3.1.7

DETECTING BUOY LIGHTS:

EFFECTS OF MOTION AND LANTERN DIVERGENCE

By

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SUMMARY

The motion of a buoy degrades the effectiveness of its signal light. We studied the extent of this degradation and showed that increased lantern divergence will reduce the degradation.

Buoy motion data were taken from video recordings of standard USCG buoys in a variety of weather conditions along the northeast coast of the United States. The motion data were transformed into signal data using mathematical models of lens divergence, flash characteristic, and atmospheric visibility. For each condition we determined the range at which a mariner has an 80% probability of detecting the signal.

Results show that buoy motion typically reduces detection range to about half of the published nominal range. Furthermore, the effect of buoy list is more significant than buoy roll.

The negative effect of buoy motion can be reduced by increasing the divergence of standard lanterns. Increasing the divergence from its present 4.2° to 7° would increase average buoy detection ranges by 12 to 15 percent.

This is an electronic version of the paper presented to 12th IALA Conference in Holland in1990. Some of the figures/graphs have been difficult to reproduce!

1.0 INTRODUCTION

The Coast Guard maintains approximately 4,100 lighted buoys upon the waterways of the United States. These buoys typically consist of a floating steel structure supporting a lighted optic. The optic is an omni-directional fresnel drum lens with a vertical filament lamp. The fresnel lens refracts the light output of the lamp toward the optical (horizontal) plane and thus increases the apparent lamp intensity. This increase of intensity on the optical plane serves to increase the range at **which the** light may be used as an effective navigational signal.

With the addition of movement, the optical plane no longer coincides with the horizon. Buoy roll and list misdirect the high intensity optical plane as shown in Figure 1. With the majority of lamp output directed into the optical plane, the light intensity directed toward an observer is severely diminished. The extent of list and roll the buoy undergoes will determine the fraction of the intensity provided in the observation plane.

This study to quantifies the signal degradation caused by buoy roll and list. To achieve this goal, it was necessary to analyze the factors which affect the performance of the entire navigational system. In this study, we considered flash period, duty cycle, lens divergence, and the observer's distance from the light.

2.0 APPROACH

Previous efforts to predict the probability of detecting light signals on rolling buoys did not consider distance from the buoy, or the flash characteristic. Intuitively, one expects the probability of detection (POD) to increase as the distance from the light decreases. Likewise, the longer a light is lit, the more likely it is to be detected.

In this study, detection probabilities were modeled as functions of distance from the buoy, the flash characteristic, buoy roll, and lens divergence. Buoy roll was obtained from video recordings of actual buoys. Lens divergence was varied mathematically within computer files. The probabilities were calculated from a time series history of intensity in the horizontal plane for flashed lights on a rolling buoy.

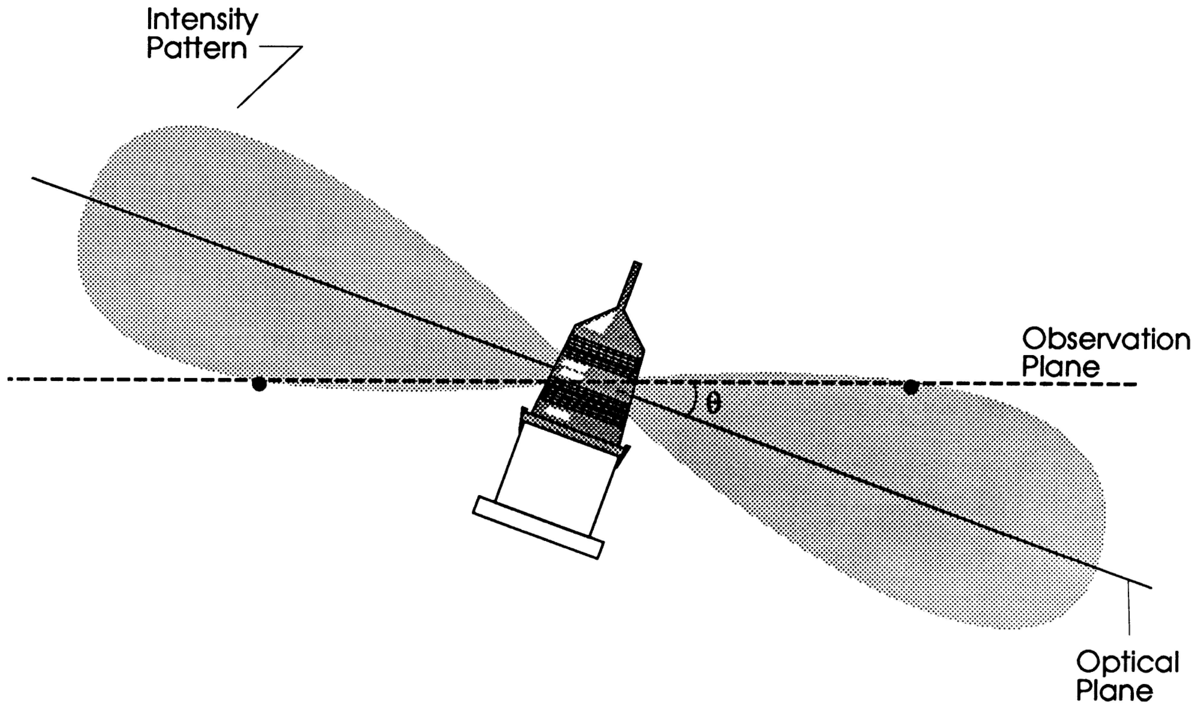

Figure 1. Effect of Buoy Angle on Observed Intensity

Source: reference1, p. 3.

2.1 DEFINITIONS

a. 80% POD RANGE - The distance at which a single flash will be detected 80% of the time. An 80% POD is a typical design criteria for Coast Guard floating navigational aids.

b. DETECTION - The delivery of at least 0.67 sea-mile-candela at the observer's position by a light.

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2.2 ASSUMPTIONS

a. Buoy motion was recorded in only one plane. The mariner is located in this plane. Effects of buoy motion in this plane of observation are representative of effects of buoy motion in all other planes of observation.

b. The mariner knows where to look for the buoy. He looks continuously in the correct direction for a finite period of time. Thus, if a flash produces at least 0.67 sea-mile-candela at the observer's position within the observation time, it will be detected.

