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A STUDY OF THE NAVIGATOR'S SIGHTING ACCURACY USING A SIMULATED VEHICLE-MOUNTED SPACE SEXTANT AND A DESCRIPTION OF THE SEXTANT SIMULATOR

by

RICHARD L. KURKOWSKI and KENNETH C. GROVER
National Aeronautics and Space Administration
Moffett Field, California

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A STUDY OF THE NAVIGATOR'S SIGHTING ACCURACY USING A SIMULATED VEHICLE-MOUNTED SPACE SEXTANT AND A DESCRIPTION OF THE SEXTANT SIMULATOR

By Richard L. Kurkowski and Kenneth C. Grover

NASA, Ames Research Center

Moffett Field, California

SUMMARY

The midcourse guidance system for manned space missions may require a navigator to measure accurately with optical instruments angles between various planets, the moon, and stars. One instrument proposed for this purpose is a sextant mounted in the space vehicle structure. The operation and performance of such a system has been investigated with a fixed-cockpit, analog-computer simulation. To obtain a sighting accuracy of ±2 arcsec (standard deviation) with a conventional analog computer and cathode ray tube display, it was necessary to derive a mathematical model (second-order perturbation angle techniques) which could resolve the angular relationships to within 1 arcsec on the analog computer. A description is given of this space-sextant simulator.

In this simulation an evaluation was made of the effects of line-of-sight motion, vehicle motion, and operator technique on the measurement accuracy of the navigator-sextant combination for several specific operating conditions. Sighting time and amount of fuel used were also measured. The results of the study indicate that the space-sextant-navigator system can effectively provide the accurate sighting information required for manned space flight navigation. For example, when the relative motion of the sighting targets due to near body and/or vehicle motion were less than 200 arcsec per sec, a 3σ accuracy level of ±10 arcsec or better was obtained.

author

INTRODUCTION

For lunar and interplanetary flights, it is recognized that simple ballistic trajectories will meet with little success. Studies indicate that a space mission will require a midcourse guidance system that will allow trajectory corrections en route.[1] For manned missions, the probability of success might be improved if the crew were incorporated into an on-board navigation and guidance system.

An on-board system has been proposed for the lunar mission vehicle, wherein the navigator will take the necessary navigation sighting measurements. The measurement accuracy is of prime importance since the accuracy level strongly influences the fuel used for the midcourse trajectory corrections. The navigator's position estimates, as calculated by an on-board computer, are directly related to the accuracy of the instrument he uses for his measurements. For a manned spacecraft, a simple and reliable instrument for measuring these angles is a sextant. A simplified sketch of a sextant is shown in Fig. 1. Basically, the angles between celestial bodies are measured by positioning the primary line of sight, and then rotating the secondary line-of-sight mirror until the two images appear superimposed in the sextant field of view. (It should be noted that for accurate measurements this superposition should occur along the reference reticle line, which defines the measurement plane of the sextant.)

The sextant has been used for many years for terrestrial navigation, both as a hand-held device in marine navigation and as a vehicle-mounted device in aircraft for celestial navigation. However, for space navigation, information on the ability of a man to use such an instrument while on board a space vehicle is obviously lacking. In space, the angles between celestial bodies may have to be measured with extreme precision (i.e., a few seconds of arc). For such accuracy a high degree of magnification is required; consequently, the field of view is small. As the relative motion of the sighting objects increases, either as a result of the vehicle's rotation or translation with respect to a sighting object, the measurement task is expected to become quite difficult. That is, the image motion is magnified and therefore the image moves rapidly across the optics field of view. Also, for a sextant mounted in the structure of a lunar mission vehicle, the vehicle attitude control will probably be about axes different from the sextant axes, and therefore the visual cues may be confusing. With such problems in mind, this simulator investigation was undertaken to obtain basic information on the navigator's ability to make the necessary navigational measurements with optical instruments on board the spacecraft.

A fixed-cockpit, analog-computer simulation of a vehicle-mounted navigator-controlled sextant was used in this study to evaluate the effects of sighting target, line-of-sight motion, vehicle motion, and other system parameters, on the measurement accuracy and operation of the navigator-sextant combination. To implement the simulation, a mathematical model was developed using second-order perturbation techniques, which could resolve the angular relationships to a high level of accuracy (1 arcsec) on the analog computer.

NOTATION

σ standard deviation of angular measurement error at "mark,"

$$\text{root mean square} = \sqrt{\frac{\sum_{i=1}^{n} (e_i)^2}{n}}, \text{ arcsec}$$

e angular measurement error at mark, arcsec

n number of trials per set of sighting conditions

t time to perform task, that is, lapsed time from "start task" to mark, sec of time

av time average time required for sighting task $= \frac{1}{n} \sum_{i=1}^{n} t_i$, sec of time

$\overline{N}_{pitch}$ average number of pitch controller pulses

$\overline{N}_{roll}$ average number of roll controller pulses

$\overline{N}_{yaw}$ average number of yaw controller pulses

M lines reticle lines perpendicular to the measurement plane of the sextant; the principal M line passes through the center of the field of view

R line reticle reference line which defines the measurement plane of the sextant

DESCRIPTION OF SIMULATED VEHICLE AND NAVIGATOR'S TASK

The simulated vehicle was patterned after a lunar mission vehicle. As shown in Fig. 2., it consists of a crew compartment plus a multistart propulsion unit for midcourse velocity corrections and return orbit injection. The navigator station is located below the roll axis of the vehicle and consists, in part, of a sextant, a telescope, a sextant optics controller, and a vehicle attitude controller. The sextant primary line-of-sight axis is fixed in the X-Z plane, 57° below the X axis. The instrument was assumed to have two degrees of freedom with respect to the vehicle; rotation about the primary line of sight, and pitch of the secondary with respect to the primary line of sight. These two degrees of freedom were controlled by the sextant optics controller. The primary line of sight was controlled by varying the vehicle attitude.

The navigator's sighting task consists of acquiring the two celestial bodies in a telescope having a large field of view, and maneuvering the vehicle and actuating the optics drive so that the two objects appear in particular areas in the telescope's field of view, whereupon both bodies may then be seen in the limited field of view of the sextant. The navigator must then control the spacecraft so that the first celestial body is maintained near the principal reticle line (sextant measurement plane) while using the optics controller to superimpose the second body on the first; when this is accomplished he strikes the "mark" button. The mark button would presumably initiate a readout system which would record the measured angle and mission time and put this information into an on-board computer to calculate the trajectory. For this investigation, the sextant primary line of sight was chosen to be oriented on a landmark. To hold this orientation the navigator operated reaction control pulse jets, mounted on the vehicle. The secondary line of sight was oriented on the desired star by the sextant optics controller. The controller rolls and pitches the secondary line of sight with respect to the primary (or shaft) axis and the trunnion axis, respectively. Both sextant lines of sight were assumed to have a 1.8° field of view.

Since this study was primarily concerned with system accuracy, the target was assumed to have been acquired in the sextant field of view, so the acquisition telescope was not simulated.

MATHEMATICAL MODEL

The usual analog computer angular resolution techniques could not be used to represent a space sextant system capable of measuring an angle to a few seconds of arc. The mathematical model developed to overcome this problem used the information flow shown in Fig. 3. The large angle rotations are used as initial conditions and subsequent motions are approximated by second-order perturbation angles in order to obtain a solution of the rotating vector frame matrix equations which could be programmed on the analog computer. With this technique, accuracy levels of the computed angles were ±1 arcsec for the ±1.5° perturbation angle range of the simulation.

