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IRRADIATION EFFECTS ON MANUAL SIGHTING ACCURACY OF A SPACE-FLIGHT-RATED SEXTANT USING SIMULATED LUNAR AND STELLAR TARGETS

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16. Abstract

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The results indicate essentially no irradiation-related error when limb on limb is viewed (e.g., when the subtense angle of an illuminated body such as the moon is measured with the sextant). In contrast, the star-on-lunar-limb results show an appreciable irradiation effect amounting to about 15 arc sec on the average at the higher levels of lunar disk luminance.

The limb-on-limb sightings were repeatable with greater precision than the star-on-limb sightings. These data are related to a physiological optical model that suggests the primary cause of the irradiation-induced angular sighting error was not within the sextant but within the eye of the observer and was due to retinal sensitivity reductions caused by entoptic scatter.

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SUMMARY

An investigation was conducted to determine the effects of lunar disk luminance on manual navigation measurement accuracy with a space-flight-rated sextant. The simulated sighting targets consisted of a +2 (visual) magnitude star and a simulated moon (approx 1/2° diam). Four values of lunar disk luminance (6.73×10^{-4}, 6.05×10^{-3}, 8.84×10^{-2}, and 0.252 cd/cm^2) (2, 18, 263, and 750 ft-L) were used with four sighting configurations (star on near lunar limb, star on far lunar limb, upper lunar limb on lower lunar limb, and lower lunar limb on upper lunar limb). Four experienced subjects obtained 1920 sextant observations. The space-flight-rated sextant was a handheld type instrument with an 8-power telescope; it was mounted in a gimbal support to eliminate sighting errors due to variable angle and parallax effects when uncollimated targets are viewed at short range.

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The limb-on-limb sightings were repeatable with greater precision than the star-on-limb sightings. These data are related to a physiological optical model that suggests the primary cause of the irradiation-induced angular sighting error was not within the sextant but within the eye of the observer and was due to retinal sensitivity reductions caused by entoptic scatter.

INTRODUCTION

This report describes one in a series of investigations conducted at Ames Research Center (refs. 1–8) concerned with the identification of both instrument and human response variables associated with the use of a handheld sextant for space navigation sightings. This and other studies have shown that the sextant is suitable for space applications that require accurate angular measurements. However, the operational accuracy requirements for using a sextant during space flight are more stringent than for aeronautical or marine situations so the full capabilities of the instrument and observer are required. It is therefore important to apply all of the corrections known in order to make the angular measurements as accurate as possible.

One correction is for the irradiation phenomenon (refs. 9–12) which is believed to cause a small increase in the apparent size of a bright body when viewed against a dark background. The irradiation model presented in references 12 and 13 suggests that the magnitude of the irradiation effect is a function of how it is measured. The model suggests that light entering the eye from the bright object does not remain confined to a retinal region of the same relative size or shape as the original object. Rather, this entoptic beam is scattered within the various optic media and falls upon most of the retina. The perceptual result is a *veiling luminance* that surrounds the bright object and tends to obscure nearby objects. Physiologically, the retinal illumination around the brightbody produces a higher threshold (i.e., decreased light sensitivity) near its retinal image than farther away. As a result of this gradient of retinal sensitivity, the image of a considerably smaller and fainter object, such as a navigation star, becomes invisible at some angular distance from the edge of the larger object's image on the retina.

The above model also suggests that irradiation related sighting errors should be less for the limb-on-limb sighting condition than for the star-on-limb condition. In the limb-on-limb case two bright and evenly sized lunar disk images are viewed just tangent to each other. The visual contrast at (and on each side of) the tangency point is greatly reduced because entoptic scatter from each lunar disk image increases the apparent background brightness. Also, less background area is seen than during a star-on-limb sighting, resulting in a smaller magnitude of irradiation-related sighting error.

In a separate study in the same testing facility (ref. 1) the effect of star magnitude on the angular sighting accuracy of star on lunar limb was investigated using a single value of lunar luminance. A small but statistically significant reduction was found in the irradiation effect with increasing star intensity. This result is in accord with the model of the irradiation phenomenon described above.

The purpose of the present investigation was to quantify the magnitude of the irradiation effect as a function of lunar disk luminance on sextant measurements in a carefully controlled laboratory environment using experienced observers and high precision equipment.

DESCRIPTION OF APPARATUS

Sextant and Gimbal Support

The primary apparatus was a space-flight-rated sextant similar to the one used in experiment T002 on the Gemini XII flight; hereinafter it will be referred to as the T002 sextant. A cutaway schematic drawing of the sextant is shown in figure 1; it is described elsewhere (refs. 2, 6, 7). This sextant exhibited an accuracy of less than 4 arc sec (1σ) and a repeatability of less than 2 arc sec (1σ), according to the manufacturer (ref. 14).

The T002 sextant was supported in the gimbal device shown in figure 2, which allowed freedom of motion in roll only. The pitch and yaw adjustments were locked so that the lunar disk was centered on the primary line of sight (PLOS).

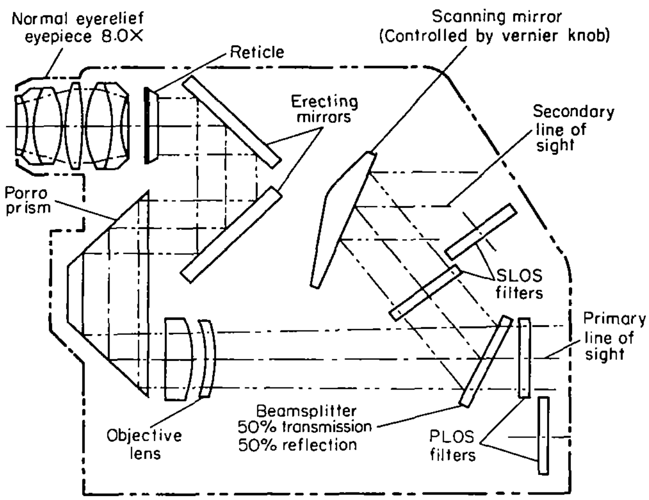


Figure 1.– Cutaway schematic drawing of T002 sextant.

Figure 2.– The T002 sextant mounted in gimbal support.

Theodolite

The reference angles used in calculating the "true" star/near limb (S_1/L_n) and star/far limb (S_1/L_f) sextant angles were measured using a standard Hilger-Watts No. 2 Microptic theodolite with 28-power telescope and fine crosshairs. This is a precision instrument having a nominal angular resolution of 1 arc sec, according to the manufacturer. The theodolite calibrated by a Watts Microptic Clinometer and a Davidson Optronics Penta Block had an average deviation of 3.0 arc sec.

Simulated Lunar and Stellar Targets

The simulated lunar target was a 15.24 cm (6.00 in.) diameter, flat aluminum disk with a back-beveled edge. It was coated with potassium silicate and appeared as a diffusely reflecting white surface. At the subject's viewing distance, the disk subtended an angle of 30′35″.

A 1200 W slide projector located outside the subject's field of view was used to produce a maximum lunar disk luminance of 0.252 cd/cm^2 (750 ft-L). This projected beam was collimated and produced negligible illumination on the black (13 percent reflectance) background. A multivaned light trap absorbed a high percentage of the projected beam that did not fall on the lunar disk. The lower levels of disk luminance were obtained by using a 750-W lamp in the projector alone and in combination with either two log 0.7 or one log 2.0 inconel neutral density filters.

The simulated navigation star S_1 was a microminiature filament lamp (approximately 1900° K) located behind a 0.025 cm (0.01 in.) diameter aperture. It subtended an angle of 3 arc sec and was adjusted in intensity (voltage adjustment) to appear as a magnitude +2 star at the sighting station.

Testing Facility

These sextant sightings were made in a totally dark room (fig. 3). The T002 sextant's primary line of sight (PLOS) was centered on the simulated lunar disk. The secondary line of sight (SLOS) was centered on the simulated navigation star S_1. The collimated star S_2 was used to check the zero bias of the sextant. The angle between the primary and secondary lines of sight was set at 8° so that the fields of view would not overlap. Sightings were made from inside a cubicle located about 16.8 m (55 ft) from the various targets. The subjects were seated behind a rigid steel column to which the sextant gimbal support was attached.