C. The lamp flashes with instantaneous rise and fall times. Lamp filament nigrescence time effects are considered minimal compared to buoy motion effects. The ideal square flash pulse is modified only by buoy roll and vertical divergence of the lantern.

d. The Schmidt-Clausen method (IALA (1978)) determines effective intensity (EFI) for each flash pulse. Flash pulse duration defines limits of integration for this method, not the actual instantaneous intensity in the horizontal plane.

e. If a mariner detects a flash pulse at a given distance within a certain observation time, he will also detect the same pulse at shorter distances within the same observation time. He may also detect other flash pulses at these shorter distances.

f.Visibility is assumed constant at 10 nautical miles (0.74 atmospheric transmissivity).

g.Background lighting is assumed to be negligible.

h. The twelve data sets of buoy motion are representative of the buoy population as a whole. The buoys were chosen at random. No effort was made to seek out buoys with noticeable list.
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1 Source: Reference 1, pp. 6-7.

3.0 DATA ACQUISITION

3.1 BUOY MOTION COLLECTION EQUIPMENT

Buoy motion data were collected with a video recording system. A Panasonic WV-3260/8AF video camera with a Canon FD60Omm telephoto lens were adequate for viewing a buoy at a range of up to 1.5 miles. we recorded the motion with a Panasonic AG-2400 video cassette recorder (VCR).

We selected Panasonic equipment because of the special features the equipment provides. The following list describes these features and their purpose in data acquisition.

* Time and date display incorporated into the recording provides a means of establishing a data sampling rate and also retains information necessary to compute tidal conditions at a later time.
* Positive / negative imagery - aids in the transference of motion information from the television to the computer by increasing the contrast of the buoy on a water background.
* Removable lens with Adaptors - makes it possible to put a lens of a different make on the video camera. In this case, a Canon FD60Omm telephoto lens was used.
* Strobe effect shutter - produces clear still frame images which aid in transferring the motion information to a computer file.

3.2 ANALOG TO DIGITAL CONVERSION OF THE MOTION DATA

To establish the angle of a buoy, we constructed a computerized angle measuring device. The device is a simple plexiglas sheet of horizontal and vertical lines attached to a digital shaft encoder. The cross-hashed screen rotates on the axle of the digital shaft encoder in front of the television screen. With a buoy video image paused on the television, the horizontal lines on the screen were aligned with the horizon on the television image to zero the shaft encoder. This step makes the vertical lines on the screen normal to the horizon. By paralleling the vertical lines to the buoy image, the digital shaft encoder represents the angle between the buoy and the normal to the horizon. An HP217 computer collects the angles from the shaft encoder and constructs the buoy motion data file (See Figure 2). The buoy angle measurements can be repeated with an accuracy of $\pm$ 0.2°.

With the pause and frame by frame advance features of the VCR and the time/date information recorded on the video tapes,

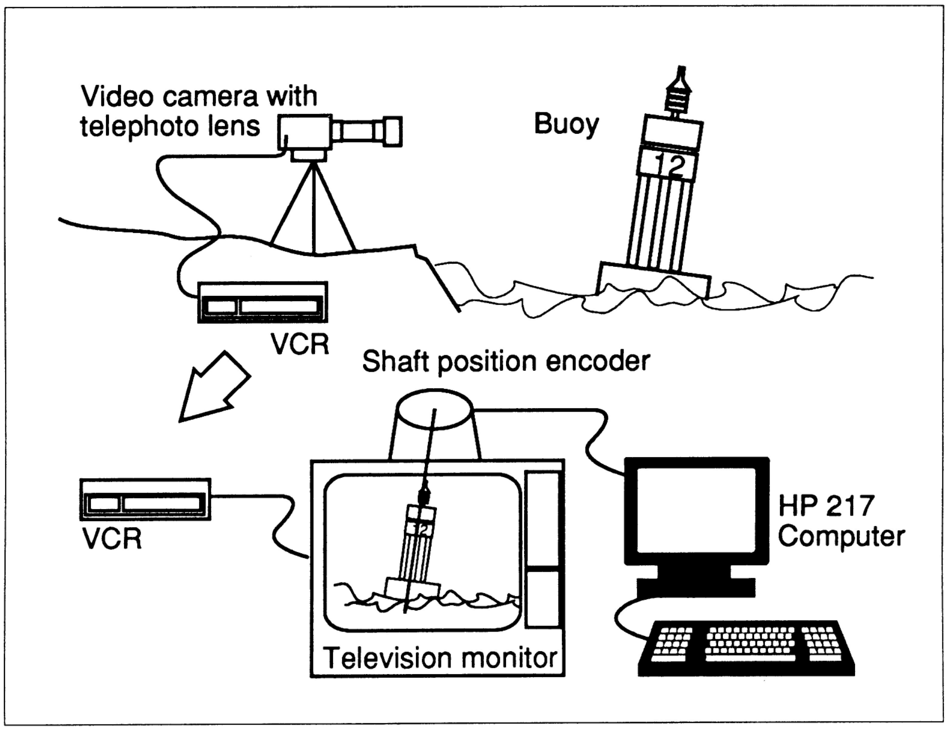

Figure 2. Buoy Motion Video Recording System

the buoy images can be sampled at a rate of 1 Hertz[2]. In this manner, twelve 10 minute data files of buoy roll versus time were obtained from nearly 10 hours of video recordings.

Various weather conditions were selected to supply a wide range of buoy motion information. We selected buoys to provide information on each buoy type in the Coast Guard inventory. Additionally, we desired buoys that are exposed to the open ocean. The buoy population close (within 1.5 miles) to land and yet exposed to the open ocean is very limited. A small collection of six buoys which meet these criteria was found. Table 1A below lists the buoys and their locations. Table 1B lists the buoy data files and the conditions experienced during the recordings.