DESCRIPTION OF APPARATUS

The fixed-cockpit simulator used in this investigation is shown in Fig. 4. It consisted of a seat, a vehicle attitude side-arm controller operated by the navigator's right hand, a sextant optics side-arm controller operated by his left hand, and the sighting optics and display. The star-planet scene as seen through the simulated sextant was presented on a cathode ray tube which the navigator viewed through a theodolite telescope. The optical characteristics of the telescope were similar to those of a typical sextant telescope (×27 and 1.8° field of view). A long tube was required for mounting the 5-inch oscilloscope at the proper distance in the small field of view (Fig. 4).

Navigator's Controllers

The navigator's controllers can be seen in Fig. 5. The vehicle attitude, and therefore the primary line of sight, was controlled by a two-axis pencil control for pitch and roll and a rocker plate for yaw. This type of on-off pencil controller was evaluated for space vehicle attitude control[2] and found to be quite effective. The controller was operated in a pulse command mode which resulted in a discrete angular rate being imparted to the vehicle per control pulse. The vehicle attitude controller characteristics are shown in Fig. 6.

The sextant optics controller commanded the orientation of the sextant secondary line of sight with respect to the primary line of sight. It was a two-axis pencil controller of the proportional type. Its characteristics are shown in Fig. 7. Three control sensitivity levels were available, with maximum over minimum rates of 360/0.36, 3600/3.6, 36,000/36 arcsec per sec/arcsec per sec. The sensitivity selector was a three position switch mounted just forward of the sextant controller.

The sextant controller was operated in two different modes, namely direct and resolved. In the direct mode, left and right stick motion commanded the roll rate of the secondary line of sight about the primary axis; forward and back motion of the stick

commanded the pitch rate of the secondary line of sight about the trunnion axis. The image motion apparent to the observer in response to the stick deflection varied as a function of roll angle about the primary, or shaft, axis. In the resolved mode, the secondary line-of-sight image moves in the same direction as the controller is moved, regardless of the shaft roll angle; that is, moving the controller stick forward causes the image to move to the top of the field of view, moving it to the left causes the image to move to the left of the field, etc.

Sextant Sighting Display

For this study, the primary line of sight of the sextant was assumed to be viewing a landmark, with the reference star being viewed by the secondary line of sight. These two fields of view appear superposed to the observer using the sextant. The display was viewed through a telescope which had a magnification power of 27 and a field of view of 1.7°. Symbols representing the star (a dot) and the landmark (a circle) were displayed on a high quality, medium persistence cathode ray tube (Fig. 8). The minimum size dot obtainable on the cathode ray tube subtended an angle of 20 arcsec. This resulted in a 540 arcsec image at the eye, when viewed through the 27 power telescope. Data[3] indicate that images subtending less than 600 arcsec are effectively point sources of light; therefore the dot representation of a star was reasonable. Since the majority of the tasks required superposition of the symbols, errors in test results caused by nonlinearities in the cathode ray tube display were essentially eliminated.

A study was made to see whether there was some effect of landmark size (inside diameter) on sighting performance with the 20 arcsec dot size. Fig. 9 shows that a maximum accuracy level (for no landmark motion and vehicle attitude fixed) occurred when the landmark inside diameter was about twice the simulated star spot diameter. Therefore, for the remainder of the study, 50 arcsec was selected for the landmark inside diameter. This corresponds to a landmark on the moon such as the crater Kepler, as seen by a navigator from 100,000 miles.

This study also brought out a significant item with respect to sighting technique. When sighting on two dots (which might represent a star and a small geographic prominence on a planetary landscape), it was seen (Fig. 9, landmark I.D. = 0) that better accuracy could be obtained in placing them side by side along an M line (Fig. 8) than in superposing one on top of the other.

INITIAL CONDITIONS AND TEST PARAMETERS

In order to achieve an accurate simulation on the analog computer, the angular range of the variables had to be limited to perturbations of approximately $\pm 1.5^{\circ}$. The initial large values of shaft roll angle, mirror pitch angle, and initial vehicle attitude angles were preselected and the effects of perturbations about these initial angles were studied. Initial sextant angle conditions could be varied but for the bulk of the program, it was assumed that a shaft roll angle of 45° and a mirror or trunnion pitch angle of 45° represented a typical situation. For all runs, the simulated star was offset by initial shaft roll and trunnion pitch perturbation angles of $1/4^{\circ}$ each; that is, the star image was offset from the principal M line and the R line by $1/4^{\circ}$.

The variables of the study were as follows:

a) optics controller mode, resolved versus direct

b) optics controller sensitivity

c) vehicle attitude controller pulse levels

d) landmark line-of-sight rates

e) initial vehicle attitude rates

For a given set of conditions, the subject repeated the sighting problem from 16 to 20 times, in order to provide a statistical basis for the study of the effects on performance of a particular parameter variation.

The two primary subjects used in this study were an Ames test pilot with considerable spacecraft simulation piloting and aircraft flight experience, and a research engineer with general aviation pilot experience. A limited amount of additional data was obtained by two experienced United States Air Force navigators (subjects 3 and 4).

RESULTS AND DISCUSSION

Since the purpose of this investigation was to obtain basic information on the performance of a navigator-sextant combination, the previously mentioned test variables were systematically varied in order to determine their specific effects. Some combinations of test variables were also studied. The performance criteria for this simulation program were: (a) accuracy of the sighting angle measurement as indicated by the standard deviation of the error for a series of sightings, (b) amount of fuel used during the sighting as indicated by the average number of vehicle controller pulses per axis, and (c) the average time to complete a sighting. The results are divided into two sections; I) basic sighting accuracy and operator techniques, and II) effects of vehicle-attitude and line-of-sight motion.

I. Basic Sighting Accuracy and Operator Techniques

The first objective of the study was to determine the base-line accuracy of the subjects in the simulator. The second objective was to determine the effects of operator technique, optics controller mode, and controller sensitivity on the measurement accuracy.

Base-line sighting accuracy.- In order to determine the best sighting accuracy that could be expected, some basic accuracy sightings were made and repeated during the investigation, wherein all effects of vehicle or target motion were eliminated. These data, presented in Fig. 10, were obtained with the following test conditions: fixed vehicle attitude, no landmark motion, 20 arcsec dot with a 50 arcsec circle, and a low speed on the optics controller. The basic accuracy or repeatability of the system when the dot is being superimposed in the center of the circle had a 1σ value of 2 arcsec or less. Learning time was negligible and navigator performance did not seem to deteriorate appreciably even when many days lapsed between sightings.

Sextant off-plane sighting errors.- In general, a sextant will measure the true angle formed by two targets and the observer only when the two images are superimposed and positioned on the R line, that is, in the sextant measurement plane. The superposition does not have to occur at any specific position along the R line. Because of the image motion caused by a moving landmark line of sight or vehicle motion, a perfect measurement reading may become too time consuming or, at very high rates, impossible. Therefore a certain amount of error will always be present in the sextant measurement as a result of the images being off-plane, that is, away from the R line. A theoretical study of these out-of-plane measurement errors has been developed. The theoretical results show that sighting at small off-plane angles can be tolerated. For instance, with the landmark on-plane and the star off-plane by a lateral angle of 0.1° (360 arcsec) the error in sighting measurement for a measured angle of 45° is 0.32 arcsec.

Effect of sextant optics controller mode and sensitivity.- The navigator could select directly from three optics controller sensitivities which spanned the following ranges; 0.36 to 360, 3.6 to 3,600, and 36 to 36,000, referred to as low, medium, and high sensitivity, respectively. Choice of controller mode was also available, either resolved or direct. The purpose of this portion of the study was to assess the performance of the navigator-sextant system when a particular sensitivity and mode were used. The typical large angle initial conditions of 45° shaft roll angle and 45° trunnion pitch angle were used. The results of the parametric study of sextant optics controller sensitivity are presented in Fig. 11. The landmark line-of-sight motion in the measurement plane was the independent parameter. The vehicle attitude was kept fixed and the navigator's task was to track the landmark (moving at its constant initial rate), with the star and "mark" when the two images appeared to be superimposed. In the concurrent series of runs, no large differences occurred for two subjects using the low controller sensitivity (360/0.36) in either the direct or resolved mode. (For sightings for many shaft roll angle conditions, it is anticipated that the resolved mode will be preferable because it tends to eliminate control reversals.) Note that when part of the landmark motion study was repeated at a later date, subject 1 performed more accurately whereas subject 2 repeated his earlier data.

