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THE BACKGROUND FOR SKYLAB EXPERIMENT T–002, MANUAL NAVIGATION SIGHTINGS

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SUMMARY

The background of the NASA-DOD manual navigation experiment (T002) on Skylab A is reviewed with emphasis on NASA's development of an error model for sextant measurements in midcourse navigation and on USAF's development of a low earth orbit manual navigation scheme. Two instruments are briefly described, a space sextant and space stadimeter, both of which are used by USAF in orbit navigation, the sextant by NASA in midcourse sightings. The rationale, data requirements, and data reduction procedures are discussed in terms of the goals of the two agencies.

INTRODUCTION

The manual navigation sighting study to be conducted aboard Skylab A is a joint effort of NASA and USAF. While both are concerned with the capability of man in space to make celestial observations - to measure angles - in terms of both accuracy and precision, the context in which the data are used differ. NASA's interest has been in use of a simple, lightweight, hand-held sextant for making navigation measurements for updating and midcourse correction of interplanetary trajectories; on board system autonomy is a prime goal. For trajectory estimation and modification based on the man-measured observables Kalman optimal filtering and linear prediction are assumed.

The USAF has developed an orbital navigation scheme which uses as observables range above the earth's surface and sextant measured angles between a selected star and the earth horizon. Range is measured using an Air Force developed stadimeter; the NASA developed sextant will be used for the star-earth measurement. The observed data and the GMT of the sightings are used to compute the orbital parameters and from these a position fix is obtained. The data reduction is carried out by reference to precomputed nomographs and computation forms are provided to hand-process the celestial observations as is done in terrestrial marine and air navigation.

The Skylab astronauts will only measure the observables and record the data. All computations will be performed on the ground by the experimenters in near real time working with post orbital telemetered data dumps. Also, error models will be utilized to evaluate the astronaut performance using the complete postmission data set.

In keeping with the above distinction, common identification of the two systems is by reference to NASA's effort as "midcourse" and USAF's as "orbital" manual navigation. Both are motivated by the need to develop an autonomous, light-weight, reliable, on-board, economical (e.g., vehicle pointing is not required, independency from ground support) navigation system.

Studies carried out at Ames Research Center and in the Gemini program indicate that the man-sextant performance provides navigational information that can be as accurate as ground tracking. It remains only to investigate the effects of the space environment including long term weightlessness on that performance.

BACKGROUND

During the decade of the 1960's both NASA and USAF were involved in studies directed toward the development of manual navigation systems. The study efforts were independent and each emphasized a different aspect of navigation in space. The NASA work was centered at Ames Research Center, the USAF at the Avionics Laboratory, Wright-Patterson Air Force Base, Ohio.

At ARC research was directed toward the several sources of error that affect a sextant measurement. Accordingly, an error model was central to the study efforts. Figure 1 shows the model schematized from information given in Reference 44. The model reflects the concern with both the accuracy ($\bar{e}$) and the precision (σ_e) of the sightings. The former accounts for biases, the latter for random variations.

Sextant error, sometimes called index error, is inherent in a given instrument. The sextant is calibrated by autocollimation in a bench set-up carried out by the manufacturer or by a qualified optical laboratory. The NASA-developed sextants fabricated by the Kollsman Instrument Corporation are all supplied with fine-grained calibrations across their full measurement range[10,31,28]

The window that will be used to sight through can, in some cases, provide considerable bias by deviating the light rays. This deviation is dependent on glass flatness and surface parallelism as well as on pressure bowing. The latter is dependent on glass thickness, the glaze structural surround, and pressure differentials between interior and exterior boundaries. Techniques for computing line-of-sight deviations, both empirically and analytically, were developed at ARC.[20,21,22,23,48,49,50,51,52]

Though not shown in the model, target irradiation can contribute to bias. This has the effect of "...displacing the apparent edge between a bright area and a darker area toward the latter."[12] Studies at ARC[4,12,13,14,38] have shown the measured angle between a bright lunar disc and a star can be in error (too small) by as much as 40 arcseconds. This error can be reduced by filtering the line-of-sight of the bright disc and leaving the star unfiltered. Neutral density filters are provided on the space sextant for this purpose.

