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RESULTS OF SKYLAB EXPERIMENT T00-2, MANUAL NAVIGATION SIGHTINGS

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16 Abstract

An analysis of navigation data collected using a hand-held space sextant on the second and third manned Skylab missions is presented From performance data and astronaut comments it was determined that (1) the space sextant, the sighting station, and the sighting techniques require modification, (2) the sighting window must be of good optical quality, (3) astronaut performance was stable over long mission time, and (4) sightings made with a hand-held sextant were accurate and precise enough for reliable interplanetary manual navigation

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SUMMARY

The purpose of the Skylab T00-2 experiment was to evaluate human performance over long-mission time in acquiring midcourse navigation data using a hand-held sextant and realistic celestial observables. Data were gathered in 22 sighting sessions on the second manned mission (SL/3) and in 19 sessions on the third manned mission (SL/4). The performance data gathered were not significantly different from premission, posttraining data, and there was no evidence of performance deterioration with long-mission time. It was demonstrated that the sighting window must be of good optical quality or the accuracy requirements for manual interplanetary navigation cannot be met. It was also demonstrated that the sighting station, the space sextant, and the sighting techniques all require some modification for optimum human use. It was concluded that a trained astronaut, cognizant of the required accuracy, using the space sextant and a sighting aperture comparable to the Skylab wardroom window, could make sextant sightings of sufficient accuracy and precision for safe interplanetary manual navigation.

INTRODUCTION

The purpose of Skylab experiment T00-2 "Manual Navigation Sightings" was to evaluate the accuracy and precision of angular measurements made with a hand-held space sextant over a relatively long period of weightlessness. The measurements were made in order to assess the operational feasibility of a manual navigation system for interplanetary missions. Manual navigation could be used as an adjunct or an alternative to primary systems which use measurements made by ground tracking stations. Implementation and processing of the measures, once obtained, were not areas of investigation in this study. It was assumed that the sextant angular measurements would simply replace or complement the ground tracking measurements in the Apollo navigation and guidance system, which is based upon Kalman optimal filtering (ref. 1).

The emphasis in this and previous studies using the hand-held sextant was on human performance variability. It had been shown by studies in simulators, high flying aircraft at Ames Research Center (ARC), and in spaceflight on Gemini XII that after appropriate training the accuracy and precision of manual sightings were commensurate with those required for interplanetary missions (ref. 2). The Skylab experiment was accomplished to investigate the reliability of that performance through an extended period of weightlessness.

The T00-2 experiment was, in one sense, the culmination of a decade of study during the 1960's of the feasibility of manual midcourse navigation. Reference 3 discusses this background and cites many studies related to the development of a reliable, manual navigation system centered around a hand-held sextant.

The T00-2 study was a joint NASA-USAF experiment. The Air Force was interested in, and developed during the same decade, a manual *orbital* navigation system. That interest is reflected in several reports cited in reference 3. Although NASA implemented and integrated the T00-2 experiment aboard Skylab, the data were analyzed and interpreted by the Air Force principal investigator. Those results are reported separately (ref. 4).

The data gathered on Skylab missions SL/3 and SL/4 indicated that long mission duration had no effect on sextant sighting accuracy and precision, and the quality of the sightings was equal to premission performance. (SL/1 was the launch and orbit of the orbiting workshop, while SL/2, SL/3, and SL/4 were the first, second, and third manned missions.) Both baseline and in-flight levels of performance were sufficiently stable for reliable midcourse navigation. It was concluded that long-mission duration does not affect manual navigation accuracy and reliability. It was also concluded that the Kollsman-ARC space sextant was not designed for optimum human use in the space environment.

METHOD

The Sextant Sighting Task

The conventional marine sextant was used in the early studies of human performance in making angle measurements for manual midcourse navigation. Study was required because of the more stringent accuracy requirements in navigation over the long distances of space as compared with terrestrial navigation. The limits of accuracy using this instrument were not known, particularly when using the well-defined celestial targets that are available in space navigation. Many studies (ref. 3) did show that the requisite accuracy was achievable but that even experienced navigators required training and a knowledge of the requirements of the task. This early encouragement prompted the procurement of the Kollsman space sextant which was used on the Gemini XII mission and in the present study.

A conventional marine sextant is shown in figure 1 in which the major components have been labeled. The primary line of sight is called the fixed line of sight (FLOS) in this report, and the secondary line of sight is now called the scanning line of sight (SLOS). The instrument is used to measure the vertical, angular altitude of a selected celestial body (sun, moon, planets, stars) above the natural sea horizon.

To accomplish the measurement task, the sea horizon is viewed through the telescope along the primary line of sight. The body (e.g., a star), is viewed through the telescope along the

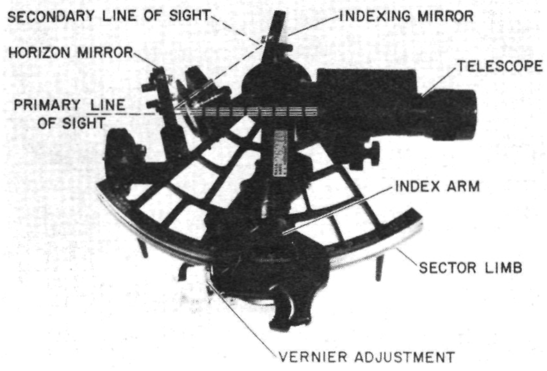


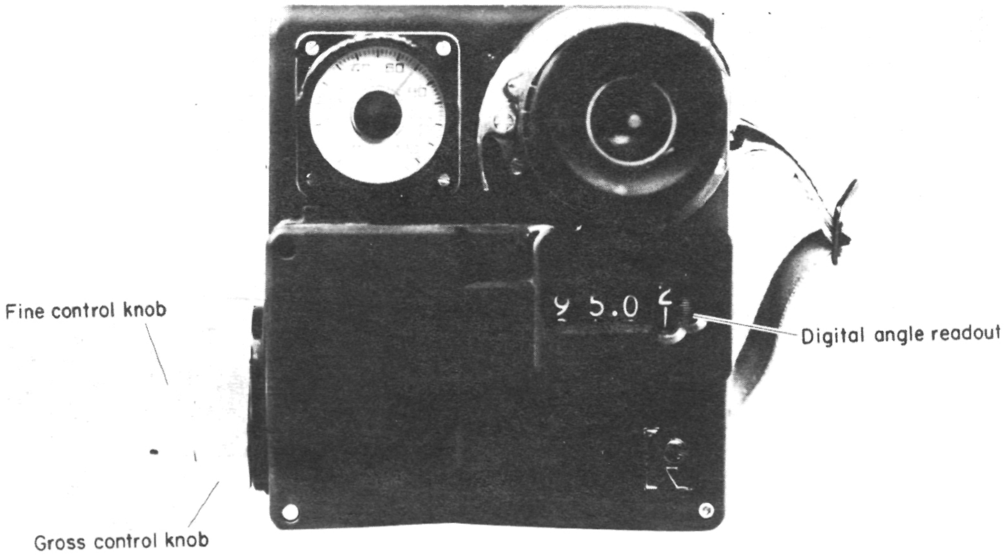
Figure 1.– Marine sextant.

secondary line of sight which is reflected into the telescope by the index mirror and the horizon mirror. The horizon mirror may be a split-field mirror or a beam splitter. Its function is to pass the horizon scene directly into the telescope, and, by reflection, similarly to direct the light rays from the star. The horizon and star are thus seen in close proximity when the index mirror is set to the appropriate angle by rotation of the index arm. The index arm may be preset by estimating the angle between the horizon and star prior to viewing through the telescope.

