NASA TECHNICAL NOTE

NASA TN D-4174

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NAVIGATOR PERFORMANCE USING A HAND-HELD SEXTANT TO MEASURE THE ANGLE BETWEEN A MOVING FLASHING LIGHT AND A SIMULATED STAR

by Bedford A. Lampkin

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1968

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SUMMARY

The performance of a navigator using a hand-held sextant to measure the angle between a moving flashing light and a simulated star has been investigated in the Ames Midcourse Guidance and Navigation Simulator. The primary variables were the rate of angular motion of the flashing light and the frequency and on time characteristics of the flashing light. Performance criteria were the standard deviation of the measurement data and the bias of the measured angle compared to the true angle. Measurements were made from a stationary sighting station and from a sighting station simulating spacecraft oscillatory motion.

An effective technique was developed for training navigators to measure accurately with a sextant. This technique uses measurement error feedback to the operator subsequent to each measurement to inform him of his error and to aid him in improving his subsequent measurements. The performance during this experiment indicates that an experienced navigator using a hand-held sextant during rendezvous navigation may obtain data with an accuracy of better than 60 arc seconds.

INTRODUCTION

The hand-held sextant has been demonstrated as having desirable characteristics applicable to obtaining navigation measurements on board manned spacecraft. These characteristics are: low weight and volume, high reliability and accuracy, and operation with little or no spacecraft power.

Investigations of the general application of the hand-held sextant to space navigation have been reported in references 1 and 2. A particular application of the hand-held sextant that is currently of interest is associated with the rendezvous of the lunar module and command module of the Apollo spacecraft after ascent of the lunar module from the lunar surface. In the rendezvous operation the command module is assumed to be the passive vehicle in orbit about the moon. The navigator, using information computed from sextant sighting data, guides the lunar module into a rendezvous position. His sighting task is to measure the angle between the command module and a reference star.

The sighting target on the passive vehicle was chosen to be a light for nighttime operation. Further, a flashing light was chosen to enhance the detectability of the target against the celestial background and to minimize the heat generated and power consumed by the light. On this basis, it was estimated that the light should flash approximately once a second and have an on-time of approximately 50 milliseconds. Investigations of the detectability of flashing lights are reported in references 3 and 4.

An investigation of sextant sighting with a stationary flashing light target is reported in reference 5. In spacecraft rendezvous, possibly high rates of motion relative to the target and the brief periods of time (50 ms) in which the command module target light is visible, make the measurement task more difficult. Therefore, in the present investigation the research study of reference 5 was extended by simulating the rendezvous sighting task with the flashing light target moving at various rates relative to the simulated star. In addition, a technique was developed by which the sextant operator was trained to perform the rendezvous measurement task effectively. The experimental variables consisted of target characteristics and sighting station dynamics. The effect on measurement accuracy of subjectively selecting data (subsequent to the measurements) was considered.

The subjects participating in this investigation were 11 college students, one research engineer, and an Air Force navigator.

TEST EQUIPMENT

Sighting Station

The investigation was conducted in the Ames Midcourse Guidance and Navigation Simulator described in reference 1. Figure 1 is a sketch of the simulator; the simulator cab is on the left and the sighting targets are at the far right. The stationary sighting station shown in figure 2 was used in the initial phase of the investigation. During the second and third phases of the investigation the sighting station was the center seat of the three-man simulator cab shown in figure 3. The cab is mounted on an air bearing which provides rotational freedom about all three axes. The cab may be rotated by an electromechanical drive system located above the cab. Signals to the drive system may be supplied either from an analog computer or from a hand controller.

Sextant

Figure 4 is a photograph of a modified Plath micrometer marine sextant used during the investigation. The sextant telescope had a magnifying power of 6 and a 30-mm aperture objective lens. The telescope field of view was approximately 7-1/2°. The minimum readout on the vernier scale was 0.1 arc minute. The sextant weighed 1.67 kg.

Sighting Targets

The targets were a star and a command module sighting target. The star was simulated by a 12-inch parabolic mirror that projected the collimated light of a small source. The magnitude of the star was approximately 2. Figure 5 is a photograph of the command module sighting target. It was simulated by a 12-inch parabolic mirror which projected the collimated light of a small source toward the sighting station. The light source of each target was a tungsten filament lamp that operated at its rated voltage. Without its flashing characteristic the simulated command module target light simulated a magnitude 2 star. The collimated light projected from each light source intersected at the sighting station as shown in figure 6. The simulated command module target was made to flash by rotating a slotted disk between the observer and the steady light source (fig. 5). The flash frequency was varied by the speed of rotation of the disk. The on-time of the flashing light was varied by changing the included angle of the slotted cutout. The relative motion between the two sighting targets was provided by rotation of the flashing light about its vertical axis. When the simulated command module target light source was rotated about its vertical axis, the projected beam of light was rotated in the horizontal plane. The horizontal plane was also the plane of the included angle between the simulated star and simulated command module sighting target. The relative motion between the two sighting targets was varied by changing the rotational speed of the command module target light. Because of limitations of the rotating drive mechanism, the maximum angular rate of rotation was 100 arc seconds per second. The drive system that rotated the target light also positioned a potentiometer. The voltage output from the potentiometer was calibrated as a function of the angular position of the command module target. The output voltage was recorded by a digital voltmeter and the recorded voltage was used with the calibration to determine the actual target angle.

Data Recording Equipment

At the sighting station a digital voltmeter and a digital printout displayed and recorded, respectively, the output of the command module target light potentiometer. The printout device was actuated by the sextant operator at the time of each measurement. The electric potential across the potentiometer was 200 V. The minimum voltage readout was 0.01 V which was proportional to a change in the command module target angle of approximately 0.65 second of arc.

TEST DESCRIPTION

This investigation was conducted in three phases. Each phase was conducted for a three week period. In the first week of phases I and II the participating subjects were trained in operating the sextant under the experimental conditions, and during the last two weeks of these phases, the experimental data were obtained. In phase III the subjects were trained during the first two weeks; however, all data obtained during the three week period were recorded. The experimental conditions were presented to the subjects in a random manner so that if performance improved with sighting experience, it would tend to be distributed evenly over all experimental conditions. The data tabulated in tables I, II, and III were obtained during phases I, II, and III, respectively, and show the standard deviation (1σ) and mean measurement bias error ($\overline{\epsilon}$) for each subject under each experimental condition.

Phase I

During phase I all sighting data were obtained from a stationary sighting station (fig. 2). The experimental variables of phase I were the flash frequency, on time, and relative motion applied to the simulated command module sighting targets as summarized in the table below.

Target characteristics		Line-of-sight motion rate, arc sec/sec
Flash frequency, flash/sec	On time, percent of flash period	
1	5	25
1-1/2	10	50
2	20	100
Steady light (100 percent on time)		

These 30 combinations of variables were presented to the subjects. Seven subjects participated in three sighting sessions each day during the final 10-day period. During each session the subjects made 5 measurements with the targets stationary and 10 measurements with one line of sight in motion.

Phase II

During the second phase of this investigation the sighting station was the center seat of the simulator cab. The cab could be oscillated sinusoidally about its three axes. The amplitude and rate of this sinusoidal motion were approximately $\pm 1^{\circ}$ and $\pm 0.5^{\circ}$ per second, respectively. The experimental variables of phase II applied to the flashing light sighting target are summarized in the following table.

Target characteristics		Line-of-sight motion rate, arc sec/sec
Flash frequency, flash/sec	On time, percent of flash period	
1	5	25
2	20	50
		100
Steady light (100 percent on time)		

With the cab in oscillatory motion about its three axes, all 15 combinations of these variables were presented to the subjects. In addition, data were obtained with the sighting station stationary, the steady light condition, and the target moving at 25, 50, and 100 arc seconds per second. There was a total of 18 experimental conditions for the second phase of the experiment. Eight subjects participated in approximately two sighting sessions each day during a 10-day period. During each session the subjects made 5 fixed line-of-sight measurements and 15 moving line-of-sight measurements under a single experimental condition.

Phase III

There were 5 experimental conditions during phase III. Three subjects participated in one sighting session each day for 14 days. Each sighting session consisted of 5 static measurements and 15 measurements under two different experimental conditions for a total of 35 measurements per session. Training was accomplished during the first 2 weeks. Data were recorded during the entire 3-week period.

Data were obtained with the subjects seated in the simulator cab. All data were obtained with the sighting station oscillating sinusoidally about the roll and yaw axes at amplitudes and maximum rates of $\pm 1^{\circ}$ and $\pm 0.5^{\circ}$ per second, respectively. The variables applied to the flashing light sighting target are indicated in the following table.

Target characteristics		Line-of-sight motion rate, arc sec/sec
Flash frequency, flash/sec	On time, percent of flash period	
1	5	20
		40
		60
		80
		100

During phase III the three subjects were asked to evaluate their own performance by rating each moving line-of-sight measurement "good," undecided," or "bad" subsequent to each measurement but prior to knowing the error. The only further instructions given the subjects was that their rating reflect their expected measurement error.

Subjects

A total of 13 subjects participated in this investigation as shown in the following table.

Phase number	Subjects
I	1 2 3 4 5 6 7
II	4 5 6 7 8 9 10 11
III	11 12 13

Subject 11 was an Air Force navigator assigned to Ames Research Center and subject 12 was a research engineer. All other subjects were male college students. Subject 11 was experienced in the operation of the bubble type sextant and while at Ames often operated the two line-of-sight, hand-held sextant. Subject 12 had seldom operated a sextant prior to this investigation. All other subjects had previously participated for several weeks in an experiment which utilized a two line-of-sight, gimbal-supported sextant sighting on stationary targets. All subjects had normal vision.

Training

During the first week of phases I and II, the subjects were instructed and trained in the use of the sextant for the measurement task. The data obtained during that period are not reported.

During phase III the subjects were trained for the first nine days of the test period. To facilitate training the measurement bias error, in seconds of arc, was available to the subjects subsequent to each measurement during training. With this type of error feedback the subjects could correlate the position of the target images in the sextant telescope field of view with their measurement error. The subjects were instructed to modify their measurements on the basis of the feedback information and to minimize the error displayed on the voltmeter. (See the elements for successful training discussed in ref. 6.)

Performance Criteria

The performance criteria were the repeatability of a group of measurements about the mean angle and the bias of the mean angle from the true angle. The measure of sighting repeatability was the standard deviation (1σ) of a group of measurements obtained during a single sighting session. During each sighting session of phases II and III, the bias error was the difference between the mean of the measured angles and the true angle. The measurement bias error was not obtained during phase I.

Sextant Measurement Task

Actual rendezvous navigation measurement.- During an actual rendezvous navigation measurement, the navigator is assumed to be using a hand-held sextant and an event timer. The navigator first positions the sextant so that the primary line of sight and secondary line of sight each receive a target image (fig. 4). The image received in the secondary line of sight is reflected from the indexing mirror and the partially reflecting surface of the horizon mirror. The image received in the primary line of sight passes through the horizon mirror with some attenuation in intensity. Thus, the two target images may be observed in the telescope field of view. The navigator then adjusts the sextant indexing arm to position the indexing mirror so that the observed target images are displaced. He allows the sextant mirror position to remain constant and because of the motion of one target image relative to the other, the two target images will eventually superpose in the telescope field of view. From an estimate of the time of superposition, he then reads the measured angle and the time of the measurement. These data are used in the rendezvous navigation computation.

Simulated rendezvous navigation measurement.- During the simulation of the rendezvous navigation measurement task, the subject was required to perform two types of measurements. The first measurements were obtained with the flashing light stationary and the second were with the flashing light moving. The first measurements were used to determine the initial target angle which in turn was used to determine the bias error of the subsequent measurements with moving target line of sight. The flashing light characteristics were the same for both types of measurements.

Figure 7 shows the relationship between the sextant measured angle and the potentiometer voltage during the two types of sextant measurements. The calibration slope, K, was obtained prior to the investigation. A theodolite was used to determine the angular position of the flashing light target, and then the change of potentiometer voltage as a function of the flashing light angular position was obtained from the calibration. The standard deviation of the calibration data about the linear slope, K, was 5 seconds of arc.

During each sighting session the subject first measured the included angle between the targets (with the simulated command module target stationary) to determine the target angle at the initial position. He then adjusted the sextant indexing mirror so that the target images became superimposed in the telescope field of view. The measured angle, A_1, was read from the sextant readout scale. A series of these measurements were obtained to provide an average value of the initial angle, $\bar{A}_1$. The potentiometer voltage, V_1, was constant during these measurements and was recorded.

At the conclusion of the first series of measurements, the sextant indexing mirror was positioned so that the sextant readout angle was displaced approximately 12 minutes of arc from the average initial target angle. The displacement of the indexing mirror by 12 minutes of arc is shown in figure 7 as ΔA. The target images were thereby displaced approximately 1° of arc in the telescope field of view by the magnification by the telescope. The indexed angle, A_2, was recorded. The indexing mirror remained at this position during the remainder of the session. While making the measurement the subject held the sextant in his right hand and an event timer switch, which operated the voltage recorder, in his left hand. At his oral command, the target light was placed in motion. The operator observed the position of the target images as they moved toward superposition in the telescope field of view. When the subject judged that superposition occurred, he actuated the event timer switch to record the potentiometer voltage, V_n. The target light was then returned to its initial position. As indicated in figure 7, the information required to determine the bias error, ϵ, was the initial angle, $\bar{A}_1$, the potentiometer voltage, V_1, the potentiometer calibration, K, and the potentiometer voltage, V_n, obtained with the target line of sight in motion.

Since the flashing target light was generally visible only briefly during each flash cycle, it would be expected that actual target superposition would seldom be observed. The subject was therefore required to estimate the instant of target superposition from the information obtained while viewing the target images. Each time the target light appeared, it was in a different position relative to the star image. The relative motion between the target light and star image resulted from two different actions. Rotation of the target light caused the image seen in the primary line of sight to move relative to the image observed in the secondary line of sight. Small rotational movements of the sextant (because of the small motions of the subject holding the instrument) also caused the image observed in the secondary line of sight to move relative to the primary line-of-sight image.

