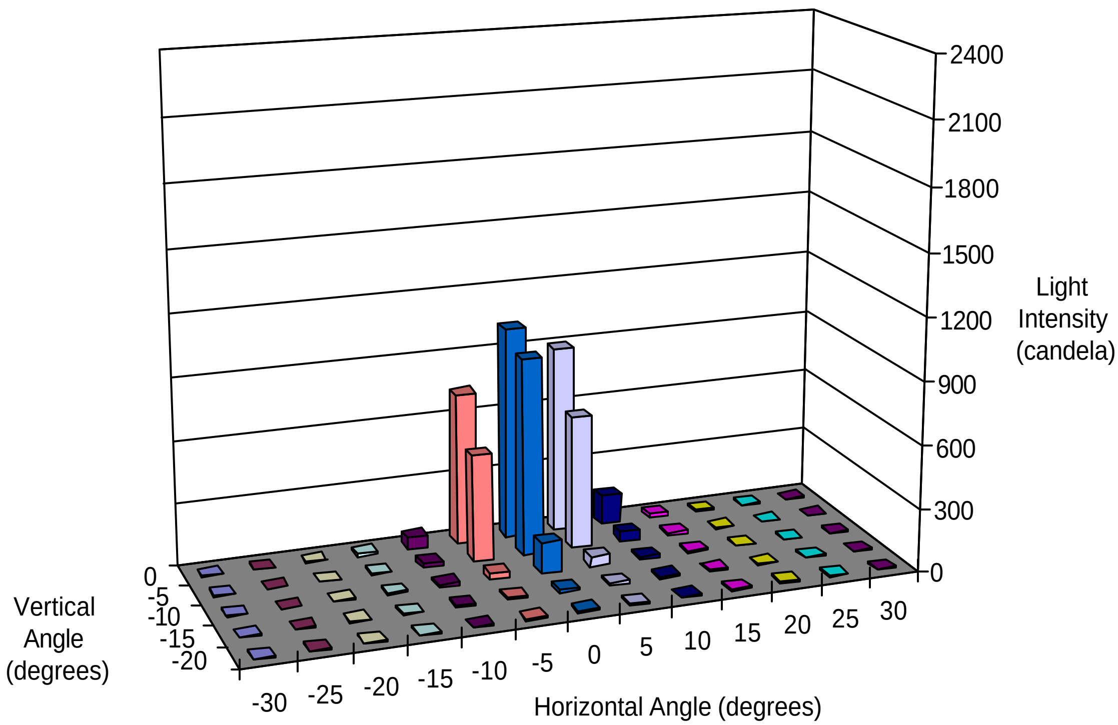

Figure A9.1.2a Output from WPS #9 (Green) signal, 12.0 volts, 38.0 ft, all elements on, TC test.

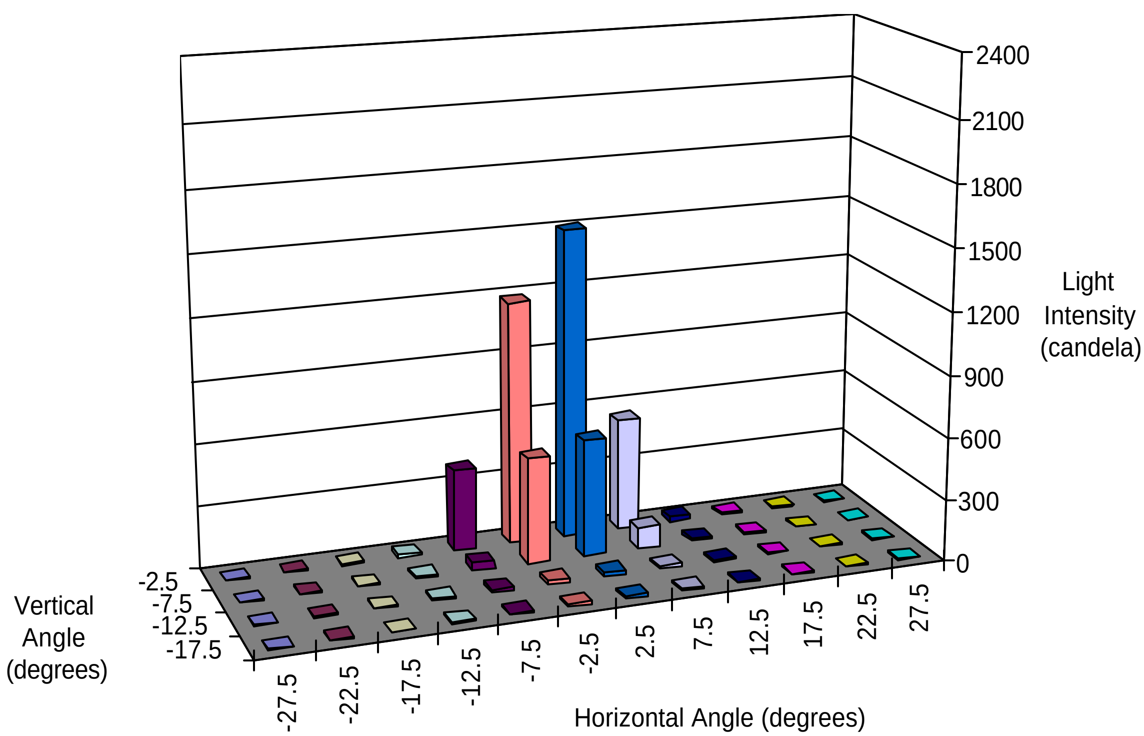

Figure A9.1.2b Output from WPS #9 (Green) signal, 12.0 volts, 38.0 ft, all elements on, ITE test.

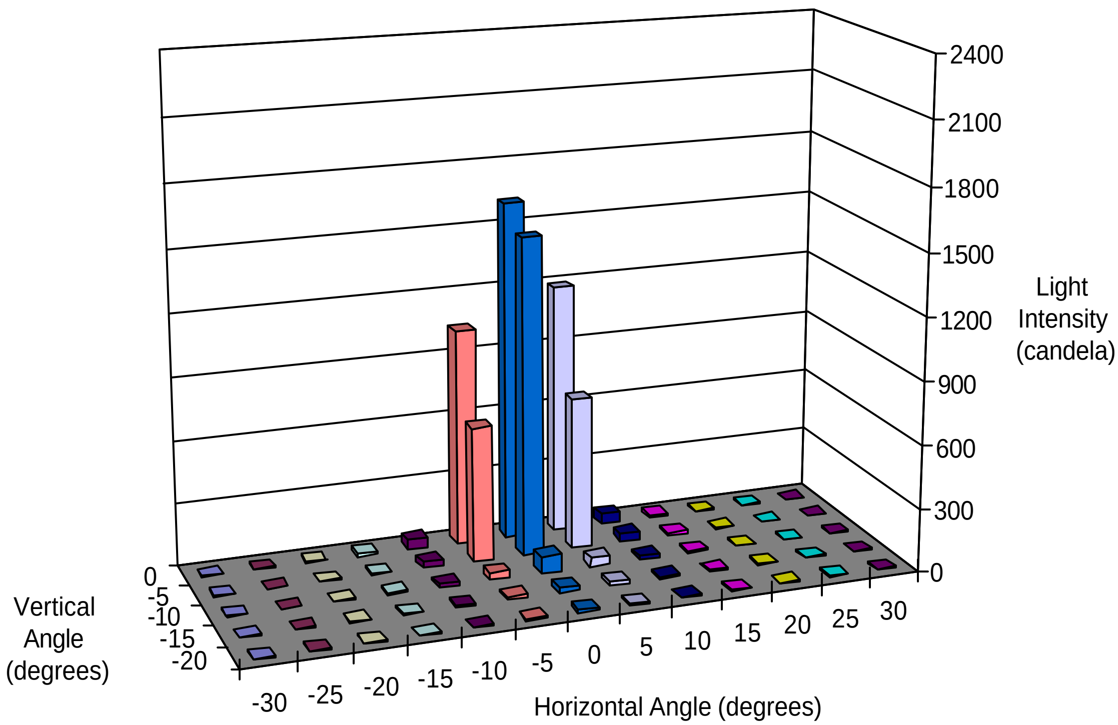

Figure A9.1.3a Output from WPS #9 (Green) signal, 10.0 volts, 40.0 ft, all elements on, TC test.

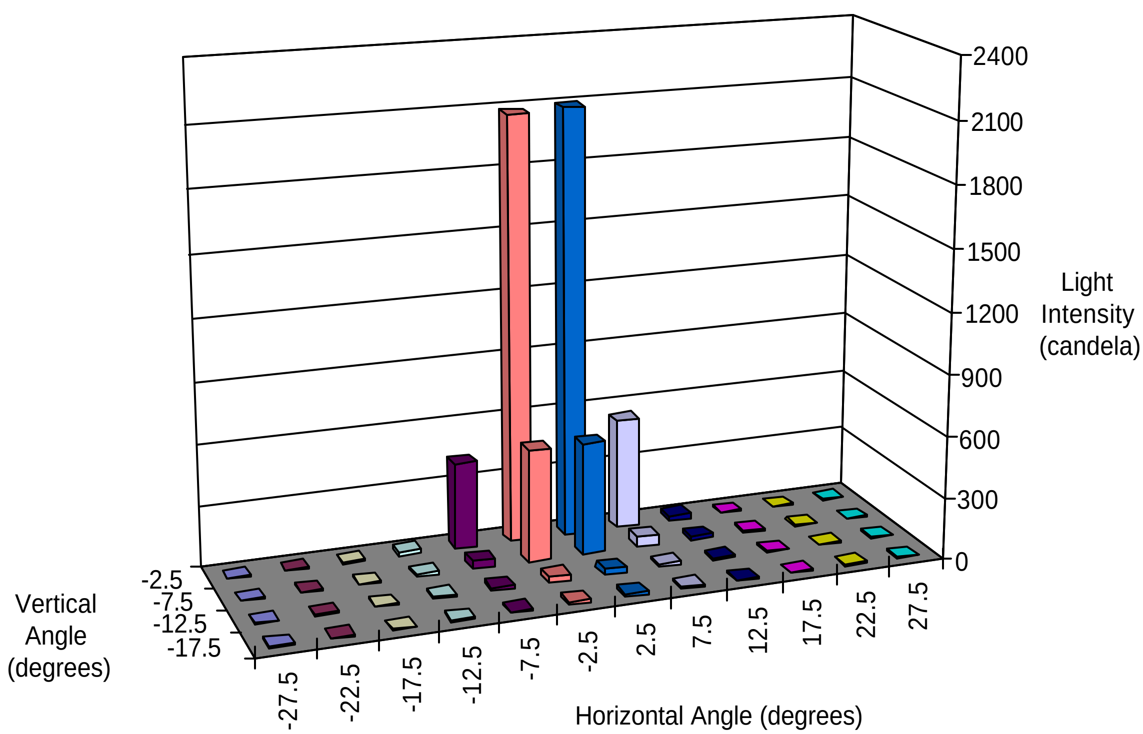

Figure A9.1.3b Output from WPS #9 (Green) signal, 10.0 volts, 40.0 ft, all elements on, ITE test.

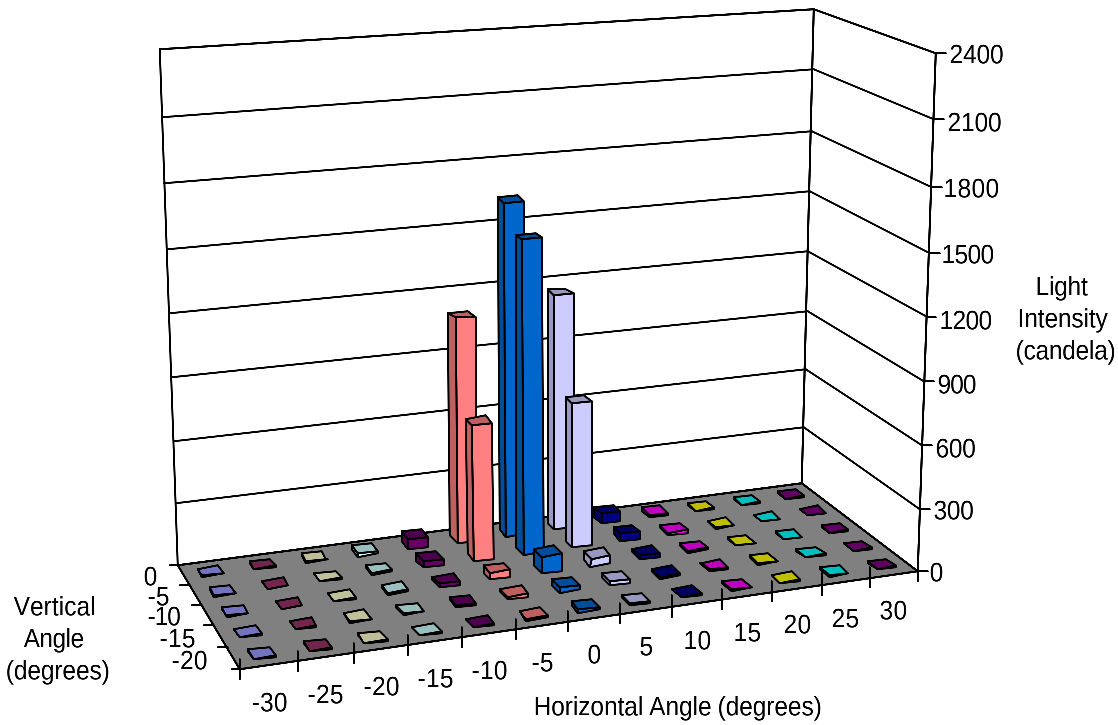

Figure A9.1.4a Output from WPS #9 (Green) signal, 10.0 volts, 42.0 ft, all elements on, TC test.

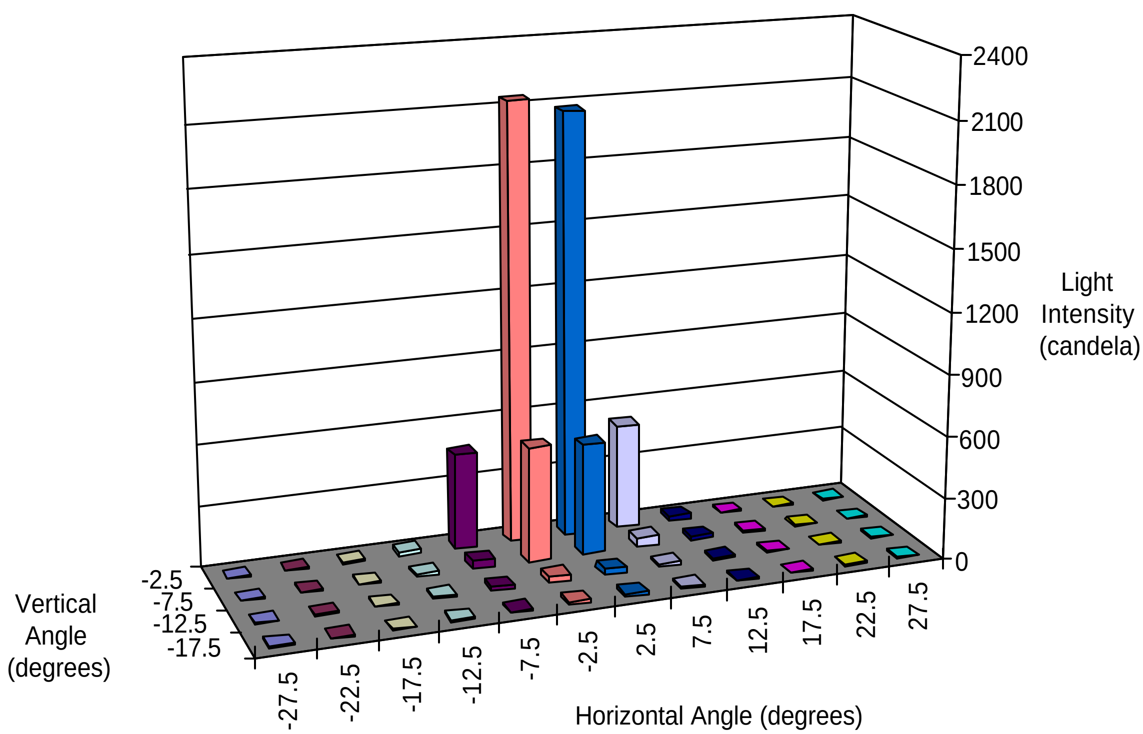

Figure A9.1.4b Output from WPS #9 (Green) signal, 10.0 volts, 42.0 ft, all elements on, ITE test.

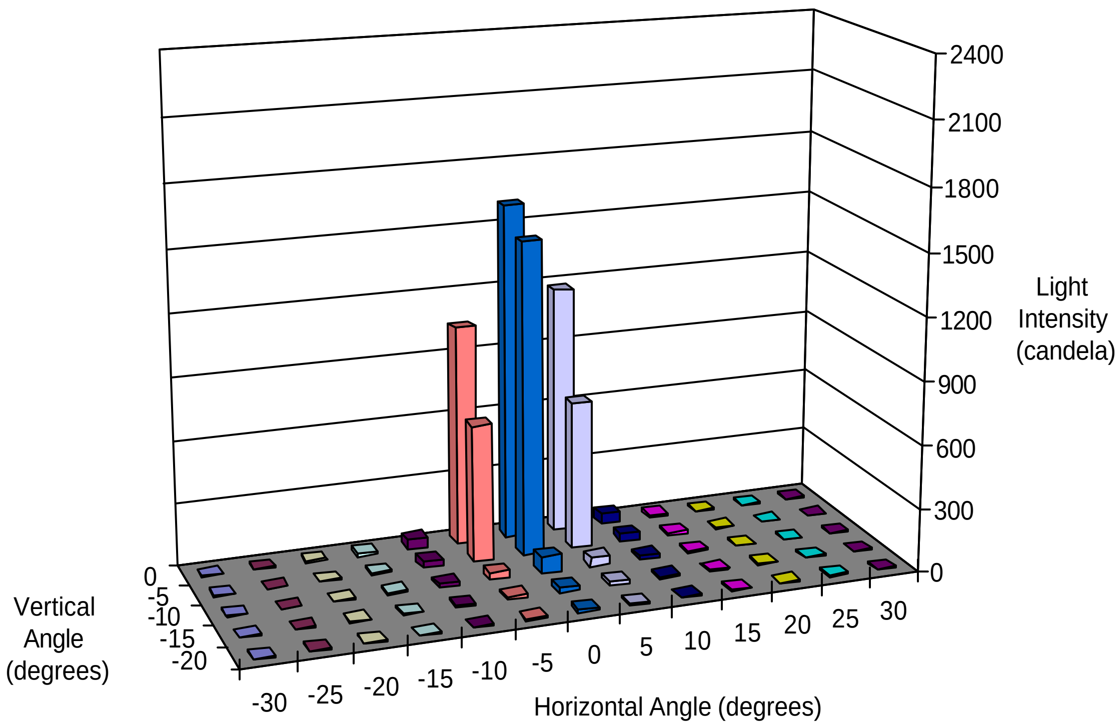

Figure A9.1.5a Output from WPS #9 (Green) signal, 10.0 volts, 44.0 ft, all elements on, TC test.

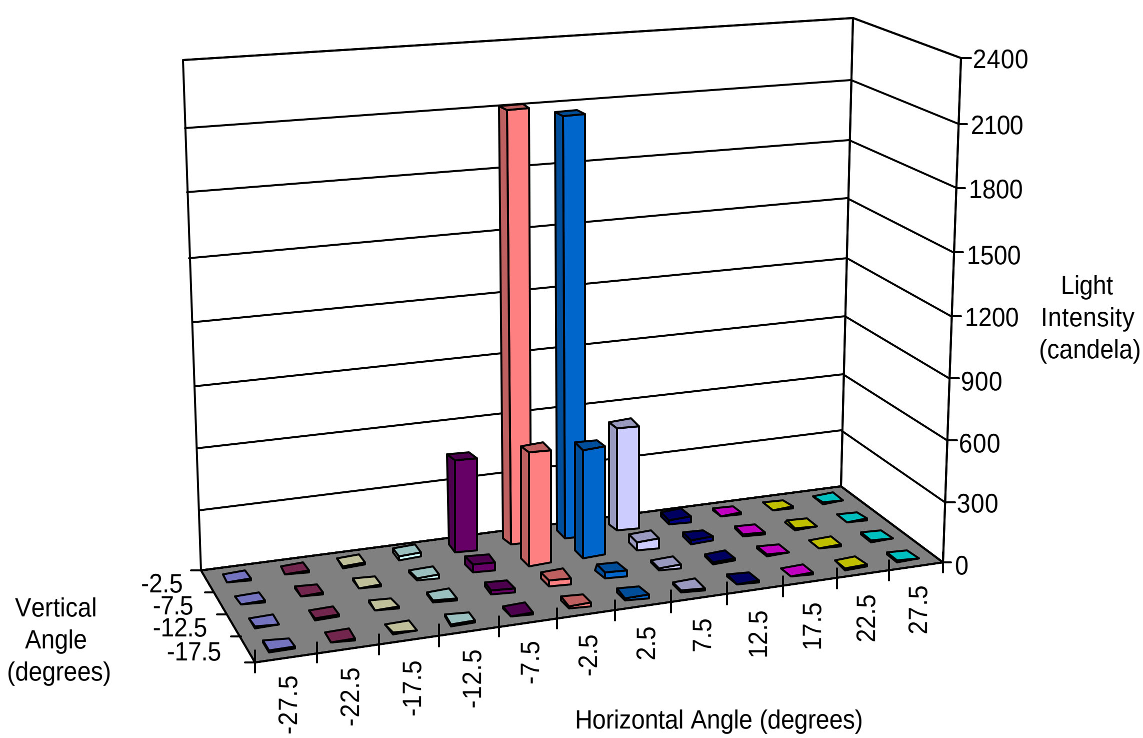

Figure A9.1.5b Output from WPS #9 (Green) signal, 10.0 volts, 44.0 ft, all elements on, ITE test.

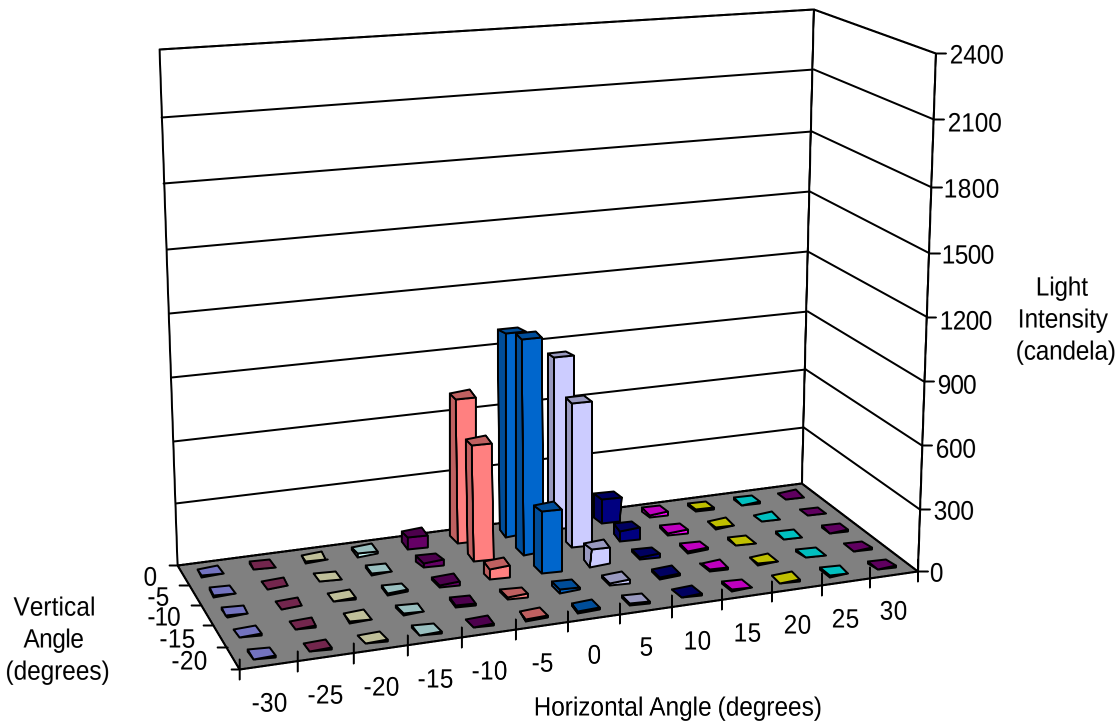

Figure A9.1.6a Output from WPS #9 (Green) signal, 10.0 volts, 34.0 ft, all elements on, TC test.

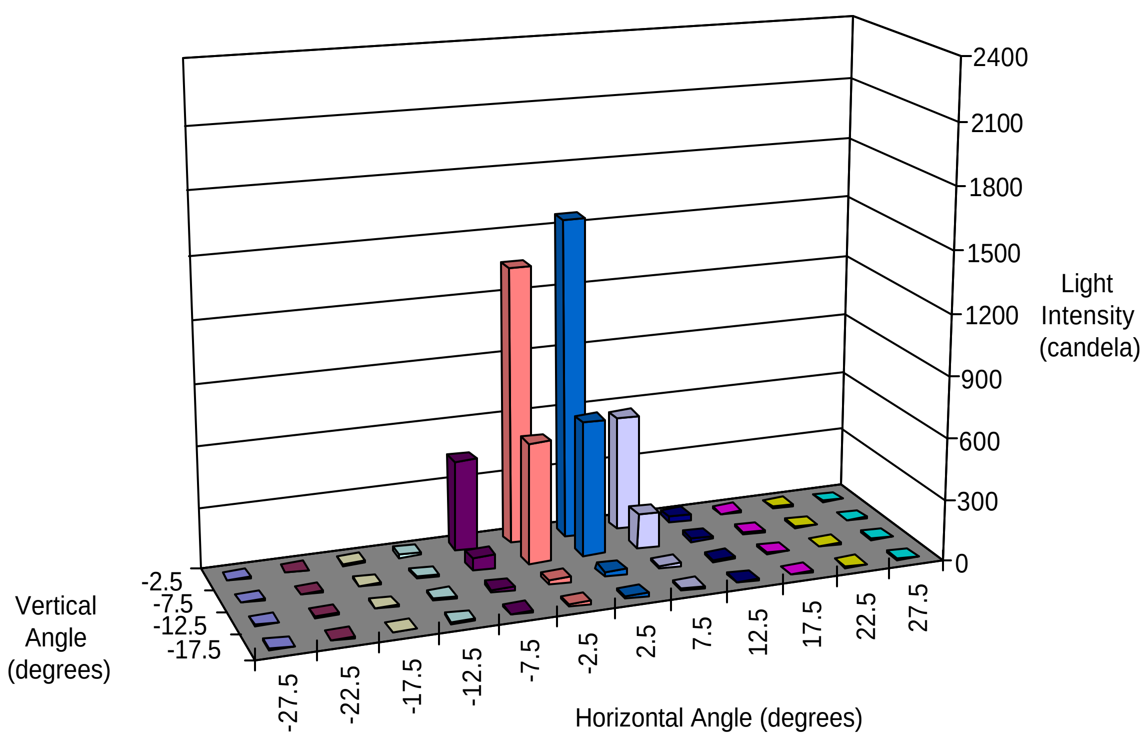

Figure A9.1.6b Output from WPS #9 (Green) signal, 10.0 volts, 34.0 ft, all elements on, ITE test.

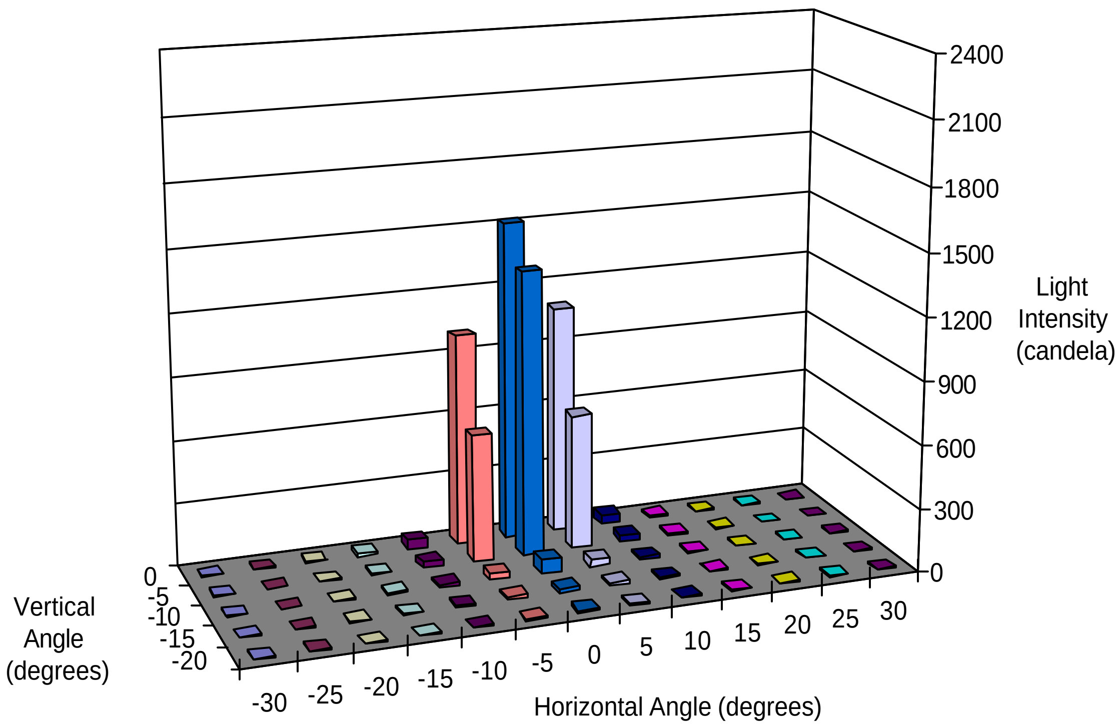

Figure A9.1.7a Output from WPS #9 (Green) signal, 10.0 volts, 36.0 ft, all elements on, TC test.

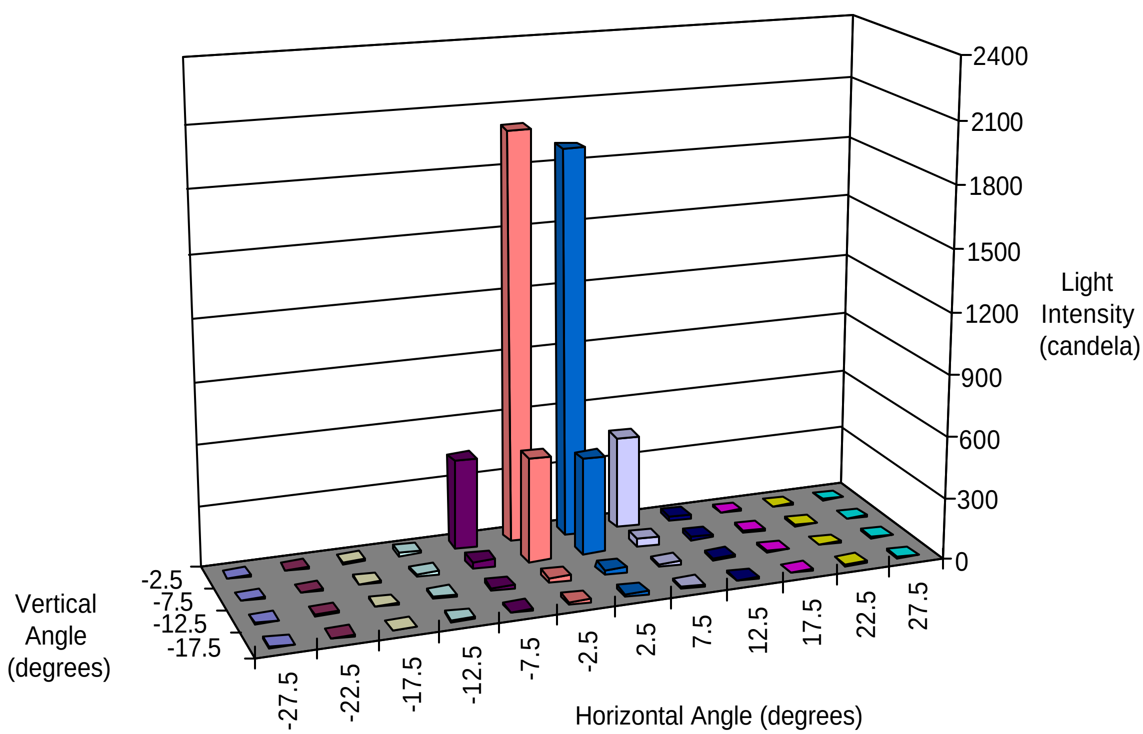

Figure A9.1.7b Output from WPS #9 (Green) signal, 10.0 volts, 36.0 ft, all elements on, ITE test.

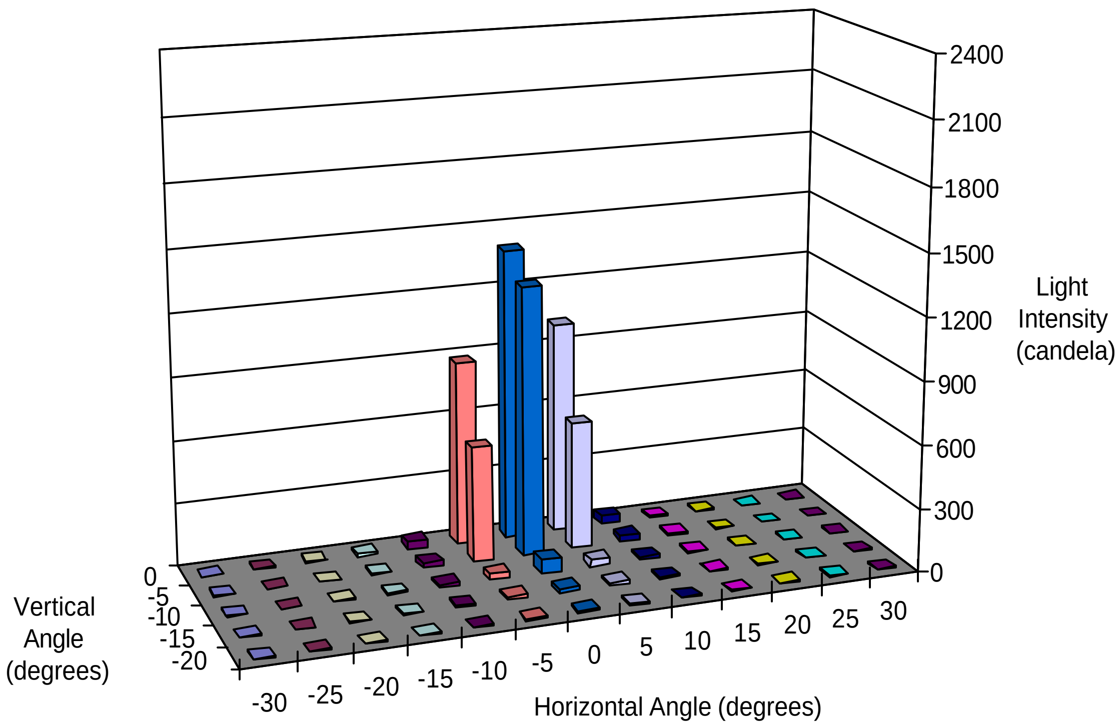

Figure A9.1.8a Output from WPS #9 (Green) signal, 10.0 volts, 32.0 ft, all elements on, TC test.

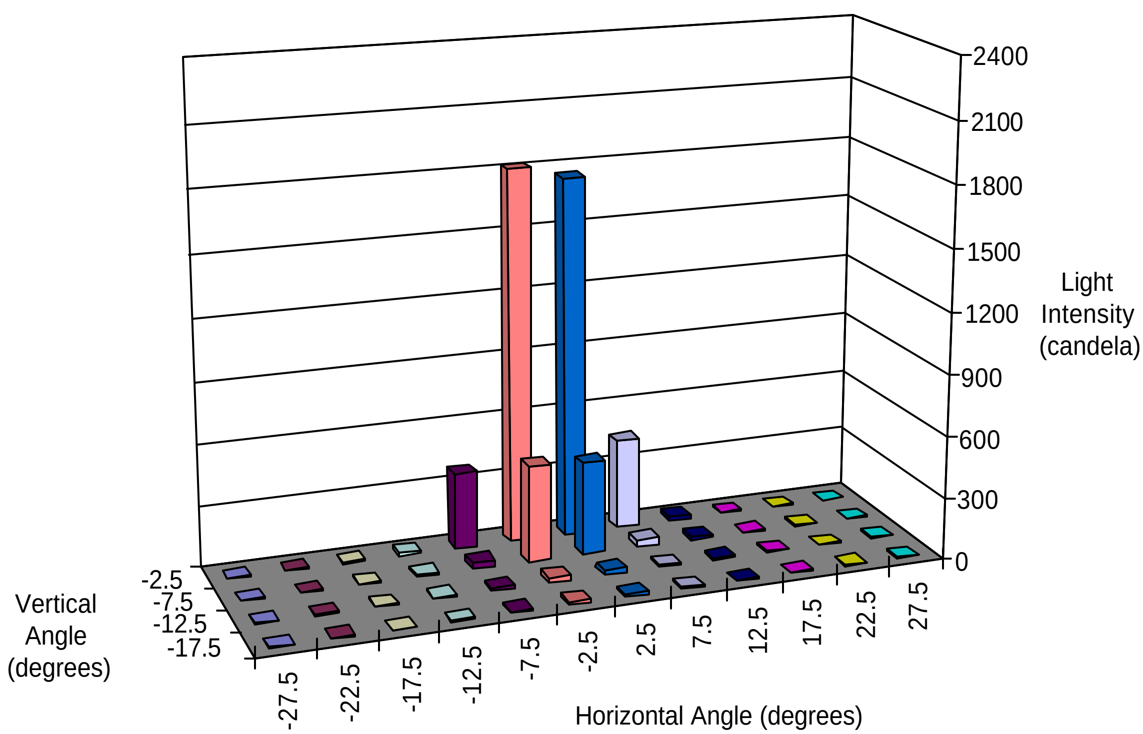

Figure A9.1.8b Output from WPS #9 (Green) signal, 10.0 volts, 32.0 ft, all elements on, ITE test.

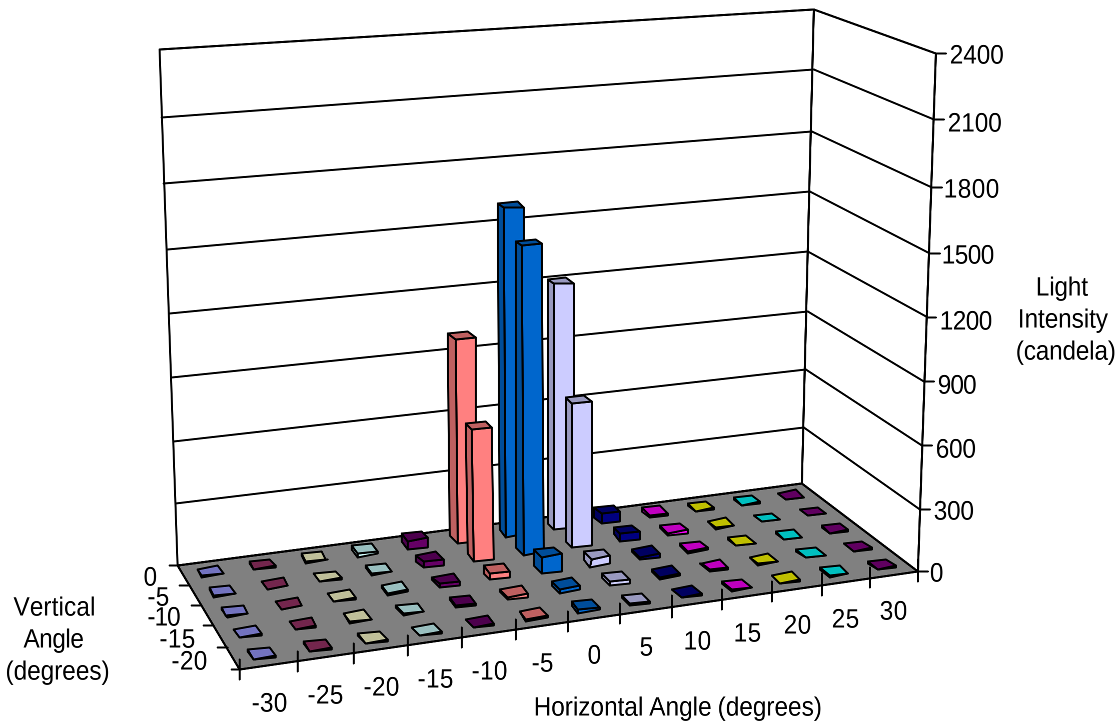

Figure A9.1.9a Output from WPS #9 (Green) signal, 8.0 volts, 38.0 ft, all elements on, TC test.

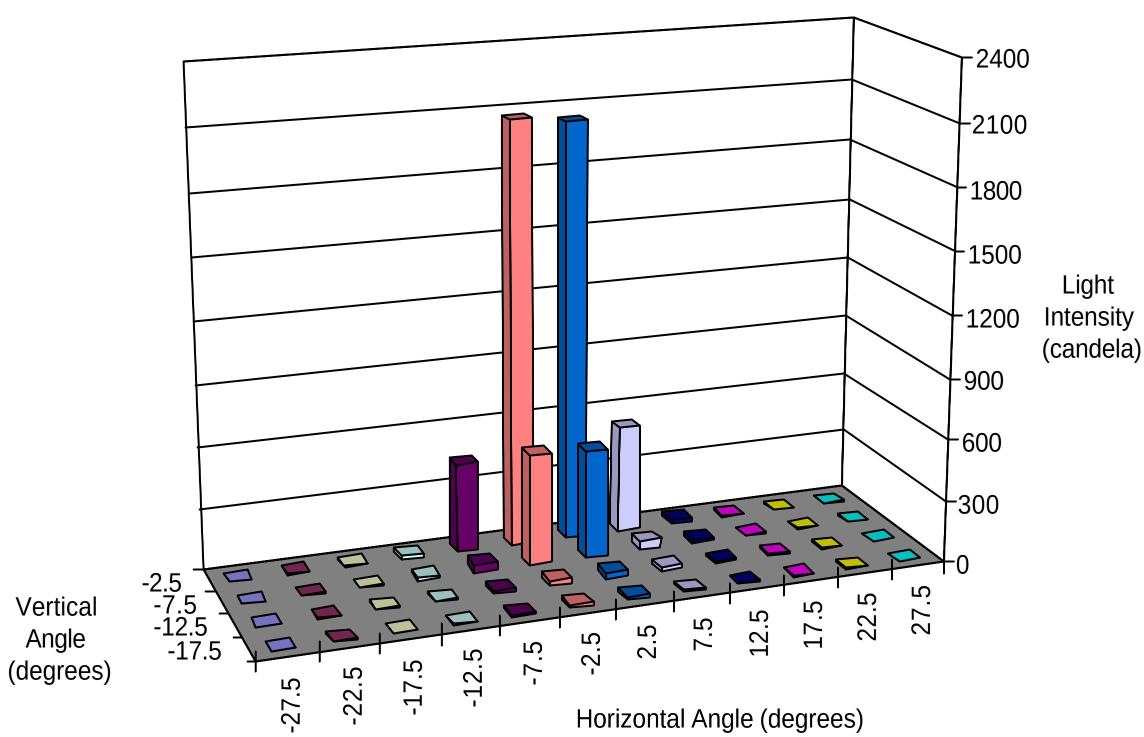

Figure A9.1.9b Output from WPS #9 (Green) signal, 8.0 volts, 38.0 ft, all elements on, ITE test.

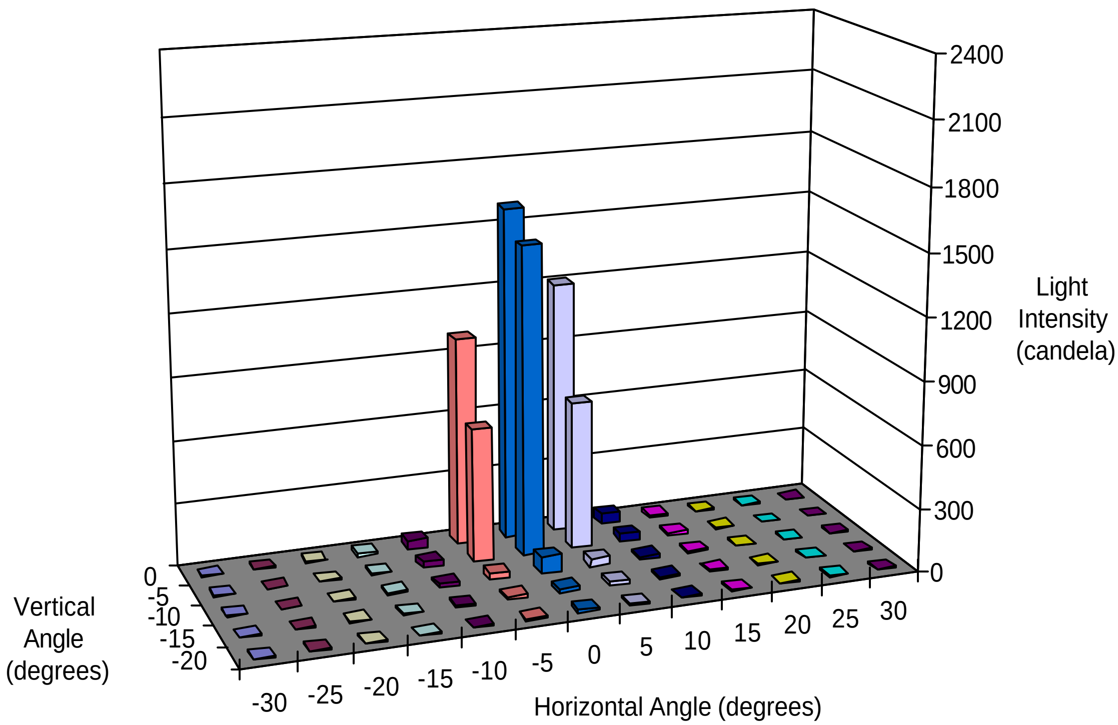

Figure A9.1.10a Output from WPS #9 (Green) signal, 9.0 volts, 38.0 ft, all elements on, TC test.

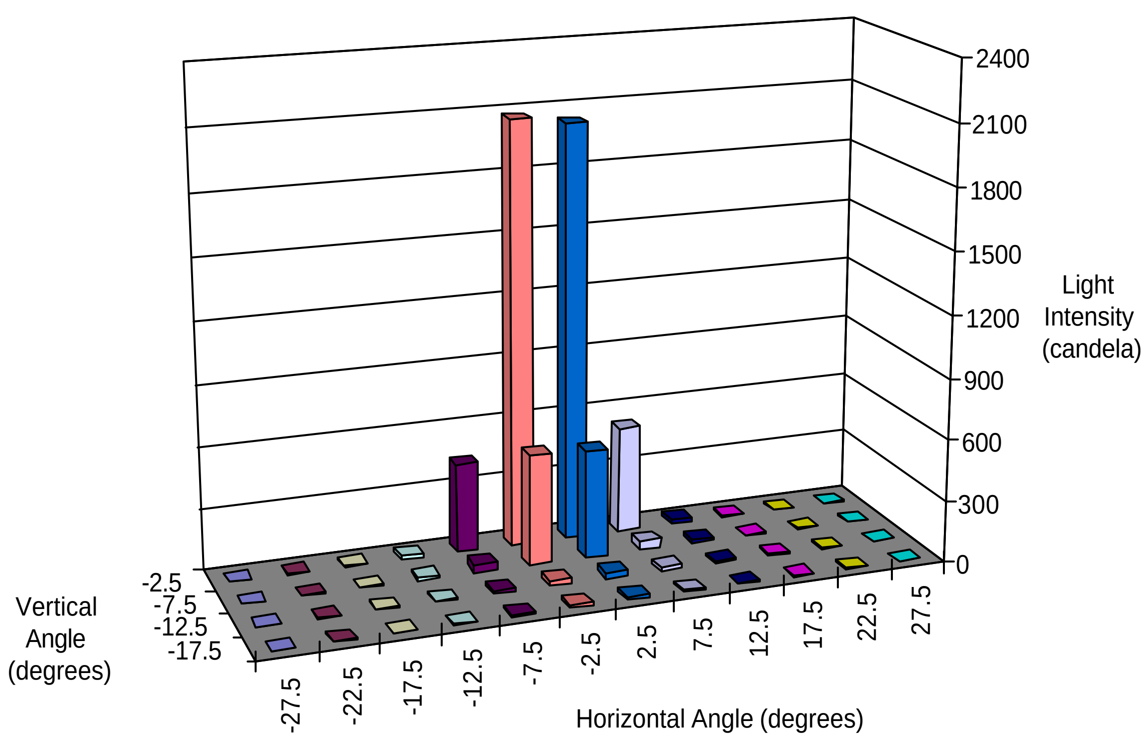

Figure A9.1.10b Output from WPS #9 (Green) signal, 9.0 volts, 38.0 ft, all elements on, ITE test.

