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Evaluation of Navigational Range Lighting Parameters for Daytime and Nighttime Conditions

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OCTOBER 1998

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16. Abstract (MAXIMUM 200 WORDS)

The purpose of this study was to evaluate, using experimental methods under actual field conditions, parameters and relationships used by the U.S. Coast Guard (USCG) in the design of daytime and nighttime lighted parallax navigational ranges. In one experiment, thresholds of minimal separability, in terms of the angle at the observer's eye subtended by two lights, were measured for various light intensity combinations under both daytime and nighttime conditions. In a separate experiment, thresholds for detection of lights under daytime conditions were determined. Results suggest that the current process used by the USCG to prevent blurring together of the two lights while minimizing required tower heights for nighttime ranges is valid. For the daytime results, the design guidelines for minimum tower height separations, for the illuminance levels evaluated, are adequate for illuminance ratios less than 1.6:1. Results for the second experiment showed that the present USCG practice of using a factor of 1000 to convert the illuminance level specified for nighttime range light signals to a level adequate for daytime use is also valid. This validation of current practices allows the USCG continued significant cost savings in the construction of towers used for navigational ranges.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

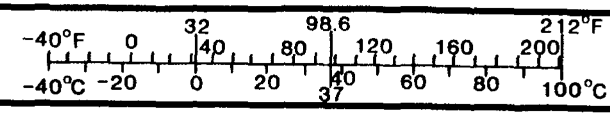

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

EXECUTIVE SUMMARY

The purpose of this study was to evaluate, using experimental methods under actual field conditions, parameters and relationships used by the U.S. Coast Guard (USCG) in the design of daytime and nighttime lighted parallax navigational ranges. Parallax ranges are commonly used around the country and other parts of the world as aids to navigation to guide vessel traffic along channels or into harbors. A parallax range consists of a pair of lights positioned on the range's centerline, or axis, with the farther light higher than the nearer one. Vertical alignment of the lights indicates that a vessel is positioned on the range axis. The USCG's *Range Design Program* provides guidelines for the design of navigational ranges, and is based on the *Recommendation for Leading Lights*, May 1977, issued by the International Association of Lighthouse Authorities (IALA). The two guidelines use different standards for determining the luminous intensity and minimum vertical separation requirements of the two signal lights for daytime ranges to ensure that the lights are visible, yet do not blur together. The USCG concern was to determine which of the two guidelines was appropriate. If the IALA recommendations were determined to be overly conservative, then using the IALA guideline would result in higher daytime illuminances and a greater vertical angular separation than were necessary, increasing range tower construction costs and operating expenses. If USCG practices were found to be overly optimistic, however, then the *Range Design Program* would not provide navigational range systems that met the needs of the mariner. Since many of the design parameters of these range systems are based on laboratory studies, the USCG sought to evaluate, under actual field conditions, the relationships and assumptions of USCG design guidelines to assess their validity. A simulated full scale 2.6 nautical mile range was constructed using 14-inch range lights. Two sets of experiments were then conducted.

In the first set of experiments, observers judged whether two vertically separated lights appeared distinct or blurred together. The experiments were conducted in both day and night conditions. For the nighttime observations, the actual illuminance values were used, while for daytime observation, the illuminances were divided by 10,000, in accordance with the USCG design guidelines. In the second set of experiments, groups of observers judged the minimum illuminance required for detection of a light under daytime conditions of bright sun and overcast.

Results of this study suggest that the USCG *Range Design Program* is suitable for designing navigational ranges for use in nighttime viewing conditions. Results for daytime conditions suggest that a modification to the equation used for calculating the required minimum vertical separation might be considered, since the observations diverge from the values calculated by the *Range Design Program* as the ratio of illuminances increases. The data obtained are insufficient to allow for development of a new equation specifically for daytime conditions; however, developing a new equation is not critical. Finally, the detection data indicate that the USCG's recommendation is adequate to provide a daytime range light signal.

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Introduction

Throughout the world, a simple visual method is used to indicate to a vessel operator the correct path or "range" to follow along such navigation channels as approaches to harbors and within rivers. This is the parallax, or two-station, range system, referred to in other parts of the world as "leading lines." It consists of a pair of lights positioned on the range's centerline, or axis, with the farther light higher than the nearer one (Figure 1). Vertical alignment of the lights indicates that the vessel is positioned on the range axis. Any deviation from this course causes the two range lights to become offset from vertical. The range lights, therefore, provide an effective and easy-to-use means of judging position within the channel, as well as constant feedback of speed and direction of motion with respect to the channel centerline.

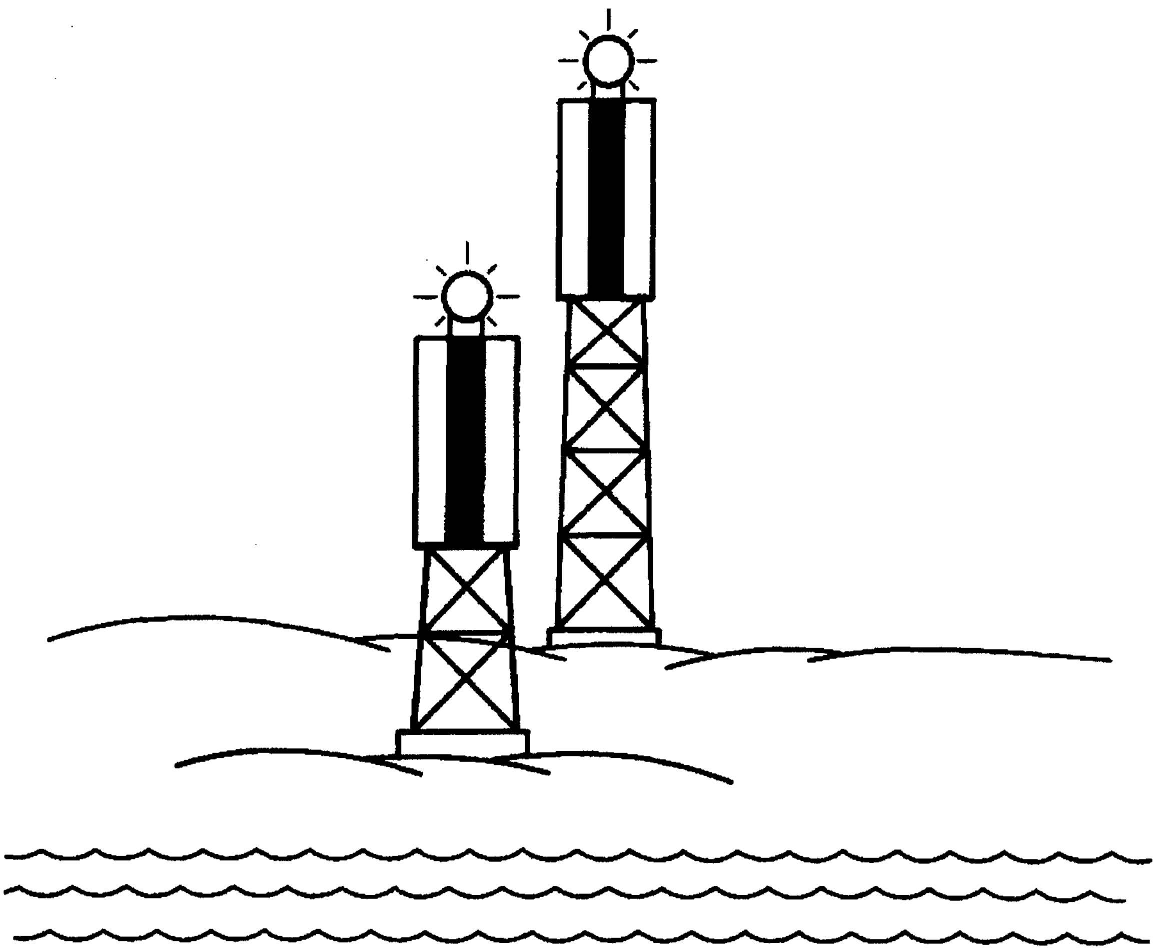


Figure 1. Front view of a navigational range, with the observer located to the right of the range axis.