As indicated in figure 7, a positive measurement error resulted when the subject made a late judgement of target superposition and caused the potentiometer voltage to be recorded after the target light had rotated past the position at which the target light and star image were superimposed in the telescope field of view; a negative measurement error resulted when the subject prematurely judged superposition.

Data Reduction

The bias error was the difference between the true angular increment and the measured angular increment. As indicated in figure 7, the true angular increment was ΔA, or the difference between the angle $\bar{A}_1$, measured with the targets at their initial position, and the angle A_2 to which the sextant was indexed for the measurements with the target moving. This angle was constant during each sighting session. The measured angular increment was the product of the potentiometer voltage calibration constant, K, and the difference between the voltage V_1, recorded at the initial target position and the voltage, V_n, recorded at apparent superposition. The measured angular increment generally varied with each measurement. During each sighting session a series of measurements with target motion were made. From these measurements the mean of the bias error and the standard deviation of the bias errors were obtained.

Error Analysis

To test the instrument-operator system performance, it is necessary first to determine the true angle the operator is attempting to measure. Unfortunately, this cannot be done perfectly; consequently, the random error in each experimental data point is the sum of the error contributed by the instrument operator and the error in determining the true angle.

$$\epsilon_{exp} = \epsilon_{I\text{-}O} + \epsilon_{cal} \tag{1}$$

where

ϵ_{exp} the random error of the experimental data

$\epsilon_{I\text{-}O}$ the random error contributed by the instrument-operator combination during the moving line-of-sight measurement

ϵ_{cal} the random error constructed by the experimental technique of defining the true angle

It may be assumed that $\epsilon_{I\text{-}O}$ and ϵ_{cal} are uncorrelated; then the variance of ϵ_{exp} can be written as

$$\sigma^2_{exp} = \sigma^2_{I\text{-}O} + \sigma^2_{cal} \tag{2}$$

The purpose of this analysis is to examine the various sources of error inherent in the determination of the true angle and to estimate the variance of the resulting error which may be expected to appear in the experimental data. If this variance is subtracted from that observed in the experimental data, the result should be a reasonable indication of navigator performance.

The experiment entails the following procedure to determine the true angle (fig. 7). First the potentiometer voltage output is calibrated in terms of the angle of the movable light source. This is done with a theodolite to obtain the proportionality constant, K, between changes in angle and changes in the voltage output of the potentiometer. It was determined that the process of using the voltmeter to indicate true angle involves an uncertainty with a standard deviation of 5 seconds of arc.

At the beginning of each sighting session the initial angle, $\bar{A}_1$, must be determined since a number of variables act to change this angle from one session to another. The procedure used was to have the subject make a series of five measurements of $\bar{A}_1$. During phase III the standard deviation from the sample mean for subjects 11, 12, and 13 was 8, 14, and 28 seconds of arc, respectively. It may be noted that reference 5 shows a similar variability of data (13 sec of arc) for a nearly identical situation; namely, determination of the angle between a stationary flashing light and a simulated star similar to the one used in this investigation.

Finally in preparation for the moving line-of-sight measurements, the sextant is indexed mechanically by an amount ΔA (fig. 7). This introduces an additional error because of the uncertainty in setting the sextant readout to a specified angle. Measurements during sextant calibrations indicate this operation entails a variability with standard deviation of 3 seconds of arc.

When the variances of these three independent error sources are subtracted (using the $\bar{A}_1$ measurement variability of ref. 5) from the variance of the experimental data, it is seen that the instrument operator error may be assumed to have a standard deviation of

$$\sigma_{I-O} = \sqrt{\sigma_{exp}^2 - (5^2 + 13^2 + 3^2)} = \sqrt{\sigma_{exp}^2 - 203} \tag{3}$$

It should be noted that in a real-life application the instrument operator would be required to read out the sextant angle, an operation which is not in the simulation described here. This readout error is equivalent to the sextant indexing error described above. Therefore if it is desired to interpret the experimental data in terms of the real-life situation, the indexing error variance should not be subtracted and the variance of the instrument-operator error would be slightly larger. However, the effect of this additional error is quite small.

RESULTS AND DISCUSSION

The data obtained during these experiments are tabulated in tables I through III and are presented in figures 8 through 19.

Phase I

The performance criterion used during phase I was the standard deviation of a group of sighting measurements about the mean. A standard deviation was computed for the measurements obtained during each sighting session. An analysis of variance was made with the standard deviation values obtained during phases I and II. The purpose was to determine whether the experimental variables significantly affected measurement performance. The results indicate that the effect of the flash frequency was not significant, but that the effect of the on time and motion rate of the target light was highly significant. The probability of explaining as chance the significance of the effect on performance of target light on time and target light motion rate was 1 chance in 200 and 1 in 1000, respectively.

The data of phase I, summarized in figures 8(a) and 8(b), show, respectively, the effects of flashing light on time and flash frequency on subject performance. For figure 8(a) the values of standard deviation obtained at the various flash frequencies have been averaged to provide a value of standard deviation for each experimental condition of on time and target motion rate. As the target motion rate increased, the standard deviation increased. The standard deviations obtained with the shorter on time generally increased more rapidly with increased motion rate than those with the longer on time.

For figure 8(b) the standard deviations obtained at the various on times have been averaged to provide a standard deviation for each flash frequency and target motion rate. The standard deviation consistently increased as the target motion rate increased from 25 to 100 arc seconds per second. At frequencies from 1 to 2 flashes per second, the effect of flash frequency on performance appeared to be small except at 100 arc seconds per second and 1-1/2 flashes per second where an increase in the standard deviation may be noted. At each target motion rate the best performance scores were obtained with the target having a steady light.

Phase II

For the data of phase II the analysis of variance also indicated a significant effect of target light on time and motion rate on measurement performance. The probability of explaining as chance the significance of the effect on performance of target light on time and motion rate was 1 chance in 1000 and 1 chance in 200, respectively.

The standard deviations in figure 9 are the averages of the values obtained by the eight subjects as a function of target motion rate. Subjects 4, 5, 6, and 7 had participated in phase I. Subjects 8, 9, and 10 had not participated in phase I, but they had experience similar to that of subjects 4 through 7 prior to phase I. Subject 11 was an experienced Air Force navigator assigned to Ames Research Center. In figure 9 all standard deviations are less than 60 seconds of arc. For each test condition an increase in the target motion rate generally increased the task difficulty as indicated by an increase in standard deviation. The flash frequency had little effect on the standard deviation. However, decreasing the on time of the flashing light increased the task difficulty as indicated by the increase in scores of standard deviation. The values of standard deviation increased both for a reduction in on time from 100 percent to 20 percent and from 20 percent to 5 percent. The sighting station oscillatory motion appeared to increase the task difficulty by a small amount at the lower target motion rates.

The standard deviations obtained during phases I and II are presented in figures 10(a) and 10(b) as a function of flashing light on time and flash frequency, respectively, at target motion rates of 25, 50, and 100 arc seconds per second. The standard deviations presented in figure 10(a) are the average of the values obtained at the several frequencies. At all motion rates the standard deviation tends to decrease as the on time of the flashing light increased. With the exception of the steady light condition (100 percent on time) the data from phases I and II presented in figures 10(a) and 10(b) correlated well. With the steady light the values of standard deviation obtained during phase II are consistently lower than those obtained during phase I. The standard deviations presented in figure 10(b) are the averages of the values obtained at the several on times. Again there is good correlation between the data obtained during phases I and II except for the steady light condition. The effect of flash frequency on the standard deviation scores in the range of 1 to 2 flashes per second appeared to be small except at 1-1/2 flashes per second with a motion rate of 100 arc seconds per second when an increase in the standard deviation was noted.

In figure 11 the mean bias errors are shown as a function of the target motion rate. These values are the average obtained by the eight subjects. The sign convention used in presenting these data is that positive values indicate a lag in judging the time of target superposition. With the measured angle decreasing, the significance of a positive bias error is that the measured angle is smaller than the true angle when the bias error is equal to the true angle minus the measured angle. The data of figure 11 indicate, therefore, that for all the experimental conditions the average time of target superposition was determined late and this tardiness increased as the target motion rate increased. However, it is difficult to detect any other consistent trends in the data. It was noted when these data were obtained there was a large degree of variability in mean bias errors for the eight subjects.

The data of figure 12 indicate the daily variability in the eight subjects' performance during the final 10 days of phase II. On each of the 10 days there were approximately 16 sighting sessions, each resulting in a standard deviation and a mean bias error. In figure 12(a) the average of the 16 standard deviations and the standard deviation about the mean is presented. In figure 12(b) the average of the 16 mean bias errors and standard deviations about this value is presented for each of the final 10 days of phase II. A comparison of the data of figures 12(a) and 12(b) shows that the average standard deviations of figure 12(a) are fairly constant and there is a consistent pattern of variability during the 10 days. However, the mean bias error of figure 12(b) varies more widely and the pattern of variability is less consistent during the 10-day period.

Phase III

Present day navigation computational techniques generally assume some procedures for detecting and eliminating the effect of consistent bias errors on the computations. However, the detection of bias errors as variable as those obtained during phase II would probably require an impractical quantity of data. The reduction of bias errors as large as those obtained in phase II was felt to be necessary if the hand-held sextant were to be used for rendezvous navigation measurements. A specialized training technique consisting of bias error feedback to the subjects subsequent to each measurement was devised in an attempt to reduce the bias errors, and phase III was undertaken to evaluate the effectiveness of such a technique. Using the error feedback information each subject attempted to correct his measurement technique to minimize the bias errors.

The data of figure 13 indicate the daily variability in the performance of the three subjects during phase III. On each test day each subject performed under two experimental conditions, giving a daily total of six standard deviations and six mean bias errors. In figure 13(a) the average of the six standard deviations and the standard deviation about the mean is presented. In figure 13(b) the average of the six mean bias errors and the standard deviation about this value is presented for each of the 14 test days. A comparison of the data of figures 13(a) and 12(a) shows that the mean standard deviations are fairly constant. The mean bias errors of figure 13(b) vary widely throughout the test period. A comparison of the data of figures 12(b) and 13(b) shows that the mean bias errors obtained during phase III are significantly less than those obtained during phase II. Also the variability of the bias errors obtained during phase III is less than the variability obtained during phase II, as indicated by the crosshatched areas of the respective figures.

To indicate further the effectiveness of the training technique, there are presented in figure 14 measurement error data obtained during phases II and III. The data of the Air Force navigator are not included in this figure since he participated in both phases and it was felt that his experience could compromise the results. In figure 14 the measurement errors in seconds of arc are shown as a function of the target motion rates in arc seconds per second. The data of phase II wherein the subjects trained without error feedback were obtained during the final two weeks of the test phase and are the average values obtained by seven subjects. The data from phase II presented in figure 14 were obtained with the same target flash characteristics as phase III. The data of phase III, where the subjects trained with error feedback, were obtained during the final week and are the means of two subjects. In each case the crosshatched areas indicate the average standard deviations for the participating subjects. The performance of the subjects during phase III is consistently better than that during phase II. At 100 arc seconds per second the total improvement (mean bias error plus the standard deviation) was approximately 26 seconds of arc.

In figure 15 the error data in seconds of arc obtained by the Air Force navigator (subject 11) during phases II and III are shown. The target flash characteristics for the phase II and III data are the same. During phase II these data were not obtained by this subject at the highest target motion rate. The phase III data were obtained during the final week. The crosshatched areas indicate the values of the standard deviation of the bias errors. The average reduction in mean error between phase II and III data is approximately 48 seconds of arc. The maximum error values during phase III was reached at a target motion rate of 60 arc seconds per second and was 62 seconds of arc.

Performance Subsequent to Error Feedback Training

A navigator on board a spacecraft performing sextant measurements will not receive immediate error feedback. To simulate this condition and to gain further insight into the value of the training technique and the retention of training, error feedback information was withheld during the third week of phase III. In figure 16 the sum of the absolute value of the mean bias error plus the standard deviation obtained with error feedback (first two weeks) and without error feedback (third week) is presented as a function of target motion rate for the three subjects participating in phase III. Subject 11 had particular difficulty when the target motion rate was approximately 60 arc seconds per second. It was his opinion that the rate was not low enough for him to observe target superposition consistently and high enough to force him to rely on error feedback training to obtain good performance scores. Apparently at this rate, this most experienced subject was attempting to observe target superposition, and being unable to do so, he was consistently tardy in completing his measurements. Being aware of this tendency and with further error feedback training, subject 11 might significantly improve his performance near a target motion rate of 60 arc seconds per second. The measurement error of subjects 12 and 13 generally improved enough during the final week, apparently as a result of continued learning, to overcome the lack of error feedback.

Normalized Values of Standard Deviation

In figure 17 standard deviations which have been normalized by two different methods are presented as a function of target motion rate. The standard deviations obtained during phases I, II, and III have been normalized, and in figure 17 the average value and the maximum and minimum values of the normalized standard deviation are shown. In method I the standard deviation has been normalized by the value of the angle through which the flashing light has rotated during its unlighted intervals per second of time. This normalizing value is a function of the target motion rate and the on time of the flashing light. As an example, the normalizing value for a rotation rate of 50 arc seconds per second and an on time of 5 percent is 95 percent of 50 or 47.5 arc seconds per second of time. In method II the value of standard deviation has been normalized by the angle through which the flashing light has rotated during its unlighted interval per flash cycle. This normalizing value is a function of the target motion rate, the on time, and frequency of the flashing light. As an example, the normalizing value for a rotation rate of 50 arc seconds per second, 5 percent on time, and 2 flashes per second is 95 percent of 50/2 or 23.75 seconds of arc per cycle. The primary point of interest in figure 17 is that the difference between the maximum and minimum values of the data normalized by method I is much less than that normalized by method II. It may be noted that the minimum boundary for both sets of data is the same. It would appear that for conditions appropriate to this investigation, subsequent measurement performance may be predicted on the basis of on time and rate and without regard to flash frequency. Based on the selected target motion rate and on time of the flashing light, the angular motion per second of the target light during its unlighted intervals may be obtained. From figure 17 the mean value of standard deviation normalized by method I and at the appropriate target motion rate may be obtained. The product of the normalized standard deviation and the unlighted intervals angular motion will indicate the expected measurement performance scores of standard deviation.