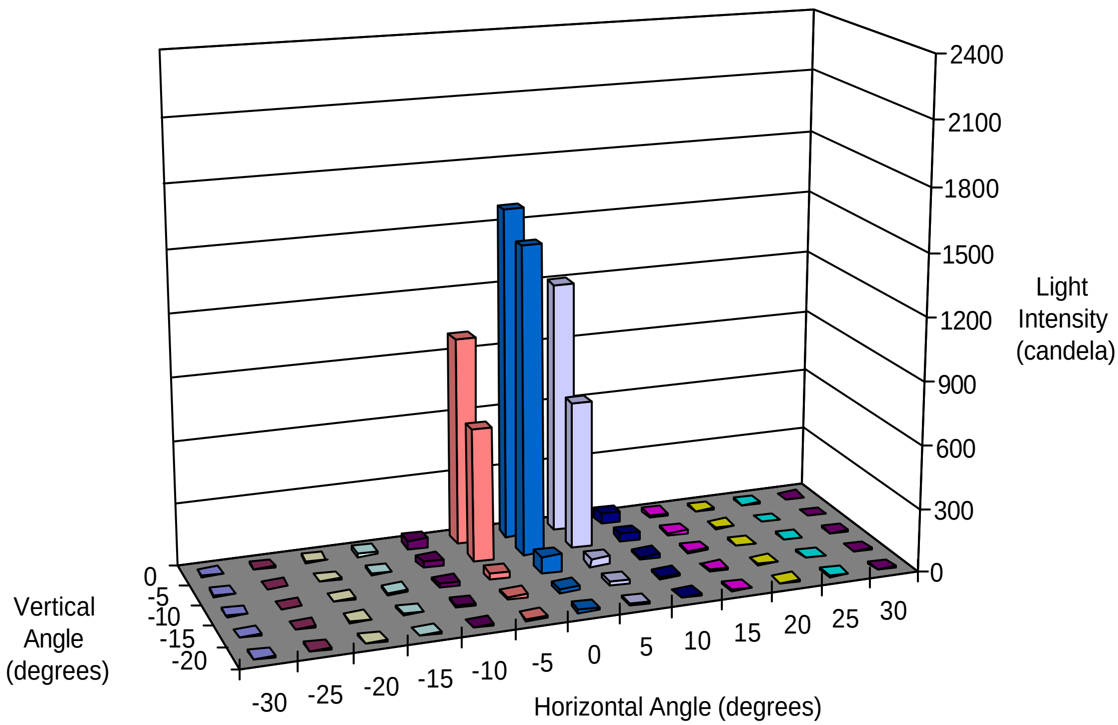

Figure A9.1.11a Output from WPS #9 (Green) signal, 10.5 volts, 38.0 ft, all elements on, TC test.

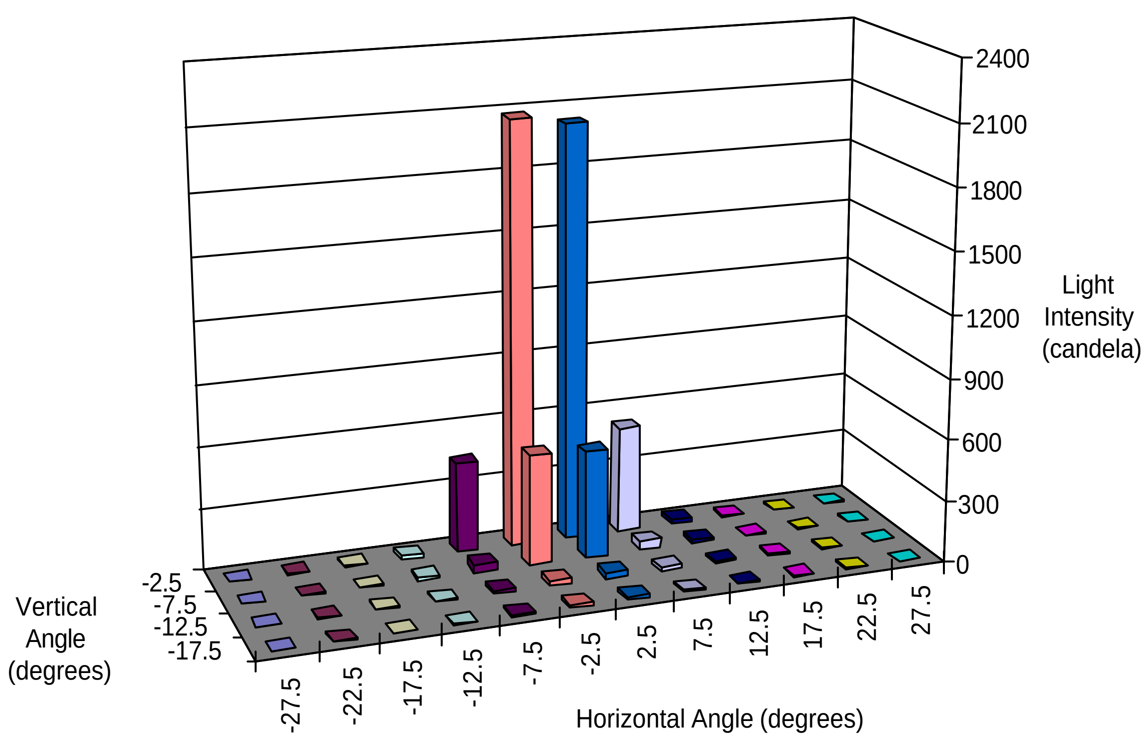

Figure A9.1.11b Output from WPS #9 (Green) signal, 10.5 volts, 38.0 ft, all elements on, ITE test.

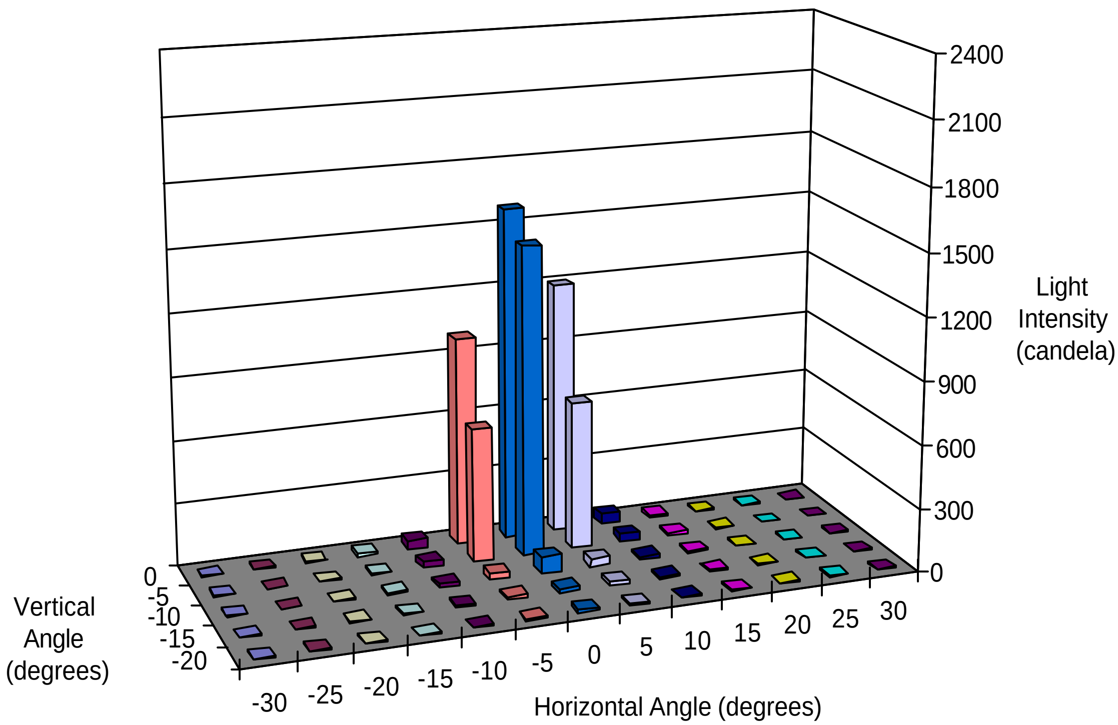

Figure A9.1.12a Output from WPS #9 (Green) signal, 13.5 volts, 38.0 ft, all elements on, TC test.

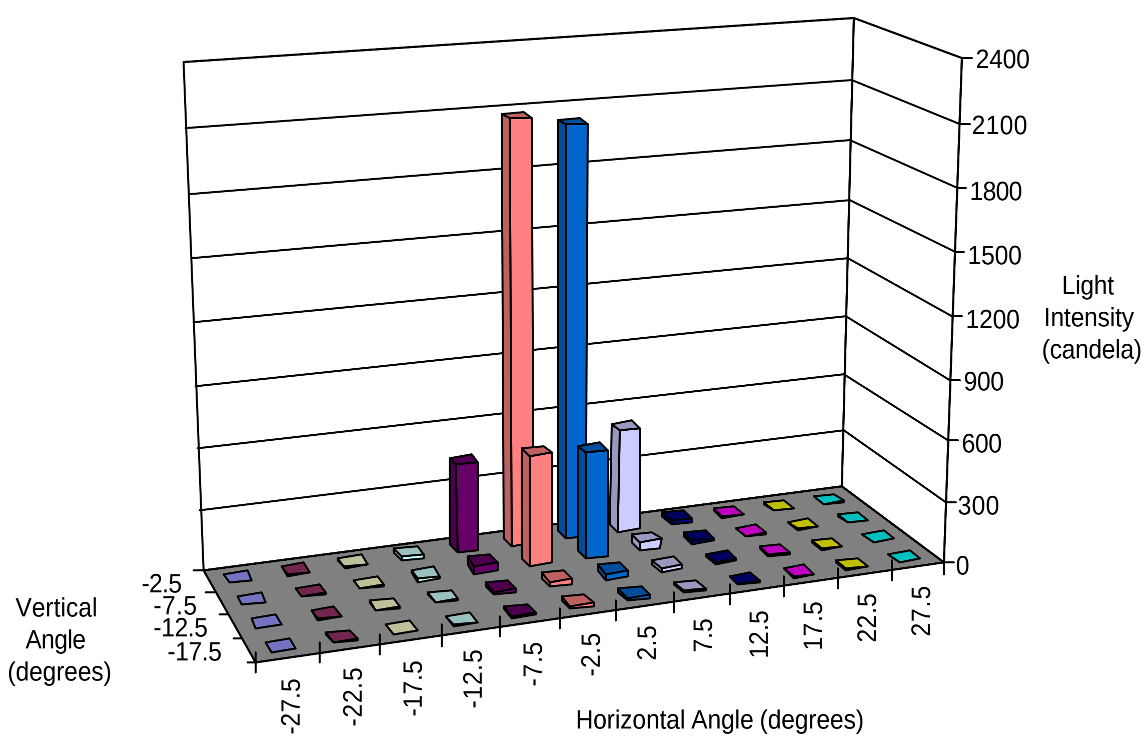

Figure A9.1.12b Output from WPS #9 (Green) signal, 13.5 volts, 38.0 ft, all elements on, ITE test.

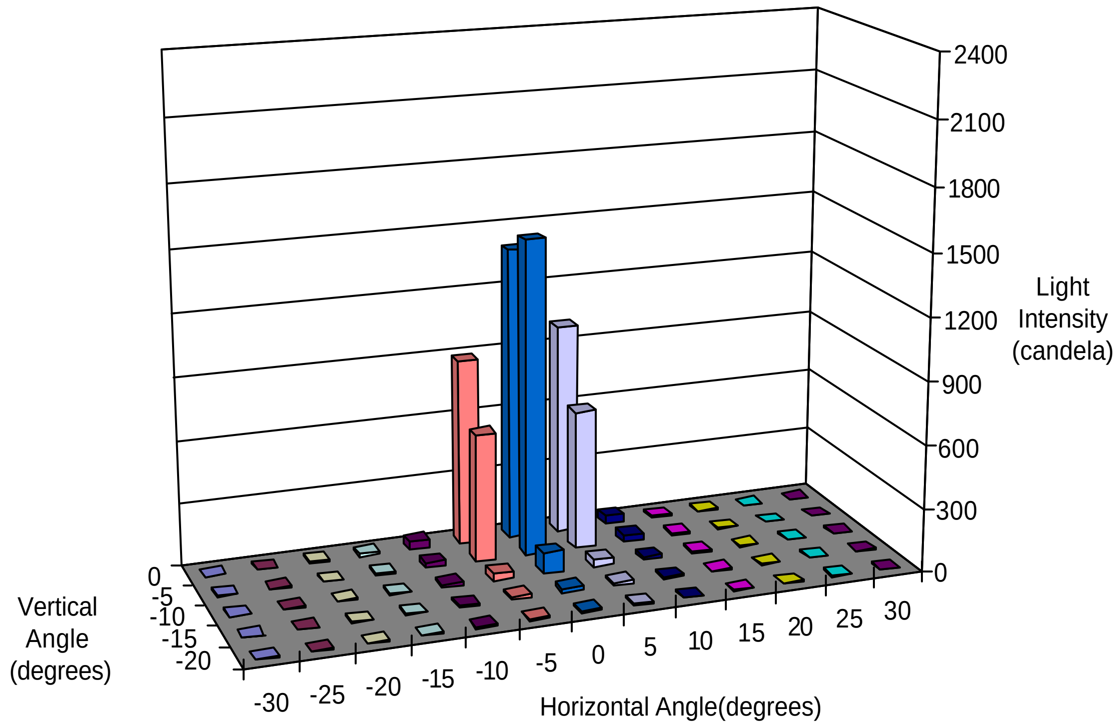

Figure A9.2.1a Output from WPS #9 (Green) signal, 10.0 volts, 32.0 ft, all elements on, TC test.

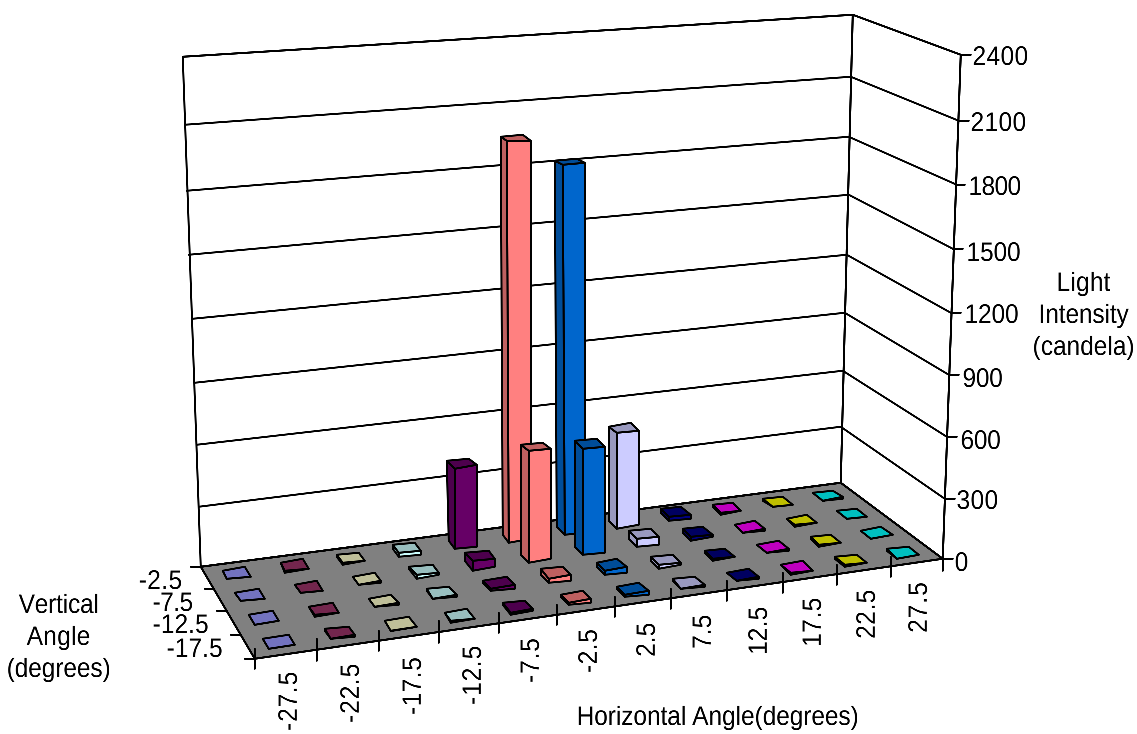

Figure A9.2.1b Output from WPS #9 (Green) signal, 10.0 volts, 32.0 ft, all elements on, ITE test.

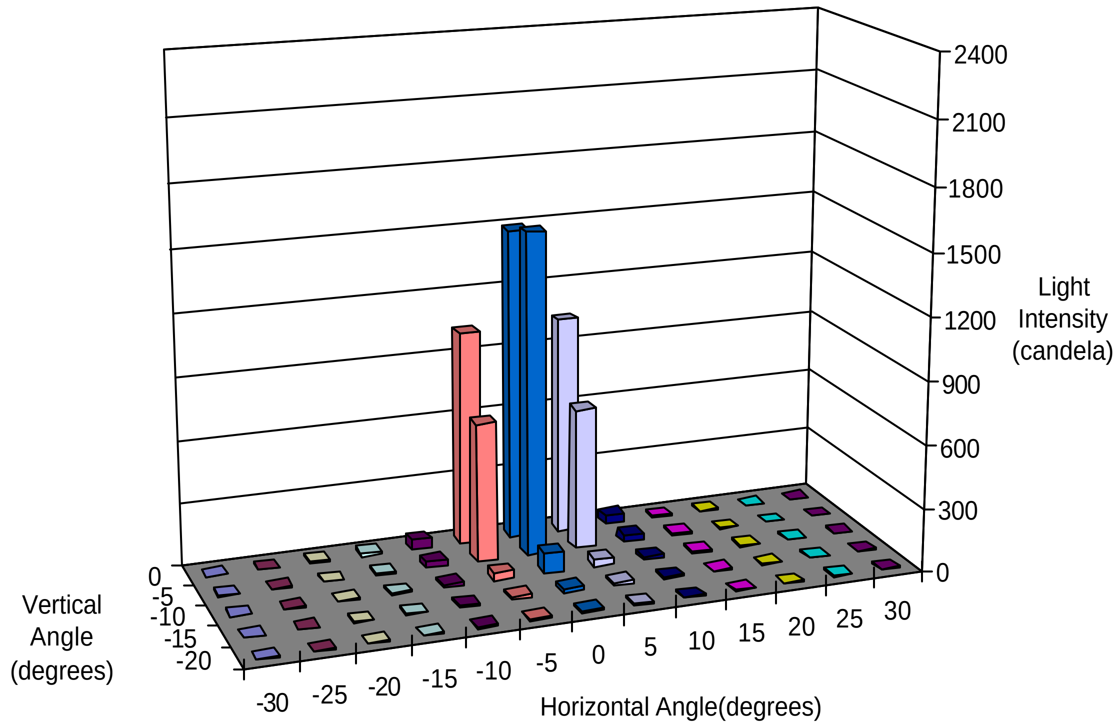

Figure A9.2.2a Output from WPS #9 (Green) signal, 10.0 volts, 34.0 ft, all elements on, TC test.

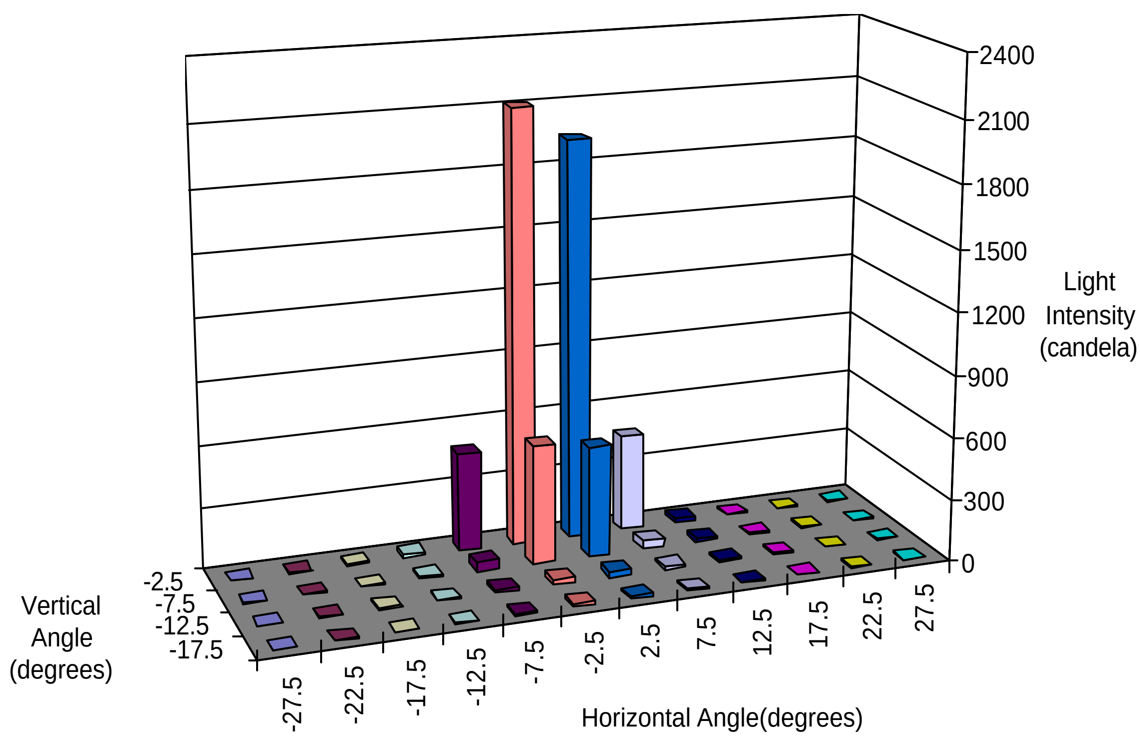

Figure A9.2.2b Output from WPS #9 (Green) signal, 10.0 volts, 34.0 ft, all elements on, ITE test.

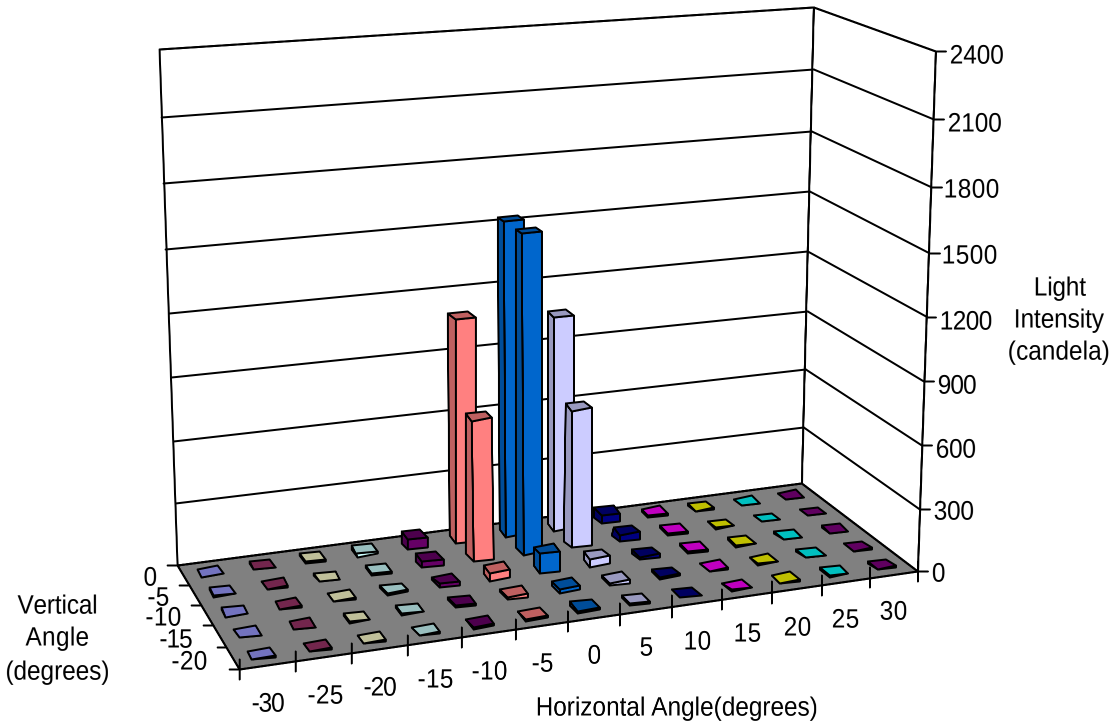

Figure A9.2.3a Output from WPS #9 (Green) signal, 10.0 volts, 36.0 ft, all elements on, TC test.

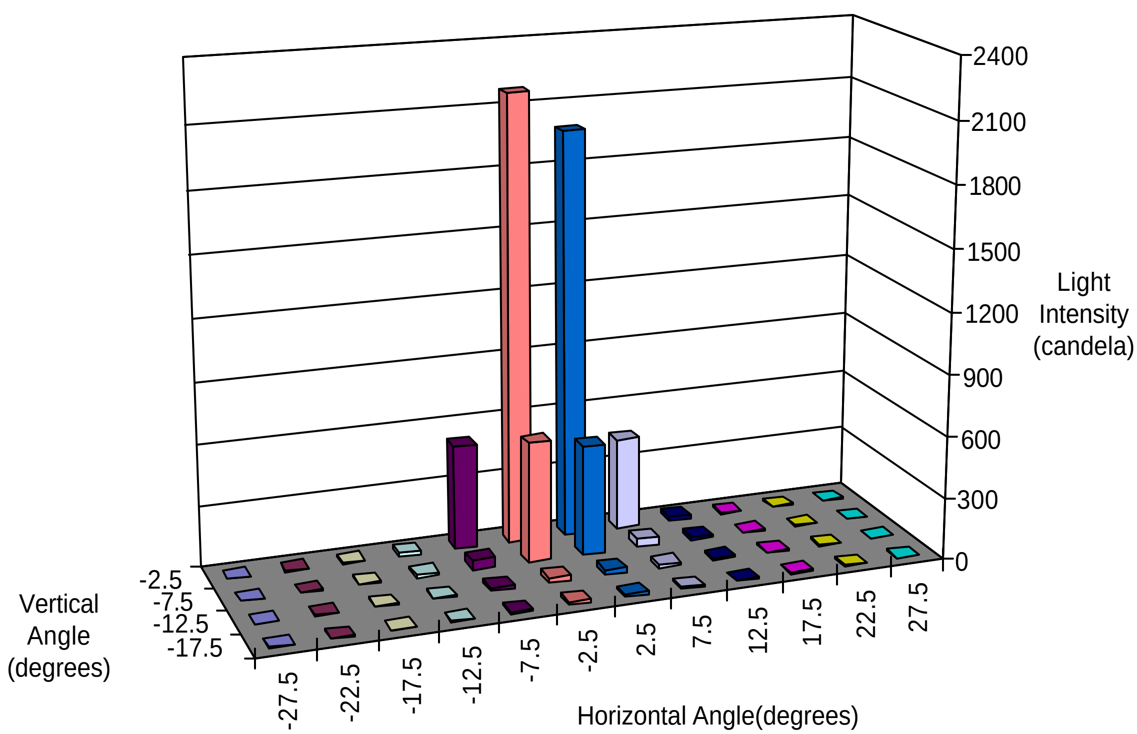

Figure A9.2.3b Output from WPS #9 (Green) signal, 10.0 volts, 36.0 ft, all elements on, ITE test.

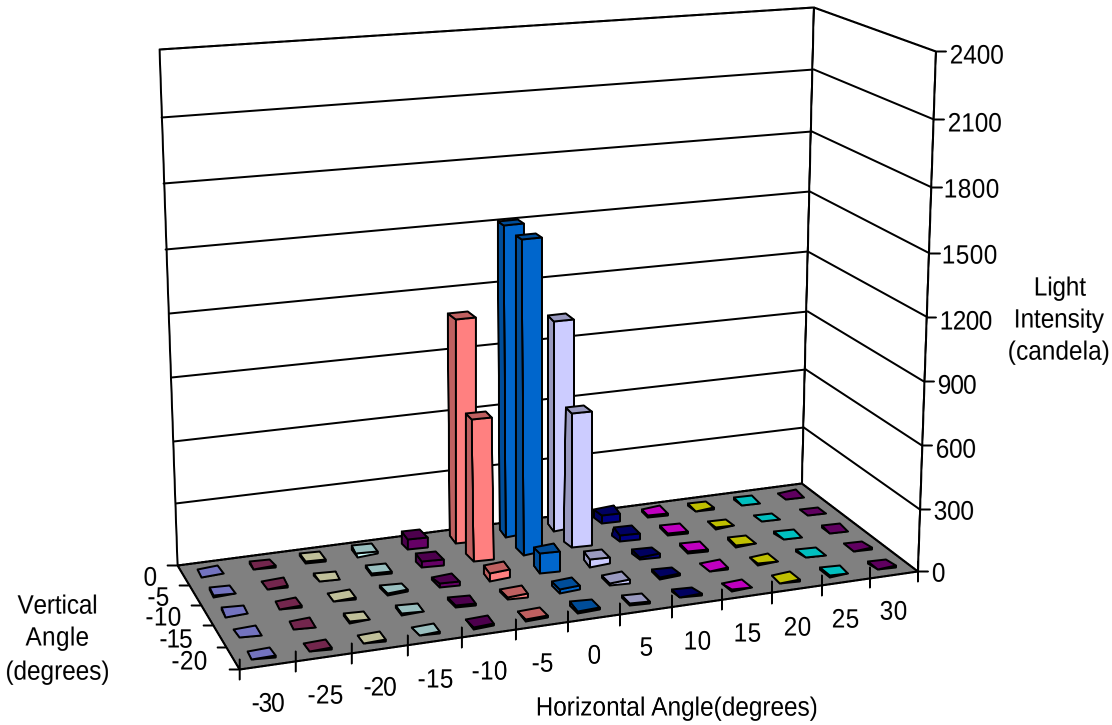

Figure A9.2.4a Output from WPS #9 (Green) signal, 10.0 volts, 38.0 ft, all elements on, TC test.

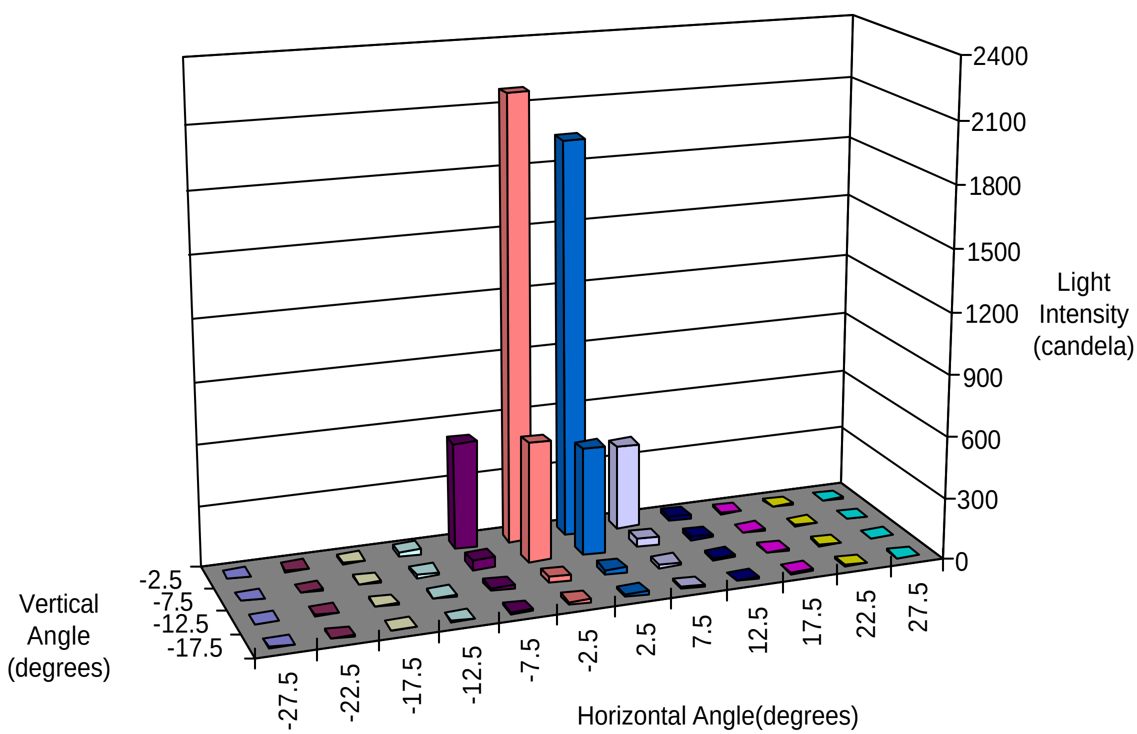

Figure A9.2.4b Output from WPS #9 (Green) signal, 10.0 volts, 38.0 ft, all elements on, ITE test.

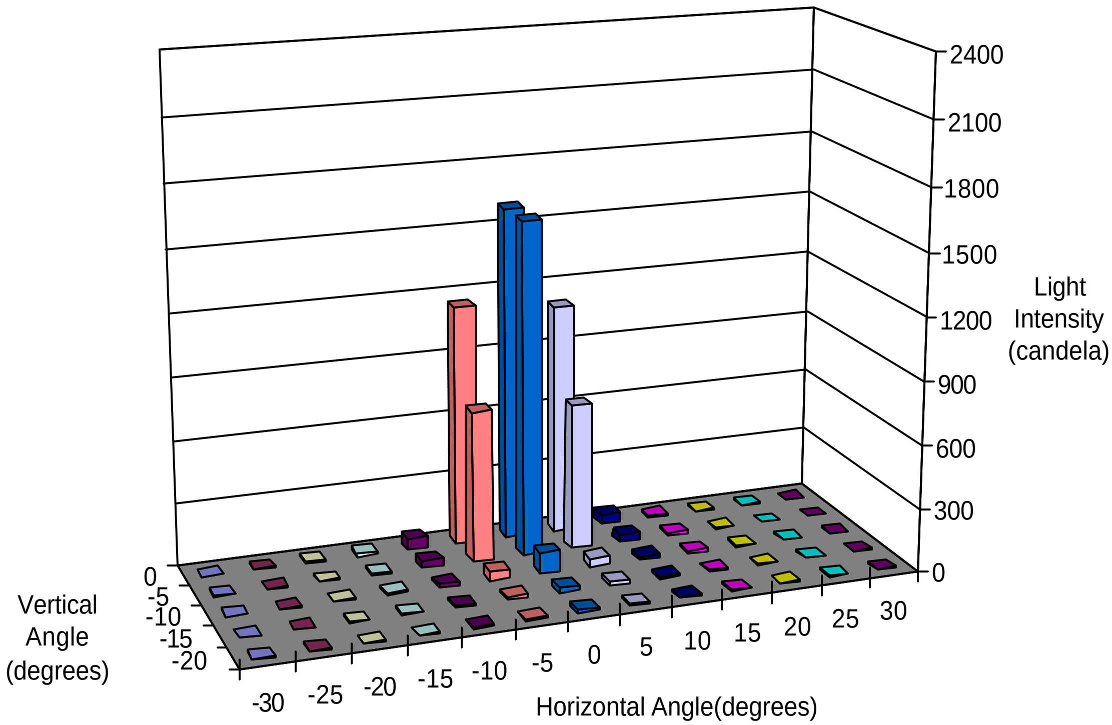

Figure A9.2.5a Output from WPS #9 (Green) signal, 10.0 volts, 40.0 ft, all elements on, TC test.

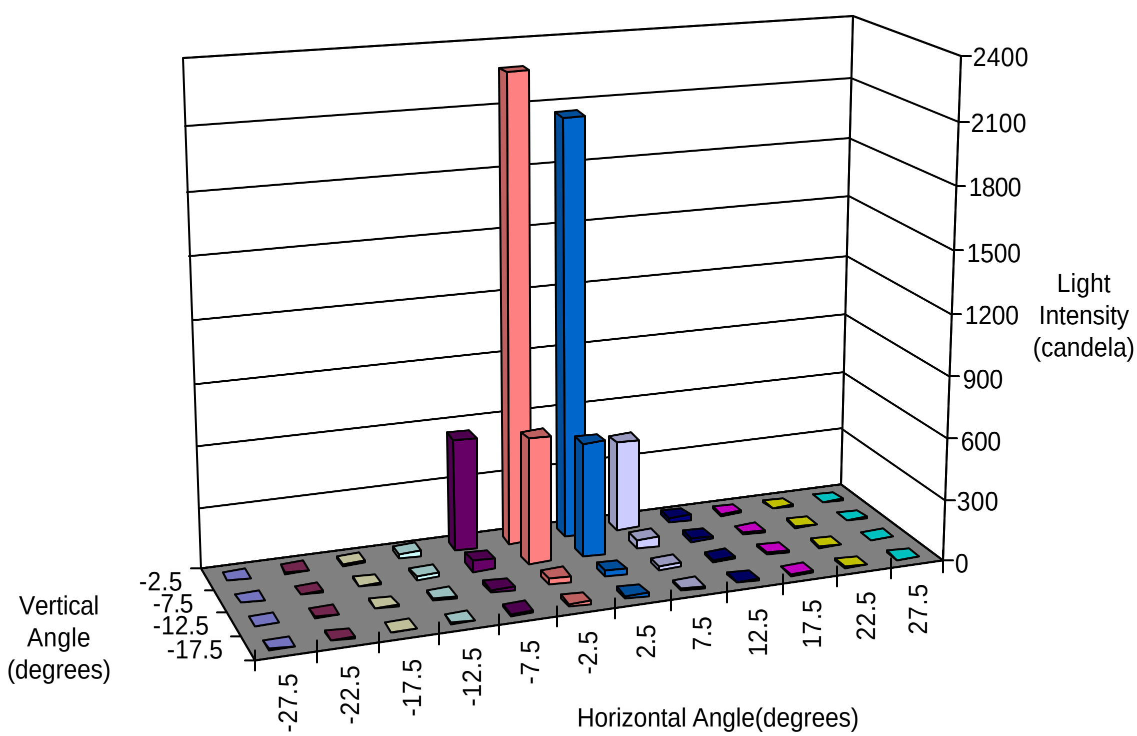

Figure A9.2.5b Output from WPS #9 (Green) signal, 10.0 volts, 40.0 ft, all elements on, ITE test.

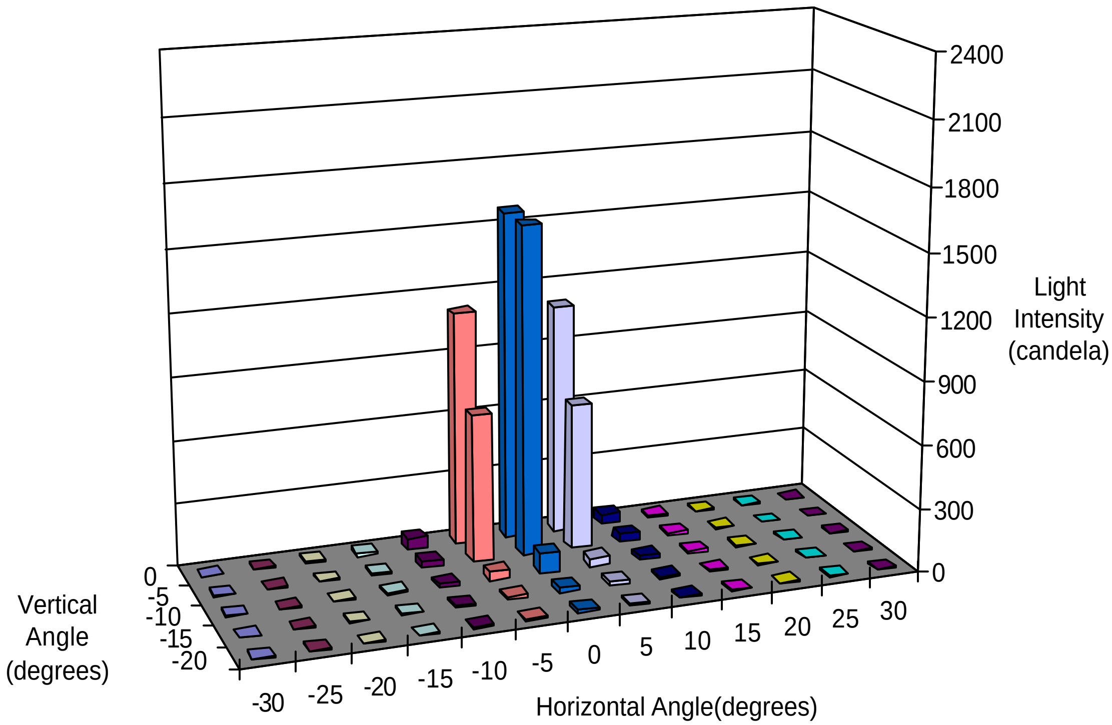

Figure A9.2.6a Output from WPS #9 (Green) signal, 10.0 volts, 42.0 ft, all elements on, TC test.

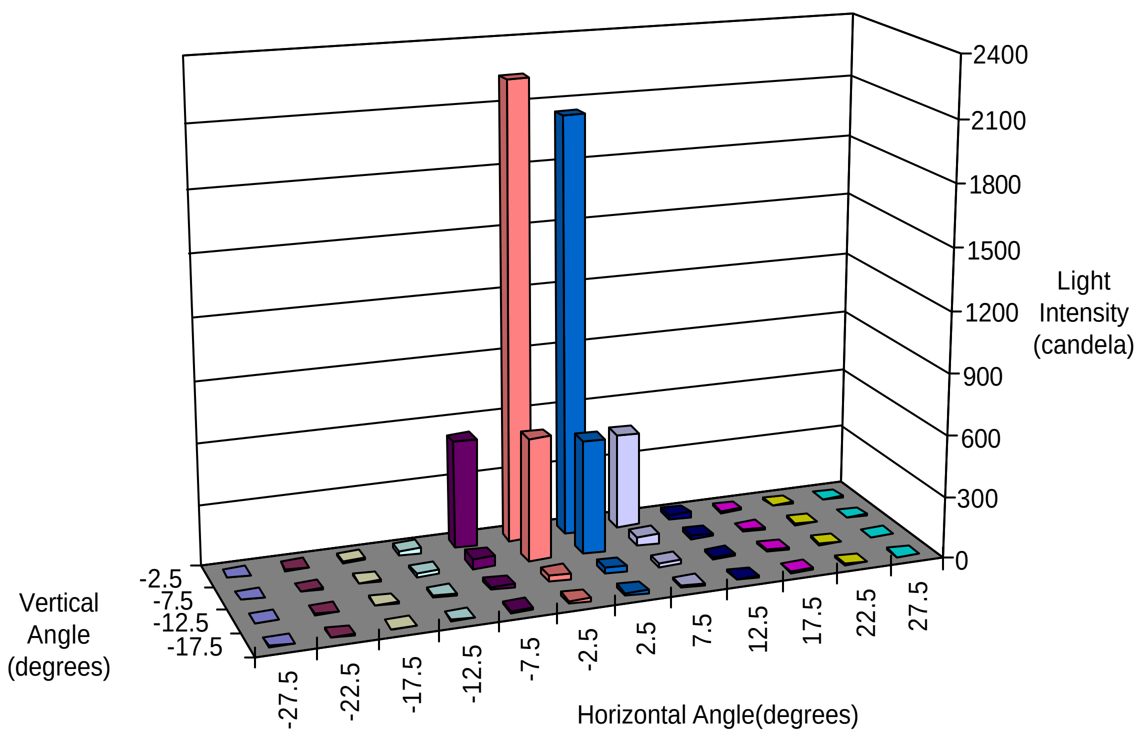

Figure A9.2.6b Output from WPS #9 (Green) signal, 10.0 volts, 42.0 ft, all elements on, ITE test.

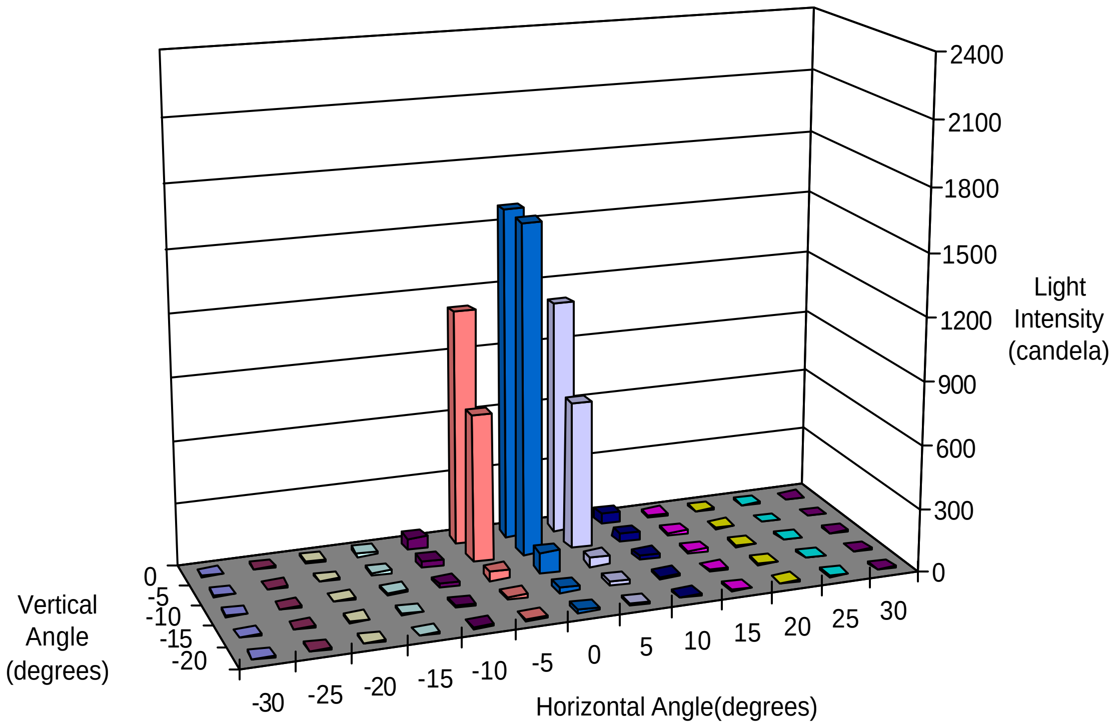

Figure A9.2.7a Output from WPS #9 (Green) signal, 10.0 volts, 44.0 ft, all elements on, TC test.

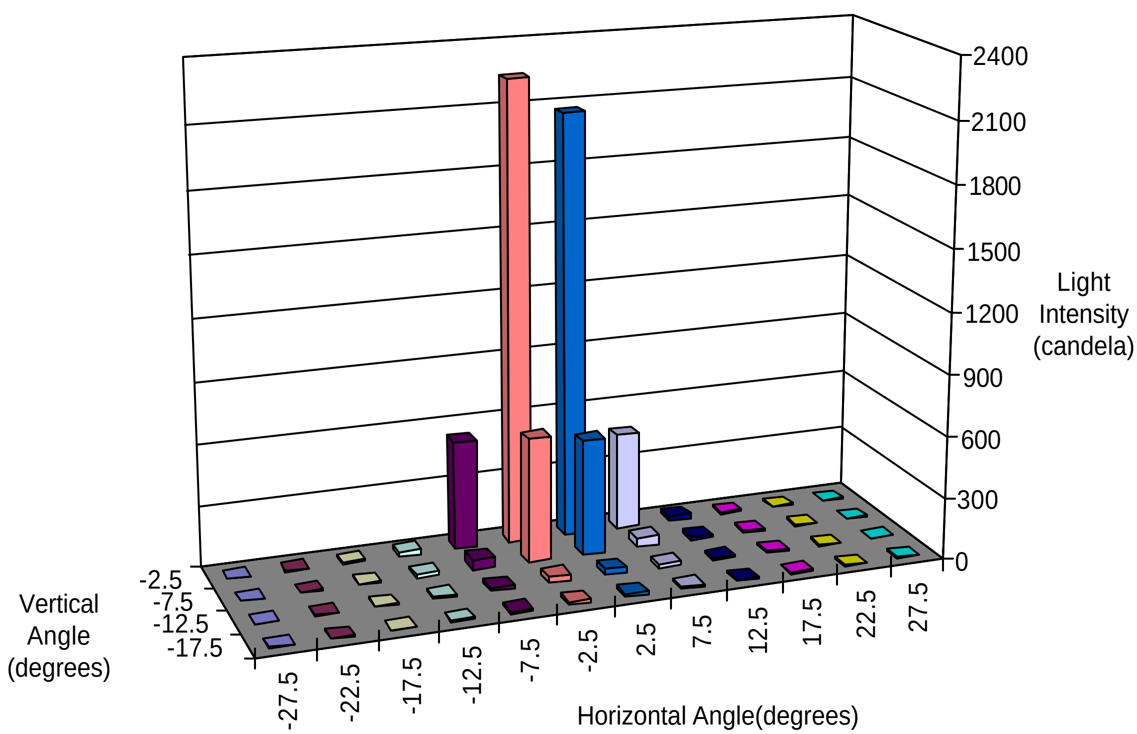

Figure A9.2.7b Output from WPS #9 (Green) signal, 10.0 volts, 44.0 ft, all elements on, ITE test.

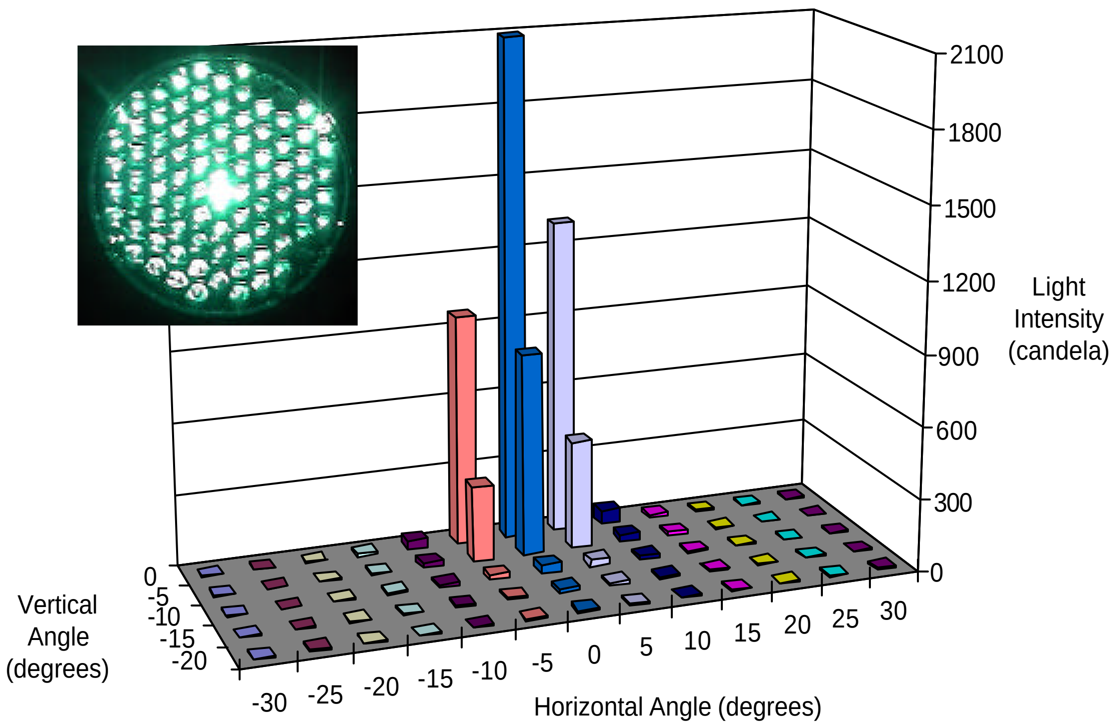

Figure A9.3.1a Output from WPS #9 (Green) signal, 10.0 volts, 86 elements (95% on), TC test.