The sighting accuracy decreased slightly when the medium controller sensitivity was used. The high controller sensitivity condition markedly decreased sighting performance (Fig. 10). An analysis of this condition is as follows: The minimum rate for the high-speed controller was, as mentioned previously, 36 arcsec per sec. Therefore, the average

image closure rates were necessarily rather large, and made the superposition task difficult. This difficulty can also be seen by comparing the two typical curves of measurement error and ortho-plane offset versus time, as plotted by a continuous recorder (Fig. 12). One sample typifies the task tracking performance for low sextant control sensitivity, and the other for the high sensitivity. Although the end-point values for these two cases are similar, at this low rate of landmark motion, it can be seen that the amplitudes of the oscillations during the sighting task are much greater for the high controller sensitivity.

Operator techniques for subsequent parametric studies.- For the subsequent parametric studies, the subjects were given their choice of modes, and selected the sensitivity they desired. They usually selected medium sensitivity for making a coarse superposition and then switched to low (360/0.36) for the final phase of the sighting. The high sensitivity was generally not used in these studies; however, it may be useful during the acquisition phase of the sighting. Subjects 1, 3, and 4 chose to use the resolved mode whereas subject 2 used the direct mode for the bulk of the investigation. In order to minimize the off-plane measurement error, the subjects were instructed to attempt superposition while maintaining the landmark within 400 arcsec of the R line. It was emphasized that centering the dot in the circle in the direction parallel to the R line (i.e., parallel to the sextant measurement plane) was of prime importance for the sighting measurement.

II. Effects of Vehicle Attitude and Line-of-Sight Motion

The operator techniques stated immediately above were applied in the remainder of the investigation. The purpose of the remainder of the study was to determine the performance of the navigator-sextant combination under conditions of line-of-sight motion, vehicle attitude motion, and combinations of these. Using the assumed typical shaft roll and trunnion pitch angles of 45° and 45° as the large angle initial condition, the following perturbation conditions were studied.

Purpose	Vehicle			Vehicle controller	
	Fixed	No initial rates	With initial rates	Inactive	Active
Effect of landmark line-of-sight motion	X	X		X	X
Effect of vehicle attitude motion			X	X	X
Effect of combined landmark line-of-sight motion and initial vehicle attitude motion			X		X

In addition, a comparison was made of two other large angle initial conditions for the fixed landmark condition, with variable initial vehicle attitude rates.

Effect of landmark line-of-sight motion.- Effects of landmark motion with vehicle control active are shown in Fig. 13. In this and subsequent figures, in-plane motion refers to landmark line-of-sight motion in the mirror pitch plane, that is, parallel to the sextant measurement plane. Ortho-plane motion refers to landmark line-of-sight motion perpendicular to the sextant measurement plane. Vehicle attitude controller sensitivities used in this portion of the study correspond to the minimum rate per pulse values expected for a typical vehicle in the transearth portion of a lunar mission, that is, yaw and pitch rates of 80 arcsec/sec per pulse, and roll rates of 320 arcsec/sec per pulse.

Midcourse sightings: For the major portion of the midcourse phase of a lunar mission, the earth or moon landmark line-of-sight rates will be less than 20 arcsec per sec of time. This low rate has negligible effect upon sighting performance for the system studied, as illustrated in Fig. 13. Accuracy levels remained close to those for a fixed landmark and vehicle, the base-line standard deviation of 2 arcsec or less. Therefore, if a normal distribution is assumed, the system accuracy for the midcourse phase can be expected to be ±6 arcsec (3σ) for 99.7 percent of the sightings. Sighting times after acquisition averaged 10 to 15 seconds.

Close-in sightings: For "close-in" sightings, outside the midcourse range (approximately 14,000 to 208,000 nautical miles from earth), the increased landmark line-of-sight rate causes considerable error. If a 3σ (99.7 percent level) value of 10 arcsec is assumed as a minimum required accuracy level, landmark line-of-sight rates must be less than 280 arcsec per sec for in-plane or ortho-plane motion, and must result in a rate of less than 280 arcsec per sec for combined in-plane and ortho-plane motion.

A summary of the data, including conditions with the controller inactive, at selected combined landmark rates of 20, 200, and 400 arcsec per sec is shown in table I.

Effect of vehicle attitude motion.- The purpose of the next group of simulated sightings was to determine the effects of vehicle attitude motion on the navigator-sextant performance, assuming no landmark motion. Image (landmark and star) motion in the sextant field of view, due to vehicle motion, is illustrated in Fig. 14. Here, three representative arrows are shown to illustrate the relative motion of images in the field of view when the vehicle is pitched, yawed, or rolled. The motion of the images in the primary (shaft) line of sight is always the same with respect to the observer. The image moves down for positive vehicle pitch, to the right for positive vehicle roll, and to the left for positive vehicle yaw. The relative motion of the images in the field of view of the secondary line of sight would vary depending upon orientation in the sweep field (Fig. 14).

Performance for the typical initial angle condition (shaft roll 45°, trunnion pitch 45°) with vehicle attitude motion is shown in Figs. 15, 16, and 17, with and without the attitude controller active. Having the vehicle attitude controller inactive is not realistic because the vehicle must be controlled for image acquisition in the primary line-of-sight field of view. However, this condition tends to emphasize the decreased accuracy due to sighting measurements off the sextant measurement plane. The results from this test should indicate the maximum vehicle attitude rates that are tolerable for accurate sightings, and in turn, the maximum vehicle control rates per pulse useful for vehicle attitude control.

The combinations of vehicle pitch, roll, and yaw rates used are representative values since pitch/roll and yaw/roll axes inertia ratios of 1/10 are typical for a transearth vehicle, and 1/4 are typical for a translunar vehicle. The same force and moment arms about all axes were assumed. The initial vehicle attitude rates were determined by the control sensitivity used. (The characteristics of an on-off type control system are such that the maximum noncancelable residual values of vehicle rate are equal to 1/2 the control sensitivity rates per pulse.) With initial vehicle attitude motion about all axes, with controller inactive (Fig. 15), maximum tolerable vehicle rates, using a $3\sigma = 10$ arcsec criteria, are approximately 180 arcsec per sec in roll with 45 arcsec per sec about pitch and yaw axes. These errors are the total of navigator error and out-of-plane measurement error.

With vehicle attitude controller active, Fig. 15 shows a 3σ accuracy better than 10 arcsec for initial vehicle attitude rates up to 240 arcsec per sec in roll with 60 arcsec per sec about pitch and yaw axes. Computer scaling prevented extension of this curve but extrapolation indicates maximum tolerable rate combinations of about 320, 80, and 80 arcsec per sec about roll, pitch, and yaw, approximately double the tolerable rates for controller inactive.

Associated sighting times are shown in Fig. 16. With the controller inactive, the subjects had to accomplish the task quickly in order to keep the out-of-plane error as low as possible. With the controller active, the subject could take more time to do the task because he was able to control the position of the landmark image. The average number of control pulses used during the sightings are presented in Fig. 17.

A comparison of the two cases (controller inactive and active) for a representative initial vehicle rate is presented in table I. With vehicle controller active, the sighting accuracy (3σ) for these rates is the same as the base-line sighting value of 6 arcsec, as compared with 9 arcsec for the controller inactive.