Over 1000 of these two-station lighted navigational ranges are in use around the United States. Each range possesses a unique design to suit the given location. In the design of the ranges, the

U.S. Coast Guard (USCG) has adopted design parameters, recommendations, and guidelines (Commandant, USCG, 1997) established by the International Association of Lighthouse Authorities (IALA) (1977). These design relationships were experimentally derived from laboratory test data for nighttime conditions. A very limited body of data was used to determine if these design relationships could be used for daytime signaling. The relationships may be very conservative to ensure that the ranges are effective aids to navigation. Overly cautious guidelines would result, however, in ranges having higher intensity lights and taller range towers than are actually needed at the given location. Because some of the range lights are necessarily battery powered, higher intensity lights require larger batteries, which substantially increases their cost. Similarly, mounting the lights on larger towers, in order to achieve greater vertical separation, is more costly to construct and maintain and more susceptible to damage by severe weather. If the range is not designed adequately, on the other hand, the vertical distance between the two lights might not be sufficient to allow the lights to be clearly distinguishable from each other. In such case, near the range axis, the two lights would blur together, appearing as one, and be useless as a range indicator. In addition, if one light is of much greater intensity than the other, it can mask out the less intense light, again making the range unusable. The USCG, therefore, sought to evaluate under actual field conditions the relationships and assumptions of the design guidelines, during nighttime and daytime, to assess their validity. If results showed that less intense lights or shorter range towers provide the required navigational information, the USCG could realize savings in the deployment of its navigational range light systems.

Two experiments were conducted to help determine the validity of the current guidelines. In the first, observers judged the minimum separability for a pair of lights of various intensity combinations to appear just clearly separated, not blurred together, under both day and night conditions. In the second, observers judged the minimum illuminance required for detection with certainty of a light during daytime conditions.

Separability Experiment

Method

<u>Apparatus.</u> A navigational range was simulated by mounting five standard 14-inch range lanterns (RL14s) on a vertical column affixed to the east side of the four-story U.S. Coast Guard Research and Development Center (CGR&DC) building at Avery Point, Groton, CT. The lanterns were spaced vertically on 1.83 meter (six-foot) centers, with the top lantern situated above the building's roof. The lanterns were pointed at the observers' location, which was a paved parking lot located 2.6 nautical miles (NM) to the northeast at about the same elevation as the lights. Each lantern was carefully aimed so that the axis of maximum intensity of the light signal was directed towards the observers' position. The lights were individually controlled by 12-volt power supplies with voltmeters and ammeters, on-off switches, flashers, and push buttons to advance the CG-6P lampchangers.

By turning on the topmost range light and one of the lower four, the vertical separation between the lights could be varied. The mounting position of the lights at the 2.6 NM distance allowed for vertical separations of 0.38, 0.76, 1.14, and 1.52 milliradians (mrad) (1.3, 2.6, 3.9, and 5.2 minutes of arc) to be presented. All separation data are given the angular measure of milliradians for general applicability; they can be converted to minutes of arc (min arc) by multiplying by 3.4377. Since the effect of horizontal offset of a pair of lights due to parallax was not being investigated, all lights were located in one vertical line at the same distance from the observers. To help observers distinguish the lights and more closely mimic operational signals, the top light was flashed at an occulting four-second (Oc 4) characteristic (3 sec on, 1 sec off per cycle), and the lower lights were flashed at an Iso 2 characteristic (1 sec on, 1 sec off). Only white lights were used.

To investigate the effect of various illuminance levels and ratios, the lampchanger in each range lantern was fitted with a set of six different lamp sizes (watts or amps). To achieve an appropriate range of illuminances for each test, a different set of six lamps was chosen for the night tests than for the daytime tests, as shown in Table 1. In addition, a clear 3° spread lens was used for the daytime tests and a clear 20° spread lens for the night to further achieve a range of illuminances that were appropriate for the respective viewing conditions. Prior to the experiment, peak intensity measurements were taken in a light tunnel by CGR&DC personnel using the actual range lanterns, lamps, and spread lenses. From the tables of Effective Luminous Intensities for the RL14 Range Lantern in the *ATON Visual Signal Design Manual* (Commandant, USCG, 1997), the ratios for the appropriate flash characteristic versus the fixed peak intensities were determined for the lamps and respective spread lenses. These tables are based on the Schmidt-Clausen correction factors for flashed light signals, outlined in IALA's *Recommendations on the Determination of the Luminous Intensity of a Marine Aid-to-Navigation Light*, December 1977. By multiplying the measured peak intensities by the flashing/fixed ratios, we could calculate the effective luminous intensities for all the lights used in the experiments, for later analysis of the experimental results. The peak intensities, the ratios, and the effective intensities for the topmost range light and the means for the four lower range lights are given also in Table 1. Intensities are converted to illuminance levels by application of Allard's Law, Equation (1) below. Since the observation distance was constant, the illuminance ratio for each pair of lights displayed was equal to the ratio of intensities of the lights.

Observers. Observers were solicited from the CGR&DC, the Naval Submarine Medical Research Laboratory (NSMRL), and the local community. A total of 27 observers participated, 16 men and 11 women, with an age range of 21 to 79 years (mean = 52.5 years). Twenty-two were paid volunteers from the community. Before the experiment, visual acuity was measured in all observers with an Armed Forces Vision Tester to ensure each met the minimum requirements of 20/40 in either eye for deck licenses (Code of Federal Regulations 46 CFR 10.202). Corrected binocular visual acuity ranged from 20/12 to 20/30, with a mean of 20/19.7. The correlation between age and visual acuity was modest, $r = .49$. Thirteen of the observers said they were "experienced" in making the kind of judgments required in the experiment, many of them pleasure boaters. Six observers wore sunglasses during the daytime sessions; examination of their data showed their performance to be no different from that of the other observers.

Procedure. Three test conditions were run, two during the day, morning and afternoon, and the nighttime condition. With several exceptions, all observers participated in all conditions. Two sessions were conducted under each condition, with approximately half the observers serving in each session. Morning and afternoon sessions were conducted to determine if time of day had an effect on perceived separability. Specifically there were two conditions: when the sun was off to the side of the observers and shining on the face of the building and the range lights, and when the sun was behind the building, with the face of the building in shadow and the observers facing the sun. Table 2 gives the observation dates, times, location, and conditions.

Before the start of the experiment, the observers were given a consent form approved by NSMRL's Committee for the Protection of Human Subjects. After the observers' visual acuities were measured, they were given clipboards, pencils, and response sheets (Appendix A) and seated in the parking lot in chairs situated in a rectangular matrix so that all could see the range lights when illuminated. With the lights in the same plane and at the observing distance of 2.6 NM, small differences in seating position did not appreciably affect the viewing distances nor the angles between the two lights. The observers were read instructions (Appendix B) and shown printed illustrations of lights that were separated and blurred together (Appendix C). They were given eight practice trials before the start of the experiment to ensure that they knew what their task was and that they were performing it correctly. The observers, who were not informed of the intensities or vertical separation of the two lights, were given a ready signal before the start of each trial. Experimenters were stationed in the building at the site of the range lights to turn the appropriate ones on and off, and to select the intensities by rotating the lampchangers to the appropriate lamps. Other experimenters were with the observers to organize the observation and data collection process. The two sets of experimenters coordinated their activities by cellular telephone. This was a double blind study, since neither the observers nor the experimenters at the observation site knew which lights were being displayed on any given trial; only the operator of the lights knew.