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Work performed previously by LT D. Brown, USCG, [Reference 1, p. 39] showed the prevalent roll period of an 8X26 buoy to be 5.7 seconds or 0.175 Hz. Likewise, for a 5X11 buoy the period was found to be 4.6 seconds or 0.217 Hz. Using the Nyquist

sampling criteria [Reference 2, pp. 121-122], the motion of the buoy can be described by sampling at a rate of at least twice the frequency of the motion. In this case, the sampling rate of 1 Hertz is well above 0.35 Hz for an 8X26 buoy or 0.434 Hz for a
5X11 buoy. Hence,the sampling rate of 1 Hz is adequate indescribing the motion of a buoy over a period of time.

TABLE 1A
BUOY LOCATIONS

BUOY SIZE - DESIGNATION	LOCATION
9X32-(a) and (b)	South of Gloucester, Mass. Marks disposal area.
8X26-A(a) thru (c)	South of New London, CT. New London Harbor entrance buoy.
8X26-B(a) and (b)	Off Watch Hill, RI.
7X17	Providence River Channel, Buoy 23.
6X20-(a) and (b)	South of New London, CT. Pine Island light 2.
5X11-(a) abd (b)	East of Green Harbor, Mass. Green Harbor entrance buoy.

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TABLE 1B
VIDEO BUOY ROLL FILES

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BUOY	SEAS (ft)	TIDALCURRENT (knts)
9X32-(a)	0-3	0.4
9X32-(b)	3-6	slack
8X26-A(a)	0-3	0.24
8X26-A(b)	0-3	0.2
8X26-A(c)	0-3	slack
8X26-B(a)	3-6	1.34
8X26-B(b)	3-6	0.9
7X17	0-3	*
6X20-(a)	0-3	0.17
6X20-(b)	3-6	0.13
5X11-(a)	0-3	0.8
5X11-(b)	0-3	0.63

* The 7X17 buoy was recorded in the Providence river, and thus tidal current information does not apply at this location. Since 7X17 buoys are

typically used to mark river channels, the video sample above is considered to be representative

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4.0 DATA ANALYSIS

POD was calculated as a function of observation distance, flash characteristic, lens vertical divergence, and buoy motion. Two data files were used for each input for program run. One file was the buoy angle versus time, the other was the intensity profile for the lantern. We simulated the lantern files with Gaussian profiles which have the same total flux as a yellow 155mm lantern with a 1.15 amp lamp. The profiles allowed the effects of lens divergence to be studied without having to construct a collection of optics. The lantern files are listed in Table 2.

TABLE 2

GAUSSIAN LANTERN DATA FILES

PEAK INTEN.	NOMINAL RANGE for a fixed-on light	FWHM*
(cd.)	(N. Mi.)	(deg.)
329.8	7.4	3.0
235.6	6.8	4.0
198.0	6.5	5.0
165.0	6.2	6.0
141.5	6.0	7.0
132.1	5.8	7.5
110.2	5.6	9.0
99.2	5.4	10.0
79.5	5.1	12.5
66.3	4.8	15.0

*FWHM - Full-Width, Half-Maximum - describes the vertical divergence of the lens.

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The nominal range of each lantern is provided in Table 2. While nominal range is used to rate a buoy, it has little to do with the probability of detecting the buoy. The nominal range is the range at which the peak intensity of the light reaches 0.67 sea-mile-candela with an atmospheric visibility of 10 nmi.

We used four standard flash characteristics in this analysis. The flash characteristics are the four most commonly found on aids to navigation. These characteristics and the buoy populations they represent are listed in Table 3.

TABLE 3

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BUOY POPULATION BY FLASH CHARACTERISTIC

CHARACTERISTIC		%OF BUOY POPULATION
Flashing 6 (0.6) *	-	6
Flashing 4 (0.4) *	-	69
Flashing 2.5 (0.3)*	-	8
Quick Flash	-	8

* - The values in parenthesis represent the flash duration in seconds. These four characteristics are graphically represented in Figure 3.

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4.1 COMPUTER PROCEDURES

The buoy angle versus time information is converted to intensity as a function of time in the horizontal plane for a fixed on light. This is done by mapping the buoy roll angles into the lantern vertical intensity profile.

A normalized flash characteristic is then superimposed onto the intensity versus time function. Observation windows are randomly selected from the fixed-on light intensity versus time record and multiplied by the normalized flash characteristic. Effective intensities are calculated (using the Schmidt-Clausen method) for each flash pulse in the window. observation times and distances are then varied to calculate the probability of detection.

Figure 4 illustrates the procedure for converting buoy roll versus time to flashed intensity versus time for one 30-second data window. The top graph is a typical 30-second recording of buoy angle versus time. The middle graph is a recording converted to intensity versus time for a fixed-on light. The bottom graph is the product of the middle graph and a normalized FL6 (0.6) flash characteristic. For this particular window, the observer (depending on distance) might detect the first two flash pulses but not the others.

For this analysis each flash is taken as an individual event. If the flash delivers at least 0.67 sea-mile-candela at the observation distance then it is seen. At some distance, 80% of all the flashes are seen. This distance is the 80% POD range. Also. as an 80% probability of detection is desired for

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3 Source: Reference 1, p. 31.

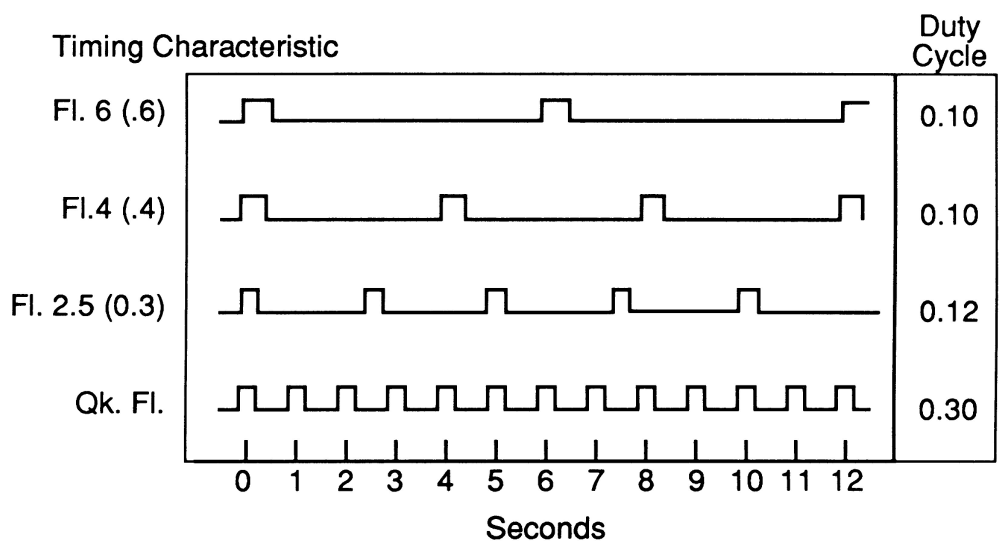

Figure 3. Standard Flash Characteristics
Source: Reference1, p. 13.

