HUMAN PERFORMANCE DURING A SIMULATED APOLLO MID-COURSE NAVIGATION SIGHTING

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ABSTRACT

This is an investigation into the effects of certain variables on the performance of man doing a precise superposition task. This simulates the task that the Project Apollo navigator will be required to perform during the mid-course (translunar and transearth) phases of the proposed lunar excursion. For this investigation, the Apollo Sextant Simulator located at the M. I. T. Instrumentation Laboratory, Cambridge, Massachusetts was used. The variables were (1) Rate of spacecraft motion, (2) Magnification of sextant telescope, (3) Orientation of landmark, and (4) Star-landmark contrast ratio. In order to determine the effect of each variable individually, only one was varied at a time.

Three subjects were used. Each performed the superposition task by using a set of hand controllers until the star was on top of the landmark, as seen through the sextant telescope. At this point the subject pressed a "MARK" button, which recorded the error that he made in seconds of arc. For each given set of conditions, the subject performed the task 25 to 30 times. For each such series, the mean error was computed (absolute mean distance from perfect superposition). Statistical tests were then applied to these means to check for significant changes in error due to changing one of the variables.

Results indicate that two of the four variables investigated have a statistically significant effect on the accuracy. The errors increase with faster craft motion, and at the higher rates more fuel must be expended to keep the landmark in the sextant's field of view. A greater magnification results in overall smaller errors, but more investigation should be done to determine if they are enough smaller to warrant heavier or more expensive equipment. Orientation of the landmark seemingly has no effect on the accuracy of the superposition task. However, orientation may have an effect on landmark recognition, and this should be kept in mind during navigator training. The contrasts studied indicated that so long as both star and landmark are lighted sufficiently to be recognizable, the errors will be essentially the same at any overall brightness level, with one exception. The exception is that a very bright star on a dim background seemingly increases the error. More studies should be made in this area to determine a maximum star brightness for acceptable error.

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The publication of this thesis does not constitute approval by the M. I. T. Instrumentation Laboratory or the National Aeronautics and Space Administration of the findings or conclusions contained therein. It is published only for the exchange and stimulation of ideas.

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CHAPTER 1

INTRODUCTION

On the Apollo lunar mission, the spacecraft will be equipped with a completely self contained navigation and guidance system (G&N). This system will provide an on-board capability to control the spacecraft throughout its mission. In particular, the navigation portion of the system will be able to determine the positions and velocity on the present orbit and to compute the future spacecraft orbit, position , and required velocity changes. It is felt that this capability is unique in space flight. Other missions such as Mariner, Mercury and Ranger have had only limited on-board navigation and guidance capabilities. However, a complete on-board system is required for Apollo when the spacecraft is orbiting the back-side of the moon and out of contact with the earth.

The components and operation of the G&N system are described in references 1 and 22. During each mission phase, the operation of the system will vary. For the midcourse phase, the basic principle of position determination from observations of celestial bodies will be used. The system can measure the angle between a star and any desired earth or lunar landmark. This angle data is obtained by a two line of sight space sextant which is operated by the astronaut. Using the sextant, the astronaut will be required to optically superimpose the star on the landmark. When he completes the superposition, he marks the event to the computer. The angle between star and landmark is measured and read out to the on-board computer where it is compared to the on-board prediction of this measurement.

The astronaut must be able to perform this superposition with great accuracy. This is necessary for two reasons. First, the angle measurement is used to help predict spacecraft position and velocity and future sightings will be compared to on-board predictions of trajectory based on past sightings. Secondly, the Apollo mission is acutely fuel sensitive due to the many required velocity changes. These velocity changes are computed on the basis of the sightings made by the astronaut, therefore, any error in superposition will create erroneous predictions and require excessive use of fuel.

Mission requirements appear to demand the astronaut to complete the superposition within 10 seconds of arc. The question then arises, can the astronaut consistently perform at this level? A search of the literature does not yield any experimental results which are strictly applicable to this question. Much work has been done on all phases of the traditional tracking problem, but the interest there seems to lie more in the time history of the error rather than an error at a specific instant. This disparity is to be expected, for the astronaut is not performing a tracking task in the strict sense of the definition. His task is, as the name implies, a pure optical superposition. Therefore, it is the intent of this thesis to determine how accurately the astronaut can perform the superposition.

The ability of the astronaut to superimpose the star and landmark will undoubtedly be influenced, either favorably or unfavorably, by a number of variables. Among those now considered important are (1) the rate of craft motion about its roll, pitch, and yaw axis; (2) shape, size, and orientation of the landmark; (3) magnification of the sextant; (4) contrast between the brightness of the star and landmark; (5) other variables such as weightlessness and fatigue. In this thesis, the effect of the first four variables on the astronaut's accuracy in completing the superposition will be investigated. These four were selected because they were considered to be most important.

To standardize the statistical analysis of the data, a null hypothesis was proposed. This hypothesis states that none of the variables has any effect on the astronaut's performance when doing the superposition.

CHAPTER 2

DESCRIPTION OF EQUIPMENT

The equipment used for this experiment was the Apollo Sextant Simulator which was constructed by the Instrumentation Laboratory.[1] Figure 1 below is a simplified block diagram of the simulator. Excluding the operator, it is composed of three basic groups: (1) Optics Group (2) Servo loops and (3) computer.

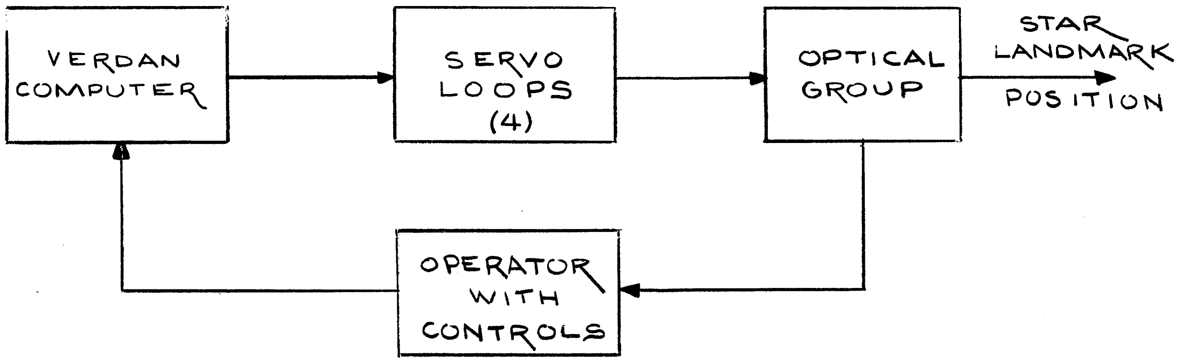


FIGURE 1

The components and specifications of the simulator are given in Appendix A, however, a description of the operator's task and his controls follows. The task performed by the operator simulates that of the astronaut as he performs a midcourse navigation sighting. It begins with the operator acquiring the star and landmark in the sextant field of view. Then by using his controls, he must optically superimpose the star on the landmark. When he considers the two superimposed, he then depresses a"MARK" button (explained later) which completes the sighting.

1- The groups responsible for this design were the Display & Controls Group and the Optics Group.

The operator has complete control over the motion of the star and landmark as observed in the sextant. The star motion is controlled by the optics hand controller located on the left side of the control panel. This controller is a two degree of freedom velocity drive type. Full deflection gives a star velocity of 2500 arc sec/sec. The star motion is described by equations (6, 7) in reference 15. Suffice it to say, these equations have been programmed into the computer. The star motion in the simulator sextant field of view then closley approximates the actual case. One further point, the optics hand controller controls only star motion, landmark motion is unaffected by this controller.

The other controller available to the operator is the attitude impulse controller. It is located on the right hand side of the control panel. The attitude impulse controller gives the astronaut control over the spacecraft attitude in the actual situation. As seen through the sextant, motion of the spacecraft causes motion of the star and landmark. This landmark motion is related to spacecraft motion by the equations.

$$\dot{Y}_L = -\dot{p} \qquad (2\text{-}1)$$

and

$$\dot{X}_L = -\dot{y} \sin A_c + \dot{r} \cos A_c \qquad (2\text{-}2)$$

where

$\dot{Y}_L$ = landmark motion vertically in the field of view

$\dot{X}_L$ = landmark motion horizontally in the field of view

$\dot{p}$ = spacecraft pitch rate

$\dot{r}$ = spacecraft roll rate

$\dot{y}$ = spacecraft yaw rate

A_c = angle between the craft yaw axis and the sextant shaft axis (33°).

In the simulator, these equations also apply but, of course, there is only simulated craft motion. Through the simulator sextant, the landmark always appears perpendicular to the line of sight and motion is thus restricted to this plane. The actual case is not much different from this, however, considering the distances involved and the small field of view of the sextant (1.8°).

Use of the attitude impulse controller by the operator has the effect of instantaneously changing the landmark velocity in the field of view. For this experiment, the controller was set so that one impulse stopped all landmark motion in roll and yaw. Another impulse in the same direction would reverse the landmark motion at the same rate. In the pitch axis, three impulses were required to stop the motion and three more to reverse it due to the large craft moment of inertia which was simulated.

Application of an impulse also caused the star to move in the field of view. The equations of motion were referenced earlier. Even though operating both controls simultaneously, the operator has enough freedom to move the star relative to the landmark and acheive superposition.

Lastly, the operator has available to him a "MARK" button which is located on the right side of the control panel next to the attitude impulse controller. When the superposition is accomplished, the operator depresses the "MARK" button. This completes the sighting, and at this time, any error in superposition from a previously determined zero position is measured. Any error is transmitted to the computer for storage and readout.

The relationship between landmark and craft motion is fixed by equations 2-1 and 2-2. To the operator, however, the apparent rate of motion will vary directly with the diameter of his visual field of view. For example, a craft pitch rate of 400 arc seconds per second will cause the landmark to cross a 1.8° field of view in 16.2

seconds, but for a 1.25° field of view, the landmark crosses the field in 11.2 seconds. Then to the operator, the rate of motion appears higher in the smaller field. For this experiment, the rates were determined by noting the time required for the landmark to traverse a 1.8° field.

Some photographs of the simulator are shown on the following page.