A series of trials was administered for each intensity combination investigated. Each series of trials was conducted as follows. After the ready signal, two lights were turned on simultaneously in their respective flash patterns. The uppermost light was always paired with one of the other four lights, which were pre-selected randomly according to a protocol sheet. The observers judged whether the two lights appeared separated vertically. The pair of lights were on for 10-15 seconds or until all observers responded. The observers marked the appropriate place on their answer sheets whether the lights appeared separated or not, and the lights were switched off. Then, after the next ready signal, the next pair of lights were turned on and the observers made another judgment, and so on until judgments were made on all four pairs of lights twice, making a total of eight judgments per observer in each series.

For the daytime experiments, the lamps were placed in the lampchangers with the highest wattage in the first position, decreasing in order of wattage to the sixth position. The first series of trials was conducted at the highest luminous intensity, with approximately a 1:1 intensity ratio between the two range lights. For the next series of trials, the lampchanger in the uppermost

Table 1. Lampchanger position, lamp, measured fixed peak luminous intensity, flash characteristic/fixed ratio, effective intensity, and illuminance for daytime and nighttime conditions.

		Top Range Light 14-1				Mean of Bottom Range Lights 14-2 through 14-5			
Lamp-changer Position	Lamp (Watts/Amps)	Peak Fixed (cd)	Oc4/Fixed Ratio	Eff. Int. Oc 4 (cd)	E (SM cd)	Peak Fixed (cd)	Iso2/Fixed Ratio	Eff. Int. Iso 2 (cd)	E (SM cd)
	Daytime -- Clear 3 degree Spread Lens								
1	110 W	752,139	0.910	684,783	41,276	655,982	0.672	440,585	26,556
2	75 W	461,352	0.915	422,088	25,442	432,609	0.702	303,746	18,308
3	50 W	282,477	0.939	265,357	15,994	279,990	0.727	203,629	12,274
4	35 W	232,837	0.920	214,210	12,912	214,609	0.760	163,103	9,831
5	2.03 A	120,322	0.929	111,728	6,734	117,211	0.786	92,094	5,551
6	1.15 A	78,593	0.935	73,490	4,430	71,675	0.805	57,712	3,479
	Nighttime -- Clear 20 degree Spread Lens								
1	0.25A	1,547	0.950	1,470	89	1,749	0.800	1,399	84
2	0.55A	5,076	0.924	4,691	283	5,506	0.803	4,421	266
3	0.77A	8,667	0.928	8,040	485	8,042	0.807	6,492	391
4	1.15A	9,721	0.929	9,027	544	13,136	0.786	10,321	622
5	2.03A	16,275	0.923	15,023	906	21,379	0.769	16,445	991
6	3.05A	33,317	0.900	29,985	1,807	37,336	0.750	28,002	1,688

Table 2. USCG Range Light Separability Experiment Observations: dates, times, locations, and conditions.

Date	Start Time	End Time	Sunset
12 Nov 1997	0910	1045	
12 Nov 1997	1315	1500	
13 Nov 1997	0850	1044	
13 Nov 1997	1305	1430	
19 Nov 1997	1730	1930	1626
20 Nov 1997	1720	1910	1625

Observation Point: Parking Lot, Grasso Tech, Groton, CT
41 deg 20 min 35 sec N
72 deg 01 min 02 sec W

Location of Range Lights: USCG R&DC Building, Avery Point, Groton, CT
41 deg 19 min 01 sec N
72 deg 03 min 49 sec W

Observation Azimuth	233.3 degrees T
Observation Elevation	Approx. Zero degrees
Visibility, all sessions:	10 miles (8.7 NM)
Transmissivity factor:	0.71 per nautical mile
Sky condition:	Bright sun.

light was changed to the next lower amperage lamp, for testing the second intensity ratio. The lamps of the lower four range lights remained the same as previously, and a randomized sequence of vertical separations was again presented. Series of 8 trials each (2 judgments at each of 4 separations) were presented in this manner until all six lamps in the changer of the uppermost light were judged with the other lights. The lampchanger in the uppermost light was then manually reset to its second position and the lampchangers in the other lamps were electrically advanced to their second positions. Another series of 8 trials was presented at that intensity ratio, still 1:1, but at the second intensity level. The lampchanger in the uppermost light was advanced and additional series of trials was presented at the new intensity ratios. The uppermost lampchanger was reset to its third position, and testing continued in this manner until all intensity combinations were presented. This sequence of lamp positions for each light is given in Appendix D.

The nighttime sessions were run in the same manner as the daytime except that the series of trials started with the lowest luminous intensity. The lamps were placed in the lampchangers with the lowest amperage in the first position, increasing in order to the sixth position. Rather than being seated outdoors in the parking lot as in the daytime, observers in the night sessions were housed in a heated bus at the same location, parked perpendicular to the line of sight. The observers used flashlights with red lenses to see their response sheets, and observations were made through the open side windows of the bus. The sky was dark during these sessions and there were few background lights.

With six lamps in each lampchanger, 21 intensity combinations were obtainable. The experimental design tested all 21 combinations and assumed that it made no difference in this perceptual study whether the greater intensity light was on the top or the bottom, although the flash characteristics were different. With 2 trials at 4 separations at each of 21 intensity combinations, 168 trials were presented in a session. Each session lasted about 1.5 hours, including at least two short rest periods for the observers while an experimenter reset the lampchanger.

Results

For each observer, the raw data were sorted and the means of the two judgments at each separation under each condition were calculated. Data from observers in the two morning sessions were combined, as were those of both afternoon and both nighttime sessions, since inspection showed that the data from each pair of corresponding sessions were highly similar.

This process produced three sets of data that gave the proportion of observers that saw a pair of lights as just noticeably separable at each of the vertical separations presented, at each intensity combination.

A probit analysis (Cohen & Cohen, 1975) was computed on the data for each intensity combination for each observation time of day. The probit procedure, a normalizing transformation of proportions based on the cumulative normal distribution, produces a probability of response function based on the values of the variable of interest, in the present case, the vertical separation between the pair of lights. Results of the morning and afternoon sessions were plotted and compared. Contrary to expectations, these means were practically identical. Therefore, the means for each observer were calculated over both daytime sessions and new probit analyses were computed to produce data for a single daytime session. With probability of response ranging from nearly zero (no one responds), to 50% (perceptual threshold: half the observers respond), to nearly 100% (all observers respond), a conservative probability of 99% was chosen to ensure that the value given for that vertical separation would be one that would allow almost all observers to see the lights as distinctly separable at that particular intensity combination. At 99% probability the given value is 2.33 standard deviations above the perceptual threshold. The mean response data that went into the probit analyses, and the vertical separation, in mrads, required for the 99% probability of seeing the two lights as distinct for each intensity combination, are given in Appendix E for daytime and Appendix F for night. Note that, as one would expect, proceeding from left to right across an intensity combination row, more and more observers judged the two lights as clearly separable as their vertical separation increased. The mean 95% confidence limits of the values were -0.17 mrad and +0.35 mrad for the daytime data and -0.24 mrad and +0.48 for the nighttime data. This confidence interval describes the range of values that contains the population mean with a probability of 95%.

From the effective intensities given in Table 1, the illuminance, in sea-mile candelas (SM cd) produced by each light at the observer's eye were computed using Allard's Law according to the following formula, as given in the *ATON Visual Signal Design Manual* (Commandant, USCG, 1997):

$$E = \frac{(I_e * T^D)}{D^2} \qquad (1)$$

where :

E = illuminance (sea-mile candela),
I_e = Effective luminous intensity of the light signal (candela),
T = Transmissivity factor (per nautical mile), and
D = Distance from the observer to the light (nautical mile).

Visibility data were obtained from the Northeast Regional Climate Center at Cornell University, Ithaca, NY. Visibility was listed at 10 statute miles (approximately 8.7 NM) for all observation sessions; this equated to a transmissivity of 0.71 per nautical mile (Kaufman & Christensen, *IES Lighting Handbook*, 1984). The illuminance values for each signal displayed are also given in Table 1.

The ratio of the illuminances (E+/E-) was calculated for each light intensity combination. Appendix G gives the table of illuminances, ratios, and 99% probability vertical separations for the daytime condition; Appendix H gives the nighttime data. The 99% probability separation values in milliradians were plotted against the log of the E+/E- ratios; the daytime data are shown in Figure 2. A curve of a second-degree polynomial equation was fit to the data.