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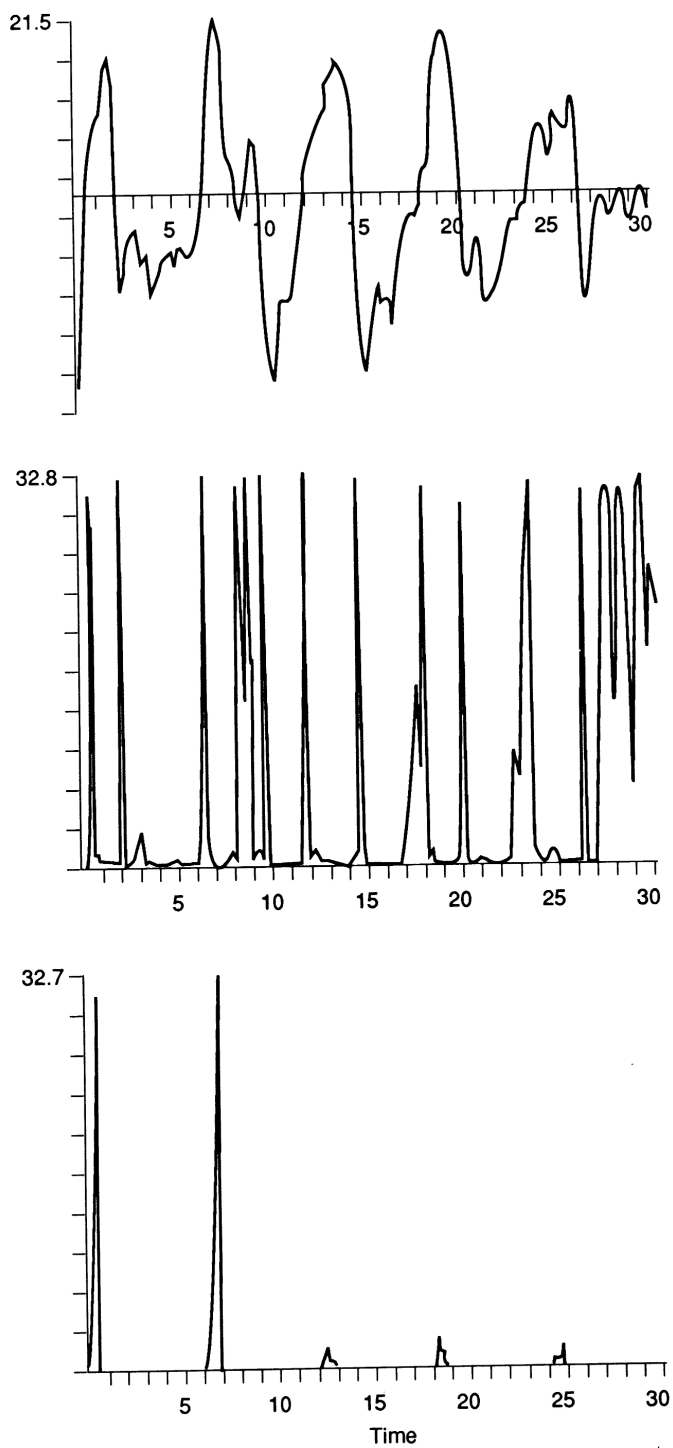

Figure 4. Buoy Angle to Flashed Intensity Conversion
Source: Reference 1, p. 15.12

navigational aids, the 80% POD range is used as the baseline in this analysis.

5.0 RESULTS

5.1 Buoy Roll and List

As expected, POD is strongly affected by the rolling motion of a buoy. Unexpectedly, every buoy measured has some degree of list varying between 1°and 7.4°. This list has a severe impact upon the detection probability of the buoy light. Table 4 below lists the 12 video files with their list, roll amplitude, and sea conditions. Note that the list exceeds the roll amplitude in 11 of 12 cases. Also note that the roll amplitude seems to be directly related to the sea conditions but the list seems to be independent of the seas. Figure 5 displays the relationship between list and roll amplitude. The list is a constant value that the buoy is offset from 0°. The buoy then rolls about this offset so that the maximum average angle the buoy experiences is list plus roll.

TABLE 4
BUOY ROLL FILE LIST AND ROLL AMPLITUDE

BUOY	SEAS	LIST (deg)	AMPLITUDE (deg)*
9X32-(a)	0-3	5.1	0.3
9X32-(b)	3-6	2.6	0.6
8X26-A(a)	0-3	2.8	0.0
8X26-A(b)	0-3	2.9	0.2
8X26-A(c)	0-3	7.4	0.1
8X26-B(a)	3-6	1.9	1.2
8X26-B(b)	3-6	1.1	3.0
7X17	0-3	1.3	0.3
6X20-(a)	0-3	3.0	0.3
6X20-(b)	3-6	6.9	3.3
5X11-(a)	0-3	3.3	0.7
5X11-(b)	0-3	2.3	0.6

*NOTE: The maximum average roll is the sum of list and amplitude. The minimum average roll is list minus amplitude.