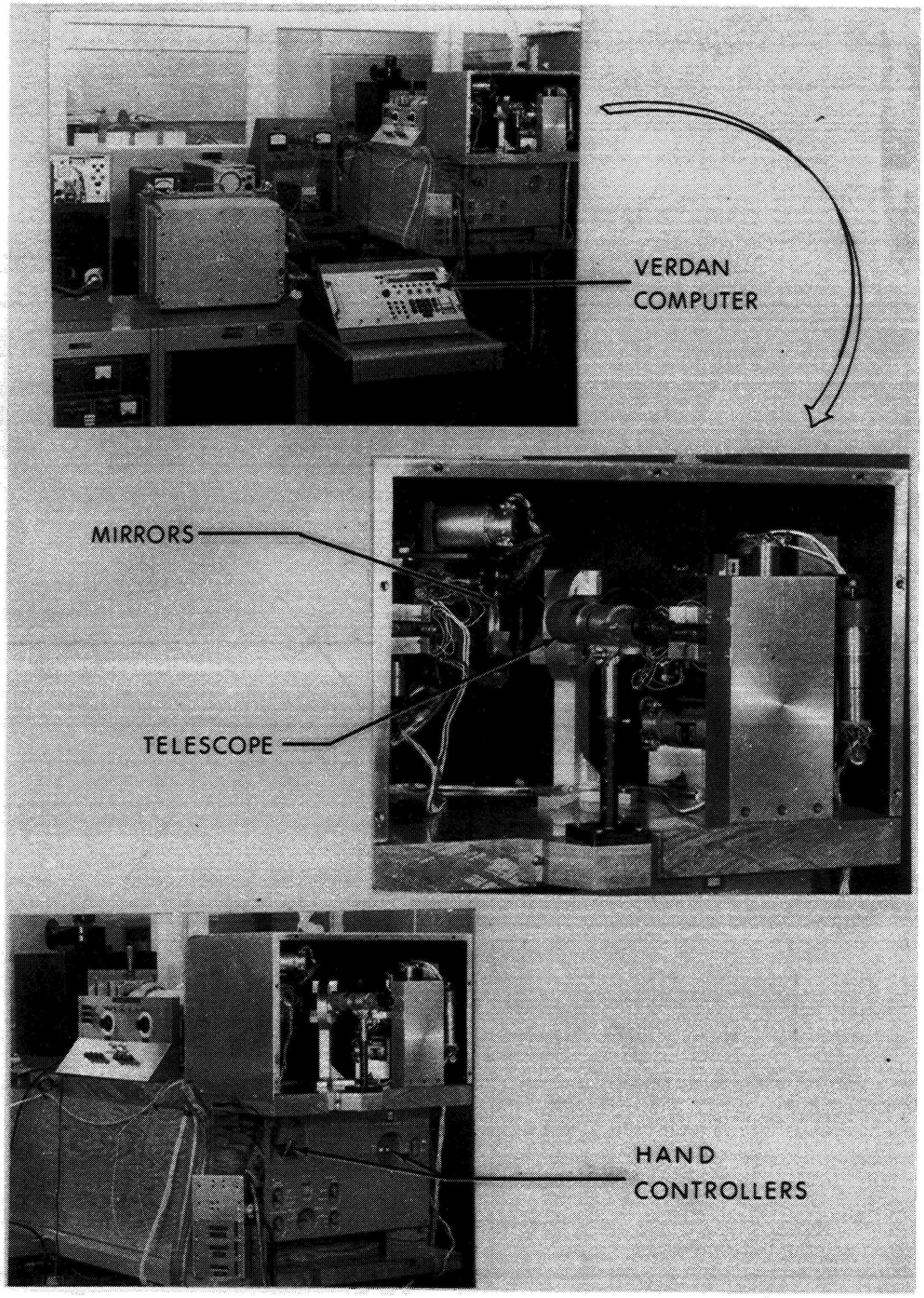


Fig. 2 Photographs of equipment

CHAPTER 3

EXPERIMENTAL DESIGN AND PROCEDURE

3.1 Design

To investigate the effect of the aforementioned variables on the magnitude of the superposition error, an experiment was formulated which affords an opportunity to systematically analyse each variable independently. No attempt was made to determine any combined effect of two or more variables. The experiment is outlined below:

(1) Step I was to determine any inherent error in the simulator. This would be error attributable to controls, readout alignment, etc. To accomplish this, each subject was required to null the error between landmark and star utilizing a high sensitivity visual display on the oscilliscope (1cm = 5 sec.). By this procedure, the resolving power of the sextant and eye were eliminated as a constraint.

(2) Step II was to determine the effect of craft motion on the magnitude of the error. This was done using a series of 14 different rates which ranged from 0 to 440 arc seconds per second. These rates were the rate at which the landmark image moved across the field of view. The rates were presented in a generally random order to minimize any learning effect. For this test, the 28X telescope (T-2 sextant) was used. (See Appendix A)

(3) Step III consisted of determining the effect of sextant magnification on the error. The 28X was replaced by a T-3 model with a 40X magnification. A series of craft rates were selected which were similar to those in Step II. These errors were then compared with those found in Step II. All other variables were identical

to those of Step II.

(4) Step IV concerns the landmark orientation in the sextant field of view. To determine the effect of orientation, the landmark lantern slide was rotated clockwise to positions 60 and 135 degrees from the original position. Each subject performed at two selected rates for each position of the slide. These results were compared with those obtained in the original position at the same rates. Sextant magnification was constant throughout, and the star and landmark were clearly visible.

(5) Step V was an attempt to determine the effect of contrast between star and landmark. For this step, a contrast ratio of 2.29 was used as a basis for comparison. This ratio is given by a 1st magnitude star on a background luminance of 47 foot-lamberts. It is computed from the formula

$$C = \frac{E_S}{E_L} \tag{3-1}$$

where E_S and E_L are the illuminance of the star and landmark respectively at the focal plane of the sextant. The units are lumens/ft.^{2}. This ratio was used throughout the experiment as it afforded a comfortable luminance level for all subjects. In this step, data was obtained at contrast ratios of .259 (bright background, dim star); 36 (dim background, bright star); .261 (dim background, very dim star). This data was compared to that obtained at the ratio of 2.29. For each test, the landmark motion was held constant at 363 arc sec/sec. (See- Appendix B for a complete discussion of these contrast ratios.)

(6) During the course of the experiment, it was discovered that a subject was able to recognize some of the larger errors that he made. These large errors were due to anticipation of a mark or incorrect judgement of star drift rate, etc. Since no allowance had been made to eliminate those obviously bad errors, a test was conducted to determine what improvement in mean error could be obtained by permitting the subject to reject any run where he considered his error to be greater than one star diameter (6 arc seconds). This test required each subject to complete a total of 30 acceptable runs during which time he could reject as many runs as he considered unacceptable. The mean error for all the runs was then compared to the mean error for the 30 acceptable runs.

3.2 Subjects

For this experiment, three subjects were used. All subjects were pilots whose physical qualifications are similar to the astronauts. Subjects A and B (the authors) are U. S. Air Force pilots while subject C is a test pilot connected with the M. I. T. Instrumentation Laboratory. All three subjects were highly motivated and well trained on the operation of the simulator. Before beginning the experiment, each subject was given a training period consisting of 100 or more practice runs.

The authors acknowledge the limitations imposed by the limited number of subjects and by using themselves as subjects. However, a personnel and time consideration made it necessary to restrict our subject sample. Even with this limitation, subject C was unable to complete the entire series of tests as he was unavailable during the initial phases due to other commitments.

3.3 Procedure

Before each test, the system was nulled to remove any initial error. This was done by manually turning the star servo motors until an error of 1 arc sec was read out on the computer. Thus if the computer read an initial error of + 1 ar sec, this error was subtracted from the results of that test. Once the star error was nulled, the landmark was superimposed by means of vernier controls on the slide.

To begin each test, the subject was seated so that he could comfortably work the controls and look through the sextant. He was given as many practice runs as he desired which rarely exceeded 3 or 4 in number. At the start of each run, the subject was allowed to look into the sextant, and at the command "Go" the run would commence. The subject would then try to superimpose the star and landmark using the hand controls. At the instant he felt they were superimposed, he would depress his "MARK" button which would stop the run. The system was then returned to the initial position for the next run. This procedure was repeated until all test runs (25-30) were completed.

For simplicity in programming, the initial conditions were the same for each run. This means that the run always started with the star and landmark in the same relative position. While not wholly realistic, this technique allowed a much better utilization of computer capacity. Also, for a test series, each run commenced with the same initial rate of landmark motion. For each series, the motion was restricted to two directions so that close control could be maintained over the rate of motion.

CHAPTER 4

SUMMARY OF DATA AND ANALYSIS

The data was compiled by having the subject perform a series of 25 to 30 superposition tasks for each set of conditions tested. The mean error (absolute mean distance from perfect superposition) and standard deviation were compiled for each series (See Appendix C). Tables 1 through 6 present these data and the analysis of it.

4.1 Symbols Used:

E: Absolute mean distance from perfect superposition in arc seconds. (With 28-Power telescope unless subscripted otherwise.)
s: standard deviation of a test sequence.
$\bar{s}$: standard deviation of means of tests having same number of samples as given test.
R: Rate of landmark motion across sextant field of view. (arc seconds per second)
$C_{1,2,3,4}$: Contrast Ratio (See Appendix B discussion)
Significance: Is the difference in the means statistically significant, and at what probability of chance?
r: correlation coefficient

Subscripts

28;40: Magnification used
0: refers to a reoriented landmark
$\bar{D}$: refers to the difference between means.

4.2 Determination of System Error

The system error is that portion of the total which is due to such errors as equipment, calibration, computer readout, servo time constants, and hand controller response to fine adjustment.

The overall system average error was found to be less than one second of arc.

The system error was not subtracted out of the data in the sections which follow. This should be done if the desired interpretation is for man only instead of for man-machine combination. It was not done here, because the sensitivity of the error readout was in one arc second increments, therefore an accurate error below one second could not be determined.

4.3 Analysis of Rate Variation

Table 1 and Graph 1 present the mean errors made at the various rates of landmark motion. To test the null hypothesis, a regression line was calculated for each subject. The regression line is that straight line which yields the least mean squared distance from the plotted points. This analysis allows a determination of the correlation, if any, between the errors and rates. For further study, 95% confidence intervals and correlation coefficients were computed for the regression lines, and 95% confidence intervals for the slopes of the lines were computed (Appendix C). These are as follows:

Subject A:

$$E = .457 \times 10^{-2} R + 3.25 \qquad (4.1)$$

(a) 95% of points fall within 1.66 arc seconds of regression line.

(b) Slope of line is between $.129 \times 10^{-2}$ and $.785 \times 10^{-2}$ at 95% confidence.

(c) $r = .633$

Subject B:

$$E = .489 \times 10^{-2} R + 3.21 \qquad (4.2)$$

(a) 95% of points fall within 1.2 arc seconds of line.

(b) Slope of line is between $.22 \times 10^{-2}$ and $.778 \times 10^{-2}$ at 95% confidence.

(c) $r = .793$

Subject C:

$$E = .111 \times 10^{-2} R + 4.30 \qquad (4.3)$$

(a) 95% of points fall within 1.53 arc seconds of line.

