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Irradiation and Manual Navigation

RICHARD F. HAINES AND WILLIAM H. ALLEN

Abstract

THE IRRADIATION PHENOMENON has the effect of displacing the apparent edge between a bright area and a darker area toward the latter. One method of quantifying this effect is by determining the minimal angle of resolution (MAR) between a point source and an extended bright source. This paper presents the results of a series of investigations on the MAR between a point and an extended circular source and between a point source and a simulated horizon. The apparent angular diameter of an extended circular source is also quantified.

A total of 11 highly trained male observers took part in the studies reported here. All had 20:20 distance acuity. Each observer moved a point source along various frontal plane meridians behind an extended source in order to determine at what position it became invisible due to the effects of irradiation. Results indicated that (1) the apparent edge of high luminance targets can be displaced as much as 15′ arc from the target's actual edge under some viewing conditions, (2) the MAR is a function of the contrast ratio between the target and background and the luminance of the point source, and (3) the detrimental effects of irradiation are not reduced by using optical filters across the entire field of view to reduce the luminance of the extended source. The findings are related to certain aspects of manual navigation presently in use.

Introduction

The purpose of this paper is to review the results of current laboratory research on the irradiation phenomenon and to identify the relation of this phenomenon to manual navigation tasks. Besides its physiological and subjective effects discussed elsewhere [13, 27], the irradiation phenomenon has the effect of displacing the apparent edge between a bright area and a darker area toward the darker area [17]. Examples are found when the solar disk is viewed against the sky from the earth's surface or against the blackness of space when viewed from an earth orbit. In these cases the disk appears larger than it actually is [12–14]. Even point sources can produce an irradiation effect if they are of sufficient intensity.

Navigators, astronomers, and others have recognized the visual problems introduced by irradiation for some time [1, 8, 9, 10, 21, 22, 29, 31, 35]. It has been only recently, however, that the effects of irradiation on various angular measurements have been quantified under controlled laboratory conditions. The results of these investigations are presented here.

No distinction is made in this paper as to whether the observer is on the earth's surface or in space. Even though no sextant was used to collect the data presented here, it is assumed that a sextant similar to that illustrated in Fig. 1 and described elsewhere [31] will probably be used in the actual navigation sightings. In order to assess the response characteristics of the unaided eye, no magnification, eye relief, field of view, or atmospheric variables were investigated.

Considering the viewing conditions under which irradiation is produced, it becomes apparent that rather large incongruities often exist between what is looked at (the physical object or bright source of light) and what is seen (the perceived object or light source). Consequently, it becomes necessary to keep separate those terms which refer to the physical domain from those which refer to the perceptual domain. Some examples which are

Both authors are with NASA, Ames, Moffett Field, Calif. Dr. Haines presented this paper at The Institute's Annual meeting in Monterey, Calif., on June 19, 1968.

used in this paper and elsewhere [13, 14] are given below.

The term *boundary* refers to the object's physical limit in space and *edge* refers to the perceived limit of the object. The term *limb* has been used by astronomers and navigators to refer to both of these concepts. The term *form* refers to the physical configuration, and *shape* to the perceived configuration of surface and boundaries.

The term *resolution* (often called acuity) [40] refers to the ability to discriminate certain visual characteristics of one or more objects. The lower limit of resolution or minimal angle of resolution (MAR) between two bright targets seen against a totally dark background is the visual response of interest in the present paper.

Although the MAR has been found to be related to a number of stimulus variables, the target to background contrast ratio is the most important [3, 5, 6, 11, 34, 36, 38]. The contrast ratio is given by $C = I_t/I_b$, in which I_t is the luminance of the target (extended source) and I_b is the luminance of the background. The contrast ratio between the point source and background can be similarly calculated by substituting I_s for I_t where I_s is the luminance of the point source.

Standard practice in terrestrial navigation incorporates only one correction for irradiation. An irradiation correction of 1.2′ (minutes) arc has been included in the altitude correction table for the sun's upper limb in the Nautical Almanac [2] since 1953, representing the combined effect of 0.6′ arc corrections for both the sun's limb and the horizon. Each value was derived empirically

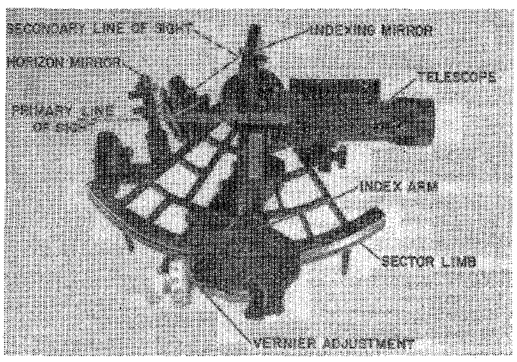

Fig. 1—Photograph of Plath micrometer sextant.