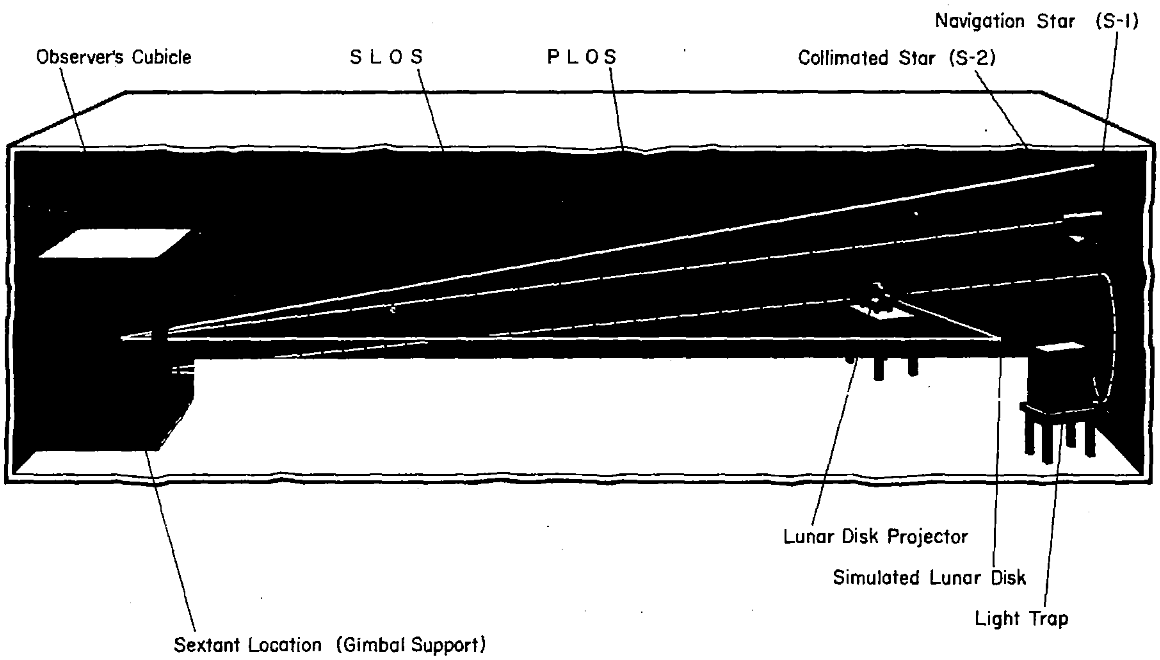
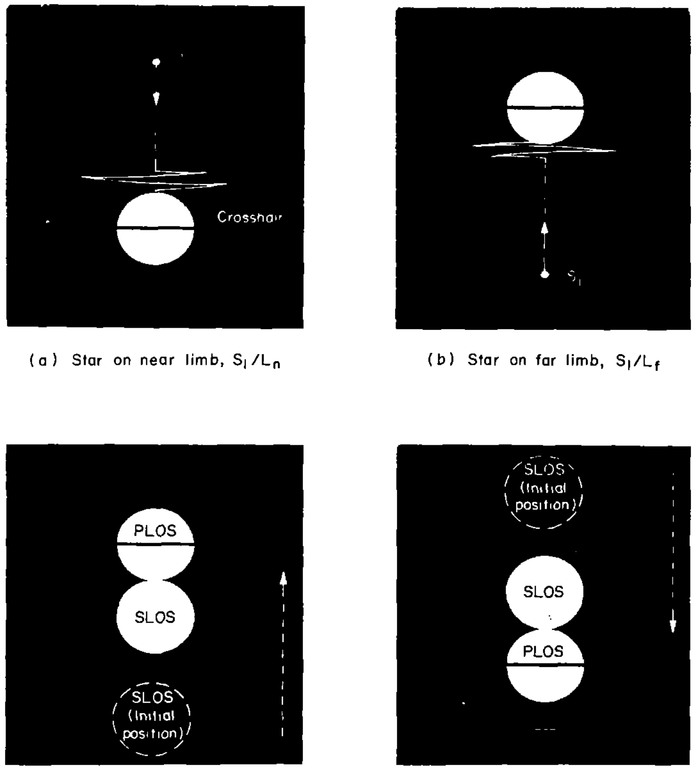


Figure 3.– Schematic illustration of the simulation facility for sextant navigation sightings.

EXPERIMENTAL DESIGN

Task Description

The experimental task performed by each subject consisted in taking repeated measurements with the T002 sextant on each of four sighting angles. For each measurement the image of the lunar disk was centered in the field of view of the PLOS. In the case of the first angle measured, star on near limb (S_1/L_n), the image of the star in the SLOS was superimposed on the near edge of the lunar disk image. In the case of the second angle measured, star on far limb (S_1/L_f), the image of the star in the SLOS was superimposed on the far edge of the lunar disk image. For the third and fourth angles measured, the image of the lunar disk in the SLOS was positioned just tangent to that in the PLOS at its lower limb (L_u/L_l) and at its upper limb (L_l/L_u). A schematic representation of each of these visual scenes is presented in figure 4. In each drawing the heavy horizontal line represents the horizontal crosshair of the sextant, and the arrow indicates the direction of image motion seen in the field of view. The pendulum-like arcs shown in parts (a) and (b) represent the apparent path of the simulated navigation star when the sextant is rolled within the gimbal support.



(a) Star on near limb, S_l/L_n (b) Star on far limb, S_l/L_f

(c) Upper limb on lower limb, L_u/L_l (d) Lower limb on upper limb, L_l/L_u

Figure 4.– Schematic representation of four sextant sighting tasks performed during experiment.

During each testing session 10 sightings were made on each of the four target configurations shown. After each sighting the subject gave a confidence estimate that ranged from 1 for very high confidence to 5 for very low confidence. These estimates were used as a subjective indication of his sighting accuracy.

Test Subjects

Four men (mean age 41.5 years) served as subjects. All had had experience in previous investigations involving navigation sightings. Subjects BL and CW had uncorrected 20/20 distance acuity; subjects DS and FB had corrected 20/20 distance acuity. All four subjects were experienced in the use of the T002 sextant so that no further training was given prior to this study. Care was taken, however, to ensure that each subject's initial level of performance was representative of that attained in previous experiments.

Test Conditions

The test conditions consisted of four levels of lunar disk luminance and four sextant sighting tasks. Thus, with four subjects the investigation consisted of a 4X4X4 factorial design. The sequence of conditions was randomized to control for serial effects in the data. A schedule of test conditions used for each subject is presented in table 1. This schedule was completed three times by each subject during the course of the investigation. Since 10 sightings were made at each sighting condition, a total of 480 sightings were made by each subject.

TABLE 1.– RANDOMIZED SCHEDULE OF TEST CONDITIONS USED BY FOUR SUBJECTS

Subject DS		Subject BL		Subject CW		Subject FB	
Luminance, cd/cm^2	Sighting task	Luminance, cd/cm^2	Sighting task	Luminance, cd/cm^2	Sighting task	Luminance, cd/cm^2	Sighting task
8.84×10^{-2}	S_1/L_n	8.84×10^{-2}	L_l/L_u	2.52×10^{-1}	L_l/L_u	6.05×10^{-3}	S_1/L_f
	L_l/L_u		S_1/L_n		S_1/L_f		L_l/L_u
	S_1/L_f		S_1/L_f		S_1/L_n		S_1/L_n
	L_u/L_l		L_u/L_l		L_u/L_l		L_u/L_l
6.05×10^{-3}	L_l/L_u	6.05×10^{-3}	L_u/L_l	6.05×10^{-3}	S_1/L_n	2.52×10^{-1}	L_l/L_u
	S_1/L_n		S_1/L_n		L_u/L_l		L_u/L_l
	S_1/L_f		S_1/L_f		S_1/L_f		S_1/L_f
	L_u/L_l		L_l/L_u		L_l/L_u		S_1/L_n
2.52×10^{-1}	S_1/L_n	6.73×10^{-4}	S_1/L_n	6.73×10^{-4}	L_u/L_l	6.73×10^{-4}	L_l/L_u
	S_1/L_f		L_l/L_u		S_1/L_n		S_1/L_n
	L_l/L_u		S_1/L_f		L_l/L_u		L_u/L_l
	L_u/L_l		L_u/L_l		S_1/L_f		S_1/L_f
6.73×10^{-4}	L_l/L_u	2.52×10^{-1}	S_1/L_f	8.84×10^{-2}	S_1/L_f	8.84×10^{-2}	S_1/L_n
	S_1/L_n		L_l/L_u		L_l/L_u		S_1/L_f
	S_1/L_f		S_1/L_n		S_1/L_n		L_l/L_u
	L_u/L_l		L_u/L_l		L_u/L_l		L_u/L_l

S_1/L_n = star on near limb
S_1/L_f = star on far limb
L_u/L_l = upper limb on lower limb
L_l/L_u = lower limb on upper limb

TEST PROCEDURE

Calibration of Equipment

A calibration of the T002 sextant used in this investigation was furnished by the manufacturer (ref. 14). This calibration consisted of the angular corrections to be appplied over the full range of angles of the instrument to give a "true" angle reading. Because of a small amount of backlash in the gear assembly, a separate calibration was provided for readings obtained while the scanning control knob was being turned either clockwise or counterclockwise.