(b) Slope lies between $-.271 \times 10^{-2}$ and $.493 \times 10^{-2}$ at 95% confidence.

(c) $r = .26$

The regression lines for subjects A and B are approximately the same. Subject C's is quite different. As seen on Graph 1, this difference is attributable to large mean errors at low rates (114 and 0). Analysis of how subject C was tested disclosed that these rates were tested after a 3-week absence and without any refresher practice. Verification tests were then made at these two rates and his errors were found to be lower. A new regression line using these new values was calculated, and the line more nearly approximated those of A and B. It is

$$E = .264 \times 10^{-2} R + 3.72 \qquad (4.4)$$

An overall regression line, using those rates which all subjects had in common, was calculated and found to have a correlation of .795, significant at the 5% level. The equation of this line is

$$E = .272 \times 10^{-2} R + 3.77 \qquad (4.5)$$

(See Graph 1)

TABLE 1

Landmark Rate Variation Data 28- Power Telescope

R	0	18	74	114	129	145	170	212	242	252	300	363	380	440
E (Subj. A)	2.9	2.6	4.21	4.41	3.45	3.63	4.90	4.70	4.96	4.68	3.51	4.27	4.57	6.14
E (Subj. B)	3.1	-	3.78	3.67	3.75	3.78	5.02	4.19	4.55	-	5.30	3.64	5.55	5.30
E (Subj. C)	4.37	-	3.81	5.17	-	-	-	4.31	-	-	4.44	4.76	-	4.89

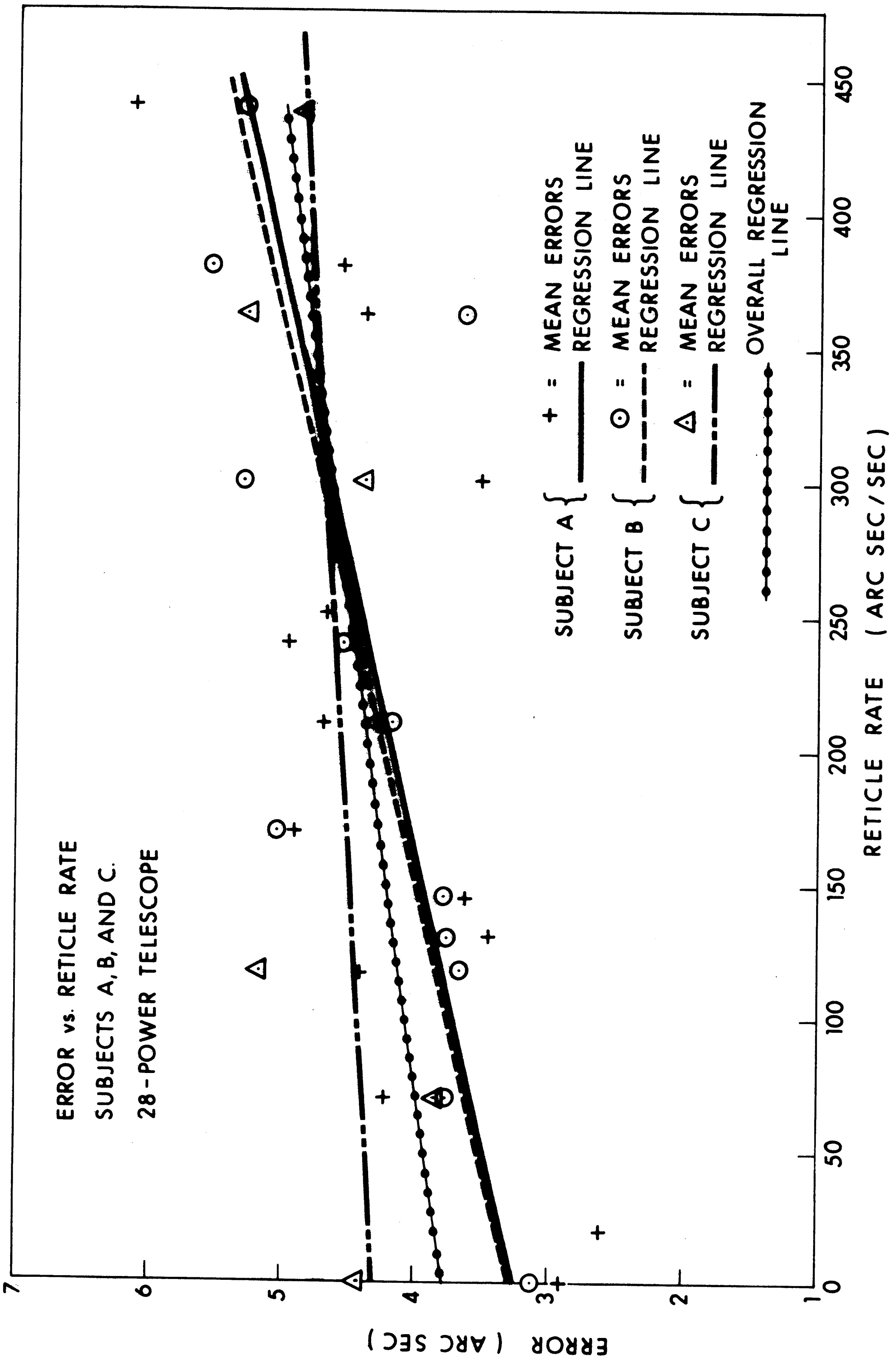
Plotted on Graph 1

TABLE 2

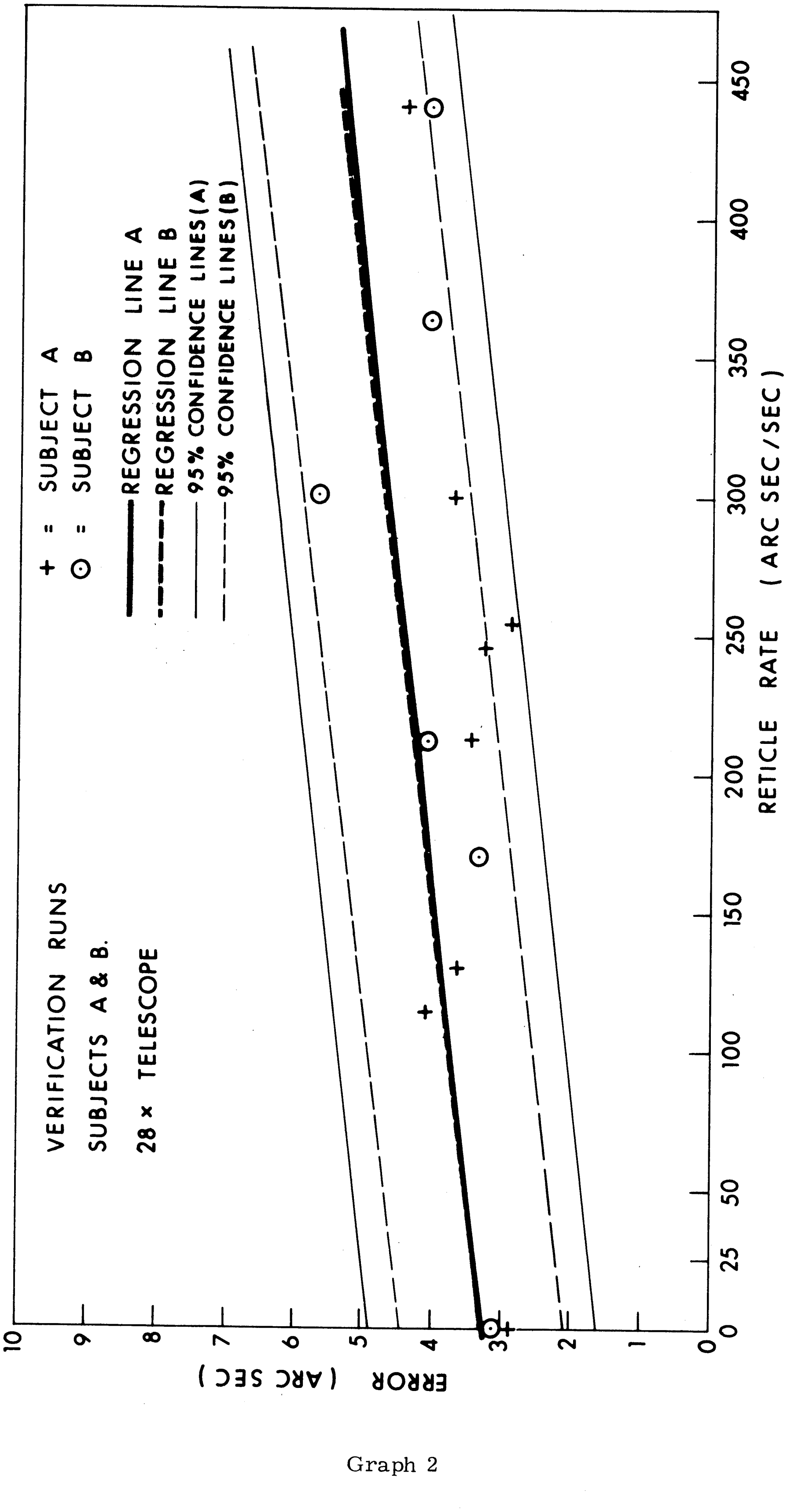
Verification Tests 28- Power Telescope

R	0	114	129	170	212	242	252	300	363	440
E (Subj. A)	-	4.1	3.64	-	3.48	3.23	2.88	3.73	-	4.45
E (Subj. B)	-	-	-	3.31	4.06	-	-	5.65	4.08	4.05
E (Subj. C)	3.91	3.82	-	-	-	-	-	-	-	-