Effect of combined landmark and vehicle motions.- During an actual space flight both the landmark and the vehicle attitude will move during the sighting task. Performance of the navigator sextant with both landmark line-of-sight motion and a particular set of vehicle attitude rates is shown in Figs. 18 to 20 for this simulation study. The initial vehicle rates chosen were 1/2 of the control sensitivity rates, and therefore at least

these minimum rates were always present. The control sensitivities were 320, 80, and 80 arcsec/sec per pulse for roll, pitch, and yaw, respectively.

In order to determine whether performance was affected by the navigator's adaptation to repeated initial conditions, the study was repeated for two subjects with random sign combinations of the initial vehicle rates. As shown in Fig. 18, the performance accuracy was about the same. Except for subject 4, the maximum allowable landmark line-of-sight resultant rate, based on the 10 arcsec (3σ) criteria, was again 280 arcsec per sec, the same as for the zero initial vehicle rate of Fig. 13. Sighting times (Fig. 19) were similar for both the repeated conditions and the random sign conditions.

Performance values for landmark rates of 20, 200, and 400 arcsec per sec both with and without initial vehicle attitude rates are presented in table I. The data are similar except that with initial vehicle rate, more pulses are required because of the noncancelable vehicle attitude rates.

Comparison of several large-angle conditions.- Fig. 21, a polar stereographic projection of the celestial sphere, illustrates the image motions due to vehicle rotations (see also Fig. 14). In order to study the effect of sweep field location of the secondary line of sight, upon the sighting task, three sets of large-angle conditions were selected and compared. As shown in Fig. 21, these were:

Case	Shaft roll	Trunnion pitch
I	0°	45°
II	45°	45°
III	180°	33°

It can be seen in the figure that at most locations in the sweep field, the visual cues of vehicle motion as seen through the small sextant fields of view (1.8°) are not independent. For example, image motion due to roll is similar to that for yaw for conditions such as case I. However, for the special case when the secondary line of sight is colinear with the vehicle Z axis, case III, the motion cues become independent. For this portion of the study, the vehicle attitude control sensitivities were assumed to be 50 arcsec/sec per pulse for all axes. The landmark was assumed to be fixed and the initial vehicle attitude rates were used in random combinations of zero, or plus or minus an even multiple of 50 arcsec per sec about each axis. The data of Fig. 22 show no significant difference in accuracy for the three cases, and since the initial vehicle attitude rate could be cancelled (because of the particular selection of vehicle initial rates and attitude control sensitivities), the terminal portion of the sighting was similar to that for zero landmark motion and fixed vehicle. However, the comparison shows a considerable difference in time to sight and number of control pulses used for each condition. For case III, the sighting time decreased markedly as shown in Fig. 23, and very little fuel was wasted as shown by the control pulse data (dashed curves with flagged symbols in Fig. 24). That is, if there was not an initial motion about a particular axis, it was readily apparent for case III and no control input was used. In the other two cases a trial and error method was necessary to discern what initial vehicle rotations were present. The comparison between case III with its independent motion cue and the other two cases indicates that additional information such as a vehicle rate indicator projected in the sextant field of view could result in fuel savings and a reduction in sighting time. For all three cases where initial vehicle attitude rates were not zero, the number of pulses used were approximately twice the number needed to cancel the initial rates (solid diamonds in Fig. 24). The additional pulses were used to bring the landmark back near the measurement plane.

CONCLUSIONS

The operation and performance of a navigator-controlled sextant mounted in a simulated space vehicle has been studied. The study indicates that the sextant-navigator system can provide accurate information required for manned space flight navigation. With no landmark motion and fixed vehicle attitude, the basic angle measurement accuracy level of several subjects was ±6 arcsec (3σ). With landmark line-of-sight rates of 200 arcsec per sec, the accuracy was reduced to ±10 arcsec. When the vehicle control was used to reduce the vehicle motion from initial rates greater than 200 arcsec per sec, the accuracy was ±10 arcsec (3σ). To obtain this accuracy the sextant had to be used properly to keep the off-plane sighting error less than 1 arcsec.

REFERENCES

1. White, John S., and Wingrove, Rodney C.: A Survey of Guidance and Navigation Problems for the Manned Lunar Mission. Paper for National Meeting of Institute of Navigation, Wash., D. C., April 19, 1962.
2. Lopez, Armando E., and Smith, Donald W.: Simulator Studies of the Manual Control of Vehicle Attitude Using an On-Off Reaction Control System. NASA TN D-2068, 1963.
3. Blackwell, H. R.: Contrast Thresholds of the Human Eye. Optical Society of America Journal, vol. 36, 1946, pp. 624-645.

Table I

Summary of Performance of Navigator-Sextant Combination

Initial Large Angles: Shaft Roll 45°, Trunnion 45°

	Base-line fixed vehicle attitude fixed landmark	No landmark motion initial vehicle attitude motion*		Landmark motion no initial vehicle attitude motion						Landmark motion plus vehicle attitude motion*		
		Controller inactive	Controller active**	Fixed vehicle			Vehicle controller active**			Vehicle controller active**		
				Landmark rates***						Landmark rates***		
				20	200	400	20	200	400	20	200	400
3σ (arcsec)	6	9	6	6	21	39	6	10-1/2	21	7-1/2	10-1/2	12
av time (sec)	10-25	8	10-25	12	6	4	15	11	5	15	10	4
$\bar{N}_{yaw}$			0				0	0	0	3	2	2
$\bar{N}_{pitch}$			2				0	0	0	1	1	1
$\bar{N}_{roll}$			2				0	1	2	1	2	2

	Roll	Pitch	Yaw
*Vehicle attitude initial rates (arcsec/sec)	160	40	40
**Vehicle attitude controller rate per pulse (arcsec/sec per pulse)	320	80	80

***Landmark line-of-sight in-plane and ortho-plane motion, equal rates

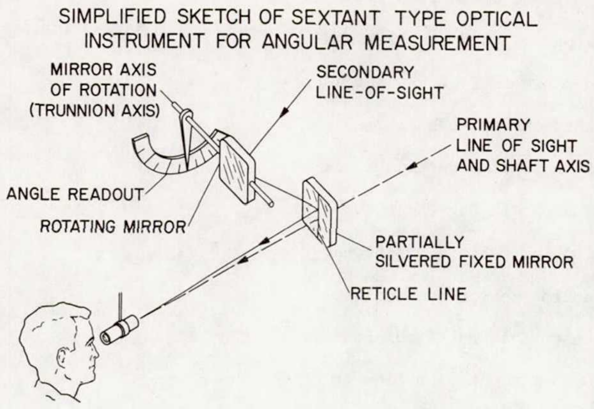

Fig. 1. - Simplified sketch of sextant.

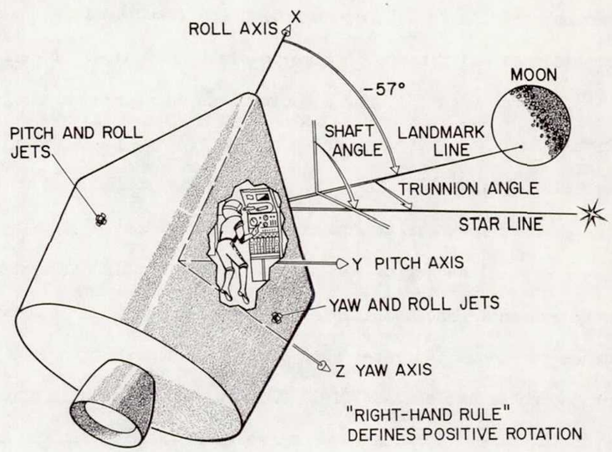

Fig. 2. - Vehicle model.