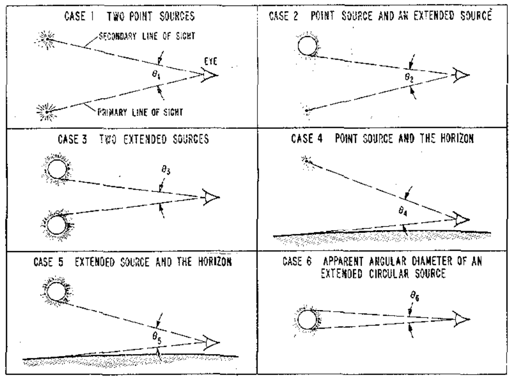

Fig. 2—Common angular measurements used in navigation.

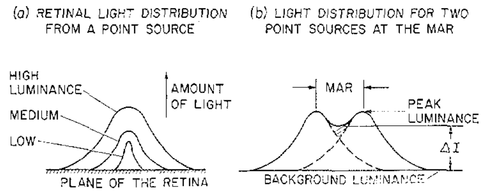

Fig. 3—Irradiation and MAR for a point source.

from results of multiple observations made by 33 observers; the performance of individual observers varied greatly [7]. Fig. 2 illustrates six angular measurements used in manual navigation. The remainder of this paper examines the effect of irradiation for cases 1, 2, 4, and 6 and reviews the psychophysical data available to quantify this effect.

Case 1. The MAR Between Two Point Sources (θ_1)

When two self-luminous point sources [41] are to be exactly superimposed, the major source of angular sighting error due to irradiation arises from the point sources themselves if they are of sufficient luminance [6, 42]. The apparent size of each point source is not determined by its angular subtense at the eye but by the amount of light it sends into the eye. By increasing point source luminance, the retinal light distribution (Fraunhofer diffraction pattern) expands over more receptors [5, 23, 36]. This effect is illustrated in Fig. 3(a). The subjective appearance of this has been described as ". . . the settings for the MAR are more difficult to make when the contrasts are high than when low, because the points tend to lose their "neatness" and the "streamers" or "spikes" radiating from the points become more troublesome. However, the mean variation of settings proved to be only a little larger than when the contrasts were low" [23]. Retinal image

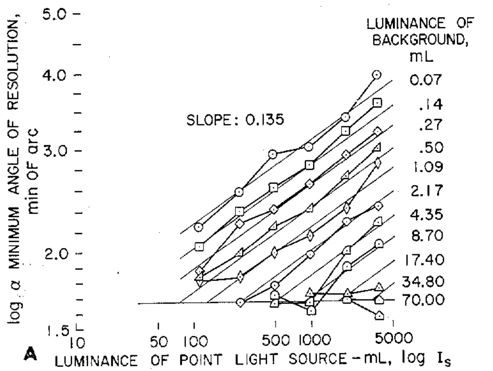

Fig. 4—The MAR for two point sources. (a) MAR between two point sources as a function ofpoint source luminance.

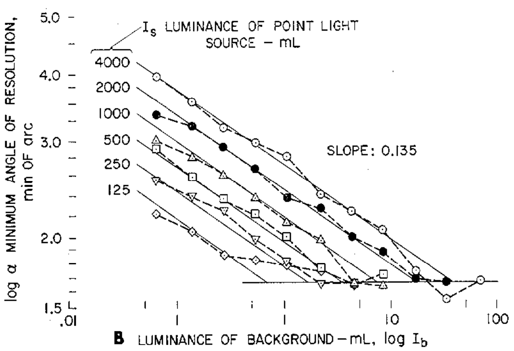

Fig. 4—(b) MAR between two point sources as a function of background luminance.