Subjective Evaluation of Measurement Performance

It is anticipated that in taking sextant measurements on board a spacecraft, the navigator will be able to improve his measurement accuracy merely by deleting those measurements in which he has the least confidence and using only those measurements in which he has the greatest confidence. During phase III it was attempted to demonstrate the improvement in measurement accuracy obtained by deleting those data in which the subjects had least confidence. During phase III the subjects were required to evaluate each of their measurements on the basis of their confidence in the agreement of the measured and true angle by rating them good, undecided, or bad. In figure 18 the percentage of the daily measurements in each "confidence rating level" is shown for each of the three subjects during the 14 test days. It can be seen that each subject's pattern of measurement evaluation remained fairly constant during the test period. The Air Force navigator, subject 11, evaluated approximately 70, 20, and 10 percent of his measurements good, undecided, and bad, respectively. Subject 12 judged 20 percent of his measurements good while subject 13 seldom judged a measurement good.

In figure 19 the variation of the sum of the absolute value of the mean measurement bias error plus the standard deviation $|\bar{\epsilon}| + 1\sigma$ is shown with target motion rate for each of the three subjects. To indicate the effectiveness of the confidence rating system, the data are shown for three conditions. For the first condition all data are averaged and presented. For the second condition all data rated bad have been deleted from the averaged values, and for the third condition all data rated undecided and bad have been deleted. The error values of subject 11 decreased by an average value of approximately 5 seconds of arc when the data rated undecided and bad were deleted. These data amounted to approximately 30 percent of the total data. When the 10 percent of the data rated bad were deleted, the decrease in the error values was approximately 2 seconds of arc. The error values of subject 12 were reduced when those data rated undecided and bad were deleted. However, the deleted data amounted to approximately 75 percent of the total data. Since subject 13 rated so few measurements good, these data are not presented in figure 18. However, with deletion of approximately 30 percent of the data which was rated bad, the error value decreased particularly at the higher target motion rates. It would appear that the measurement accuracy for an experienced navigator would increase slightly if he deleted a substantial portion of the measurement data on the basis of his confidence in the data.

Effect of Error Feedback Bias on Training

A navigator trained to use error feedback is expected to perform subsequent to training only as accurately as the error information displayed to him during training. If a bias exists in the error feedback, a similar bias will appear in operational measurements. Two factors that may contribute a bias in the error feedback are the reaction time of the navigator and the reaction time of the display mechanism. The reaction time of the navigator should apply equally to the training and the real world measurements. The reaction time of the display mechanism will not apply equally to training and real world measurements. The error bias introduced by the display mechanism must be minimized if the training method is to be effective.

CONCLUSIONS

A navigator's ability to measure the angle between a simulated star and a moving flashing light with a hand-held sextant has been investigated in the Ames Midcourse Guidance and Navigation Simulator. Sextant measurements have been obtained with a flashing light target having various flash characteristics and having several rates of motion from both a fixed sighting station and a sighting station simulating spacecraft oscillatory motion. A navigator training technique has been developed and evaluated. From a consideration of the data, the following conclusions are presented.

1. With the standard deviation of the measurement data as the criterion, the effect of flashing light characteristics on measurement performance was found to be such that a variation in flash frequency from 1 to 2 flashes per

second had little effect on performance while with an increase in on time of 5 to 20 percent of the flash period, the measurement performance was significantly improved.

2. A navigator training technique in which measurement error feedback was presented to the sextant operator subsequent to each measurement was effective in improving measurement performance. The primary improvement was a reduction in the values of the mean bias error while the standard deviation of the measurement data was only slightly reduced. This improvement was indicated at all tested target motion rates.

3. Improving the measurement accuracy by using a subjective evaluation of the measurement is marginally effective. The use of the technique might be predicated on the amount of data that may be deleted and the accuracy required.

4. The performance obtained during this investigation indicates that an experienced navigator using a hand-held sextant during rendezvous navigation may be expected to obtain measurements with the combined error of the measurement bias and the standard deviation less than 60 seconds of arc.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif. 94035, June 12, 1967
125-17-02-09-00-21

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TABLE I.- TABULATION OF DATA OBTAINED DURING PHASE I,

SECONDS OF ARC

Characteristics of target light			Standard deviation for subject -						
On time, percent	Flashes per sec	Target motion rate, arc sec/sec	1	2	3	4	5	6	7
5	1	25	---	21.0	37.2	---	31.2	37.2	26.4
		50	26.4	55.2	43.2	54.0	39.6	108.0	36.6
		100	80.4	63.6	39.6	67.8	43.2	54.0	37.8
	1-1/2	25	37.8	47.4	62.4	27.0	---	35.4	54.0
		50	28.8	117.0	47.6	30.0	56.4	74.4	42.0
		100	51.0	65.4	91.2	92.4	34.2	84.6	62.4
	2	25	37.2	57.6	30.6	---	19.2	36.0	24.6
		50	38.4	52.2	55.8	97.2	18.6	90.6	48.0
		100	36.6	36.6	75.0	47.4	76.2	61.8	63.0
10	1	25	38.4	47.4	22.2	31.8	34.2	16.8	30.0
		50	42.6	24.6	29.4	37.2	48.0	33.6	41.4
		100	65.4	63.6	38.4	---	28.2	64.8	31.8
	1-1/2	25	39.6	40.2	39.6	33.6	21.0	42.0	28.2
		50	28.8	40.8	39.6	72.6	28.2	56.4	12.0
		100	52.2	38.4	46.8	52.8	61.8	65.4	61.2
	2	25	26.4	45.0	31.8	28.8	26.4	54.0	21.0
		50	29.4	31.8	49.2	44.4	42.6	39.0	22.8
		100	35.4	51.0	29.4	52.2	27.6	54.0	51.6
20	1	25	34.8	31.8	36.6	13.2	22.8	52.2	33.0
		50	18.6	42.0	22.8	43.2	42.6	65.4	25.8
		100	40.8	48.0	28.2	22.2	37.2	36.6	37.8
	1-1/2	25	23.4	39.6	27.0	33.0	23.4	48.0	27.6
		50	72.0	30.0	42.0	22.8	8.4	55.2	22.8
		100	---	33.0	49.2	22.2	26.4	102.6	28.2
	2	25	37.2	62.4	17.4	39.0	39.6	80.4	23.4
		50	16.2	40.8	28.8	22.8	18.6	71.4	25.8
		100	21.6	29.4	34.8	34.8	34.2	62.4	30.6
Steady light		25	13.8	39.6	36.6	21.6	9.0	25.2	22.2
		50	27.0	36.6	74.4	35.4	64.2	16.2	10.2
		100	50.4	21.0	115.2	16.2	31.2	30.6	35.4

TABLE II.- TABULATION OF DATA OBTAINED DURING PHASE II, SECONDS OF ARC

Sighting station dynamics	On time, percent	Flashes per sec	Target motion rate, arc sec/sec	Subject 4 $\bar{\epsilon}$	4 1σ	5 $\bar{\epsilon}$	5 1σ	6 $\bar{\epsilon}$	6 1σ	7 $\bar{\epsilon}$	7 1σ	8 $\bar{\epsilon}$	8 1σ	9 $\bar{\epsilon}$	9 1σ	10 $\bar{\epsilon}$	10 1σ	11 $\bar{\epsilon}$	11 1σ
Three-axis motion	5	1	25	41.4	32.4	7.8	36.6	58.8	39.0	17.4	38.4	-37.2	30.0	-0.6	49.8	94.2	31.8	37.8	47.4
			50	78.0	30.0	44.4	31.2	75.6	58.2	43.2	48.0	30.0	27.0	-140.4	65.4	18.0	60.0	63.0	45.6
			100	86.4	72.0	9.6	48.6	57.0	65.4	47.4	51.6	37.8	64.2	17.4	42.6	52.8	63.0	---	---
		2	25	3.0	52.2	-19.2	21.6	45.6	29.4	15.6	34.2	61.2	35.4	-79.8	37.8	16.8	41.4	6.0	29.4
			50	-13.2	36.0	10.8	39.6	52.2	47.4	48.6	32.4	40.8	58.2	9.0	93.0	59.4	60.0	87.0	38.4
			100	72.0	51.6	49.2	42.0	104.4	74.4	133.2	61.2	81.0	64.8	94.2	51.6	68.4	48.0	95.4	40.2
	20	1	25	12.6	20.4	18.6	15.0	30.6	43.8	---	---	64.2	44.4	4.8	21.0	35.4	28.2	47.4	22.8
			50	33.0	25.2	36.6	40.8	22.2	49.8	63.6	41.4	43.8	33.6	.6	55.8	18.6	31.8	39.0	31.8
			100	86.4	49.2	53.4	22.2	72.0	71.4	60.6	32.4	59.4	28.2	1.2	63.6	105.0	43.8	63.6	26.4
		2	25	22.8	16.8	-21.6	20.4	31.8	45.6	54.0	33.6	18.6	20.4	-97.8	55.2	17.4	36.6	46.2	25.8
			50	21.0	33.6	25.2	29.4	22.2	38.4	30.6	25.8	-12.6	27.0	-25.2	30.0	-36.6	29.4	---	---
			100	99.0	34.8	45.6	30.0	61.2	53.4	---	---	75.6	69.6	2.4	31.8	45.6	35.4	95.4	31.8
	Steady light		25	19.2	18.0	7.2	24.0	28.8	29.4	28.8	22.8	-17.4	21.6	-6.6	42.6	45.0	21.0	39.6	12.0
			50	48.0	18.0	10.2	21.6	39.6	16.8	48.6	22.8	-2.4	30.0	-43.8	37.8	46.2	30.6	49.2	19.8
			100	57.0	17.4	33.6	21.6	97.8	24.6	66.6	10.2	3.0	31.2	16.2	52.2	27.6	32.4	---	---
Static	Steady light		25	22.2	9.6	0	13.2	-3.0	15.6	27.6	13.8	-6.0	17.4	-31.2	21.6	-18.0	42.0	12.0	16.8
			50	3.6	15.6	20.4	15.0	44.4	24.6	33.0	10.8	4.8	16.2	10.2	21.6	34.8	18.0	---	---
			100	22.2	19.2	60.0	25.2	84.6	21.0	12.0	32.4	28.2	22.8	25.2	54.6	-6.6	18.0	---	---

Note: $\bar{\epsilon}$ = mean error
1σ = standard deviation

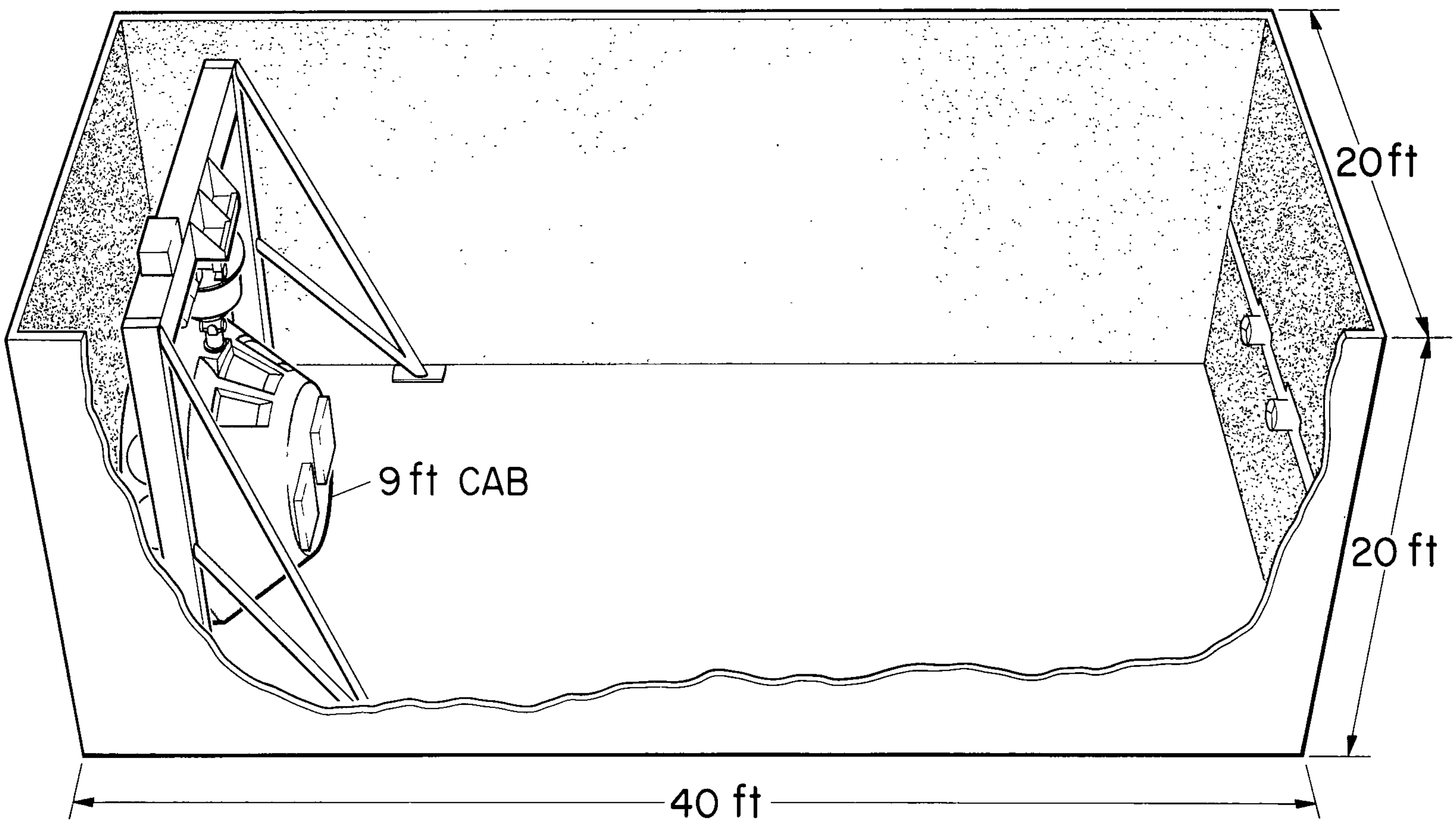
TABLE III.- TABULATION OF DATA OBTAINED DURING PHASE III,