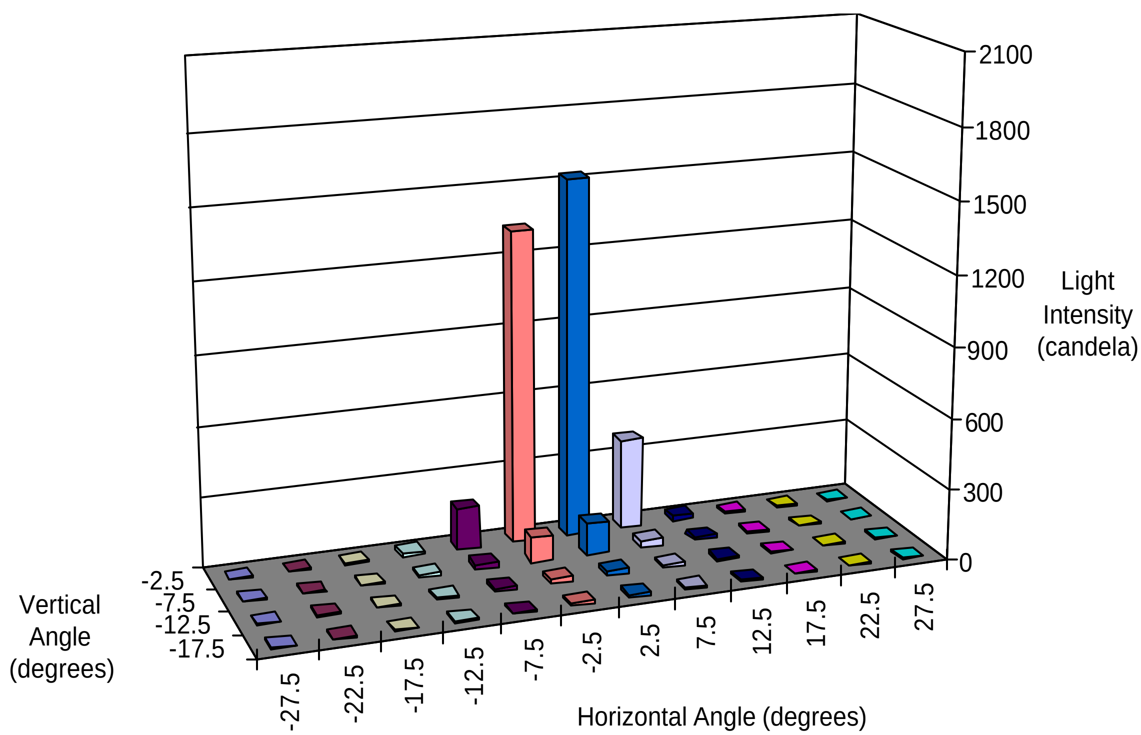

Figure A9.3.1b Output from WPS #9 (Green) signal, 10.0 volts, 86 elements (95% on), ITE test.

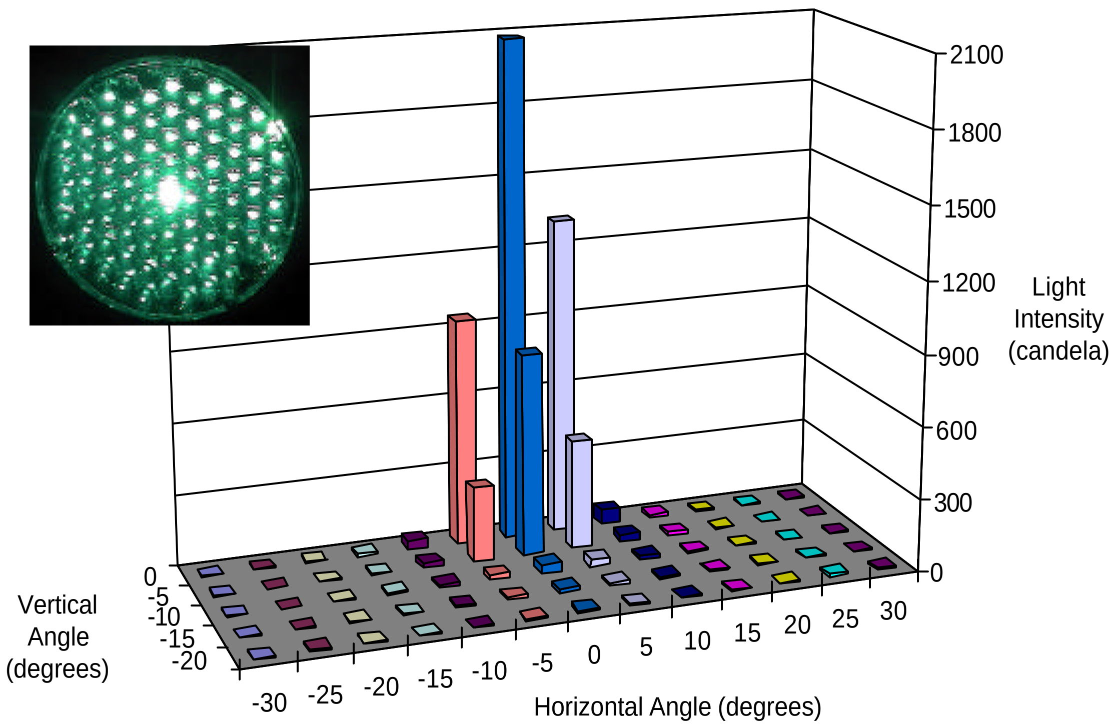

Figure A9.3.2a Output from WPS #9 (Green) signal, 10.0 volts, 86 elements (95% on), TC test.

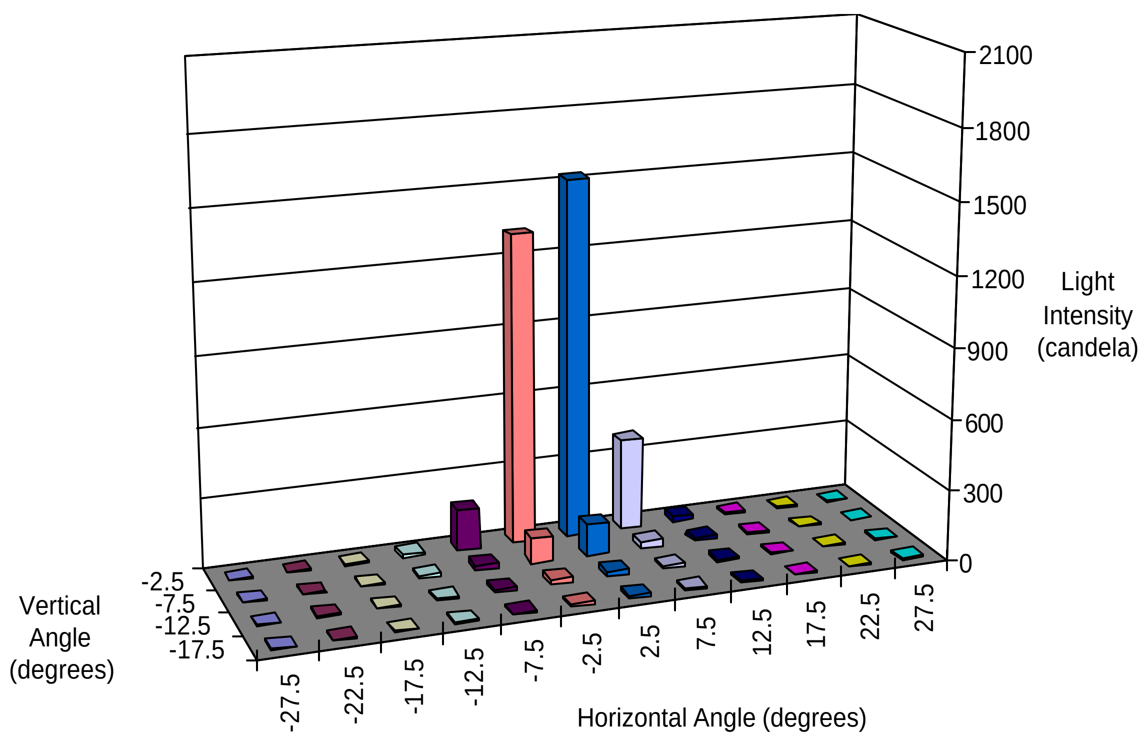

Figure A9.3.2b Output from WPS #9 (Green) signal, 10.0 volts, 86 elements (95% on), ITE test.

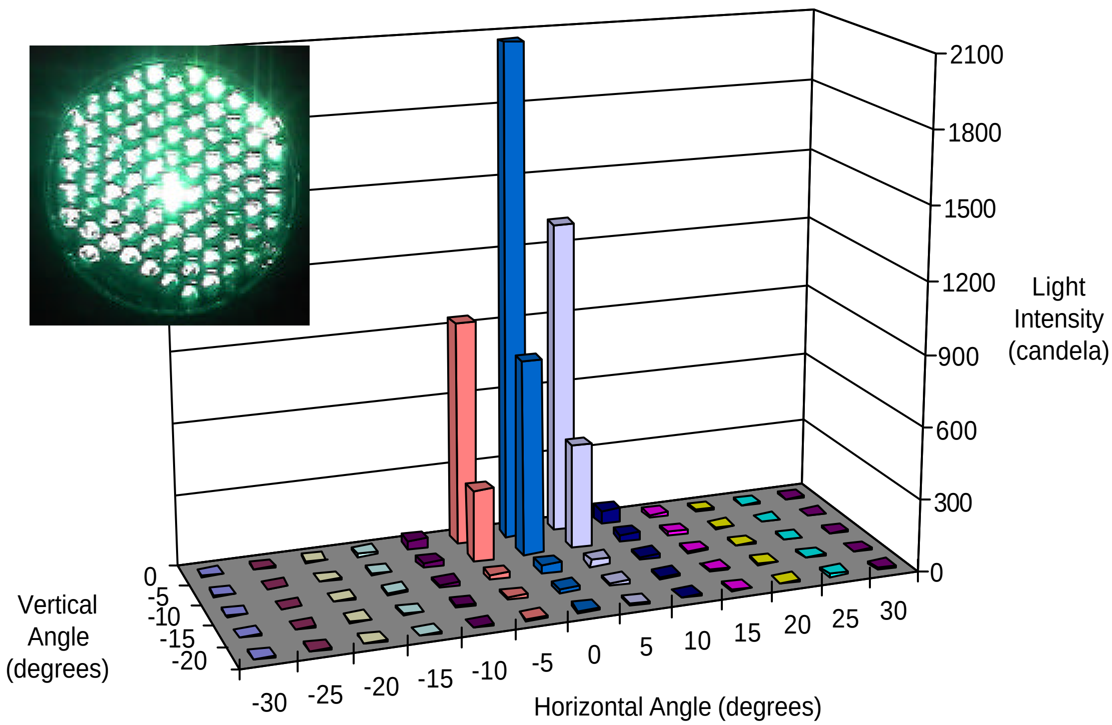

Figure A9.3.3a Output from WPS #9 (Green) signal, 10.0 volts, 86 elements (95% on), TC test.

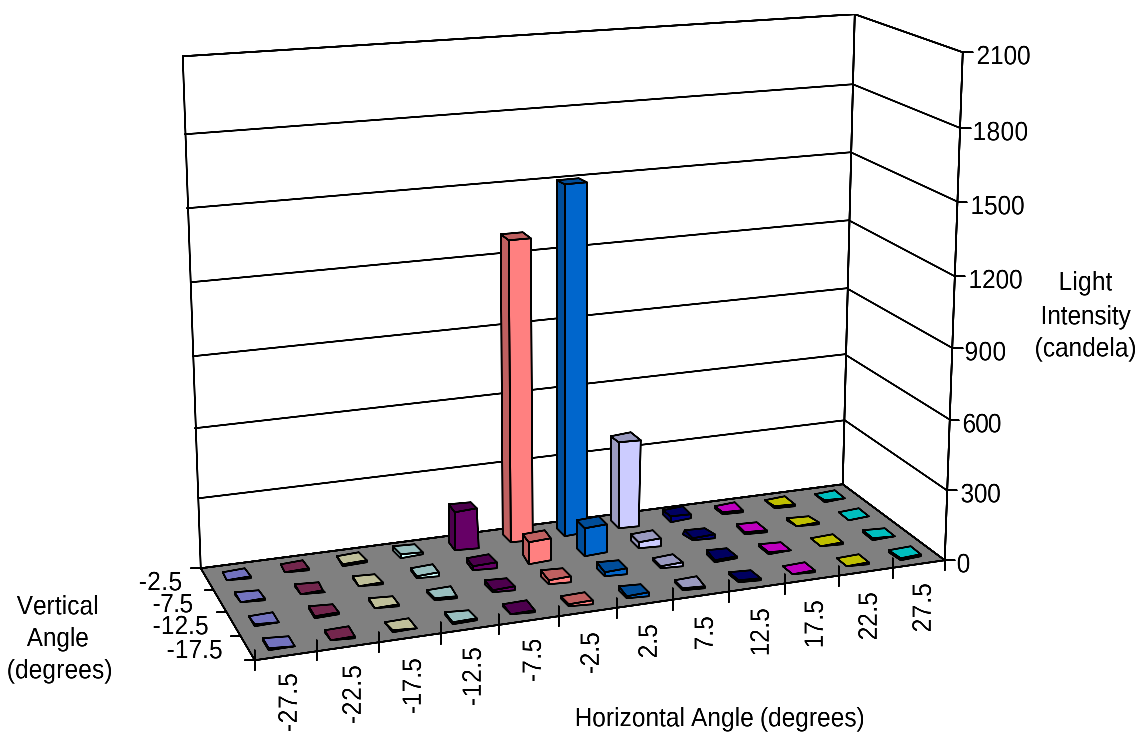

Figure A9.3.3b Output from WPS #9 (Green) signal, 10.0 volts, 86 elements (95% on), ITE test.

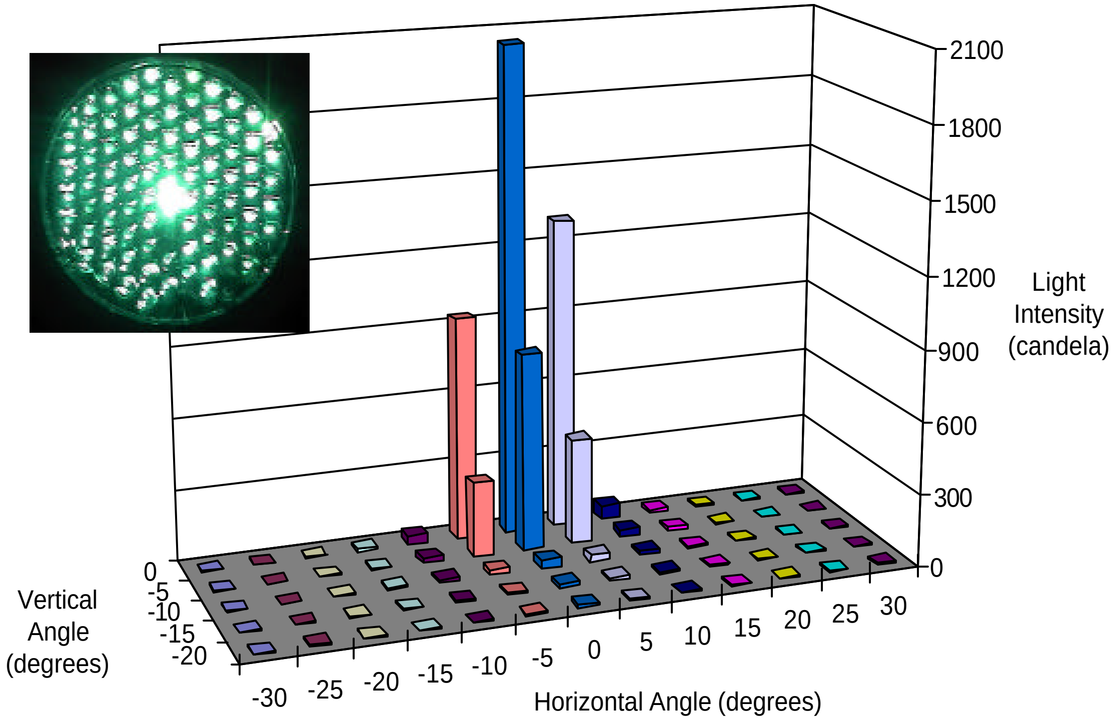

Figure A9.3.4a Output from WPS #9 (Green) signal, 10.0 volts, 86 elements (95% on), TC test.

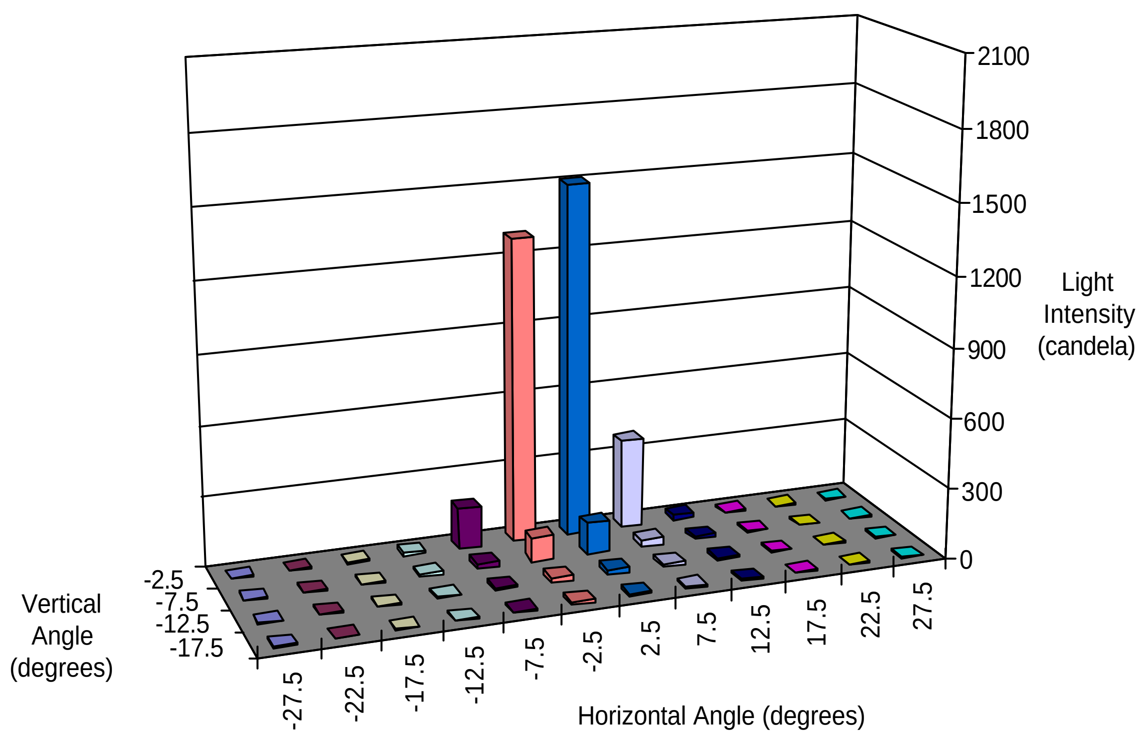

Figure A9.3.4b Output from WPS #9 (Green) signal, 10.0 volts, 86 elements (95% on), ITE test.

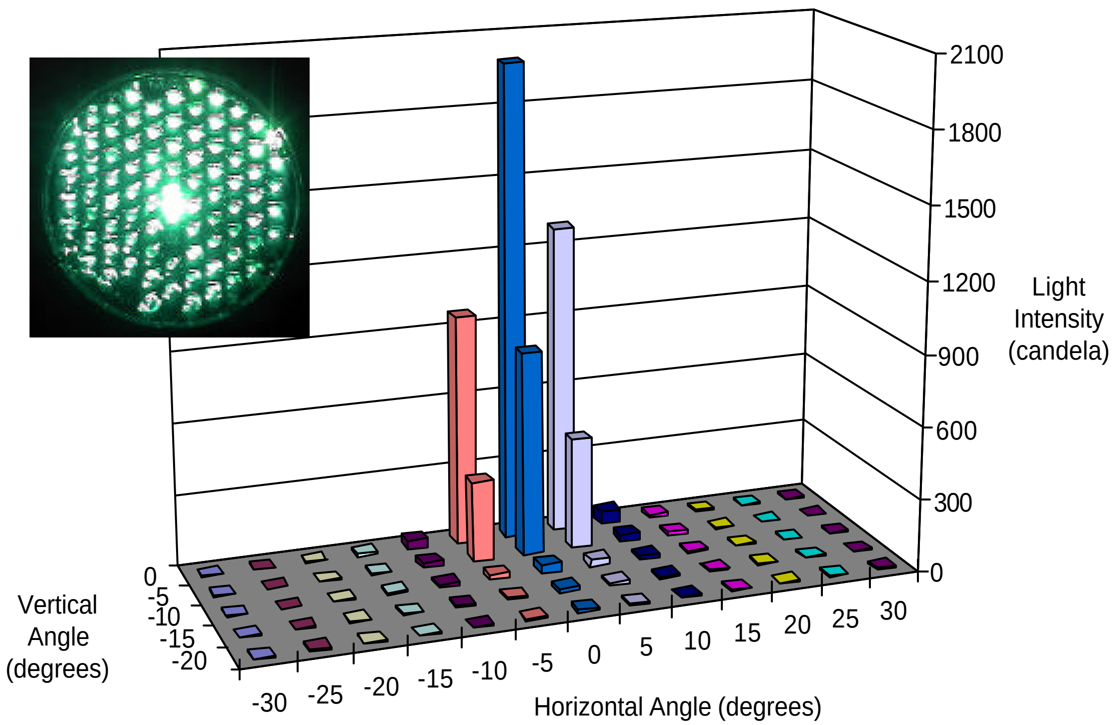

Figure A9.3.5a Output from WPS #9 (Green) signal, 10.0 volts, 86 elements (95% on), TC test.

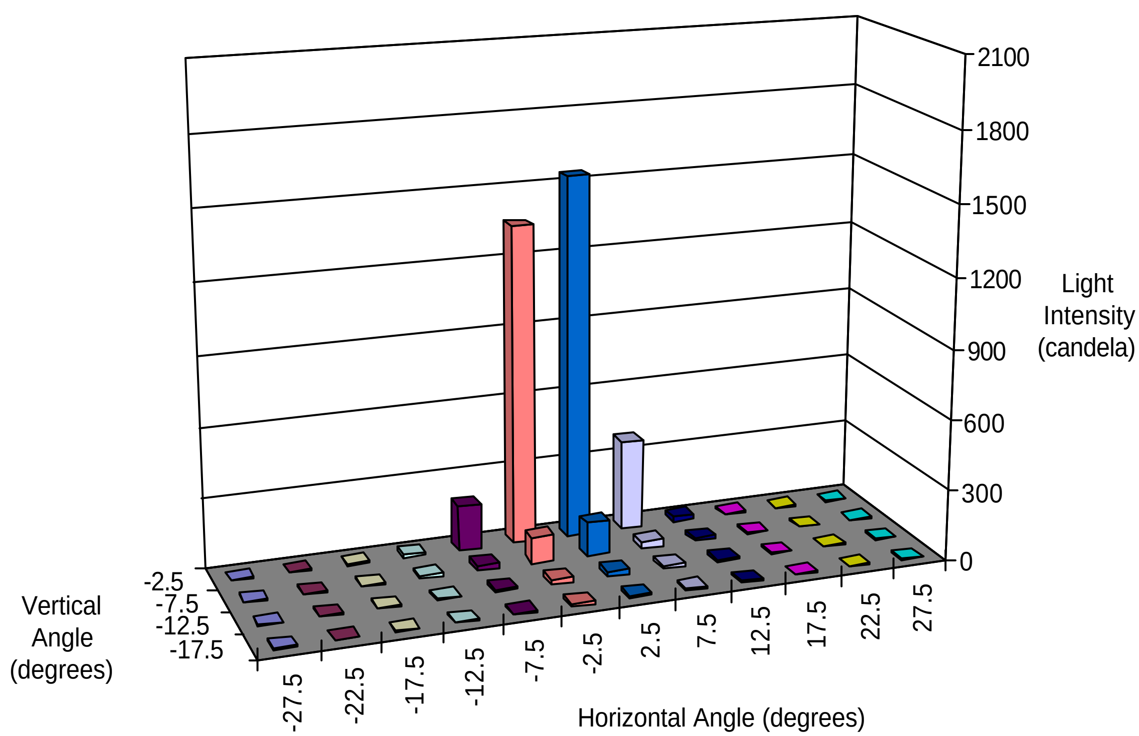

Figure A9.3.5b Output from WPS #9 (Green) signal, 10.0 volts, 86 elements (95% on), ITE test.

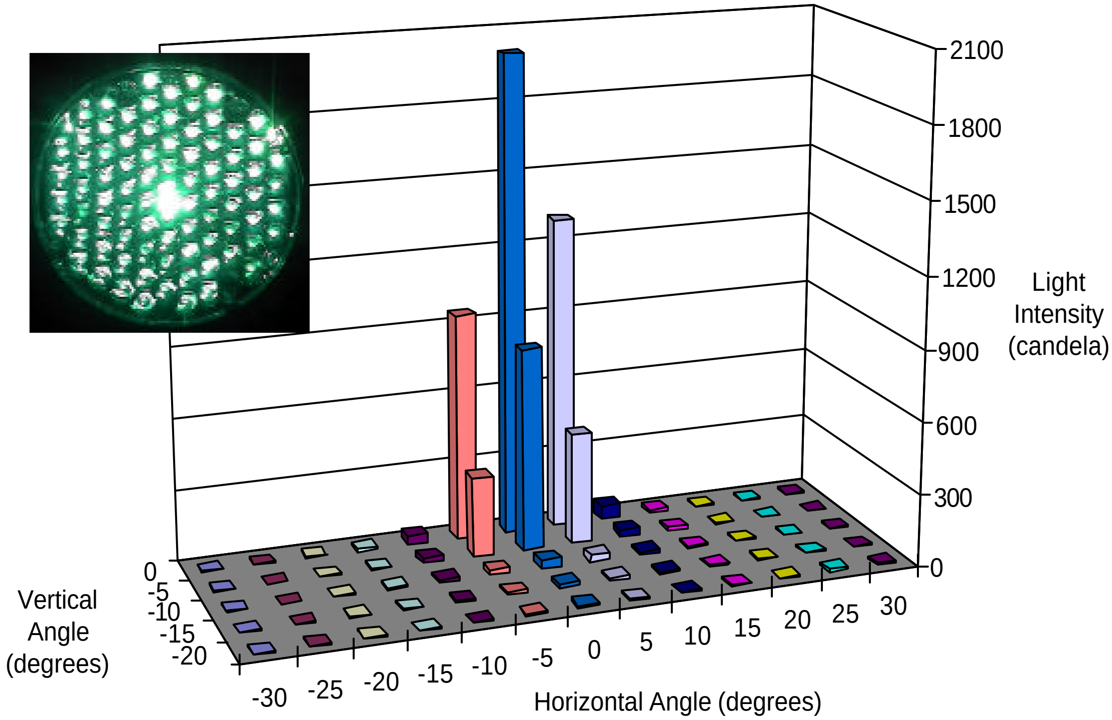

Figure A9.3.6a Output from WPS #9 (Green) signal, 10.0 volts, 86 elements (95% on), TC test.

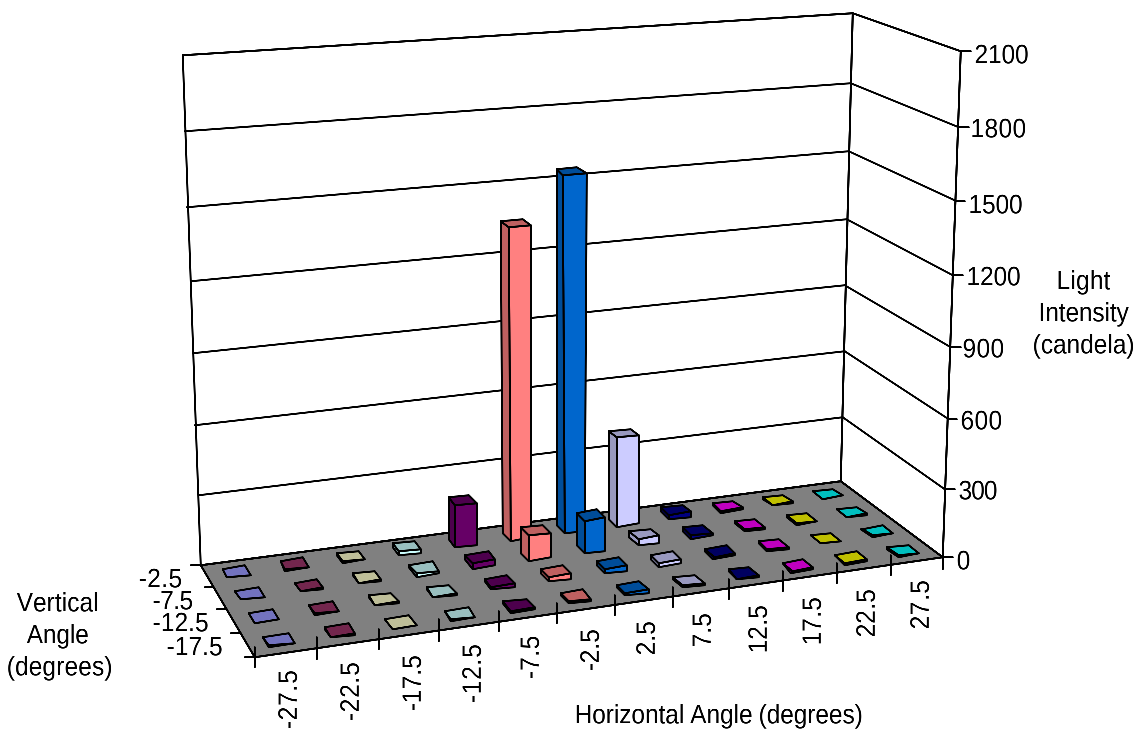

Figure A9.3.6b Output from WPS #9 (Green) signal, 10.0 volts, 86 elements (95% on), ITE test.

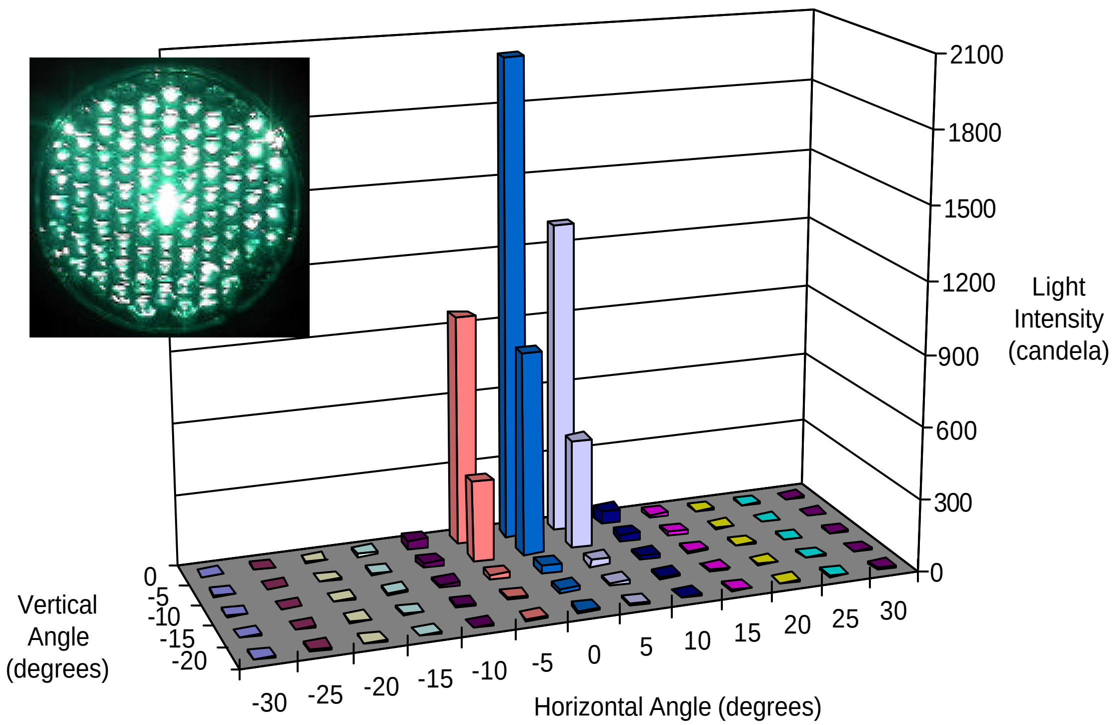

Figure A9.3.7a Output from WPS #9 (Green) signal, 10.0 volts, 82 elements (91% on), TC test.

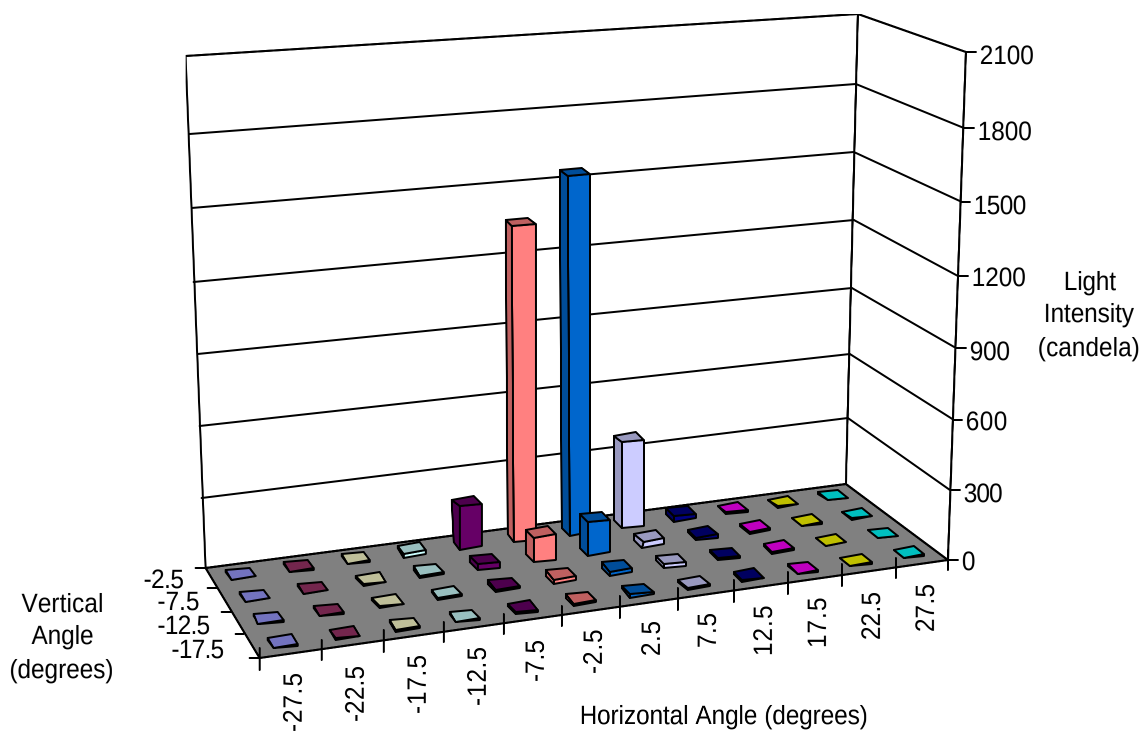

Figure A9.3.7b Output from WPS #9 (Green) signal, 10.0 volts, 82 elements (91% on), ITE test.

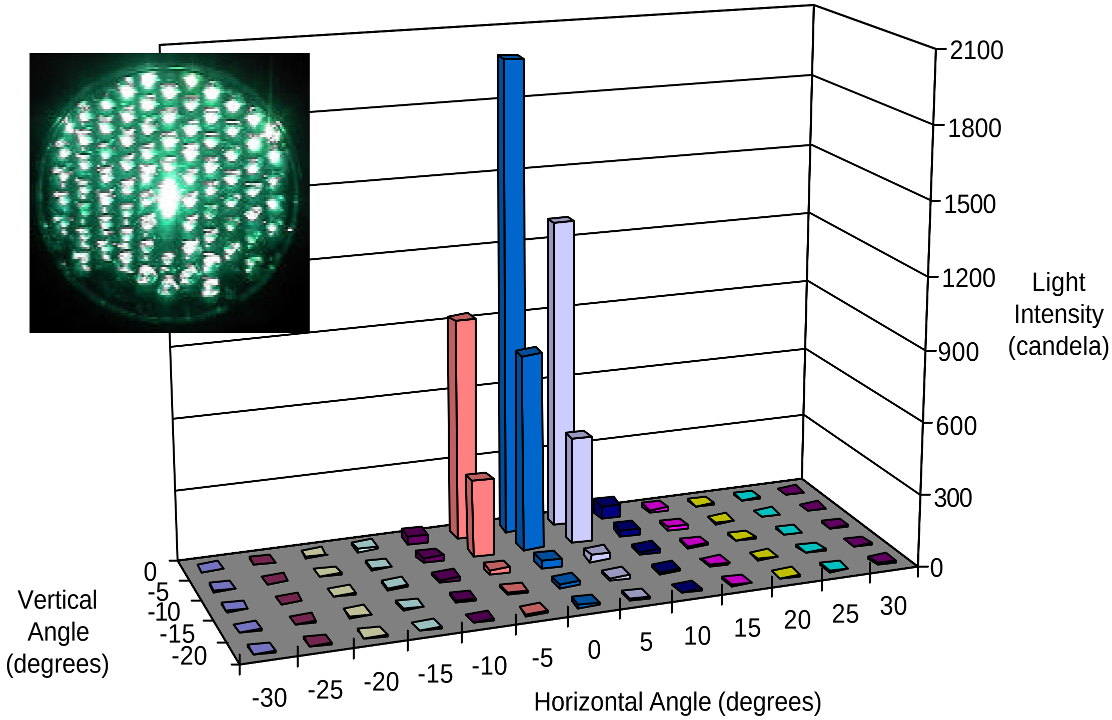

Figure A9.3.8a Output from WPS #9 (Green) signal, 10.0 volts, 82 elements (91% on), TC test.

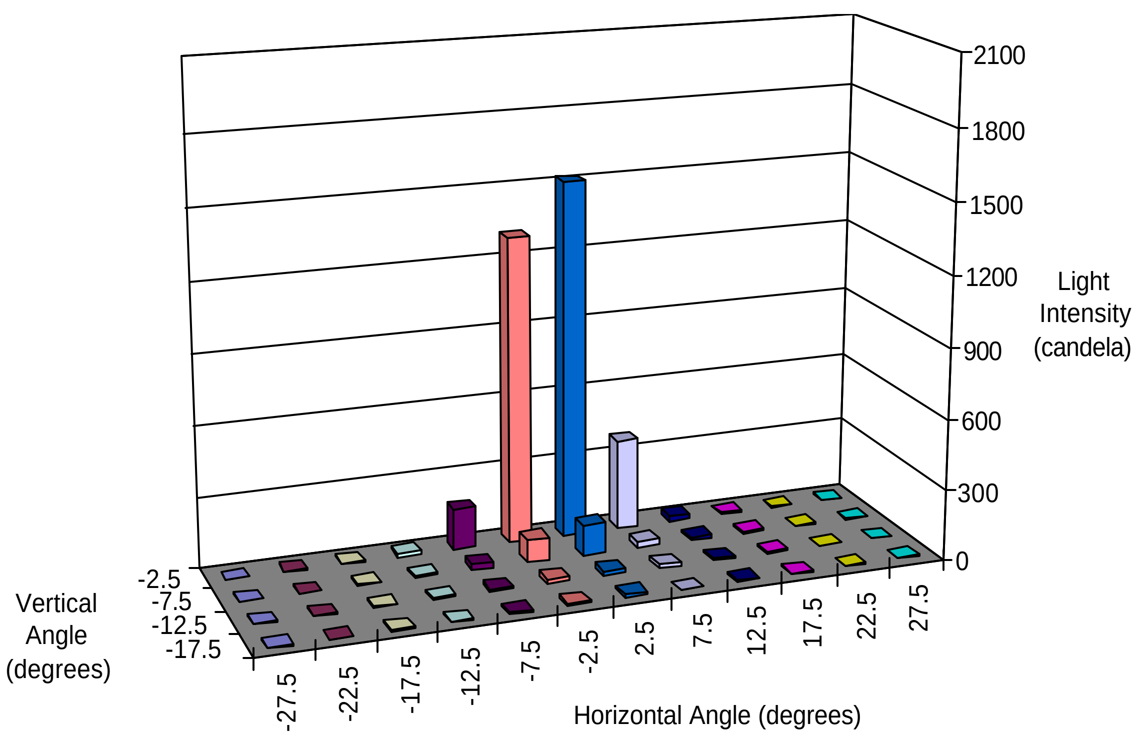

Figure A9.3.8b Output from WPS #9 (Green) signal, 10.0 volts, 82 elements (91% on), ITE test.

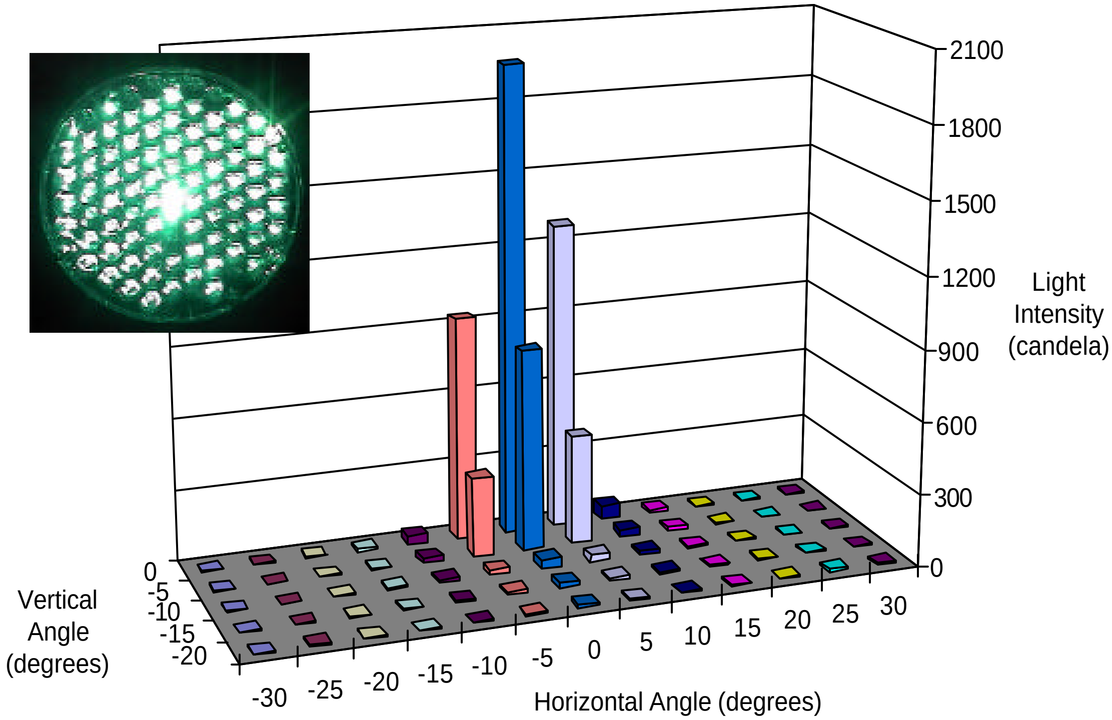

Figure A9.3.9a Output from WPS #9 (Green) signal, 10.0 volts, 82 elements (91% on), TC test.

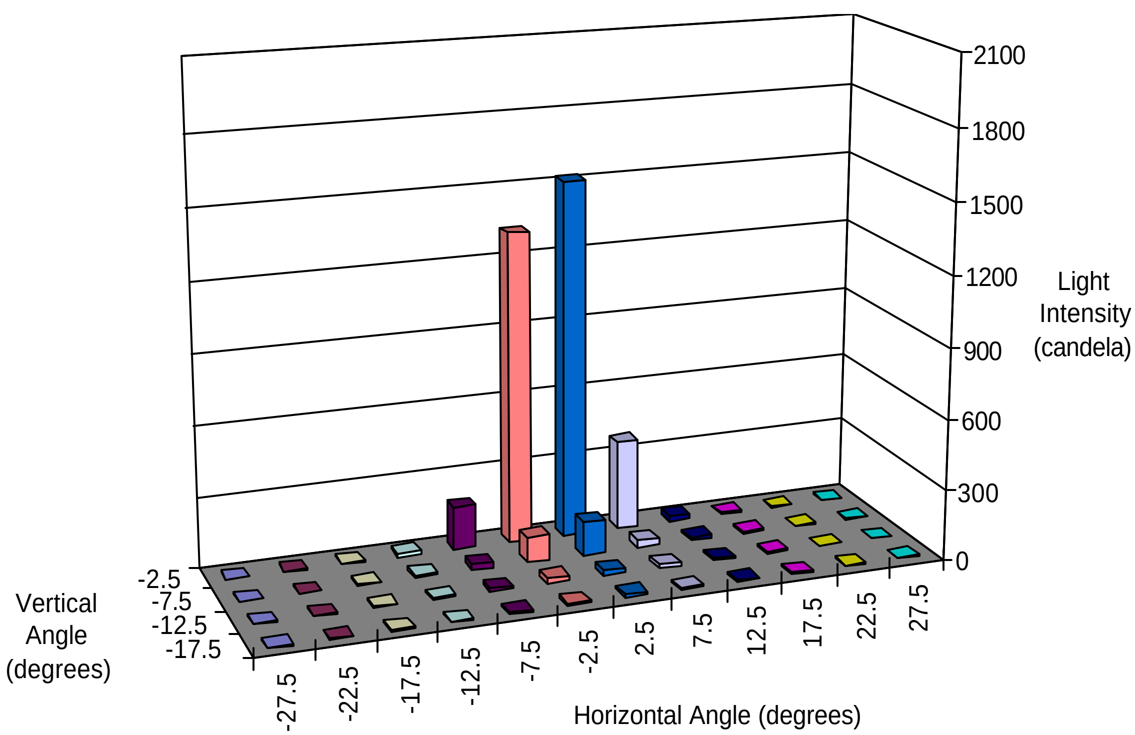

Figure A9.3.9b Output from WPS #9 (Green) signal, 10.0 volts, 82 elements (91% on), ITE test.

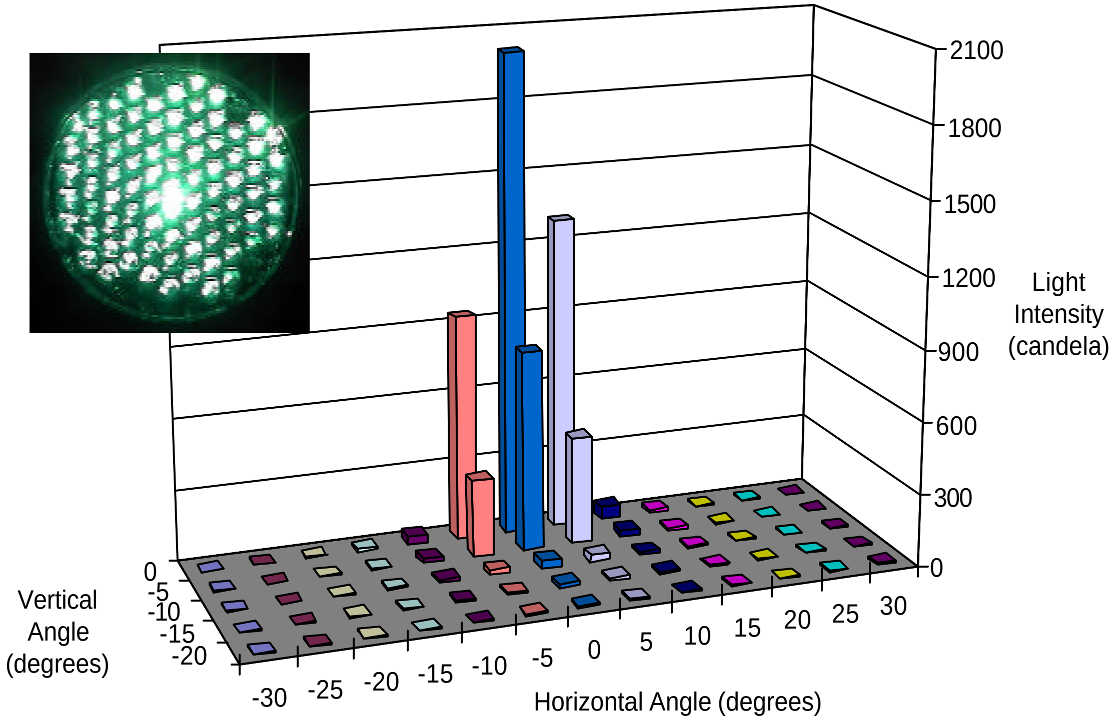

Figure A9.3.10a Output from WPS #9 (Green) signal, 10.0 volts, 82 elements (91% on), TC test.