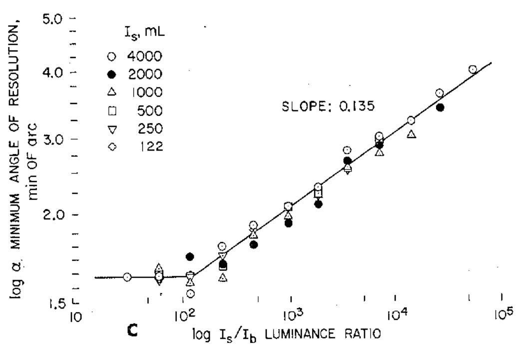

Fig. 4—(c) MAR between two point sources as a function of luminance ratio.

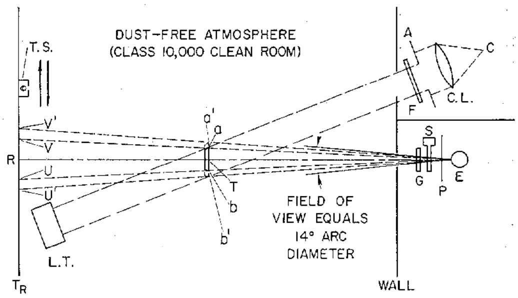

Fig. 5—Schematic diagram of testing facility.

sharpness is reduced when contrast is increased. When the two point sources are so close to one another that their diffraction patterns overlap on the retina, the MAR may depend upon whetrhe or not the observer can discriminate any darkness (shaded area in Fig. 3(b)) between the two diffraction pattern peaks and whether or not the observer judges that darkness to be the same as that found in the background [3, 11].

In a study using the unaided eye [23], point source and background luminance were varied independently. Each point source subtended under 10″ arc diameter and was seen within a circular 5° arc diameter field of view. Both eyes viewed the background screen but only one eye was used to make the MAR settings. The results obtained are reproduced as Fig. 4 (by the kind permission of the editor of the Journal of the Optical Society of America). These graphs show the relationship between the MAR and (a) background luminance (I_b), (b) point source luminance (I_s), and (c) contrast ratio (I_s/I_b). They indicate that: (1) for a constant background luminance increasing the point source luminance increases the MAR. This finding confirms earlier data on the same topic [4]. (2) For a constant point source luminance increasing the background luminance decreases the MAR. (3) The contrast ratio between the point sources and the background determines the MAR. This is shown in Fig. 4(c) by the straight line fit of the data points. Finally, (4) the smallest MAR obtained by the observer was about 1′45″ arc. Earlier studies [17, 33] found a value of approximately 1′ arc under comparable viewing conditions.

The temporal characteristics of the experiment are also important in determining the MAR. It has been pointed out before [11] that a long period of dark adaptation, e.g., about 15 minutes or more, is required to achieve optimum resolution in low (rod vision) luminance environments. Resolution is poor at these low levels, but it is even poorer when the dark adaptation of the eye is not complete. Resolution is also reduced when the eye is adapted to a low level and then an intense glare source is introduced into the field of view [21, 37]. For the eye to attain as small an MAR as is possible in high luminance environments (cone vision), the eye must be given a reasonably long period of light adaptation, e.g., several minutes [11, 28].

The reader is referred to other references for results of laboratory investigations of the MAR between two point sources over a range of luminances when a sextant was used [18–20, 24–26, 31, 39].

Apparatus and Procedure Used to Determine the MAR of Other Angular Measurements

The facility used to collect all the following data was the Ames High Luminance Vision Laboratory [12, 15]. The major equipment used is presented schematically in Fig. 5. Symbols given in the illustration refer to the following items.

E, observer's right eye (exactly centered on P)

P, circular viewing aperture used to limit the field of view to 14° arc diameter

S, shutter used to control viewing time

G, Inconel neutral density glass filter used to control the luminance across the entire field of view [43]

T, target (extended source). Each target was coated with MgO so as to possess a perfectly diffuse surface. The exact form and dimension of each target are given in the text.

T.S., point source (test spot) used by the observer to outline his area of test spot visibility along a given meridian [44]

T_R, servo-driven track-carriage assembly upon which the test spot moved. Since the entire track could be rotated into any orientation about point R (center of track rotation) the test spot could be used to investigate a number of meridians.