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The reasons for the list experienced by the buoys are not known. Initially, tidal currents were suspected but computation of these currents proved otherwise. (Tidal currents are listed in Table 1B.) Currently, it is believed that the list is a product of the many natural forces acting on a buoy hull and cannot be

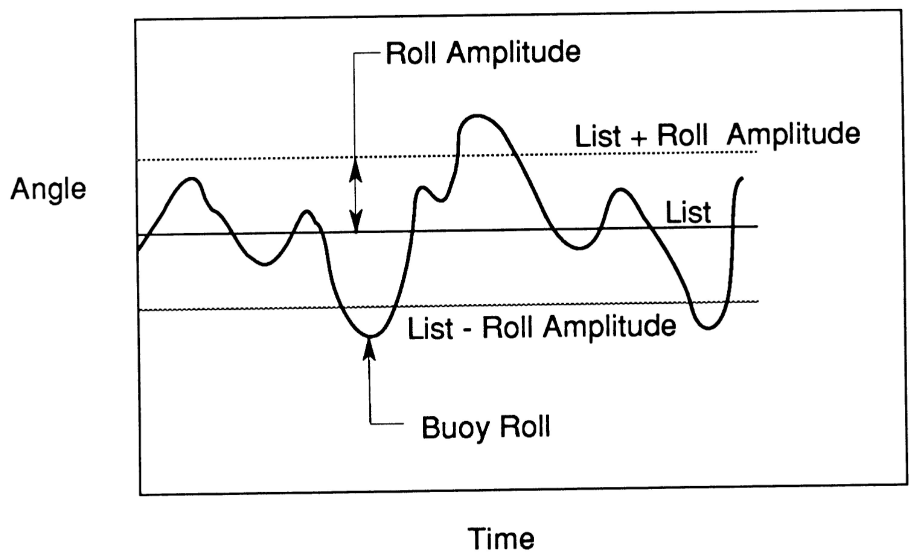

Figure5. relation Between Buoy List and Roll

attributed to any single dominant force (e.g. wind/buoy sail area, moorings, balancing, etc.).

5.2 LENS DIVERGENCE

The standard Coast Guard optic has a vertical divergence (full-width, half-maximum) of 4.2°. Any list in any direction of 2.1' or more will decrease the time-averaged intensity in the horizontal plane by at least half. This occurs because the list is the offset about which the buoy rocks. As time progresses, the buoy angle will increase and decrease as it rolls (See Figure 5) but its average angle will be the buoy list. Therefore, any buoy with a list of 2.1° or more (9 of the 12 - cases) will, on average, be putting less than half their intensity into the observation plane.

We sought to determine if an increase in the divergence of our optics could compensate for the effects of list and roll on POD. However, any increase in lens divergence is associated with a subsequent decrease in lamp peak intensity and therefore a decrease in the nominal range of the buoy. Figures 6 through 9 show the effects of lens divergence on the 80% POD range and the nominal range for the flashing 4 characteristic. Each f igure represents a different buoy size and each curve is labeled with the associated list. Figures 10 through 12 are the curves for the other three flash characteristics. While the label of each individual curve is not supplied on figures 10, 11, and 12, the trends are evident. Figures 6 through 12 display buoy detection range increasing with increased lens divergence up to between 7°, and 10° in most data samples. The majority of the curves tend to level off within the range of divergence angles of 7° to 10°. From the curves, it is evident that a substantial increase in the 80% POD range can be achieved with a divergence of 7° to 10° instead of a lens divergence of 4.2°.

Table 5 shows the percentage of published nominal range (6 nmi.) achieved at the 80% POD range with a 4.2° lens. The 80% POD range is typically less than half of the published nominal range of the buoy light.

Table 6 compares the 80% POD range of a 4.2° lens with a 7° lens. An increase in divergence from 4.2° to 7° causes a reduction in the nominal range from 6 nmi. to 5.5 nmi. Yet, the 80% POD ranges of the 7° lens exceed the 80% POD ranges of the 4.2° lens in 11 of 12 cases. It is clearly evident, both from Table 6 and Figures 6 through 12, that an increase in lens divergence will improve the mariner's likelihood of detecting a navigational aid.

One curve stands out on Figures 8, 10, 11, and 12. This one curve begins above the rest, peaks at 4° and declines continuously as divergence increases. Figure 8 identifies this curve as the 7X17 buoy in the Providence river. From Table 4 it is seen that the sum of list plus roll amplitude is 1.6° for this

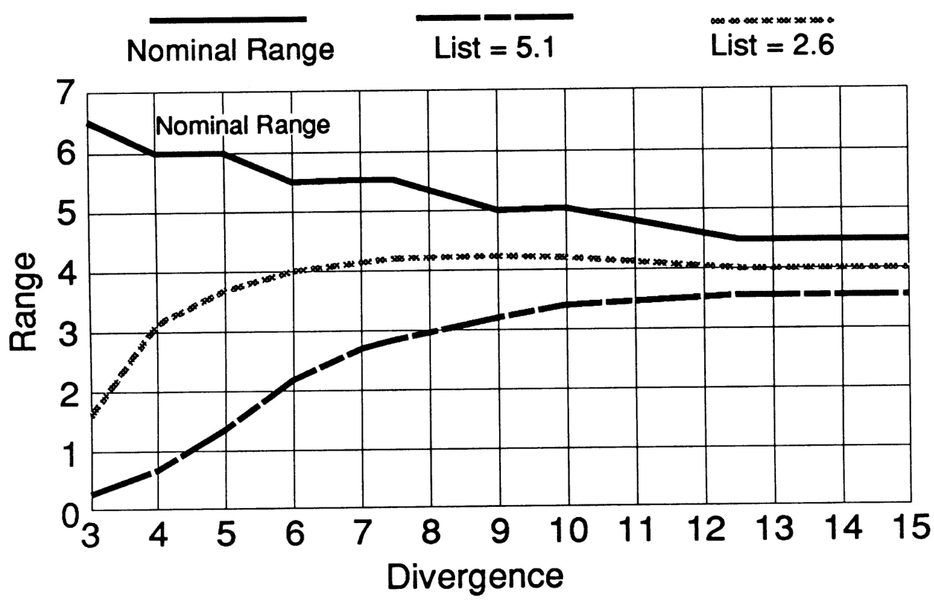

Figure 6. Flashing 4 – 80% POD Range vs. Diver.
9 x 32 Buoy – 4 Second View Time.