The final adjustment is made when the horizon and star are seen close together in the telescope field of view. Using the vernier adjustment control knob the star is brought to tangency on the horizon. The sextant is gently rocked about the telescope axis so that the star describes a small arc, and the visualized arc is checked for tangency to ensure that the *vertical* angle, normal to the horizon, is being measured. The navigator marks the time of tangency and reads the angle from the sector limb in degrees and from the vernier in minutes and tenths of minutes of arc.

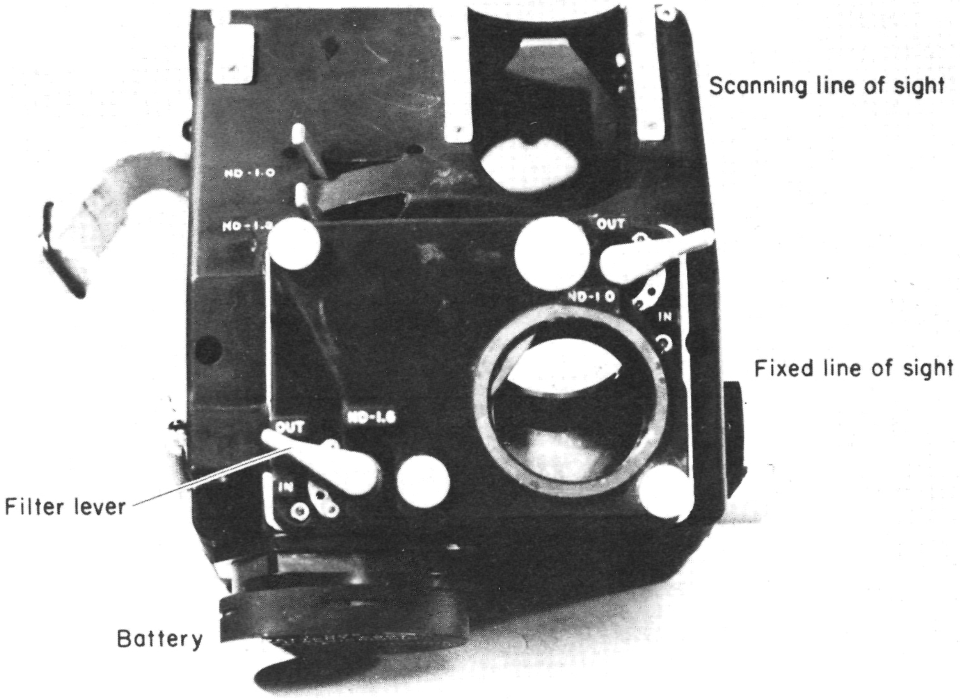
The visual task in measuring the angle between two celestial targets is similar. See figure 2 for illustration of the Kollsman space sextant. One target is acquired in the fixed line of sight, the other in the scanning line of sight. However, verticality has now no particular significance, and the astronavigator attempts to determine the least angular distance between the two objects. The "rocking technique" is used to do this.

Note that both the marine sextant and the space sextant can be rotated 180° and the angle measurement made with the lines of sight reversed. This feature is particularly useful in sighting on two celestial objects whose orientation to each other may be vertical, horizontal, diagonal, etc. Although Skylab was sun-stabilized and could not be rotated to take the sextant sightings, it would be feasible to rotate an interplanetary vehicle to achieve verticality if such were desired. The astronavigator's body could also be rotated for the same purpose.

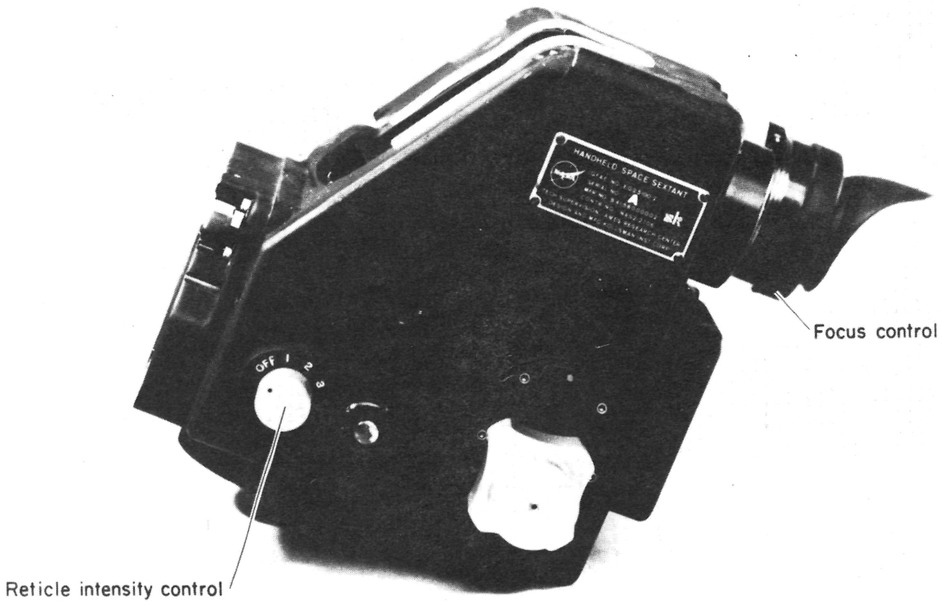


(a) User view.

Figure 2.– ARC - Kollsman sextant.



(b) Light entry side.



(c) Left side view.

Figure 2.– Concluded.

Training

The astronauts were prepared in three steps to accomplish the T00-2 experiment: 1) first, they were given a thorough briefing on the purpose and goals of the experiment and the part they would be asked to play in its implementation; 2) they were trained in star identification and acquisition using the space sextant in the planetarium at the USAF Academy in Colorado Springs; 3) finally, a sextant sighting training facility was set up in the building in which they occupy offices at the Johnson Spaceflight Center. The astronauts gained proficiency in this facility by taking sightings on collimated simulated stars and on a collimated lunar disk. Several training sessions were required to achieve the requisite accuracy—a standard deviation of about 10.0 arc sec in a set of 10 or 15 angle measurements.