C, carbon arc (5800°K) solar simulator operated at 165 A, 70 V D.C. with 13-mm-diameter positive and 11-mm-diameter negative cored electrodes

C.L., collimating lens, 12-inch diameter, fused quartz

A, aperture used to limit the simulator's beam size and shape

F, Inconel neutral density filter used to vary just the target's luminance [43]

L.T., Light trap used to capture excess light passing beside the target so as to reduce the ambient illumination to a very low level

The distance between opposite edges of the target under relatively low luminance levels (e.g., below 100 ft-L) is indicated by the distance from a to b in Fig. 5. When the target is at a higher luminance and is viewed against a totally dark (or dim) background [45] it appears to expand so that its perceived edges now appear to extend from a′ to b′. Points V′, V, U, and U′ on the track correspond to extensions of lines drawn from the center of P past points a′, a, b, and b′, respectively. Knowing the distance from eye to target and distances U to V and U′ to V′, it is possible to calculate the visual angles subtended by the target under various illumination conditions.

To eliminate the possibility that backscattered solar radiation would not contribute to the apparent background luminance (by reflecting off airborne particulate matter), the target and track-carriage assembly were located within a class 10,000 clean room [15].

The solar simulator produced a maximum target luminance of 13,000 ft-L; this is equivalent to the luminance produced by the sun outside earth's atmosphere. The other target luminances that were investigated are noted in the text and results section.

An unilluminated target "control" condition was included in the investigations against which the results from the illuminated target conditions could be compared. During the unilluminated target condition the observer fixated a small dim red spot of light which was projected upon the exact center of the totally dark target; the settings were made as described below for the illuminated target conditions. Thus, three measures of the target's dimensions could be obtained: a trigonometrically determined target dimension, an unilluminated target (control) dimension, and the apparent target dimension obtained under illuminated target conditions.

A typical white circular target, its support and adjustment equipment, and the track-carriage assembly are shown in Fig. 6. An experimenter can be seen wearing special black nylon clean

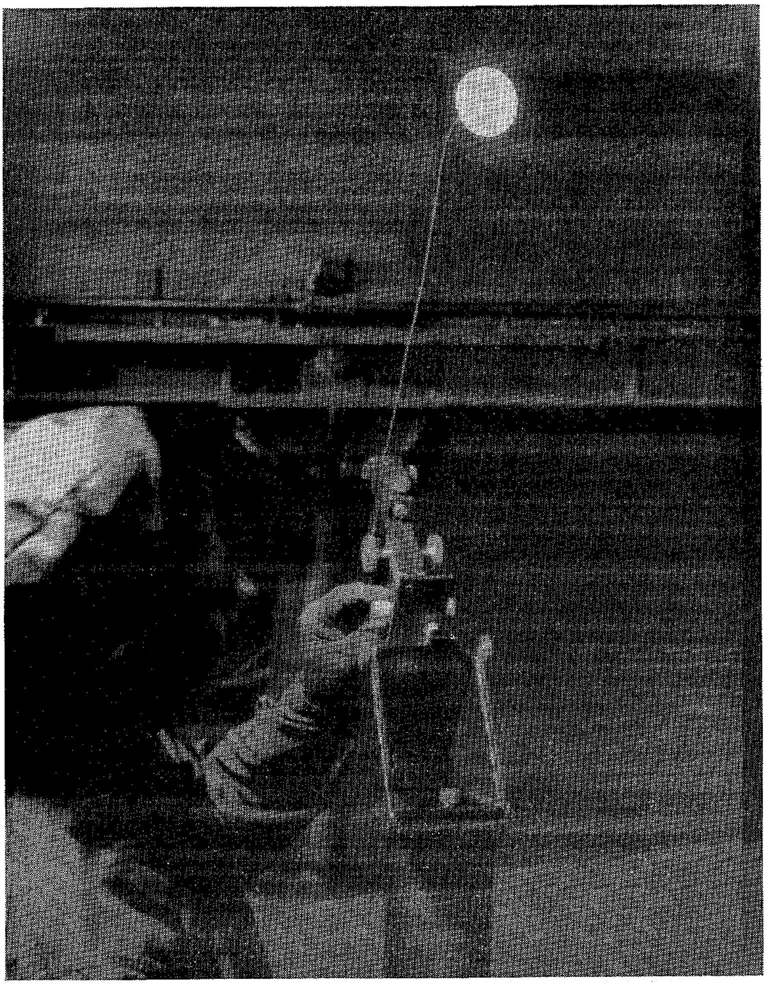

Fig. 6—The experimenter is shown adjusting the target (white circular disk) support device. The track-carriage assembly is shown in the background.

room garments. These garments were required apparel for everyone in the laboratory.