Power, logarithmic, and exponential functions were also fit to the data, but the second-degree polynomial was chosen as most representative since it gave the overall best least-squares fit. A linear fit was not considered since we assumed that an asymptotic separation value would be reached at some optimal intensity ratio. The polynomial curve and its equation are also shown in Figure 2. One can see that the highest E+/E- ratio required the greatest angular separation for the two lights to be seen as clearly separable, a value of approximately 2.2 mrad. As the ratio approached 1:1, the required separation fell to a minimum, approximately 1 mrad, the same result that Blaise (1965) had found in the laboratory under nighttime conditions.

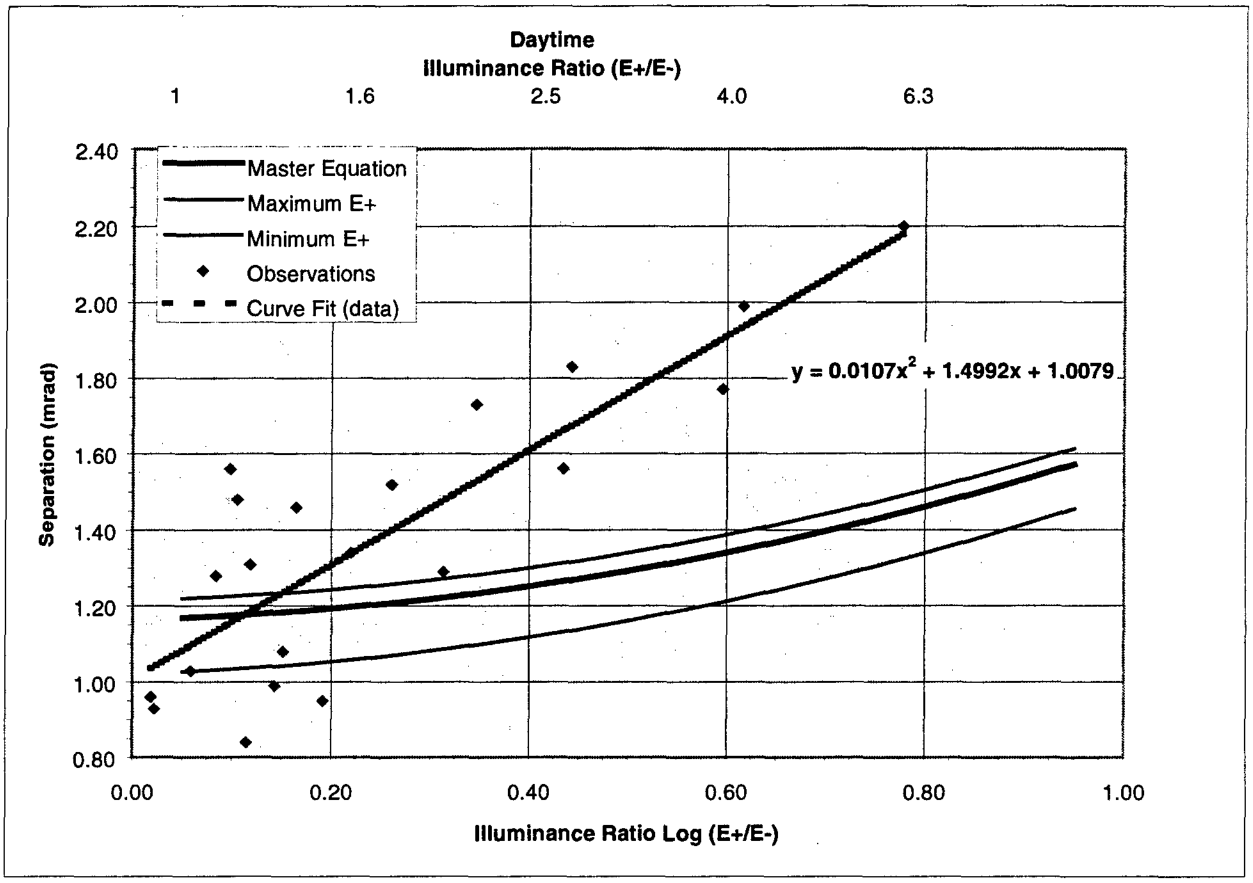


Figure 2. Separation between lights by illuminance ratio for the experimental data at 99% probability and for the Master Equation -- Daytime. The straight line "curve" is the best least-squares fit of a second-degree polynomial to the respective data points. The equation shown describes this curve for the empirical set of data. The Master Equation values and the resultant bolded curve were calculated by dividing the actual sea mile candelas by 10,000, using the mean of the E+ values. The fine curves above and below the Master Equation curve used the highest and lowest of the E+ values investigated.

Also given in Appendix G are the values calculated by the *Range Design Program* for the minimum separation of lights for the given illumination levels and ratios so as to prevent the two lights from blurring together. The curve annotated as "Master Equation" in Figure 2, and the values provided in Appendix G were calculated using the *Master Blur Equation* from the *Range Design Program* (Commandant, USCG, 1997). This equation is the same as that specified for the general separation of lights from IALA (1977), modified for illuminances in SM cd instead of lux. The Master Blur Equation (Master Equation) is:

$$\text{delta} = \{2.4 - 0.06\text{Log}(E+/E-) + 0.26\text{Log}^2(E+/E-) + [(\text{Log}(E+) - 6.535)*(0.2 - 0.02\text{Log}(E+/E-) - 0.02\text{Log}^2(E+/E-))]\} \quad (2)$$

where:

delta is the minimum required angular separation of the two lights (mrads),
E+ is the greater of the two illumination levels provided by the range lights at the observer's position (SM cd),
E- is the lesser of the two illumination levels provided by the range lights at the observer's position (SM cd).

Because the Master Equation is based on nighttime observation conditions and has not been shown to be valid for daytime conditions, U.S. Coast Guard practice has been to design the range for nighttime conditions with no background lighting, and multiply the resultant minimum required intensities by 1000 to achieve the required illuminances for daytime use. The resultant daytime illuminances, however, are divided by 10,000 before the *Range Design Program* applies the Master Equation to check for blur. To calculate the Master Equation separation values plotted in Figure 2 and tabulated in Appendix G, the illuminances produced at the eye of the observer by the lights were, therefore, first divided by 10,000.

Note that the dependence on E+ yields a family of curves, not a single curve, from the Master Blur Equation. The curve presented in Figure 2 was generated using the mean of the E+ values. The fine lines above and below the Master Equation curve were produced using the highest and lowest values of E+ investigated.

The empirical data in Figure 2 show a greater increase in required vertical angular separation as the ratio of illuminances (E+/E-) rises than was calculated by the Master Equation. The empirical data increased by about 1.2 millirad over the range of ratios evaluated, whereas the Master Equation only provided a rise of about 0.3 millirads over the same range. The curves intersect at an illuminance ratio of 1.3:1, and begin to diverge significantly (> 0.1 mrad) for ratios above 1.6:1, Log (E+/E-) = 0.2, below which many ranges are designed to fall.

The illuminance levels at the eye of the observer, for the lantern/lamp combinations used were calculated from Equation (1) using the reported visibility of 10 statute miles (8.7 NM) to determine the transmissivity in calculating the illuminance values. Reported visibilities are from human observations, however, and are not precise. Therefore, to see the effect on the illuminance values for the range of possible atmospheric conditions, the separation values from the Master Equation were recalculated assuming visibilities of 7 and 15 statute miles (6.1 and 13 NM). The results were a difference of only +/- 0.03 mrad, due to the relatively short 2.6 nautical mile viewing distance, and were not considered any further.