Sextant

The sextant used by the astronauts was the Kollsman space sextant developed under contract to Ames Research Center. It is shown in figure 2 and fully described in references 5 and 6. The major differences between the space sextant and a conventional high quality marine sextant is that the former is a digital instrument, inherently more accurate, and is designed and engineered for use in the space environment. It has a magnification of 8 and a 7° field of view. Its size is 7 X 7-1/4 X 6-1/16 in. (17.78 X 18.42 X 15.66 cm) and it weighs 6 lbs 4 oz (2.84 kg). It has an erect image and an angular measurement range of 76°. The eyepiece can be adjusted from −3 to +5 diopters. Data readout is accomplished by direct reading of a digital counter. The measured angle between the fixed and scanning lines of sight is indicated in degrees, the least count being 0.001 or 3.6 arc sec. Interpolation on the thousandths drum is possible to one-half of a division, giving a potential readout accuracy of 1.8 arc sec.

Neutral density filters are provided to decrease celestial target brightness where necessary. The two provided for the FLOS have values of 1.0 and 1.6 $\log_{10}$ units. For the SLOS they are 1.0 and 1.3. A variable-intensity reticle light is provided, as well as a pushbutton-operated light which illuminates the digital counter for readout in darkness.

For the Skylab mission, some modifications were made to the sextant configuration that was used on the Gemini XII mission. A dial thermometer was mounted on the sextant on the same side as the eyepiece. The event-timing switch and connector were removed. The battery installation plate was changed so that batteries could be removed and replaced without the use of tools. The battery used was a 2.5-V dual cell, nickel-cadmium wafer. Spare batteries were transported to Skylab in the Command and Service Module (CSM).

Sighting Station

Sightings were taken through the wardroom window (WRW) in the orbiting workshop (OWS). The window was constructed of two 1-in. (2.54 cm) thick optical quality panes separated by a 1-in. (2.54 cm) air space which was pressurized to the same level as the OWS living area, 5.5 psi (0.852 pscm). The WRW was optically the *second best* window of thirteen aboard Skylab. (The best window was that used for the S-190 experiment in the Multiple Docking Adaptor (MDA). It was not possible to use this window for T00-2 because it was sensitive to radiation so could not be exposed for long periods of time.) From the specifications for the two glazings, their thickness, rigidity, and structural interface with the OWS bulkhead, it was determined that deviations of light rays would be minimally random (refs. 3 and 7) in their passage through the WRW. An expensive and time-consuming premission calibration was thus omitted.

The sextant, space batteries, and a collapsible window hood were stored in wardroom locker W-740. The locker was to the left and below the WRW. A special micro-syl, deep draft mold, form-fitted to the locker and the sextant (and the USAF Stadimeter), and with compartments for the hood and batteries, was fabricated at ARC for this purpose. The hood was used to shield the WRW from reflections from the OWS interior lights. The hood unfolded into a 3 X 3 X 3 ft (0.91 X 0.91 X 0.91 m) cube which was positioned, using Velcro fasteners, in front of the WRW. The bottom and window sides of the Beta-cloth cube were open, allowing the astronaut to stand inside it and sight through the WRW.

Celestial Targets

There were three kinds of celestial target pairs whose angular separation was measured by the astronauts. These were:

Two stars. – Since the angle between any two given stars does not change anywhere within the solar system, its measurement yields no interplanetary navigation data. However, since the angle between two stars may be computed to a very high degree of accuracy, this kind of sighting may be used as a performance standard; it is a basic kind of sighting used in many simulator studies at ARC (ref. 3), and it was the only angular sighting technique used on the Gemini XII mission. In Skylab operational terminology this was known as Functional Objective number one (FO-1; see ref. 8, for example). Six sets of these sightings were required. Each set, taken during a single sextant sighting session, was to include 10 to 15 individual angle measurements or "marks." When the astronaut was satisfied with his sighting, he would voice-mark the time-correlated, audio data tape and then read on to the tape the value in the sextant digital-counter window. The time reference was Greenwich Mean Time (GMT).

A star and the lunar limb. – This was a realistic navigation-type measurement since the angle between the moon (or planet) and a star is a time-varying function of spacecraft position. The measurement was used for the first time in space flight (using a hand-held sextant) on SL/3. This was FO-2; 12 sets of sightings were required with 10 to 15 marks per set, and, as before, GMT correlated. To assess the effects of irradiance, it was hoped that several levels of lunar-disk brightness would be sampled by use of appropriate sextant neutral density filters, but a rigid filter schedule was not included in the Mission Requirements Document (MRD). Suggested filter values were "up-linked" on the teletyped schedules, but astronaut usage was based mainly on a desire for a balance between stellar and lunar brightness.

The lunar limb– In this kind of sighting the angular subtense of the lunar disk diameter was measured by placing in tangency one limb of the moon viewed through the FLOS and the opposite lunar limb in the SLOS. Since the angular subtense of a planetary disk is a function of spacecraft range from the planet, this too is a potentially usable navigation measurement. It should be noted, however, that changes in the moon's angular subtense as measured from a vehicle in low earth orbit are extremely small This was FO-3, six sets of sightings were required with 10 to 15 marks per set, GMT correlated.

Prior to the accomplishment of each of these sessions the astronaut voice-recorded the temperature, the neutral density filter settings if used, the eyepiece diopter setting, and the celestial target pairs (FO) to be used. Next, he recorded five zero-bias sextant readings These are accomplished by sighting a single star whose image in the SLOS is superimposed on the image of the same star viewed in the FLOS The sextant readout should indicate zero when no bias is present. He then recorded a voice mark each time he made a measurement of the angle between the selected celestial targets The sextant reading in degrees and decimal degrees was recorded after each voice mark. There were 24 sighting sessions required 6 FO-1's, 12 FO-2's, and 6 FO-3's.

Experiment Data Retrieval

Voice-data tape dumps from Skylab to ground stations were accomplished on a regular basis. The data tapes (and transcripts) were generally available within about 24 hr from session accomplishment in the Corollary Experiments Staff Support Room (SSR) at the Johnson Space Center (JCS) Mission Control Center (MCC). Postmission ephemeris data were provided by the Huntsville Operational Support Center (HOSC) on a tape labeled Skylab Best Estimate of Trajectory (SKYBET). Also, the unit vector normal to the WRW was provided by the HOSC in the form of a taped, interpolative time history of the WRW centerline. The ARC computer analysis, carried out postmission, required that the spacecraft position (SKYBET) and the WRW pointing vector be known for the computation of the true angle between the selected celestial targets which existed at the time (GMT) of each individual sighting (mark) In the analysis, this true or computed angle was compared with the angle measured by the astronaut and voice recorded on the data tape retrieved at the MCC.