Unless otherwise specified, the test spot was a tungsten filament (1900°K) lamp having a luminous intensity of 2.93 ft-L [42]. It was situated behind various small diameter circular apertures so that it subtended visual angles ranging from 10″ to 7′12″ arc diameter, depending upon the experiment. When it was seen against an unilluminated background it appeared (at maximum luminance) about the same as a fourth (visual) magnitude star.

The following general procedure was used to collect the data. Each observer was instructed to move the test spot by means of a center off, spring-loaded toggle switch in the following manner. When the viewing shutter opened the test spot would be moved to the right by the observer along a preselected meridian (e.g., the horizontal); first it would appear on the left side of the target. He was instructed to stop its travel the instant it disappeared behind the left-hand edge of the target. This was called an in to the right (IR) trial. After this test spot position was recorded the observer again moved the test spot to the right and stopped it immediately after it reappeared on the right-hand edge of the target. This was called an out to the right (OR) trial. The test spot was then repositioned by the experimenter to a new randomly selected starting position on the right side of the target and its direction of travel was reversed 180° whereafter an in to the left (IL) and an out to the left (OL) trial was made as before. By using this technique human response errors such as reaction time latencies, anticipation and perseveration errors [38] could be eliminated. Further details of the procedure used are presented elsewhere [12, 13]. Meridians other than the horizontal were investigated in some of the studies reported here; however, the procedure used was the same as just described (even though the nomenclature for test spot direction of travel changed).

All observers were young male college students having 20:20 (Snellen) acuity, normal color perception (Ishihara color plates), fully functioning visual fields, and normal ocular motility and fixation stability. Each observer was given a large amount of pretraining for the required observation task before any data were collected for analysis, i.e., sighting performance was asymptotically high.

Case 2. The MAR Between a Point and an Extended Source (θ_2)

Table I presents the results of several investigations which are related to this kind of angular measurement. Data set (a) indicates that the edge of a small foveally fixated extended source appears to move outward from the target's center by over 6′ arc at a luminance of 1,699 ft-L and by over 13′ arc at a luminance of 4,249 ft-L. For the

Table I

MAR Between a Point and an Extended Circular Source (θ_2)

Data Set	Extended Source Trigonometric Size	Luminance (ft-L)	Point Source		MAR (min. sec.)	Comments	Reference
			Size (diam.)	Luminance (ft-L)			
(a)	1°34′35″ (diameter)	1,700	7′12″	8.5	6′0.4″	MAR based upon mean of 5 observers, 24 (IR-OL), and 24 (IL-OR) settings per observer. Viewing time = 10 sec.	13
		4,249	"	"	13′2.5″		
(b)	1°09′44″	0	3′54″	2.94	−1′14″	MAR based upon mean of 24 (IR-OL) and 24 (IL-OR) settings per observer. This data set for observer JP. Viewing time per setting = 21 sec. Artificial pupil = 4 mm diam.	14
	"	147	"	0.03	15′19″		
	"	1,285	"	0.29	7′33″		
	"	2,602	"	0.58	6′01″		
	"	7,897	"	1.85	7′55″		
	"	13,000	"	2.94	13′59″		
(c)	1°17′44″	0	3′54″	2.94	2′25″	Same conditions as for data set (b). This data for observer EC.	14
	"	147	"	0.03	13′07″		
	"	1,285	"	0.29	14′30″		
	"	2,602	"	0.58	12′11″		
	"	7,897	"	1.85	10′29″		
	"	13,000	"	2.94	12′21″		
(d)	2°35′29″	0	3′54″	2.94	−3′14″	Same conditions as for data sets (b) and (c). This data for observer JP.	14
	"	147	"	0.03	11′03″		
	"	1,285	"	0.29	7′12″		
	"	2,602	"	0.58	36′17″		
	"	7,897	"	1.85	7′44″		
	"	13,000	"	2.94	7′16″		

data given in data sets (b), (c) and (d) all neutral filtering was done just in front of the eye so that the point source and the luminance of the extended source always varied by the same proportion. This situation is comparable to the manual navigation situation in which a neutral density filter is used in the sextant between the horizon mirror and the eye (see Fig. 1). It is apparent from the above findings that relatively large MAR values due to irradiation can be expected when the sextant uses filters in this position (or when sun glasses are worn while using the sextant). If the neutral density filter is used only in the primary or the secondary line of sight it is possible to reduce the detrimental effects of irradiation. If, for instance, the sun is viewed through a neutral density filter while the horizon is viewed without filters it is obvious that the solar irradiation error would be reduced while the irradiation error produced at the horizon would not.