To determine whether there was any residual zero bias in the sextant that needed to be accounted for, a star-on-star sighting (S_2/S_2) were made using the collimated simulated star in the laboratory as well as a real star in the night sky. In addition, a precision check of the zero bias was made using the interference fringe pattern obtained by passing a collimated beam of light through the sextant optics. It was found that the zero bias was less than 2 arc sec.

No manufacturer's calibration was available for the Hilger-Watts theodolite. To be sure the theodolite was sufficiently accurate for this purpose, the instrument was calibrated at several angles within the measurement range required for this investigation. The results of this calibration indicate that the theodolite was accurate to better than 3 arc sec in the measurement of the nominal sextant angle (uncorrected for parallax) between the simulated star and the near and far limbs of the simulated lunar disk.

Determination of True Sextant Angles

Two different computation methods were used to determine the true values of the sighting angles measured with the sextant. The first method consisted in using target distance and size measurements in conjunction with equations relating the lines of sight to the specific target points and through the optics of the sextant. This method was adequate for an accurate determination of limb-on-limb sextant angles, since the only dimensions required were the distance to the lunar disk and the disk diameter.

The second method involved using the theodolite angular measurements between specific target points. These measured angles were then corrected by an amount necessary to adjust the theodolite position to the location where the two lines of sight through the sextant would intersect. Since the theodolite was located nominally at the proper position with respect to the gimbal-supported sextant for measuring the angle between the star target and the center of the lunar disk, linear perturbation theory was used to calculate the correction factors to be applied to the star/limb angles measured at the fixed theodolite position. Further details of the two methods used in computing true sextant angles for the four sighting configurations are presented in the appendix. Tables 2 and 3 present a summary of computations of true star-on-limb and limb-on-limb sextant readings.

TABLE 2.– SUMMARY OF COMPUTATIONS OF TRUE STAR ON LIMB SEXTANT READINGS

	Sighting condition	
	S_1/L_n	S_1/L_f
Mean measured theodolite angle (based on 20 sightings)	7.79129°	8.30074°
Theodolite calibration correction	0	2.2″ = 0.0006°
Theodolite irradiation correction	4.3″ = 0.0012°	-4.3″ = -0.0012°
Total theodolite correction	4.3″ = 0.0012°	-2.1″ = -0.0006°
Corrected theodolite angle	7.7925°	8.3001°
Adjustment to theodolite angle (for correction in fixed theodolite position)	-18.7″ = -0.0052°	56.5″ = 0.0157°
Correction for refraction of primary line of sight	-13.7″ = -0.0038°	-13.7″ = -0.0038°
Ideal sextant angle (equal to adjusted theodolite angle) including refraction correction	7.7835°	8.3120°
Sextant calibration correction	-10.0″ = -0.0028°	-9.0″ = -0.0025°
Final computed sextant reading	7.7807°	8.3095°

TABLE 3.– SUMMARY OF CORRECTIONS APPLIED TO LIMB ON LIMB SEXTANT READINGS

	Sighting condition	
	L_u/L_l	L_l/L_u
Ideal sextant angle (based on linear measurements) including correction for refraction of primary line of sight	0.2540°	-0.8018°
Sextant calibration correction	0	-9.0″ = -0.0025°
Final true sextant reading	0.2540°	-0.8043°

Photometry of Targets and Background

A Pritchard model PR–1970 spectra photometer was used to calibrate all light sources used in the investigation. The lunar disk and background luminance cited here are the mean of four separate readings.

The luminous intensity of the simulated +2 magnitude star was calibrated by measuring the illumination of a flat, diffusely reflecting white surface located 5.1 cm (2 in.) in front of the star aperture. For this investigation, as well as elsewhere (see ref. 15), a value of 3.90×10^{-8} ft-c was used for the illuminance of a second magnitude star.

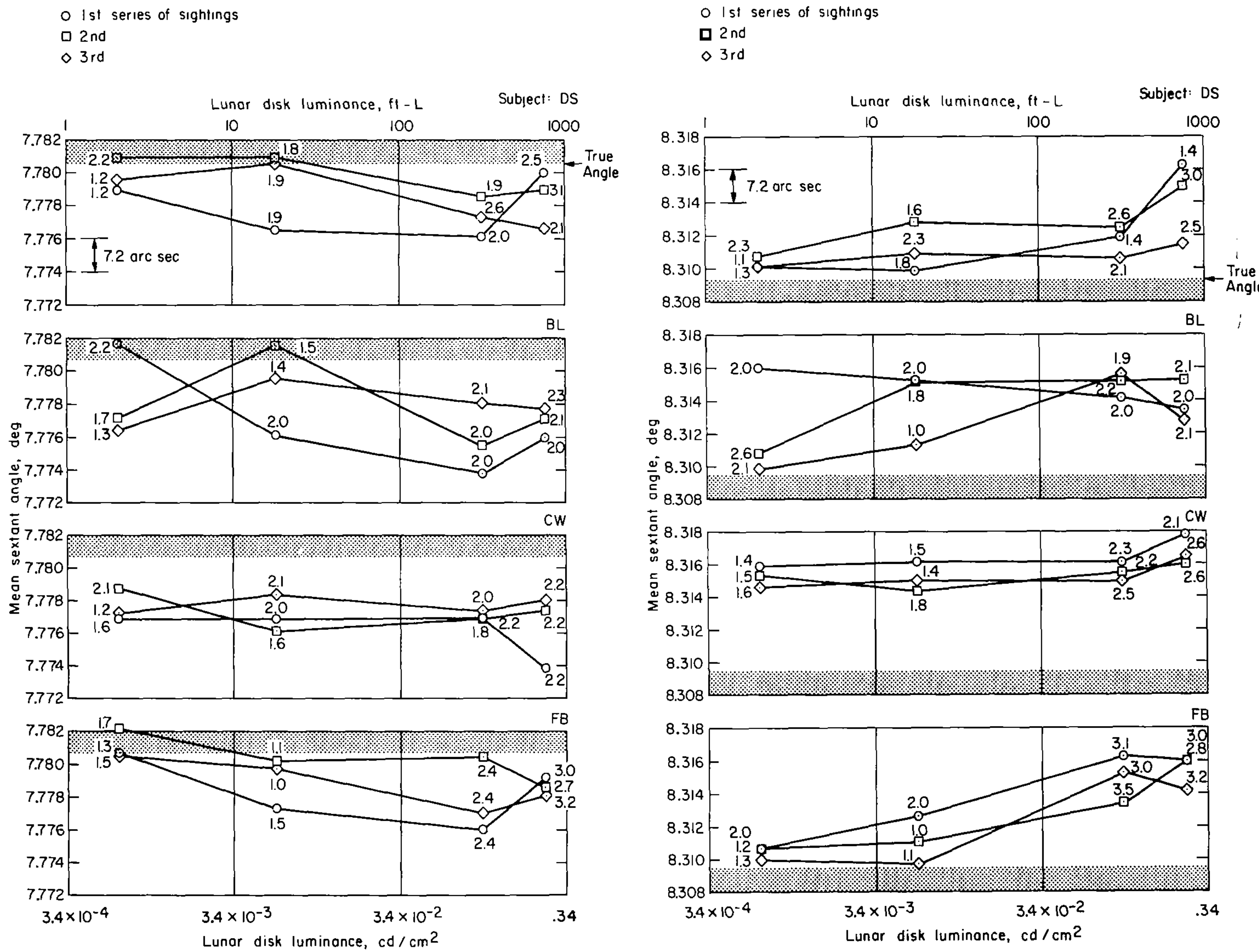
RESULTS AND DISCUSSION

Evaluation Criteria

Two criteria were used to evaluate the sighting performance of the four subjects: (1) the mean measurement error or "bias," and (2) the standard deviation of the measurement error. The data for each subject and sighting condition as a function of lunar disk luminance[1] are presented in figures 5 and 6. Each point shown in figure 5 represents the average of 10 measurements. The small number beside each data point in figure 5 indicates the average confidence estimate for each set of 10 readings.