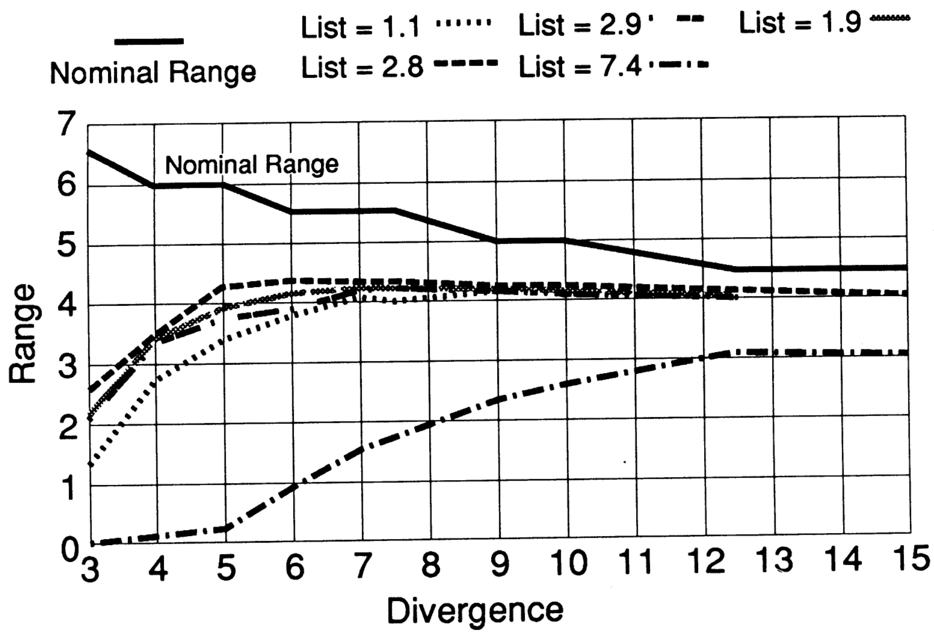

Figure 7. Flashing 4 – 80% POD Range vs. Diver.
8 x 26 – 4-second View Time

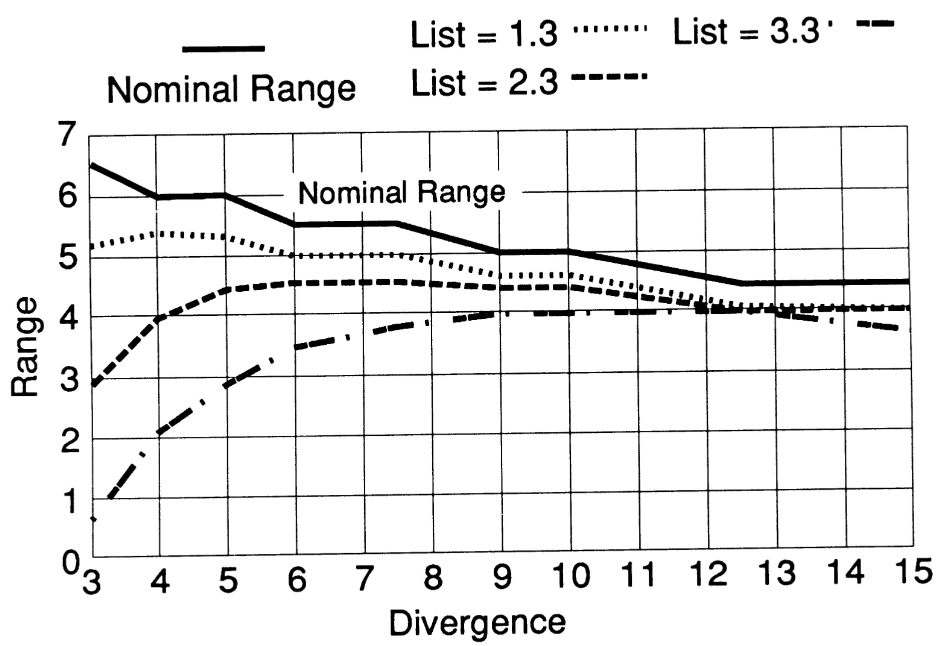

Figure 8. Flashing 4 – 80% POD range vs. Diver.
7 x 17 and 5 x 11 Buoys – 4-second View Time