SECONDS OF ARC

	Target motion rate, arc sec/sec	Session no.	Subject 11 $\bar{\epsilon}$	Subject 11 1σ	Subject 12 $\bar{\epsilon}$	Subject 12 1σ	Subject 13 $\bar{\epsilon}$	Subject 13 1σ
Measurement error displayed to each subject	20	1	0.6	27.6	-12.0	20.4	9.0	42.6
		2	-6.6	17.4	-30.6	48.6	32.4	32.4
		3	-.6	27.6	8.4	42.0	21.6	27.0
		4	12.0	25.2	---	---	.6	27.0
	40	1	19.8	24.6	27.6	45.0	1.8	22.2
		2	14.4	33.0	18.0	33.0	41.4	42.0
		3	3.6	27.4	46.2	59.4	34.2	24.6
		4	-4.8	21.0	73.2	48.0	19.8	35.4
	60	1	9.6	30.6	43.2	48.6	34.2	30.6
		2	18.0	23.4	28.8	57.6	42.6	52.2
		3	21.6	34.2	7.2	47.4	14.4	34.2
		4	---	---	40.2	46.8	---	---
	80	1	-.6	28.8	35.4	63.0	31.8	60.6
		2	22.8	31.8	3.6	50.4	39.6	49.2
		3	13.2	28.8	3.0	38.4	13.2	40.8
		4	25.2	39.0	---	---	---	---
	100	1	1.8	28.2	21.6	30.6	70.8	54.0
		2	19.8	27.0	25.8	58.8	11.4	42.6
		3	3.6	48.6	-1.8	60.0	30.0	47.4
		4	---	---	-.6	31.8	---	---
No error information display	20	5	-4.8	17.4	-81.6	39.6	-4.8	29.4
		6	-17.4	28.2	-4.8	25.8	-16.8	24.0
	40	5	-5.4	21.6	.6	54.0	-36.6	33.0
		6	26.4	27.6	19.2	28.8	26.4	36.0
	60	5	18.0	38.4	27.0	51.0	8.4	45.6
		6	35.4	33.6	8.4	31.2	1.8	51.6
	80	5	17.4	16.2	22.2	60.6	59.4	42.6
		6	27.0	40.2	.6	25.2	-7.8	73.8
	100	5	-19.8	30.6	38.4	46.2	41.4	38.4
		6	-18.6	31.2	-15.6	38.4	2.4	54.6

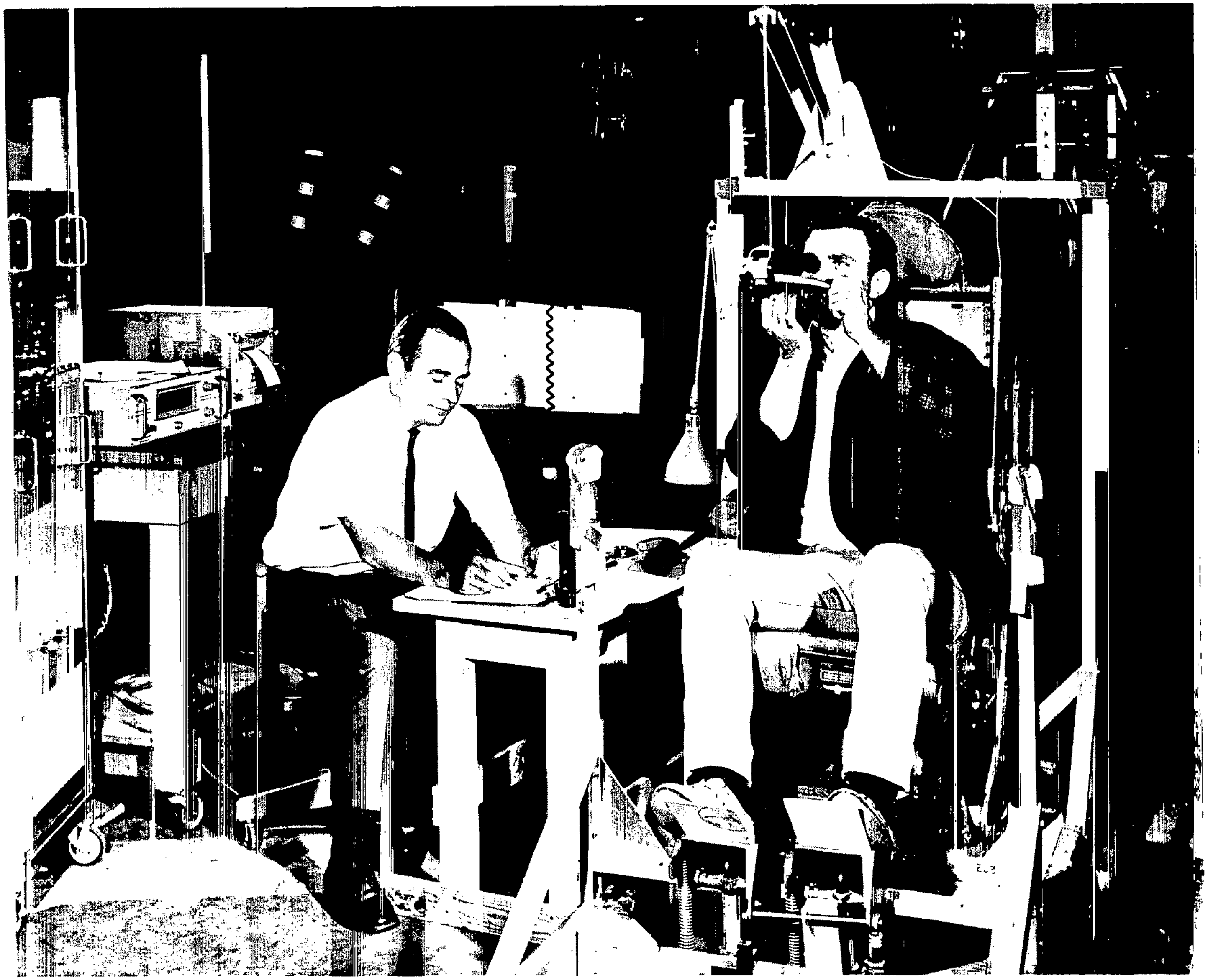
Note: $\bar{\epsilon}$ = mean error

1σ = standard deviation



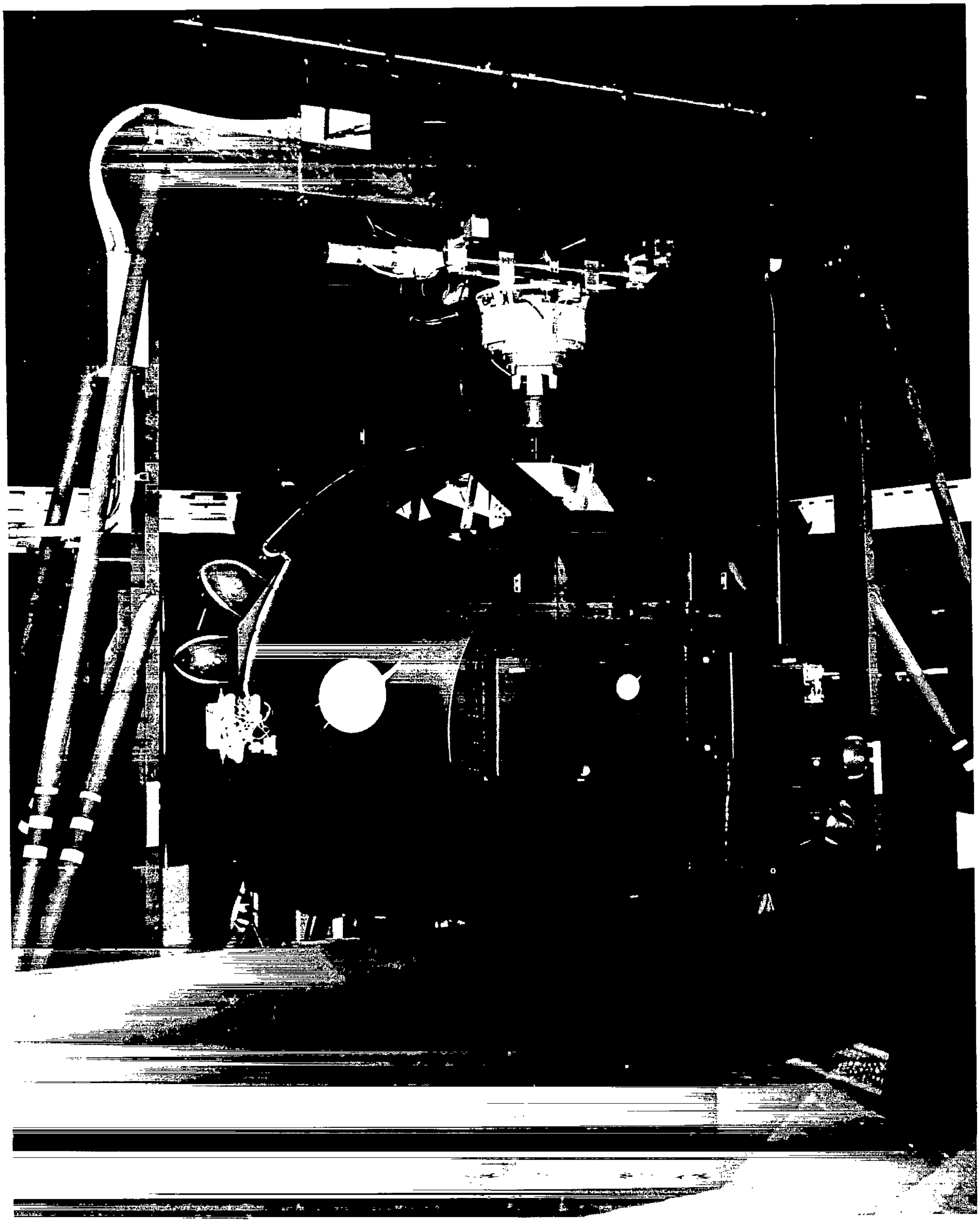
AAA243-4

Figure 1.- Sketch of Ames Midcourse Guidance and Navigation Simulator.



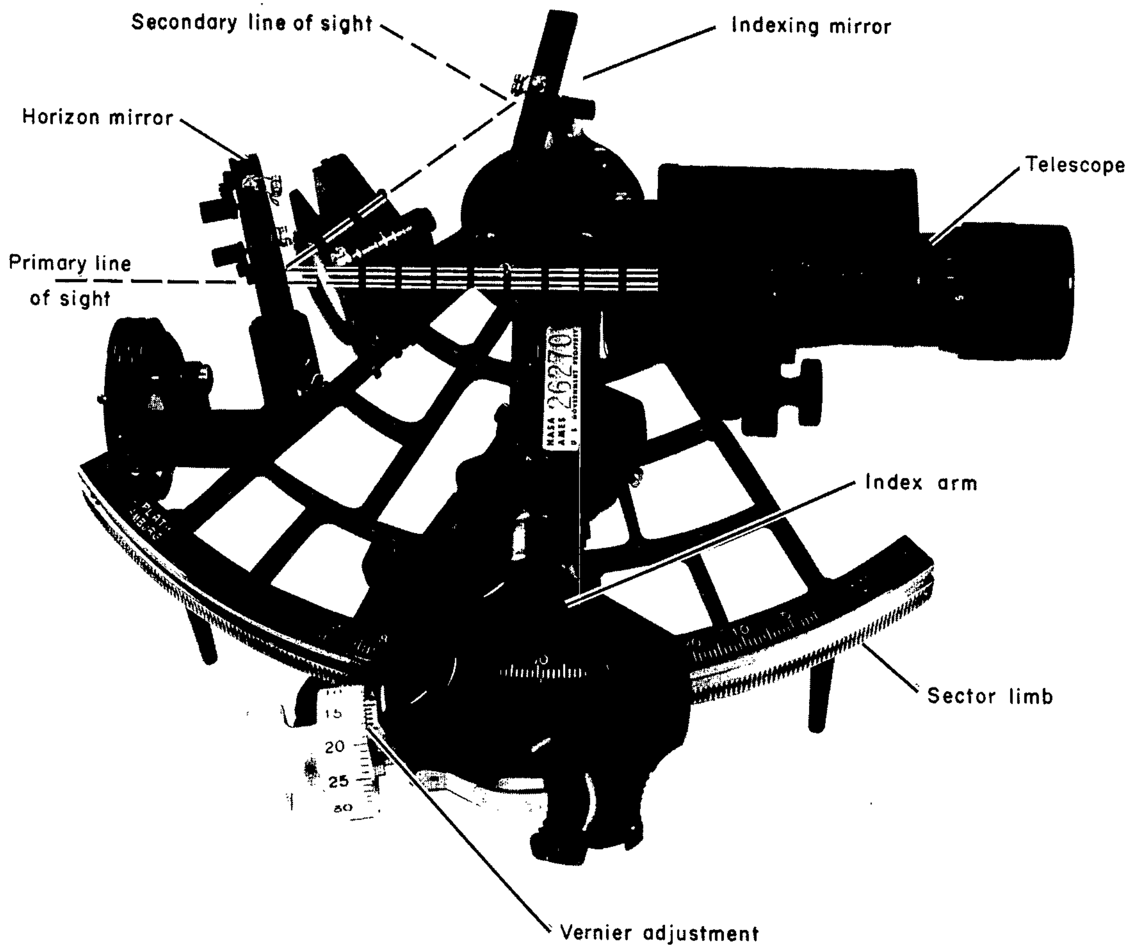
A-34791

Figure 2.- Photograph of sighting station used during initial phase of study.