Each data point in figure 6 represents the standard deviation of the measurement error associated with the corresponding data points in figure 5. The results shown in figure 7 were obtained by determining a linear, least-squares fit of the data in figure 5. To provide a comparison among the four subjects, the results have been superimposed and the calculated true sextant angles (in the absence of irradiance or other effects) are indicated separately. Also shown in this figure are the mean values obtained by averaging the results of the four subjects.

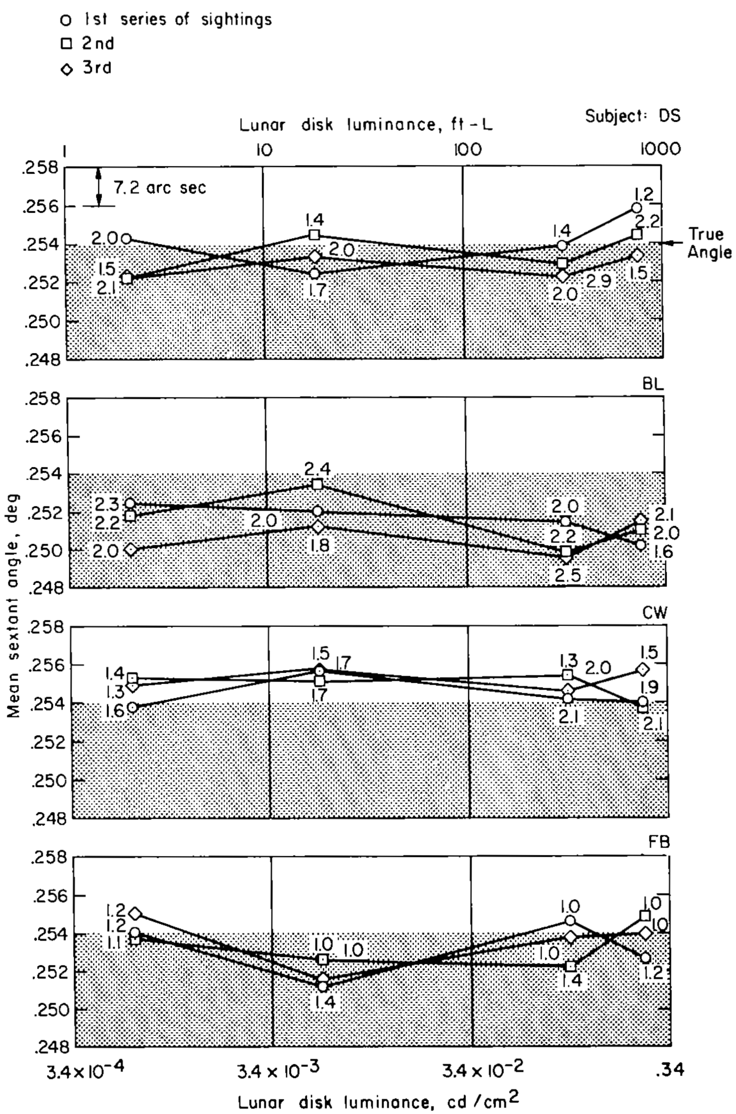
[1] Unless otherwise indicated, the lunar disk luminance used throughout the report refers to the value measured with the photometer and does not include the effect of transmission losses through the optics in the T002 sextant.



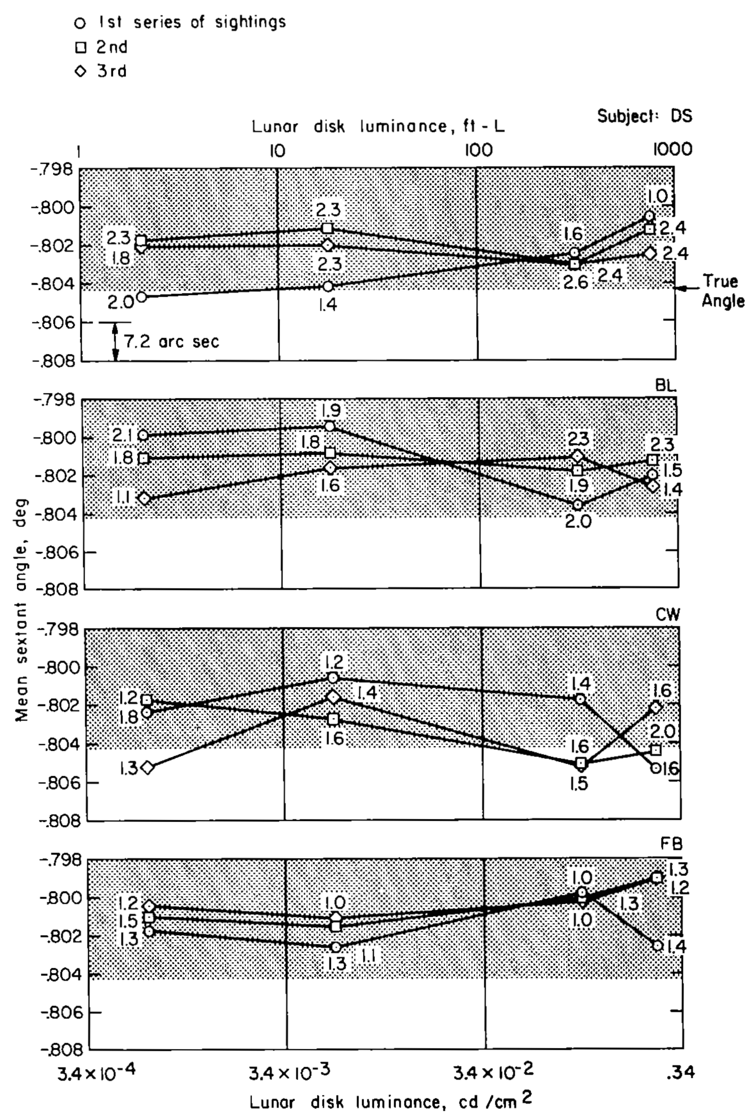
(a) Star on near limb, S_1/L_n.

(b) Star on far limb, S_1/L_f.

Figure 5.– Results of sextant measurements by four subjects sighting on simulated star of magnitude +2 and illuminated lunar disk subtending an angle of 0.5°.