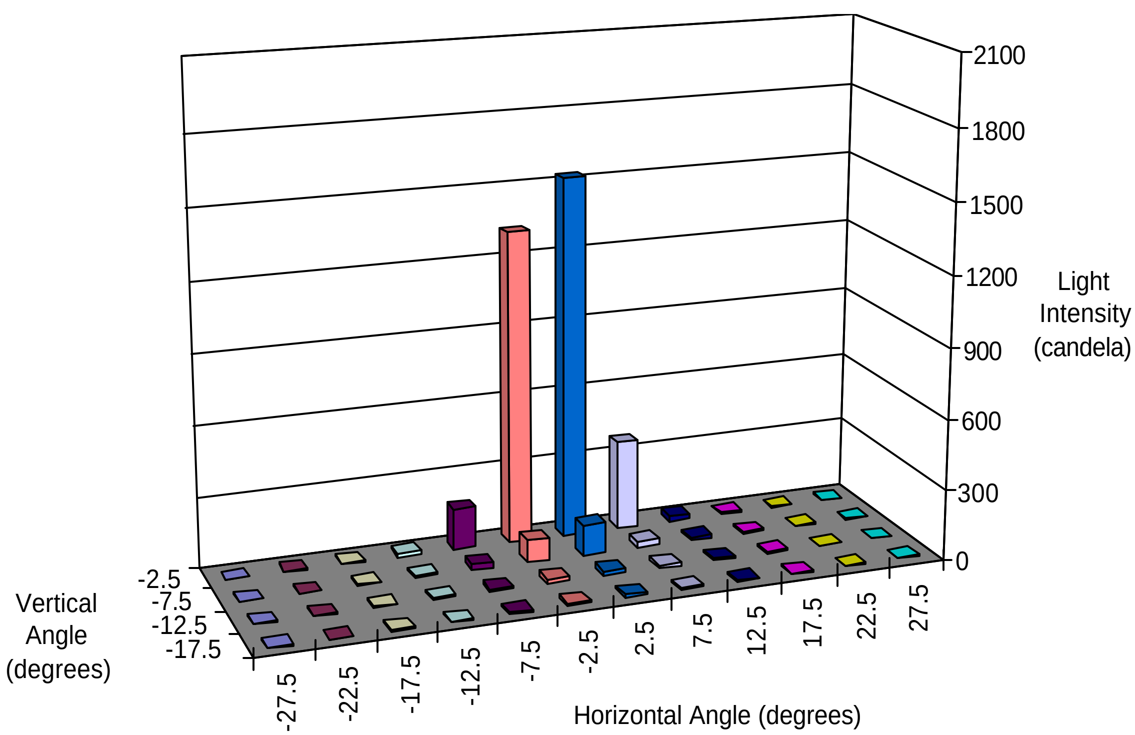

Figure A9.3.10b Output from WPS #9 (Green) signal, 10.0 volts, 82 elements (91% on), ITE test.

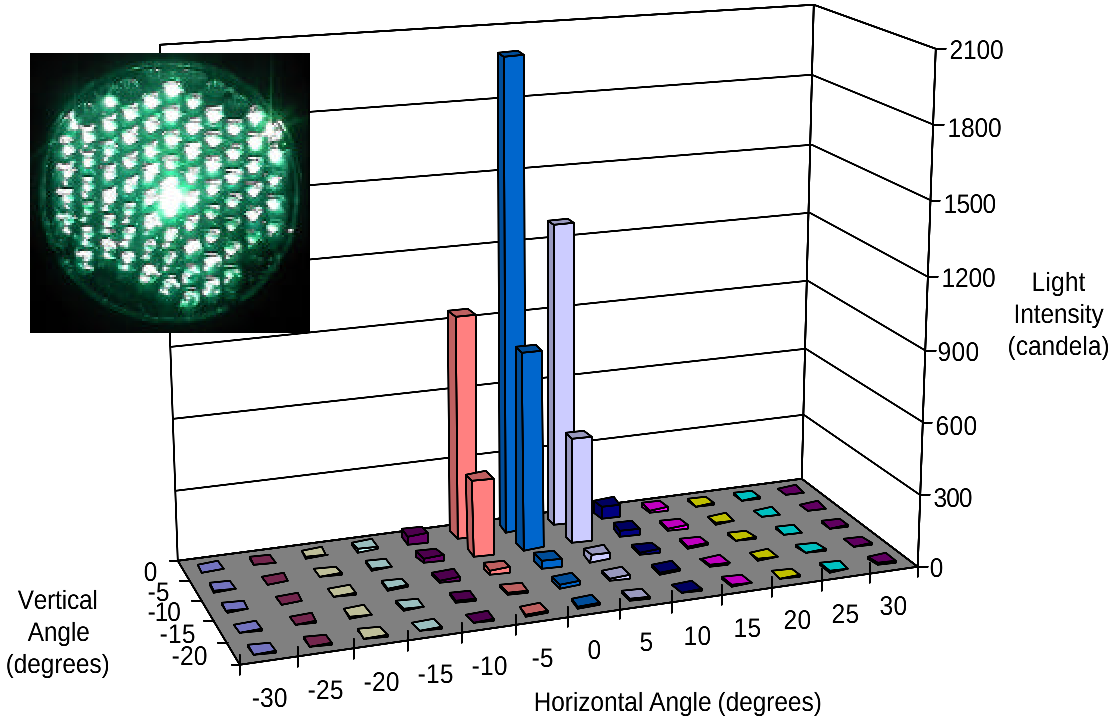

Figure A9.3.11a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (86% on), TC test.

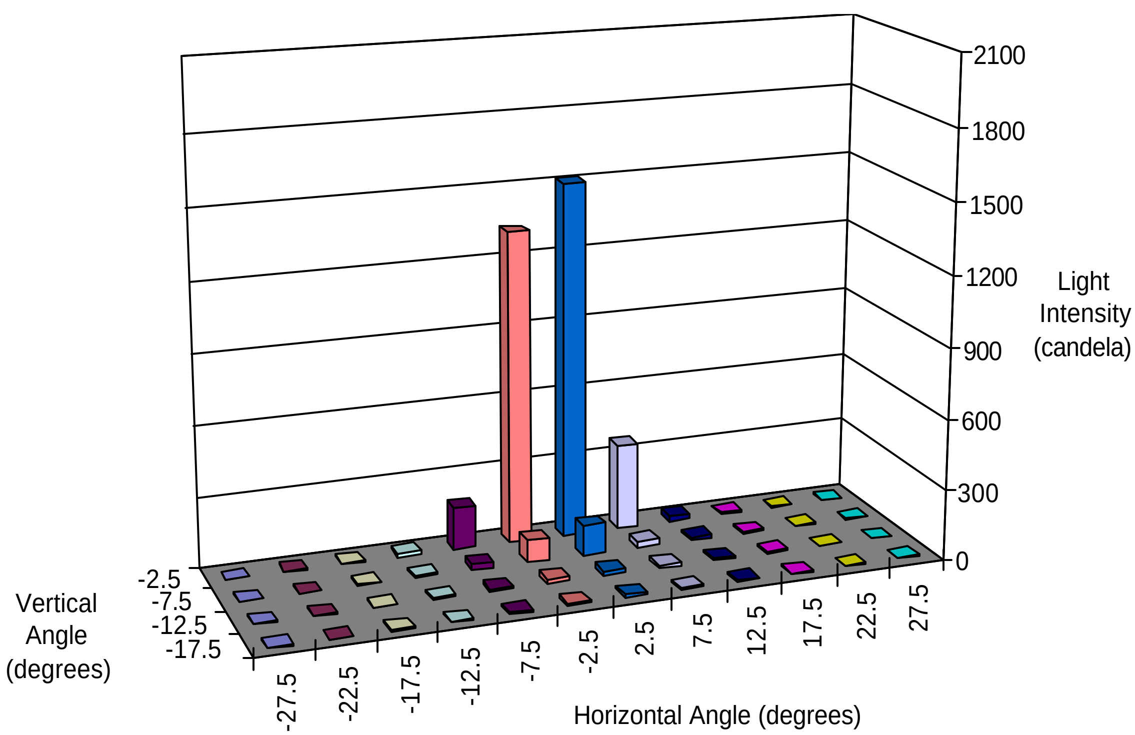

Figure A9.3.11b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (86% on), ITE test.

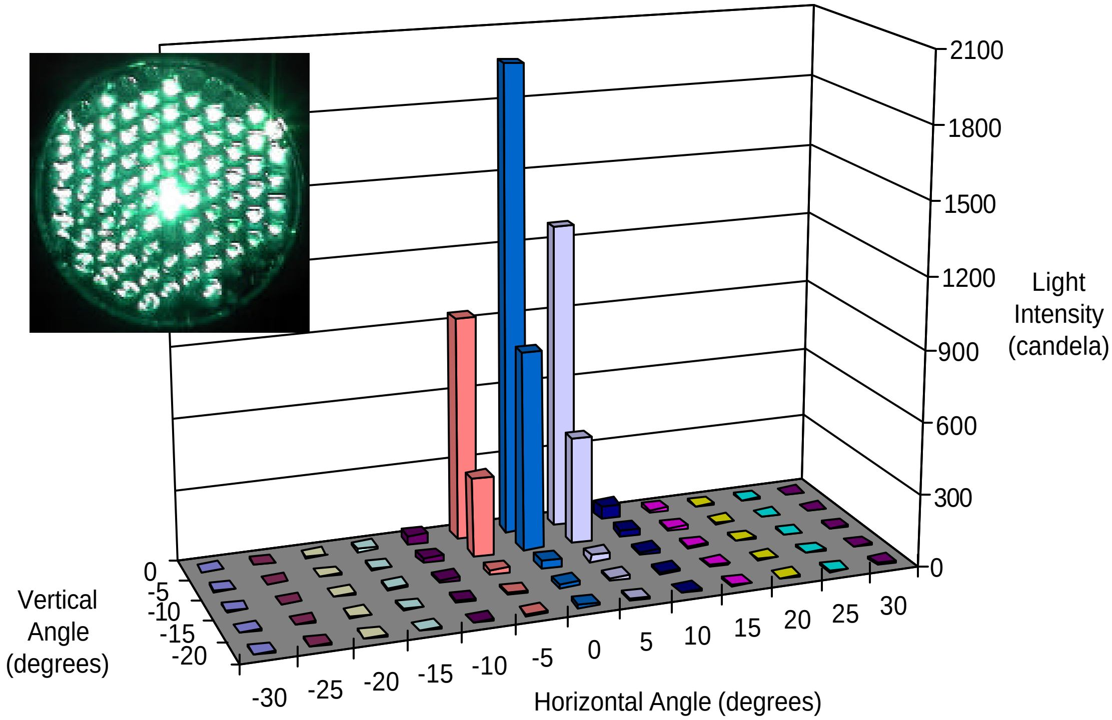

Figure A9.3.12a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (86% on), TC test.

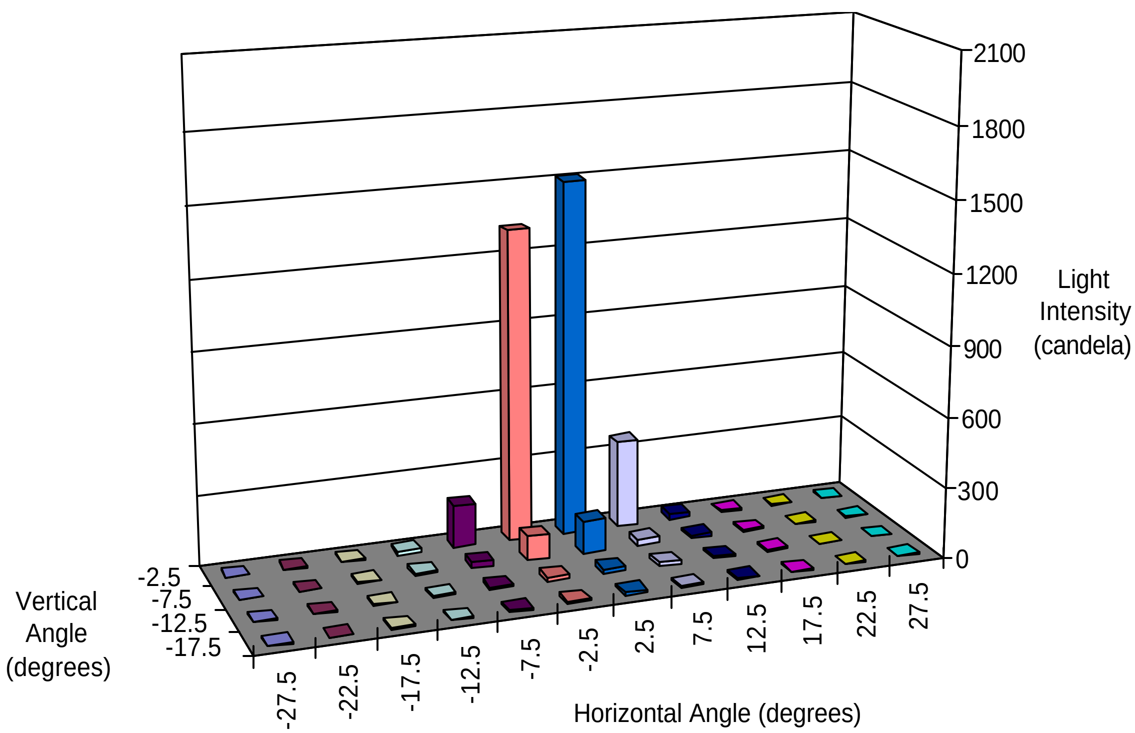

Figure A9.3.12b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (86% on), ITE test.

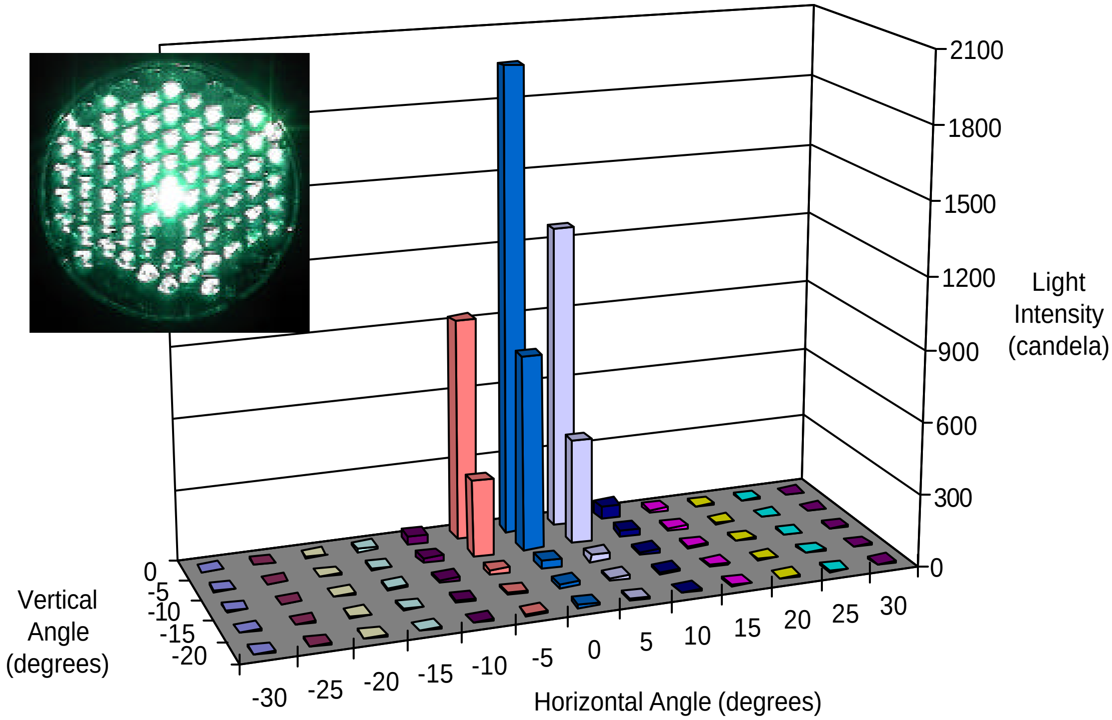

Figure A9.3.13a Output from WPS #9 (Green) signal, 10.0 volts, 75 elements (83% on), TC test.

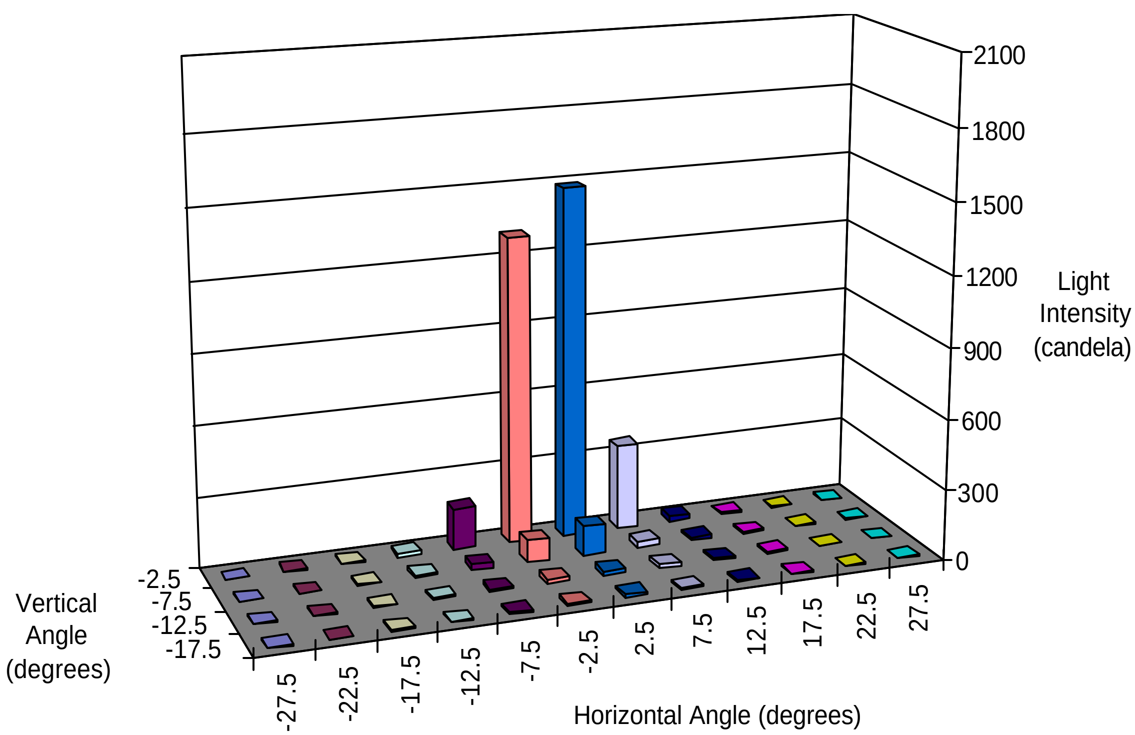

Figure A9.3.13b Output from WPS #9 (Green) signal, 10.0 volts, 75 elements (83% on), ITE test.