ERROR SOURCES

A full discussion of the sources of errors in sextant sightings is not possible here, but each will be mentioned to the extent that it was accounted for in the T00-2 experiment An excellent report on the theory of the correction of celestial observations is available in reference 7, and related studies are given in reference 3

Sextant Instrument Error

There are several possible sources of error connected with the sextant itself These are the following

Index and arc.— These sextant errors are due to small, residual, optical and mechanical misalignment after fabrication. They are typically present in any sextant and they are corrected for by use of a calibration curve. The calibration is accomplished using a high-precision optical bench. Angular values to correct for mirror misalignment (index) were determined for preselected increments of angle across the full readout range (arc) of the sextant (ref 9).

Filter – The neutral density filters used for decreasing celestial target brightness each introduce a unique but constant error. This is also determined by postmanufacture calibration, and, as with index and arc, calibration values were supplied when the sextant was delivered (ref. 9)

Zero bias – Any biases which might appear and which might be due to changes in the sextant or to the human operator would be presumed to appear as a readout value other than zero when the angle between a celestial target and itself is measured. Prior to each sighting session the astronauts took five zero bias readings on a single star. The mean value of these was applied to each measured angle as a constant correction To accomplish the zero reading the image of the star in the FLOS was superimposed on its image in the SLOS.

Refraction

Light rays from the celestial targets are undeviated in their travel through the interplanetary vacuum until they encounter a refractive medium in which their velocity is altered. Two such media were present aboard Skylab.

Wardroom window – The first refractive medium that the light rays pass through is the glass in the wardroom window. Characteristics of the glazing which will impart spurious deviations to light rays are departures from surface flatness, lack of parallelism between its two surfaces (wedge), and structural deformations due to the pressure differential between its interior and exterior surfaces The amount of deformation is determined by its thickness (rigidity) and the structural integrity of its mounting in the OWS bulkhead

It was assumed early on that the WRW was not subject to any of these anomalies. It was of sufficiently good optical quality and thickness that residual errors would not be measurable, and the glazing would have only a trivial contribution to line-of-sight deviations If this were not so, an expensive and time-consuming calibration would have had to be accomplished for the full evaluation of sextant sighting performance Although not used in the Skylab study, the mathematical method for window calibration is given in reference 7.

Over the WRW interior surface a transparent protective shield was normally fastened in place This shield was to be removed prior to the accomplishment of experiments using the window. The transparent shield was a polyvinyl, butyral sheet, 0.06-in. (0 15-cm) thick, sandwiched between two pieces of 0.2-in. (0 15-cm) thick tempered glass (Corning Chem-Chor). The refractive characteristics were unknown, and a map of the refractive anomalies across its surface did not exist.

OWS cabin gas –The remaining refracting boundary was formed by the OWS cabin gas, and the correction for refraction was reduced to the use of equations 18 and 20 in reference 7. The index of refraction of the cabin gas was computed using equation A5 in appendix A of reference 10 The recording of the temperature of the cabin gas by the astronaut using the thermometer on the sextant was necessary for this purpose

Irradiance

Celestial-target irradiance can contribute to sighting bias A bright, extended object in a dark surround will appear larger than it actually is The effect is that of " . displacing the apparent edge between a bright area and a darker area toward the latter" (ref 11). The effect would be to spuriously decrease the measured angle between a star and the *near* limb of a bright lunar disk (FO-2) It would spuriously increase the measured angular subtense of the lunar disk (FO-3) itself

Ephemeris Anomalies

The ultimate test of the "goodness" of the sextant-sighted angle is the extent to which it agrees with the true angle which exists at the time and location of the measurement It is thus necessary to compute what the true angle is at that instant. Tabulated ephemeris data is valid only for a given epoch and is uncorrect for certain parameters of the dynamic equations of motion. For example, from reference 7 ". . if the transformation from universal to ephemeris time is neglected, the position of the Moon, as seen from the Earth, will be in error by approximately 18 sec of arc If the sight has been made in the lunar orbital plane, the error will show up directly as an error in the measured angle " The corrections applied in the determination of the true angles for the three types of angle measurement are shown in the Data Reduction section below.

KINDS OF ERRORS

Any measurement instrument or process has associated with it two major kinds of errors. It can have one or more systematic errors, called biases, which decrease its *accuracy*, it can be subject to nonsystematic or random errors which decrease its *precision* and which refer to the repeatability or reliability of a sample of measured values

Biases are introduced by systematic physical factors which are, theoretically, completely quantifiable, so ultimately may be eliminated by appropriate calibration techniques For instance, the line-of-sight deviations caused by window refraction are now quantifiable due to techniques developed at ARC (ref 3), and a closed-form analytical solution exists (ref 7) for their determination In fact, all corrections applied in this study are derived from known biasing influences.

Random variations, on the other hand, are probabilistic in nature and must be processed statistically. Most of the random-measurement fluctuations are due to human variability in the use of the sextant (ref 12), with a small part due to unknown variability in the physical factors That part due to human use of a precision optical instrument is reflected in the standard deviation of a set of sightings. This is the performance measure (criterion or dependent variable) of interest in the T00-2 study Its magnitude will fluctuate with training, practice, disuse, motivation, fluctuating life processes, and environmental stresses.

It should be mentioned that the small variability due to the physical factors can become quite large, to the extent that it can mask the human variability whose quantification is sought For instance, the protective transparent shield for the WRW has unknown refractive characteristics. Since the amount of refraction or the line-of-sight deviations are functions of the locus of intersection of the light rays and window (shield) surface, any movement of the sextant will result in spurious changes in the sighted angle This inadvertent change from sighting to sighting will influence the variance of the set of sightings This will be reflected in the standard deviation and be indistinguishable from human performance variability

DATA REDUCTION

Computer programs were developed for use on the ARC-IBM 360 digital computer to process the data acquired in the Skylab study. The documentation of the computer programs, called "Spacegazer," resides in the files of the Man-Machine Integration Branch, ARC, and is available to qualified requestors. Details will not be given herein since they are otherwise retrievable.

Data inputs to the program are of three kinds

(1) Ephemeris data on the planets and the 37 navigational stars used in Apollo and Skylab programs (refs. 13 and 14). Of the planetary data only the lunar ephemeris was used The star data were in fixed form and were taken from reference 15 for the epoch of 1973.

(2) The Skybet data tape provided by the HOSC, postmission. This provided the coordinates for Skylab's position as a function of GMT in 1-min time increments and in epochs corresponding to T00-2 sighting periods

(3) A taped time history of the unit pointing vector normal to the wardroom window surface in increments and segments as with the Skybet tape This was also supplied, postmission, by the HOSC

All of the input data were precessed to the equator and equinox of date, which represents the orientation of the equatorial coordinate system at the date and GMT of observation. All computations were then carried out in this coordinate system of "date." The computations required are given in reference 7 Since the window through which the observations were made required only that it be treated as an optically flat boundary between two transmissive media of low differential pressure, only equations 11, 18, 20, and 21 were used.