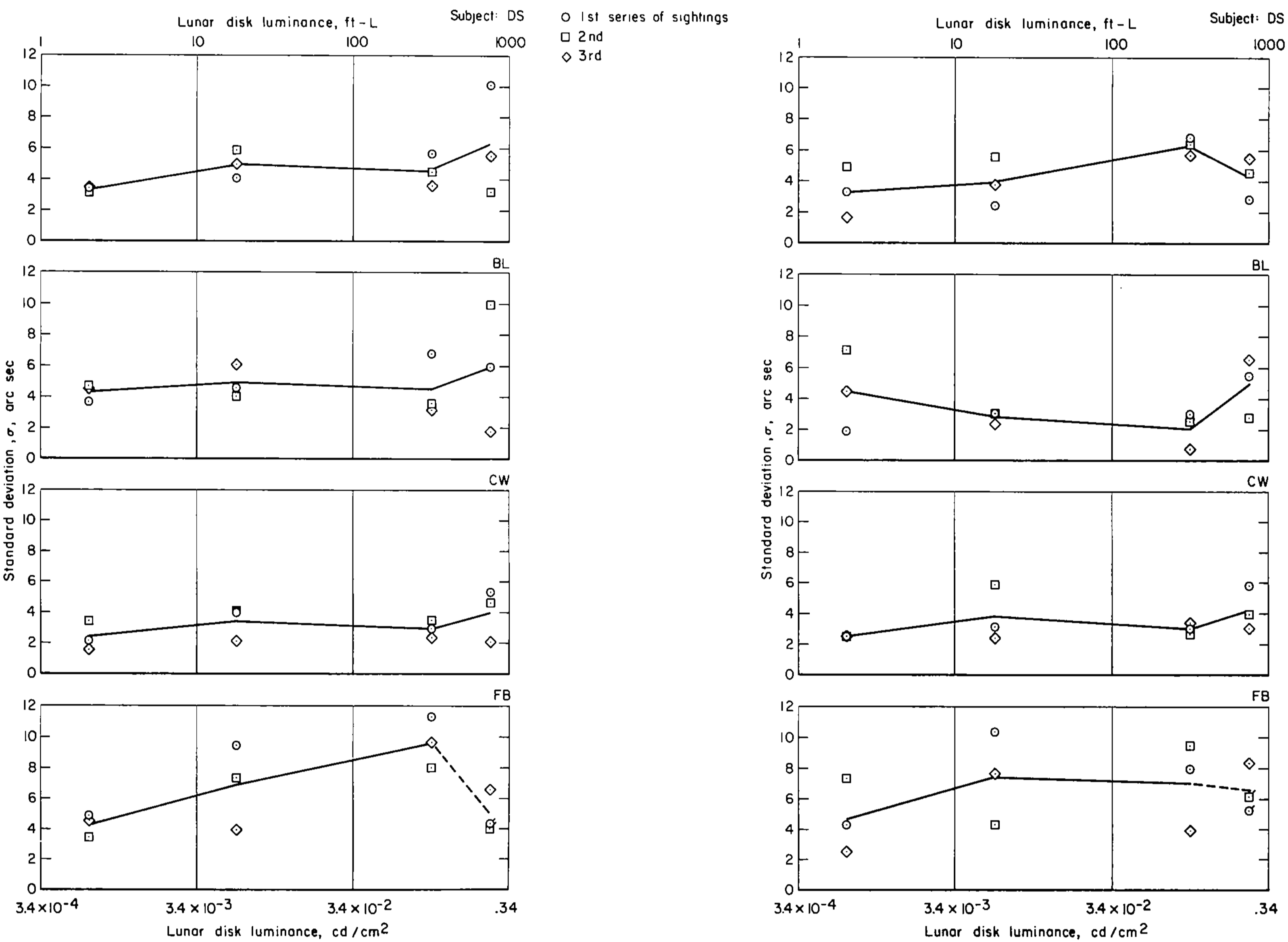


(c) Upper limb on lower limb, L_u/L_l.



(d) Lower limb on upper limb, L_l/L_u.

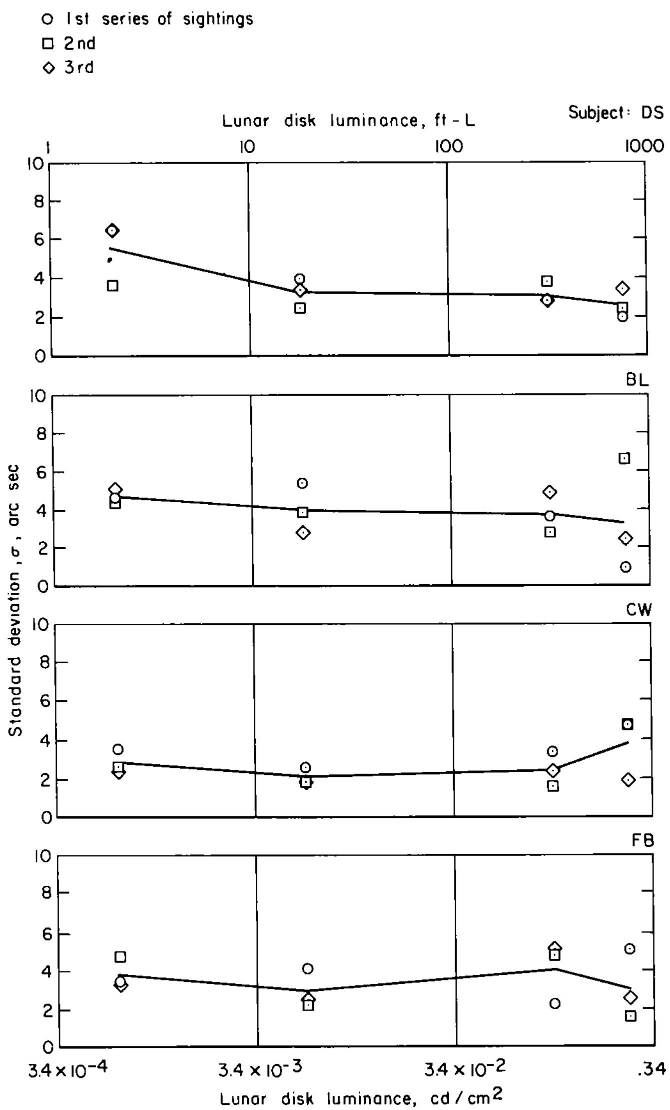
Figure 5.– Concluded.



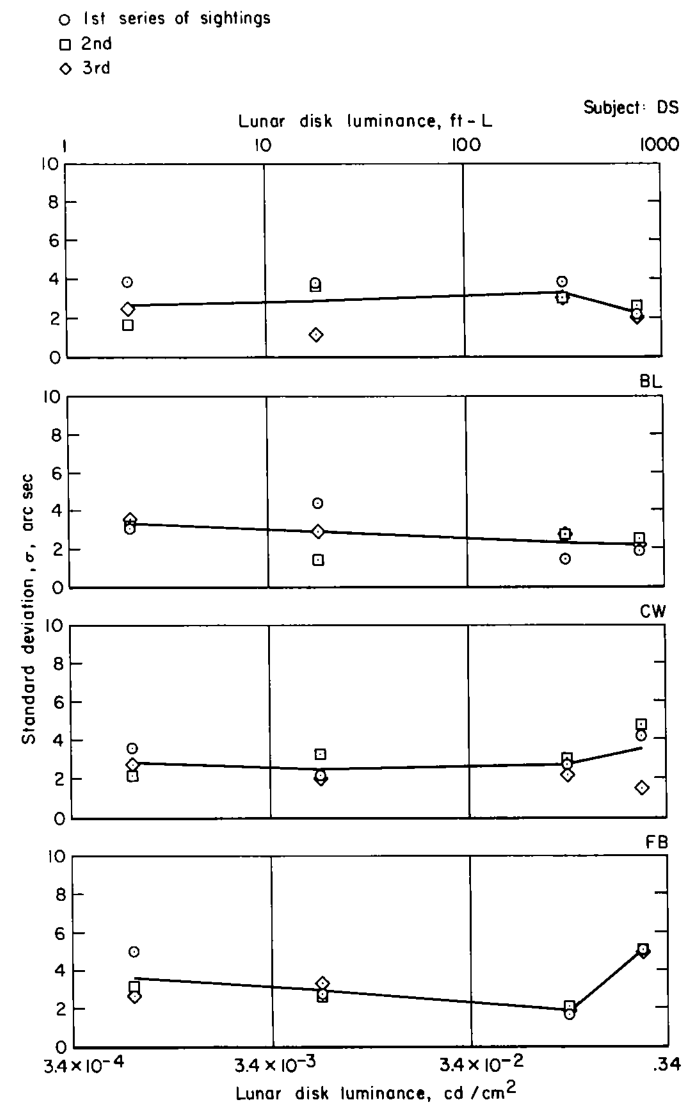
(a) Star on near limb, S_1/L_n.

(b) Star on far limb, S_1/L_f.

Figure 6.– Standard deviations of sextant measurements by four subjects sighting on simulated star of magnitude +2 and illuminated lunar disk subtending an angle of 0.5°.



(c) Upper limb on lower limb, L_u/L_l.



(d) Lower limb on upper limb, L_l/L_u.

Figure 6.– Concluded.