A-37371

Figure 3.- Photograph of simulator cab.



AAA243-3

Figure 4.- Photograph of Plath Micrometer sextant.

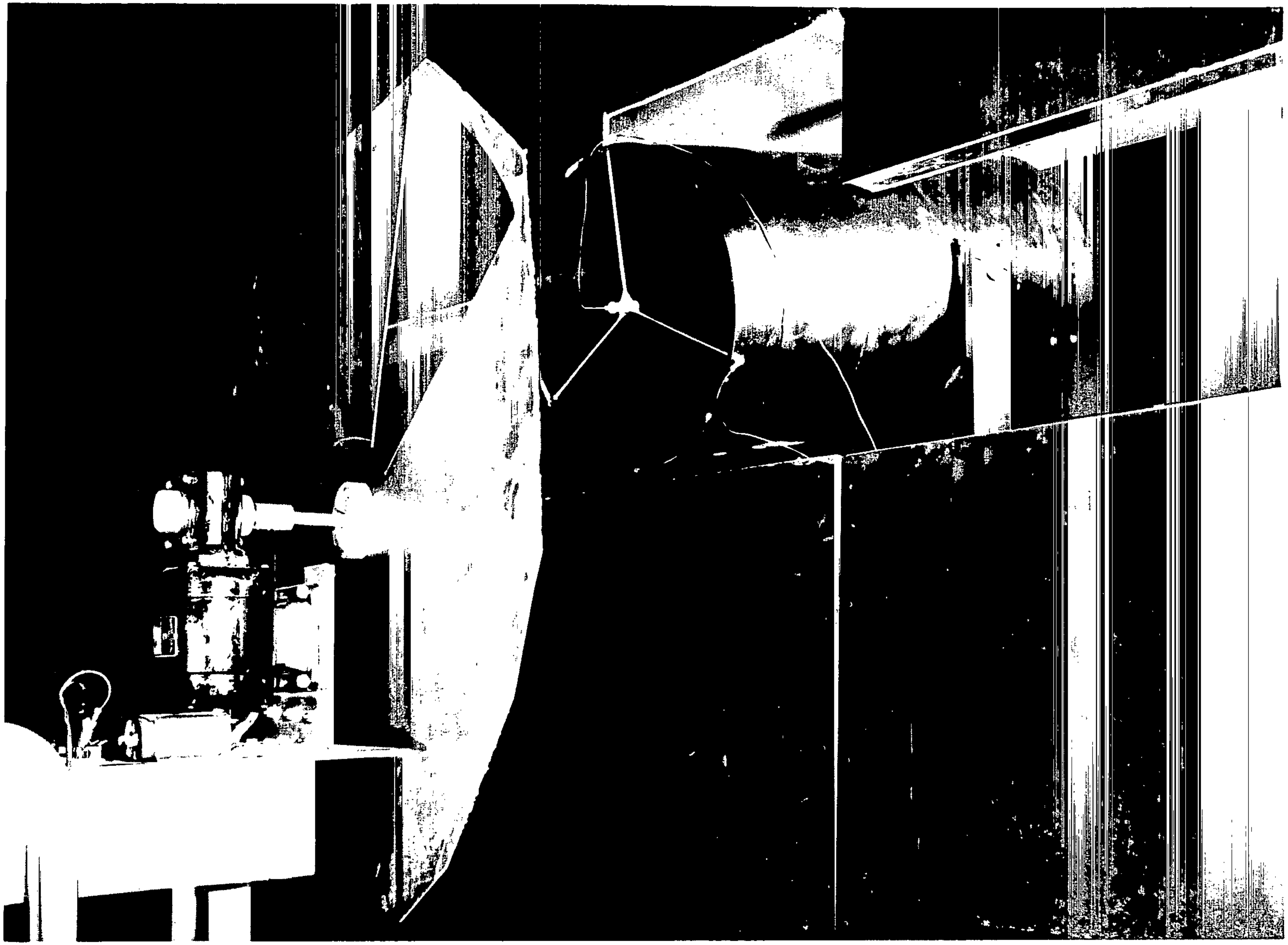


Figure 5.- Photograph of simulated command module sighting target.

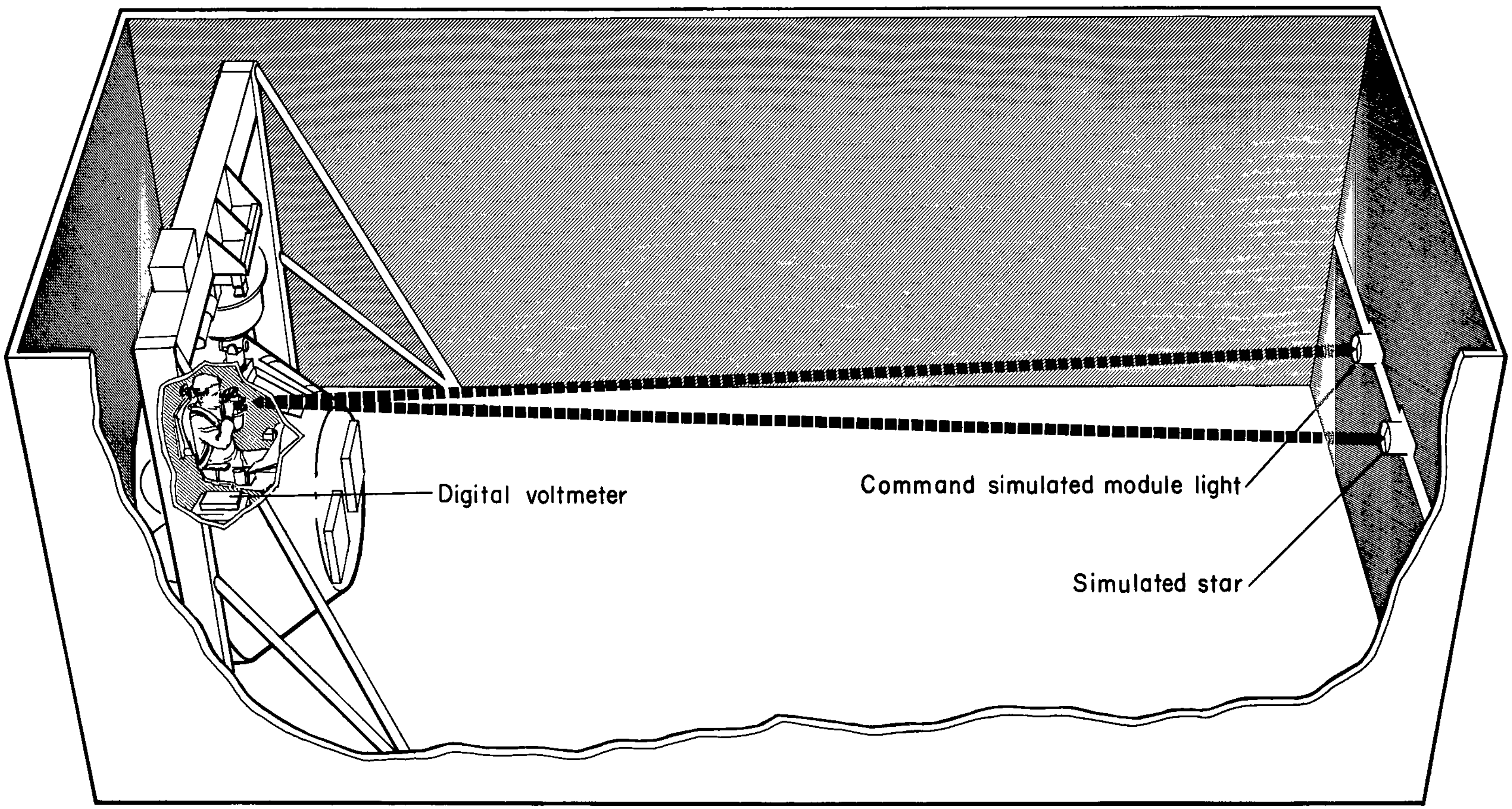


Figure 6.- Sketch of sighting station and targets.

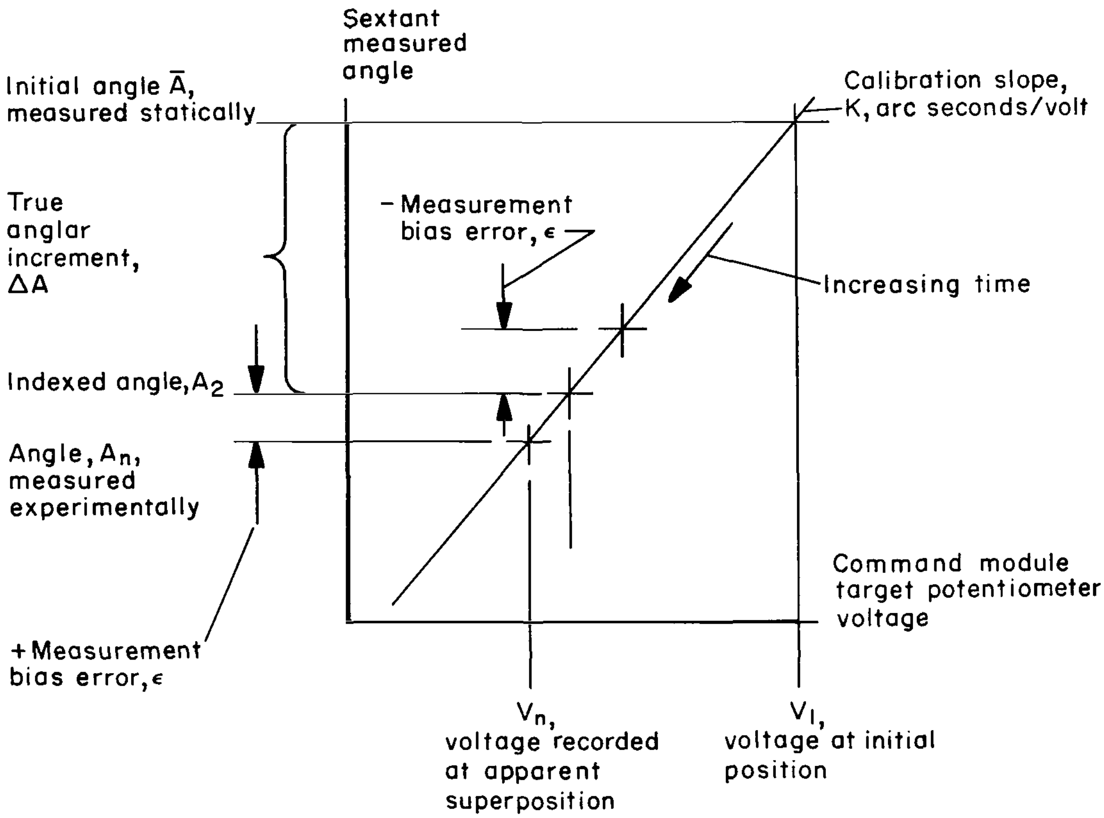


Figure 7.- Schematic diagram of sextant measured angle and target light potentiometer voltage relationship.

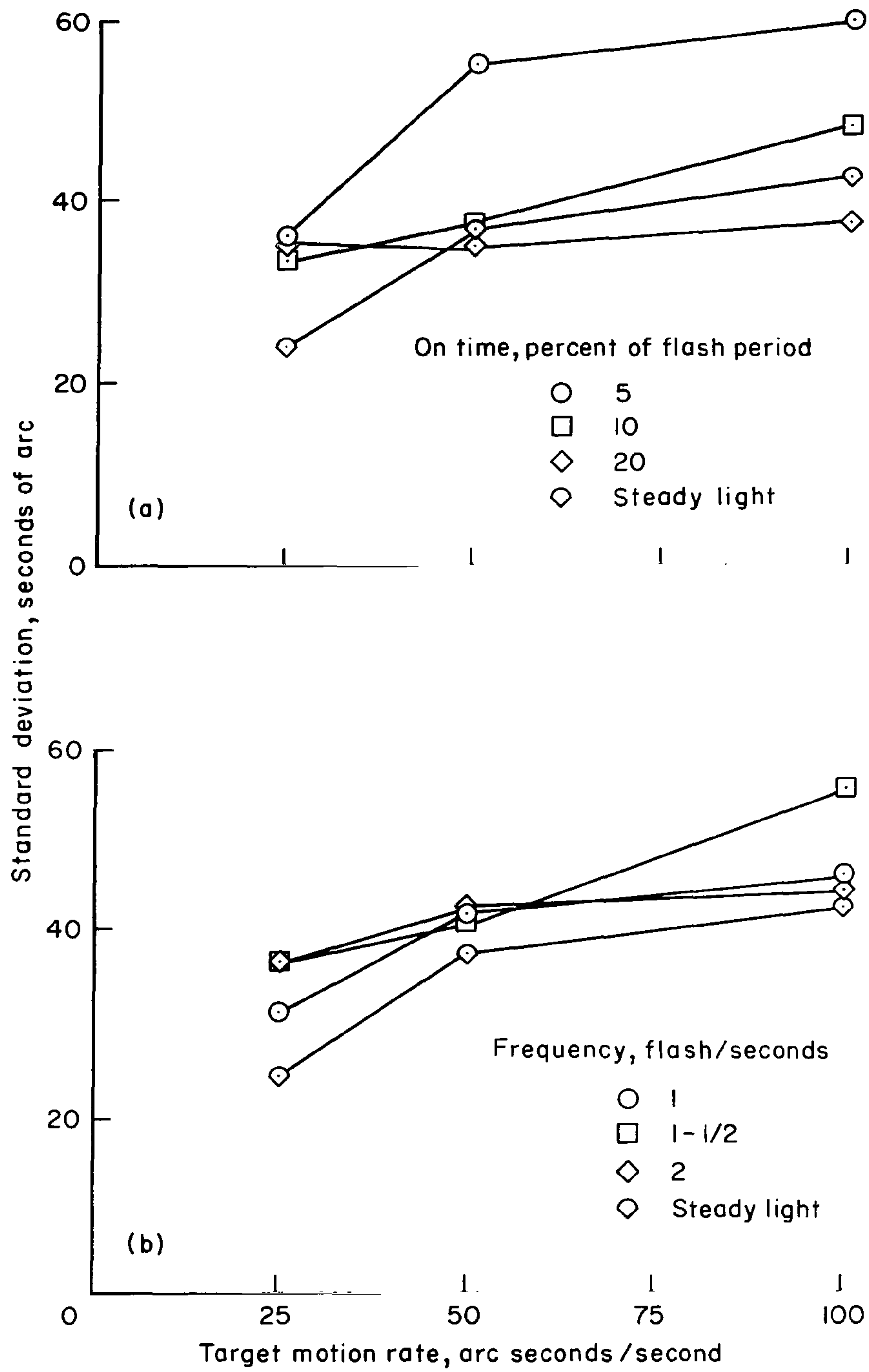


Figure 8.- The effect of target flash characteristics on measurement performance with an increase in target motion rate, phase I.