Random variations, which decrease the precision of sextant sightings, are mainly attributable to human use of the instrument. Many navigator performance studies were carried out at ARC to assess the extent of this variance. These studies were concerned with training;[29,32,40] with the effects of slow rotational motion on performance;[29] with performance measuring the angle between a star and a flashing point source for possible space rendezvous applications;[30,37] and with the influence of sextant telescope magnifications and aperture stop.[39] One in-flight study was conducted[1] to compare in-flight results with the above and to assess error due to irradiation using the real moon. Two studies were concerned with the task related problem of star detection and identification through spacecraft windows.[16,17] These studies served to demonstrate that, after training, a standard deviation of less than 10 arcseconds was obtainable. This variability was deemed to be within the accuracy required for safe perilune and perigee as determined by computer and simulator studies instrumented for navigation based upon Kalman filtering and linear prediction. A theoretical discussion of all the errors which can influence a sextant sighting in space is given in Reference 9.

The navigation model which best processes stochastic inputs is based on the Kalman filter.[19] The reader is referred to the textbook on Kalman filtering that was issued by AGARD and from which Reference 3, a simple explanation, was taken. Several papers were published at ARC in the course of adopting optimal filtering to manual navigation.[5, 33, 45, 46, 47] The first of these references summarizes the results as follows: "The results further confirm theoretical studies based on assumed-error models and indicate that an on-board system that utilizes hand-held sextant observation data, processed by statistical filter techniques, and linear prediction, has the potential of providing acceptable guidance and navigation performance. No serious anomalies or discontinuities were detected in the use of statistical filter processing."

In an operational trial of sextant sighting performance the ARC-Kollsman space sextant was flown on Gemini XII and sightings were taken using two stars for the angle measurement. The results are summarized in the statement that "The total measurement error ... had a standard deviation of less than 10 arcsec (precision) and an average mean sighting measurement error of only 2 arcsec (accuracy)."[44]

During the same period that NASA was studying midcourse manual navigation, the decade of the 1960's, the USAF was concentrating its study effort on manual orbit navigation. Two instruments were central to that effort. One was a space sextant and the other a space stadimeter, the latter to be used for measuring range in low orbits.

The first study effort was accomplished by the Kollsman Instrument Corporation.[24] It had to do with space position fixing techniques, concentrating on manual space navigation in low altitude, low eccentricity, and elliptical earth orbits. It was assumed that most Air Force manned space flights would fall within this category. The Phase I study by Kollsman considered manual solution of the navigation problem, techniques of computational instrumentation, astronomical variables, e.g., the indefinite earth horizon, and techniques of optical instrumentation. Phase II[25] described the results of both theoretical and experimental studies providing a basis for the solution of a large class of space navigation problems in terms of totally manual techniques. The Phase IIIa report[26] documented the development of techniques, procedures, tables, and computational aids to mechanize a manual technique for determining the position of an orbiting vehicle.

Ensuing from these study efforts were the development of two space navigation instruments,[11,27,28] a sextant for measuring celestial angles, and a stadimeter for measuring the range above the earth's surface based on the angular measurement of the earth horizon curvature. Also, having found a focus, the Air Force effort began to be explicitly oriented to orbit navigation through sight reduction procedures and instrumentation.[2,15,41,43]

Although the stadimeter was never used operationally, the Air Force-Kollsman space sextant was tried on Gemini IV and VII (model 1) and on Gemini VI and X (model II). On Gemini IV there was a loss of timing data that prevented the experimenters from deriving any useful navigation information from the measurements. The sextant-measured data gathered on Gemini VII were subjected to postflight analysis and compared with ground tracking data. The results indicated navigation errors using the manual method to be of the same order of magnitude as generally acceptable ground tracking errors.[42]

On Gemini VI the modified sextant was used to investigate optical rendezvous techniques. The rendezvous results measured as angles between the star Sirius and the Gemini VII vehicle were "... so precise and sensitive to changes in relative vehicle position that ground track data were too gross to check the accuracy". [Ref. 18, pg. 11] The sextant was again flown on Gemini X, the mission including an operational check of orbit determination based upon sextant measurements. Also, the sextant was used to make optical ranging measurements to the Agena 8 vehicle. The results again compared favorably with other methods of position fixing.