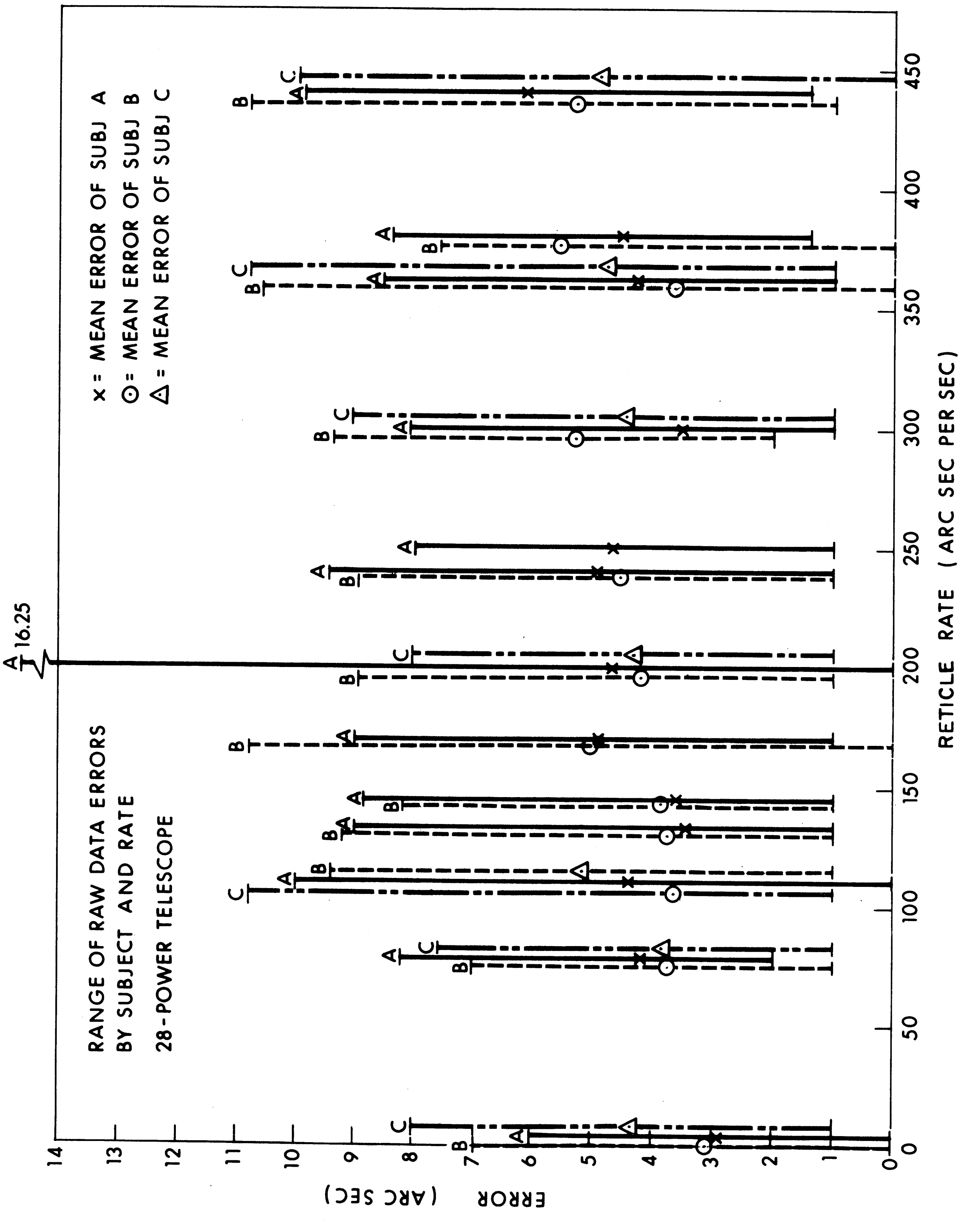
Plotted on Graph 3 for Subjects A & B


ERROR vs. RETICLE RATE
SUBJECTS A, B, AND C.
28-POWER TELESCOPE
ERROR (ARC SEC)
RETICLE RATE (ARC SEC / SEC)
1
2
3
4
5
6
7
0
50
100
150
200
250
300
350
400
450
SUBJECT A { + = MEAN ERRORS
REGRESSION LINE
SUBJECT B { ⊙ = MEAN ERRORS
REGRESSION LINE
SUBJECT C { △ = MEAN ERRORS
REGRESSION LINE
OVERALL REGRESSION LINE

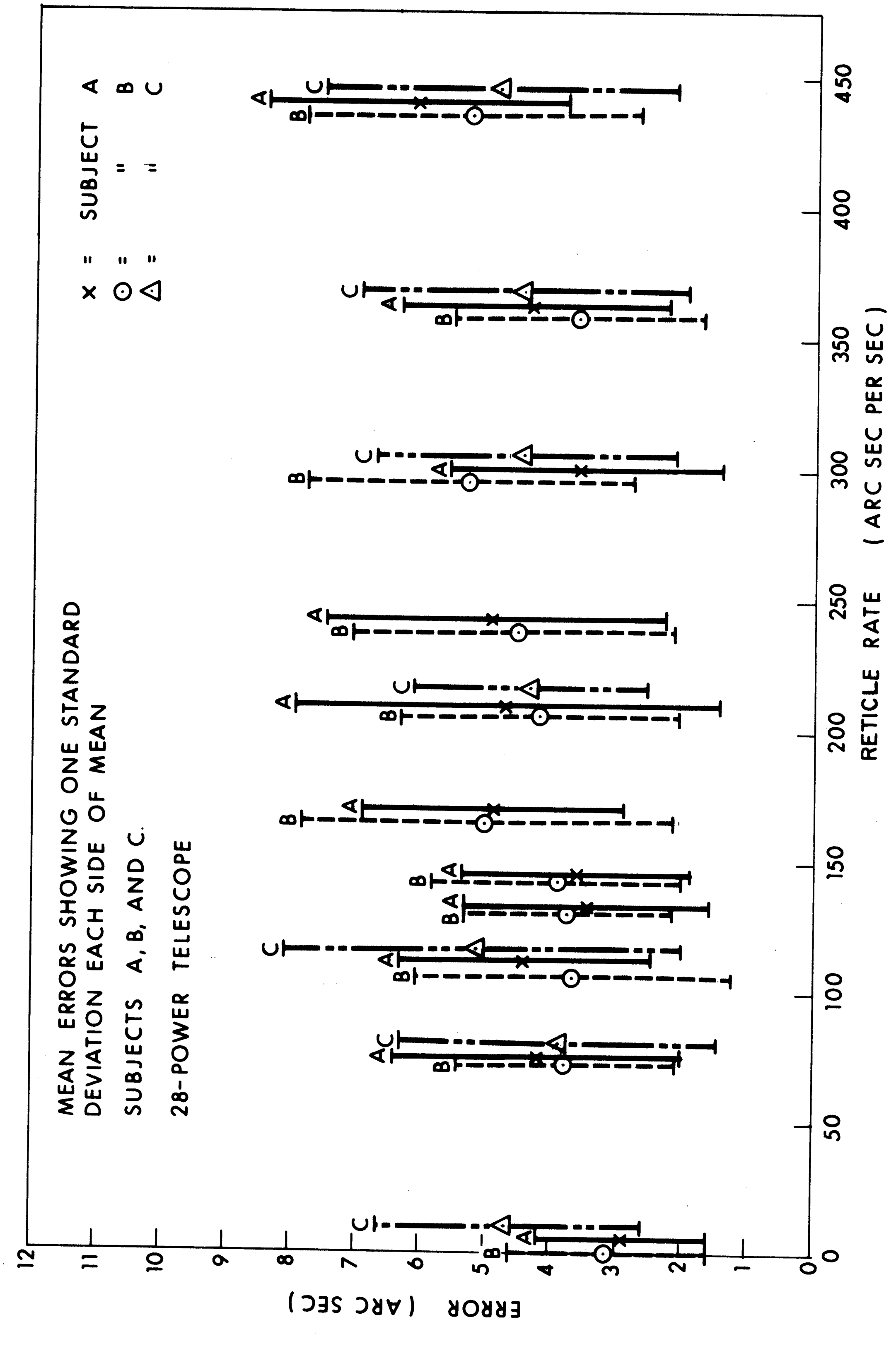
Graph 1


VERIFICATION RUNS
SUBJECTS A & B.
28 × TELESCOPE
+ = SUBJECT A
⊙ = SUBJECT B
REGRESSION LINE A
REGRESSION LINE B
95% CONFIDENCE LINES (A)
95% CONFIDENCE LINES (B)
ERROR (ARC SEC)
RETICLE RATE (ARC SEC/SEC)
0
1
2
3
4
5
6
7
8
9
10
0
25
50
100
150
200
250
300
350
400
450

Graph 2


RANGE OF RAW DATA ERRORS
BY SUBJECT AND RATE
28-POWER TELESCOPE
x = MEAN ERROR OF SUBJ A
⊙ = MEAN ERROR OF SUBJ B
△ = MEAN ERROR OF SUBJ C
ERROR (ARC SEC)
RETICLE RATE (ARC SEC PER SEC)
16.25
A
B
C
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
50
100
150
200
250
300
350
400
450

Graph 3


MEAN ERRORS SHOWING ONE STANDARD DEVIATION EACH SIDE OF MEAN
SUBJECTS A, B, AND C.
28-POWER TELESCOPE
× = SUBJECT A
⊙ = " B
△ = " C
ERROR (ARC SEC)
0
1
2
3
4
5
6
7
8
9
10
11
12
RETICLE RATE (ARC SEC PER SEC)
0
50
100
150
200
250
300
350
400
450
A
B
C

Graph 4

Verification tests were made on A and B also; these are tabulated in Table 2 and plotted on Graph 2. Graph 2 also includes the regression lines for A and B and their 95% confidence intervals. Notice that 7 of the 12 verification tests had lower mean errors than the original tests at the same rates. The remaining five were very close to or slightly higher than the original tests. Also, note that 11 of the 12 verification points fell within the 95% confidence interval of the individual's regression line.

Looking at the correlation coefficients we see that A's (.633) is statistically significant at 5%, B's at 1 % and C's is not significant at 5%. However, C's second (adjusted) regression line has a correlation of .95, significant at 1 % (See table C of ref. 5)

Graphs 3 and 4 show the means, extremes, and standard deviations of the raw data.

4.4 Magnification Effect

Table 3 compares the errors made using the 40 x magnification with those made using the 28 x magnification. For statistical testing, the "student-t" test was applied to the difference in mean errors at a given rate. (See Appendix C).

Looking at the significance column some variations are apparent. Subject A's performance improved significantly with the 40x telescope 4 of 5 times, and degenerated insignificantly once. Subject B improved significantly 3 of 5 times, and insignificantly twice. Subject C improved each time, but not significantly.