Case 3. The MAR Between Two Extended Sources (θ_3)

No laboratory research on this sighting task could be found in the literature nor has this situation been investigated in the High Luminance Vision Laboratory. Based upon what is known about the MAR between a point and an extended source, however, the MAR could be an angle as large as 15′ arc. In this situation both extended sources would contribute to the light distribution upon the retina so as to raise the retina's adaptation level at a point between the just separated extended sources. Whether or not the observer could see them as separate (or just tangent) would depend upon their respective luminances, size, and the background luminance. This viewing situation should be thoroughly investigated in the laboratory.

Case 4. The MAR Between a Point Source and a Simulated Horizon (θ_4)

The irradiation phenomenon has been found to increase the MAR for this type of angular measurement. Table II presents data for various angular widths and luminances of the simulated horizon and for various point source sizes and luminances. In all cases the simulated horizon was a white diffusely reflecting surface (either MgO or matt cardboard). The MARs ranged from about 2′ to 23′ arc, depending upon the luminance of the horizon and test spot. Even at zero ft-L horizon luminance a relatively large MAR was found. Possible bases for this effect have been discussed in greater detail elsewhere [14]; the effect may be ascribed to refraction of the point source's rays at the horizon so that the observer has an advanced warning of the point source's reappearance from behind the horizon. This advanced warning could help the observer compensate for reaction time latencies while making out (reappearing) settings of the test spot. This advanced warning is not available on out settings of the test spot when the horizon (or extended source) is illuminated, however.

It is apparent that the MARs obtained in the laboratory using the normal unaided eye and an extremely sharp horizon boundary presents an unrealistic situation when compared to most actual navigation tasks. Atmospheric properties such as absorption, scattering, clouds, smoke, fog, etc., all contribute to the poor horizon definition sometimes encountered [30, 32]. Be that as it may, the present data indicate that even with optimal sighting conditions (in terms of atmospheric transmission) irradiation can increase the MAR by amounts that can be considered intolerably large for many space navigation applications.

Case 5. The MAR Between an Extended Source and the Horizon (θ_5)

As in case 3, no laboratory data have been collected on this sighting situation. Due to the mutually enhancing effect upon irradiation-produced sighting errors from both extended sources, it is likely that the MAR between these sources will be large. If the sun's upper limb, for instance, is positioned just tangent to the horizon so that it does not contribute significantly to the irradiation effect, the MAR can be expected to be smaller than if the sun's lower limb is positioned just tangent to the horizon. As has been pointed out, standard practice in terrestrial navigation incorporates only one correction for navigation effects. An irradiation correction of 1.2′ arc has been included in the altitude correction table [7] for the sun's upper limb on the earth's horizon. This value is based on the assumption that the

Table II

MAR Between a Point Source and a Simulated Horizon (θ_4)