SKYLAB A

The space sextant designed and fabricated by Kollsman Instrument Corporation for NASA-ARC (Figure 2) has a magnification of 8.0 and a 7.0° field of view. Its size is 7 × 7-1/4 × 6-1/16 inches (17.78 × 18.42 × 15.66 cm) and it weighs 6.0 pounds, 4.0 ounces (2.84 kg). It has an erect image and a measurement range of 76.0°. The eyepiece can be adjusted from -3.0 to +5.0 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 00.001° or 3.6 arcseconds. Interpolation on the thousandths drum is possible to 1/2 division giving a potential readout accuracy of 1.8 arcseconds. For a full description see Reference 31.

The space stadimeter, also designed and fabricated by the Kollsman Corporation, for the USAF, is a three-line-of-sight instrument (Figure 3). It combines three separated arcs of the horizon into a single image display. The two outer segments (arcs) in this display, viewed by the astronaut observer, are maintained at a fixed 65.0° apart. The center field (arc) can scan in a plane at right angles to the axis connecting the outer fields. The instrument readout is the angular separation between the chord of the center arc and the line connecting the centers of the outer segments. With a correction to allow for the angular difference between the center of the center arc and its chord, this angle can be related directly to the altitude of the spacecraft above the body of interest. The optical system provides a 3.4 power magnification with true fields of 2° to 8° in the scanning line-of-sight. The eyepiece is adjustable over +4.0 to -3.0 diopters. Data readout is by digital counter with a least count of 00.001° or 3.6 arcseconds. The measurement range is 20°. The stadimeter is 7-1/8 × 5-61/64 × 5-1/8 inches (18.10 × 15.12 × 13.02 cm) in size and weighs 4.0 pounds, 6.0 ounces (1.99 kg). See Reference 11 for a complete description.

Both the sextant and stadimeter have neutral density filter options on both the fixed and scanning lines-of-sight for equalizing targets of widely varying brightness. Both have internally lighted reticles, lamp current being supplied by 2.5 volt, dual cell, nickel cadmium, rechargeable batteries. For the Skylab experiment, batteries are interchangeable between the two instruments and may be replaced by the astronaut without the use of tools.

The results of the NASA-USAF studies have indicated that manual navigation is both accurate and reliable for short term orbital flight and for idealized target configurations. The most important aspect of the Skylab trials is the assessment of the possible deleterious affects on sighting performance of the space environment and long-term weightlessness. Accordingly, the sighting periods are to be evenly distributed over the 56-day mission so that beginning and ending performance may be compared and evaluated against premission and postmission baseline data gathered in ground-based training facilities.

An additional new aspect of the Skylab study will be the use of dynamically changing target pairs that will yield navigation information as a further check on the NASA error model. The star pair targets used on Gemini XII will be supplemented by star-lunar limb and lunar-limb-limb (ranging) sightings. Only the sextant will be used in the NASA part of the T002 experiment. Six star-star sighting periods (10 to 15 sightings), 12 star-lunar limb periods, and six limb-limb periods will be accomplished. The main performance measure will be the standard deviation of the astronaut's set of sightings taken during a single sighting period. This will be computed near real time and can be up-linked to the astronaut for his information.

Postmission analysis will be concerned with comparing the corrected, sighted angles (see error model) with angles computed from ephemeris data for the evaluation of both bias and random errors. This requires an accurate Greenwich mean time correlation that will be provided by the astronaut's time "mark" at the moment of target superposition in the sextant field of view for each single sighting.

The Air Force portion of T002 differs on Skylab in that, for the first time, the stadimeter will be used in orbit. In fact, the full operational sequence of sextant sightings interspersed with stadimeter sightings will be employed in addition to separate sextant and stadimeter sighting periods.[8] Three sighting periods (10 to 15 sightings) will be given to using the sextant to measure the angle between a star and the earth horizon. A standard deviation will be computed for each period in near real time and used as a performance measure. The stadimeter will be used alone in two sighting periods and, again, a performance measure will be computed and stored. The sextant and stadimeter will be used together in operational sequence in five sighting periods. In each period at least three ranging measurements will be made with the stadimeter and at least two angular measures using two separate stars. Nonreal-time analysis of these operational sightings will be based on the USAF manual orbit navigation sight reduction scheme. The first step is the solution, using the sextant and stadimeter angles, for the orbital parameters of the orbit plane. The geometric parameters - eccentricity, period, and time of periapsis passage - are found using the stadimeter angles (ranges). The orientation parameters - inclination, right ascension, and true anomaly - using the sextant angles. Once the six orbital parameters have been determined, the position of the spacecraft subpoint on the earth at any desired time can be computed.[43] The position fixing procedure is fully supported by work sheets, tables, and figures for paper and pencil solution. The solution will be carried out by the experimenters, however, not the orbiting astronauts. Such being the case, it is relegated to the category of postmission analysis. Performance evaluation of the total orbit navigation scheme will be accomplished by GMT correlated comparison of the manual position fixes with those provided by ground tracking. A full and detailed experiment description may be found in References 6, 7, 8, 34, 35, 36.