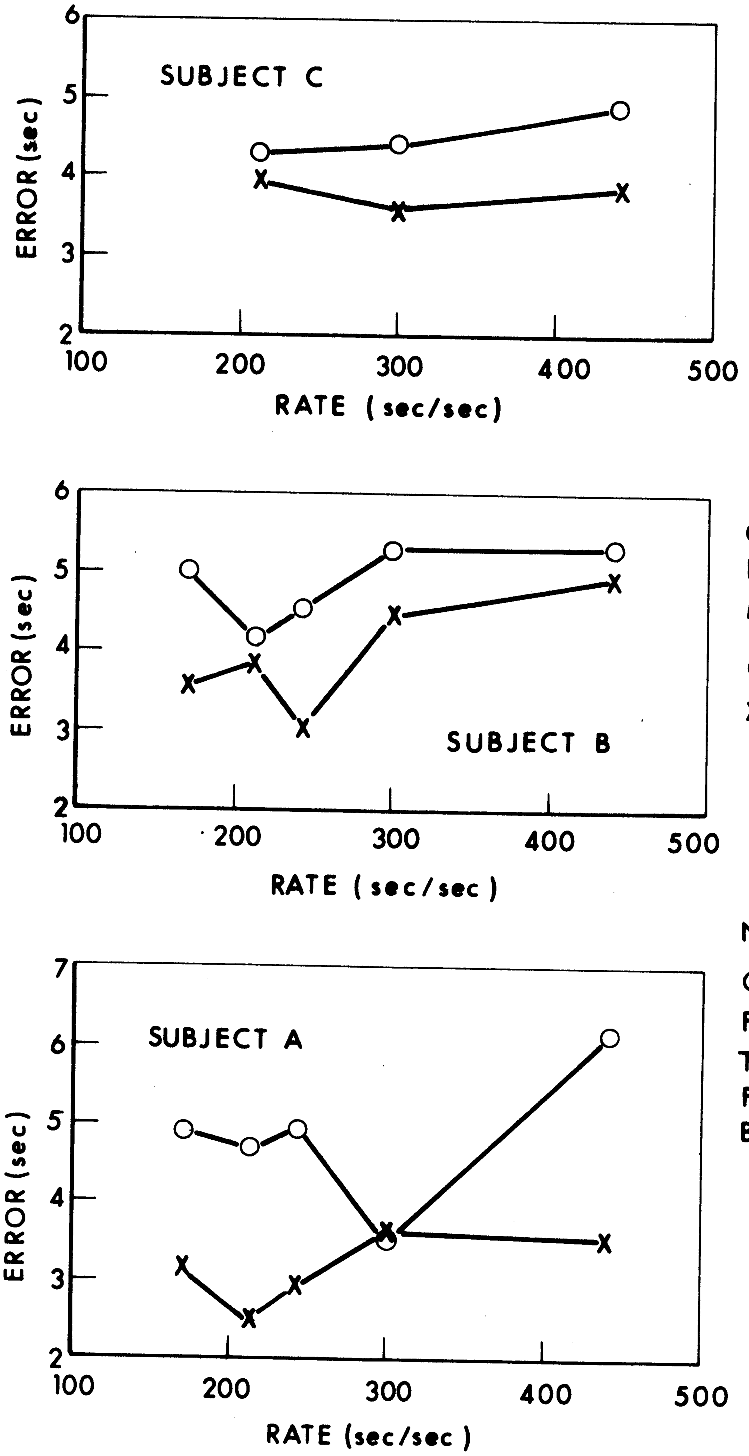
To further investigate this trend, the data was subjected to a Wilcoxon "Signed-rank test" (Ref. 16 p. 596). This test indicated there is an overall significance in the improvement of performance with the higher magnification at a .1% level.

Graph 5 shows the comparison between the mean errors at the two different magnifications.

TABLE 3

Landmark Rate Variation Data -40 Power Compared to 28- Power

RATE		E_{28}	E_{40}	S_{28}	S_{40}	$\bar{S}_{28}$	$\bar{S}_{40}$	$S_{\bar{D}}$	"t"	Significance & Level of Chance
SUBJECT A	212	4.7	2.5	3.24	1.86	.625	.358	.720	3.06	yes at 1%
	242	4.96	2.98	2.67	1.47	.496	.273	.565	3.51	yes at 1%
	300	3.51	3.61	2.10	1.45	.420	.290	.510	1.96	no at 5%
	440	6.14	3.56	2.31	2.31	.472	.641	.798	3.23	yes at 1%
	170	4.9	3.16	2.02	1.82	.375	.350	.513	3.34	yes at 1%
SUBJECT B	212	4.19	3.84	2.12	1.87	.384	.358	.525	.616	no at 5%
	242	4.55	3.02	2.41	1.65	.440	.301	.533	2.49	yes at 2%
	300	5.30	4.48	2.51	1.91	.492	.374	.618	1.325	no at 5%
	440	5.30	4.9	2.55	2.45	.491	.500	.701	.52	no at 5%
	170	5.02	3.56	2.82	2.25	.505	.477	.695	2.1	yes at 5%
SUBJECT C	212	4.31	3.92	1.78	1.79	.321	.335	.465	.84	no at 5%
	300	4.44	3.60	2.28	2.10	.407	.414	.58	1.45	no at 5%
	440	4.89	3.84	2.70	2.09	.447	.440	.627	1.675	no at 5%



GRAPH OF MEAN ERROR FOR 28X AND 40X MAGNIFICATION

O = 28 X
X = 40 X

NOTE:

CONNECTING LINES ARE FOR CLARITY ONLY. THEY ARE NOT INTENDED FOR INTERPOLATION BETWEEN POINTS

Graph 5

4. 5 Effects of Landmark Orientation

Tables 4 and 5 compare each of two different landmark orientations with the original tests run.

TABLE 4

Orientation Data - 60^o Rotation Compared With Original Position

RATE		E	E_o	S	S_o	$\bar{S}$	$\bar{S}_o$	$S_{\bar{D}}$	"t"	Significance & Level of Chance
SUBJ. A	74	4.21	3.79	2.19	3.24	.394	.338	.52	.807	no at 40%
	212	4.70	5.33	1.87	1.85	.50	.465	.685	.92	no at 30%
SUBJ. B	74	3.78	3.80	1.63	1.68	.362	.303	.473	.0423	no at 90%
	212	4.19	4.49	2.12	1.67	.379	.344	.512	.587	no at 60%
SUBJ. C	212	4.31	4.31	1.78	1.53	.303	.308	.433	0	no at 100%

TABLE 5

Orientation Data - 135^{o} Rotation Compared With Original Position

RATE		E	E_o	S	S_o	$\bar{S}$	$\bar{S}_o$	$S_{\bar{D}}$	"t"	Significance & Level of Chance
SUBJ. A	74	4.21	4.09	2.19	1.41	.387	.329	.506	.237	no at 80%
	212	4.70	4.51	1.87	1.67	.346	.322	.472	.402	no at 50%
SUBJ. B	74	3.78	4.24	1.63	1.54	.343	.292	.450	1.02	no at 30%
	212	4.19	5.29	2.12	1.55	.360	.341	.497	2.22	no at 3%
SUBJ. C	212	4.31	3.69	1.78	1.87	.333	.333	.471	1.315	no at 20%

The student-t test was applied for statistical analysis. The "significance" column shows that all but one test had no significant difference at 20% or higher level of chance. Significance for the other point is listed as "no at 3%", but it could be "yes at 5%" just as well.

For a further investigation, a Wilcoxon "signed-rank test" was used to test all orientation points against the original orientation. It indicated no significant change in error due to change in landmark orientation at the 1% level.

4.6 Effect of Differing Contrast Ratios

Table 6 shows the comparison of each of three different contrast ratio conditions. The statistical tests used were the student-t test where applicable, or the chi-square test (see Appendix C)

TABLE 6

Contrast Data - Varied Contrasts Compared To Original

Contrast

	SUBJ. A				SUBJ. B				SUBJ. C			
	C_1	C_2	C_3	C_4	C_1	C_2	C_3	C_4	C_1	C_2	C_3	C_4
$E_{1, 2, 3, 4}$	4.26	4.70	6.86	4.48	3.64	4.55	7.50	4.82	4.76	6.99	5.59	5.64
$S_{1, 2, 3, 4}$	2.10	2.00	3.05	2.35	1.91	1.93	3.86	2.54	2.52	2.95	3.37	3.25
$\overline{S}_1$	-	.375	-	.407	-	.357	-	.418	-	.508	.564	.535
$\overline{S}_2$	-	.411	-	-	-	.377	-	-	-	.517	-	-
$\overline{S}_3$	-	-	-	-	-	-	-	-	-	-	.564	-
$\overline{S}_4$	-	-	-	.414	-	-	-	.411	-	-	-	.565
$S_{\overline{D}}$	-	.566	-	.578	-	.521	-	.587	-	.722	.783	.780
"t"	-	1.61	*	.371	-	1.78	**	2.01	-	3.09	1.06	1.03
Sig. & Level of Chance	-	No at 10%	Yes at 1%	No at 70%	-	No at 5%	Yes at 1%	No at 4%	-	Yes at 1%	No at 30%	No at 30%

* used chi-square test (=17.70) Because this sample did not obey rules for normal "t" test.

** used chi-square test (=36.8) Because this sample did not obey rules for normal "t" test.

C_1 = original contrast = 2.29 (star over landmark)

C_2 = .259 (background very bright, 3rd magnitude star)

C_3 = 36 (background very dim, 1st magnitude star)

C_4 = .261 (background very dim, 4th magnitude star)

Note that the results of Subjects A and B agreed generally, but both differed from C for contrasts 1 and 2. For further investigation of any significance, a Wilcoxon "2-sample test" was applied comparing each contrast ratio with the original contrast ratio. The test showed a significant difference (at 5%) only at C_3 (bright star with very dim landmark). This test was also applied to C_2 versus C_4. These had approximately the same contrast ratio but C_4 had a lower background (landmark) brightness. No significant difference was indicated at a 50% level.

This seems to indicate that the only contrast ratio showing any significant effect on the error was where a very bright star was used with a dim, but recognizable landmark. The contrasts where the star was barely distinguishable over the background brightness indicated no significant change in error, regardless of whether the background brightness (which determines the eye's adaptation level and visual acuity) was high or low.

4.7 Rejection Tests

As mentioned previously the subjects were often aware of a mark which would have been unacceptable for a navigation sighting. Hence a series of tests were run on subjects A and B as described in Chapter 3. To the results of this test were added results of later runs in which the subject was allowed to say when he considered the mark to be bad. The results are in Table 7.

TABLE 7

Percent of Errors Greater Than 6, 8, & 10 Arc Seconds Which Were Detected

Errors Greater Than	Subject A	Subject B	Total
6 seconds	11 of 35 (31.4%	8 of 28 (26.6%)	19 of 63 (31%)
8 seconds	6 of 16 (37.5%	6 of 13 (46.2%)	12 of 29 (41.4%)
10 seconds	3 of 6 (50%)	5 of 8 (62.5%)	8 of 14 (57.5%)

In other words, subject B had eight errors greater than ten seconds, but he was able to reject 5 of these. The six second errors were harder to detect, but this could possibly be improved through a training program emphasizing a knowledge of exactly what six arc seconds looks like.

4.8 Fatigue Tests

To test for a suspected eye fatigue error factor, subjects A and B were tested for a period of approximately forty minutes each (continuous except for necessary error readout and any necessary renulling of equipment). Four test series were run on each subject during this time, each series taking approximately ten minutes. For this length of time, we found no significant increase in errors.