Figure 3 shows the plot of the nighttime data, from the numerical values tabulated in Appendix H. As with Figure 2, the curve annotated as "Master Equation" is based on the mean value of E+ evaluated, with fine lines above and below indicating the Master Equation values produced using the extreme values of E+. The two curves are generally similar and are in agreement for illuminance ratios below 4:1, Log ratio = 0.6.

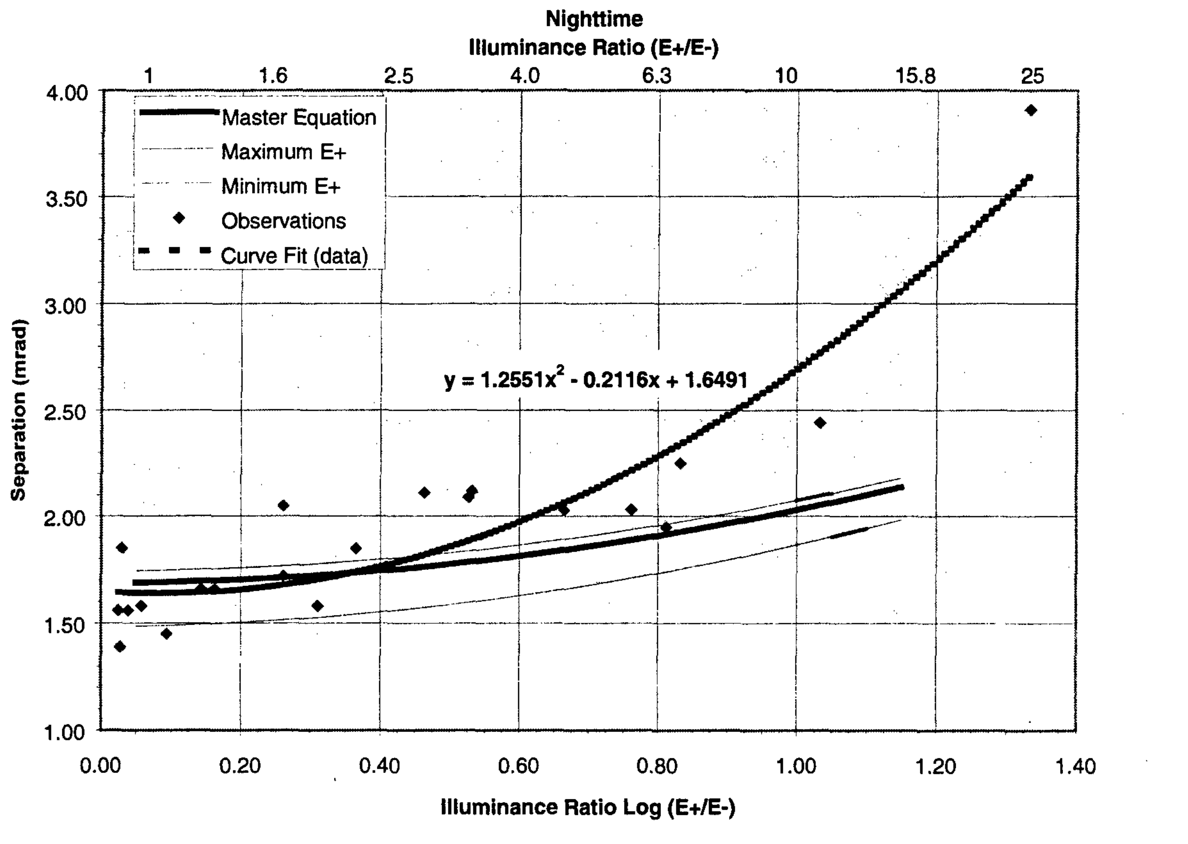


Figure 3. Separation between lights by luminance ratio for the experimental data at 99% probability and for the Master Equation -- Nighttime. The curve is the best least-squares fit of a second-degree polynomial to the respective data points. The equation shown describes this curve for the empirical set of data. The Master Equation values and the resultant bolded curve were calculated using the mean of the E+ values. The fine curves above and below the Master Equation curve used the highest and lowest of the E+ values investigated.

Discussion

The Master Equation does a fairly good job of predicting the vertical separation obtained in the field experiment under nighttime conditions, although at the highest E+/E- ratios the empirical data indicate that greater vertical separation would be required (Figure 3).

For daytime conditions IALA (1977) recommends using the same design parameters as night, except that the luminous intensities be increased by a factor of 2000 to 5000. As noted above, U.S. Coast Guard practice has been to initially use the rules for night and then increase the luminous intensity by a factor of 1000. The elevated illumination levels are then reduced by a factor of 10,000 before the Master Equation is used to evaluate the blur constraint (minimal angular separation required). For the limited range of illuminance levels and ratios tested, when compared with the Master Equation values derived following USCG practice, the data we obtained suggest that the Master Equation holds for ratios close to 1:1. The data we obtained, however, follow a markedly different curve than the Master Equation. As the ratios rise above approximately 1.6:1, the data suggest that greater separations are required than those generated by either USCG practice or IALA recommendation. Many ranges are designed to fall below this 1.6:1 illuminance ratio (For comparison, the fine line above the "Master Equation" curve in Figure (2) is almost identical to the separation values that would be obtained following the IALA recommendation for daytime illuminances of range lights.)

Daytime Detection Experiment

IALA (1977) recommends that the same design parameters be used for daytime as for night, except that the luminous intensities be increased by a factor of 2000 to 5000. This would result in an illuminance at the eye of the mariner, at the far end of the channel, of 2.0 to 5.0 millilux. USCG practice has been to use a factor of only 1000, resulting in an illuminance roughly 1/2 to 1/5 as great as that recommended by IALA. To determine whether the daytime factor used by the USCG is adequate, or whether the IALA recommendation should be followed, minimum thresholds for detection of lights with certainty were measured under daytime conditions. Note that the illuminance level required for detection of a light with certainty under daytime conditions must be compared to the comparable value for night. IALA (1977) recommends that, at any point in a channel, illuminance at the eye of the mariner produced by a range light be a factor of 5 greater than the usually accepted value required for detection with certainty at night. This factor of 5 is included in the design guidelines for a range for use at night and is also subsumed into the practice for design of daytime ranges. The commonly accepted value for the threshold of detection with certainty at night is 0.67 SM cd, or approximately 0.195 microlux. IALA (1977) uses a value of 0.2 microlux, or approximately 0.686 SM cd.

Method

Apparatus. The same simulated navigational range was used as in the previous experiment. Only the topmost range light was used to determine thresholds, which had part of a narrow, dark roofline as background, with the light colored building below and the sky above. The lamps previously used for the nighttime separability experiment were installed in the lampchanger, with 3°, 11°, or 20° spread lenses installed on the range light to adjust the light intensity for different sessions.

Observers. Between three and eight observers were used in each session, most of whom participated in the separability experiment. Ages ranged from 28 to 58 years, and the mean corrected visual acuity for both eyes combined of all observers was 20/17.

Procedure. Four observation sessions were conducted, with the details given in Table 3. Two were in the morning, with the sun from behind the left shoulders of the observers; one was in the afternoon, with the observers facing the sun, all under clear conditions. The fourth session was conducted around noon under overcast, slightly hazy conditions. Observers were instructed to determine whether they could see the range light and mark their responses on a response sheet. The Observers' Instructions are given in Appendix I and the response sheet is given in Appendix J. For the first session, the lights were presented in order of decreasing intensity in a single series. For the other sessions, three series of decreasing intensities and three series of increasing intensities of the six lamps were administered, with two extra "catch trials" of randomly chosen intensities repeated a second time to help minimize guessing or other bias effects. Measurements of sky luminance were taken with a Model PR-650 spectroradiometer (Photo Research Inc., Chatsworth, CA).