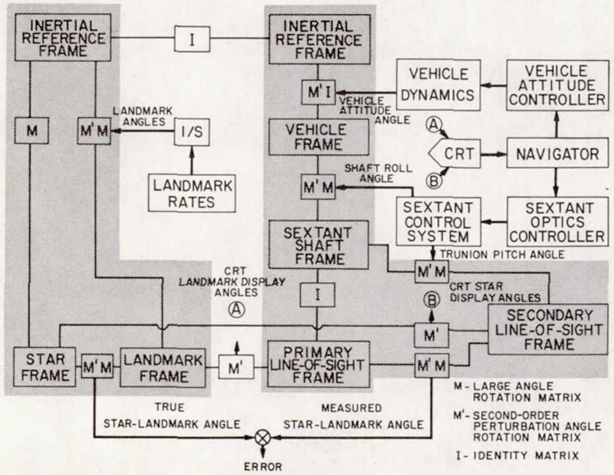

Fig. 3. - Mathematical model information flow diagram.

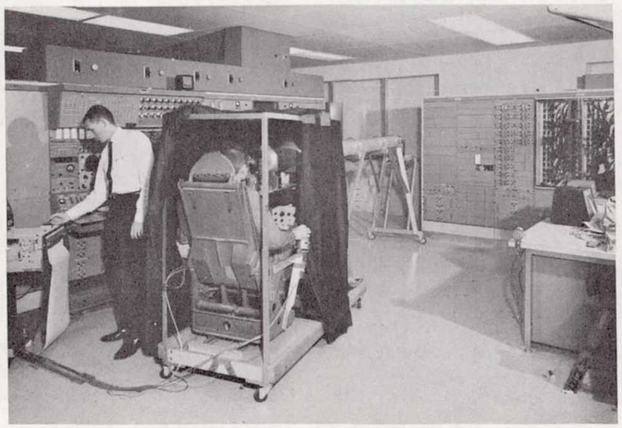

Fig. 4. - Sextant sighting simulator.

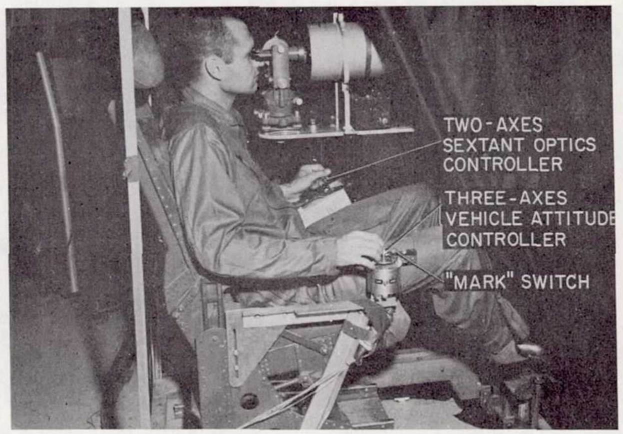

Fig. 5. - Simulated navigator's station.

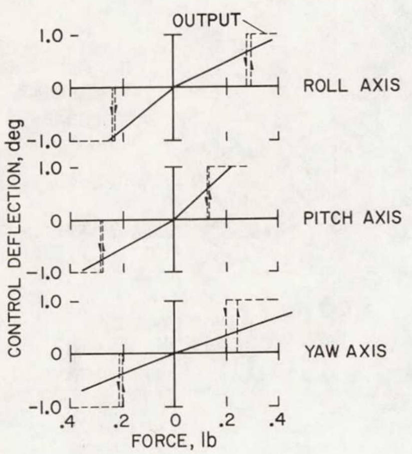

Fig. 6. - Vehicle attitude controller characteristics.

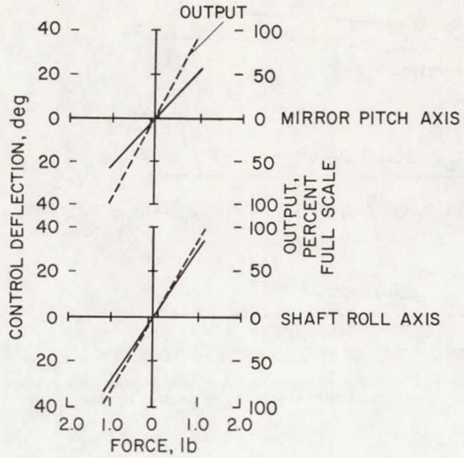

Fig. 7. - Sextant optics controller characteristics.

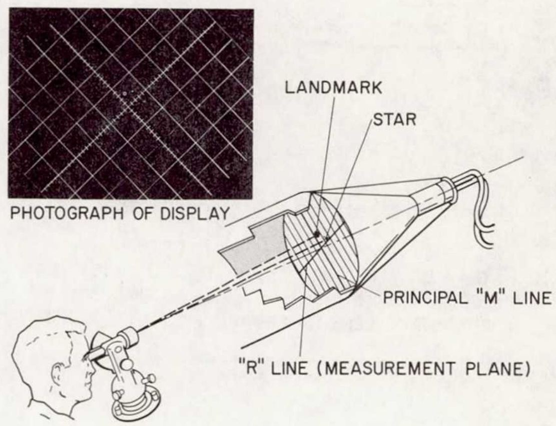

Fig. 8. - Sextant simulation display.

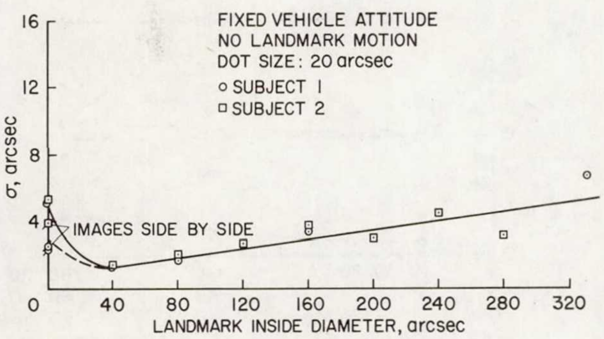

Fig. 9. - Effect of circular landmark size on sighting accuracy.

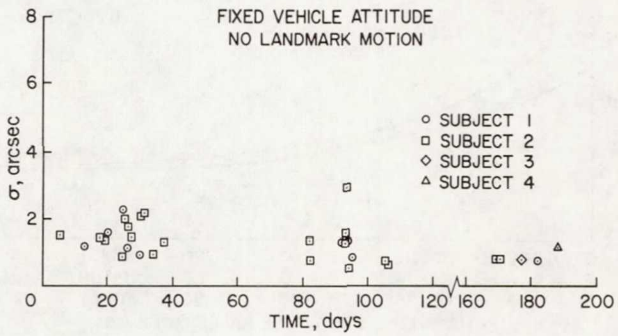

Fig. 10. - Chronological base-line performance data.

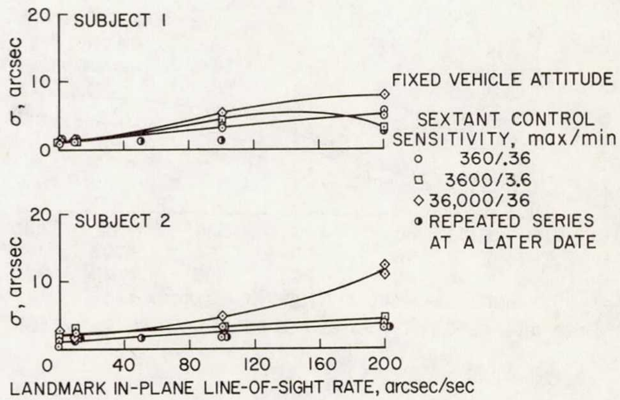

Fig. 11. - Effect of sextant controller sensitivity on accuracy.