TABLE 8

Fatigue Test Data (28 - Power Telescope)

Test No.	1	2	3	4
E (A)	2.64	2.50	2.37	3.28
E (B)	2.25	3.36	2.49	2.53

CHAPTER 5

DISCUSSION OF RESULTS AND CONCLUSIONS

5.1 General

The results given in the preceeding chapter have all been subject to the two major constraints of limited subject sample size and the prevalance of laboratory conditions. With a limited number of subjects, day to day variations are evident in the results. A larger population probably would have smoothed out these variations and reduced their effect, if any, on the results. Also, the authors could not tell if all subjects were average, above average, or below average, at the outset of this work. However, graph 4 of chapter 4 indicates that the variations within the individual subjects' tests were greater than the variations among the subjects. This would indicate all three subjects were of about equal ability, and this was assumed to be average.

Undoubtedly, the laboratory conditions used in this experiment will yield the most optimistic results. The actual operating conditions of the astronaut, such as weightlessness, standing, and perhaps operating in his space suit under pressure have not been simulated, therefore some thought must be given to these combined conditions and to the mental condition of the astronaut before more realistic results are obtained. The results given are intended to be a base line for future work.

In the following sections, some statements are made which are not supported by data. These mainly reflect observations and feelings of the subjects which should be helpful in the design of an experiment for any future work.

5.2 Rate Variation

The regression line analysis shows an overall correlation coefficient of .795, significant at the 5% level. We must therefore reject our null hypothesis at this level, and say that the rate of landmark motion does have an effect on the magnitude of the error. Though the tasks differ, Bowen and Chernikoff (Ref. 12) reach a similar conclusion as pertains to the velocity of the command course. Here, in a compensatory tracking task, the tracking error increased with an increase in the average course velocity (cycles per minute times amplitude of the signal) of the command course signal.

Inspection of the individual regression lines indicates that Subject C differed quite a bit from the other two, due primarily to the larger errors at the lower rates. The rate tests were given to Subject C sporadically since he was frequently busy on other matters and could not devote his full time to the experiment. The lower rate tests were administered after one of these absences of a few weeks. The high errors reflect, in part, this absence, since a series of verification tests were given at a later date and the error was significantly lower. In future tests, care must be taken to minimize any effect of this kind.

There existed some support at the beginning of the work for the theory that the errors would increase approximately linearly up to a certain rate, above which the curve would break and the subject would no longer be able to accurately complete the superposition task. However, over the range of rates tested, the data does not show this to be the case. To be sure, this relationship evolved from data taken under laboratory conditions, but less favorable conditions would undoubtedly shift up not merely one point, but the entire error spectrum.

Even though all subjects were considered to be well trained at the commencement of the experiment, the verification tests seem to indicate a gradual improvement in performance with practice. Perhaps more familiarity with the simulator accounts for this improvement as the simulator has certain characteristics, notably in the hand controller, which required quite a bit of experience to master. The fact that 11 of the 12 verification points fell within the 95% confidence limits indicates a consistancy which should prove helpful in future experiments.

Below rates of about 200 secs/sec, all subjects were able to obtain a mark while resorting to the attitude controller only occasionally to reverse the landmark motion. Above 200 secs/sec, the landmark moved to the edge of the sextant field of view before a mark could be obtained and the attitude controller was then used more often. On the average, above 200 secs/sec, the landmark motion was reversed once before a mark was obtained. On the mission, this would require an expenditure of fuel. We did not attempt to translate the use of the attitude controller into a specific fuel consumption, as the magnitude of the specific impulse (yet to be determined) will determine how much fuel will be required. It is only pointed out that the higher rates will require expenditure of fuel to keep the landmark in the field of view.

Recalling that the optical resolution of the system is limited by the sextant at 3.5 seconds of arc, a look at the data in Table 1 at zero rate indicates a mean error of nearly that value. Thus the subjects were able to perform at the system limit when unhindered by landmark motion. It could not be expected that the mean error would be less than this limit, since the two objects tend to appear as one when separated by less than 3.5 seconds of arc. Below this distance, the subject must guess the apparent size of the combined star and landmark in order to improve his accuracy.

It is anticipated, with no proof, that a hand-controller having a servo dead band will tend to increase the errors, due to a lack of fine control over the star.

5.3 Magnification

These results varied between the individual subjects, but taken as a whole, the Wilcoxon test indicates a high significance in the reduction of error 12 times out of 13 with the higher magnification. This indicates that a sextant of higher power would improve the navigator's performance. However, other considerations such as size, weight, and shape of the sextant may dictate whether the improvement warrants putting the higher power into the vehicle. Reference 12 again reaches a similar conclusion that magnification will improve the performance of the human operator. Another factor to consider is that, having a smaller field of view, even more fuel may have to be used with the higher magnification in order to keep the landmark in the field.

5.4 Orientation of the Landmark

The results of these tests indicate that the orientation of the landmark in the field of view had no significant effect on the subjects' performance. In these tests, only a mosaic of one general land area (San Francisco Bay area) was used, so the subjects became quite familiar with the area. The acquisition of the proper landmark then presented no problem regardless of orientation. The effect of varying size and shape of the landmark was not investigated. The landmark was changed midway through the experiment, but the new one was similar in size and shape to the old one. The size and shape problem should be the subject of further work. The selection of the proper size landmark as a function of distance from the earth will present a unique problem. For best accuracy, it appears that a landmark the same size as the star should be selected.

5.5 Contrast

The results of these tests generally tend to agree for subjects A and B; however, the results from subject C's tests are opposite to the other subjects at contrasts C_2 and C_3. No reason for this variation could be found in the data. Upon questioning, all subjects reported that the bright star in contrast C_3 produced quite an apparent glare. Subjects A and B indicated that this glare seriously hindered their performance as the star blotted out the landmark when the two were brought close together. Though Subject C reported the same glare, it did not significantly affect his performance. This may indicate a need to determine a maximum star illuminance for dim backgrounds.

The tests run at contrast C_2 also produced some interesting results. At this ratio, the star was barely visible against a bright background. On 7 of the 86 runs, the run was aborted when the subject lost the star and was unable to find it again. Had not the initial conditions been constant (run begins with the star in the same position relative to the landmark), the star would probably have been very difficult to locate and identify. Each loss of the star occurred when the direction of landmark motion was reversed at the edge of the field of view. When the star was maintained in sight, Subjects A and B had errors which were not significantly different from those at C_1, while Subject C's were significantly worse. However, the Wilcoxon test indicates no overall significant change in error.

As noted in other sections, the ratios C_2 and C_4 were very nearly the same; however, the overall luminance was higher in C_2. The Tiffaney data (Ref. 19) indicates that as the light wanes, the liminal angular subtense increases at a given contrast ratio. The tests run at C_4 and C_2 simulated light conditions from twilight to a very dark day, and in this range, the liminal angular subtense that can be seen is almost constant. If adapted to these levels, the astronaut should be able to distinguish star and landmark equally well and no significant change in mean error should occur. The results verify this.

From these tests, it is apparent that man can perform over a wide range of visual conditions, but it cannot be stated that these tests establish limiting conditions. More exhaustive studies are needed using filters to change contrasts before these limits are set. Also, weightlessness will undoubtedly affect his visual capacity. Pigg and Kama (Ref. 7) found that under conditions of weightlessness, man's visual acuity is reduced by about 10%. This may prove to be unimportant for this mission.

5.6 Rejection Test

This series was conducted primarily to determine if any points could be eliminated from the original raw data. The results indicate that approximately 30% of the errors greater than 6 arc seconds were detected, 40% of those greater than 8 seconds, and 57% of those greater than 10 seconds. These results did not justify elimination of any points from the original raw data. Therefore, on later tests only those points which the subject verbally rejected were eliminated. It is felt, however, that the astronaut should be provided with a rejection capability, so that he may eliminate the bad marks. Rejection of a good mark will not hurt the mission, but forced acceptance of a bad mark will compound into false trajectory predictions, and may result in undue fuel expenditure.

5.7 Fatigue Tests

The results of this test appear to be inconclusive for the time period considered. It was undertaken because Subject A, at one point in the experiment, felt his performance was being affected by an eye twitch, caused by extended use of the simulator. The visible background around the sextant field of view is very cluttered with motors, mirrors, etc. To eliminate this distraction, all subjects closed the eye not being used for the run. Between runs, the subject relaxed to rest the eye, but after 20 minutes or so, frequently a slight twitch developed indicating fatiguing muscles. A neutral color shield properly placed to eliminate the cluttered background would allow the subject to keep both eyes open and relieve this annoying, though harmless twitch.

5.8 Conclusions

On the basis of the data and the statistical analysis, we can conclude:

1. There is positive correlation between rate of landmark motion and size of error. Higher rates result in higher errors, however, no rate was found (up to 440 seconds per second) where the subjects were unable to perform the superposition. At all rates tested, the mean errors were below 7 arc seconds.
2. The errors are reduced with higher power magnification. Factors of additional cost, weight, and possible fuel expenditure must be weighed against the magnitude of the decrease in error.
3. No significant changes in error occur when the landmark is seen from a different angle (reoriented). This does not include any problems of visual acquisition of the proper landmark which may be encountered.
4. At contrasts where a bright star occurs on a dim background, the astronaut will have trouble due to star glare. At contrasts where a dim star appears barely visible on the background, the astronaut may have difficulty acquiring and identifying the proper star. However, once identified, he will not have particular difficulty marking it.
5. Some form of reject control is desirable on the simulator and the spacecraft to allow the navigator to discard any undesirable sightings.
6. A neutral color background is desirable for the simulator so that the subject can leave both eyes open without being distracted from the task.

5.9 Recommendations for Further Work

It is suggested that further work be done notably in the area of contrast and the use of filters to achieve the most desirable contrasts. More data should be obtained on the effect of landmark size and shape. Photo mosaics which simulate greater distances from the earth would also be beneficial in future work. Also, a test series should be designed whereby a correlation among all variables could be determined. Further work with the rejection tests may indicate a possibility of truncating the error distribution curve on the high end.

Finally, it would be extremely advantageous to equip the simulator with a scanning telescope and allow the subject to perform the initial alignment and acquisition problems. In this manner, the initial conditions for each run could be changed which would allow the simulation of a more realistic situation.

APPENDIX A

A full description of the Sextant Simulator follows:[2]

(1) Optics Group

The optics group consists of a telescope, mirrors, beam splitter, a sensitive two axis refractosyn, and two collimators. Figure 3 shows schematically the general arrangement of the optics group.