Results

The percentage of occurrences that a light of a given intensity was detected was calculated by combining the data from all observers and light presentations for each condition;
the results obtained in morning and afternoon sessions were virtually identical, which permitted this combining. The illuminance in sea mile candelas was then calculated using Equation (1), Allard's Law, from the peak fixed intensities for each lamp with the appropriate spread lens. The results, which were very clear cut, are given in Table 4 for bright sunny, clear conditions. For the range lantern with the 3° spread lens, which produced the highest values of intensities used, all observers saw all the lights 100% of the time. With the 11° spread lens, all observers saw all presentations of the lights at an illuminance level of 723 SM cd and higher, while an illuminance level of 223 SM cd was detected only 2.5% of the time. For the 20° spread lens, the cutoff between detected and not detected was between 522 and 586 SM cd. Linear interpolation was used to arrive at a best estimate of threshold of detection (the 50% point) of 554 SM cd for the bright sun condition. The 99% probability value (detection with certainty) cannot be calculated due to limited resolution of the data, but would be somewhat less than 586 SM cd.

Table 3. USCG Range Light Detection Experiment Observations: Dates, times, and conditions. Locations and other conditions same as Table 2.

Date	Start Time	End Time	No. of Observers	Spread Lens
19 May 1998	1000	1030	3	3 & 20 degree,
27 May 1998	0945	1015	8	11 degree
27 May 1998	1440	1500	8	11 degree

Visibility:	10 miles (8.7 NM)
Transmissivity factor:	0.71 per nautical mile
Sky luminance:	1.48×10^4 cd/m^2
Sky condition:	Bright sun.

Date	Start Time	End Time	No. of Observers	Spread Lens
29-Jun-98	1215	1230	5	20 degree

Visibility:	6 miles (5.2 NM)
Transmissivity factor:	0.56 per nautical mile
Sky luminance:	4.0×10^3 cd/m^2
Sky condition:	Overcast, moderately heavy clouds.

The results for the overcast conditions are given in Table 5. Here, with much less sky luminance, the detection threshold was substantially lower, with lights of 169 SM cd detected 60% of the time and lights of 51 SM cd detected 2.5% of the time. Linear interpolation resulted in the 50% threshold of 148 SM cd for overcast conditions. An illuminance level of 323 SM cd was detected 100% of the time, while 288 SM cd was detected 97.5% of the time. Again using linear interpolation, we might expect that the 99% probability of detection (detection with certainty) would be at an illuminance of 309 SM cd, although given the small number of observers such a conclusion is tentative at best.

Table 4. Daytime detection thresholds, sunny conditions: lamp, fixed peak luminous intensity,illuminance (E), and percent of trials in which the light was detected, morning and afternoon sessions combined;sky luminance: 1.48 x 10^4 cd/m^2 (4.32 x 10^3 ft-L).

Lamp Amps	3 Degree Spread Lens			11 Degree Spread Lens			20 Degree Spread Lens		
	Peak Fixed (cd)	E (SM cd)	Percent Detected	Peak Fixed (cd)	E (SM cd)	Percent Detected	Peak Fixed (cd)	E (SM cd)	Percent Detected
3.05	194,448	11,720	100	73,000	4,400	100	33,317	2,008	100
2.03	120,322	7,252	100	48,000	2,893	100	16,275	981	100
1.15	78,593	4,737	100	26,000	1,567	100	9,721	586	100
0.77	55,006	3,316	100	15,000	904	100	8,667	**522**	**0**
0.55	30,892	1,862	100	12,000	723	100	5,076	**306**	**0**
0.25	12,879	776	100	3,700	**223**	**2.5**	1,547	**93**	**0**

Note: The 3 degree and 20 degree spread lens peak luminous intensities are measured values. The 11 degree values are taken from the ATON Visual Signal Design Manual.

Detection Threshold: 554 SM cd

Table 5. Daytime detection thresholds, overcast conditions: lamp, fixed peak luminous intensity, illuminance (E), and percent of trials in which the light was detected, morning and afternoon sessions combined; sky luminance: 4.0 x 10^3 cd/m^2 (1.17 x 10^3 ft-L).

Lamp Amps	20 Degree Spread Lens		
	Peak Fixed (cd)	E (SM cd)	Percent Detected
3.05	33,317	1,107	100
2.03	16,275	541	100
1.15	9,721	323	100
0.77	8,667	288	97.5
0.55	5,076	**169**	**60**
0.25	1,547	**51**	**2.5**

Detection Threshold: 148 SM cd

One caveat should be noted, however. Since the lights appeared against a narrow dark background just below the sky, this probably resulted in a slightly greater detection sensitivity than would obtain if on a featureless bright sky background.

Discussion

The IALA recommendation concerning the nominal daytime range of signal lights provides the following equation for the illuminance threshold of a light as a function of the luminance of the sky in the direction of observation:

$$E = 0.242 * 10^{-6}(1 + \sqrt{0.4L})^2 \tag{3}$$

where:

E = threshold illuminance (lux), and
L = sky luminance (cd/m^2).

Given that: 1 lux = $3.43 * 10^6$ sea-mile candelas,

with the sky luminance measured under the bright sun conditions of 14,800 cd/m^2, the expected threshold illuminance from Equation (3) is 5,050 SM cd, which is 9.1 times the threshold value measured.

As expected, a substantial difference was found between daytime threshold conditions under bright sun and heavy overcast. For the observations made under overcast conditions, with a measured sky luminance of 4,000 cd/m^2, Equation (3) gives a threshold of 1397 SM cd, which is 9 times the detection threshold of 148 SM cd we found empirically. The threshold illuminance found for bright sun conditions was nearly four times that for overcast conditions, or 0.57 log SM cd greater. This is exactly the difference in thresholds predicted by Equation (3) based on the 0.57 log cd/m^2 difference in sky luminance.

The detection with certainty value of 586 SM cd found for bright sun conditions is slightly less than 900 times the nighttime detection level with certainty value of 0.2 microlux (0.686 SM cd) used by IALA (1977). It must be noted, however, that even the detection with certainty values are such that one can just see the lights under the conditions tested. The observers agreed that these would be insufficient levels for use as range lights in a practical setting. Judging informally from the appearance of the other illuminance levels in the series, values of 2 to 5 times the detection levels (i.e., 1,200 to 3,000 SM cd) seem to be sufficient for use as navigational range lights. This is 18% of the minimum illuminance level recommended by IALA (1977) (6,700 to 16,750 SM cd) for daytime range design, but very close to the 3,350 SM cd value established by the U.S. Coast Guard Range Design Program. If the lights had been viewed against the sky rather than the narrow dark background, the thresholds would have been somewhat higher. The figures obtained in this study, nonetheless, suggest that the illuminance of daytime range lights could be reduced from those levels recommended by IALA without losing their effectiveness. Continued use of an illuminance level of 3,350 SM cd, for daytime range lights, appears to be appropriate to provide an adequate marine navigational signal.

Summary and Conclusions

The first set of experiments in this study examined the minimum perceptible vertical separability for a pair of range lights of various illuminance combinations under both daytime and nighttime conditions. For daytime conditions, the minimum separation was 1 mrad at an illuminance ratio between the two lights of 1:1 increasing to 2.2 mrad at the 6:1 ratio, Log (E+/E-) = 0.8 (Figure 2). The separation values were found to be slightly less than those given by the Master Equation (using illuminances divided by 10,000) near the 1:1 illuminance ratio, but became significantly greater as the illuminance ratio rose above about 1.6:1 (Log ratio = 0.2). For nighttime conditions, the minimum separation measured empirically was similar to that given by the Master Equation, with some departure from the Master Equation as the ratio increased above 4:1 (Log ratio = 0.6) (Figure 3). It is therefore concluded that the Master Equation for blur is adequate for designing nighttime ranges and daytime ranges with illuminance ratios less than 1.6:1, at least for the intensity levels and ratios tested here.