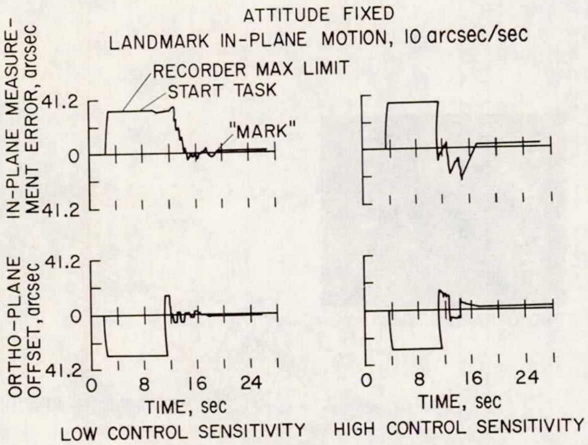

Fig. 12. - Typical time histories of in-plane measurement error and ortho-plane offset vs. time.

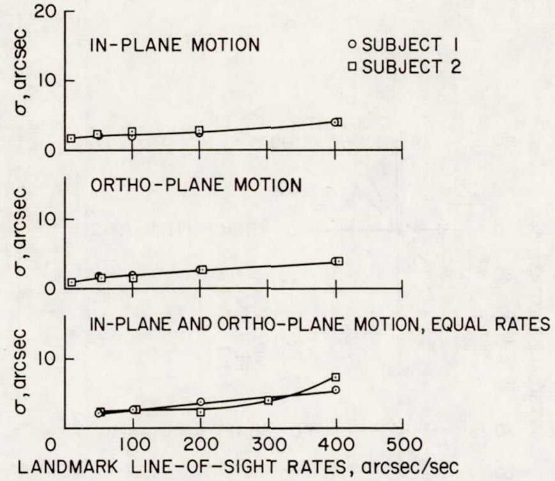

Fig. 13. - Effect of landmark line-of-sight rates on accuracy with vehicle attitude controller active and no initial vehicle attitude rates.

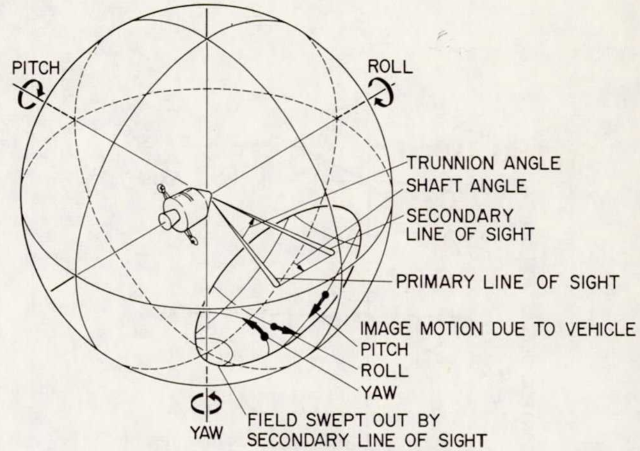

Fig. 14. - Illustration of image motion in the sextant field of view due to vehicle attitude motion.

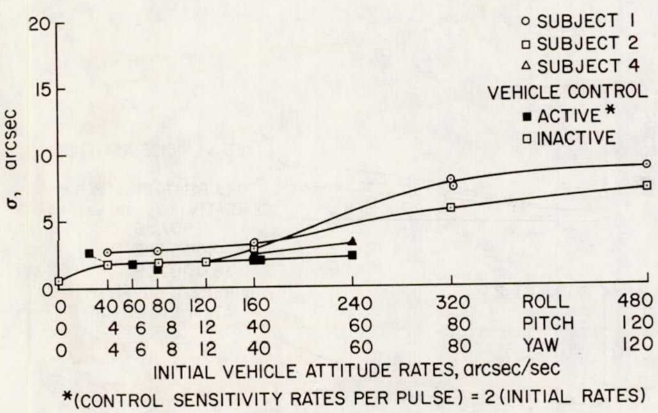

Fig. 15. - Effect of initial vehicle attitude rates on accuracy, with vehicle attitude controller active and inactive, and no landmark motion.

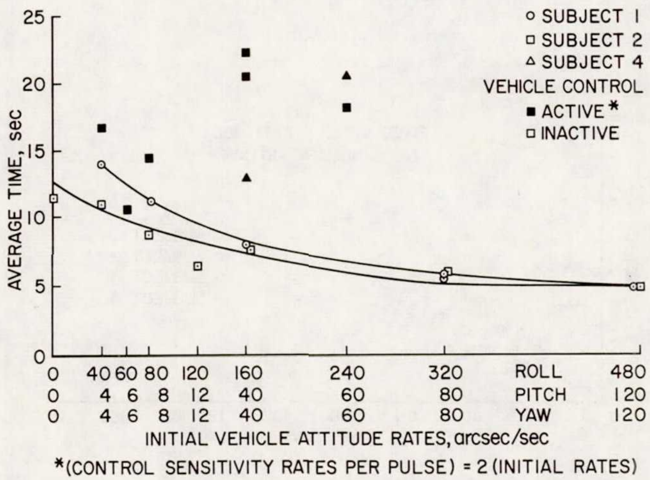

Fig. 16. - Effect of initial vehicle attitude rates on average sighting time, with vehicle attitude controller active and inactive, and no landmark motion.

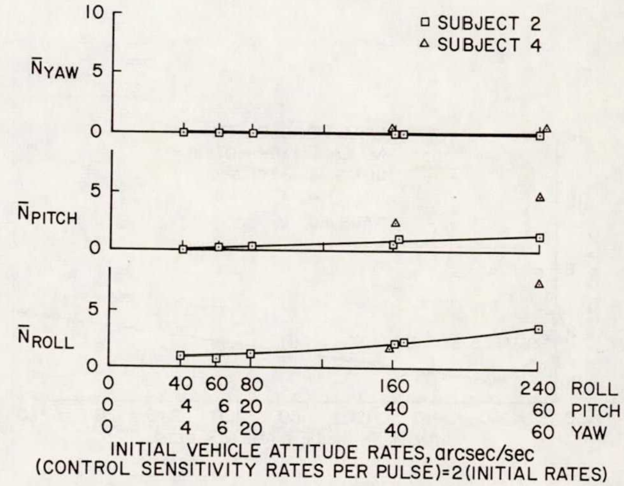

Fig. 17. - Effect of initial vehicle attitude rates on average number of control pulses, with vehicle attitude controller active and inactive, and no landmark motion.

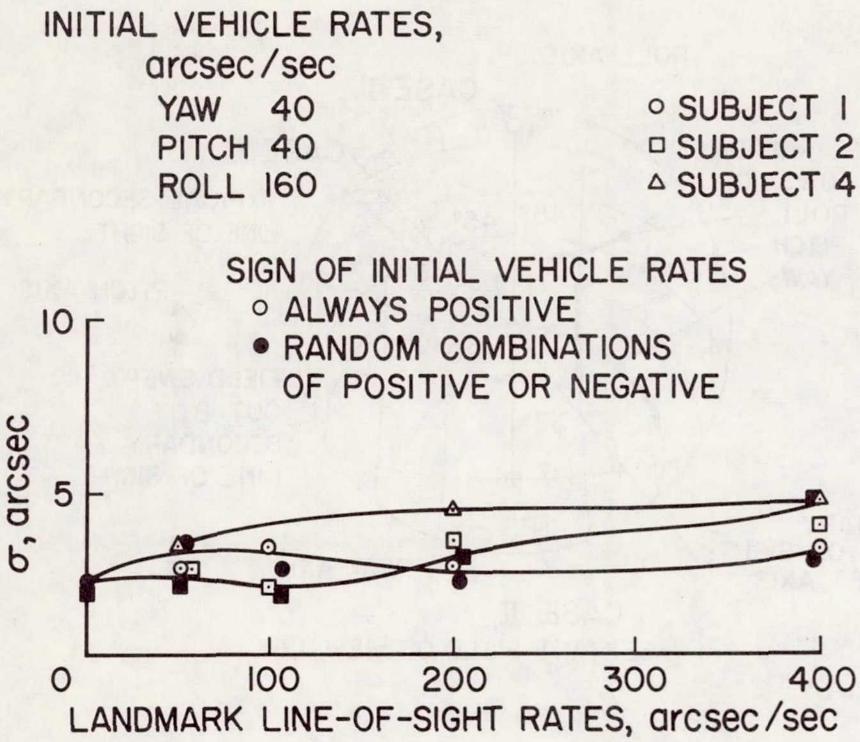

Fig. 18. - Effect of combined landmark line-of-sight rates and initial vehicle attitude rates on sighting accuracy.