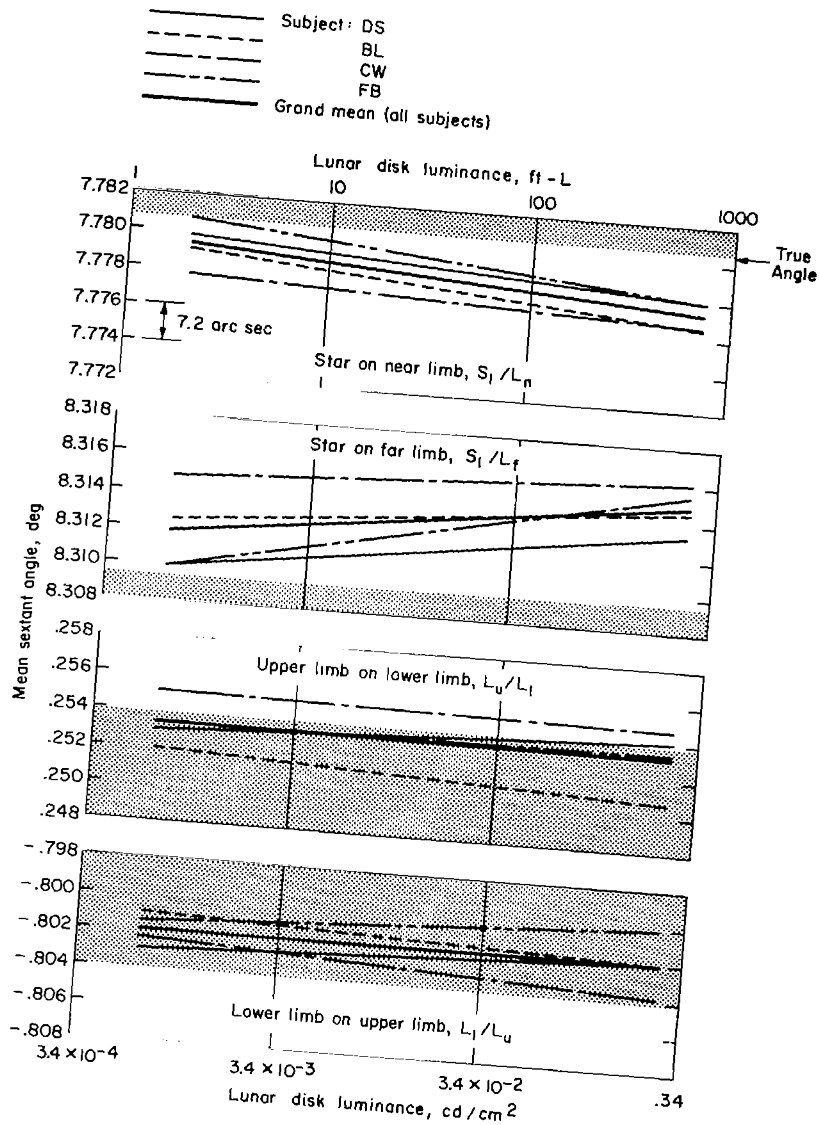


Figure 7.– Summary of sextant mean angle results for four subjects showing linear least squares fit of all experimental data.

Mean Measurement Error

The results presented in figures 5 and 7 show that increasing lunar disk luminance reduced the mean measured angle between the star and the near limb and increased the mean measured angle between the star and the far limb. Little effect of increasing lunar disk luminance was found, on the average, for either limb-on-limb measurement. Moreover, this case indicates that the mean angular errors were opposite in sign to those that would be expected from irradiation. These mean angular errors were about -3 arc sec for the upper-limb-on-lower-limb configuration and about 8 arc sec for the lower-limb-on-upper-limb configuration.

The star-on-lunar-limb results shown in figure 7 also indicate a difference in bias of about 5 arc sec between near-limb and far-limb effects at a given lunar disk luminance. Part of this difference is attributable to the large angular bias obtained by subject CW for the star-on-far-limb condition that, in turn, significantly increased the overall bias. Note that subject CW's results exhibit the largest overall irradiation effect.

Standard Deviation of Measurement Error

The results presented in figure 6 show that the standard deviation of measurement error varied from 1 to 12 arc sec. Most values, however, were between 2 and 6 arc sec. The mean results shown in figure 6 are summarized in figure 8. In general, slightly smaller standard deviations were found for the limb-on-limb measurements than for the star-on-limb measurements. Taken as a whole, the limb-on-limb measurements also appear to have a smaller range of standard deviations than do the star-on-limb measurements. Moreover, a rather consistent increase in standard deviation was found in the star-on-limb results at the highest value of lunar disk luminance which is not revealed in the limb-on-limb results.

Comparison With Other Data

A comparison of present star-on-limb irradiation results with those obtained in other investigations (refs. 1, 2, 4, and 8) is presented in figure 9.

To provide a common basis for comparison, the data are plotted as a function of apparent lunar disk luminance (i.e., disk luminance corrected for transmission losses through the beamsplitter, filters, and lenses in the T002 sextant). In all cases the mean angular error due to irradiation is positive for star-on-far-limb measurements and negative for star-on-near-limb measurements. As an indication of the precision of these data, one standard deviation of the measurement error for each disk luminance is shown by a vertical line. In general, the standard deviations obtained in this study are smaller than those obtained in the other studies. However, no such data were available for plotting from the investigation of reference 4 in which only the combined effect of irradiation for the star-on-near-limb and star-on-far-limb sightings were available in the form of a change in the measured angular diameter as a function of disk luminance. For purposes of comparison in figure 9 this change in subtense angle has been split into two equal parts for near limb and far limb. If the same plotting procedure were used with the results from the present investigation, it is evident that good agreement in the magnitude of the irradiation effect obtained would occur at a lunar disk luminance of about 3.4×10^{-2} cd/cm^2 (100 ft-L). Sextant

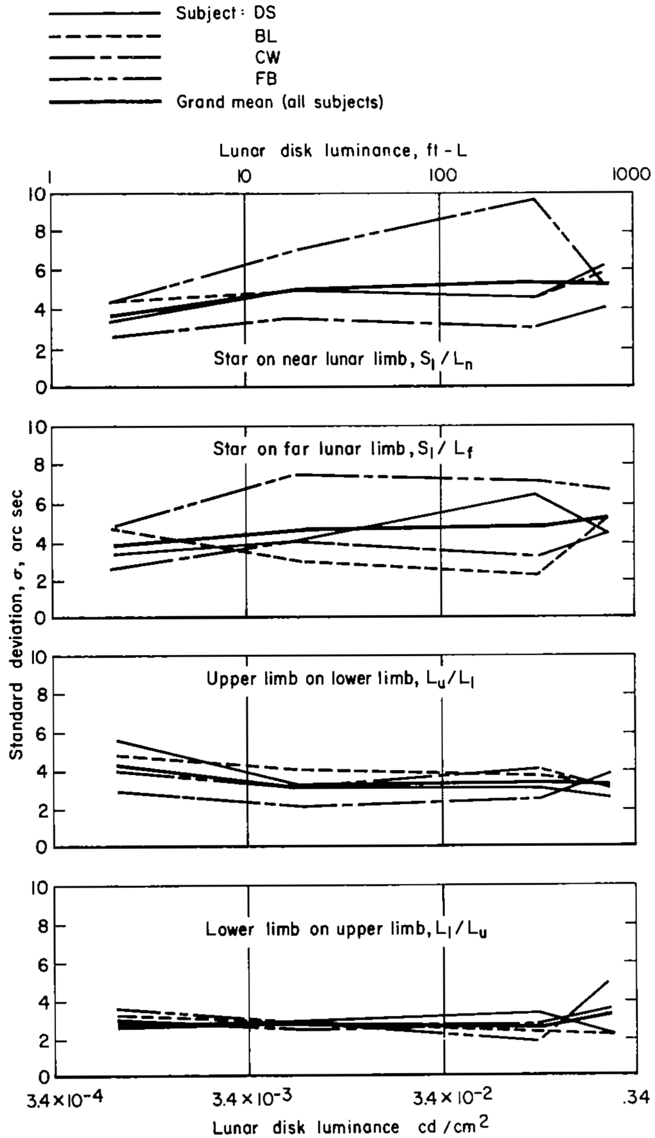


Figure 8.– Summary of sextant standard deviation results for four subjects showing mean values of all experimental data.