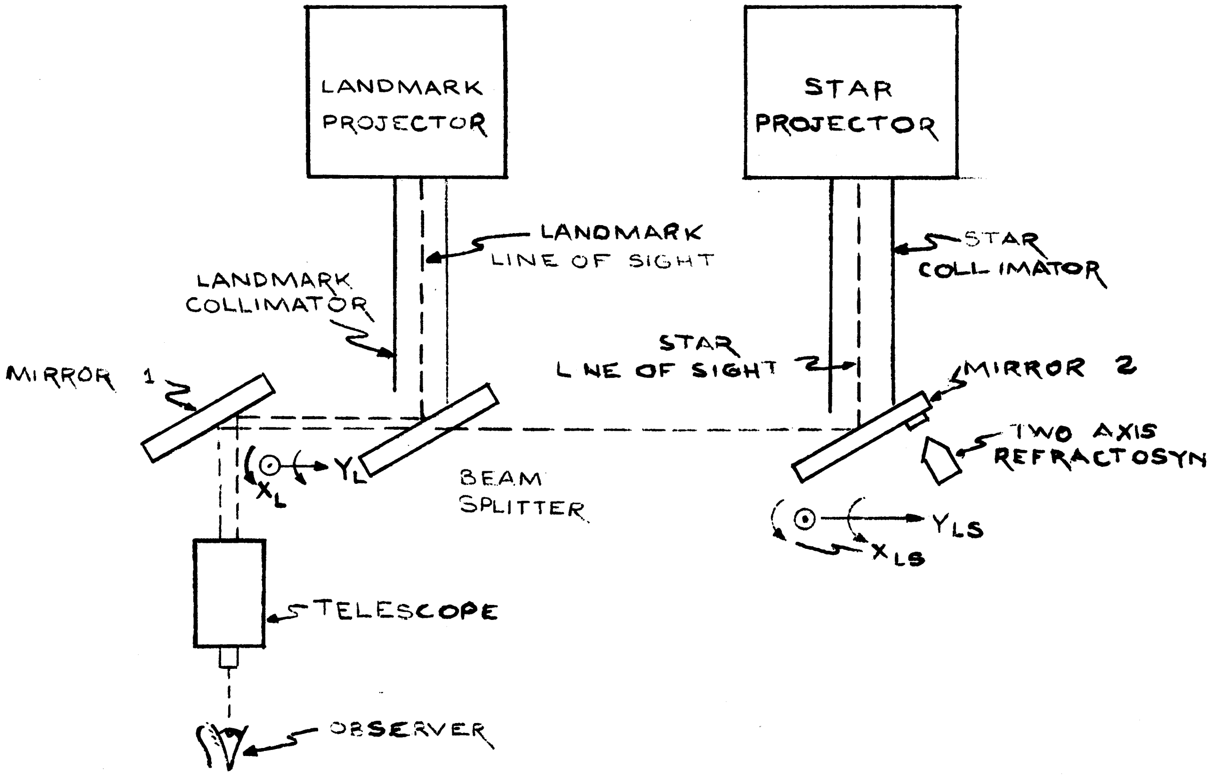


Figure 3

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[2] This information was obtained from Mr. Frank MacKenzie of the Instrumentation Laboratory and from Reference 15.

The basic telescope is a Wild telescope model T-2. It has a 1.8 degree field of view, an entrance pupil of 40 mm. an exit pupil of 1.4 mm., with a magnification of 28 x. It transmits 70 per cent of the light incident on the objective and has a resolution of 3.5 seconds of arc. Also used was another Wild telescope model T-3. It has a 1.25 degree field of view, an entrance pupil of 61 mm., exit pupil of 1.5 mm., with a magnification of 40 x. The resolution is 3.5 seconds of arc, and it transmits 70 per cent of the light incident on the objective.

The mirrors are used to reflect the star and landmark images into the objective of the telescope. They are mounted so that they can rotate about two orthogonal axes. This rotation will simulate vehicle and star motion. The mirrors are octagonal 4 x 3.25 inches and are first surface.

The beam splitter combines both lines of sight. It is 4 inches in diameter, coated to reflect 80 per cent, and transmit 20 per cent of incident light in the spectral region to which the eye and telescope are most sensitive.

The two axis refractosyn is used to determine very precisely the position of mirror 2 from a known reference position. This reference position is such that the star and landmark are superimposed and the refractosyn output is nulled. The refractosyn is a device which reflects a collimated beam of light from a small mirror placed on the back of mirror 2. This reflected beam is picked up by a series of four photoelectric tubes placed at 90 degree intervals around the collimator. Thus tubes at 0^{o} and 180^{o} correspond to one mirror axis while those at 90^{o} and 270^{o} represent the other axis. Each pair of tubes has a voltmeter connected to them which reads the difference in voltage on the tubes. This voltage difference is caused by different amounts of light striking the tubes when mirror 2 is rotated from the reference position. In this manner then, it is possible to determine the error from the exact superposition of the star and landmark.

Two collimators are used to eliminate the parallax problem when the optical superposition of two objects is desired. The landmark collimator is a lantern slide in the focal plane of a 3.25 inch diameter, 48 inch focal length objective. This diameter was selected so that it would be larger than the entrance pupil of the telescope. This means the system resolution is limited by the telescope. The slide is illuminated by a 75 watt projection lamp set at the center of curvature of a 12 inch diameter, magnesium oxide coated, integrating hemisphere. At one side of the hemisphere is a condensing system to focus the illuminated surface onto the slide. This system allows an evenness of luminance over the entire field of the slide with a maximum difference of 10 per cent as measured with a photometer.

The star collimator is an arc eroded aperture in the focal plane of a 3.25 inch diameter, 48 inch focal length collimating lens. The aperture is 5×10^{-4} inches in diameter and is unresolved by the T-2 or T-3 telescopes. It is illuminated by a 75 watt projection lamp with a condensing system.

(2) Servo Loops

The four servo loops are all similar in design. Each consists of a summing network, 400 cps chopper, preamplifier, amplifier, a combination motor-tachometer, a demodulator, and a gear train. Each loop controls one of the four axes of the mirror system. The input to each loop is a combination of voltages from the computer and the operator's hand controls. The output of the loop is rotation of the mirror axis. The gear backlash has been eliminated by attachment of a small spring to the mirror and mount. This requires the gears to overcome the spring force.

(3) Computer

The computer in this simulation is the Verdan model developed by Autonetics. It provides the convenience of digital computation with the ability to receive and transmit information in analog form. Its purpose in the simulation loop is to provide four outputs which, when combined with voltages produced by movement of the operator's controls, will drive the servo loops to position the mirrors. The computer has been programmed to provide varying rates and direction of craft motion, and it has the capacity to store the superposition errors until a test series is completed. The program implements the equations of motion which relate the craft motion to landmark motion and to star motion. (See Chap. 2 for equations.)

The entire system simulates the spacecraft motion and the actual sextant operation. The simulation is capable of measuring superposition errors down to 1 second of arc.

APPENDIX B

CALIBRATION PROCEDURE FOR STAR AND LANDMARK

Throughout this experiment, different values of earth luminance and stellar magnitudes were simulated. To accurately simulate the appearance of the star and earth as seen by the astronaut under varying light conditions, the equipment had to be correctly calibrated.[3] As mentioned previously, the light source for the star and landmark is a 75 watt projection lamp. The luminance of each lamp is controlled by a variable transformer. In this appendix, the procedure used to determine the correct luminance of the lamps is presented.

To measure the lamp illuminance, a Spectra-Pritchard Photometer was used whose scale was calibrated as follows. The stellar magnitude of Jupiter was found in the Nautical Almanac, and this was converted to a luminance value. By observing Jupiter near its zenith over Cambridge, the scale of the photometer was set to give the value as found in the Nautical Almanac.

The photometer calibration can be checked by drawing a straight line graph of stellar magnitude versus illuminance. This graph is constructed by using Fabrey's value of 8.3×10^{-7} lumens/m^2 as the illuminance of a 1st magnitude star, and the fact that the illuminance of stellar magnitudes decrease by the fifth root of 100. Now, using the photometer, the illuminance of the stars in the constellation Ursa Major near its zenith over Cambridge were measured. These measured values were found to fall slightly below the values obtained from the graph. This error perhaps could be attributed to atmospheric haze present during the measurement. From this, one may conclude that the photometer is correctly calibrated.

The next step in the procedure was the calibration of the simulator. The light from the lamps was focused down two collimator tubes and

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[3] The original calibration was carried out by Mr. F. MacKenzie of the Instrumentation Lab.

then reflected by the mirror system into the objective lens of the sextant. Since one is interested in the amount of light that actually impinges on the eye, one must account for the transmission properties of the sextant. The sextant in the Command Module (CM) transmits only 30% of the light incident upon the objective for the star line of sight, while the simulator sextant transmits 70% of the light. Therefore, for the astronaut observing a 1st magnitude star through the CM sextant, he would see an illuminance of 2.49×10^{-7} lumens/m^2.[4] In the simulator to obtain the same illuminance, one must divide this value by .70. This calculation is based on the illuminance of a star as seen through the earth's atmosphere. Outside the atmosphere, these values would be higher by about 1/4 magnitude.

A similar calculation can be made for the luminance of the earth. As a basis for this calculation, the luminance of the sunlit earth was taken from Ref. 18. This value is 3.3×10^3 foot-lamberts and is from outside the earth's atmosphere. For the earth line of sight, the CM sextant transmits only 2% of the light incident upon the objective. To obtain the same value in the simulator, we again divide by .70.

The amount of light needed at the subject's eye is now known. To obtain this light, the transformers are varied to control the luminance of the lamps. The simulator sextant is replaced by the photometer, and the lab is darkened to eliminate background light. Now the star lamp is turned on, and the transformer is varied to yield the required stellar magnitudes. The landmark lamp is next turned on, and the transformer varied in a like manner to yield the required photometer readings for the earth's luminance. It must be pointed out that the earth's luminance is an average value over a non-uniform background.

This calibration was maintained throughout the experiment by periodic checking of the lamps. This was necessary due to the aging of the lamp filaments.

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[4] This is obtained by multiplying $(8.3 \times 10^{-7}) \times .30$ to yield 2.49×10^{-7}.

In Step V of the experiment, certain contrast ratios were used to study the effect of contrast on the astronaut's performance. Here, one is interested in the contrast between the star and the landmark as it appears at the focal plane of the sextant. This is essentially the same contrast as the eye sees since the sextant exit pupil is larger than the pupillary diameter of the eye.

The overall illuminance at the focal plane would be the sum of the star and landmark illuminance. Since one would like to measure the contrast between the star and the background a contrast ratio is defined as follows:

$$C = \frac{(E_L + E_S) - E_L}{E_L}$$

where E_L = average illuminance of the background in lumens/ft^2

E_S = illuminance of the star in lumens/ft^2

Now E_L is found from the formula

$$E_L = \frac{B}{4(f_{no.})^2}$$

where B = luminance of the background in foot-lamberts

and E_S is found from the expression

$$E_S = \frac{\pi r^2 (E)}{A}$$

where r = radius of the objective lens in feet

E = illuminance of star at the focal plane in lumens/ft^2

A = area of the star image at the focal plane in square feet.