In the second set of experiments, the minimum illuminance for detection with certainty of a range light under daytime conditions was assessed. A detection threshold of 544 SM cd was found for bright sun conditions, with a detection with certainty value of 586 SM cd. This is slightly less than 900 times the nighttime detection with certainty level used by IALA (1977). For overcast conditions, the threshold was 148 SM cd, correspondingly lower in proportion to the measured sky luminances. Detection with certainty, under overcast conditions, would probably be close to 300 SM cd. Increasing the illuminance level required for detection with certainty under bright sky conditions by a factor of 5, to provide an illuminance level adequate for a navigational range light, results in a value (3,000 SM cd), which is very close to the value of 3,350 SM cd presently used by the U.S. Coast Guard.

Results of this study show that the Master Equation for the blur constraint can continue to be used for designing nighttime ranges. For daytime conditions, at the highest E+/E- illuminance ratios tested, the present practice of both IALA and the U.S. Coast Guard for determining the vertical separation of lights may not be appropriate and should be further investigated with a wide range of illuminances against a sky background. Finally, the detection data indicate a possible reduction in the IALA recommendation for the required illuminance of daytime range lights by a factor of 5. The U.S. Coast Guard should continue to use the existing *Range Design Program*, which currently results in reduced costs for construction, maintenance, and repair of navigational range light systems used during daytime.

References

Blaise, P. (1965). Minimum angular separation of signal lights between the limits of illumination on the eye acceptable for marine aids-to-navigation, Report No. 5-3-1. *VIIth International Conference on Lighthouses and Other Aids to Navigation, Rome,* 1-21.

Cohen, J., & Cohen, P. (1975). *Applied multiple regression/correlation analysis for the behavioral sciences.* Hillsdale, NH: Lawrence Erlbaum Associates.

Commandant, United States Coast Guard. (1997). *Range Design Manual* (Commandant Instruction M16500.4B). Washington, DC.

Commandant, United States Coast Guard. (1997). *ATON Visual Signal Design Manual* (Commandant Instruction M16510.2A). Washington, DC.

Kaufman, J. E., & Christensen, J. F. (Eds.). (1984). *IES Lighting Handbook.* New York: Illuminating Engineering Society of North America.

International Association of Lighthouse Authorities. (1974). Recommendation for a definition of the nominal daytime range of maritime signal lights intended for the guidance of shipping by day (April 1974). *Extract from IALA Bulletin n° 60—1974-3.*

International Association of Lighthouse Authorities. (1977). Recommendation for leading lights (May 1977). *Extract from IALA Bulletin n° 71—1977-3.*

International Association of Lighthouse Authorities. (1977). Recommendations on the Determination of the Luminous Intensity of a Marine Aid-to-Navigation Light (December 1977). *Extract from IALA Bulletin n° 75—1978-3.*

Appendix A
Observer Response Form for Separability Experiment

Observer Response Form

Date____/____/1997 Time of Day________ Obsrvr. No._________
mo day (Last 4 digits Soc. Sec. No.)

X = Yes, they look separated. O = No, they do NOT look separated, they look combined.

Series	Trial							
	1	2	3	4	5	6	7	8
Prac.							XX	XX
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
21								

Appendix B

Observers Instructions for Separability Experiment

Instructions to Observers

Off in the distance is a set of lights called Range Lights, actually used by the U.S. Coast Guard. The lights are positioned at various heights, one above another. We'll be running a series of trials with two lights turned on at a time. Both will be flashing, but at different flash rates. What we'd like you to do is to tell us if you can see the two lights as being distinct one from the other. For some trials, the lights might look widely separated. On other trials, they might look blurred together as one.

At the start of each trial, look at the lights and determine whether the two lights appear separated, that is, if you can see, even if just barely, a line of darkness separating the two lights. To do this task successfully, you will have to wait until both flashing lights appear ON at the same time. If you can see them as two distinct lights, mark an **X** in the appropriate box on your Observer Response Sheet. If the lights look blurred together, mark an **O** in the box on your Observer Response Sheet. Then we will go on to the next trial. The vertical distance between the two lights will be randomly varied for each trial, and for some trials, one of the lights might look considerably brighter than the other. In any case, we want your best judgment as to whether the two lights look separate or not. Any questions?

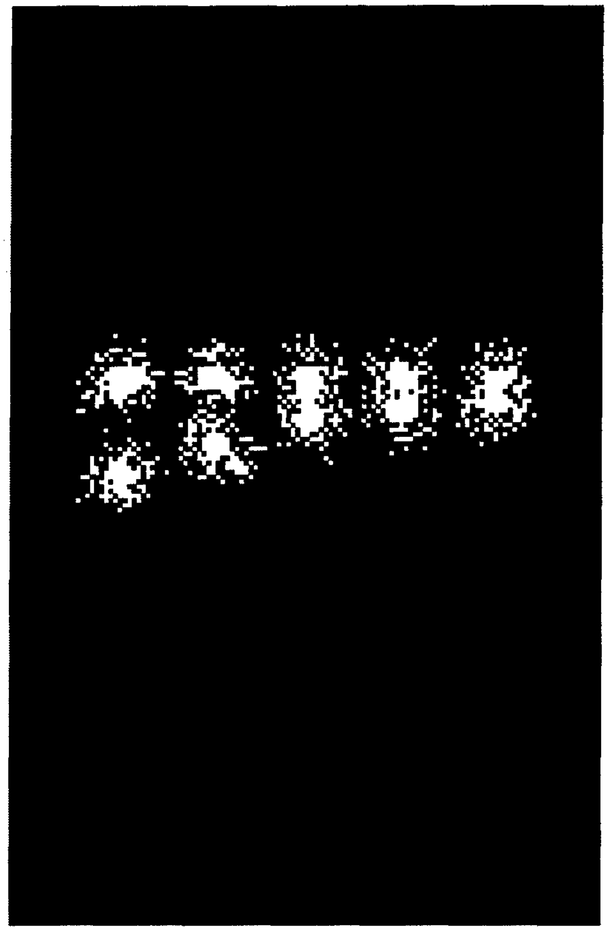
Please work independently. Don't let your neighbors know how you are responding.

Thank you.

We will start with six practice trials to show you how the task works.

Appendix C

Illustrations of range lights shown to observers as part of their instructions; left panel Day, right panel Night. In each panel, the four leftmost pairs of lights were examples of lights that were separated; the rightmost pair illustrated lights that were blurred together.



Appendix D

Range light lampchanger positions (1-6) to achieve the various light intensity combinations.

Intensity Combination	-Top-	Range Lights		-Bottom-	
	RL14-1	RL14-2	RL14-3	RL14-4	RL14-5
	Range Light Separation (mrads)				
	0.0	0.38	0.76	1.14	1.52
1	1	1	1	1	1
2	2	1	1	1	1
3	3	1	1	1	1
4	4	1	1	1	1
5	5	1	1	1	1
6	6	1	1	1	1
7	2	2	2	2	2
8	3	2	2	2	2
9	4	2	2	2	2
10	5	2	2	2	2
11	6	2	2	2	2
12	3	3	3	3	3
13	4	3	3	3	3
14	5	3	3	3	3
15	6	3	3	3	3
16	4	4	4	4	4
17	5	4	4	4	4
18	6	4	4	4	4
19	5	5	5	5	5
20	6	5	5	5	5
21	6	6	6	6	6

Appendix E

Total and mean number of observers seeing the pair of lights as clearly separated, and the 99% probability value by light intensity combination -- Daytime Session.

Intensity Combination	Total No. Observers	Range Light Separation (mrads)				99% Prob (mrads)
		0.38	0.76	1.14	1.52	
1	23	0.25	18	23	23	0.95
2	23	1	19	23	23	0.96
3	23	1	15.75	21.75	22.5	1.34
4	23	0.5	14.75	21.75	22.75	1.29
5	23	0.5	11	17.75	21	1.77
6	23	1	6.25	13.5	18	2.20
7	23	3	20.5	22.75	23	0.99
8	23	1.75	19	22.75	23	1.03
9	23	0.5	15.75	22.75	23	1.08
10	23	1	10	21	21.75	1.56
11	23	1	6.25	18.25	18.5	1.99
12	23	2	22	23	23	0.84
13	23	0.75	19.5	23	23	0.93
14	23	1.5	12.25	21.25	22	1.52
15	23	0.75	8.25	18.75	20	1.83
16	23	2.5	21.25	22.5	22	1.31
17	23	2	17.75	22	21.75	1.46
18	23	1.75	11	20	21	1.73
19	23	0.5	21	22.5	22	1.28
20	23	1.25	14.25	21.25	21.5	1.56
21	23	0	13.75	21.5	21.75	1.48

Appendix F

Total and mean number of observers seeing the pair of lights as clearly separated, and the 99% probability value by light intensity combination --Nighttime Session.