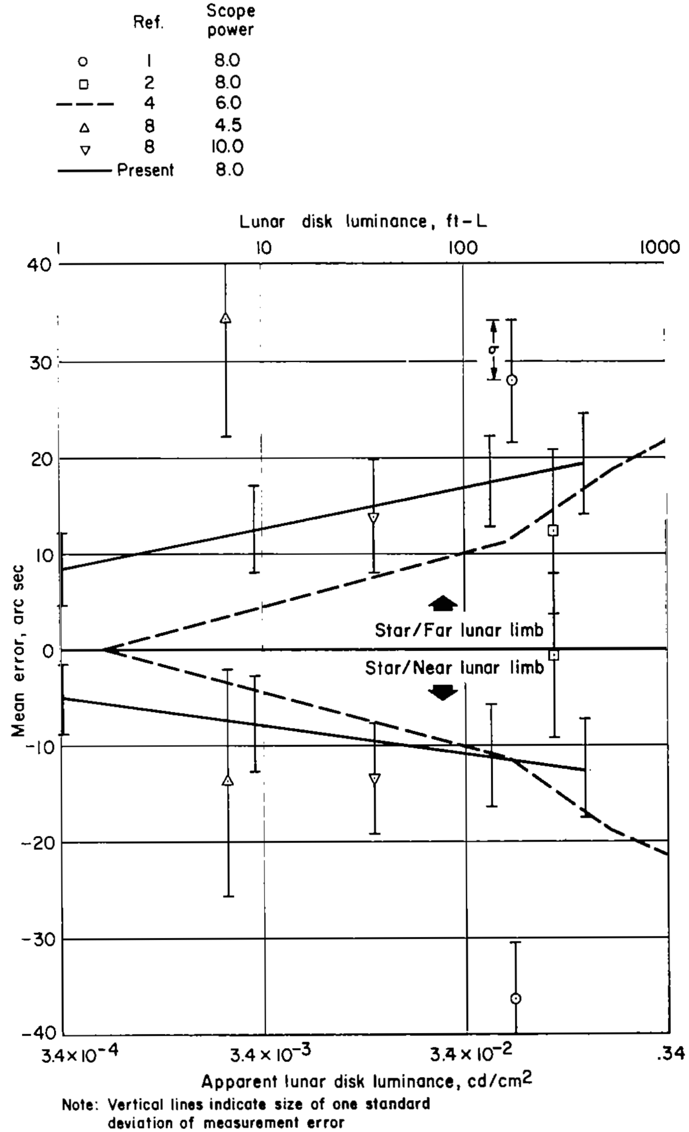


Figure 9.– Comparison of present study star/lunar limb irradiation effects with those obtained in other investigations.

telescope magnification probably contributes to the magnitude of the irradiation error as shown in the data presented in figure 9. However, except for a definite reduction in sighting performance variability with increasing magnifying power reported in reference 5 it has not been definitely established just what magnitude of angular error may be expected.

Comments of Subjects

Subjective information obtained from each of the four subjects provided a basis for assessing the degree of difficulty with which each subject performed the various sighting tasks. The elapsed time per sighting was also recorded. These data, together with the standard deviation of measurement error, serve as a reasonable index of performance motivation, sighting proficiency, and task difficulty.

In general, it was found that the limb-on-limb sighting task was comparatively easy for all four subjects. This was true for all disk luminance conditions and is reflected in the relatively short mean sighting times required (from 10 to 15 sec per sighting).

The subjects agreed that the star-on-limb sightings were the most difficult at the highest disk luminance. The mean sighting times do not necessarily reflect this as they were fairly constant throughout the entire range of disk luminances (from 15 to 20 sec per sighting). Moreover, no definite trends were noticed in the standard deviation results at the lower disk luminances. Nevertheless, a definite increase in variance was observed for the star-on-limb results at the highest disk luminance that substantiates this subjective comment.

Physiological-Optical Factors

Although the results of this investigation are generally in accord with those of similar studies on the effects of irradiation, certain unexpected trends were found that warrant further discussion. In particular, the relatively poor repeatability of results is of interest because of the implications this has on interpreting previous sextant irradiation studies. Differences in mean angular sighting values of from 10 to 15 arc sec were obtained by the same subject for several series of measurements under identical sighting conditions and yet the standard deviation for each of these series was only about 5 arc sec. Although reference 2 indicates that this poor repeatability might be due partially to various mechanical features of the sextant itself, it is probably due mostly to various physiological optical factors within the subject's visual system as well as his use of the sextant.

It is unlikely that sextant target-image vignetting (ref. 16) is occurring here (because of the relatively large 4 mm diam sextant exit pupil); it is likely, however, that the eye's pupil acts as the limiting aperture. That this is probably so is suggested by studies (refs. 17 and 18) showing that field luminances greater than about 3.4×10^{-3} cd/cm^2 (10 ft-L) produce natural pupil diameters smaller than 4 mm. Another study (ref. 19) showed that large individual differences exist in the field luminances required to produce a given pupillary diameter. Pupillary diameter is an important factor in determining retinal illumination and thus adaptation level. Further, since many researchers (e.g., refs. 20, 21, and 22) have found visual acuity (minimal resolvable angle) to depend on adaptation level above the cone threshold, any significant variation in pupillary diameter may well evidence itself in a change in acuity.

It is not difficult to show how the present sextant sighting task could be considered an acuity task. The lunar disk and navigation star are both viewed against a darker background. Therefore, as the two images approach each other to the "tangency" point, the subject's task is one of determining when there is no longer any perceptible background darkness between the two images; this is a task representative of almost all acuity tests.

The physiological optical model presented elsewhere (refs. 12 and 13) provides a basis for discussing this effect further. The light entering the eye from both bright objects is scattered within the various transparent media so that a gradient of illumination extends from all borders of these images. This "halo" of veiling, retinal illumination, as it is commonly called, raises the retina's threshold (i.e., it reduces the retina's sensitivity to light) in these regions so that the *background* as well as brighter images become more difficult to perceive. If visual fixation is not maintained on the same location on the lunar disk on each sighting trial, the retinal image of the disk will periodically light adapt the retinal area on which the navigation star is imaged. The result is greater variability in setting the star-limb tangency over a series of sightings.

Thus, entoptic light scatter and eye pointing stability are two other important factors in determining day-to-day sextant sighting accuracy.

The effect of the sextant's optics in this regard should also be noted. The 8-power telescope used would produce an image $\tau D^2/d^2$ more intense than the same source viewed by the naked eye, where, τ = the percentage of light transmitted through the telescope, D = diameter of the sextant telescope's entrance lens, and d = diameter of the (eye's) entrance pupil (ref. 23). Consequently, the resolving power of this telescope is d/D times the angle that would be resolved by the same eye with an artificial pupil of diameter d and a source of $\tau D^2/d^2$ more intense. This is why stars that are invisible to the naked eye can become visible through a magnifying telescope. The importance of this fact to the present investigation is that the lunar disk luminance and navigation star intensity are retinally more intense than otherwise with correspondingly more scattered light, which, in turn, raises the retina's threshold even more. Therefore, the choice of an optimal sextant telescope should consider (as a minimum), field of view needs, image magnification needs, transmission light losses, and natural pupil diameter under representative environmental illumination levels.

CONCLUSIONS

An analysis of this investigation into the effects of lunar disk luminance on the sextant sighting performance of four subjects with simulated lunar and stellar targets indicates that:

1. There was an apparent effect of irradiation on the sighting accuracy in measuring the angle between the simulated +2 magnitude star and either limb of the illuminated disk with the T002 sextant. This effect was found to increase from about 7 arc sec on the average at the lowest level of disk luminance to about 15 arc sec at the highest level.

2. There was no apparent effect of irradiation on the sighting accuracy in measuring the subtended angle of the illuminated disk (limb-on-limb configuration). The mean angular errors obtained in this case (-3 arc sec for upper limb on lower limb and 8 arc sec for lower limb on upper limb) were opposite in sign to those that would be expected because of irradiation effects.

3. An angular bias of about 5 arc sec in irradiation effect was obtained between the star-on-near-limb results and the star-on-far-limb results. This bias was due in part to a much larger than average irradiation effect obtained by one of the four subjects for the star-on-far-limb sighting condition.

4. The magnitude of the mean irradiation effect on sighting accuracy in this investigation is similar to that reported in other studies. The present results suggest that the effect is probably due to a change in retinal sensitivity that results from light scattered within the optic media and sextant optics. This scattered light then falls upon retinal regions adjacent to the image of the lunar disk, thereby causing the image of the star to be less visible than if scattered light was not present.