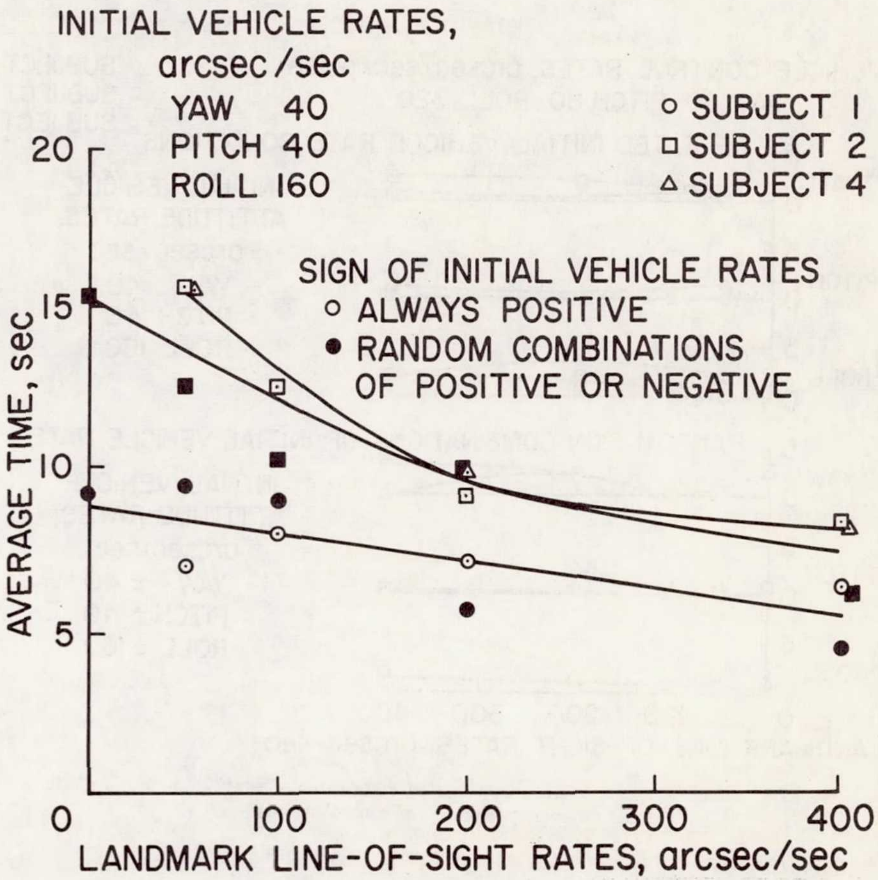

Fig. 19. - Effect of combined landmark line-of-sight rates and initial vehicle attitude rates on average sighting time.

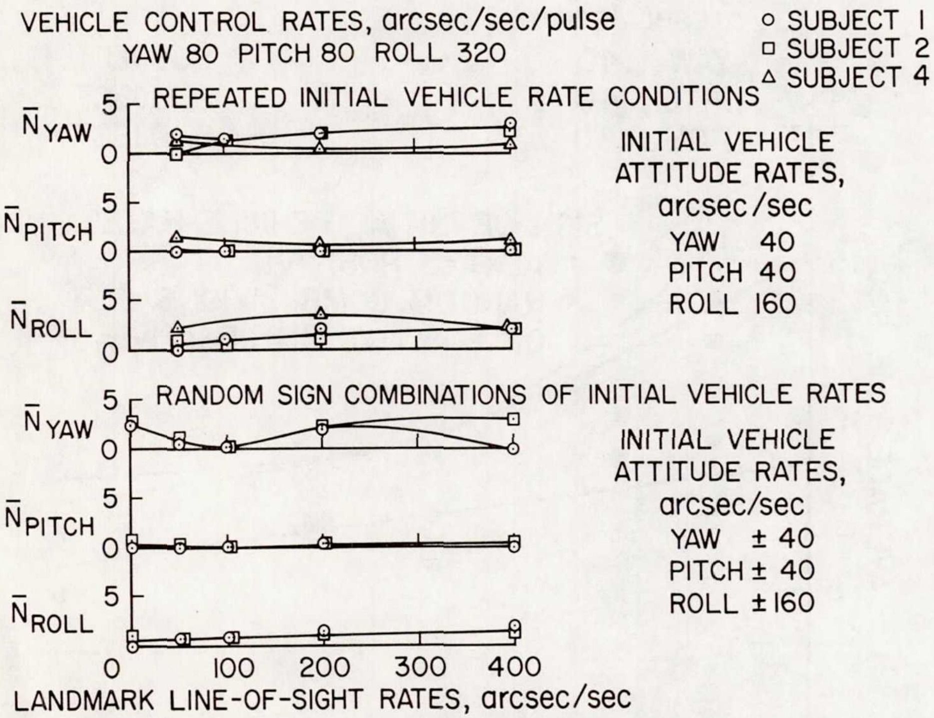

Fig. 20. - Effect of combined landmark line-of-sight rates and initial vehicle attitude rates on average number of control pulses.

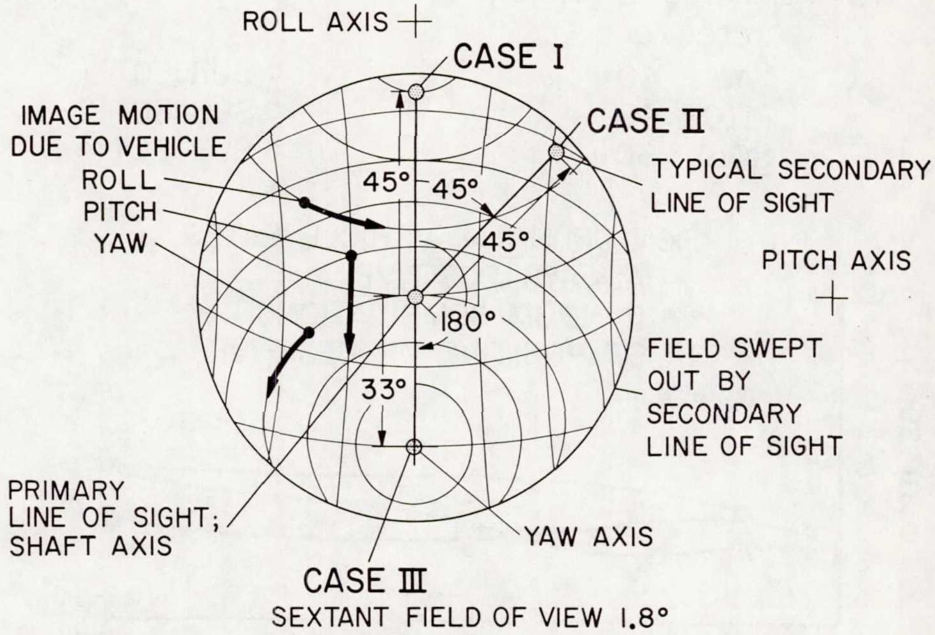

Fig. 21. - Illustration of the large angle conditions.