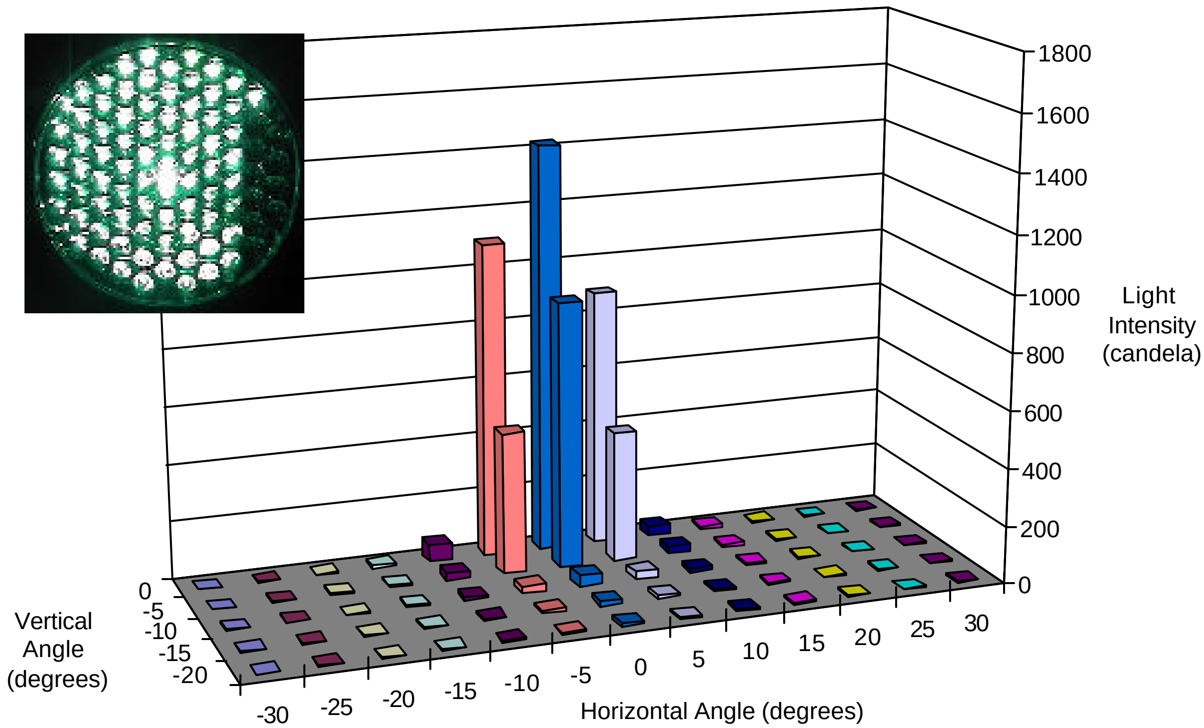

Figure A9.4.1a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

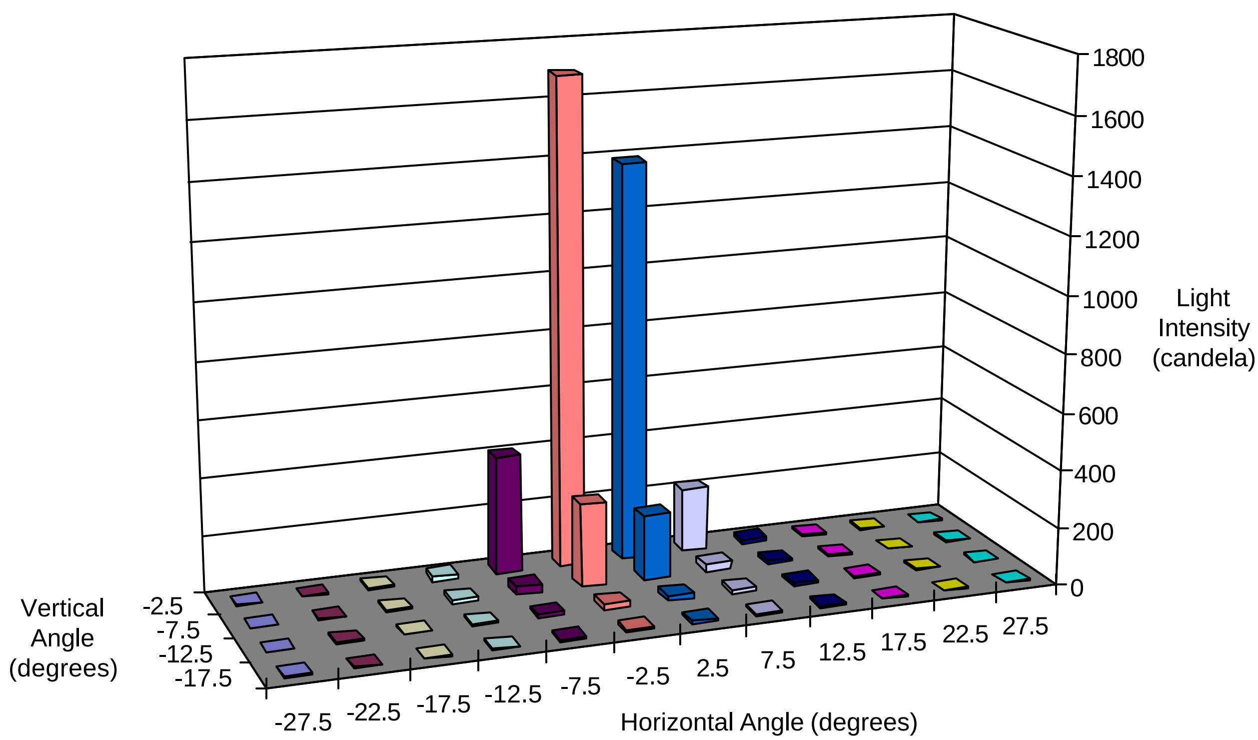

Figure A9.4.1b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

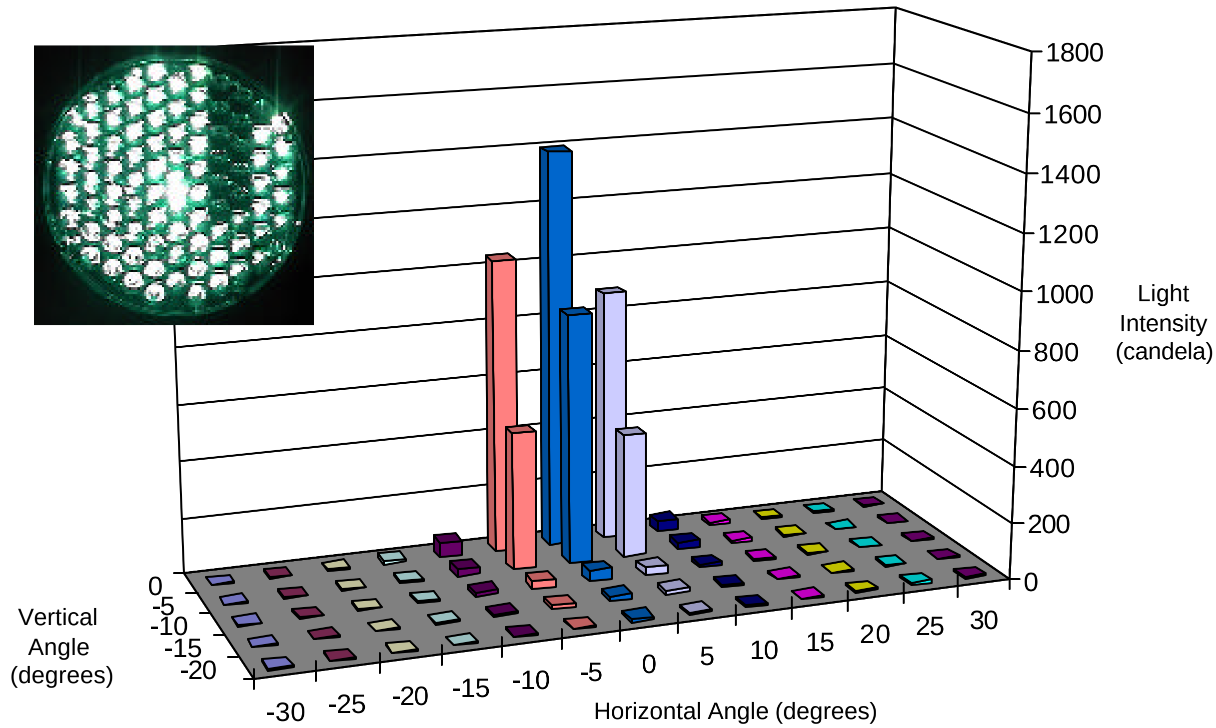

Figure A9.4.2a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

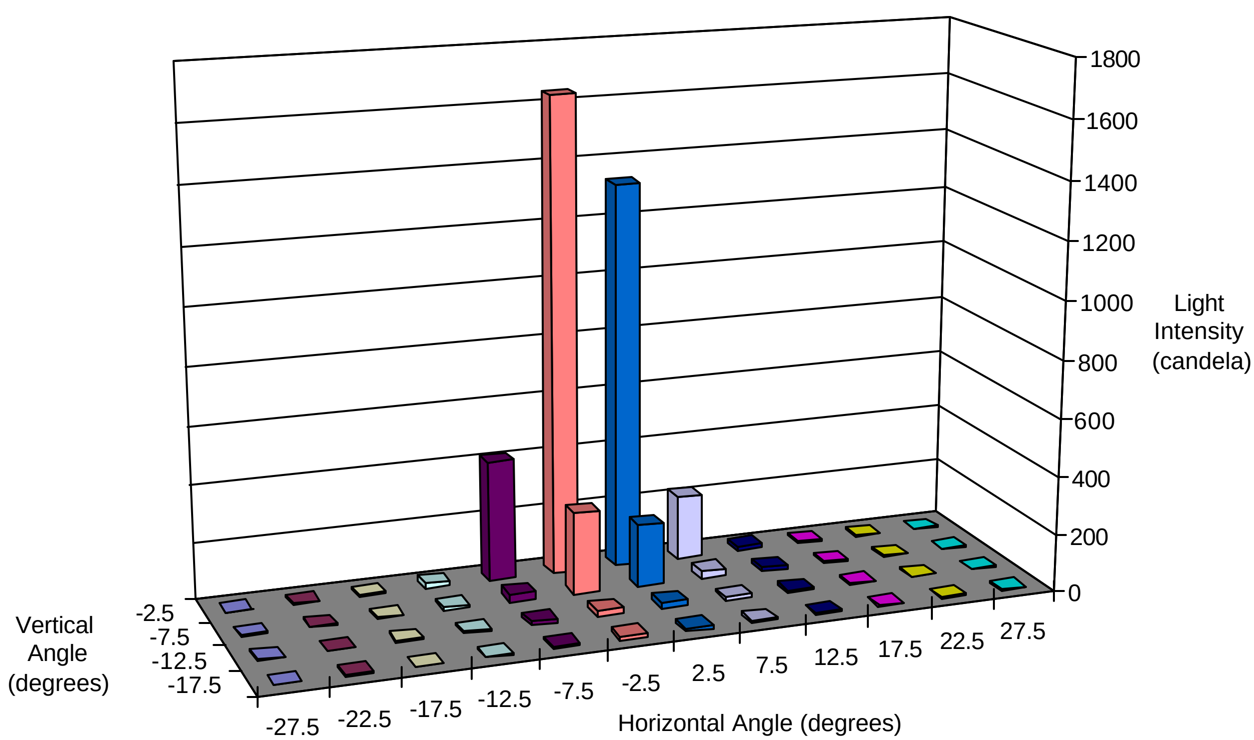

Figure A9.4.2b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

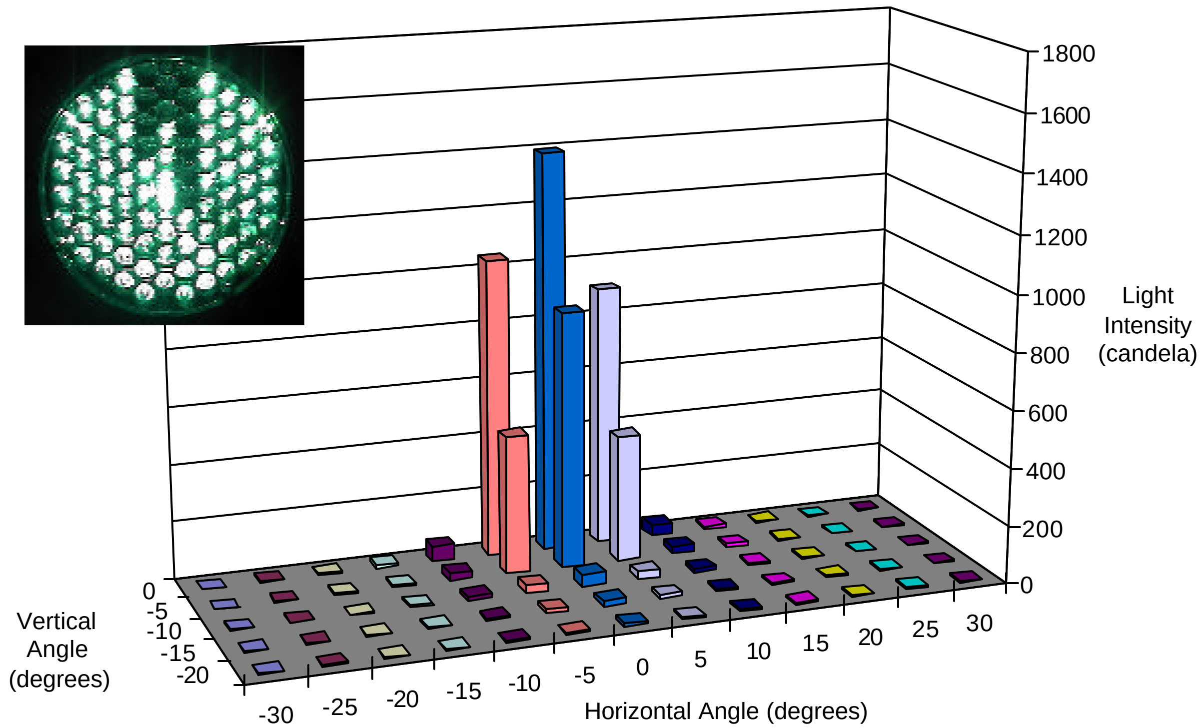

Figure A9.4.3a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

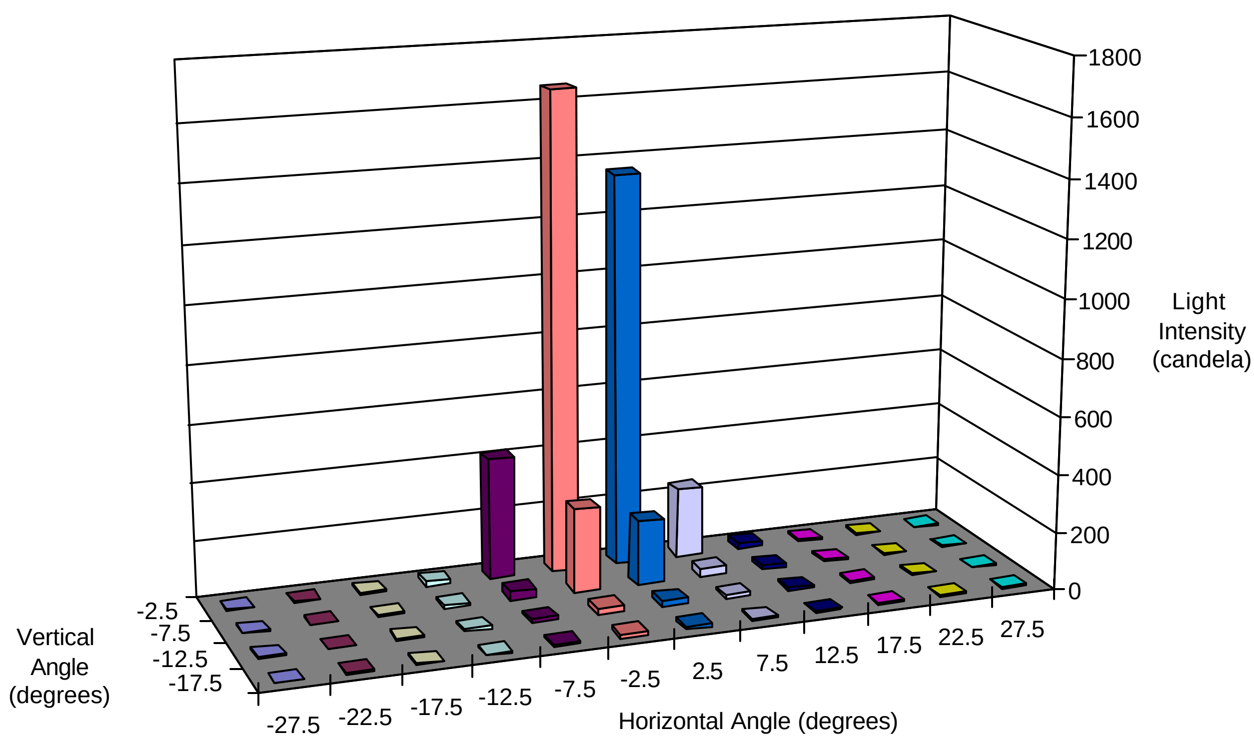

Figure A9.4.3b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

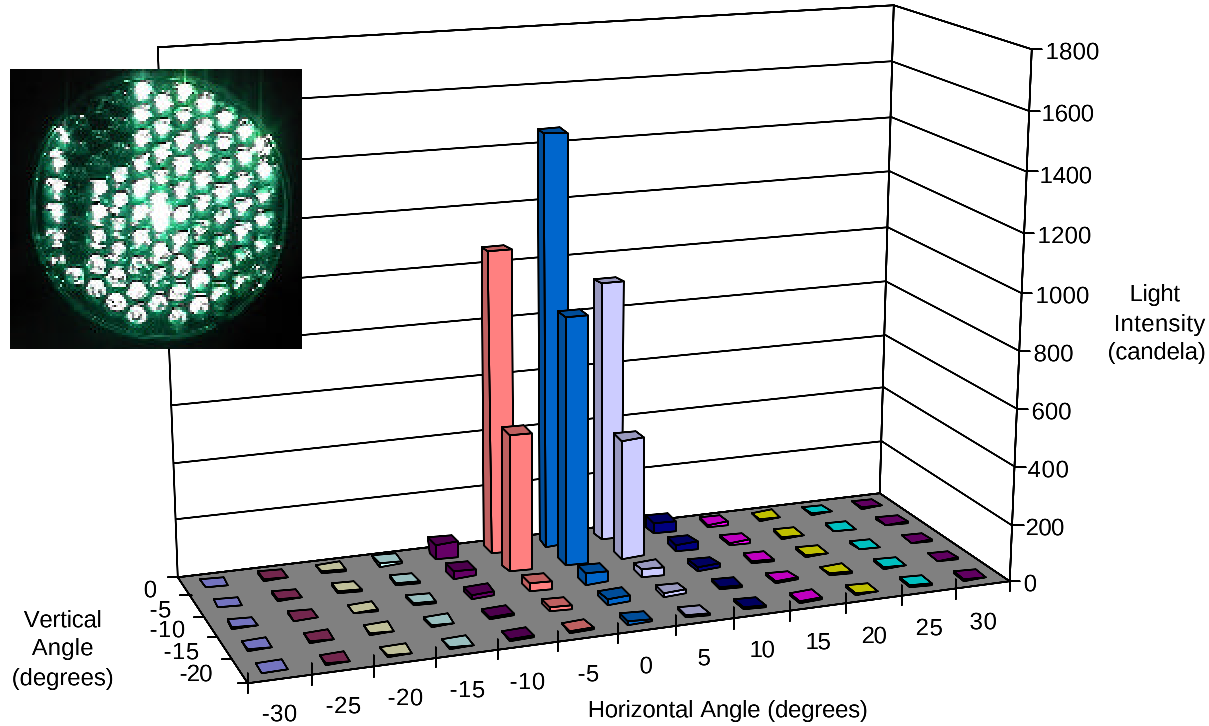

Figure A9.4.4a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

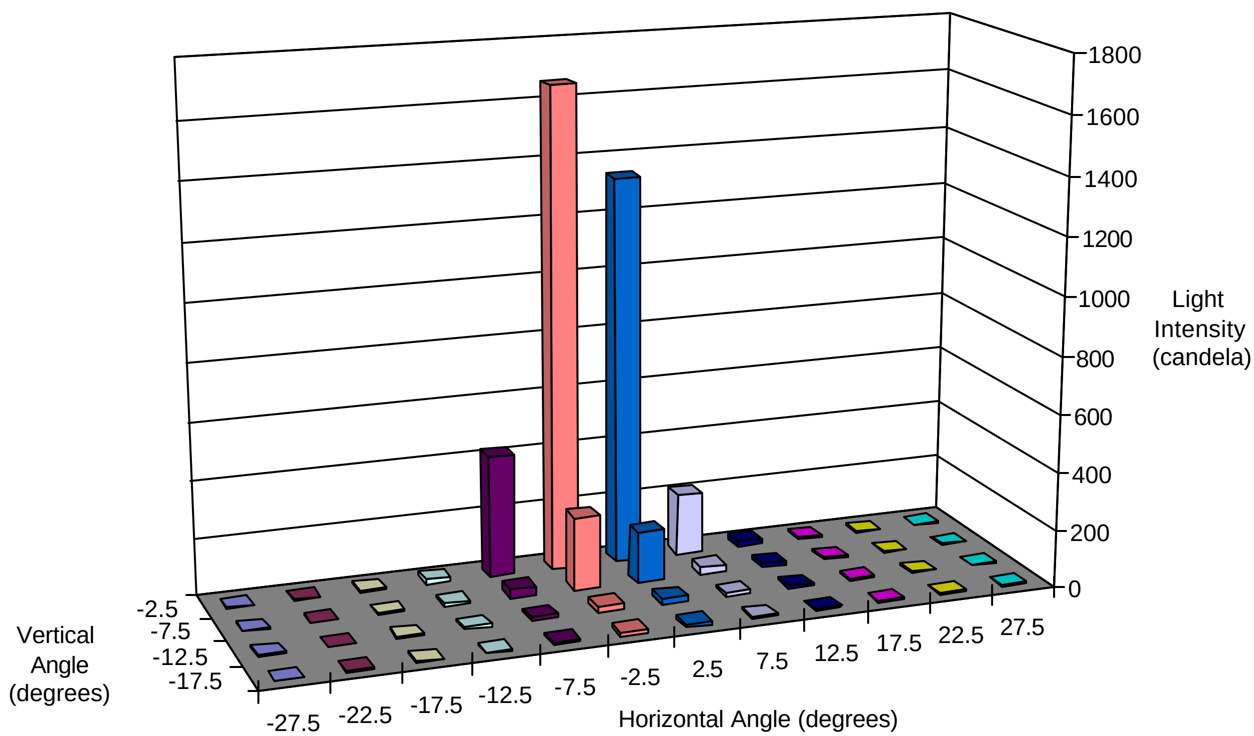

Figure A9.4.4b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

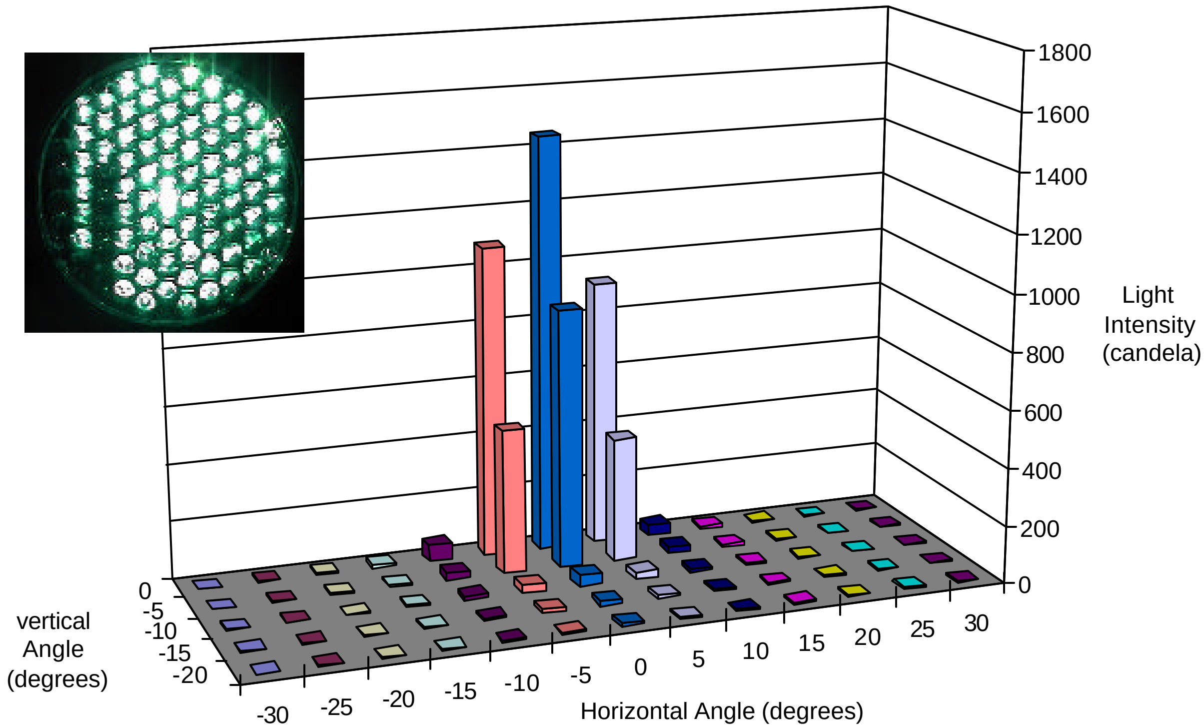

Figure A9.4.5a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

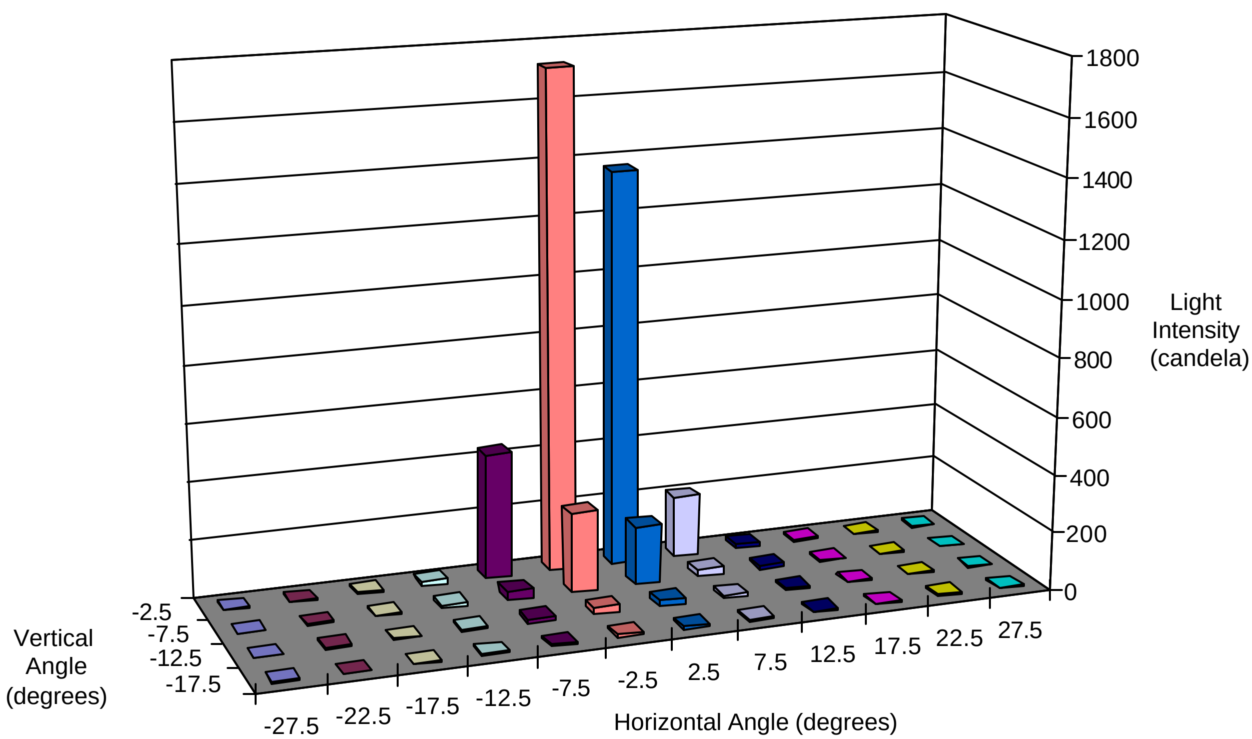

Figure A9.4.5b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

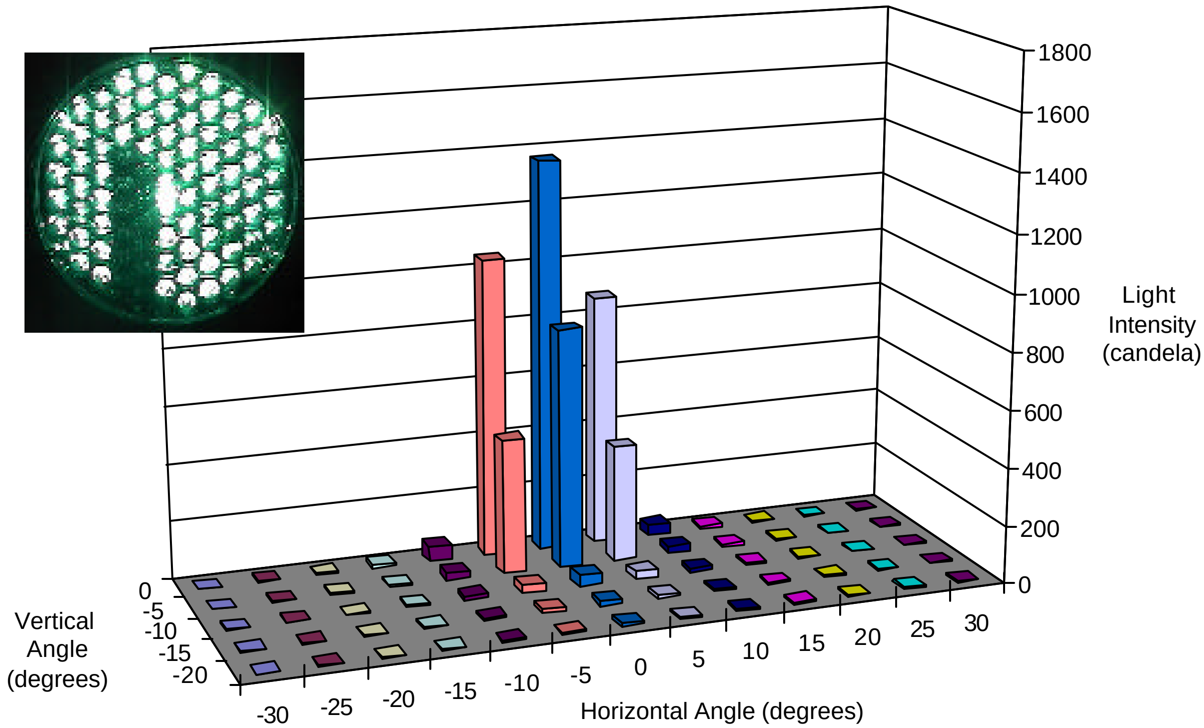

Figure A9.4.6a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

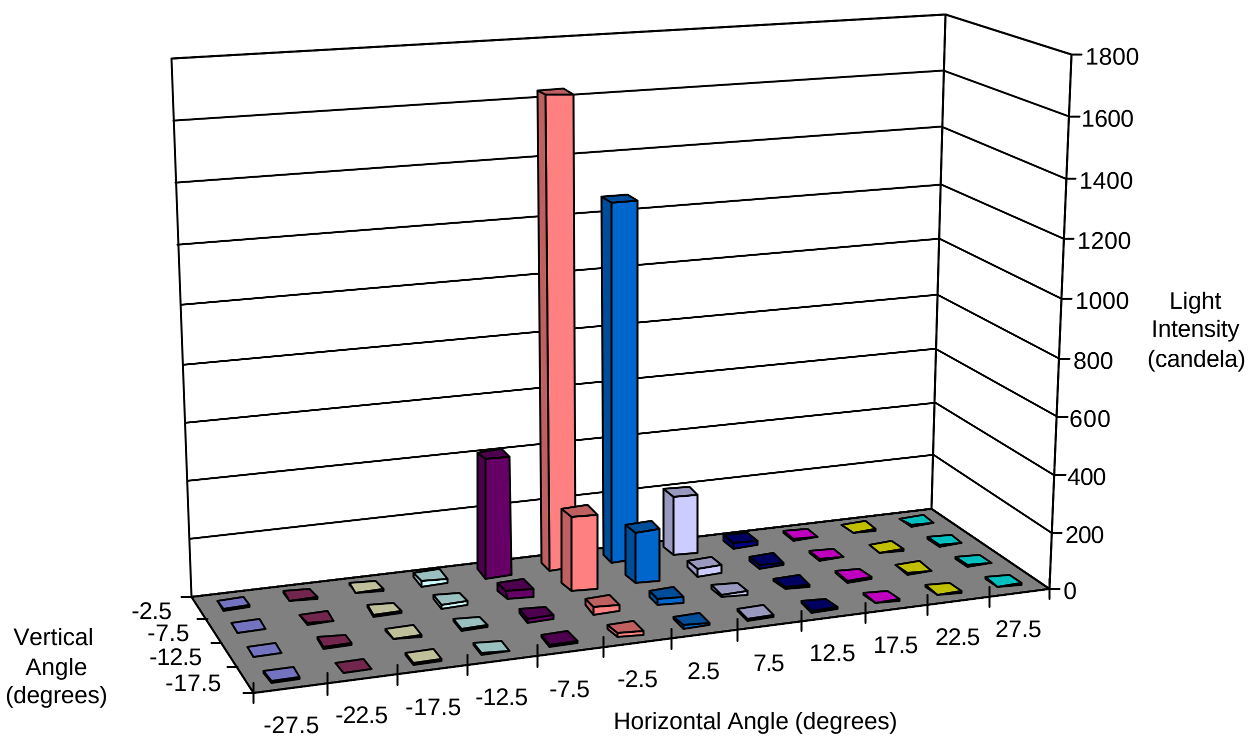

Figure A9.4.6b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

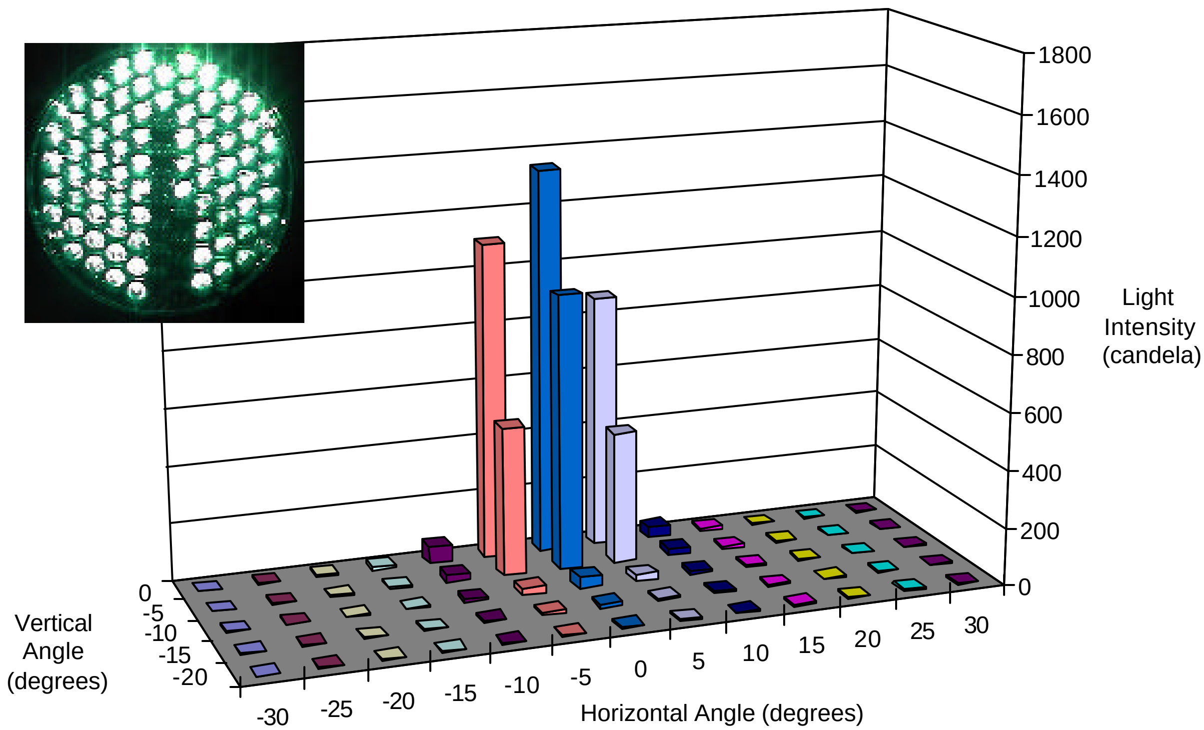

Figure A9.4.7a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

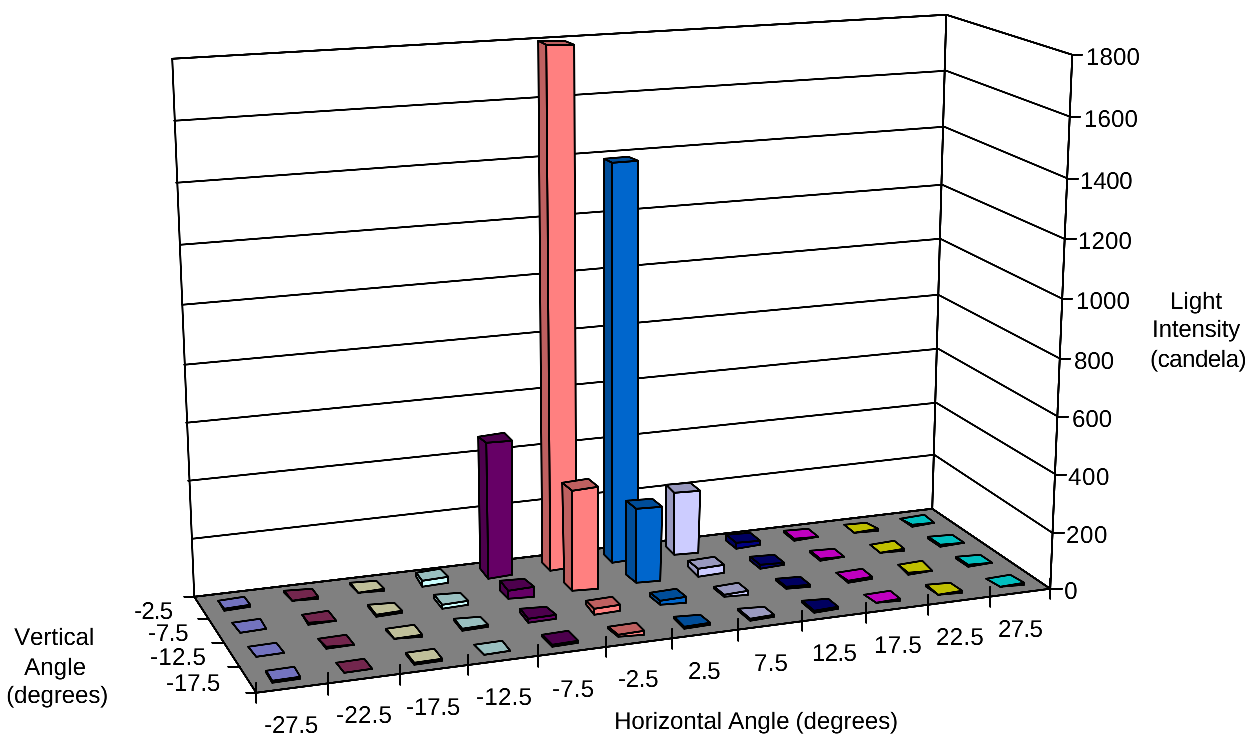

Figure A9.4.7b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

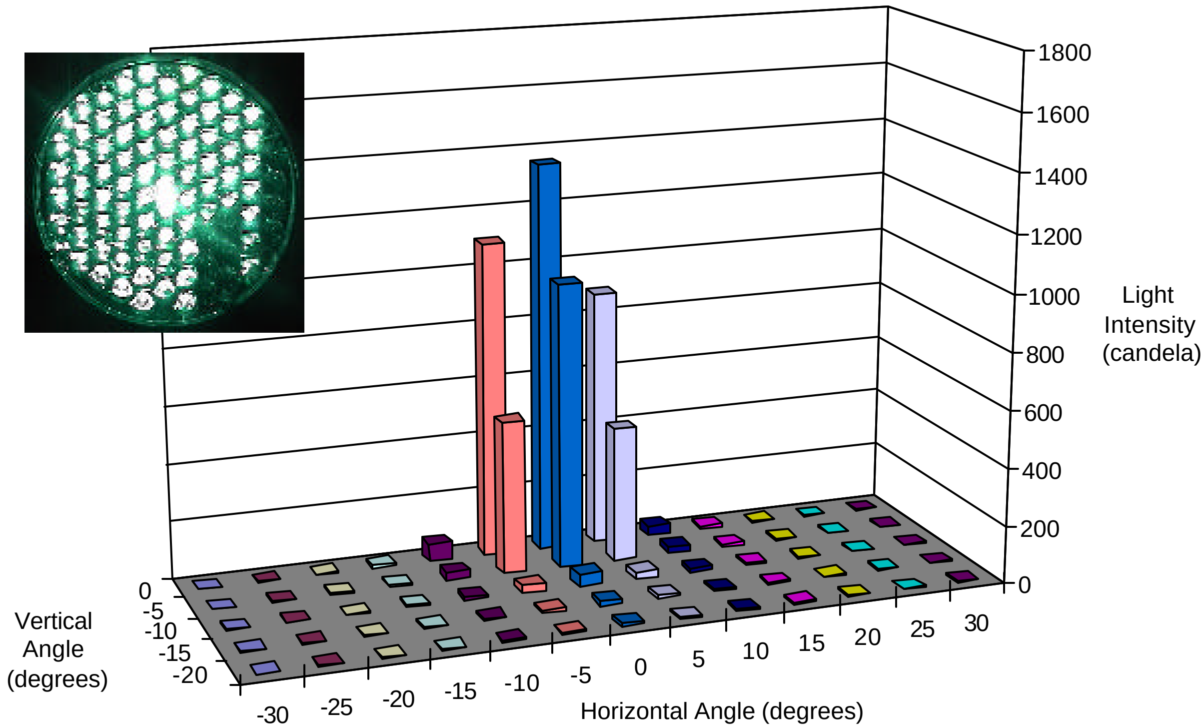

Figure A9.4.8a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

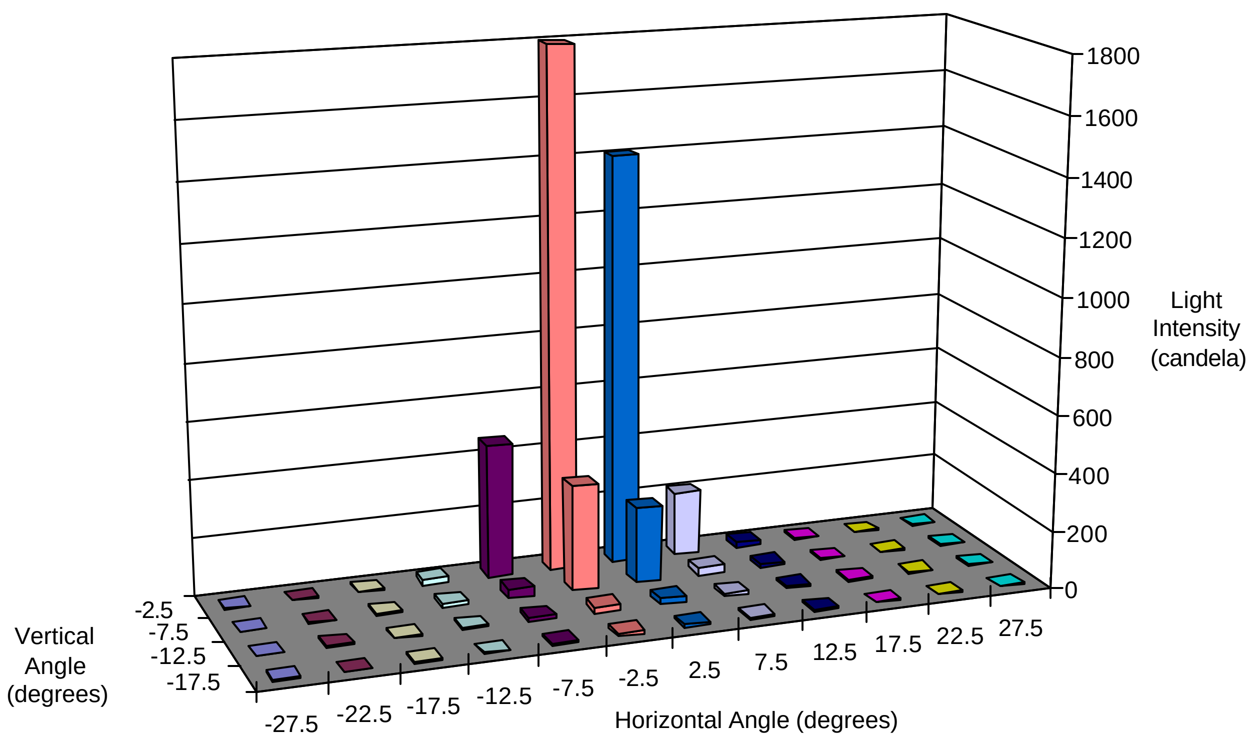

Figure A9.4.8b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

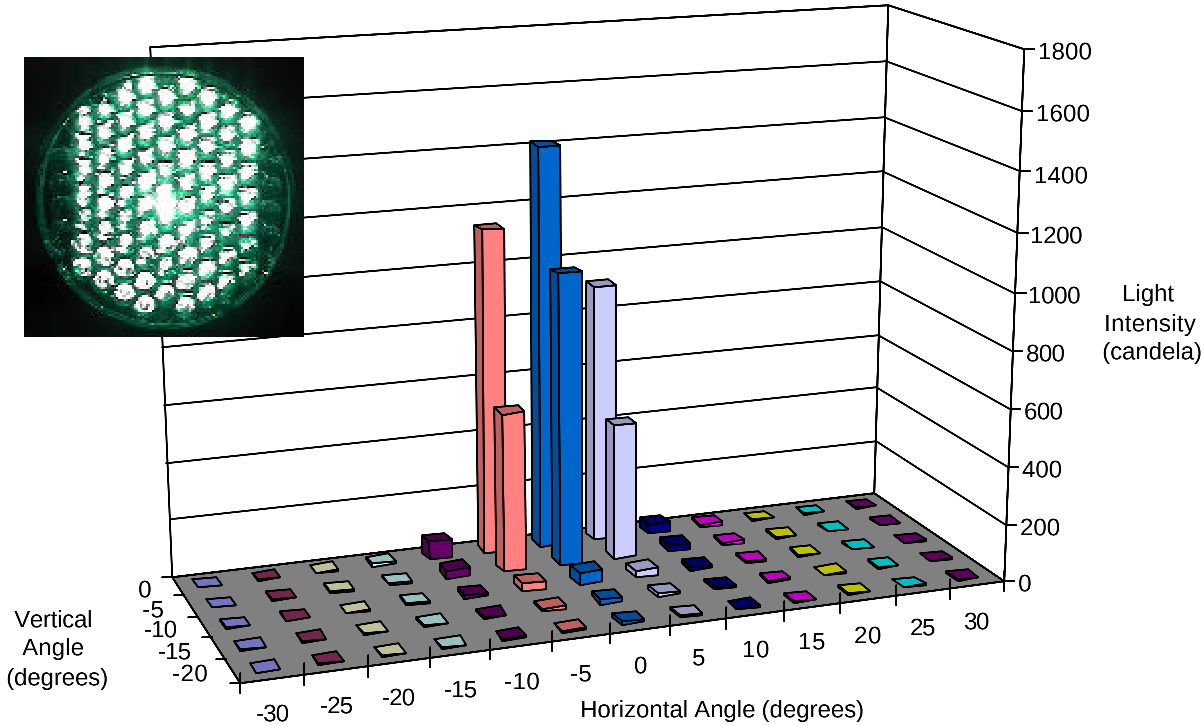

Figure A9.4.9a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

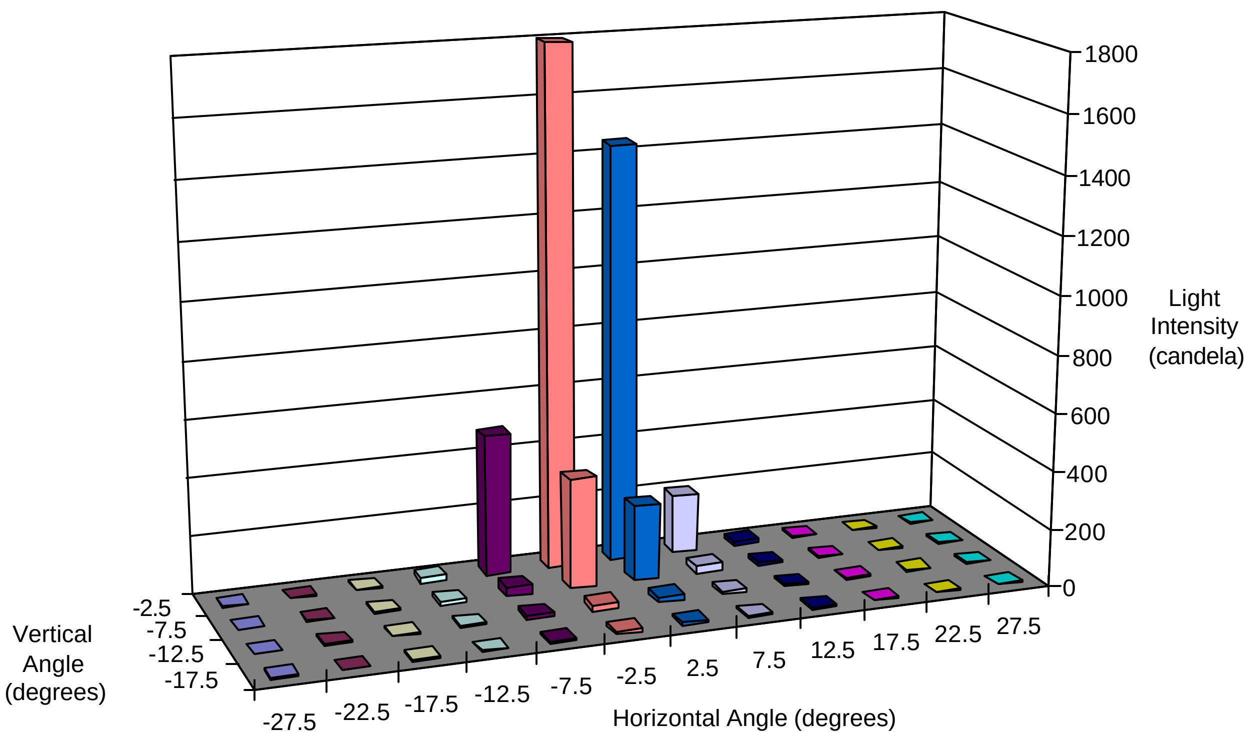

Figure A9.4.9b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

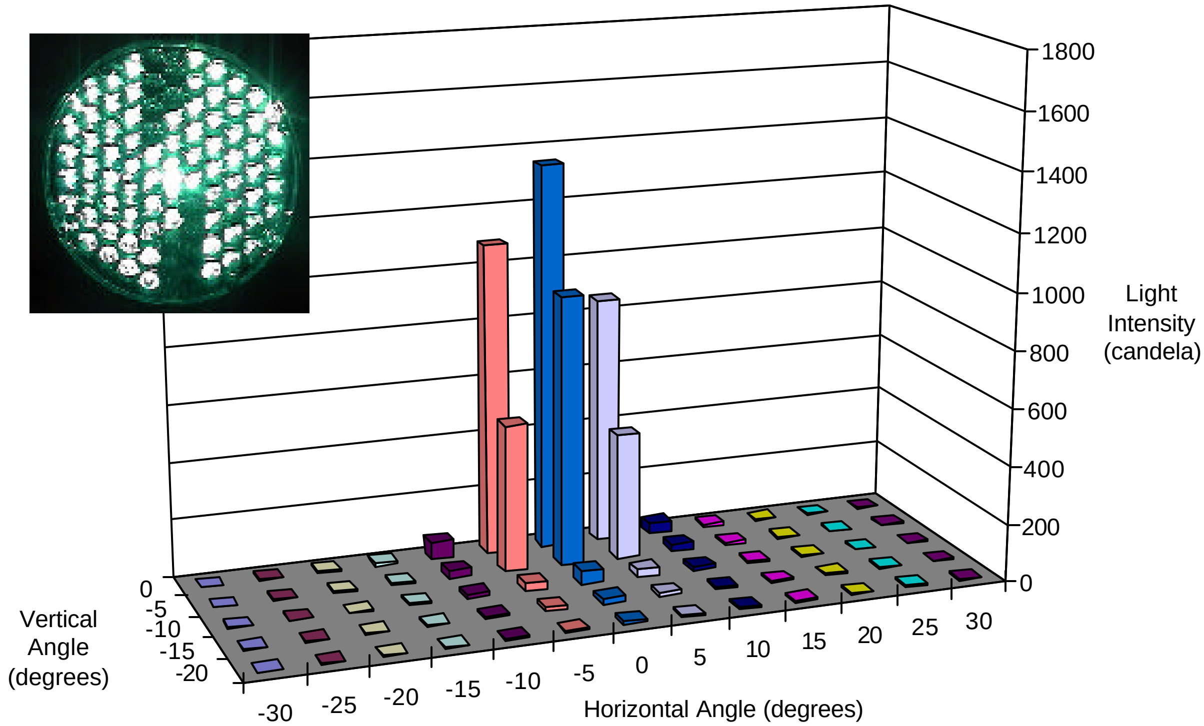

Figure A9.4.10a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

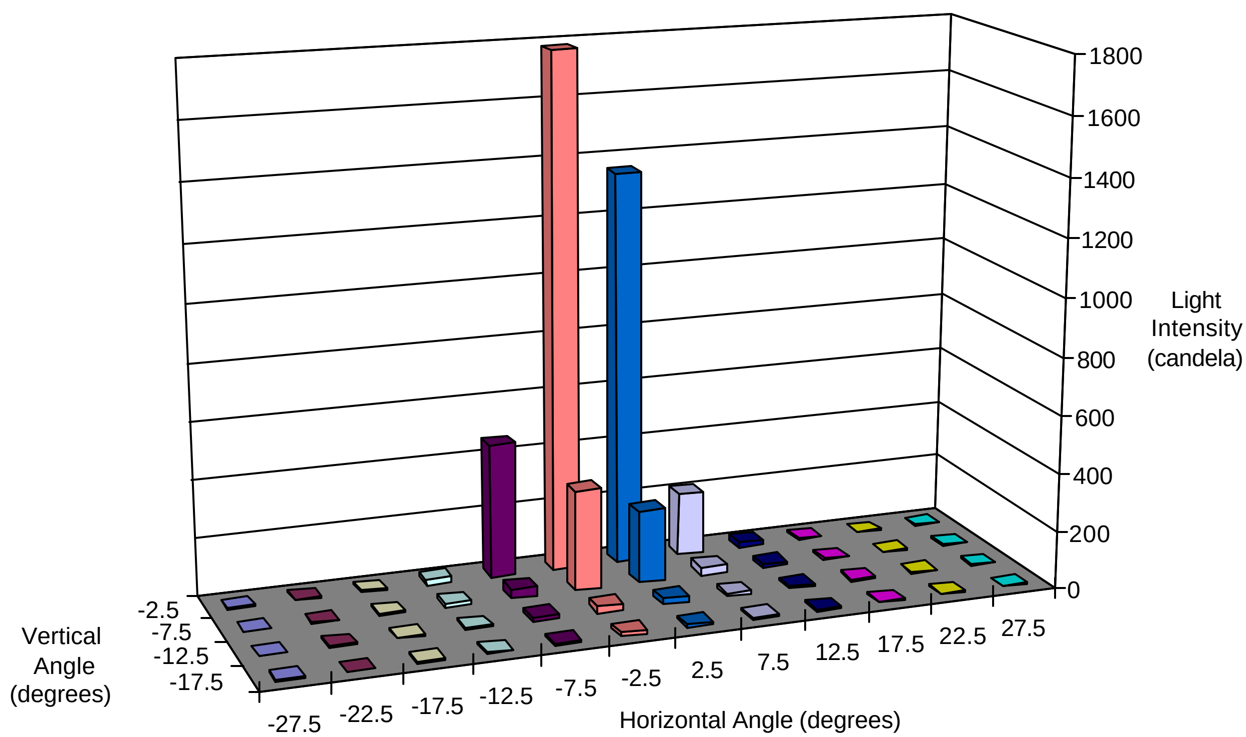

Figure A9.4.10b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

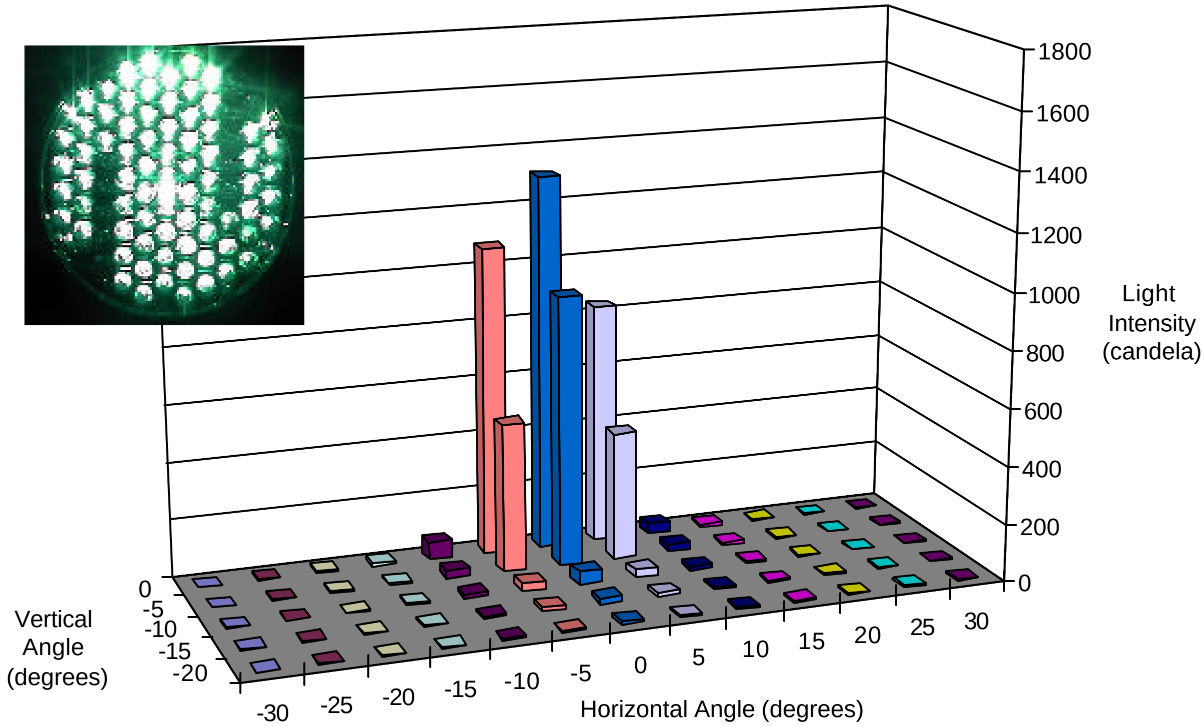