(See Reference 23.)

Using formulas (3-1); (B-2, 3), the contrast ratios were calculated and are presented below. All values are in the previously given units.

No.	B	E	E_L	E_S	C
1	47	3.3×10^{-8}	.413	.946	2.29
2	68.5	$.544 \times 10^{-8}$	.601	.156	.259
3	3	3.3×10^{-8}	.026	.946	36
4	25	$.200 \times 10^{-8}$	.219	.059	.261

The above are the contrasts actually seen by the subject as he was allowed to adapt his eye to the luminance level of what he saw in the sextant. This was done by extinguishing all extraneous light in the lab and allowing time for the adpative process to occur before the tests were begun.

In all cases, the pupillary diameter was assumed to be less than or equal to the diameter of the sextant exit pupil when the eye was adapted to the level seen in the sextant. This assumption was made on the basis of data presented in Professor Hardy's report (Ref. 19). With this assumption, one can ignore any stray light entering the eye from outside the field of view of the sextant.

APPENDIX C

SAMPLE CALCULATIONS

C. 1 Mean Error

$$E = \frac{\sum E_i}{n} \qquad (C.1)$$

where E_i = error of an individual test run, measured radially from perfect superposition (absolute value)

n = number of test runs in the series.

C. 2 Standard Deviation

$$S = \left(\frac{\sum (E - E_i)^2}{n-1} \right)^{1/2} \qquad (C.2)$$

where E = mean error.

C. 3 Regression Line Calculation

a = slope of ($E = aR + b$)

c = slope of ($R = cE + d$)

$\bar{R}$ = overall average value of R

$\bar{E}$ = overall average value of E

For this calculation, the overall average values of E and R are assumed to plot a point on the line.

Sample Used Will Be Subject A

Table C-1

E	E^2	R	R^2	RE
2.9	8.4	0	0	0
2.6	6.75	18	324	47
4.21	17.80	74	5,476	312
4.41	19.60	114	13,000	503
3.45	11.95	129	16,641	445
3.63	14.15	145	21,025	526
4.90	24.10	170	28,900	832
4.70	22.20	212	45,000	996
4.96	24.75	241	58,081	1196
4.68	22.00	252	63,500	1179
3.51	12.20	300	90,000	1051
4.27	18.30	363	131,769	1550
4.57	21.00	380	144,400	1735
6.14	37.85	440	193,600	2695
58.93	259.16	2838	811,600	13,078

$$\Sigma(E-\bar{E})^2 = \Sigma E^2 - \frac{(\Sigma E)^2}{n} = 259.16 - 247.5 = 11.66$$

$$\Sigma(R-\bar{R})^2 = \Sigma R^2 - \frac{(\Sigma R)^2}{n} = (8.116 - 5.55)\ 10^5 = (2.57)\ 10^5$$

$$\Sigma(E-\bar{E})(R-\bar{R}) = \Sigma ER - \frac{(\Sigma E)(\Sigma R)}{n} = (13.078 - 11.89)\ 10^3 = (1.188)\ 10^3$$

$$a = \frac{\Sigma(E - \bar{E})(R - \bar{R})}{\Sigma(R - \bar{R})^2} = \frac{(1.888)10^3}{(2.57)10^5} = (.457)\ 10^{-2}$$

hence:

$$(E - \bar{E}) = (.457)\ 10^{-2}\ (R - \bar{R})$$

but $\bar{E} = 4.18$ and $\bar{R} = 203$

therefore:

$$E = .457 \times 10^{-2}\ R + 3.252 \qquad \text{(C. 3)}$$

Now r (correlation coefficient) = $(ac)^{1/2}$

$$c = \frac{\Sigma(E - \bar{E})(R - \bar{R})}{\Sigma(E - \bar{E})^2} = \frac{(1.188)\ 10^3}{11.66} = 101.5$$

hence $r = (.457 \times 1.015)^{1/2} = .633$

(significant at 5% from reference 5, Table C).

For 95% confidence interval must compute standard error of estimate of regression line. (Call it S_1 here).

$$S_1 = \left[\frac{\Sigma(y - \bar{y})^2 - a\Sigma(x - \bar{x})(y - \bar{y})}{n - 2}\right]^{1/2} \qquad \text{(C. 4)}$$

(See Ref. 16, p. 536.)

Putting in the numbers from above one arrives at

$$S_1 = .722$$

For 95% confidence interval

$$S_{1_{95}} = (2.30)\ S_1 = 1.66 \qquad \text{(C. 5)}$$

i.e., 95% of points fall within 1.66 arc seconds of the regression line. For confidence interval of slope a:

$$S_a = \frac{S_1}{(\Sigma(R - \bar{R})^2)^{1/2}} = .143 \times 10^{-2} \qquad (C.6)$$

hence a = .457 ±(2.3) (S_a); or a is between .129 x 10^{-2} and .785 x 10^{-2} with 95% confidence.

This entire procedure is outlined in Wallis and Roberts (Ref. 16).

C.4 "Student - t" Test for Significance

Sample calculation used here is subject B's magnification test (Table 3 of Chapter 6) at a rate of 212.

First, one must test for a t-test requirement, namely $S_{28}^2 = S_{40}^2$. To do this the F-test is used, where

$$F = \frac{S_{28}^2}{S_{40}^2} \text{ or } \frac{S_{40}^2}{S_{28}^2} \qquad (C.7)$$

(whichever yields an F value greater than 1).

Hence: $F = \frac{(2.12)^2}{(1.87)^2} = 1.29$

From Tables of Ref. 17, it is seen that the listed value of F for these conditions is 1.90 (at 5% level). Since 1.29 is less than 1.90, we conclude that S_{28}^2 is close enough to S_{40}^2 to use the t-test.

Now one may say

$$S_{28} = S_{40} = S = \left[\frac{\Sigma(E_{40} - E_i)^2 + \Sigma(E_{28} - E_k)}{n_{28} + n_{40} - 2}\right]^{1/2} \qquad (C.8)$$

Substituting in the numbers, yields

$$S = \left[\frac{213.7}{54}\right]^{1/2} = 1.96$$

$$\text{Now } \bar{S}_{28} = \frac{S}{(n_{28})^{1/2}} \text{ and } \bar{S}_{40} = \frac{S}{(n_{40})^{1/2}} \tag{C. 9}$$

$$\text{hence } \bar{S}_{28} = \frac{1.96}{(26)^{1/2}} = .384$$

$$\text{and } \bar{S}_{40} = \frac{1.96}{(30)^{1/2}} = .358$$

$$\text{Now } S_{\bar{D}} = (\bar{S}^2_{28} + \bar{S}^2_{40})^{1/2} = .525 \tag{C.10}$$

$$\text{and "t"} = \frac{E_{28} - E_{40}}{S_{\bar{D}}} = \frac{.35}{.525} = .616 \tag{C. 11}$$

Tables of Ref. 17 indicate this is not significant at 5% level of chance for 54 degrees of freedom (D. F. $= n_{28} + n_{40} - 2$).

This entire procedure is outlined in Lacey (Ref. 5).

C. 5 Wilcoxon "Signed-Rank Test"

The essence of this test is the computation of a standard normal variable, making use of a ranking system. (Wallis and Roberts, p.596).

The magnification data is used as a sample calculation.

TABLE C-2

E_{28}	E_{40}	Difference	Rank
4.7	2.5	2.2	12
4.96	2.98	1.98	11
3.51	3.61	- .10	1
6.14	3.56	2.58	13
4.9	3.16	1.74	9
4.19	3.84	.35	2
4.55	3.02	1.53	8
5.30	4.48	.82	5
5.30	4.9	.40	4
5.02	3.56	1.46	7
4.31	3.92	.39	3
4.44	3.60	1.84	10
4.89	3.84	1.05	6

T is defined as the sum of all ranks associated with a minus sign or the sum of all ranks associated with a plus sign, <u>whichever is smaller</u>. K is the standard normal variable to be computed.

$$K = \frac{2T + 1 - \frac{n(n+1)}{2}}{\left[\frac{n(n+1)(2n+1)}{6}\right]^{1/2}} \qquad (C.12)$$

where n here is the number of non-zero differences in Table C-2 (n = 13 in this case).

Putting in the numbers yields K = 3.08. This gives a probability of .001, or the Forty-power magnification errors were less by much more than chance. (See Wallis and Roberts table 365.)

C.6 Wilcoxon "Two-Sample Test"

Here again, a ranking technique is used to compute a standard normal variable, K. As a sample calculation, the test is applied to the contrast test C_1 versus C_3.

TABLE C-3

Errors

C_1	C_3
4.26 (2)	5.86 (5)
3.64 (1)	7.50 (6)
4.76 (3)	5.59 (4)

( ) indicates rank by size, smallest to largest

Now T = sum of ranks of either sample C_1 or C_3.
n = number in the same sample for which T is calculated.
$N = n_1 + n_3$

now:

$$K = \frac{2T \pm 1 - n(N+1)}{\left[\frac{n(N+1)(N-n)}{3}\right]^{1/2}} \qquad \text{(C.13)}$$

Regarding the ±1, use a plus sign if 2T is less than n(N + 1), and use a minus sign if 2T is greater than n(N + 1).

Putting in the numbers, using sample C_1 for T and n yields

$$K = -1.745$$

The probability of this by chance is .0427, indicating that this contrast change caused a significant increase in error. (Ref. 16, p.594 outlines this test.)

C.7 Chi-Square Test

Sample used here is Subject B's contrast test, C_1 versus C_3.

The total error at C_1 is 3.64 x 29 or 105 arc seconds. The total at C_2 is 7.50 x 26 or 195. The overall total is therefore 300 arc seconds. Under the null hypothesis, one would expect an error distribution for C_1 of

$$E_1 = \frac{29}{55} \times 300 = 158 \qquad \text{(C.14)}$$

and

$$E_3 = \frac{26}{55} \times 300 = 142 \qquad \text{(C.15)}$$

Now

$$E_3 = E_3(\text{exp}) = 53$$

and

$$E_1 - E_1(\text{exp}) = 53$$

$$\text{Chi-square} = \frac{(52.5)^2}{158} + \frac{(52.5)^2}{142} = 36.85$$

(Each 53 is corrected for the presence of only one degree of freedom by subtracting 0.5.)

Tables of Ref. 17 indicate this to be significant at 1% level.

Reference 5 outlines this procedure.

APPENDIX D

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