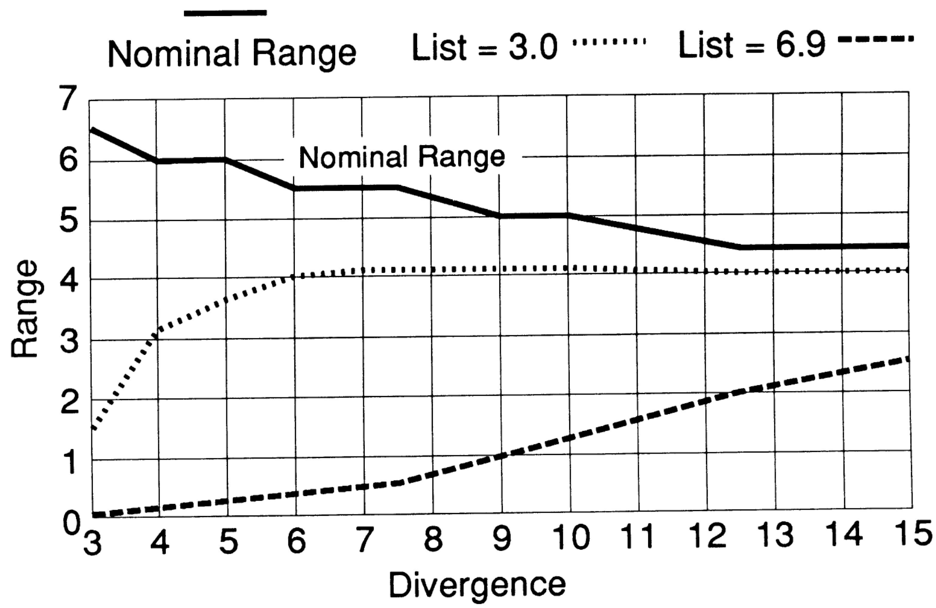

Figure 9. Flashing 4 – 80% POD Range vs. Diver.
6 x 20 Buoy – 4-second View Time

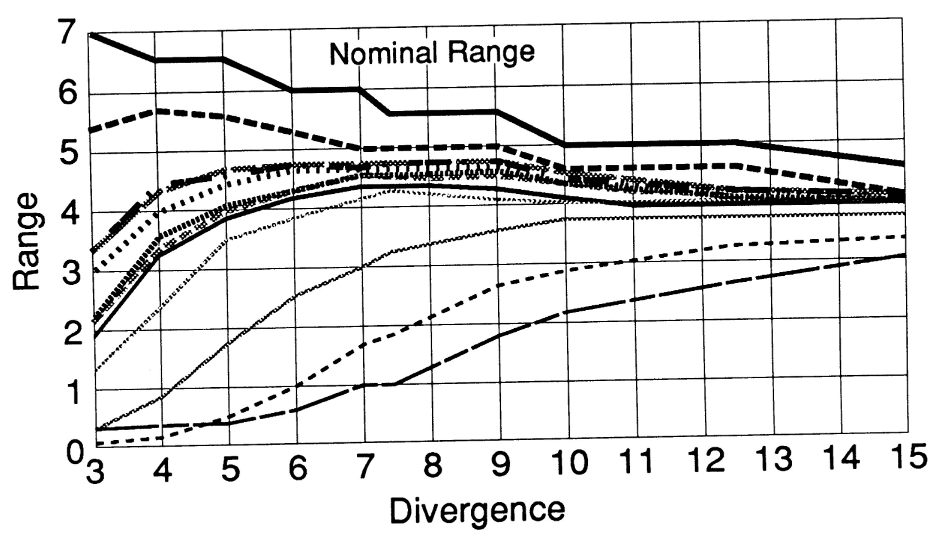

Figure 10. Flashing 6 – 80% POD Range vs. Diver.
6-second View Time

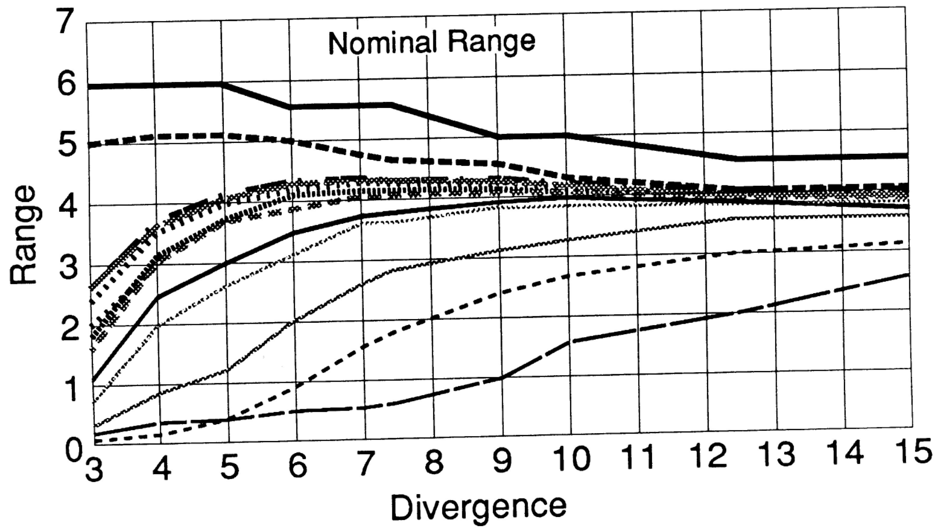

Figure 11. Flashing 2.5 – 80% POD Range vs. Diver.
2.5-second View Time

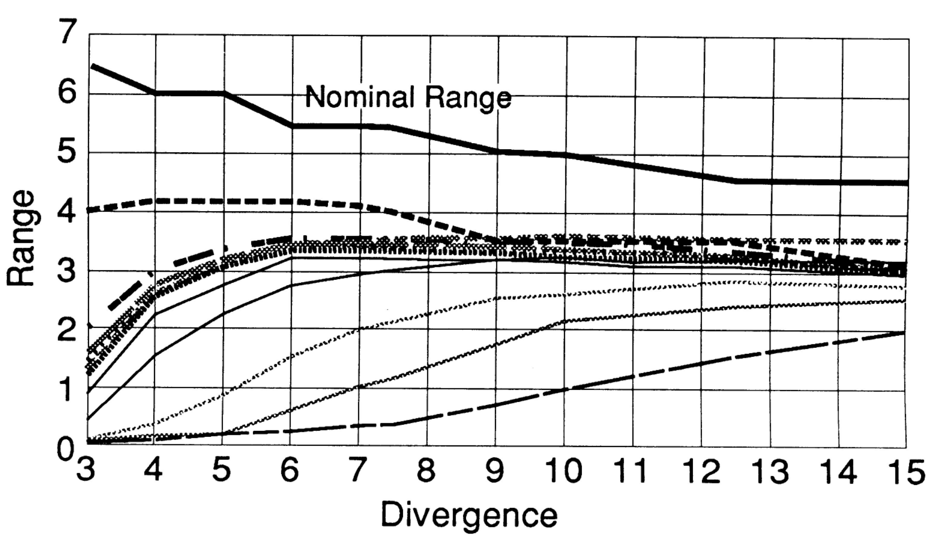

Figure 12. Quick Flash – 80% POD Range vs. Diver.
1-second View Time

buoy. This would indicate that a lens with a divergence of 3.2° would provide the best 80% POD range for this particular light. For all the other data sets, a divergence of 3.2° would severely decrease the 80% POD range to a point well below the already insufficient 80% POD range achieved with a divergence of 4.2°.

In three instances the 80% POD range continues to increase as divergence increases beyond 10° regardless of the flash characteristic. (See Figures 6, 7, and 9 through 12.) The lists associated with these three curves are 7.4°, 6.9°, and 5.1°. The divergence which would maximize the 80% POD range falls well above of a divergence of 10°. However, buoy optic design cannot be performed on a case by case basis. Secondly, by reviewing Table 4, it is shown that the 9X32 buoy with a 5.1° list in one data sample has a 2.6° list in another sample taken at a different time. Likewise, the 8X26 buoy with 7.4° of list has had a list of 2.8° and 2.9° when video samples were taken at different times. With such day to day variations, we can only hope to maximize the 80% POD range for the majority of the buoy population.