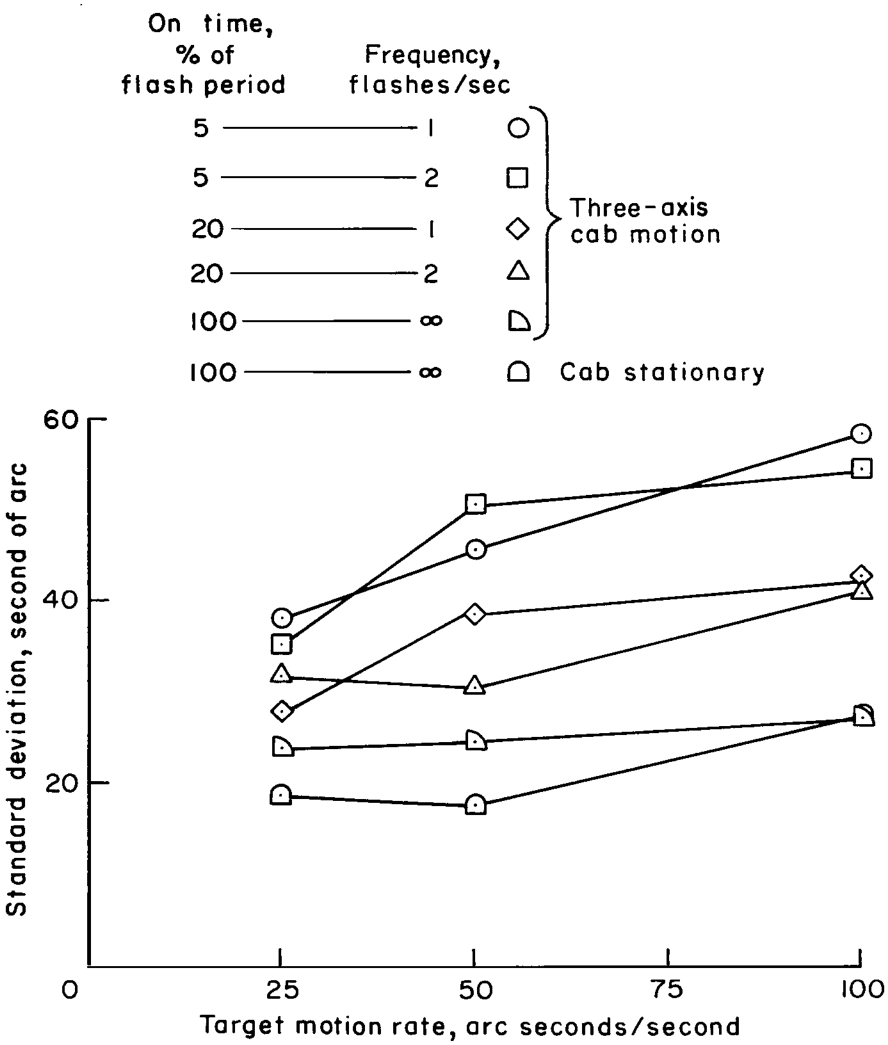


Figure 9.- The variation of the average standard deviation of sextant measurements with an increase in target motion rate, phase II.

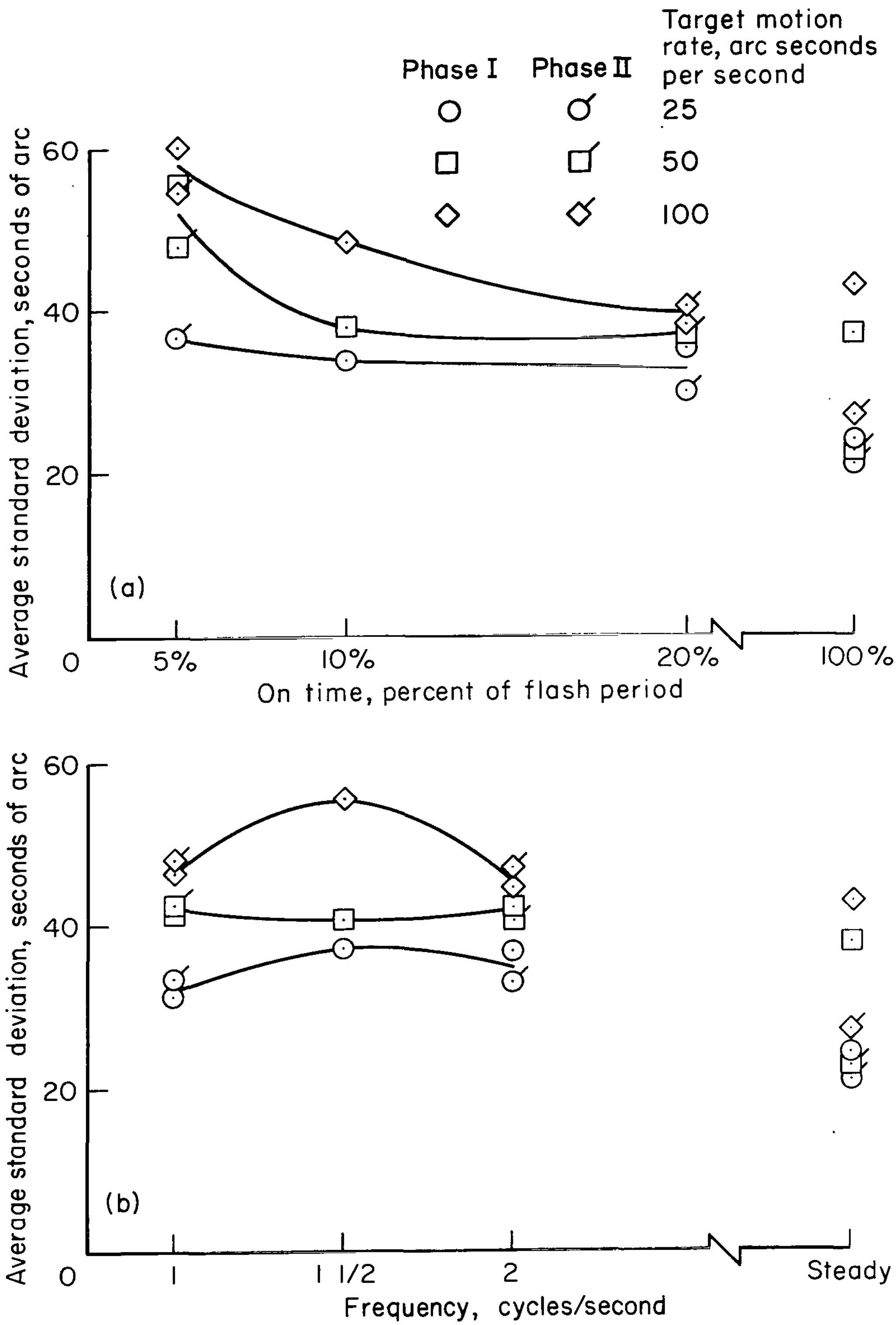


Figure 10.- The variation of the standard deviation of sextant measurements as a function of the flash characteristics of the target light.

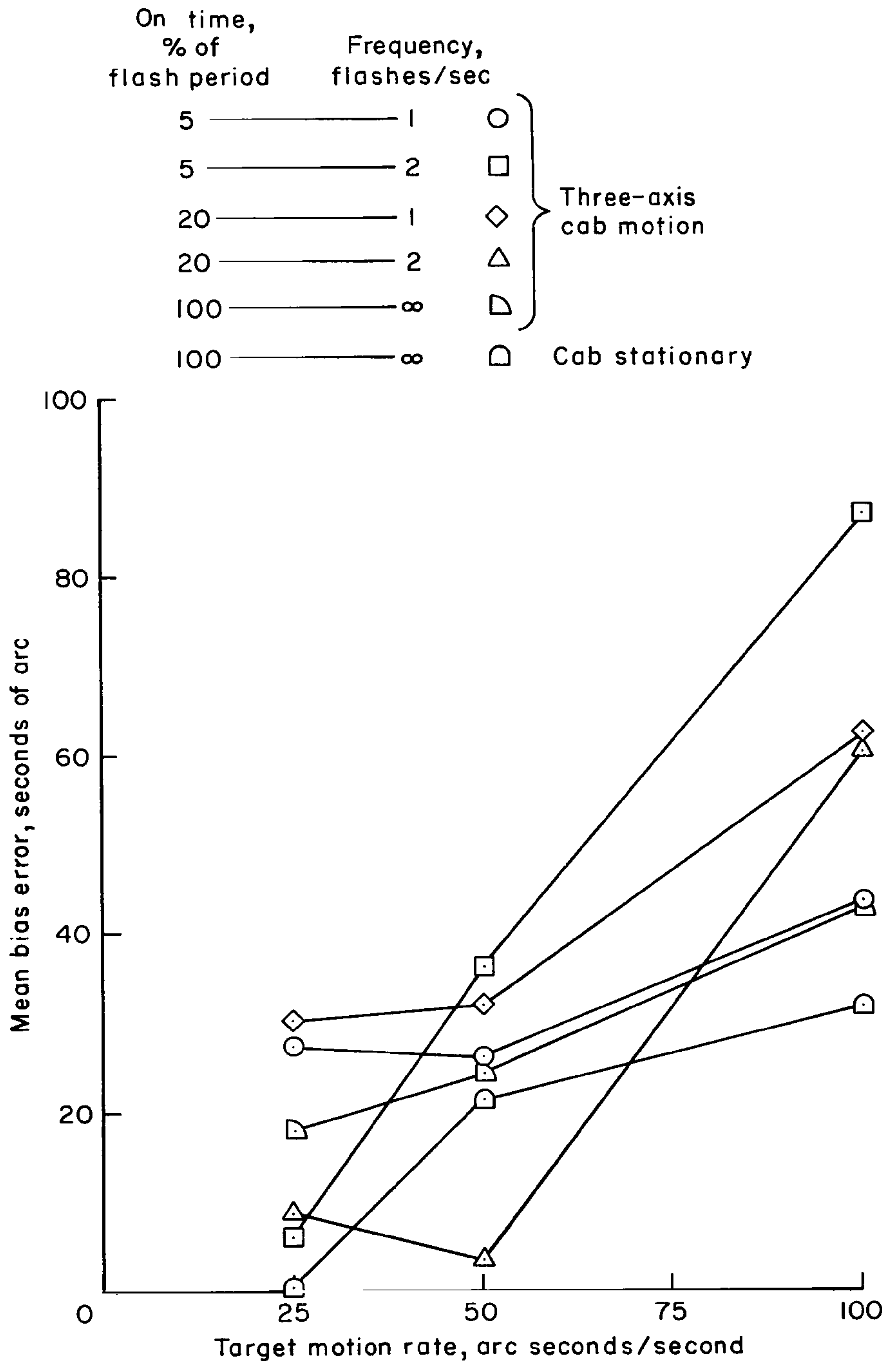


Figure 11.- The variation of the mean measurement bias error with an increase in the target motion rate, phase II.