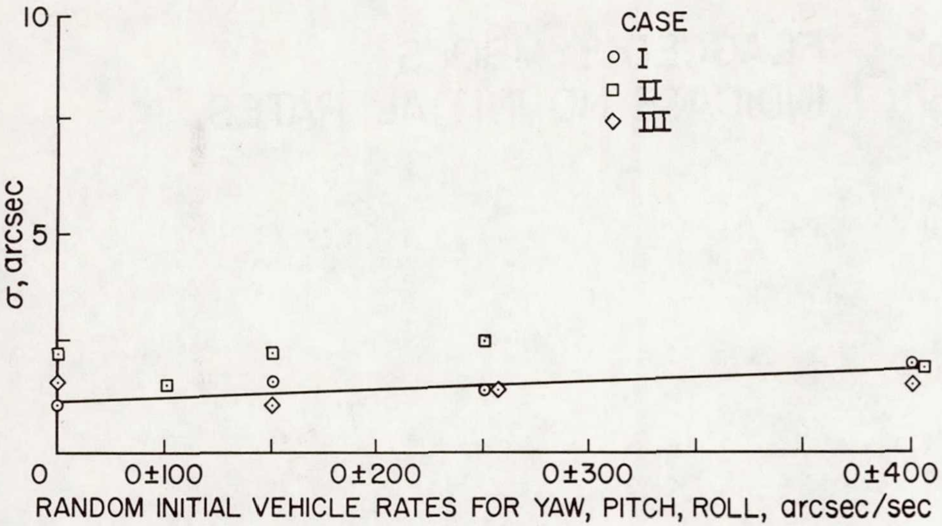

Fig. 22. - Comparison of accuracy for several large angle conditions, with variable initial vehicle attitude rate and no landmark motion.

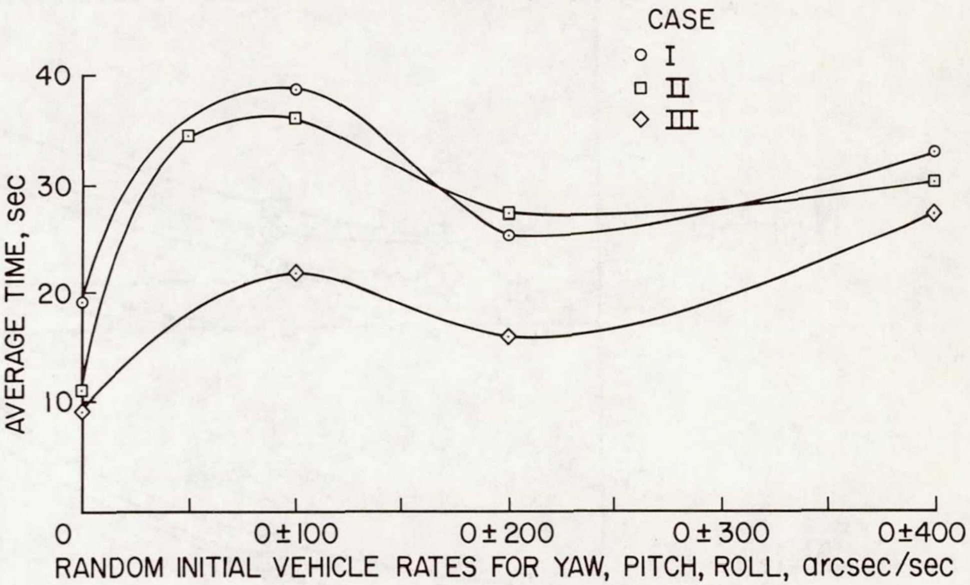

Fig. 23. - Comparison of average sighting time for several large angle conditions, with variable initial vehicle attitude rate conditions and no landmark motion.

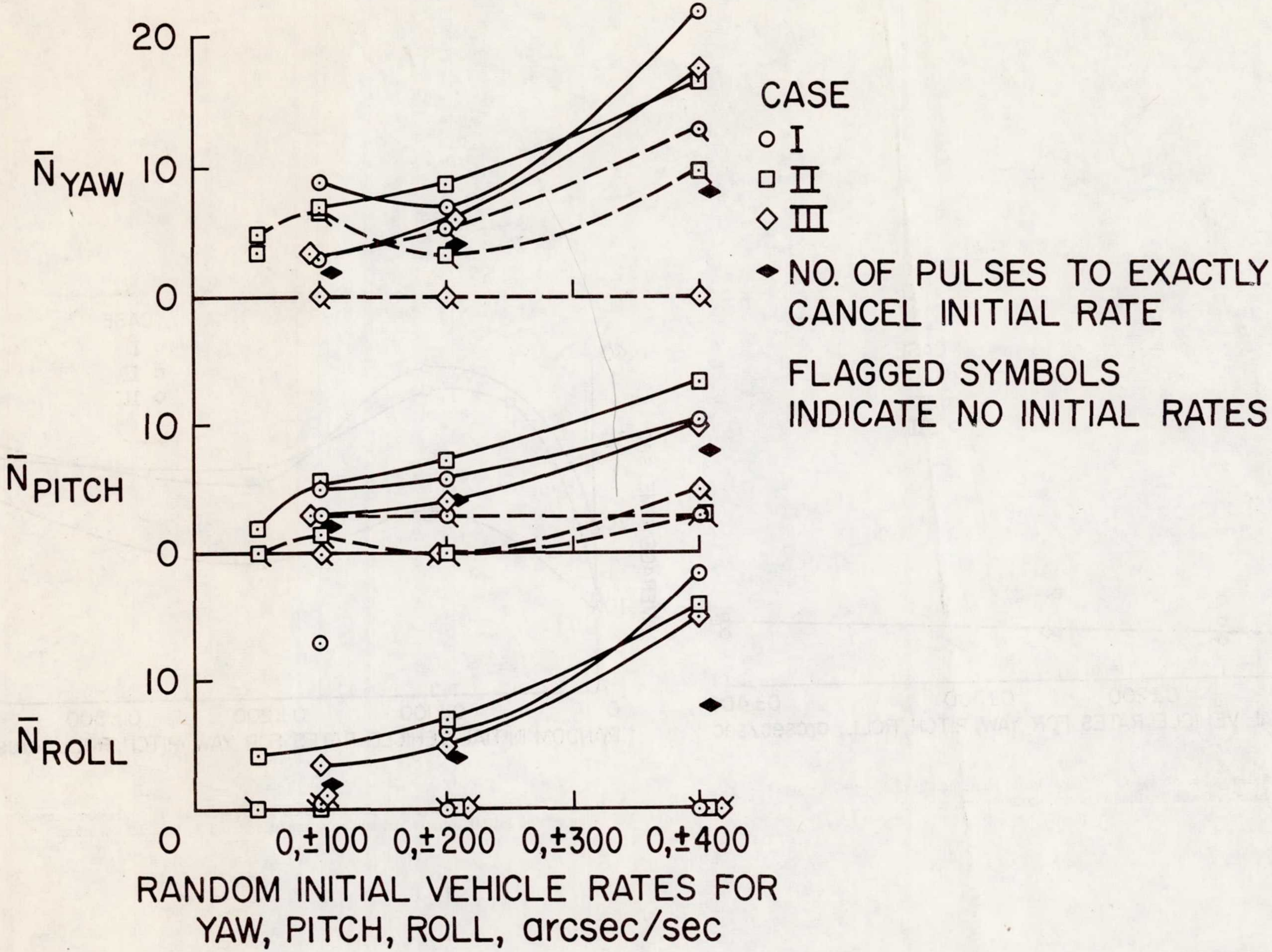

Fig. 24. - Comparison of average number of control pulses for several large angle conditions, with variable initial vehicle attitude rate conditions and no landmark motion.

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