Figure A9.4.11a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

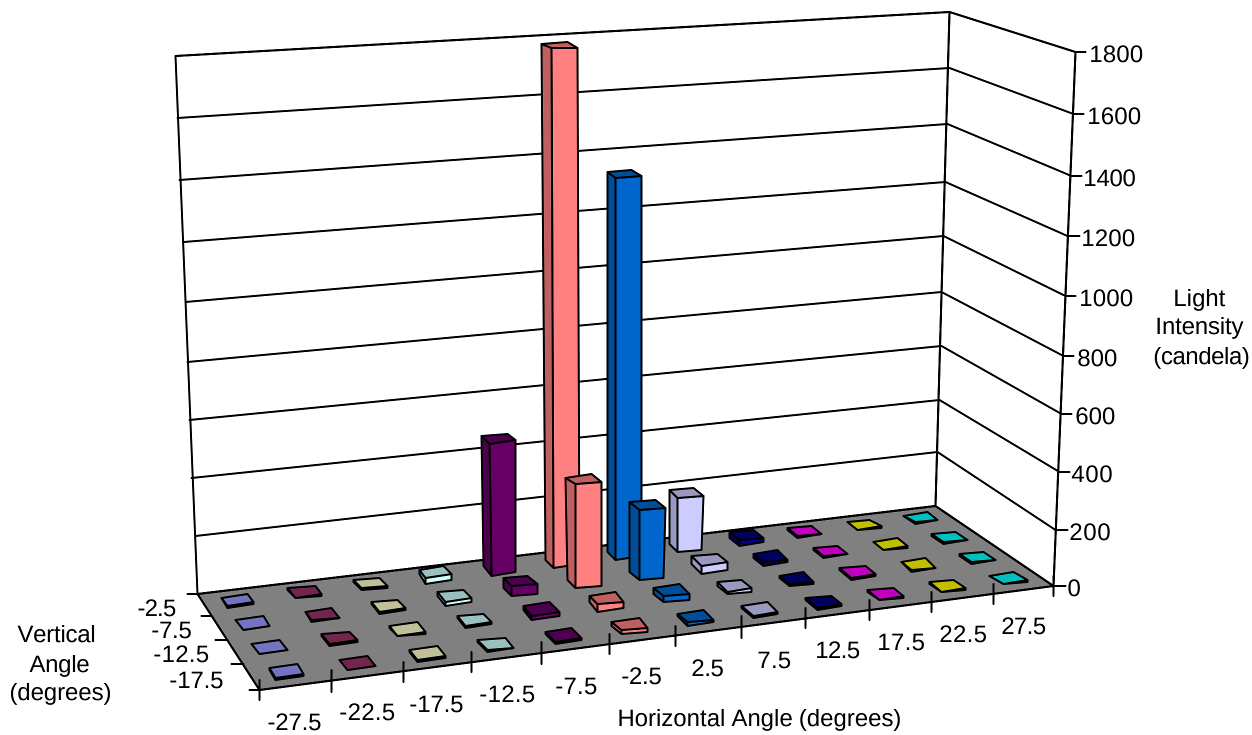

Figure A9.4.11b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

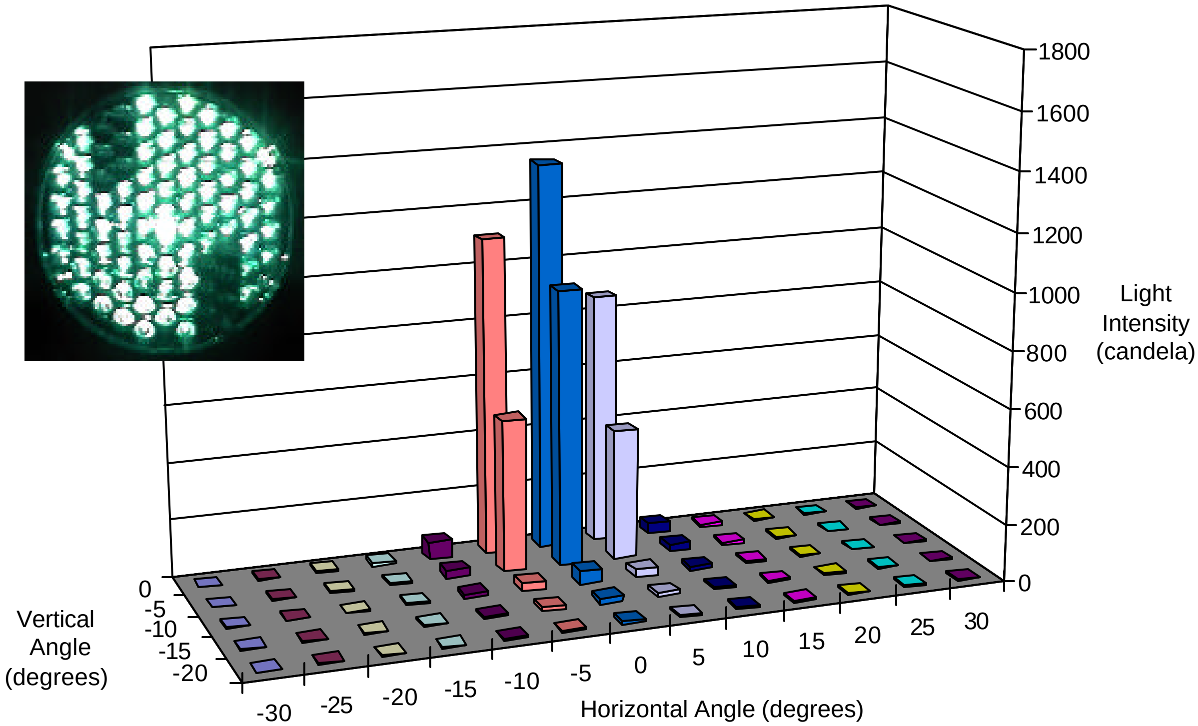

Figure A9.4.12a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

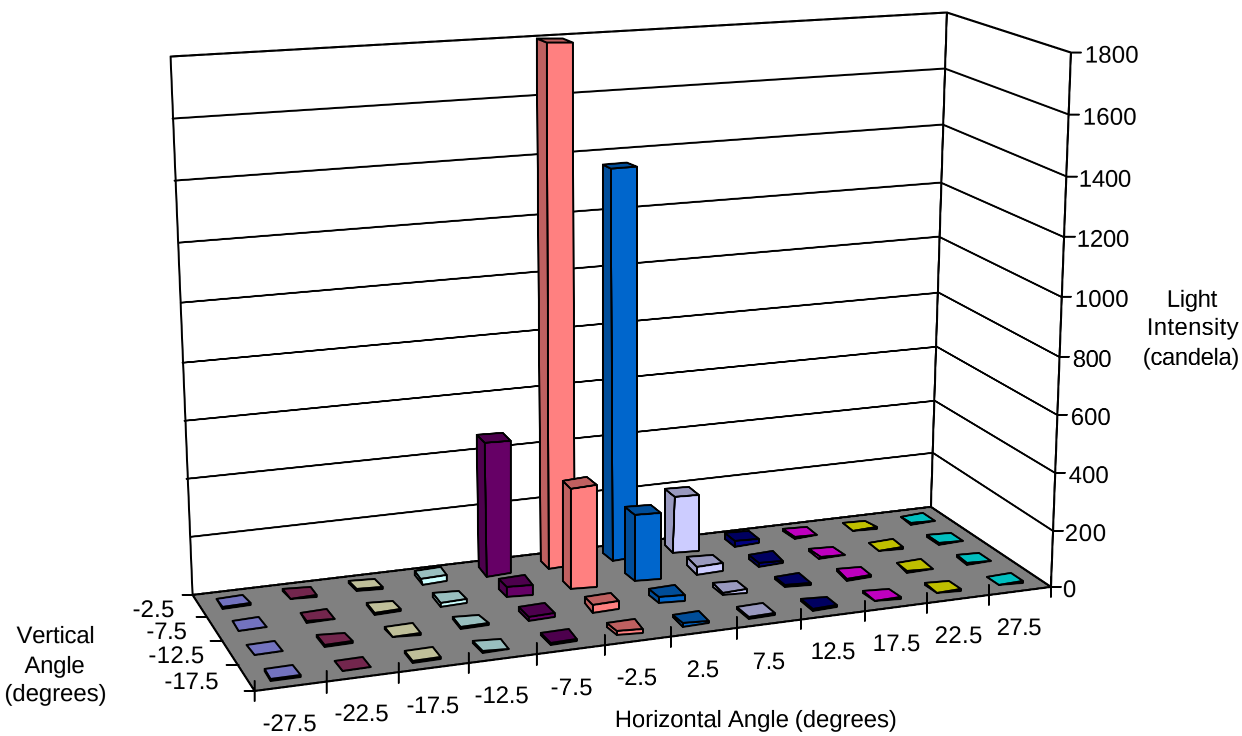

Figure A9.4.12b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

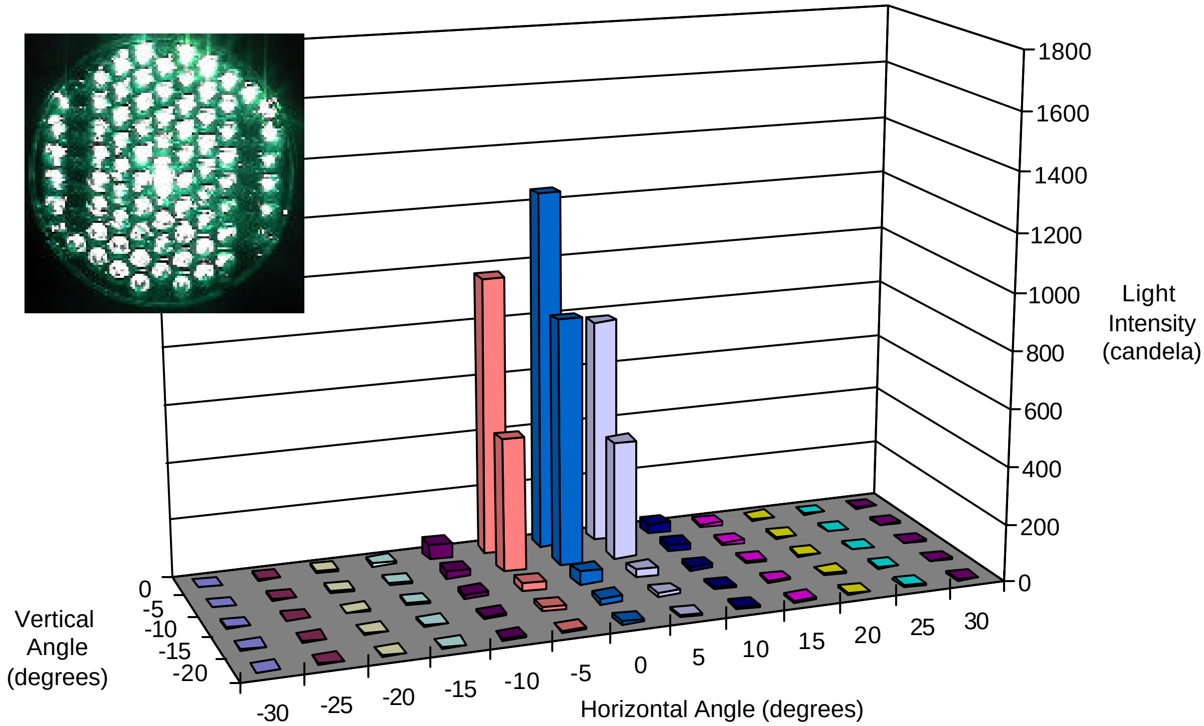

Figure A9.4.13a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

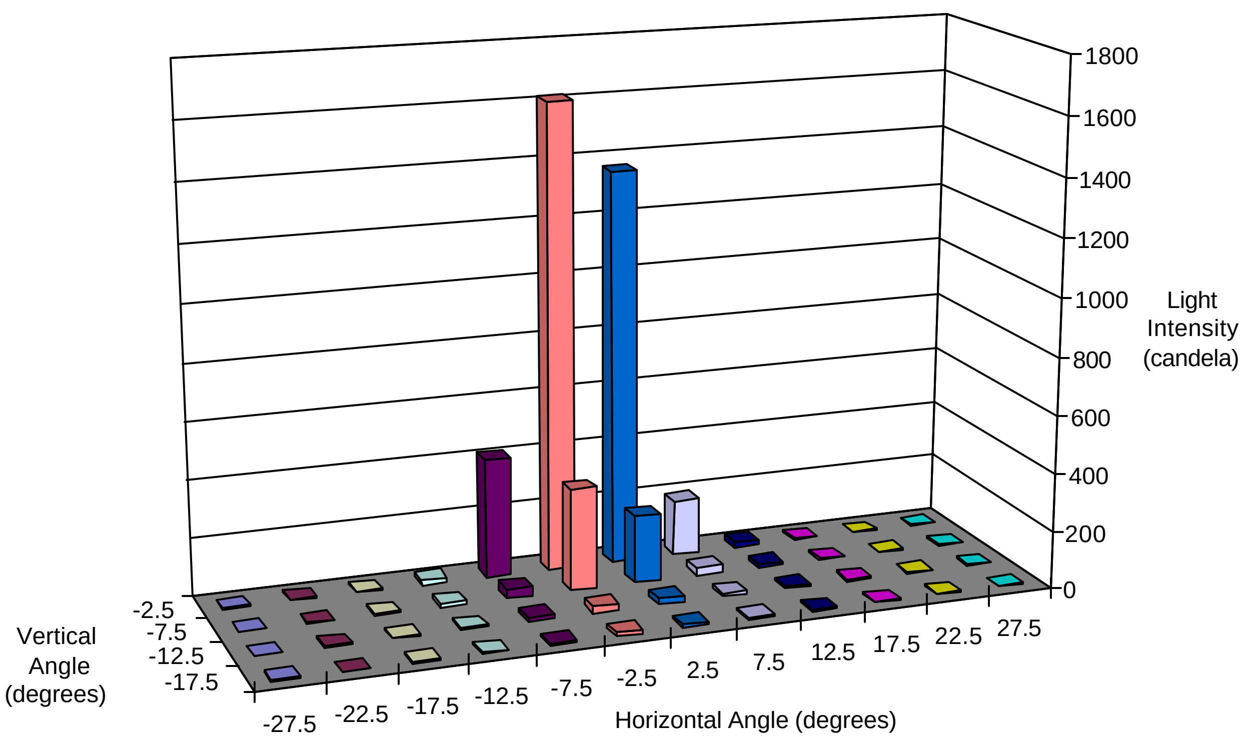

Figure A9.4.13b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

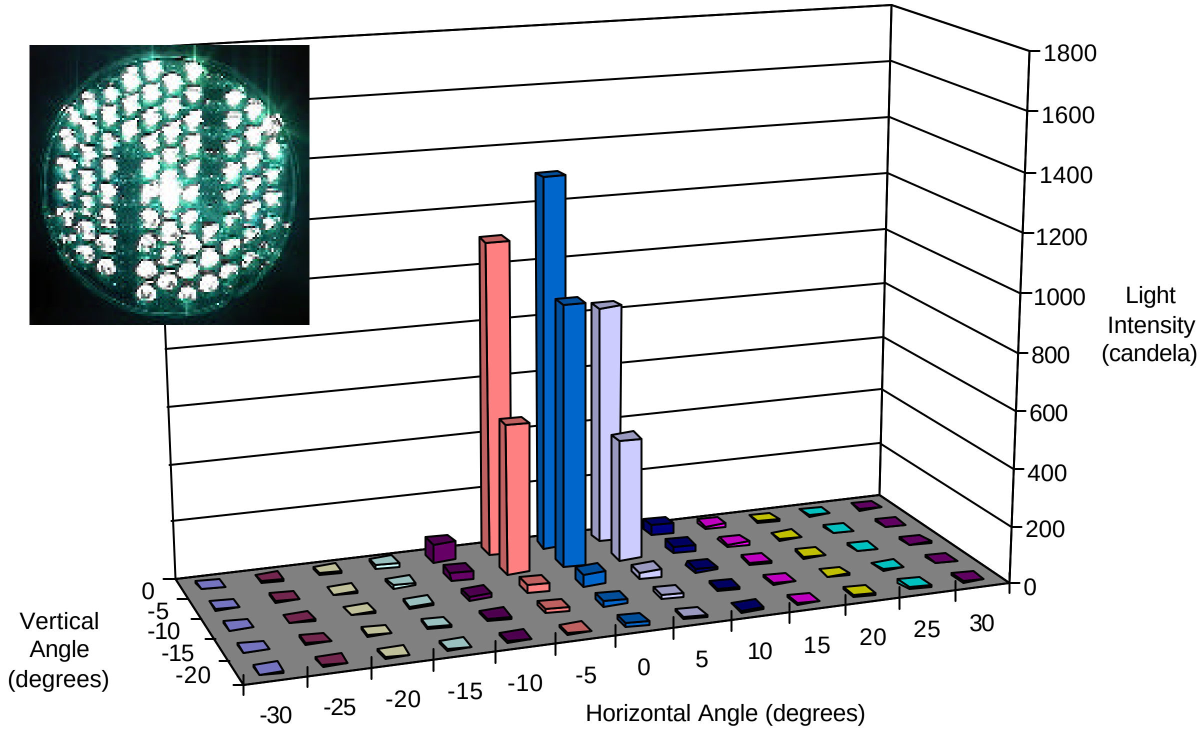

Figure A9.4.14a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

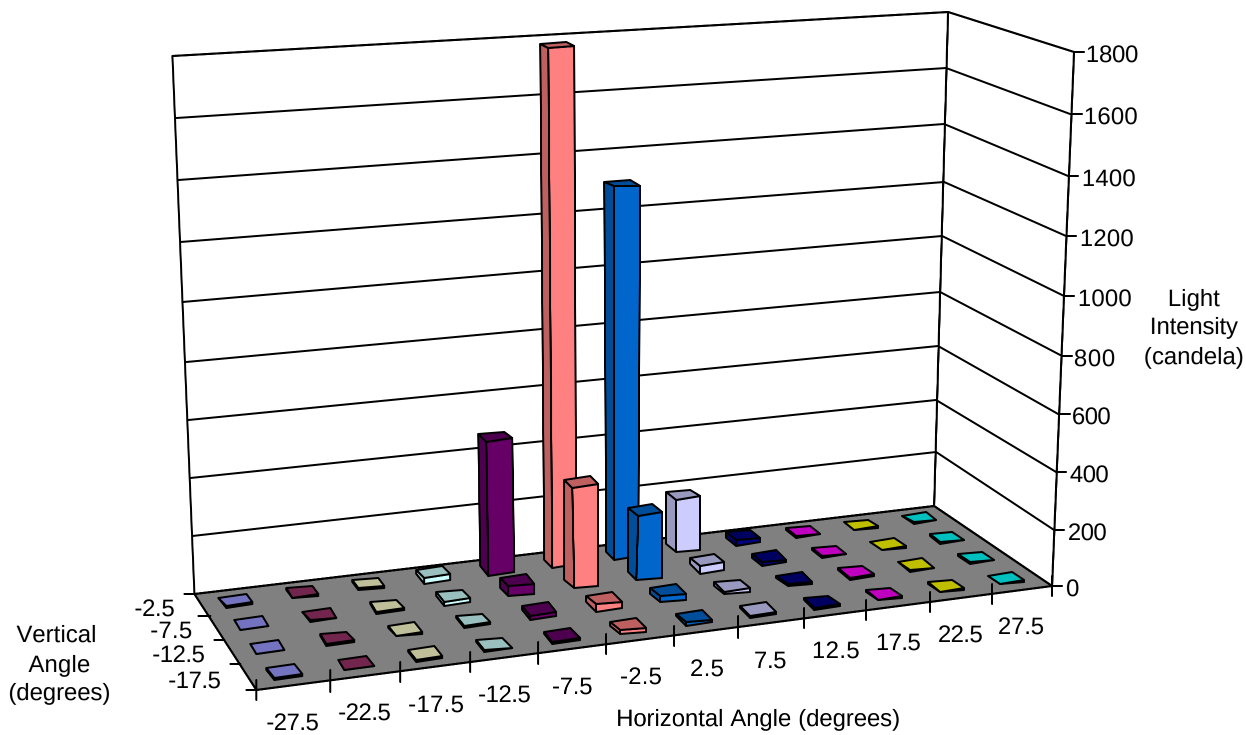

Figure A9.4.14b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

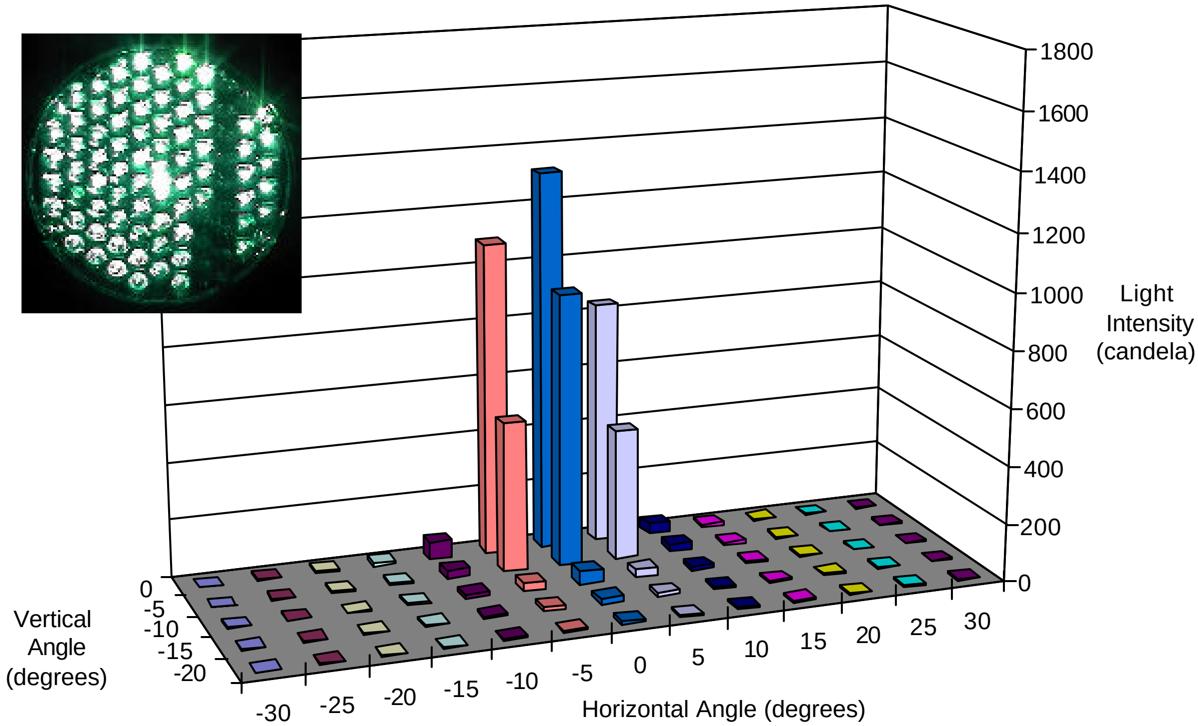

Figure A9.4.15a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

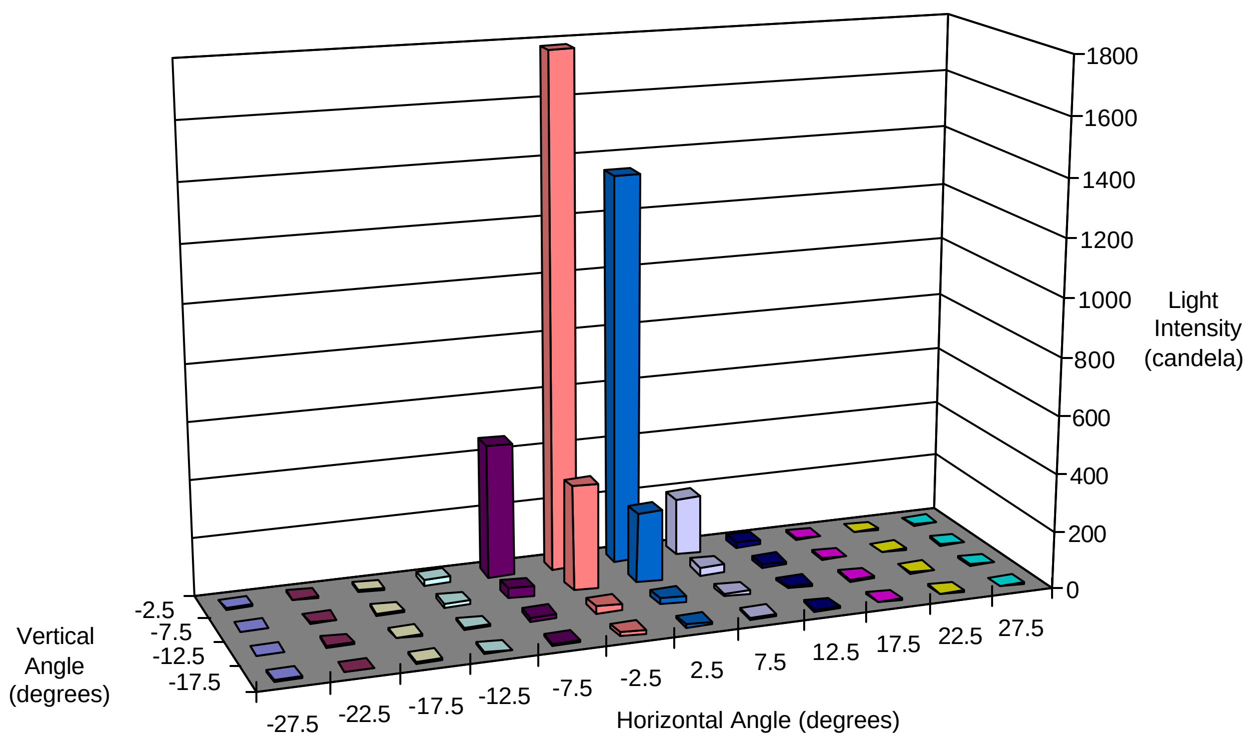

Figure A9.4.15b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

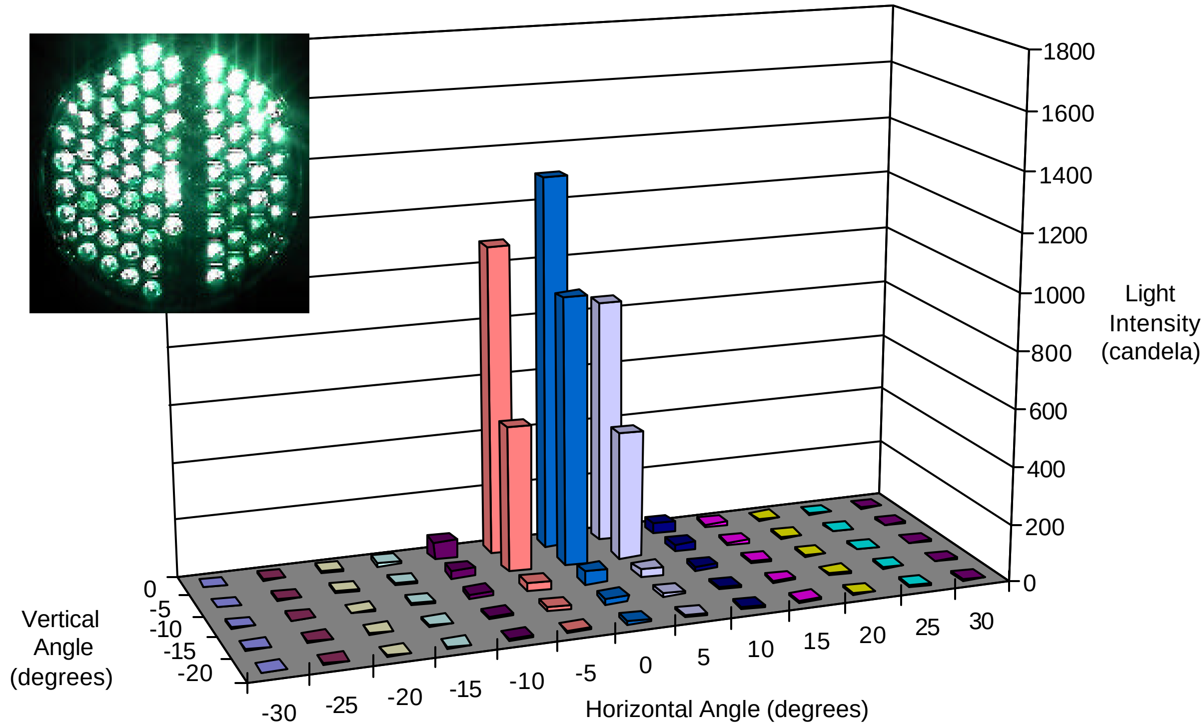

Figure A9.4.16a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

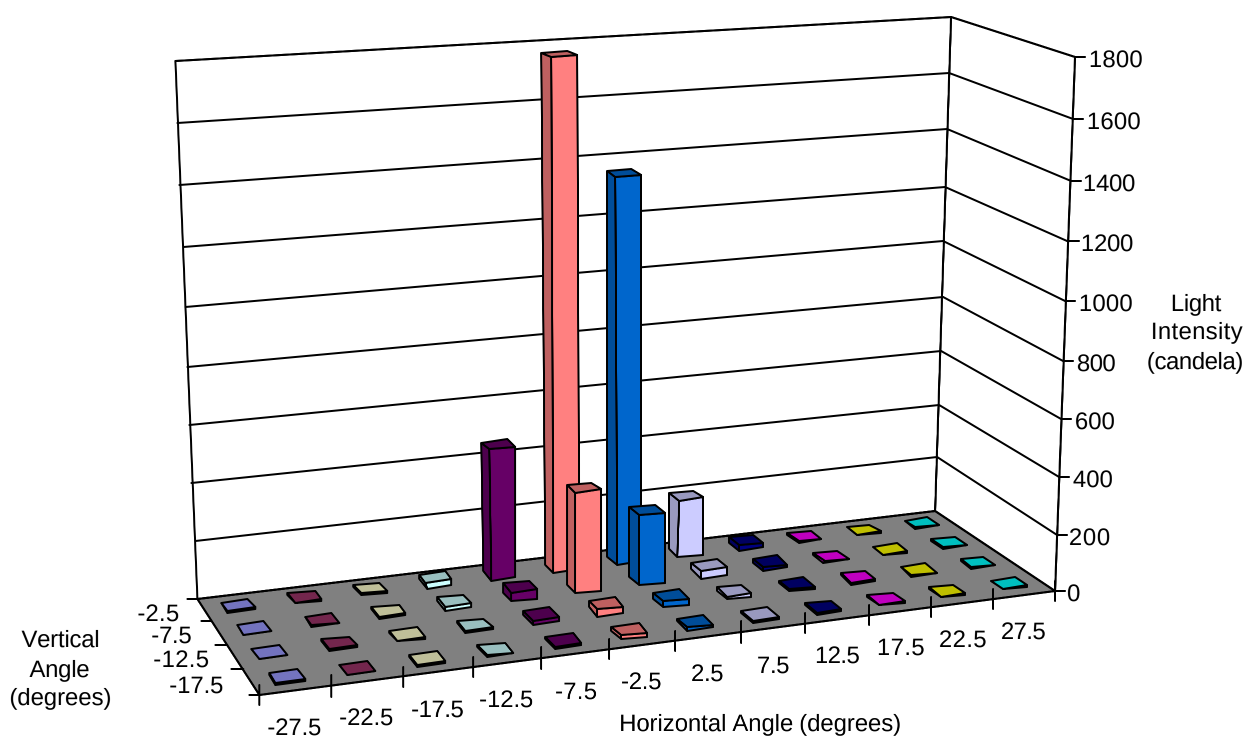

Figure A9.4.16b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

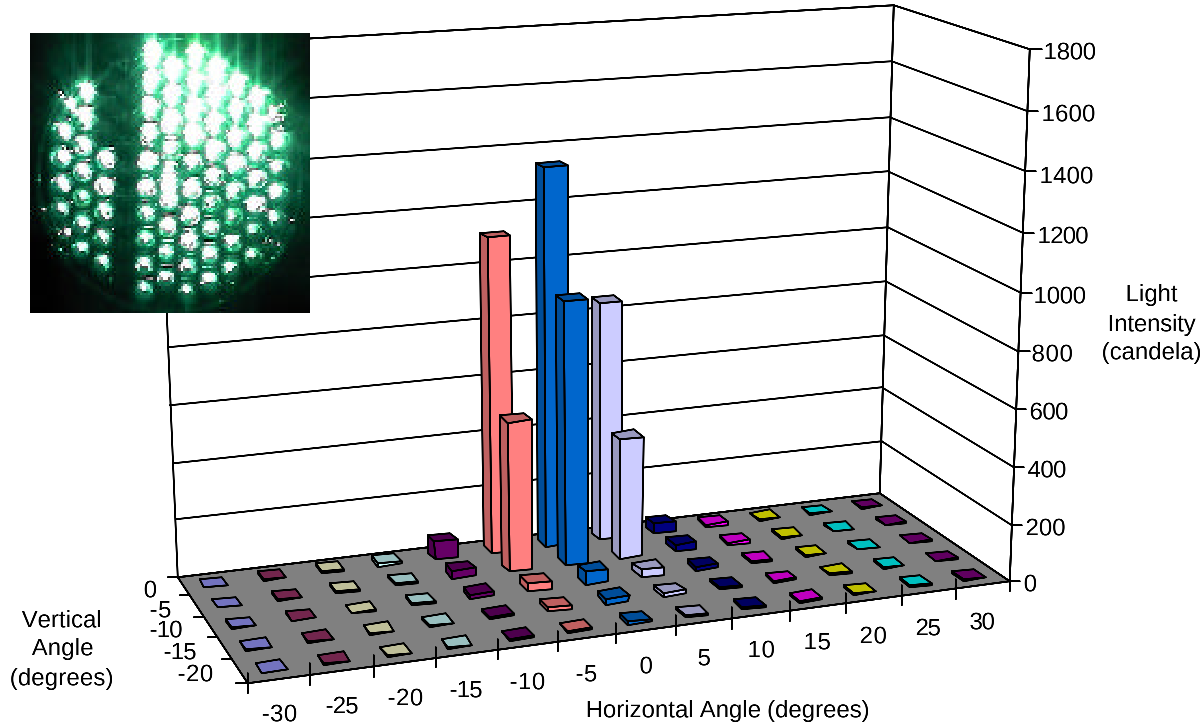

Figure A9.4.17a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

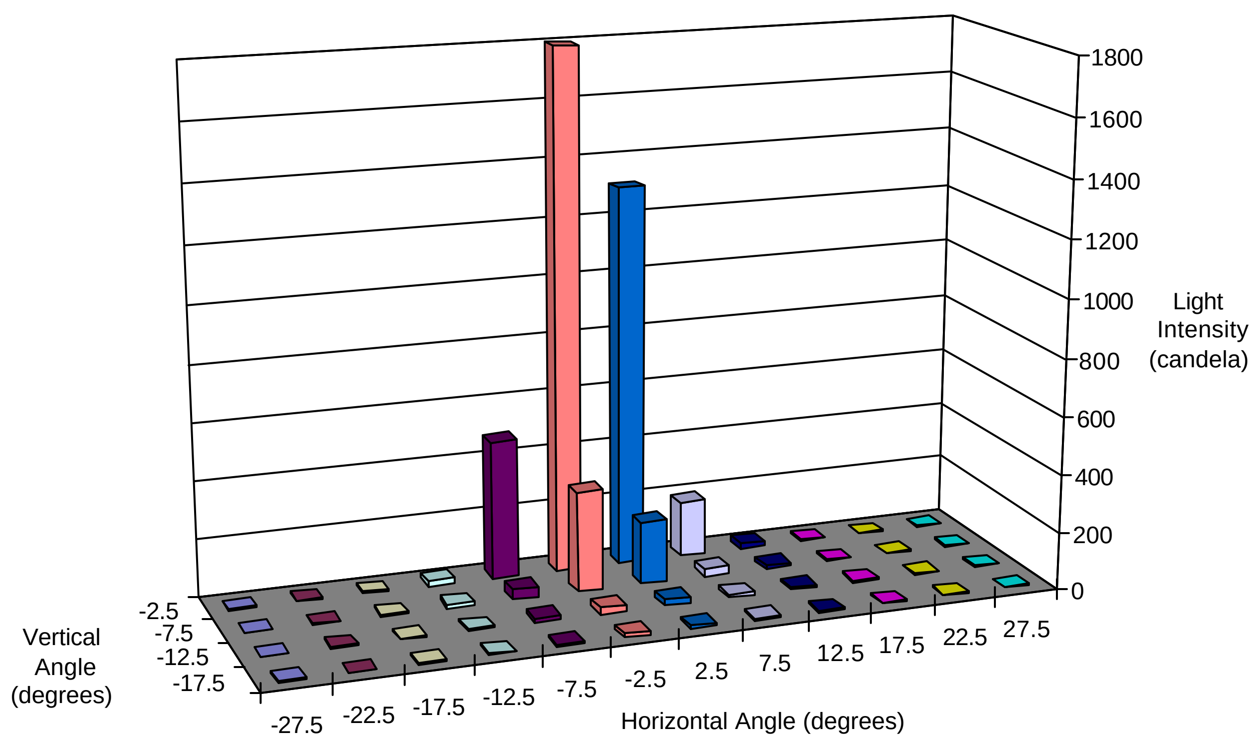

Figure A9.4.17b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

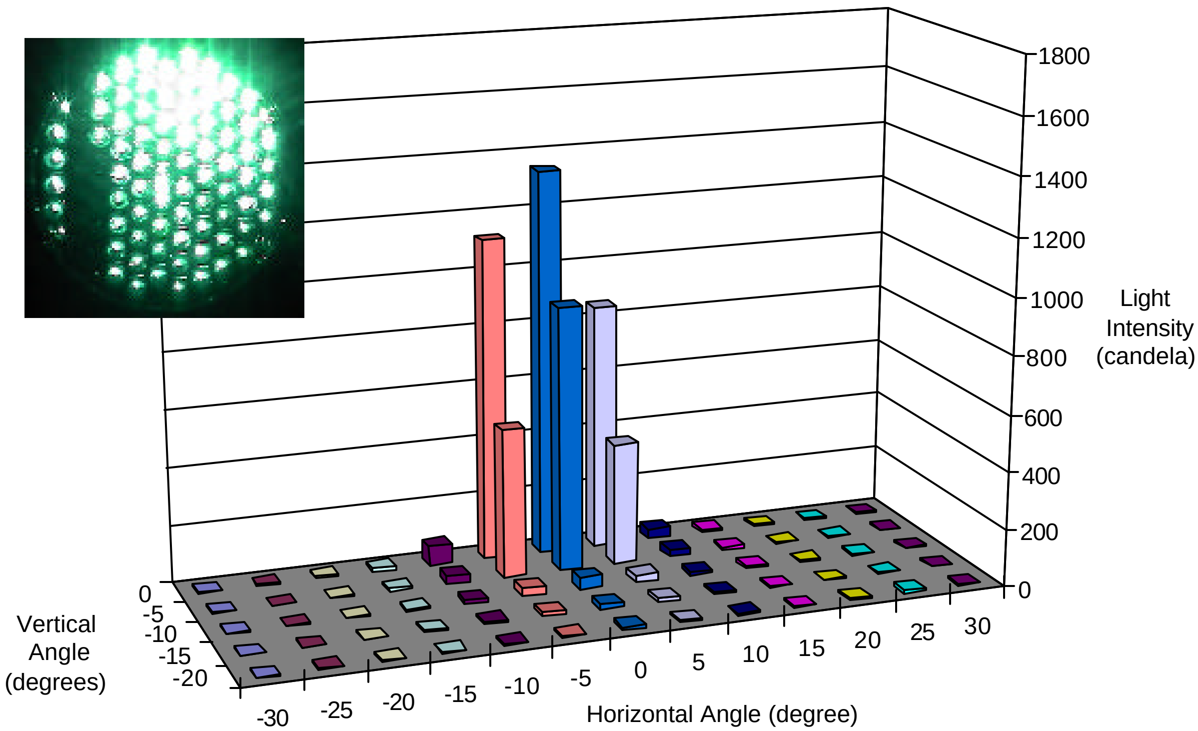

Figure A9.4.18a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

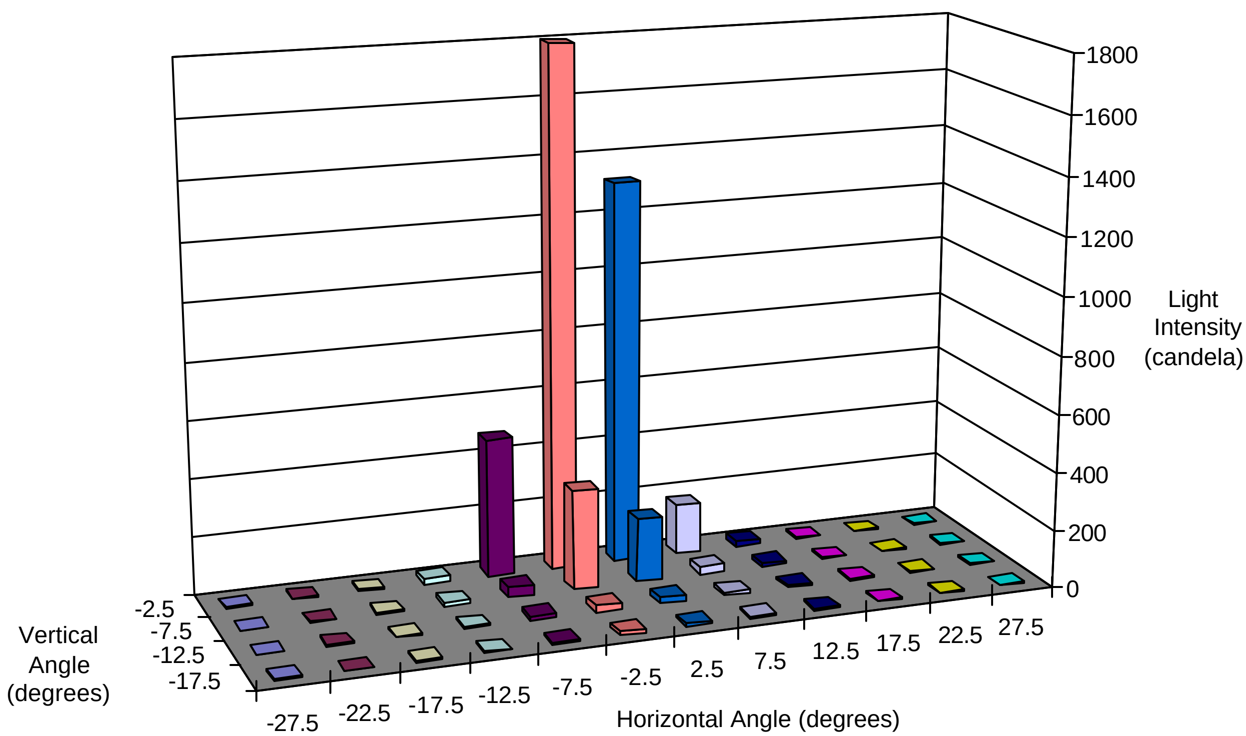

Figure A9.4.18b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

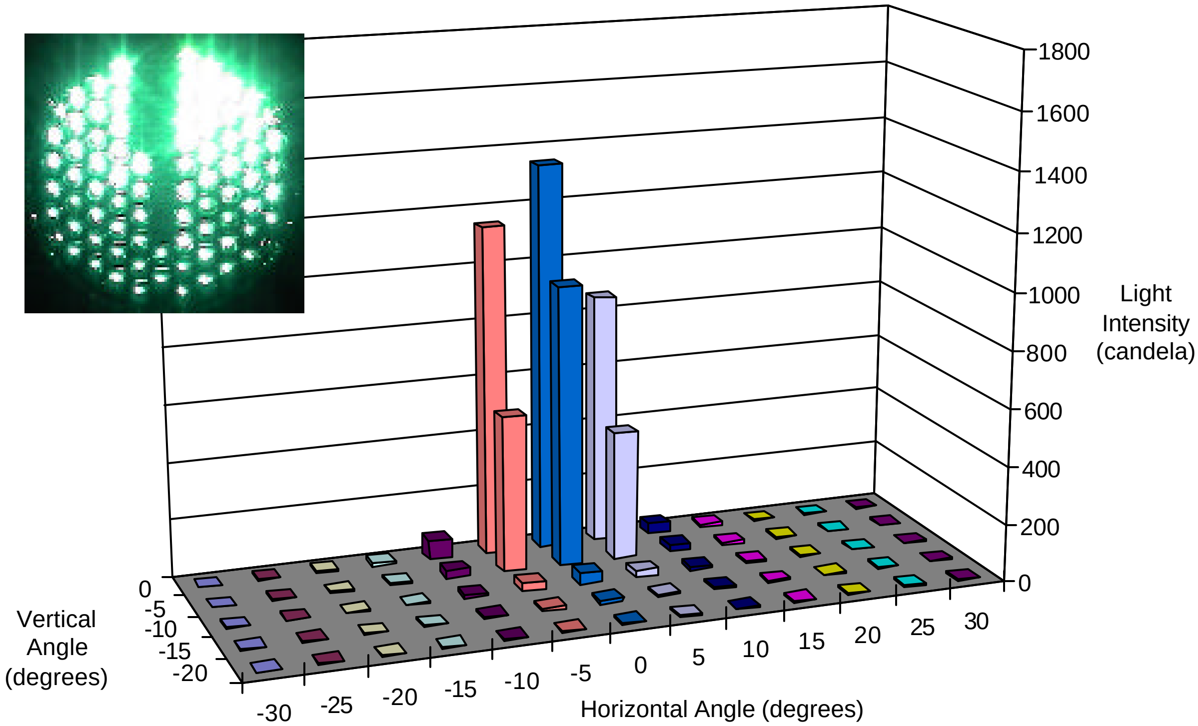

Figure A9.4.19a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

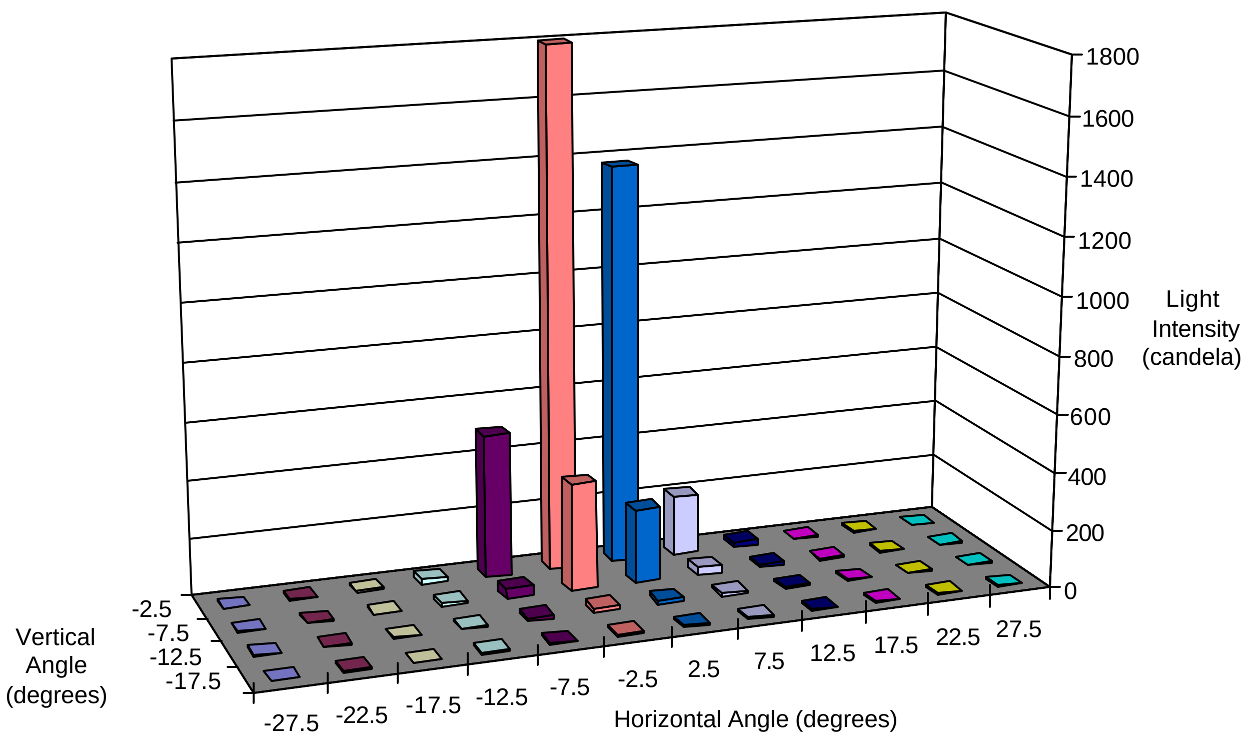

Figure A9.4.19b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

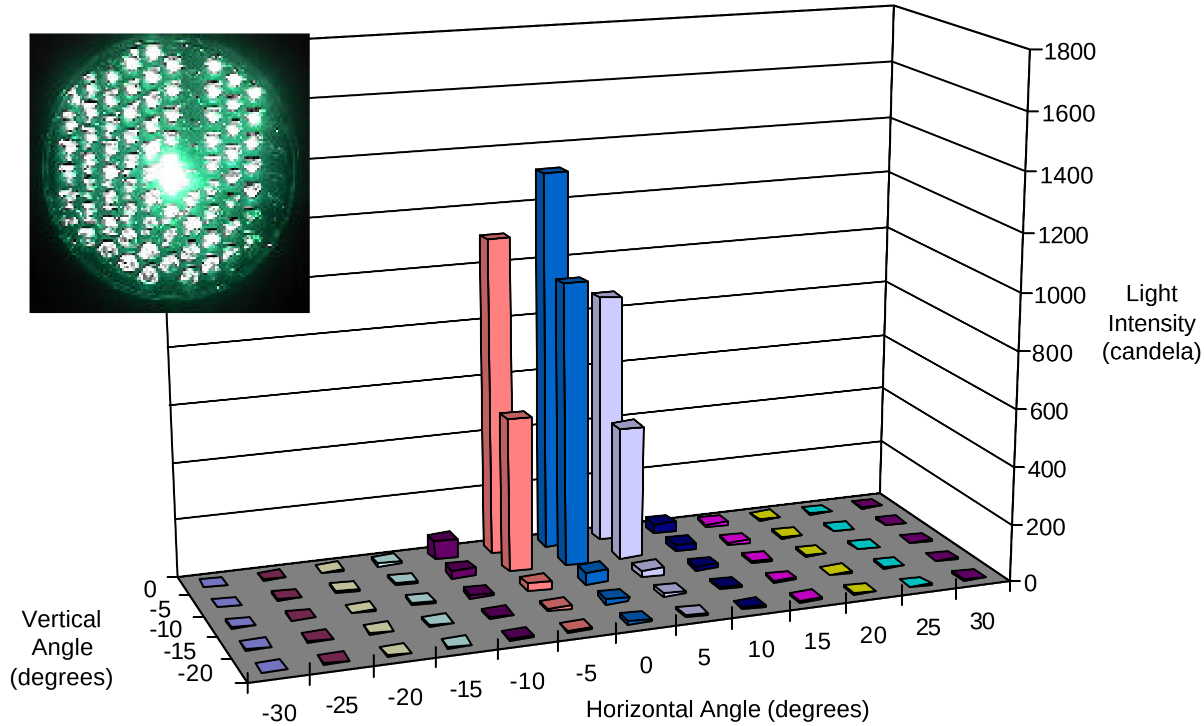

Figure A9.4.20a Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), TC test.

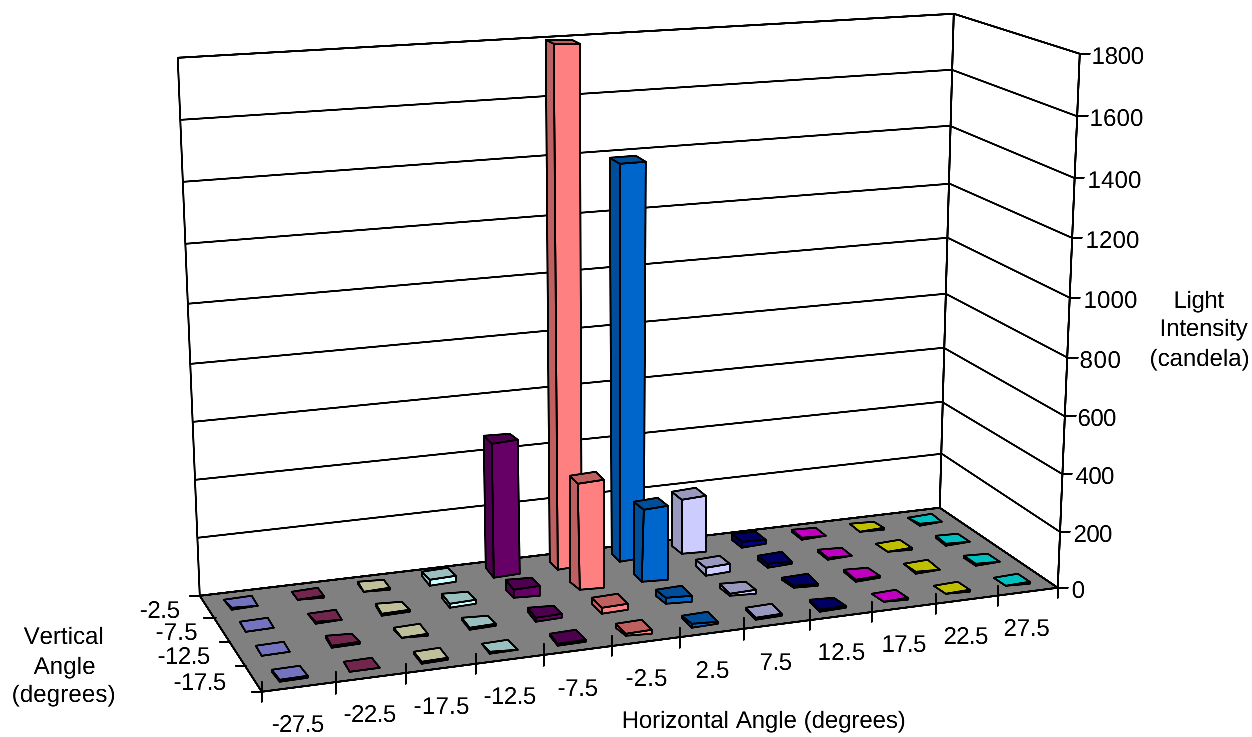

Figure A9.4.20b Output from WPS #9 (Green) signal, 10.0 volts, 78 elements (87% on), ITE test.