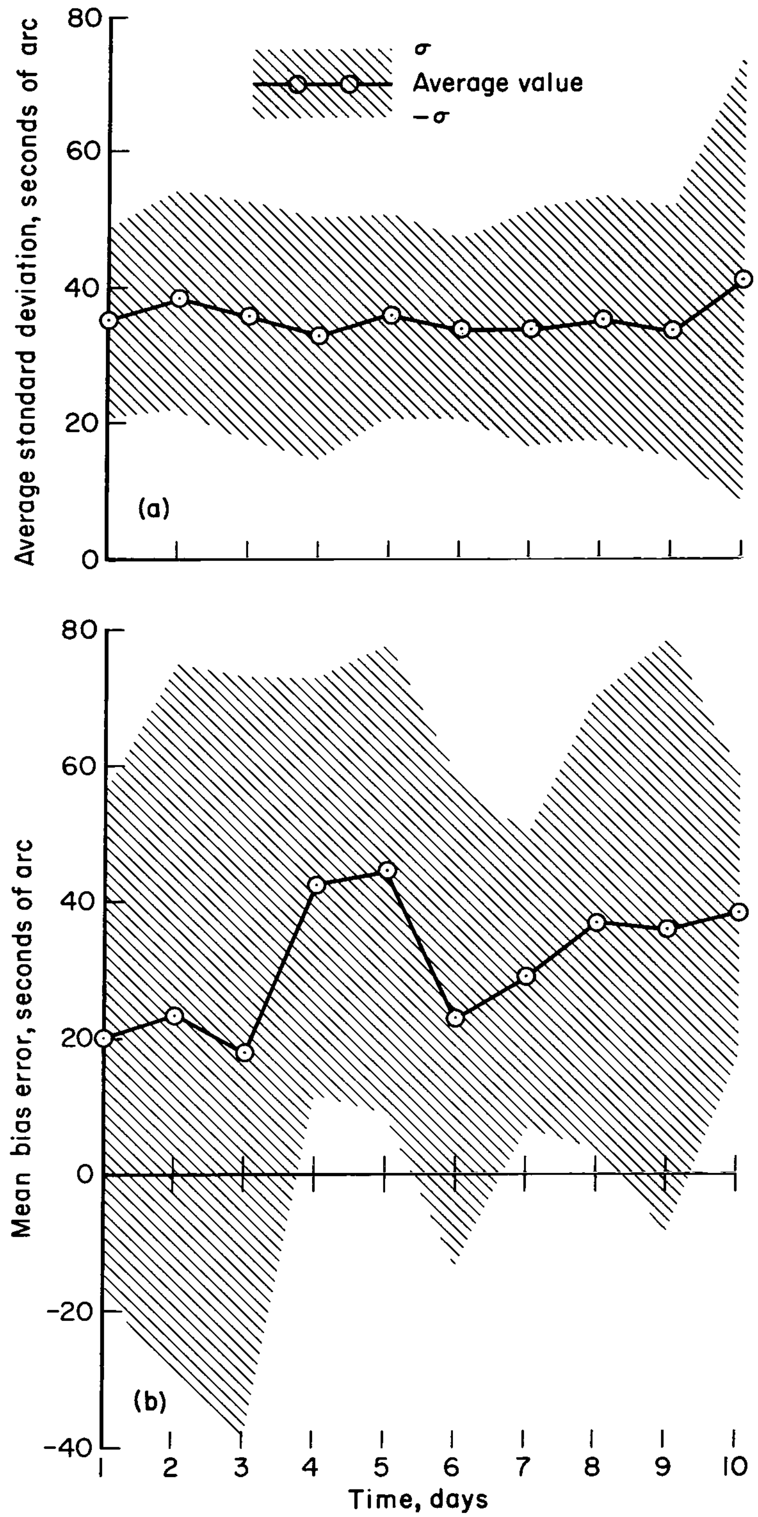


Figure 12.- The variation of the performance criteria during the final 10 days of phase II.

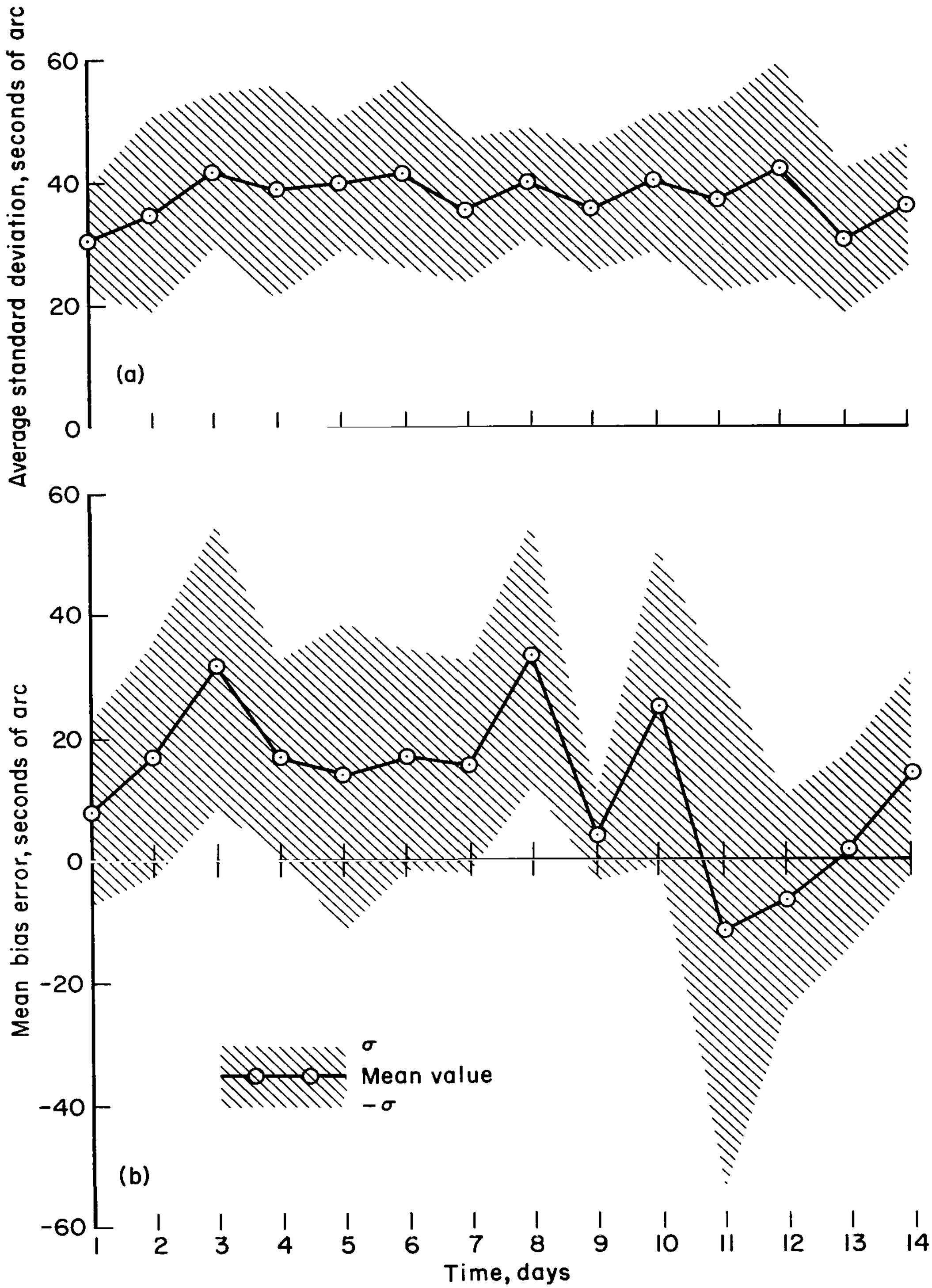


Figure 13.- The variation of the performance criteria of subjects trained with error feedback, phase III.

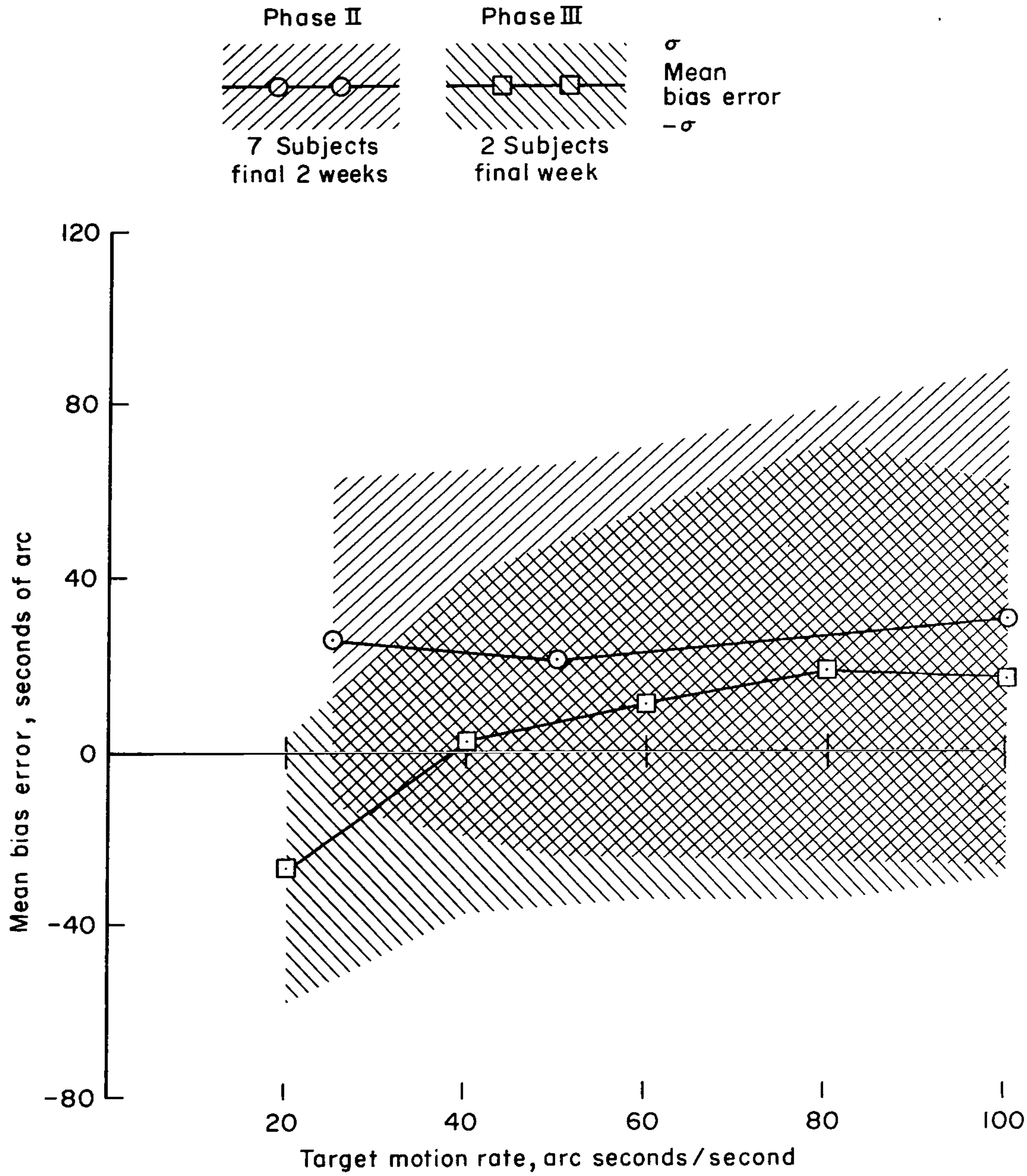


Figure 14.- Measurement error characteristics during phases II and III - subject 11 excluded.

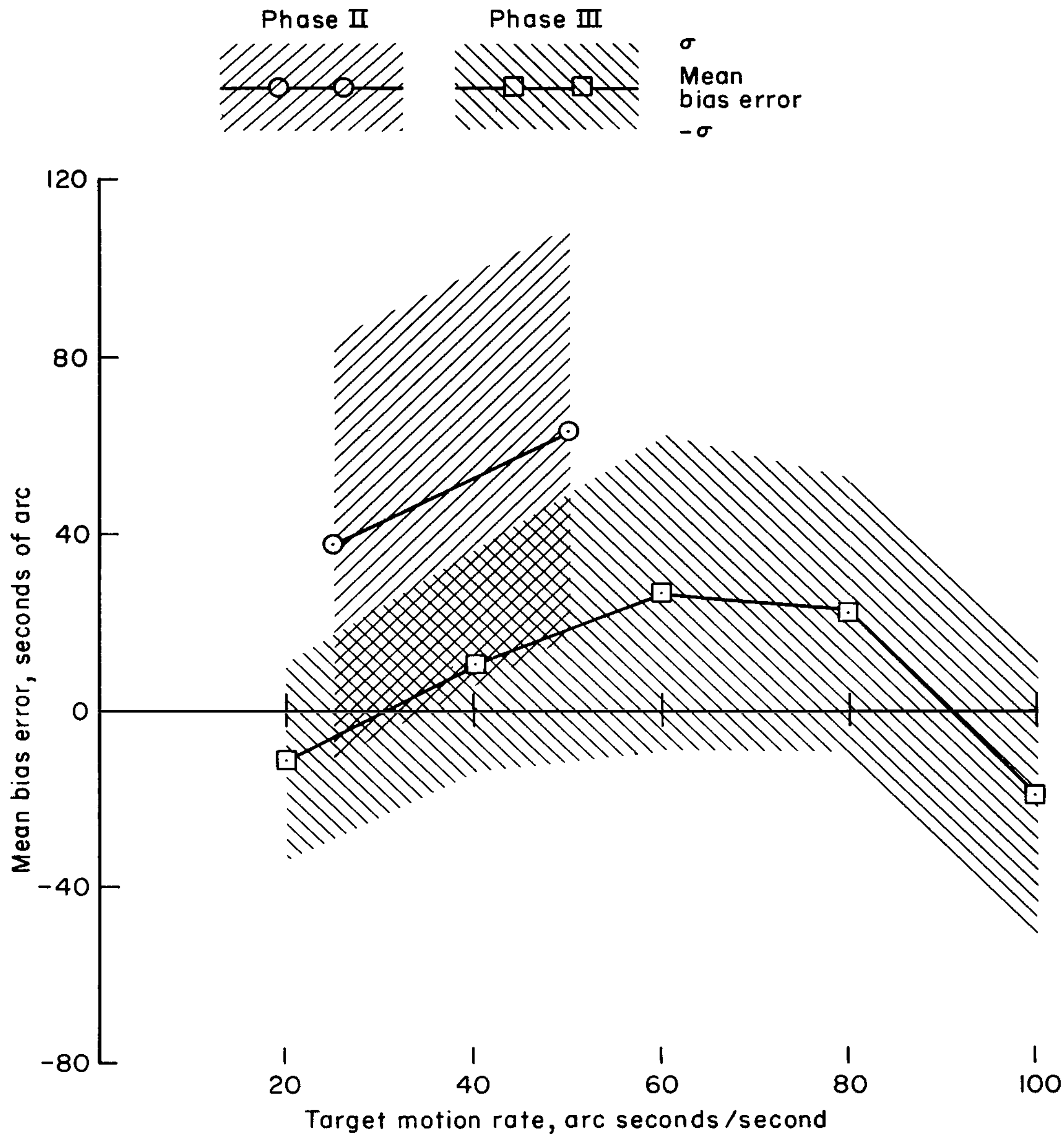


Figure 15.- Measurement error characteristics during phases II and III - subject 11 only.