Figure 3 shows the corrections applied to each of the three kinds of sightings used in the T00-2 study. Also shown is the order in which the corrections were applied to achieve the ultimate parameters of interest, the mean and standard deviation for each set of multiple sightings.

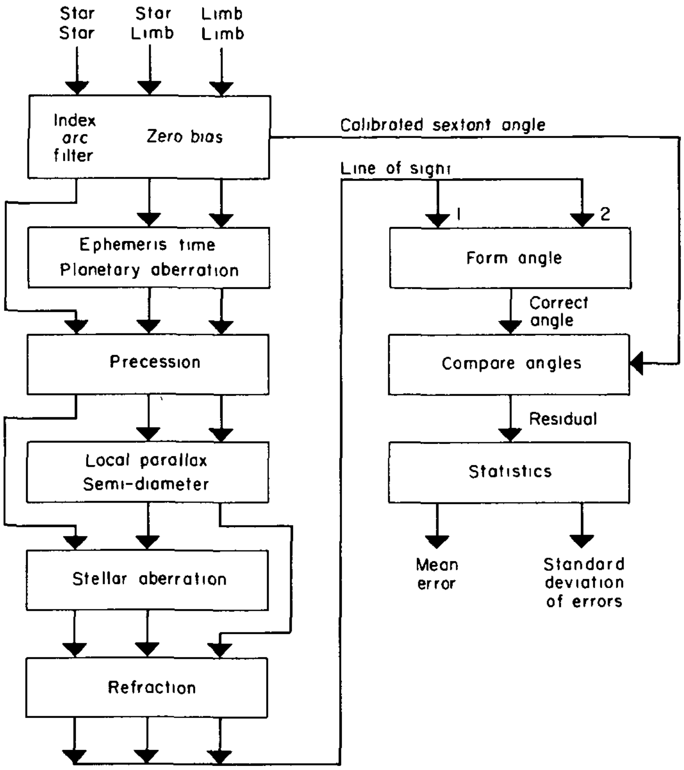


Figure 3.– Computational flow for sighting corrections.

RESULTS

SL/3

Table 1 shows the experimental conditions and results of the second manned mission. It had been required that the sextant sighting periods be spread out as evenly as possible throughout the mission. If that were not possible, then one-half of the sextant sighting sessions were to be accomplished in the first half of the mission and one-half during the last half of the mission. A constraint upon this was the fact that the experiment was to be performed at the convenience of the crew and on a noninterference basis (ref. 8). Although this latter requirement resulted in some FO's being clustered, e.g., four lunar limb sessions on mission day (MD) 17, it can be seen that the sightings were accomplished as required. Twelve sessions were accomplished between MD's 15 and 20 and 10 between MD's 39 and 49. These clusters coincided with he appearance of the moon in the usable field of view of the WRW: MD's 15 to 23 and 39 to 50.

Note that two sessions were not used because the WRW transparent cover was not removed – MD 19, sessions 12 and 13. Astronaut Jack Lousma (pilot) recognized that this occurred and disqualified the sightings from his tally of FO's accomplished. They are included here to illustrate the resulting performance variance with the optically poor transparent shield. They are not

TABLE 1 – MEANS AND STANDARD DEVIATIONS OF ALL SL/3 MIDCOURSE SEXTANT SIGHTINGS BY FUNCTIONAL OBJECTIVE

Day of year	Mission day	Order of sighting	Target pair	Number of angle measurements	Filter		Diopter setting	Limb[a]	Zero bias[b] arc sec	Mean error arc sec	Stand dev , arc sec
					FLOS	SLOS					
					F0-1						
223	15	1	Fomalhaut-Enif	8			-1 25		2 88	4 90	15 00
	15	2	Fomalhaut-Enif	10			-1 25		10 80	0 19	10 00
224	16	3	Fomalhaut-Diphda	10			-1 25		5 04	6 39	10 84
227	19	10	Fomalhaut-Diphda	10			-1 25		12 24	-6 27	8 49
247	39	15	Fomalhaut-Peacock	41			-0 5		18 00	-1 45	14 61
254	46	21	Fomalhaut-Peacock	16			-0 5		18 00	16 56	9 99
										Mean 3 39	Mean 11 49
					F0-2						
227	19	11	Lunar Limb-Diphda	13	2 6		-1 25	Near	13 68	11 47	20 70
	19	12[c]	Lunar Limb-Diphda	11	2 6		-1 25	Near	2 16	106 46	40 41
	19	13[c]	Lunar Limb-Diphda	11	2 6		-1 25	Near	2 16	34 45	23 64
228	20	14	Lunar Limb-Diphda	10	2 6		-0 5	Near	8 64	5 47	11 54
248	40	16	Lunar Limb-Nunki	18	2 6		-1 25	Far	18 00	21 90	11 83
	40	17	Lunar Limb-Nunki	34	2 6		-1 25	Far	10 80	27 67	13 37
	40	18	Lunar Limb-Nunki	33	2 6		-1 25	Far	17 28	20 08	11 89
250	42	19	Lunar Limb-Nunki	42	2 6		-1 25	Near	15 84	-19 19	9 01
254	46	20	Lunar Limb-Fomalhaut	18	1 6		-1 25	Near	14 40	-32 16	9 48
255	47	22	Lunar Limb-Fomalhaut	17		2 3	-1 25	Far	17 28	3 99	8 63
257	49	23	Lunar Limb-Fomalhaut	16		2 3	-1 25	Far	13 68	-19 99	11 54
	49	24	Lunar Limb-Fomalhaut	18		2 3	-1 25	Far	12 96	-11 35	11 69
										Mean 79	Mean 11 97
					F0-3						
255	17	4	Lunar limb-limb	10			-1 25		12 24	17 45	4 25
	17	5	Lunar limb-limb	10			-1 25		12 24	13 13	4 60
	17	6	Lunar limb-limb	9	1 0	1 0	-1 25		12 24	28 24	4 65
	17	7	Lunar limb-limb	10	1 6	1 3	-1 25		7 20	21 32	5 31
226	18	8	Lunar limb-limb	10	1 6		-1 25		3 60	19 90	2 25
228	18	9	Lunar limb-limb	10		1 0	-1 25		3 60	36 22	2 25
										Mean 22 71	Mean 3 88

[a] Moon limb used in moon-star sightings

[b] Means of five presession readings

[c] Wardroom window transparent cover not removed

included in the mean values shown. In spite of the low priority of the experiment, 22 of 24 sessions (92 percent) were accomplished.