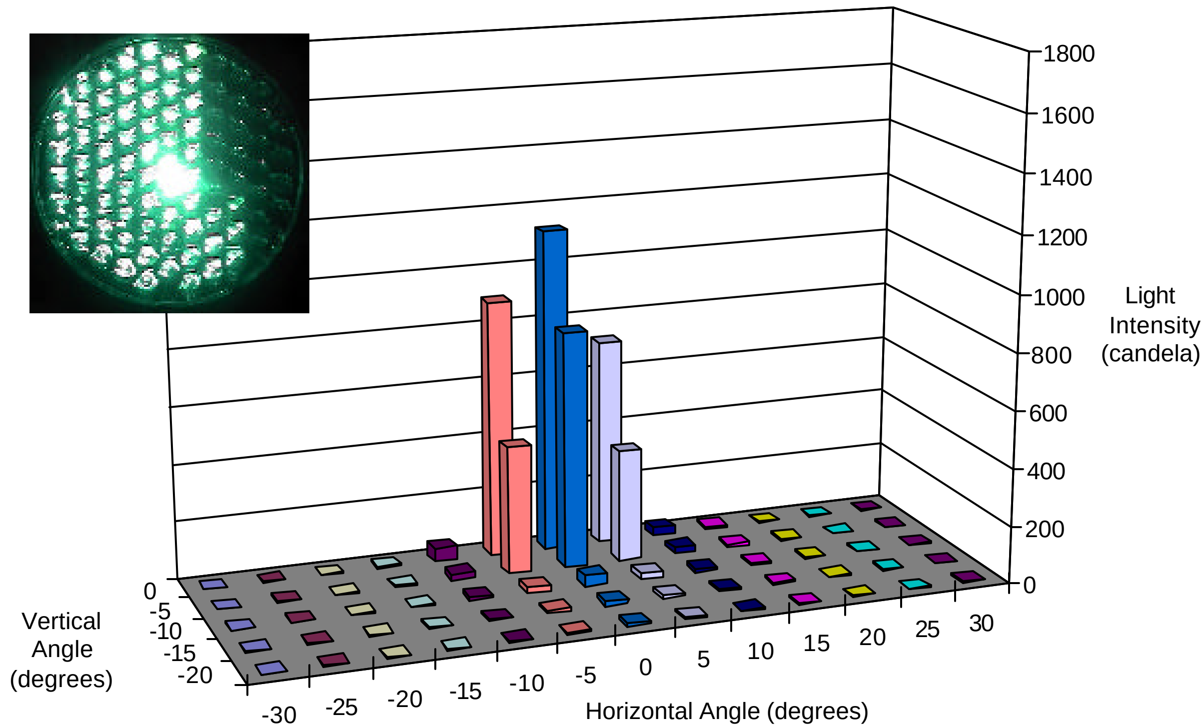

Figure A9.5.1a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

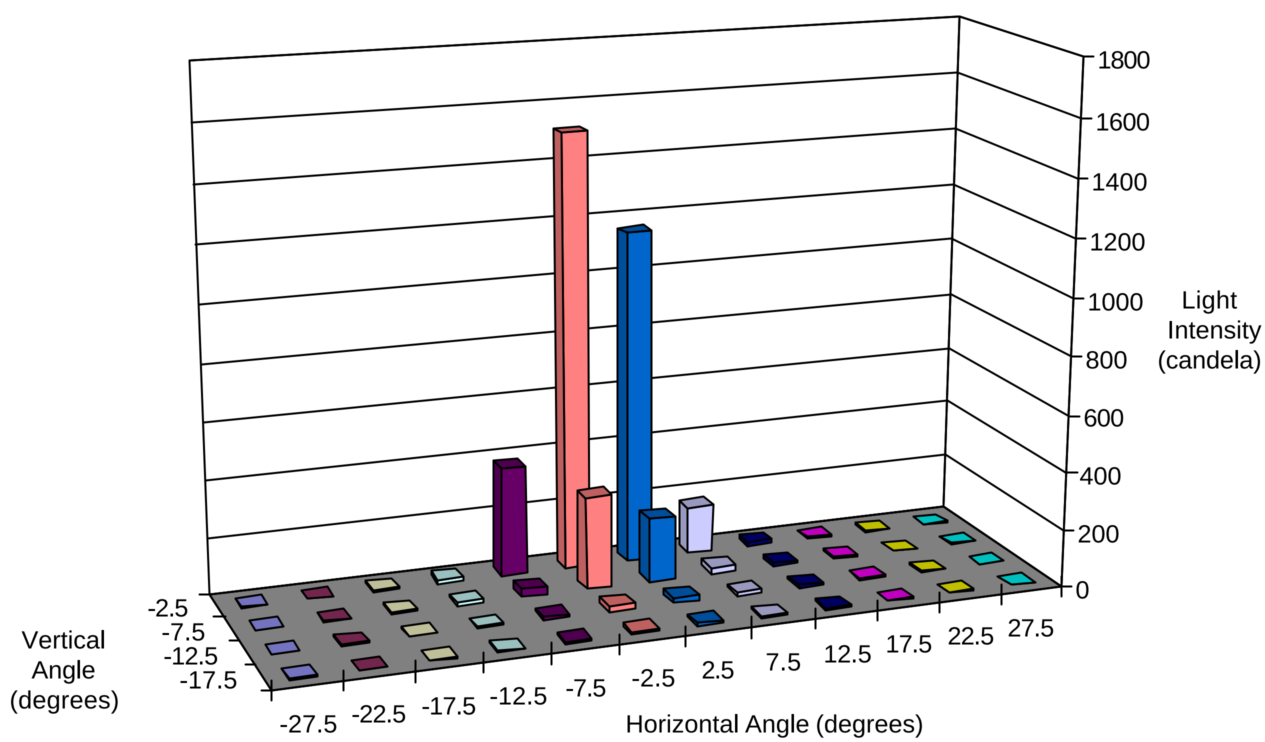

Figure A9.5.1b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

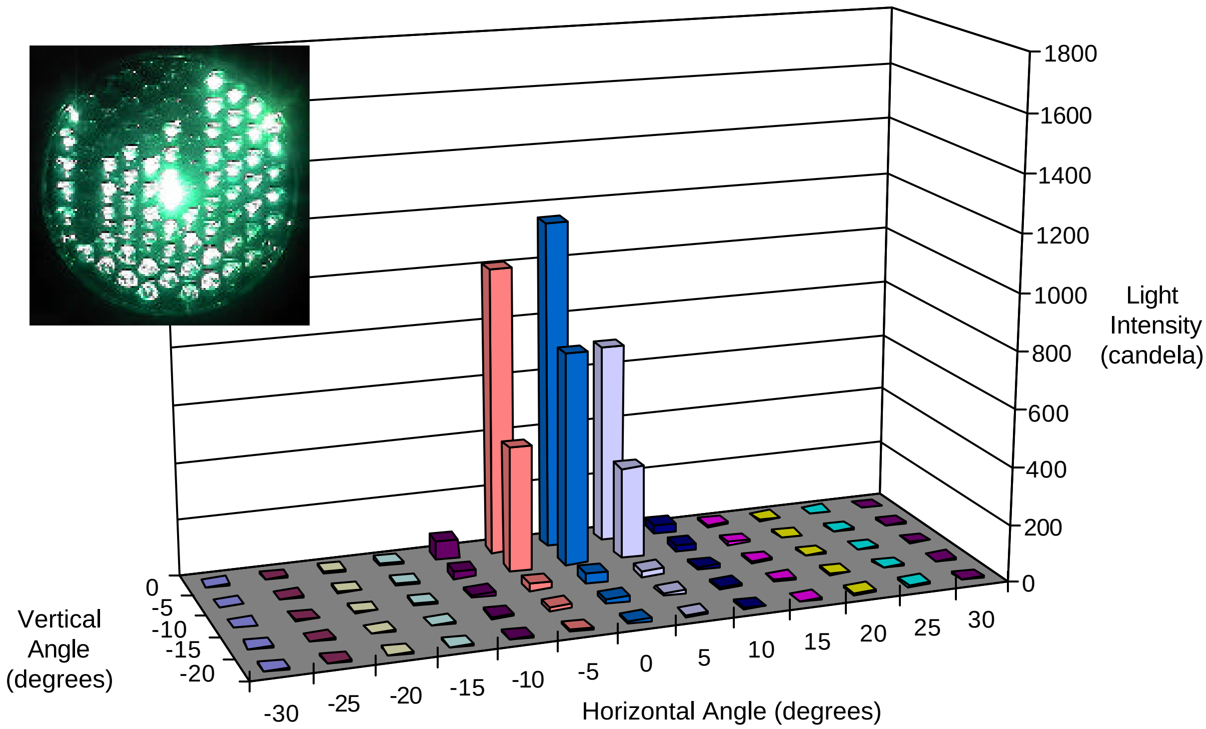

Figure A9.5.2a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

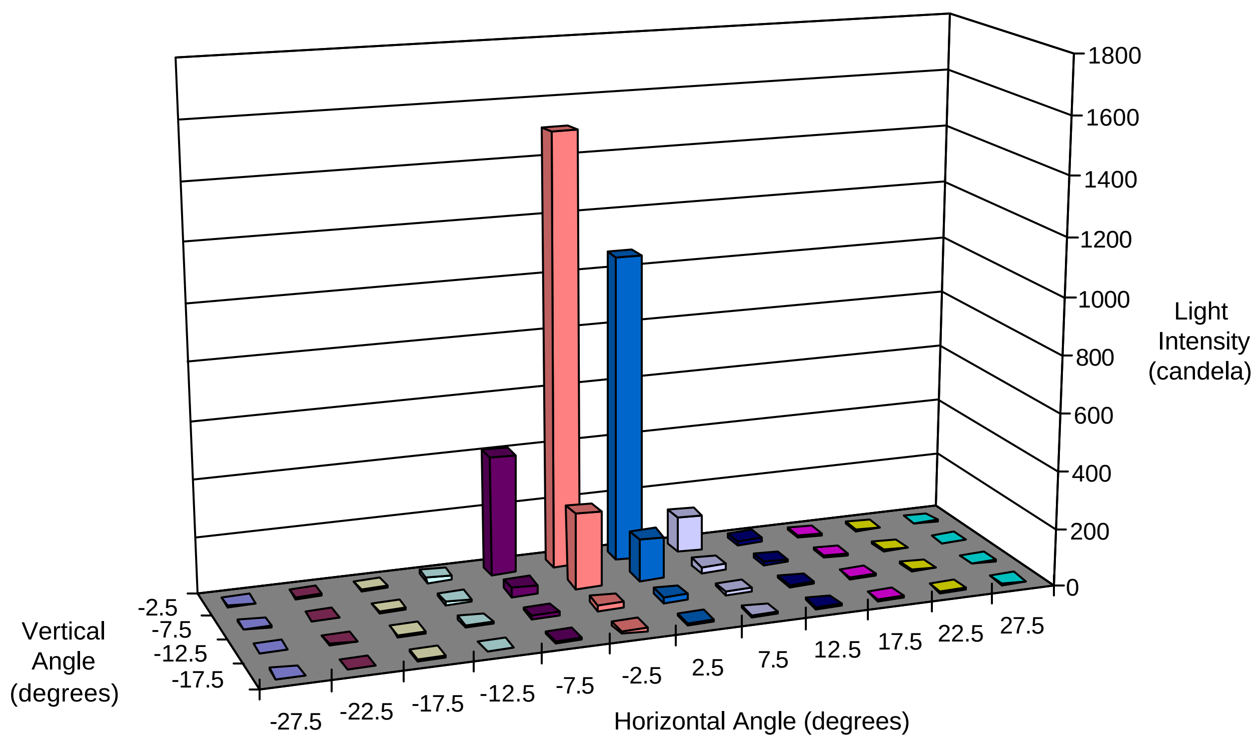

Figure A9.5.2b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

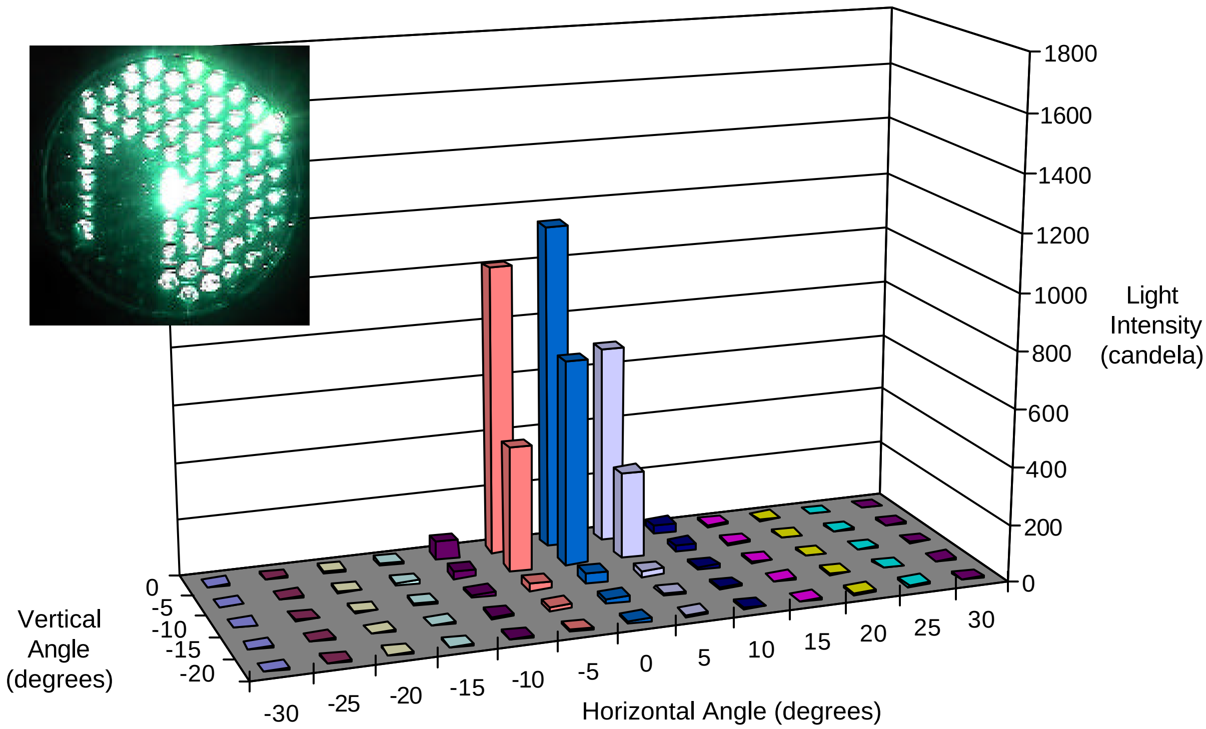

Figure A9.5.3a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

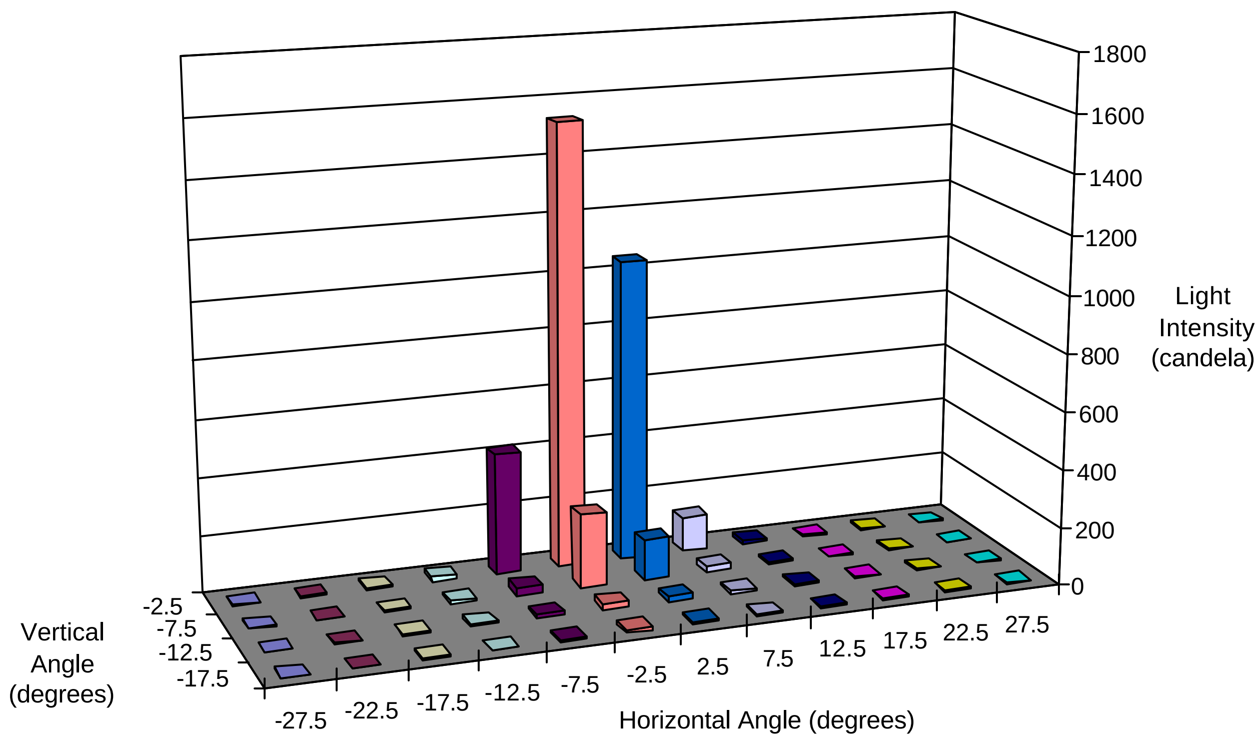

Figure A9.5.3b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

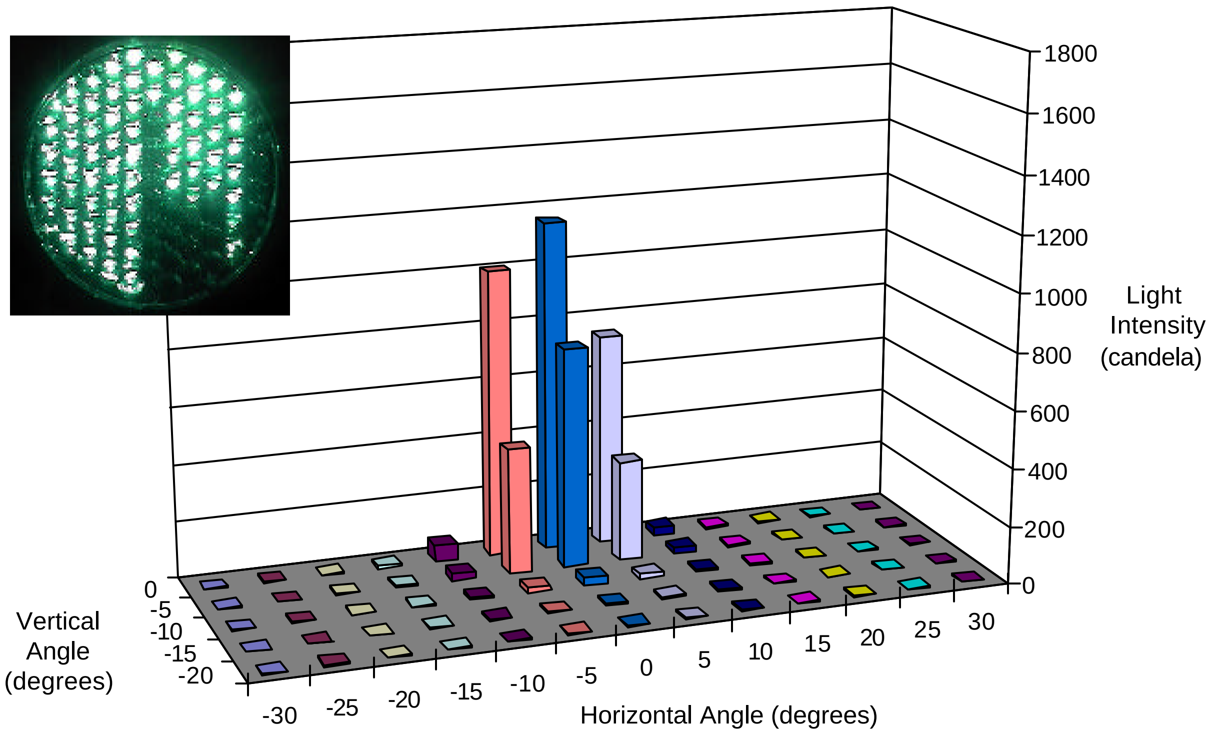

Figure A9.5.4a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

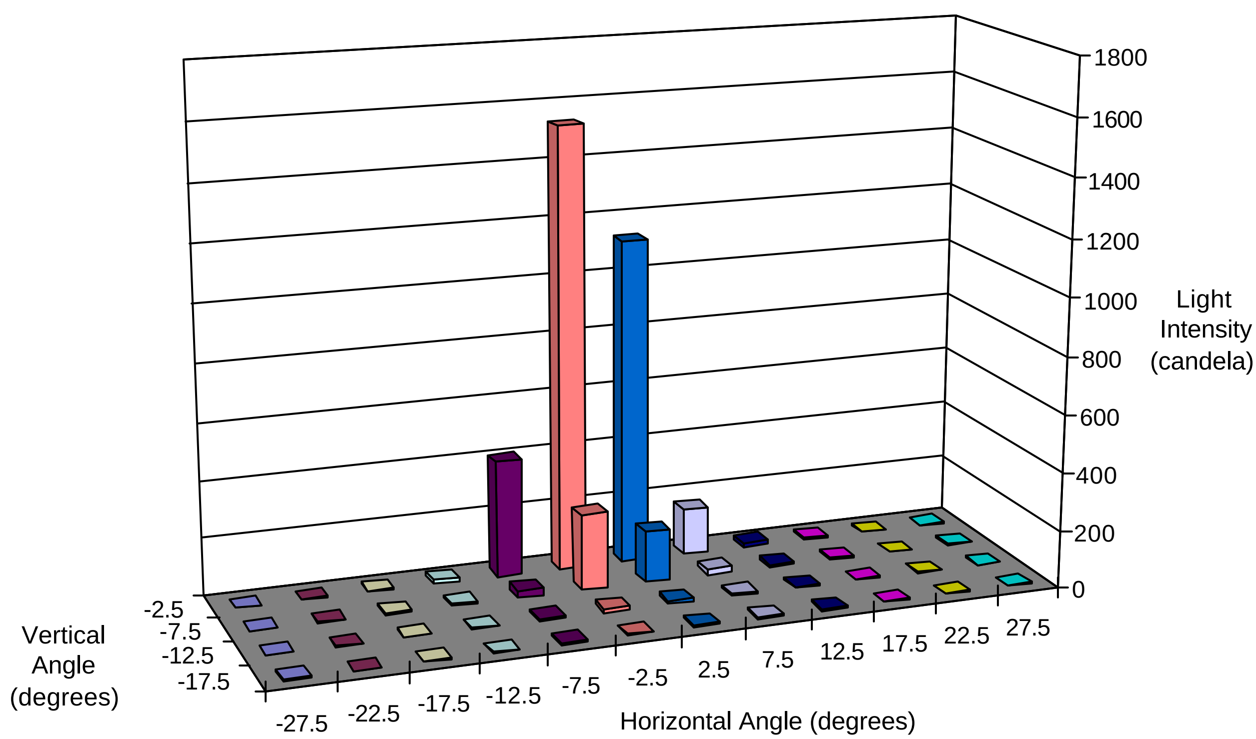

Figure A9.5.4b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

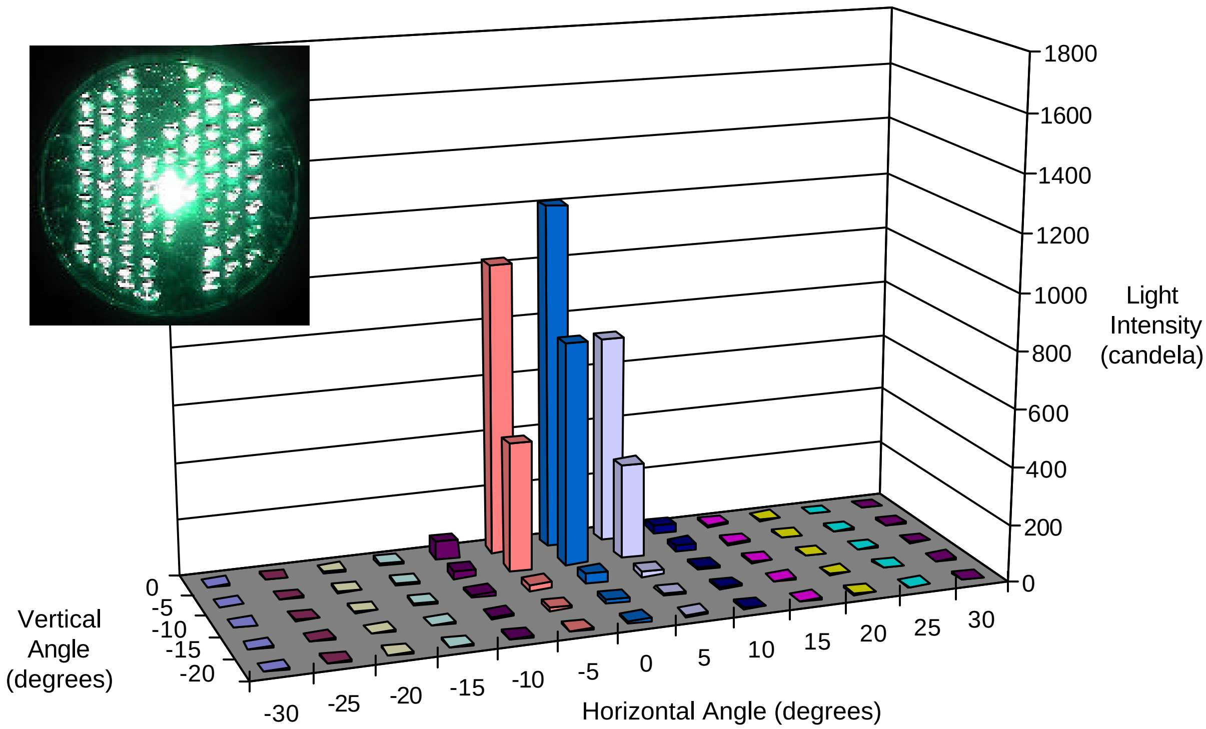

Figure A9.5.5a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

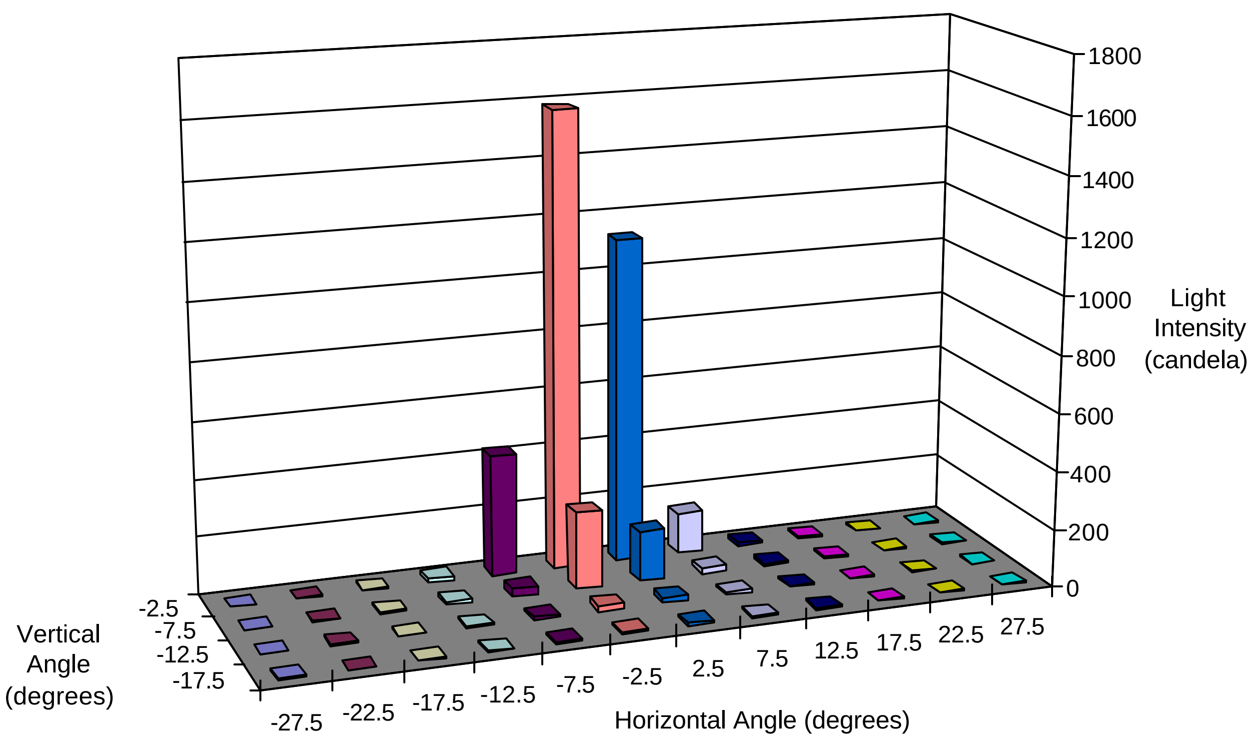

Figure A9.5.5b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

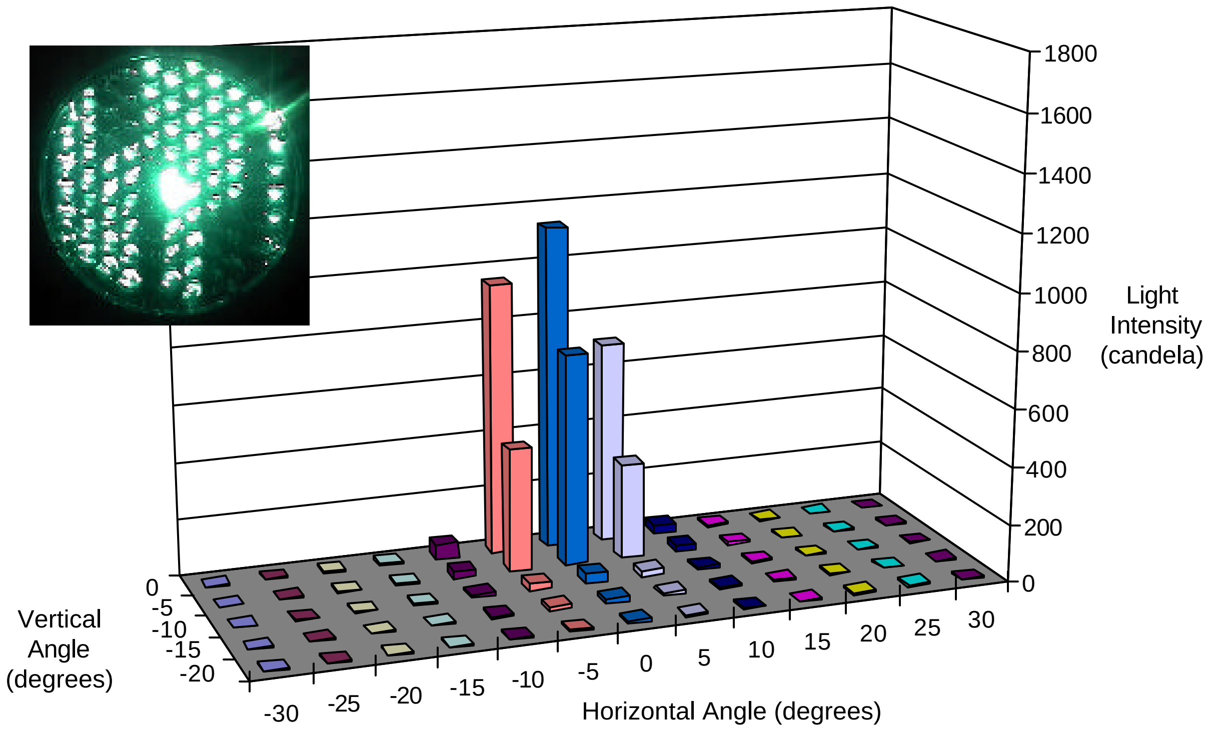

Figure A9.5.6a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

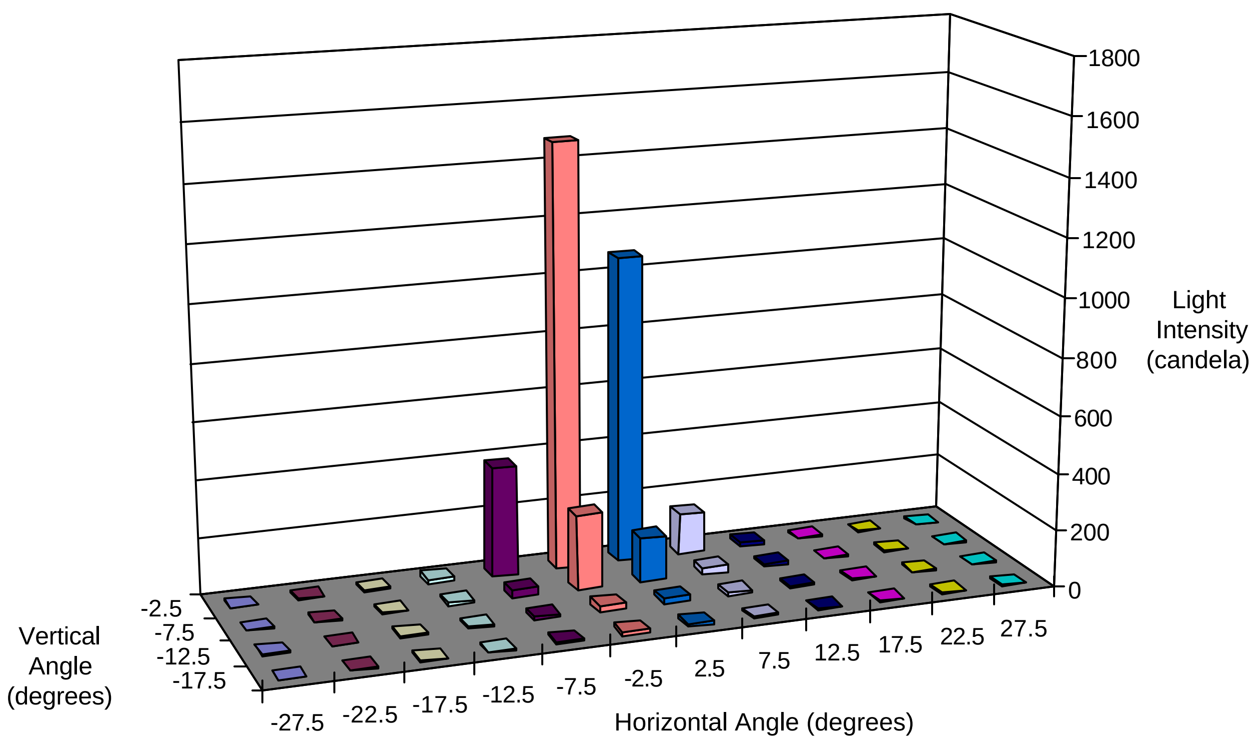

Figure A9.5.6b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

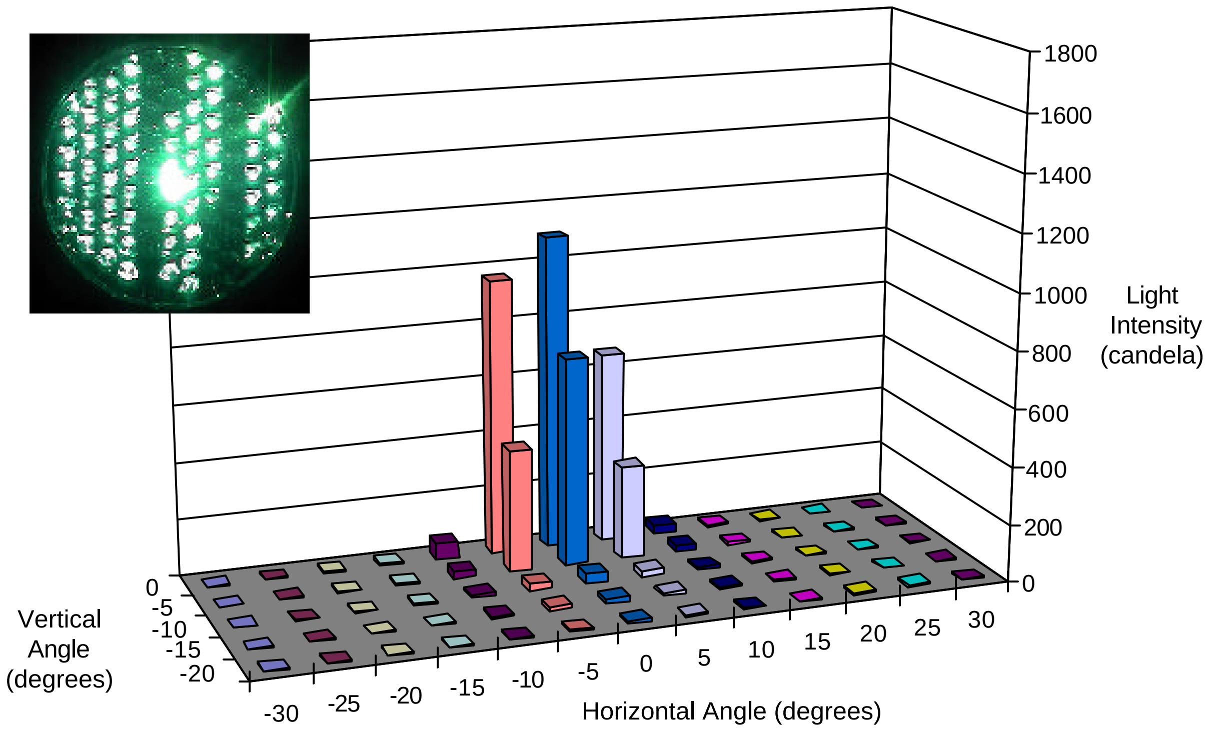

Figure A9.5.7a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

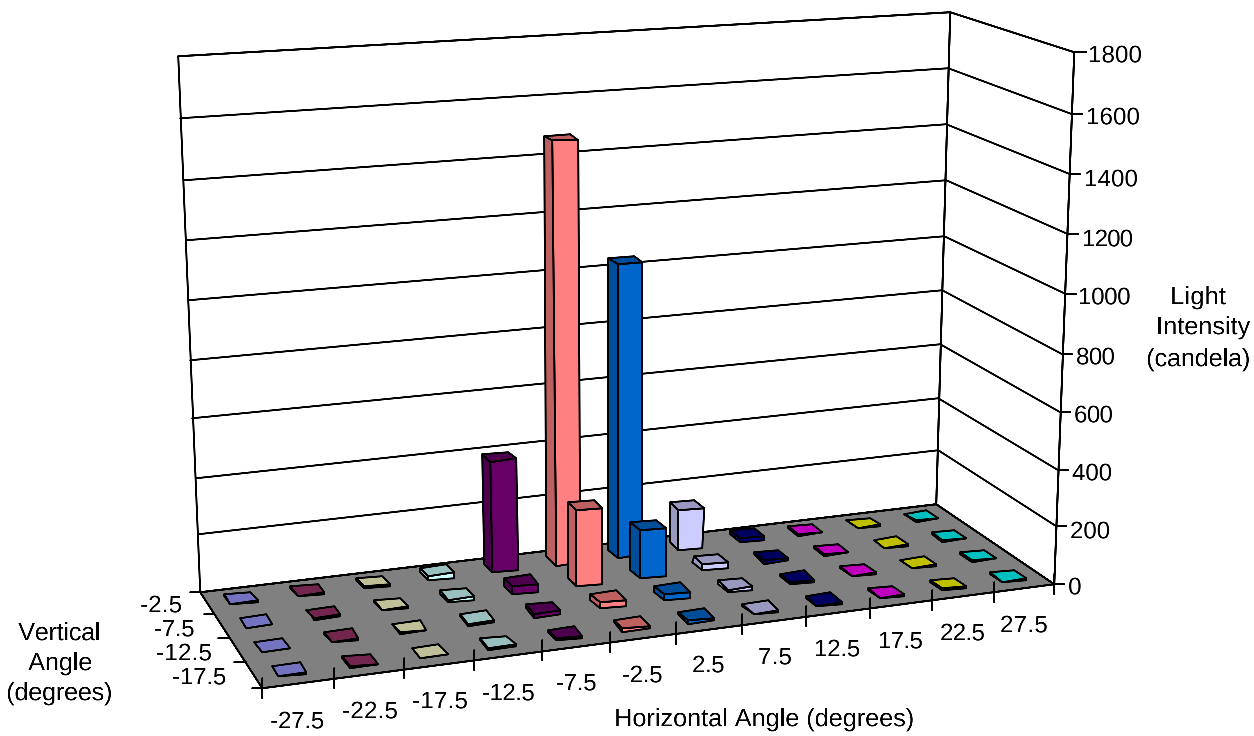

Figure A9.5.7b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

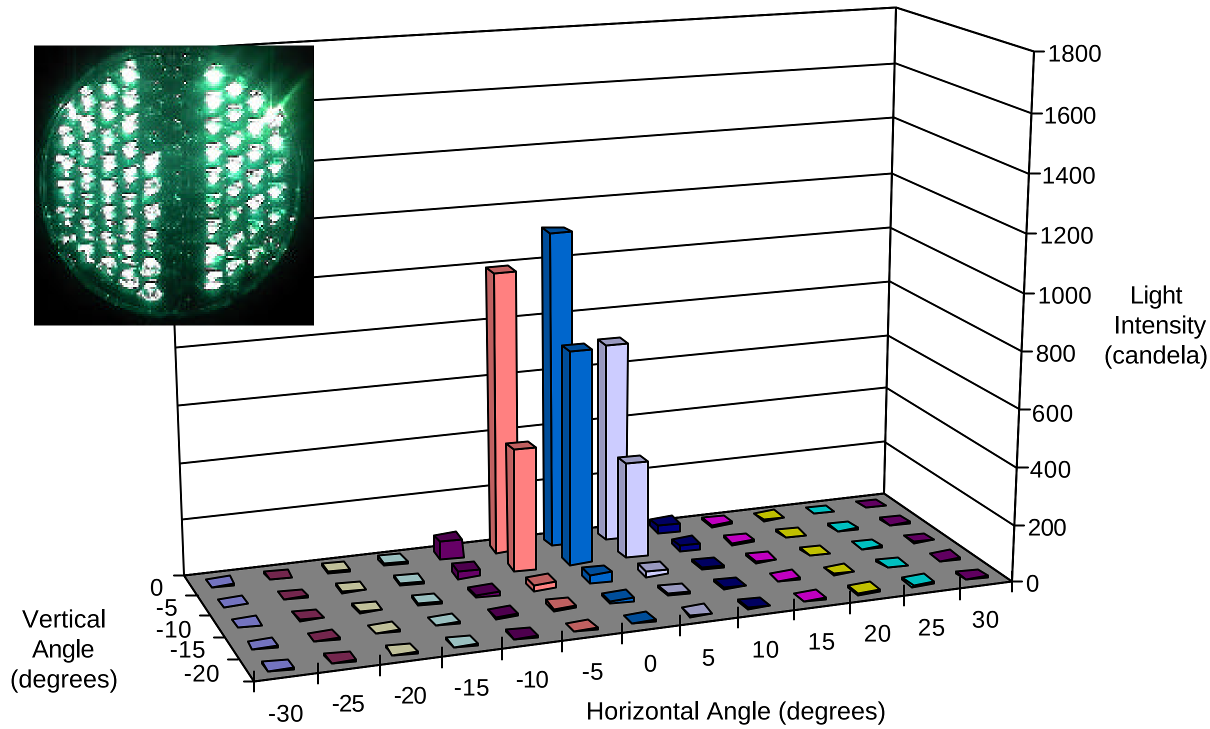

Figure A9.5.8a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

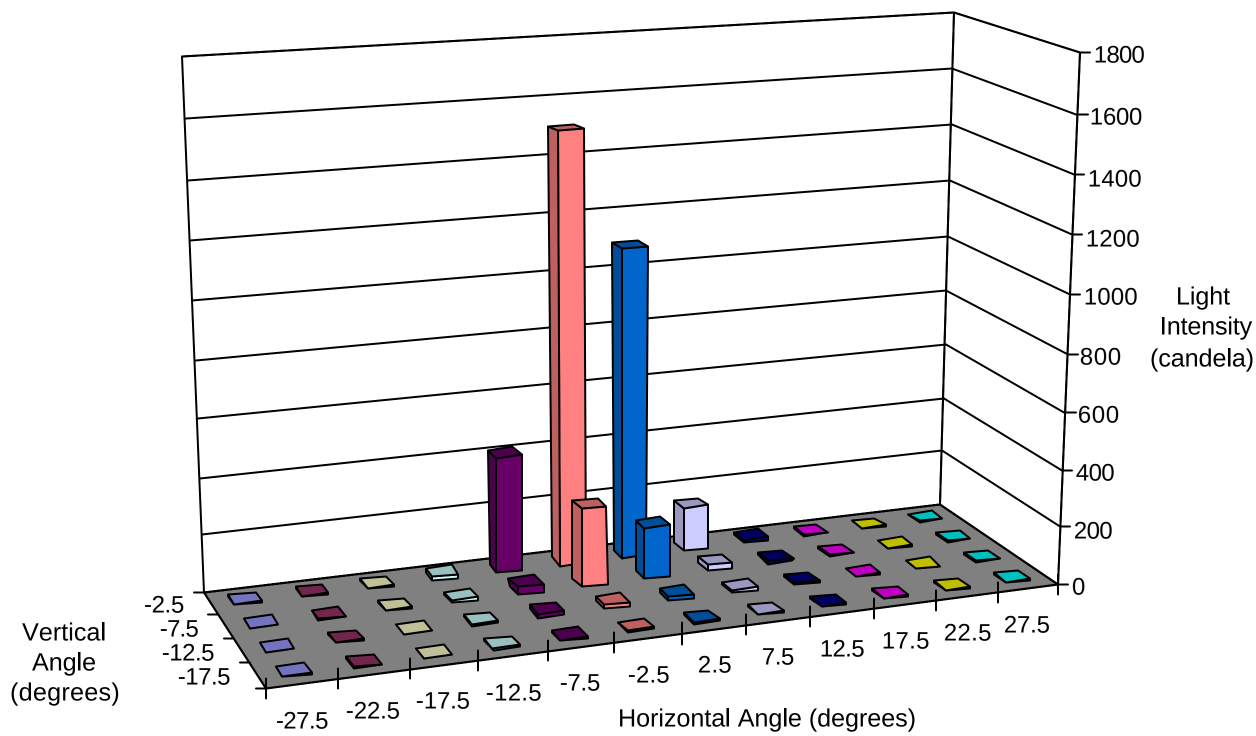

Figure A9.5.8b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

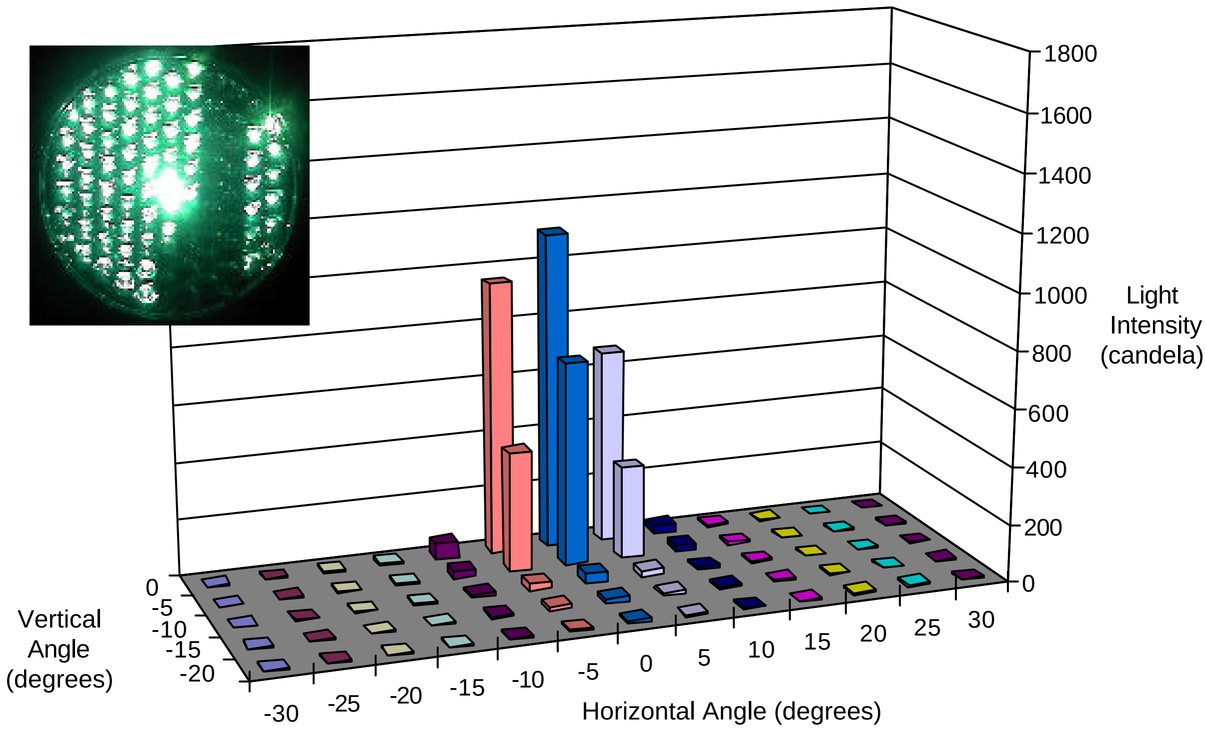

Figure A9.5.9a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

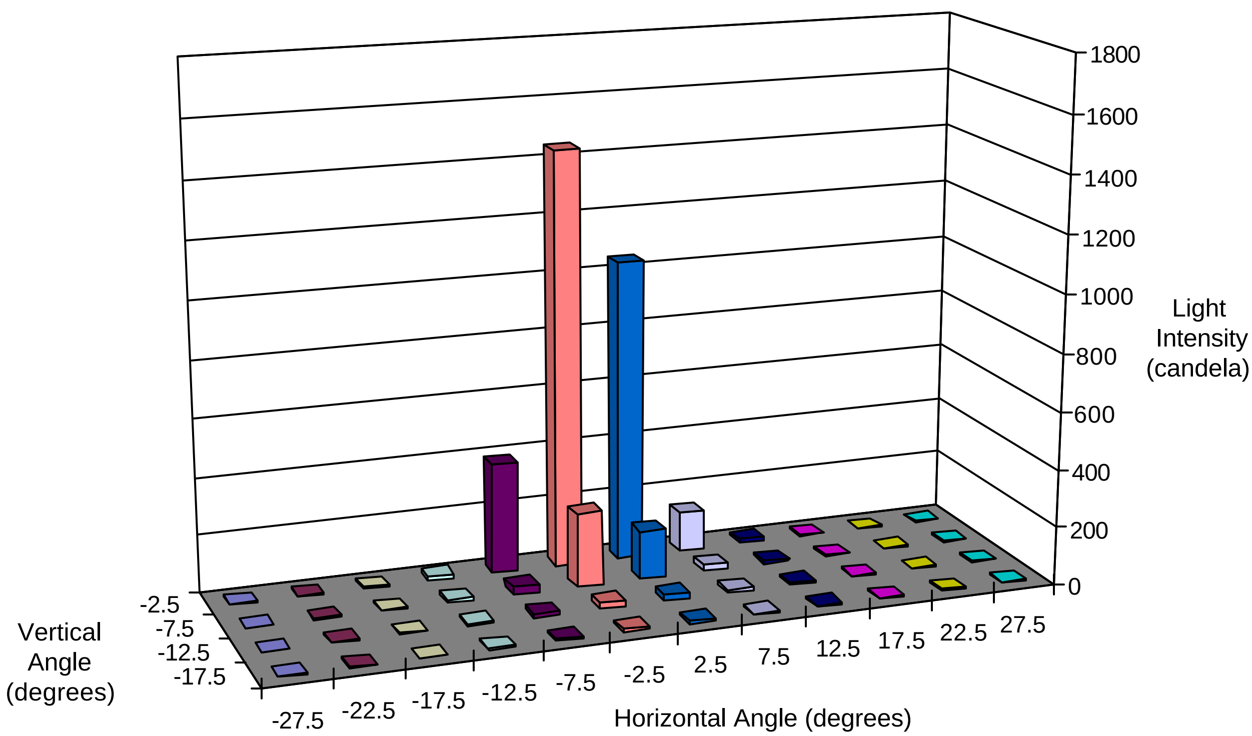

Figure A9.5.9b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

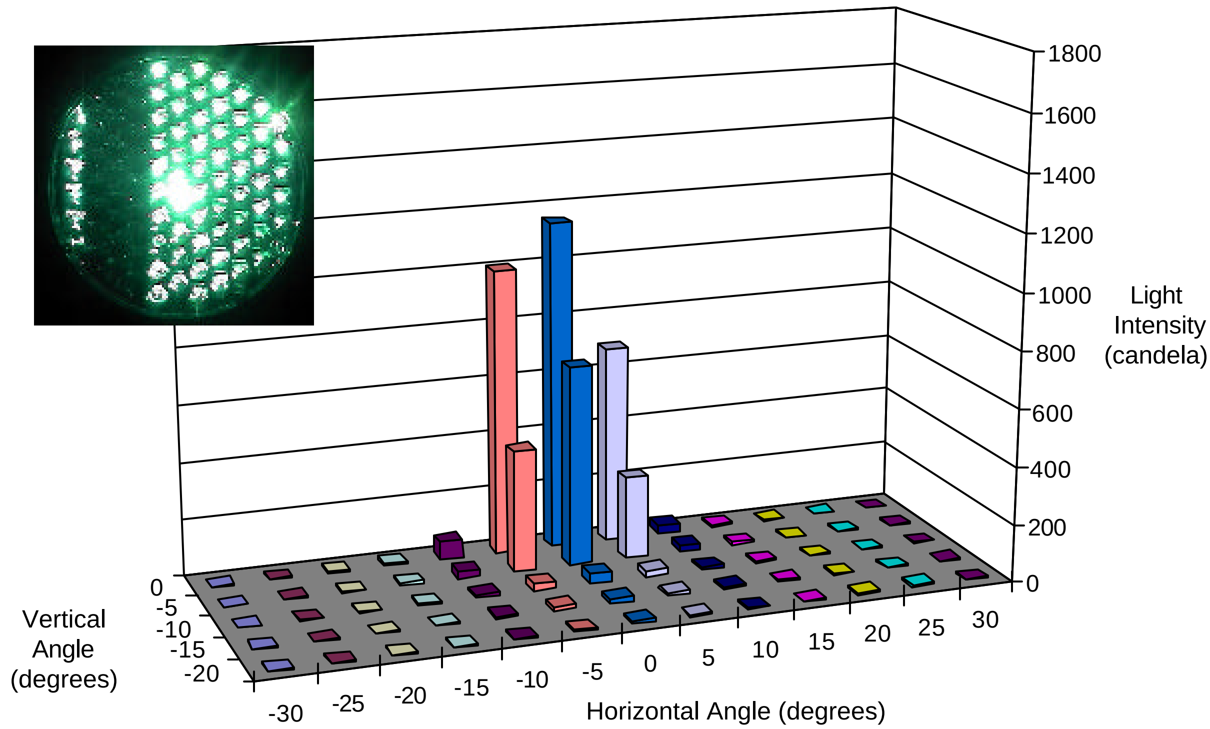

Figure A9.5.10a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

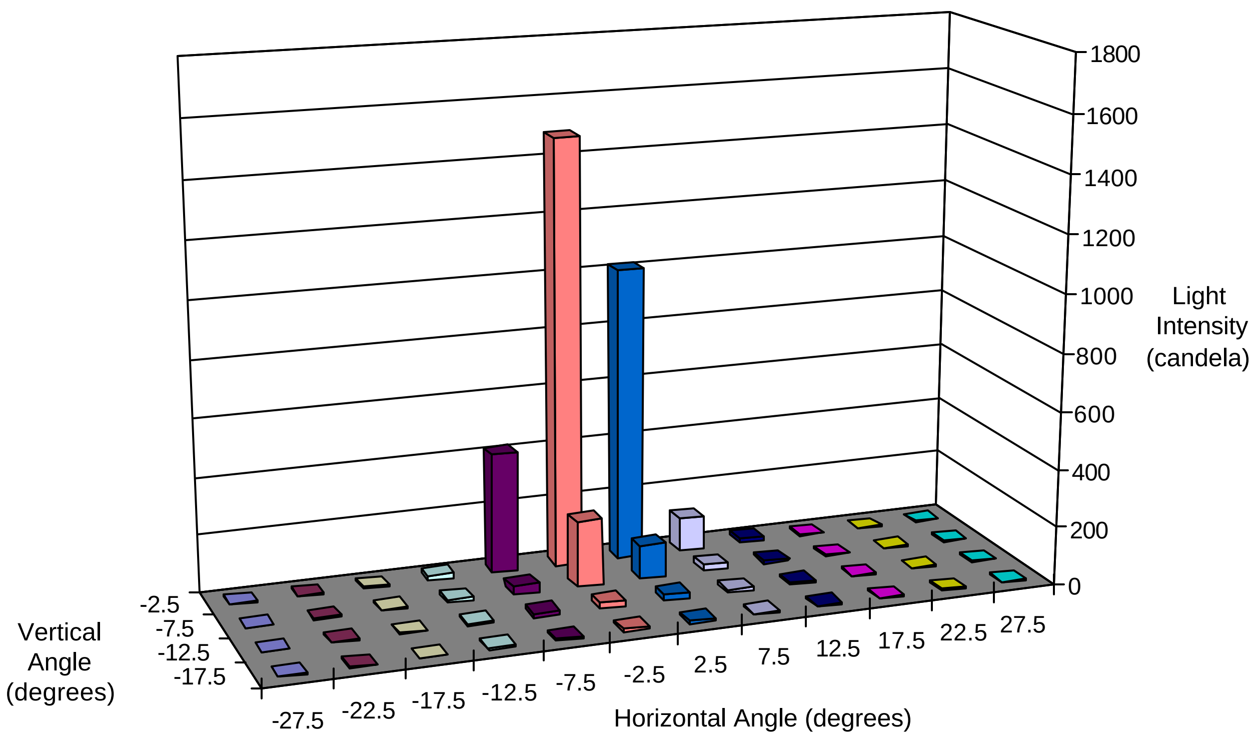

Figure A9.5.10b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

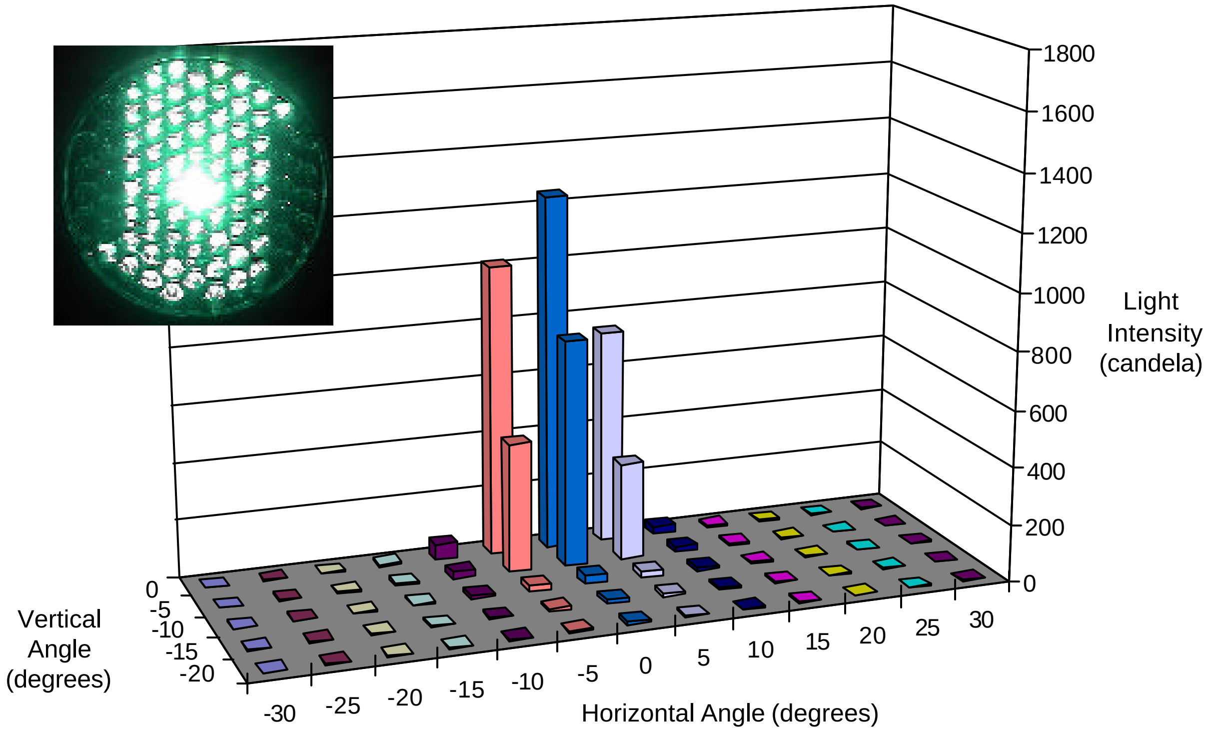