5. Although the overall sighting accuracy in this investigation was sufficiently high to define the general effects of irradiation, the repeatability of the measurements was not as good as anticipated. Lunar-limb-on-lunar-limb sightings were repeatable with greater accuracy than star-on-lunar-limb sightings. The reason suggested by this investigation is that a visual (irradiation-related) effect limits the accuracy of such sightings on high luminance objects.

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Moffett Field, Calif., 94035; June 15, 1971

APPENDIX

ANALYSIS OF FACTORS CONSIDERED IN DETERMINING SIGHTING ERRORS

COMPUTATION OF TRUE SEXTANT ANGLES

To determine the true values of the angles measured with the sextant between the near and far limbs of the simulated lunar disk and the star target, a method was devised whereby the values obtained for these angles using a precision theodolite could be used as the reference values (see fig. 10). When these values are properly related to sextant line-of-sight equations[1] and the sextant-theodolite geometry, sextant angles can be obtained to the same accuracy as those measured with the theodolite. The method makes use of the following linear expression that relates the sextant angle θ_s to the theodolite angle θ_t when these angles are nearly equal.

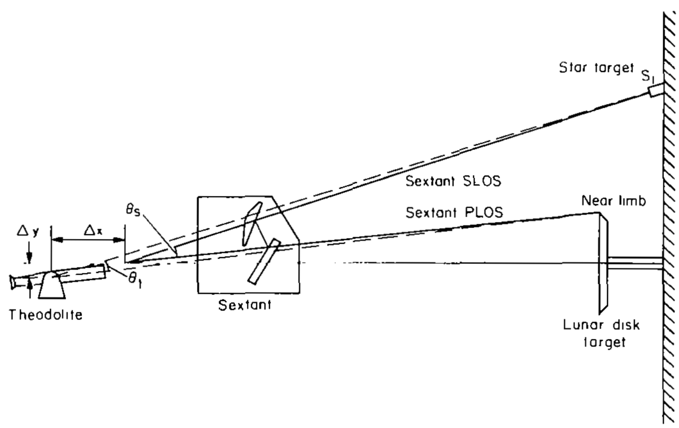

Figure 10.– Schematic representation of lines of sight from target points to the theodolite and through the optics (beamsplitter and scanning mirror) of the sextant.

$$\theta_s = \theta_t + \Delta\theta$$

$$= \theta_t + \frac{\partial \theta_t}{\partial x} \Delta x + \frac{\partial \theta_t}{\partial y} \Delta y$$

[1]These equations implicitly relate the x and y coordinates (with respect to the center of rotation of the scanning mirror) of the location of the projected intersection point of the primary and secondary lines of sight to the sextant angle setting (scanning mirror angle), fixed beamsplitter angle, and sextant-target geometry. For the sake of brevity they are not given in this report.

The sensitivity coefficients $\partial\theta_t/\partial x$ and $\partial\theta_t/\partial y$ are readily expressed in terms of the sextant-theodolite-target geometry depicted in figure 10. Since the sextant line-of-sight equations are also required in the computation to relate θ_s to Δx and Δy, the unique value of θ_s is obtained by the simultaneous solution of two sets of equations. The most important feature of this method is that it does not require a high order of accuracy in the linear measurement of distance between sextant and theodolite and to the targets[2] – not even the precise size of the lunar disk is necessary.

In the case of limb/limb sightings made with the sextant it is not possible to apply the method indicated above to determine the "true" sextant angles because the primary and secondary lines of sight do not cross at some point close to the sextant position. Rather, the sextant line-of-sight equations must be used together with the linear dimensions of and to the lunar disk. Fortunately, the distance from the sextant to the lunar target is not critical (i.e., the sensitivity of sextant angle to change in this distance is very small). Thus, the only stringent requirement is that the vertical diameter of the disk be known precisely which is the case (diam = 15.243 cm ± 0.001 cm).

EFFECTS OF PARALLAX AND REFRACTION

Because of the small distance between the sextant sighting station and the uncollimated lunar and stellar targets (~17 m), the angles measured with the sextant were extremely sensitive to changes in parallax effects arising from small angular movements of the sextant in pitch. (Although the sextant measured angles were also sensitive to small amounts of translation of the sextant, especially in the longitudinal direction, this presented no problem since the sextant was locked in the gimbal support and constrained from any movement in translation.) The parallax effect resulted from the displacement of the scanning mirror (which reflects the sextant secondary line of sight onto the beamsplitter and the PLOS) about 3 in. from the PLOS. Changes in the amount of parallax occur for a given sighting condition when the sextant pitch angle in the gimbal support is altered. To prevent this happening inadvertently during the course of the experiment, the gimbal support was locked in pitch. As a further safeguard, care was taken at the beginning of each sighting session to ensure that the lunar disk target was precisely centered in the PLOS.

Even though all due caution was exercised in eliminating parallax as an extraneous effect or variable in the angular measurements, the gimbal support was flexible enough to allow very small changes in the pitch setting of the sextant (or, equivalently, the centering of the primary target). To establish the magnitude of the sextant angle change associated with small angular displacements of the primary target in the field of view, the sextant line-of-sight equations were modified to provide the capability of calculating the sextant angle reading when the sextant was rotated about its pitch axis. These modified equations showed that an approximately linear relationship exists between sextant angle reading and rotation or pitch angle for sextant angles close to 8° and for values of pitch angle between -1.0° and 1.0°. Thus, in relation to the experimental apparatus used, the change in sextant angle reading corresponding to a given change in pitch angle can be expressed as

$$\delta\theta = \left(\frac{d\theta}{d\phi}\right)_{\phi=0} \delta\phi$$

[2] This is because the partial derivatives $\partial\theta_t/\partial x$ and $\partial\theta_t/\partial y$ are not very sensitive to small variations in the sextant-theodolite-target geometry. Furthermore, since $\Delta\theta$ is a very small quantity (~0.01°), it is not necessary to specify it to more than three significant figures.

where $\delta\phi$ is the change in pitch angle from the zero value and the derivative has the value -0.027 for sighting on the star and near limb and has the value -0.030 for sighting on the star and far limb. As an example of the practical aspect of parallax effects, consider the extreme condition when the lunar disk is not centered in the field of view but is moved so that one edge is tangent to the horizontal crosshair (i.e., the sextant is rotated in pitch 0.25°). The sextant angle reading between the star and near limb will be changed by 24.3 arc sec and the sextant reading between the star and far limb will be changed by 28.8 arc sec. It is unlikely that more than 1 or 2 arc sec error on the average can be ascribed to the noncentering of the primary target in this investigation.

Another effect that must be considered is caused by the refraction of light passing through the plate glass beamsplitter in the sextant (fig. 11) when the angle between the targets at comparatively short range is measured with the T002 sextant. This element of optical glass is 0.265-in. thick and is set at an angle of 26° from the vertical. Assuming an index of refraction of 1.5 it is found, using Snell's law, that entering light at incidence 26° is refracted 9° in passing through the glass. This refraction results in a vertical offset of 0.043 in. for light rays passing through the beamsplitter. Thus, a point on the viewed object in the primary line of sight, from which light is refracted through the sextant beamsplitter to the eyepiece, is lower by 0.043 in. than would be the case without refraction. The practical effect of this vertical displacement of viewed objects in the primary field of view is to reduce the sextant angle by the corresponding angular displacement of 13.7 arc sec. This effect has been accounted for in the computation for parallax corrections.

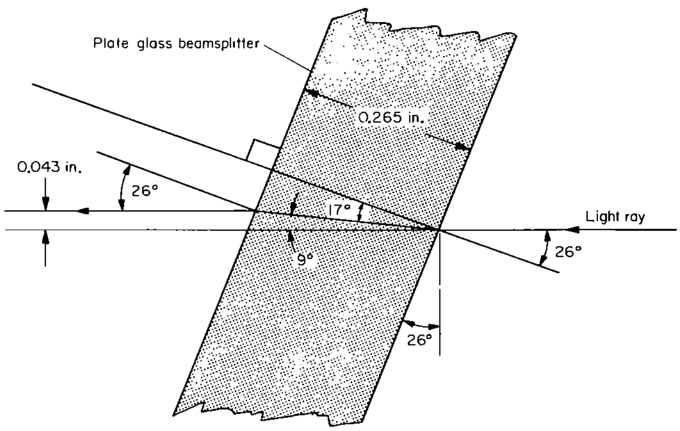

Figure 11.– Schematic representation of refraction of light through beamsplitter (along primary line of sight) of sextant.

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