Intensity Combination	Total No. Observers	Range Light Separation (mrads)				99% Prob (mrads)
		0.38	0.76	1.14	1.52	
1	25	1	12	20.5	24.5	1.56
2	25	0.5	4.5	13.5	20	2.09
3	25	0.5	1	9.5	20	2.03
4	25	0	2.5	13	20.5	1.94
5	25	2	3	8	19	2.44
6	25	2.5	2.5	5	11	3.91
7	25	3	19.5	23	24.5	1.39
8	25	2	12	19	24	1.72
9	25	0	11	19	24.5	1.58
10	25	2	6.5	14	21.5	2.12
11	25	0.5	1	8.5	17	2.25
12	25	3	13.5	23.5	24.5	1.45
13	25	0.5	11	19	24	1.66
14	25	1	10	15.5	23.5	1.85
15	25	0	0.5	8.5	18	2.03
16	25	2	11	21	24.5	1.58
17	25	1	8.5	18	24.5	1.66
18	25	0.5	6	12.5	20.5	2.11
19	25	0.5	10	18.5	25	1.56
20	25	0.5	6.5	12	21.5	2.05
21	25	0	4.5	13.5	22.5	1.85

Appendix G

Light Illuminances, Illuminance Ratios, Vertical Separation from Data, and Vertical Separation according to Master Equation, by Presentation Series -- Daytime.

SER	TOP LIGHT Lamp-Chngr.	BOT LIGHT Lamp-Chngr.	TOP LIGHT	BOT LIGHT	Ratio	Ratio	99% Prob Data	delta (Master Eqn.)
			(SM cd)	(SM cd)	E+/E-	E-/E+	(mrad)	(mrad)
1	1	1	41,276	26,556	1.55	0.64	0.95	1.24
2	2	1	25,442	26,556	1.04	0.96	0.96	1.18
3	3	1	15,994	26,556	1.66	0.60	1.34	1.21
4	4	1	12,912	26,556	2.06	0.49	1.29	1.23
5	5	1	6,734	26,556	3.94	0.25	1.77	1.35
6	6	1	4,430	26,556	6.00	0.17	2.20	1.46
7	2	2	25,442	18,308	1.39	0.72	0.99	1.19
8	3	2	15,994	18,308	1.14	0.87	1.03	1.15
9	4	2	12,912	18,308	1.42	0.71	1.08	1.16
10	5	2	6,734	18,308	2.72	0.37	1.56	1.25
11	6	2	4,430	18,308	4.13	0.24	1.99	1.33
12	3	3	15,994	12,274	1.30	0.77	0.84	1.15
13	4	3	12,912	12,274	1.05	0.95	0.93	1.12
14	5	3	6,734	12,274	1.82	0.55	1.52	1.16
15	6	3	4,430	12,274	2.77	0.36	1.83	1.22
16	4	4	12,912	9,831	1.31	0.76	1.31	1.13
17	5	4	6,734	9,831	1.46	0.69	1.46	1.11
18	6	4	4,430	9,831	2.22	0.45	1.73	1.16
19	5	5	6,734	5,551	1.21	0.82	1.28	1.07
20	6	5	4,430	5,551	1.25	0.80	1.56	1.05
21	6	6	4,430	3,479	1.27	0.79	1.48	1.03

Appendix H

Light Illuminances, Illuminance Ratios, Vertical Separation from Data, and Vertical Separation according to Master Equation, by Presentation Series -- Nighttime.

SER	TOP LIGHT Lamp-Chngr.	BOT LIGHT Lamp-Chngr.	TOP LIGHT	BOT LIGHT	Ratio	Ratio	99% Prob Data	delta (Master Eqn.)
			(SM cd)	(SM cd)	E+/E-	E-/E+	(mrad)	(mrad)
1	1	1	89	84	1.05	0.95	1.56	1.48
2	2	1	283	84	3.35	0.30	2.09	1.69
3	3	1	485	84	5.75	0.17	2.03	1.84
4	4	1	544	84	6.45	0.15	1.94	1.87
5	5	1	906	84	10.74	0.09	2.44	2.05
6	6	1	1,807	84	21.39	0.05	3.91	2.33
7	2	2	283	266	1.06	0.94	1.39	1.58
8	3	2	485	266	1.82	0.55	1.72	1.66
9	4	2	544	266	2.04	0.49	1.58	1.68
10	5	2	906	266	3.40	0.29	2.12	1.78
11	6	2	1,807	266	6.78	0.15	2.25	1.97
12	3	3	485	391	1.24	0.81	1.45	1.63
13	4	3	544	391	1.39	0.72	1.66	1.65
14	5	3	906	391	2.31	0.43	1.85	1.73
15	6	3	1,807	391	4.62	0.22	2.03	1.89
16	4	4	544	622	1.14	0.87	1.58	1.65
17	5	4	906	622	1.46	0.69	1.66	1.70
18	6	4	1,807	622	2.91	0.34	2.11	1.82
19	5	5	906	991	1.09	0.91	1.56	1.69
20	6	5	1,807	991	1.82	0.55	2.05	1.77
21	6	6	1,807	1,688	1.07	0.93	1.85	1.74

Appendix I

Observers Instructions for Detection Experiment

Instructions to Observers

Off in the distance is an actual U.S. Coast Guard Range Light, mounted on top of the Coast Guard R&D Center building. We'll be running series of trials with the light turned on some of the time. What we'd like you to do is, for each trial, simply tell us if you can see the light.

At the start of each trial, the trial number will be announced. Look at the top of the building and determine if you can see the light, even if just barely. If you **can** see the light, mark an **X** in the appropriate box on your Observer Response Sheet. If you **cannot** see the light, mark an **O** in the box on your Observer Response Sheet. Then we will go on to the next trial. Between trials, do not look in the direction of the light. I will tell you when to look for the next light presentation.

The lights will be steady, that is, fixed ON, but due to atmosphere conditions they may appear to blink or flicker. Some lights will be much brighter than others, and some lights you will not be able to see at all. In any case, we want your best judgment as to whether you can see the light or not.

Please do not wear sunglasses. You may shade your eyes, however.

Any questions?

Please work independently. Don't let your neighbors know how you are responding.

Thank you.

We will start with eight practice trials to show you how the task works.

Appendix J

Observer Response Sheet for Detection Experiment -- Each Series was on a different page.

Daytime Light Thresholds

Observer Response Form

Date____/____/1998 Time of Day________ Obsrvr. No.________
mo day (Last 4 digits Soc. Sec. No.)

X = Yes, I can see it. **O** = No, I cannot see it.

Practice Series

Protocol 5
Page 1

Trial							
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**

X = Yes, I can see it. **O** = No, I cannot see it.

Series 1

Protocol 5
Page 2

Trial							
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**

X = Yes, I can see it. **O** = No, I cannot see it.

Series 2

Protocol 5
Page 3

Trial							
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**

X = Yes, I can see it. **O** = No, I cannot see it.

Series 3 **Protocol 5**
Page 4

Trial							
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**

X = Yes, I can see it. **O** = No, I cannot see it.

Series 4 **Protocol 5**
Page 5

Trial							
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**

X = Yes, I can see it. **O** = No, I cannot see it.

Series 5 **Protocol 5**
Page 6

Trial							
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**

X = Yes, I can see it. **O** = No, I cannot see it.

Series 6 **Protocol 5**
Page 7

Trial							
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**