Data Set	Observer	Simulated Horizon: Angular Width (deg. min.)	Simulated Horizon: Luminance (ft-L)	Point Source: Size (diam.)	Point Source: Luminance (ft-L)	MAR (min. sec.)	Comments	Reference
(a)	LC	1°39′	0	9.6″	2.94	3′59″	MAR based upon 41 (disappearance) and 41 (reappearance) settings per illumination condition. Viewing time = 18 sec. Artificial pupil = 3 mm diam.	Unpubl.
		"	674	"	"	3′33″		
		"	2,602	"	"	4′06″		
		"	13,000	"	"	6′41″		
(b)	DF	1°39′	0	9.6″	2.94	7′39″	Same conditions as for data set (a)	Unpubl.
		"	674	"	"	3′32″		
		"	2,602	"	"	3′14″		
		"	13,000	"	"	7′50″		
(c)	RH	1°39′	2,602	9.6″	2.94	8′31″	Same conditions as for data sets (a) and (b)	Unpubl.
(d)	RH	1°08′49″	1,700	7′12″	8.5	3′38″	MAR based upon 96 settings. Viewing time = 10 sec. Artificial pupil = 3.5 mm diam.	13
		"	4,249	"	"	10′23″		
	RH	"	1,700	"	"	2′53″	MAR based upon 96 settings. Viewing time = 13 sec. Artificial pupil = 3.5 mm diam.	13
		"	4,249	"	"	6′16″		
(e)	RH	8°30′	0	15.8″	2.94	19′51″	MAR based upon 15 (disappearing) and 15 (reappearing) settings. Viewing time = 19.5 sec. Natural pupil.	Unpubl.
		"	1,643	"	"	1′42″		
		"	6,088	"	"	1′20″		
		"	0	"	1.56	5′54″		
		"	1,643	"	"	14′34″		
		"	6,088	"	"	1′58″		
		"	0	"	0.29	2′29″		
		"	1,643	"	"	3′32″		
		"	6,088	"	"	5′59″		
(f)	MS	8°30′	0	15.8″	2.94	3′53″	Same conditions as for data set (e).	Unpubl.
		"	1,643	"	"	5′18″		
		"	6,088	"	"	5′25″		
		"	0	"	1.56	3′28″		
		"	1,643	"	"	4′03″		
		"	6,088	"	"	7′43″		
		"	0	"	0.29	2′26″		
		"	1,643	"	"	17′29″		
		"	6,088	"	"	23′54″		

Table III

Apparent Angular Diameter of an Extended Circular Source (θ_6)

Data Set	Ob-server	Extended Source Diameter Determined Trigono-metrically (deg. min.) (A)	Lumi-nance (ft-L)	Point Source		Apparent Diameter (B)	Difference Between (A) & (B)	Comments	Refer-ences
				Size (diam.)	Lumi-nance (ft-L)				
(a)	RH	1°34′00″ "	1,700 4,249	7′12″ "	8.5 "	1°45′02″ 1°57′11″	11′02″ 23′11″	Value (B) based upon 192 settings. Viewing time = 10 sec. Artificial pupil = 3.5 mm diam.	13
(b)	RH	1°33′00″ "	1,700 4,249	7′12″ "	8.5 "	1°46′02″ 2°01 59″	13′02″ 28 59″	Same conditions as for data set (a) except Viewing time = 13 sec.	13

sun and the horizon each contribute 0.6′ arc error to this measurement. Further studies using both the unaided eye and the aided eye (magnification, field of view sizes, etc.) in this sighting situation should be carried out.

Case 6. The Effect of Irradiation Upon the Apparent Angular Diameter of an Extended Circular Source (θ_6)

Laboratory data related to this angular measurement are presented in Table III. The illuminated extended source appears increasingly large as its luminance increases (irradiation phenomenon). Values given in the column labelled difference between (A) and (B) indicate the magnitude of this apparent expansion.

It is obvious that stadiametric measurements will also be in error due to the effects of irradiation. Corrections for irradiation will be particularly important when lunar and planetary diameters must be determined for possible use in midcourse guidance calculations. Small changes in the apparent angular diameter of a planetary body could represent significantly large differences in estimated distances from the spacecraft to the planet.

Discussion

In the past it has often been possible to ignore the effect of irradiation upon angular measurements for navigation because either the accuracy of measurement did not necessarily justify a separate correction (for irradiation) or the effect was masked by other uncontrollable errors such as atmospheric refraction. For purposes of space navigation, however, the effect of irradiation must be considered in any system in which the eye is used as the final sensor. It is impossible to eliminate irradiation from the eye but its effect in angular measurements may be reduced by changes in the optics of the measurement system or by optimizing the stimulus conditions. If the irradiation effect cannot be reduced below allowable tolerance limits, corrections must be made to the recorded measurements. To do this the observer must be calibrated.

Although a detailed discussion of the possible causes of the irradiation phenomenon is beyond the scope of the present paper and can be found elsewhere [12–14, 16, 17, 27], it can be pointed out that most of the experimental evidence to date suggests that it is the scattering of light within the observer's eye that produces increased MAR values. The actual scatter gradient at the edges of bright extended sources is presently being quantified to gain a better understanding of the optical and neural factors underlying the irradiation phenomenon.

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