Figure A9.5.11a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

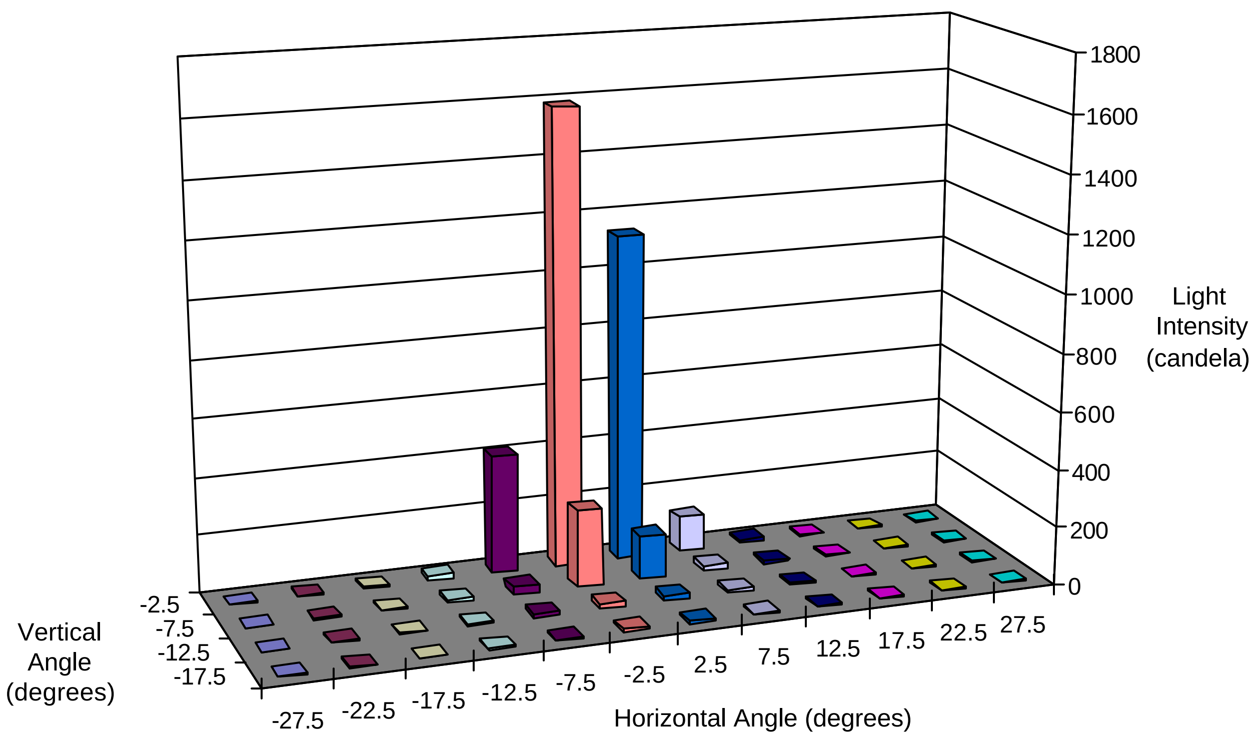

Figure A9.5.11b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

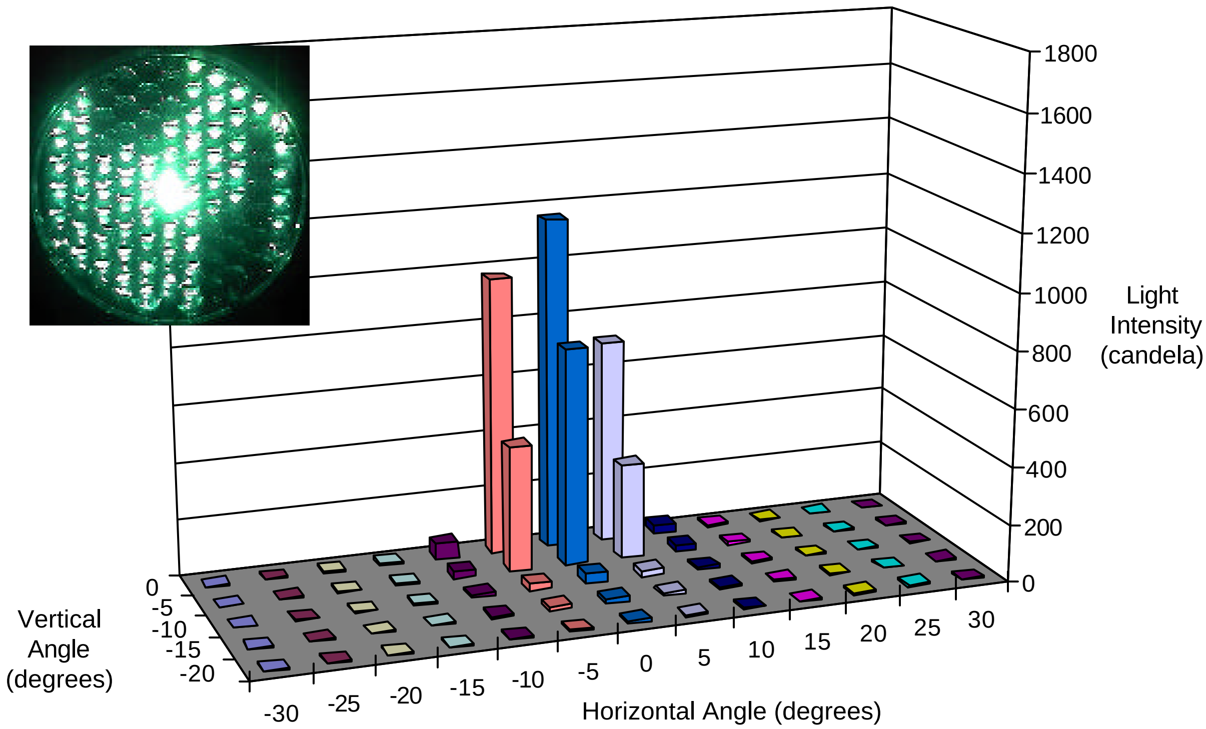

Figure A9.5.12a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

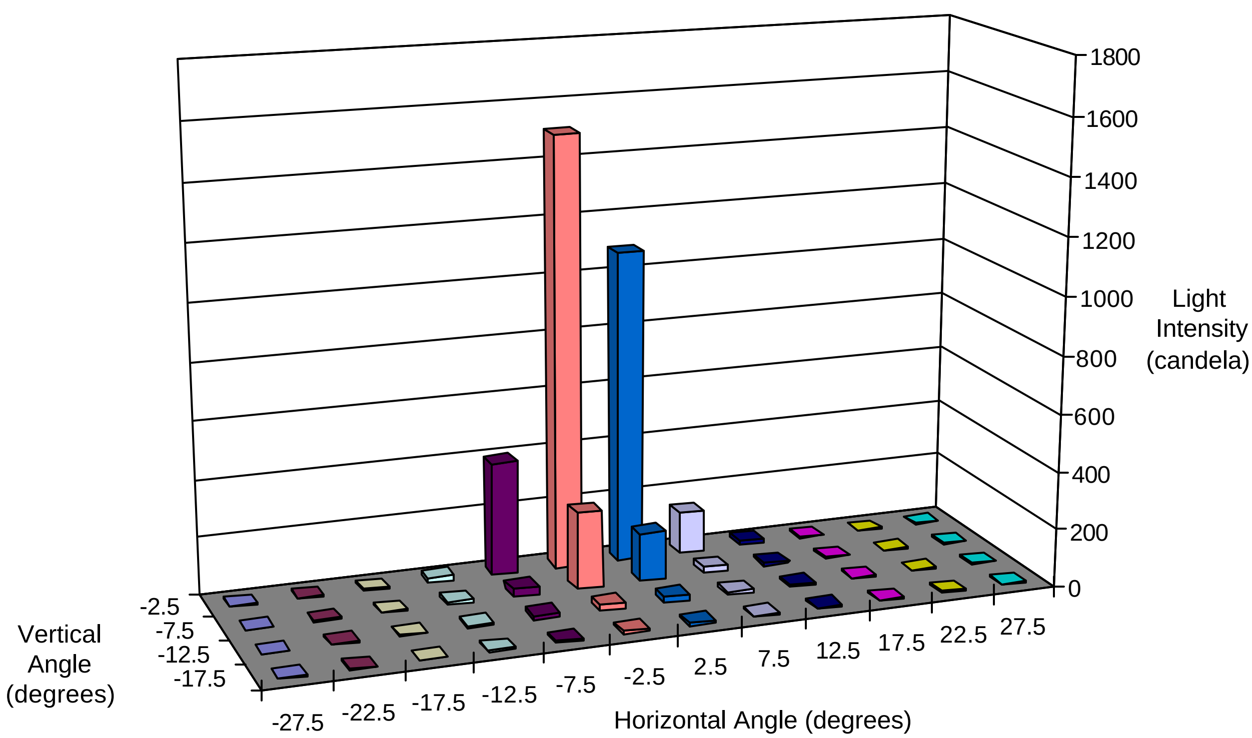

Figure A9.5.12b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

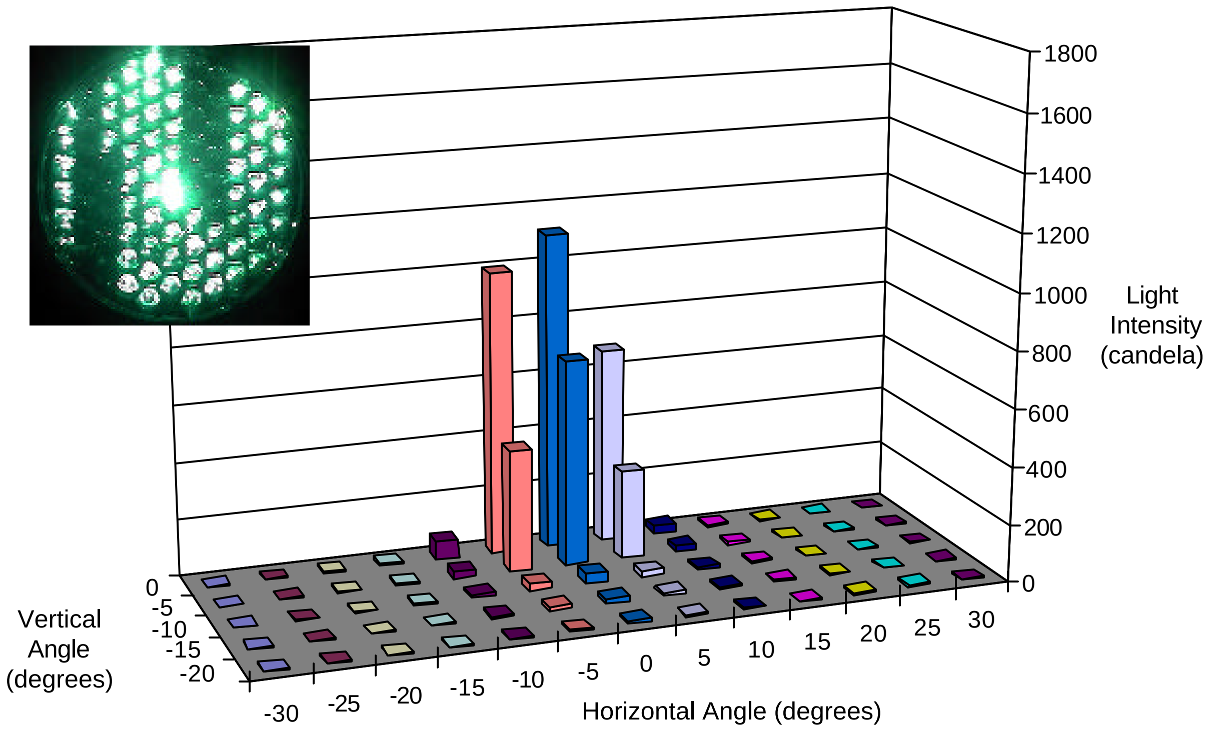

Figure A9.5.13a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

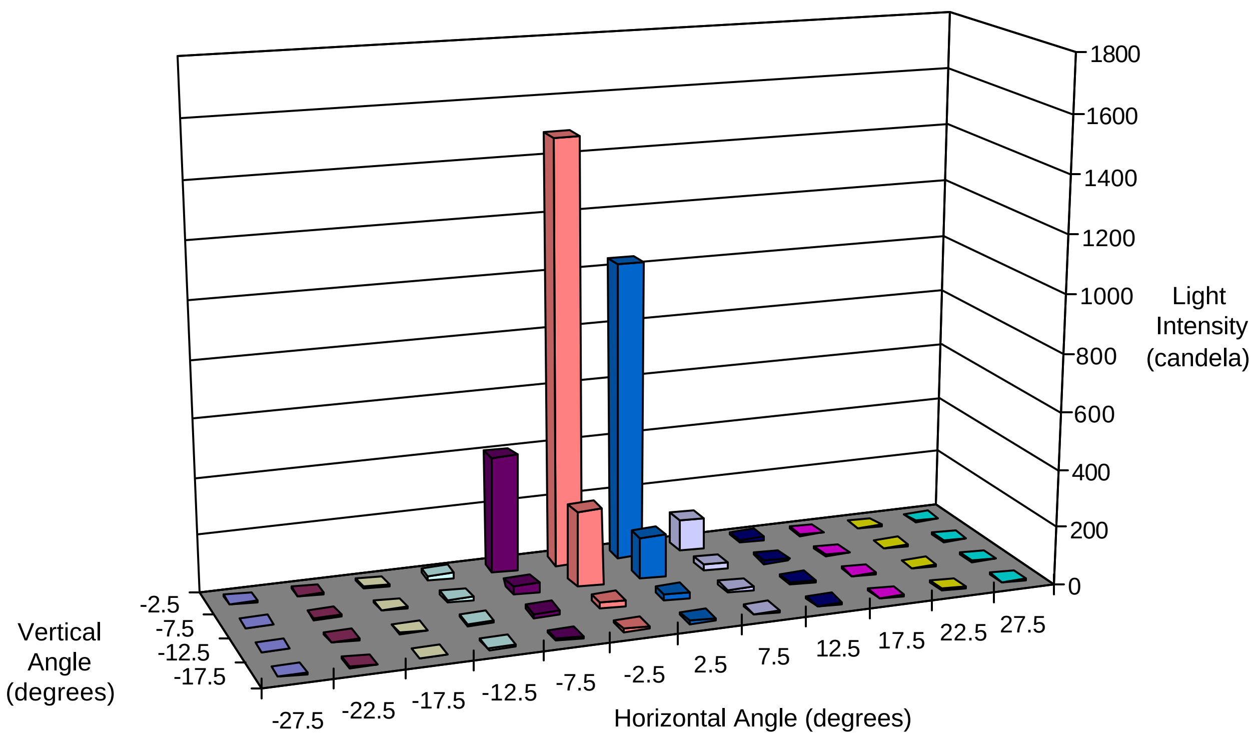

Figure A9.5.13b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

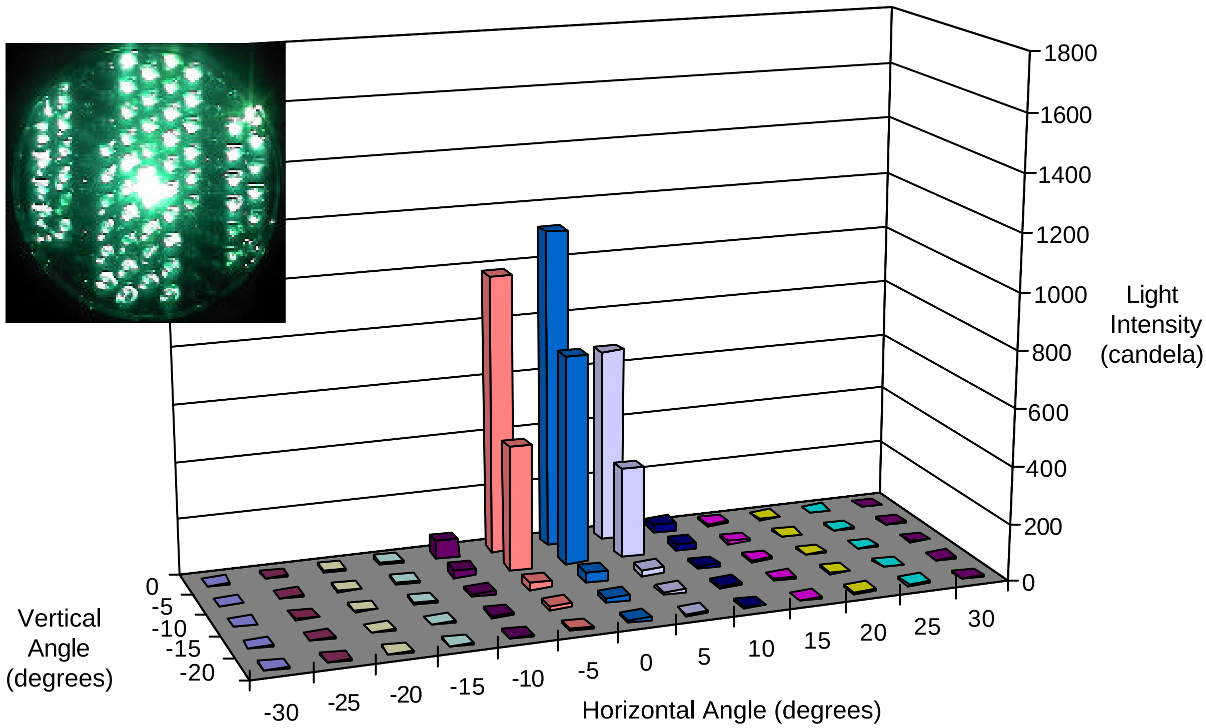

Figure A9.5.14a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

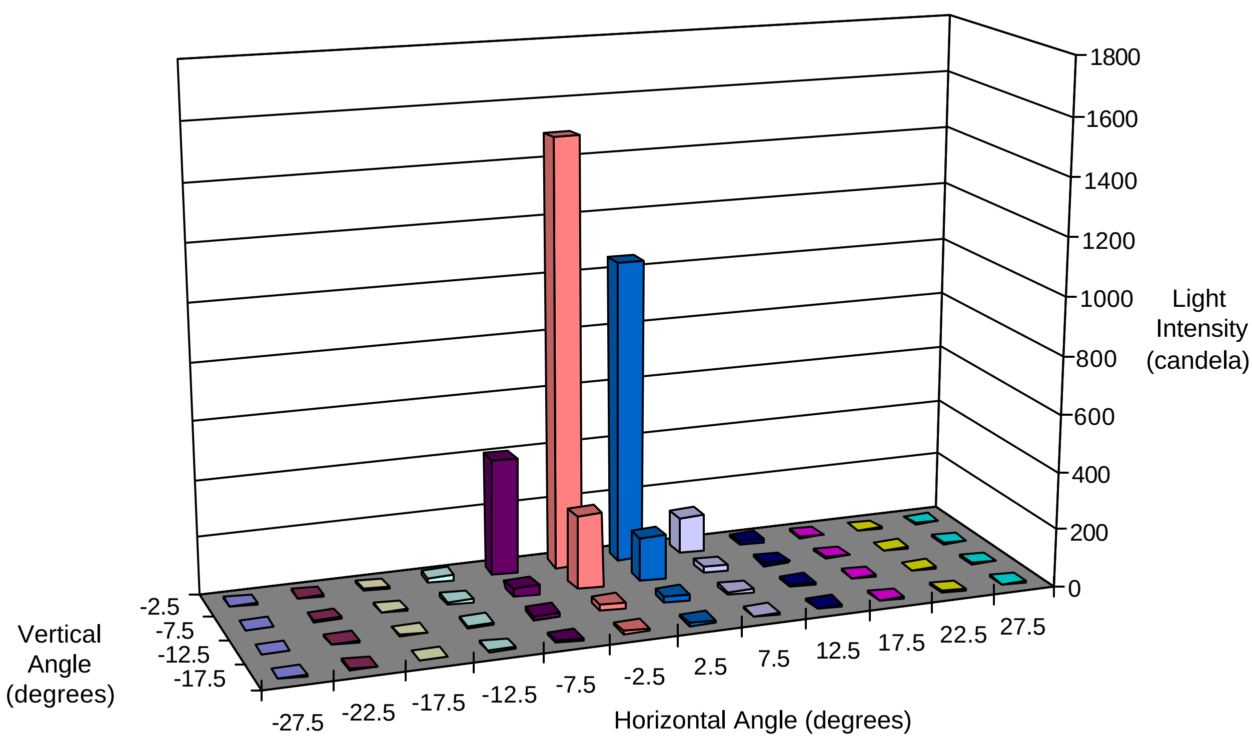

Figure A9.5.14b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

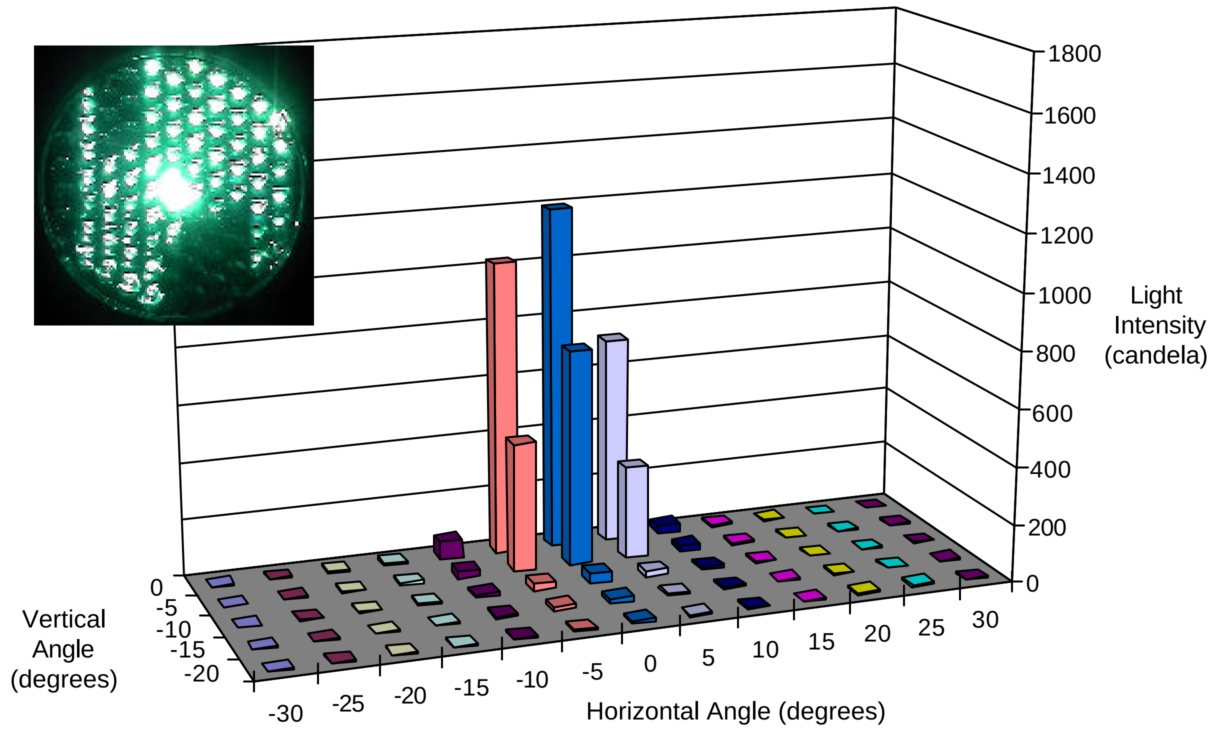

Figure A9.5.15a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

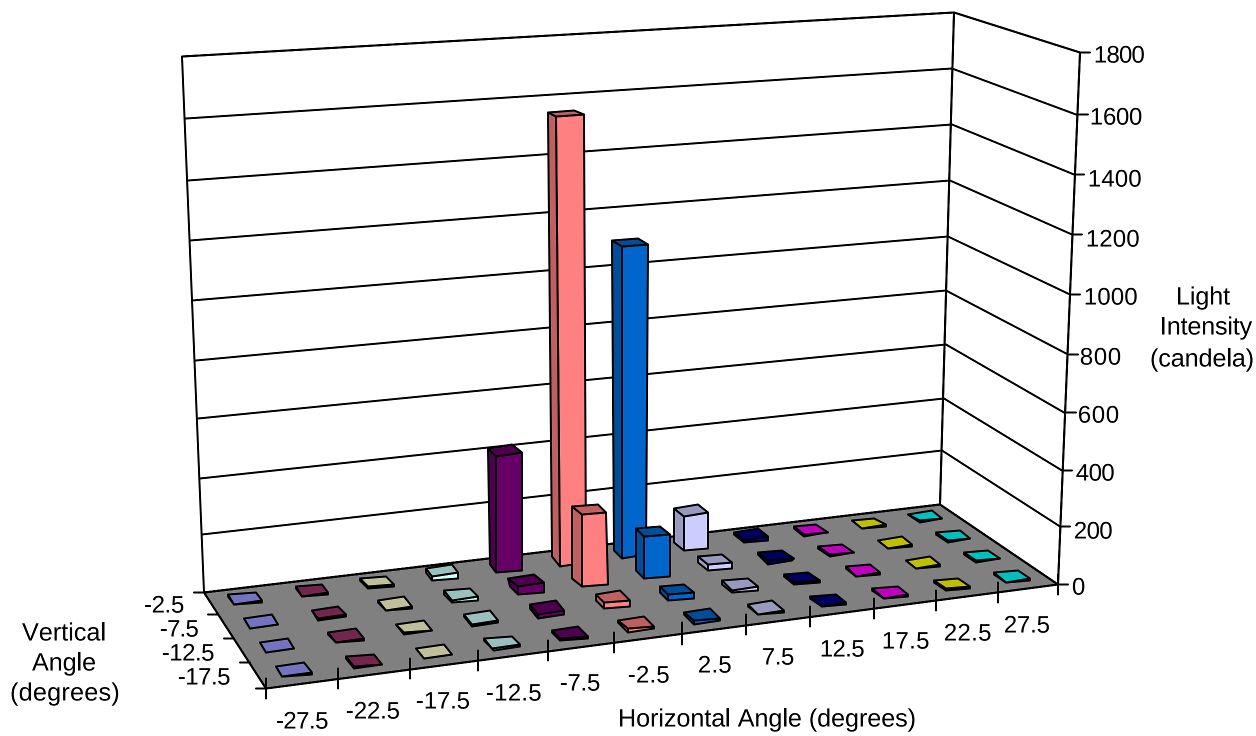

Figure A9.5.15b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

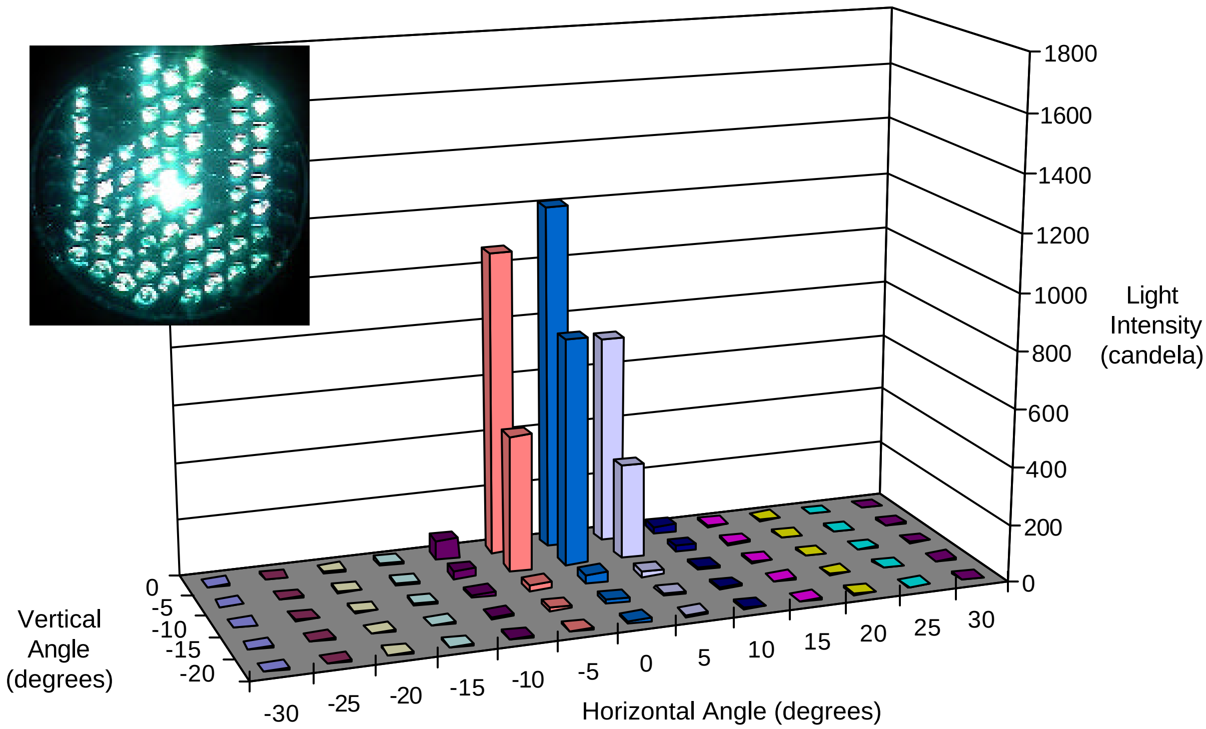

Figure A9.5.16a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

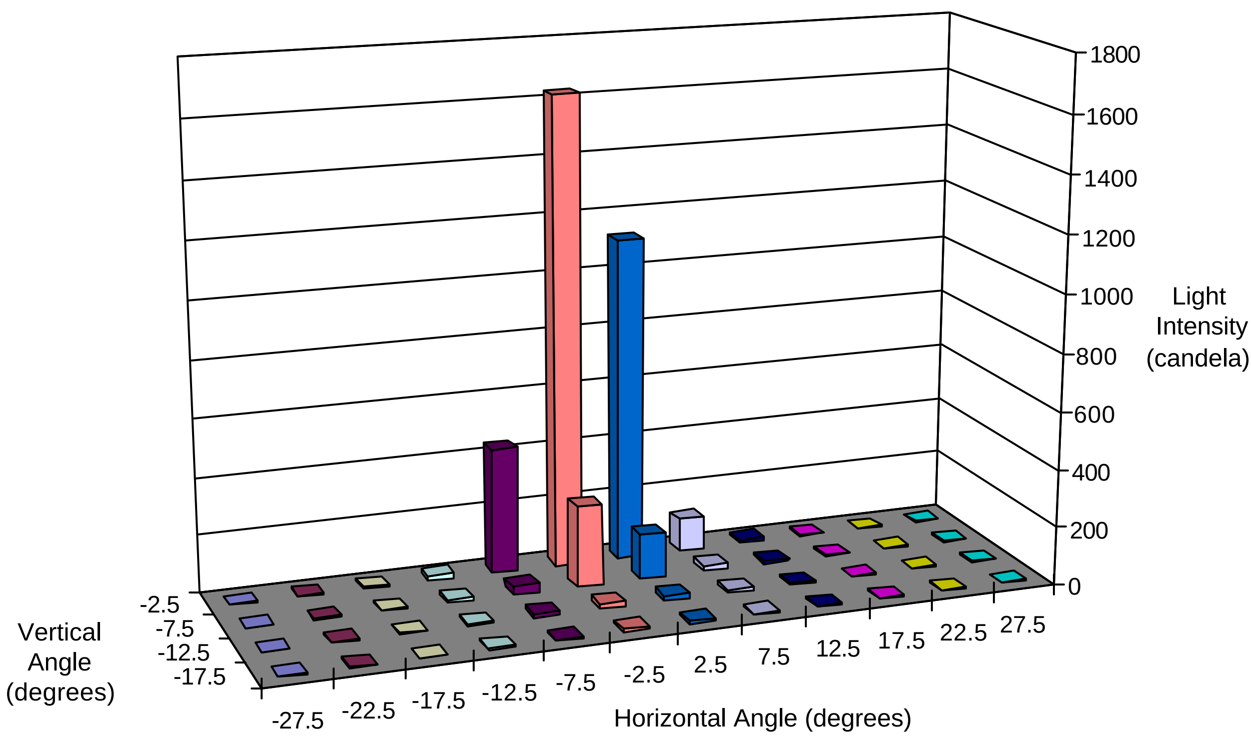

Figure A9.5.16b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

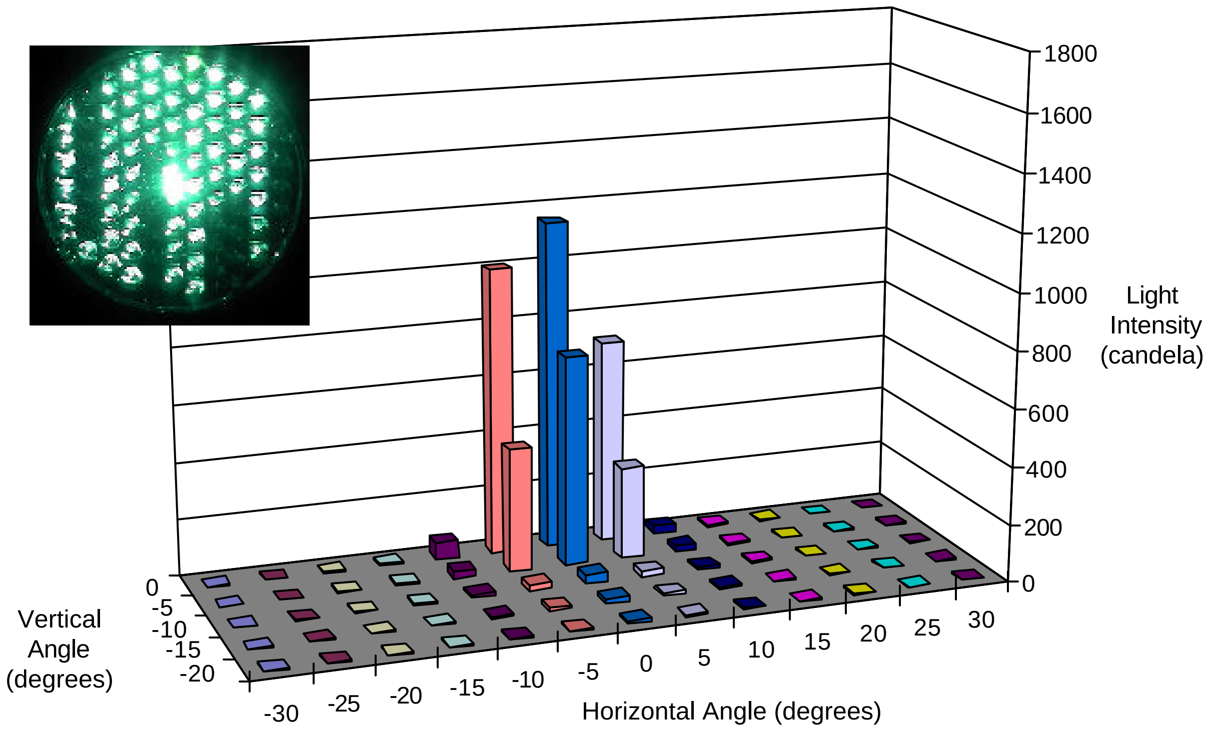

Figure A9.5.17a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

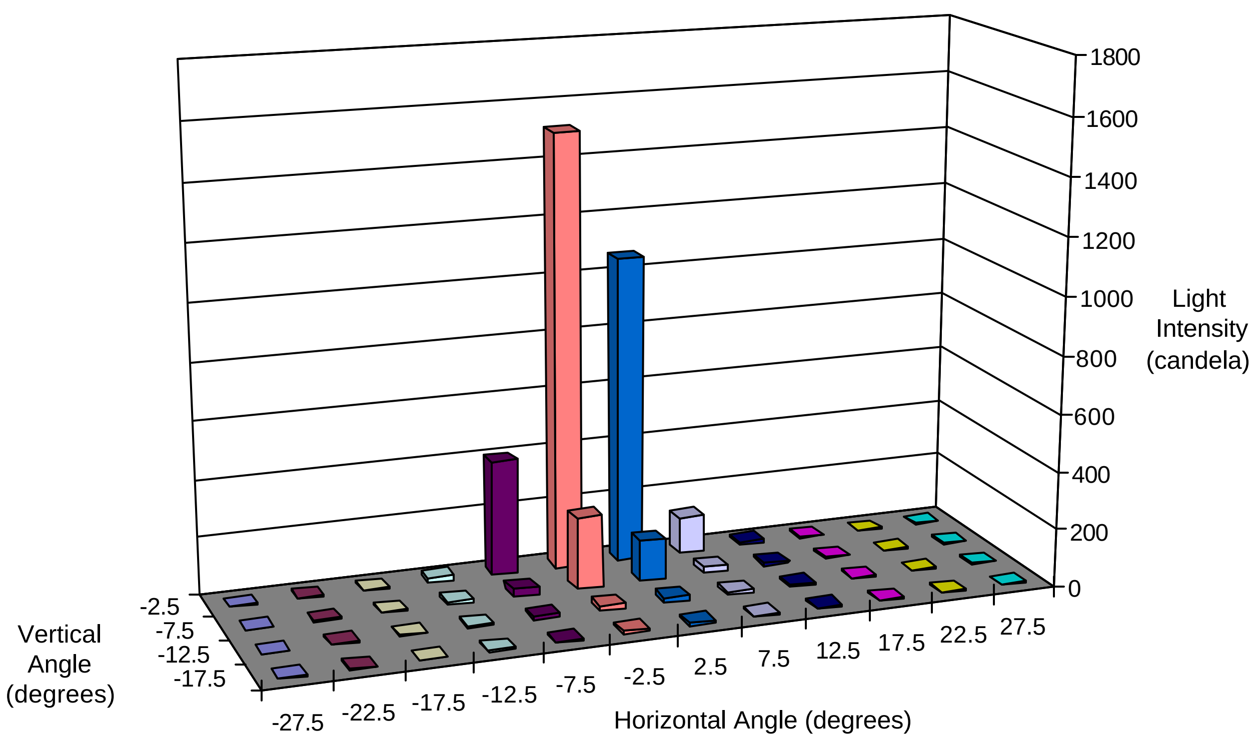

Figure A9.5.17b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

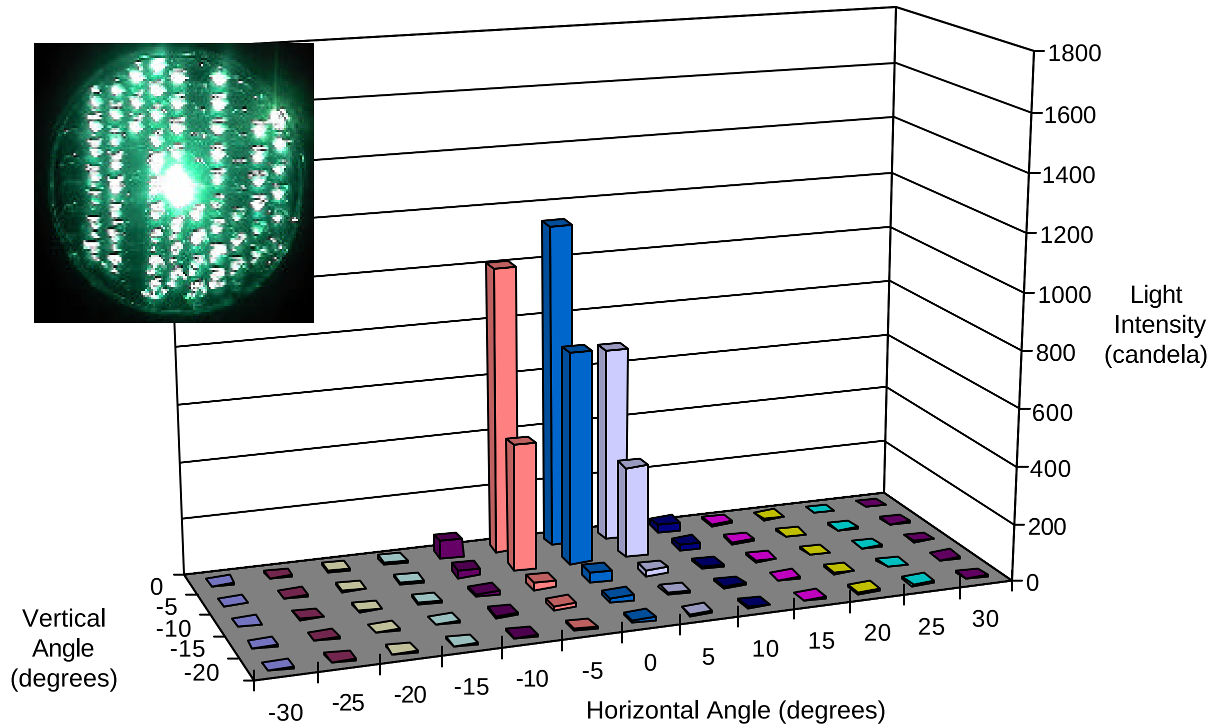

Figure A9.5.18a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

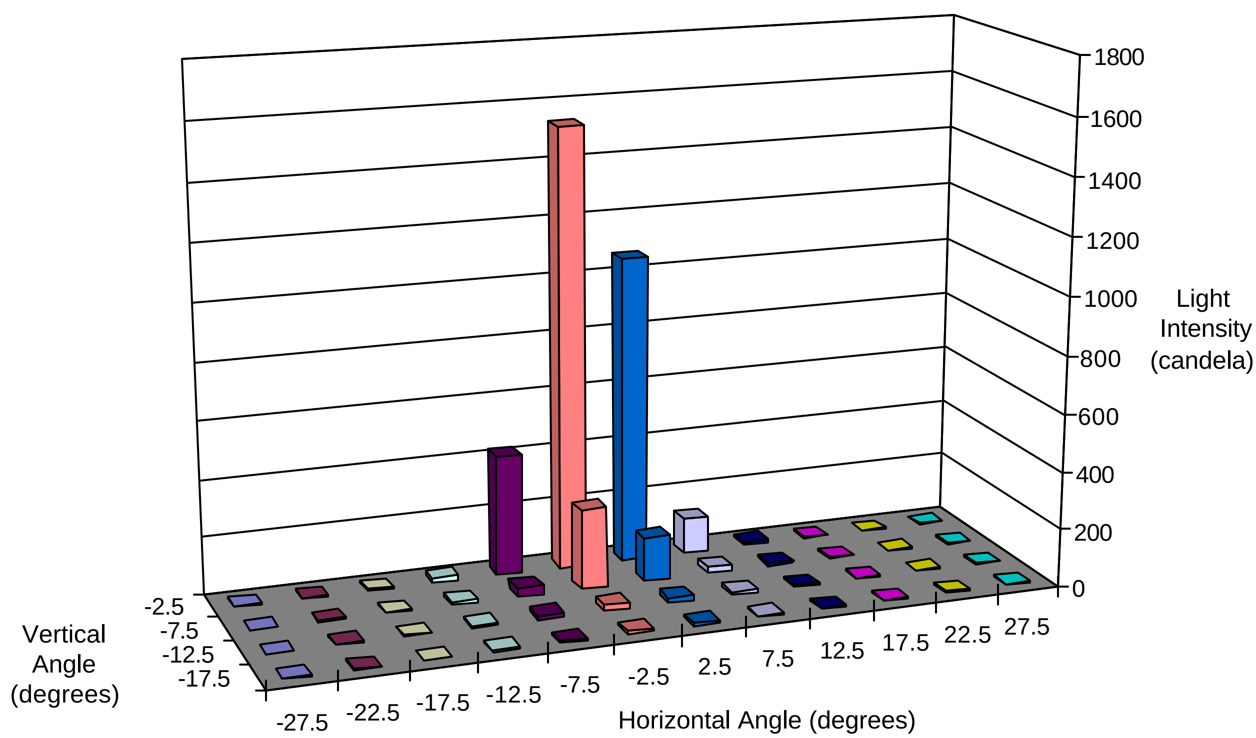

Figure A9.5.18b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

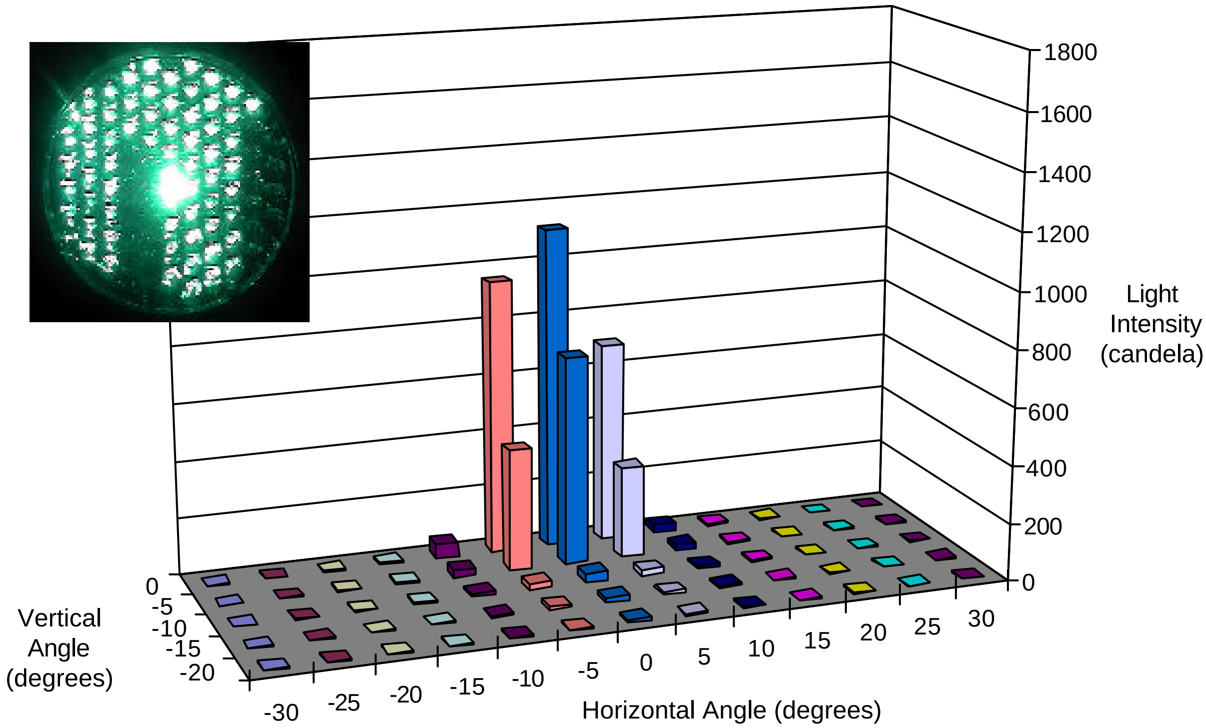

Figure A9.5.19a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

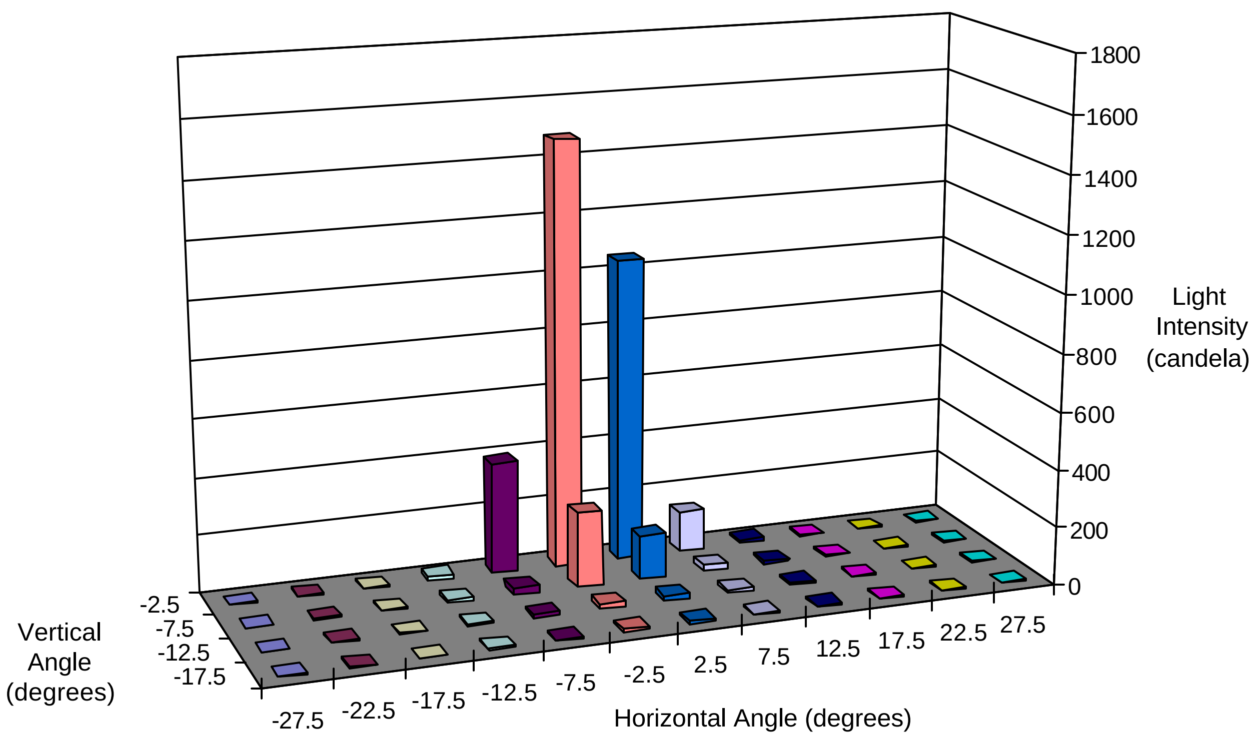

Figure A9.5.19b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.

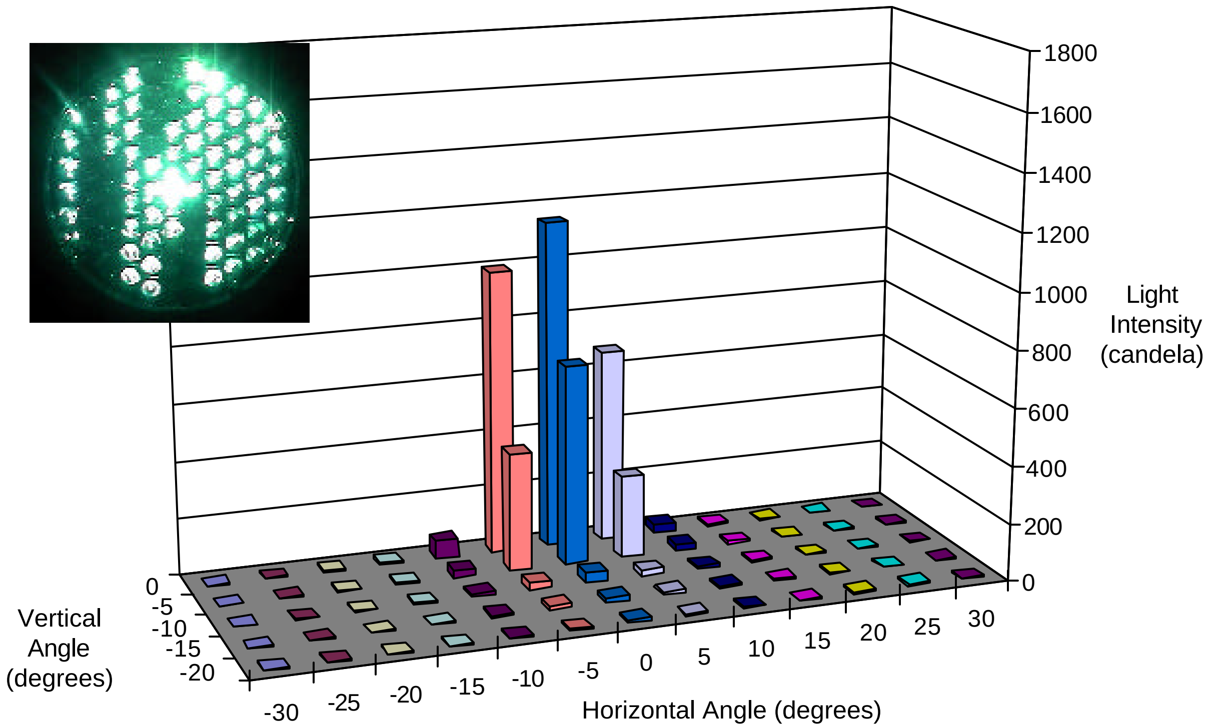

Figure A9.5.20a Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), TC test.

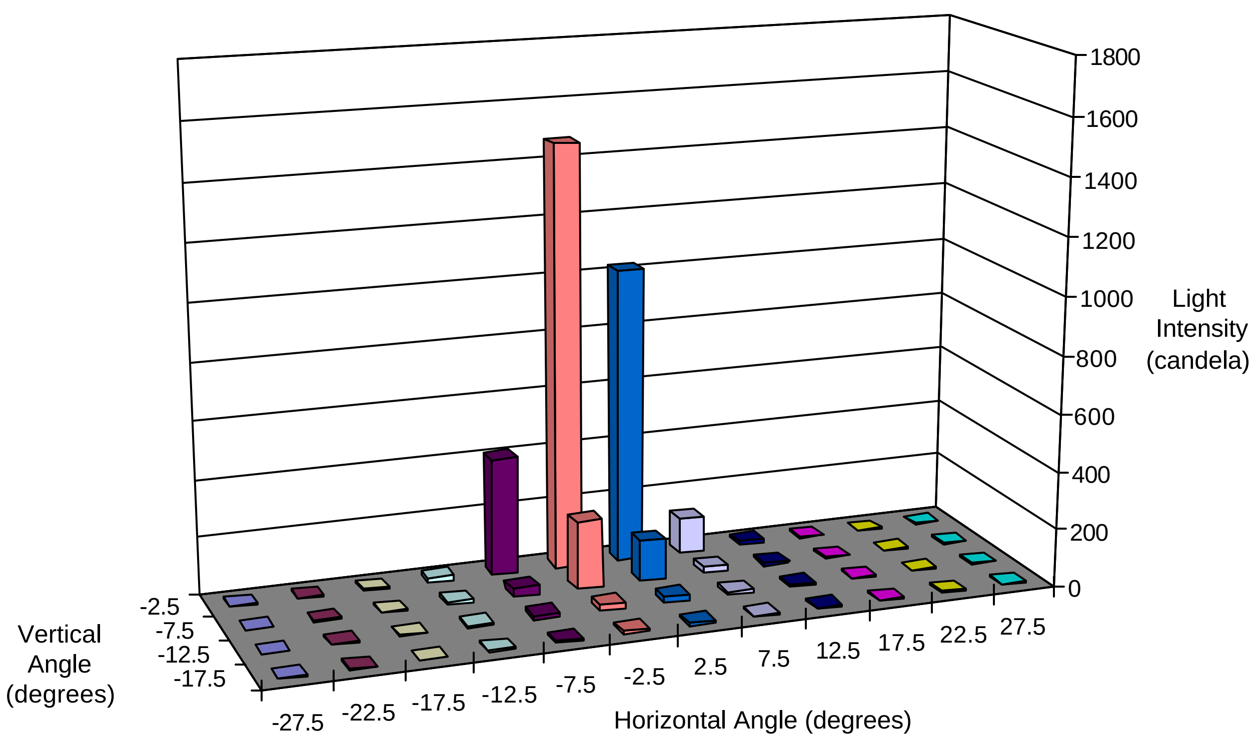

Figure A9.5.20b Output from WPS #9 (Green) signal, 10.0 volts, 66 elements (73.33% on), ITE test.