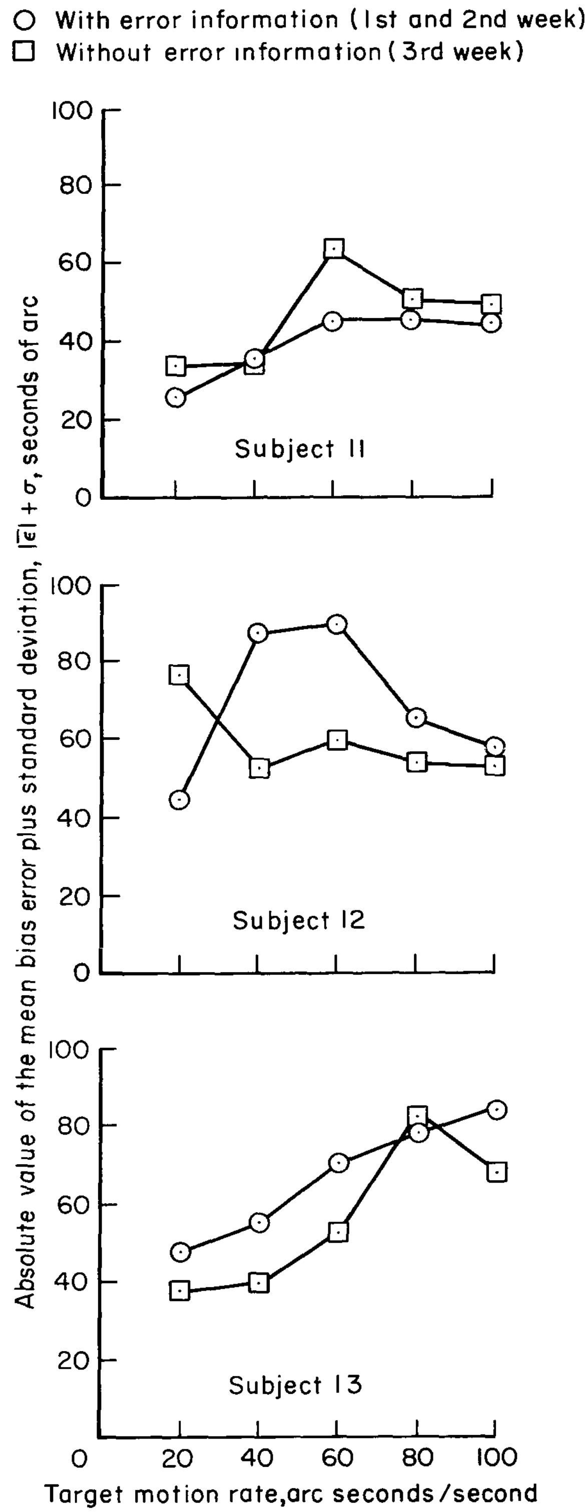


Figure 16.- The effect of error feedback on subject performance during phase III.

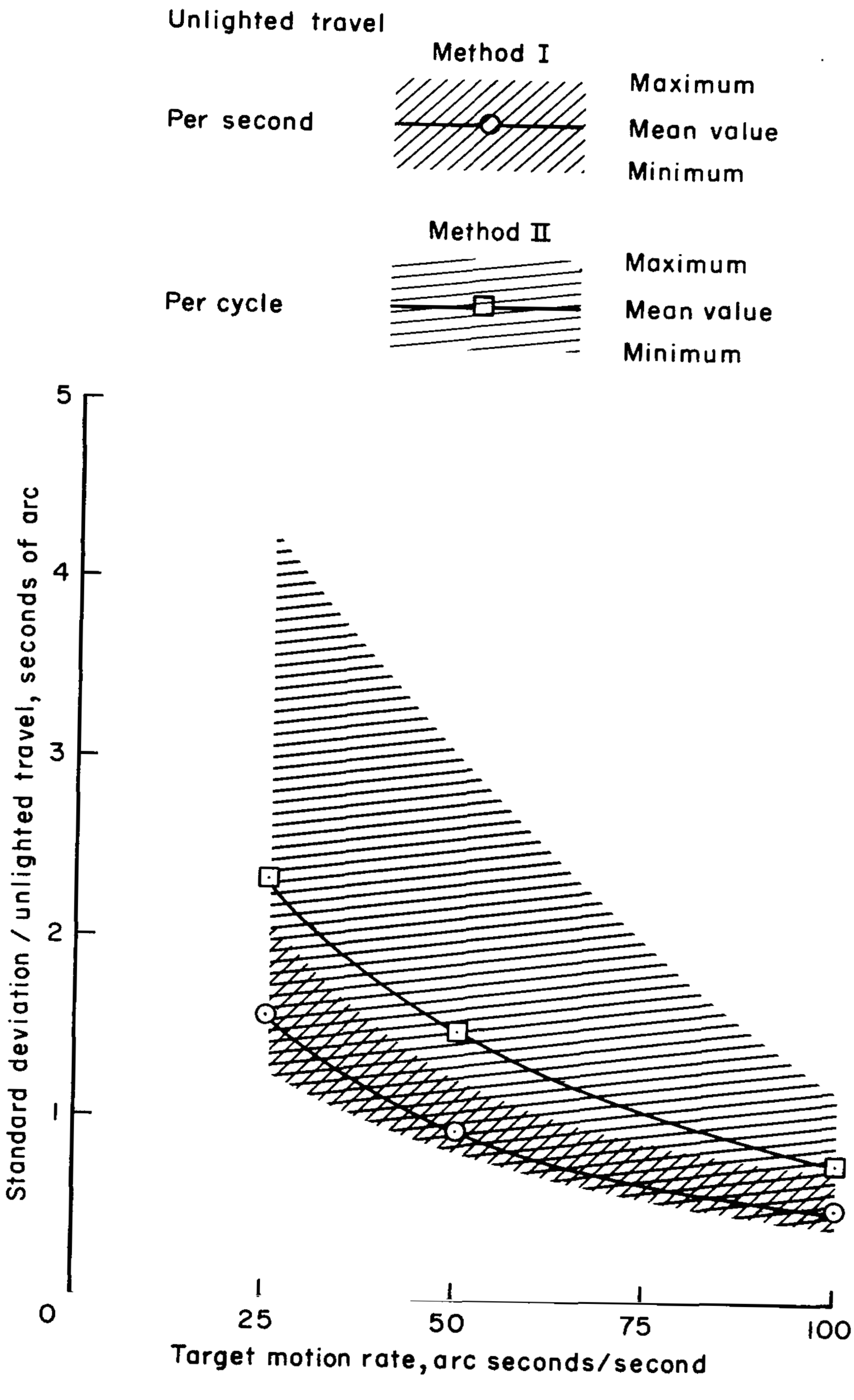


Figure 17.- A comparison of the values of standard deviation of sextant measurements normalized by two methods.

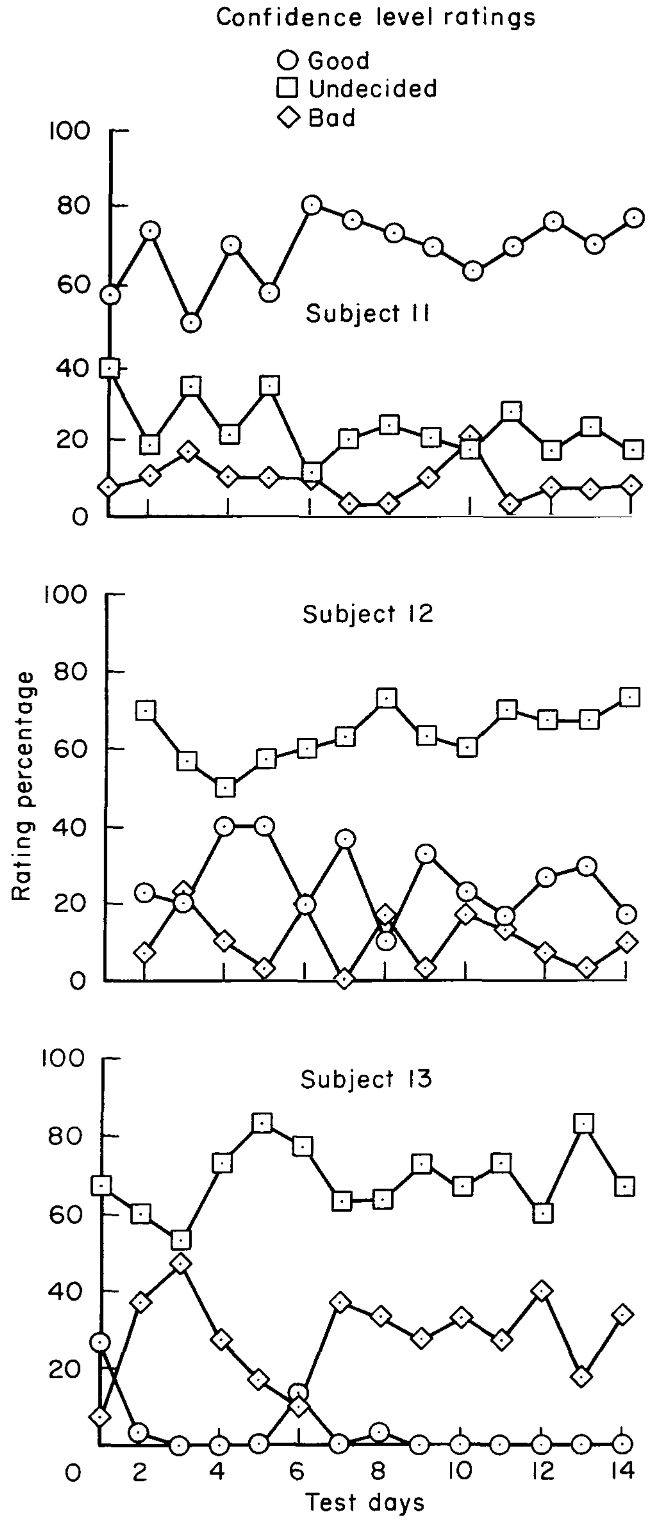


Figure 18.- The percentage of measurements in each confidence rating level for each test day of phase III.

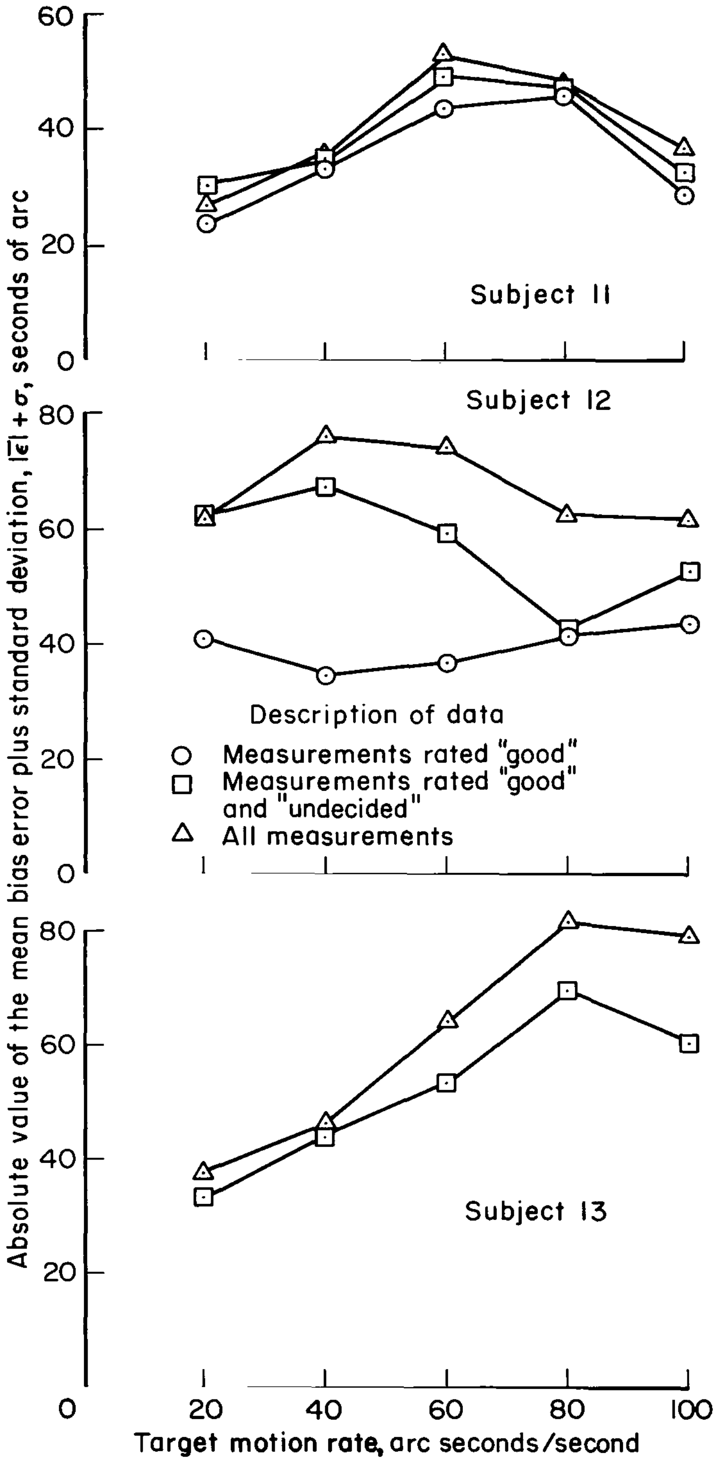


Figure 19.- The effectiveness of the confidence rating technique in improving measurement accuracy, phase III.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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