TABLE 5
COMPARISON OF 80% POD RANGES
WITH THE NOMINAL RANGE (nmi.)
OF A LENS WITH 4.2° OF DIVERGENCE

FLASHING 4

80 % POD RANGES (nmi) 4.2°	% of nom.	BUOY
0.7	11.7	9X32-(a)
3.2	53.3	9X32-(b)
3.4	56.7	8X26-A(a)
0.1	1.7	8X26-A(b)
3.5	58.3	8X26-A(c)
3.5	58.3	8X26-B(a)
2.8	46.7	8X26-B(b)
5.3	88.3	7X17
3.2	53.3	6X20-(a)
0.2	3.3	6X20-(b)
2.2	36.7	5X11-(a)
4.1	68.3	5X11-(b)
AVERAGE =	44.7%	

FLASHING 6

80 % POD RANGES (nmi) 4.2°	% of nom.	BUOY
1.0	16.7	9X32-(a)
3.5	58.3	9X32-(b)
3.5	58.3	8X26-A(a)
0.2	3.3	8X26-A(b)
4.0	66.7	8X26-A(c)
4.3	71.7	8X26-B(a)
3.6	60.0	8X26-B(b)
5.6	93.3	7X17
3.3	55.0	6X20-(a)
0.3	5.0	6X20-(b)
2.5	41.7	5X11-(a)
4.3	71.7	5X11-(b)
AVERAGE =	50.1%	

FLASHING 2.5

80 % POD RANGES (nmi) 4.2°	% of nom.	BUOY
0.7	11.7	9X32-(a)
3.1	51.7	9X32-(b)
3.2	53.3	8X26-A(a)
0.1	1.7	8X26-A(b)
3.7	61.7	8X26-A(c)
3.5	58.3	8X26-B(a)
2.4	40.0	8X26-B(b)
5.1	85.0	7X17
3.0	50.0	6X20-(a)
0.2	3.3	6X20-(b)
2.0	33.3	5X11-(a)
3.7	61.7	5X11-(b)
AVERAGE =	42.6%	

QUICK FLASH

80 % POD RANGES (nmi) 4.2°	% of nom.	BUOY
0.5	33.3	9X32-(a)
2.4	40.0	9X32-(b)
2.6	43.3	8X26-A(a)
0.0	0.0	8X26-A(b)
3.1	51.7	8X26-A(c)
2.7	45.0	8X26-B(a)
1.7	28.3	8X26-B(b)
4.2	70.0	7X17
2.4	40.0	6X20-(a)
0.2	3.3	6X20-(b)
1.7	28.3	5X11-(a)
2.9	48.3	5X11-(b)
AVERAGE =	36.0%	

TABLE 6
COMPARISON OF 80% RANGES FOR
LENSES OF 4.2° AND 7° DIVERGENCES
AND THE PERCENTAGES OF 6 nmi. THE 7° LENS ACHIEVES

FLASHING 4: 80 % POD RANGES (nmi)				FLASHING 6: 80 % POD RANGES (nmi)		
4.2°	7.0°	% of 6nmi	BUOY	4.2°	7.0°	% of 6nmi
0.7	2.7	45.0	9X32-(a)	1.0	3.0	50.0
3.2	4.1	68.3	9X32-(b)	3.5	4.3	71.7
3.4	4.2	70.0	8X26-A(a)	3.5	4.4	73.3
0.1	1.5	25.0	8X26-A(b)	0.2	1.6	26.7
3.5	4.3	71.7	8X26-A(c)	4.0	4.6	76.7
3.5	4.2	70.0	8X26-B(a)	4.3	4.7	78.3
2.8	4.0	66.7	8X26-B(b)	3.6	4.5	75.0
5.3	5.0*	83.3	7X17	5.6	5.0*	83.3
3.2	4.1	68.3	6X20-(a)	3.3	4.2	70.0
0.2	0.5	8.3	6X20-(b)	0.3	1.0	16.7
2.2	3.6	60.0	5X11-(a)	2.5	4.1	68.3
4.1	4.5	75.0	5X11-(b)	4.3	4.7	78.3
	AVERAGE =	59.3			AVERAGE =	64.0

FLASHING 2.5: 80 % POD RANGES (nmi)				QUICK FLASH: 80 % POD RANGES (nmi)		
4.2°	7.0°	% of 6nmi	BUOY	4.2°	7.0°	% of 6nmi
0.7	2.5	41.7	9X32-(a)	0.5	2.0	33.3
3.1	4.0	66.7	9X32-(b)	2.4	3.3	55.0
3.2	4.1	68.3	8X26-A(a)	2.6	3.4	56.7
0.1	1.5	25.0	8X26-A(b)	0.0	1.1	18.3
3.7	4.3	71.7	8X26-A(c)	3.1	3.5	58.3
3.5	4.2	70.0	8X26-B(a)	2.7	3.4	56.7
2.4	3.6	60.0	8X26-B(b)	1.7	3.0	50.0
5.1	4.7*	78.3	7X17	4.2	4.1*	68.3
3.0	4.0	66.7	6X20-(a)	2.4	3.2	53.3
0.2	0.5	8.3	6X20-(b)	0.2	0.4	6.7
2.0	3.5	58.3	5X11-(a)	1.7	2.9	48.3
3.7	4.2	70.0	5X11-(b)	2.9	3.5	58.3
	AVERAGE =	57.1			AVERAGE =	46.9

* NOTE: The 80% POD range for a lens with a divergence of 4.2° exceeds the 80% POD range for lens with a divergence of 7° in only one case. The one case is the 7X17 buoy in the Providence River.

6.0 CONCLUSIONS

The designed buoy nominal ranges are never achieved with the slightest amount of buoy movement or list. Buoy movement and list are present in all but the calmest atmospheric and sea conditions.

The following general observations and trends are supported by the results:

* -Nominal range is not a realistic measure of the detection range of a lighted buoy.

* -Buoy list, more than buoy motion, is a severe problem which merits further study.

* -Increasing the lens divergence can significantly increase the 80% POD range of a buoy.

7.0 REFERENCES

1. Brown, D. M., "PROBABILITIES OF DETECTION AND RECOGNITION OF FLASHING LIGHTS ON ROLLING BUOYS," U. S. Coast Guard Research and Development Center, Report No. CG-D-10-88, August 1987.

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DETECTING BUOY LIGHTS: EFFECTS OF MOTION AND LANTERN DIVERGENCE

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