The zero-bias mean values were all positive, and the grand mean was 11.85 arc sec The cause for this departure from zero is not known, but it was not large and it was fairly stable across all sighting sessions

The mean error in measuring the angle between two stars was quite small (FO-1) The overall mean of 3.39 arc sec indicates that the measurement error was probably an insignificant random variable. Biasing influences were not appreciable. The standard deviations were all within the skilled performance range (from past studies, after training, the range was about 5.0 to 15 0 arc sec). In his premission training Astronaut Lousma had achieved a standard deviation of 8.5 arc sec.

On the star-moon sightings (FO-2) the precision was again high and stable with an average standard deviation of about 12 arc sec It is notable, however, that the mean absolute errors are higher than the mean absolute errors for the measurement of the stationary star pairs. Although the overall mean error of +0 79 arc sec might indicate an *overall* lack of bias (random variable with zero mean), this may not be the case since the angle between a star and the moon is a fairly rapidly changing quantity, even in low earth orbit. The mean rate of change for all FO-2's on SL/3 was 30 arc sec/sec. This was not linear; the rate itself was changing, but slowly.

The astronauts had received no preflight training in sighting on moving celestial targets Although the data are relatively meager, some things may be tentatively stated regarding this influence When the star was brought to tangency on the lunar limb in the sextant field of view, it would not remain in tangency because the angle between the two targets was constantly changing This requires a compensatory tracking technique with a near motion-perception-threshold error rate The *precise* moment of tangency was difficult to determine, and the error bias was probably in a direction determined by whether the angle between the star and moon was increasing or decreasing If the angle was increasing, a lag in marking tangency would be expected to produce a measured angle which was too small – a negative error If the angle was decreasing, a positive error would result The data partially support this interpretation In the four cases where the mean error in the sighted angle was negative, the angle between the star and moon was increasing. In three of the six cases where it was positive, the angle was decreasing Thus, in seven of 10 cases the results appear to support the hypothesis, but this provides an impetus for further study, not a conclusion.

The filters used on the sextant for the star-moon sightings were, except for session 20, the most dense available. For instance, the value 2.6 was achieved by placing both neutral density filters, 1.0 and 1 6, over the FLOS The value 2.3 was a combination of the two SLOS filters, 1.0 and 1.3. There were some positions of the moon which required that it be imaged in the SLOS rather than the FLOS When the 1.6 filter was used alone, the astronaut felt that the moon remained too bright for both comfort and accuracy A rigid schedule of filter use was not imposed upon the astronaut so it was not possible to estimate the effects of irradiance as a function of lunar disk brightness. The effect of high disk brightness is to increase the apparent size of the disk (irradiance). The general effects upon an angle measurement between a star and a lunar limb would be a spuriously small measured angle when using the near limb and a spuriously large angle when using the far limb. It is not possible to discern specific instances of this in the present data, particularly when they may be masked by the dynamic effects related to moving targets, discussed above.

The star-lunar limb sightings were a first instance in which a hand-held sextant was used in a spacecraft to measure the *changing* angle between a celestial pair which could yield useful navigation data. The results were most satisfactory, particularly the precision (low variability) of the sightings. This "new" source of bias should be extinguishable through appropriate training or premission determination of the typical magnitude of the error for the particular astronaut when sighting on moving targets.

The third kind of sighting, measuring the angular subtense of the moon (FO-3), can be done with extreme precision as is indicated by the very small average standard deviation, 3.88 arc sec. The mean errors are fairly large, and the bias is positive. This is in the direction to be expected from the enlarging effects of irradiance (refs. 11 and 16) However, it is not clear how the use of filters to decrease image brightness affected the angle measurements The measured angular subtense was smaller in sessions 4 and 5 when *no* filters were used than in 6 and 7 where both images were filtered Again, the filters were selected by the astronaut, based presumably upon his subjective assessment of the amount of brightness reduction required.

In future applications of the hand-held sextant for manual navigation, correction factors for irradiance will need to be determined A table of values will probably be necessary with entry arguments being line-of-sight, filter values, near-far limb, etc

As indicated in the standard deviation column of Table 1, that portion of the measurement process relating to its precision remained high and stable. That demonstrates that the astronaut's performance variability was constant over the mission duration (at least through 49 days in orbit) and did not differ significantly from his performance on the ground. His premission average standard deviation was 8 50 arc sec, during the mission it was 9.11, and his postmission average standard deviation was 6.70 arc sec.

In the diopter-setting column of Table 1 the sextant telescope focus settings are shown. Except for a few cases where the astronaut was experimenting with the setting, a constant setting of -1.25 diopters was used With normal visual acuity and accommodation this is a typical setting and probably indicates the use of negative lens power to compensate for instrument myopia. The stability of the setting over the duration of the T00-2 experiment may indicate that, at least to a first order, visual accommodation was unaffected by the extended period of weightlessness and confinement.

SL/4

Table 2 shows the experimental conditions and results from the third manned mission. The Skylab pilot, William Pogue, acted as astronavigator It is not possible to draw any specific inferences from the data because all but two of the sighting sessions were accomplished with the transparent protective cover left on the WRW Unfortunately, the astronaut checklist for the accomplishment of the T00-2 experiment did not make clear that *both* the metal window protector *and* the transparent cover were to be removed for sightings. It stated simply, "Remove window protective cover." This was too easily interpreted as instruction to remove only the opaque metal cover as the first in a series of distinct steps in the execution of T00-2. The necessity to remove the transparent shield was not made explicit.

TABLE 2.– MEANS AND STANDARD DEVIATIONS OF ALL SL/4 MIDCOURSE SEXTANT SIGHTINGS BY FUNCTIONAL OBJECTIVE

Day of year	Mission day	Order of sighting	Target pair	Number of angle measurements	Filter		Diopter setting	Limb[a]	Zero bias[b] arc sec	Mean error, arc sec	Stand dev , arc sec
					FLOS	SLOS					
F0-1											
365	46	1[c]	Rigel-Procyon	40			−1.6		−109.54	96.84	33.75
	46	2[c]	Rigel-Sirius	22			(d)		−112.20	51.56	9.71
	46	3[c]	Rigel-Aldebaran	25			(d)		−80.20	34.05	15.99
367	48	4[c]	Sirius-Aldebaran	9			(d)		−68.12	104.74	17.99
	48	5[c]	Sirius-Aldebaran	22			−1.6		−68.12	104.74	12.19
372	53	7[c]	Rigel-Procyon	12			−1.5		−81.69	100.70	37.93
374	55	11[c]	Rigel-Aldebaran	9			−1.2		−115.80	11.54	18.40
	55	12[c]	Rigel-Procyon	19			−1.6		−72.40	123.98	23.08
378	59	16[c]	Rigel-Procyon	24			−1.6		−131.14	−22.90	26.41
	59	17[e]	Regulus-Procyon	21			−1.7		−39.60	27.66	18.27
388	69	18	Alphard-Procyon	38			−1.6		−19.80	20.67	18.59
	69	19	Alphard-Regulus	13			−1.6		−10.08	3.22	6.98
										Mean 54.73	Mean 19.94
F0-2											
373	54	8[c]	Lunar limb-Procyon	12	(d)	(d)	(d)	Near	−133.20	16.57	25.95
	54	9[c]	Lunar limb-Sirius	20	(d)	(d)	−1.6	Near	−133.20	2.32	23.33
374	55	13[c]	Lunar limb-Rigel	17	2.6		−1.6	Far	−100.80	29.03	18.40
	55	14[c]	Lunar limb-Aldebaran	18	1.0		−1.6	Far	−100.80	101.78	36.23
										Mean 37.42	Mean 25.98
F0-3											
371	52	6[c]	Lunar limb-limb	26	(d)	(d)	−1.0		−93.24	−2.16	10.83
374	55	10[c]	Lunar limb-limb	25	1.0	1.0	−1.2		−115.80	−18.82	8.19
375	56	15[c]	Lunar limb-limb	23	1.6	1.3	−1.6		−143.28	9.51	9.79
										Mean −10.16	Mean 9.60

[a] Moon limb used in moon-star sightings
[b] Means of five presession readings
[c] Wardroom window transparent cover not removed
[d] Not reported
[e] Using S190 window

Session 17 was accomplished at the S-190 experiment window in the Multiple Docking Adapter (MDA) with its protective cover in place. This cover is a 0.29-in. (0.74 cm) thick (Corning chem-chor) glass plate. This MDA window was the best optical window on Skylab, but, like the WRW transparent cover, the glass plate cover made an unpredictable contribution to line-of-sight deviations.

Sessions 18 and 19 were accomplished at the WRW with the transparent cover removed (ref. 17). These are considered to be the only valid measurements for the SL/4 mission. For all other sessions the zero-bias reading is consistently negative and abnormally large. The overall mean bias is about 110 arc sec compared to 40 for session 17 using the S-190 window and 20 and 10 for sessions 18 and 19, respectively, when the WRW transparent cover was removed It is extremely high in relation to the mean bias reading on SL/3, which was 11.85 arc sec.

Normally, the zero bias is applied as a correction factor to the sextant-sighted angle between the two celestial targets The angles shown in the mean error column have been so "corrected " However, this may be a fruitless procedure. Since the window-generated (cover) errors depend upon location, the error determined by the zero-bias procedure would not apply to the measurement of the angle between two stars whose rays would not intersect the window surface at the same location. The zero-bias correction was not meant to be used in this way.

Only two sessions remain from which to draw inferences regarding astronaut performance in the manual navigation task over long-mission time. Sessions 18 and 19 were done with the transparent cover removed, and the data here appear to be more nearly equal to that expected. For the two sessions the mean bias was -14.9 arc sec, the mean error was 11 95 arc sec, and the mean standard deviation was 12.78 arc sec The measure of performance variability, the standard deviation, is not significantly different from the astronaut's premission, posttraining standard deviation of 12.00 arc sec and his postmission standard deviation of 16.79 arc sec.

Although the diopter settings selected by Astronaut Pogue were more variable than those used by Astronaut Lousma, the variability was not significant The mean for all of his settings was −1 50 diopters This was one fourth of a diopter more negative than Astronaut Lousma's mean setting of −1.25 This difference is well within the range of individual differences to be expected in the visual accommodation response (ref. 18) Again, the stability of the response over long-mission time is obvious

It is clear from these results that the sighting window used to take manual navigation sightings must be of high quality to achieve the accuracy and precision required for successful midcourse navigation. Where that quality exists, the well-trained astronavigator using a fully calibrated space sextant may be expected to be equal to the requirements. While the evidence from the SL/4 mission is not overwhelming, the results of SL/3 seem not to have been contradicted. There is no evidence to indicate that astronauts, after training, differ significantly from each other in their ability to take sufficiently accurate and reliable sightings, and no evidence in either SL/3 or SL/4 that performance is affected by long-mission time, weightlessness, and confinement

It appears from these results, then, that with appropriate training and a continuing awareness of the precision required for reliable midcourse navigation in space, sufficient reliability may be achieved and maintained through extended periods of weightlessness to make manual navigation with a hand-held instrument entirely feasible. For instance, given the magnitude of the standard deviations maintained by these astronauts, safe interplanetary missions using manual navigation would appear to be possible. Quoting reference 2, "For the Venus swing-by return from a Mars mission, calculations indicate that with onboard sextant measurements ($1\sigma \leqslant 10$ arc sec) for midcourse navigation the entry corridor might be missed 2,500 times in 1,000,000 flights . . ." Thus, the probability of safe re-entry for the astronavigor is 0.99750.

OPERATIONAL CONSIDERATIONS

The purpose of this section is to provide for the future system designer some of the considerations which are peripheral though pertinent to the main purpose of the T00-2 study. Included here are some of the operational problems which were gleaned from the extremely valuable comments made by the astronauts during the course of the study. The sources of these items are the dump tape transcripts and the debriefing records. All quotations presented here are taken verbatum from these records.

(1) The astronauts did not have an unrestricted choice of celestial targets. Skylab was sun-stabilized with the z-axis along the vehicle-sun line, positive toward the sun. It was maintained in this solar inertial attitude except for certain prescribed, short-term maneuvers, for instance control moment gyro momentum desaturation (CMG dumps) and Earth Resources Experiments Package (EREPS) local vertical attitude maneuvers. Though somewhat different on each mission, only a restricted portion of the celestial sphere was within the field of view (60°) of the WRW for the total mission. Pointing the window was not possible. This required careful calculation by the principal investigators and flight controllers in the Corollary Experiments Staff Support Facility to apprise the astronaut of target availability in the WRW field of view. In actual midcourse navigation, such a constraint would not exist. In Skylab, it was the source of many operational difficulties.

(2) The purpose of the T00-2 study was to evaluate the *measurement process* rather than to check-out a complete manual navigation system. If the data acquisition process were deemed accurate, reliable, and stable, then the total system would be considered feasible since the astronaut-sighted angles would be processed by the onboard computer or ground stations as is presently done. The mathematical procedure for processing the astronaut-determined quantities is based upon Kalman linear filtering and prediction (ref 1). The output of the processed data is a midcourse velocity (ΔV) correction for the maintenance of a desired trajectory. However, the ways in which the data are processed and vehicle guidance effected were not concerns in this study. And the implementation of a fully autonomous, onboard, data-processing system is also left to future designers

(3) A major problem in using the sextant at the WRW was the lack of a good body restraint system to prevent floating about while in the process of making a measurement. Astronaut Pogue was quite specific in his solution of the problem. He used three standard straps and strapped himself into place before the WRW. A comment in reference 17, the debriefing record, is worth quoting "You can make fairly accurate manual observations, but the station must be designed for the purpose." The problem of sextant-body-target orientation became quite severe when the astronauts were asked to sight objects near the periphery of the window. It necessitated a dexterity and effort not required when the window itself could be pointed. Both astronauts commented extensively, and

justifiably, on this difficulty. For instance, from reference 17, Astronaut Lousma remarked, "... you can't see as much out that wardroom window as you would think you might be able to because of the angles involved in looking around the sill. Whatever you look at has to be directly out the window."

And from the dump tape, Astronaut Pogue said, "Muscle cramp, I'm having – getting muscle cramps in my arms and in my legs from trying to get my – hold my body in the right position to angle between the two stars." And, on a later tape, " ... the posture is deadly on this Posture stability's a real problem."

The question of appropriate body restraint appeared to be a major problem, and it was, indeed, not given full consideration in the design of the study.

(4) It was difficult to shield the WRW from lights in the OWS. Since many other concurrent activities had to be carried out, the light shield, or hood, was essential. Concerning the hood, Astronaut Lousma stated, "I didn't always use the hood, but I always used the hood when it was necessary to bring a star down to the Earth horizon [This was an Air Force Orbital navigation sighting].... You can get by with turning the lights down for doing the star to star, or star to moon, or moon to moon. Those all worked good" (ref. 19). These latter three were the midcourse navigation sightings, FO-1, FO-2, and FO-3

(5) One of the major difficulties alluded to many times by the astronauts was the inadvertent activation of the control knob which controls the mirror position on the SLOS and thus the number displayed in the digital readout window. The knob was so sensitive that merely removing the thumb and finger would cause it to rotate and nullify the sighting. As perceived by the astronauts, the mechanical requirements for ideal manipulation were in conflict. Sensitivity was required to make the final adjustment with precision, but more inertia was required to maintain it in position when removing the fingers.

(6) The space sextant, though similar to a conventional marine sextant, is used somewhat differently. Two celestial targets may be sighted which are not oriented vertically to each other, unlike marine navigation where the single celestial object (sun, moon, planet, star) is optically placed on the sea horizon, i.e., it is "brought down" and the sextant is always vertically oriented. Lacking this vertical orientation, some pairs of celestial targets require that the space sextant be rotated to make the measurement. This is difficult to do because the sextant is neither shaped nor "human engineered" for this unconventional usage. For instance (a) In rotating the sextant the eyepiece rubber eyerest had to be rotated. The bond between this and the diopter-setting ring was too tight. Frequently, after rotating the eyepiece, the telescope focus had to be reset. (b) The hand strap and control knob were placed in an optimum position for vertical operation. For extreme rotations the sextant had to be held like a box, and in the dark, the location of the knob was not readily apparent. (c) The eyepiece was not in line with the sextant entrance aperture as in a telescope. It was thus not obvious how to point or aim the sextant As astronaut Pogue stated on the dump tape, "... you've got to design this thing so you can go by feel, particularly when you got to hold it at all kinds of odd angles."

(7) Related to and confounding the pointing problem was the extreme difficulty in identifying and acquiring stars in the sextant field of view. There were two reasons for this difficulty. One was the small field of view (7°) which included too little of the star patterns for ease of identification. The other was due to the relatively high light-gathering power of the sextant telescope which revealed many more stars than could be seen with the naked eye. This lack of correspondence between direct and aided viewing made it very difficult to make the transition from a visually located star to its image in the sextant field of view. The filters provided on the sextant were too dense to correct the problem. A major redesign would allow for varying selectively both the field of view and the light-gathering power.

(8) Once acquired and once angle measurements were begun it was possible to lose the star target again when the eye was pulled away from the sextant to read the angle in the readout window Two suggestions were made for the alleviation of this problem. One was to have the FLOS and SLOS of different colors so that each would be readily identifiable. This would be of particular value when sighting on two point objects, such as a star and a distant planet, and, in the case of the Skylab trials, two stars In fact, while operating the sextant, it is generally a good idea to know which images are coming from which line of sight. A specific example is the requirement always to move the two images together from the same direction to minimize the effects of gear backlash Confusion between the two lines of sight results in confusion as to which way to turn the control knob. The other suggestion made by the astronauts was to provide an optical digital readout within the sextant field of view. This would have several benefits The astronaut would not be expected to write down the angle so would have no need to remove his eye from the eyepiece during the entire series of sightings. An automated version of the sextant technique could have the sextant connected directly to the onboard computer such that by activating an event-record button the angle and its measurement time would be sent automatically to the computer. And, since the astronaut would not remove his eye from the eyepiece, dark adaptation would be maintained throughout the series of sightings.

(9) With increasing experience using the sextant, it becomes apparent that the position of the eye with respect to the exit pupil of the sextant telescope affects the shape, clarity, and brightness of the image. This, in turn, subtly affects the variability of the set of angle measurements (e.g., vignetting, ref. 20). Astronaut Lousma noticed this effect and carefully described the changing star-image shape with changing eye position. The accuracy required and the accuracy possible with the space sextant tend to sensitize the practiced user to error sources, even to a lack of coplanarity of sextant exit pupil and eye entrance pupil

(10) Also, as one gains skill using the sextant, one occasionally notes the small discontinuities in the geared measurement train For instance, Astronaut Pogue stated, ". . . seems like I'm caught between cogs in a gear. And I'm either not far enough or I'm too far, and I can't get in between " An illustration of this effect was when he was sighting on the moon, measuring its angular subtense He took three sightings in a row whose last three digits were 484, 485, and 489 He then said, " . between the cogs and gears . . If I click over I go to 9. If I don't, I stay on 4, looks like " Since each index mark in the right-most window of the readout is 0.001°, the difference of 5 counts that he noted is equal to 18 arc sec (5 X 0.001 X 3600) This seems to be an intermittently occurring phenomenon in the space sextant which requires further investigation.

CONCLUSIONS

(1) The accuracy and precision of angle measurements made with a hand-held space sextant are of sufficient quality for manual navigation in interplanetary missions

(2) There is no deterioration of human performance over long-mission time.

(3) Irradiance of an extended planetary disk biases angular measurements systematically, and its effect needs to be quantified further and appropriate calibration nomographs developed.

(4) Relative motion between two celestial targets biases performance. Training techniques need to be developed to minimize this effect. Posttraining residual bias should also be quantified and corrected for.

(5) Accurate and precise sextant sightings can only be made through a window whose optical quality is high or whose refractive characteristics are completely known.

(6) The space sextant needs to be redesigned to meet the needs of the human user as well as the task. Many instances of poor human engineering in its operational use were pointed out by the astronauts.

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