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ERROR MODEL

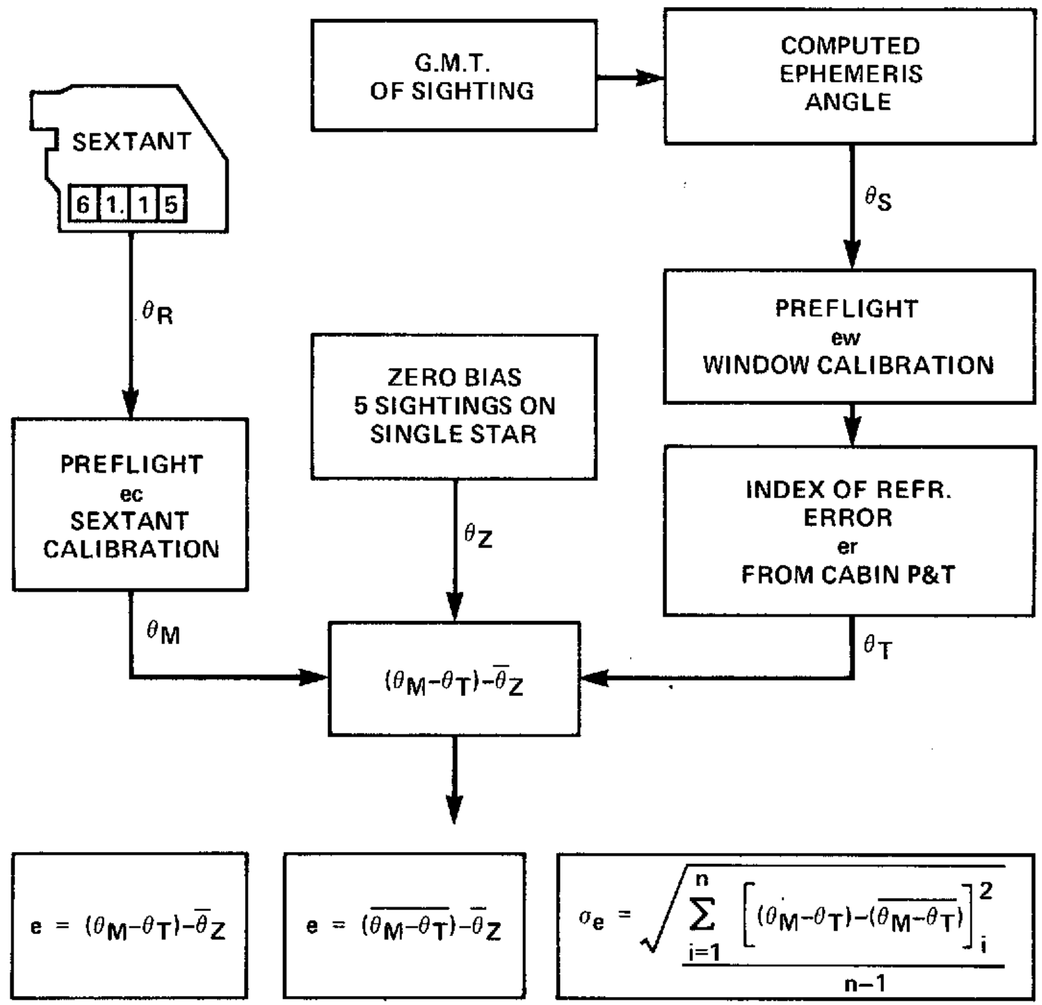

Figure 1.- Sextant sighting error model.

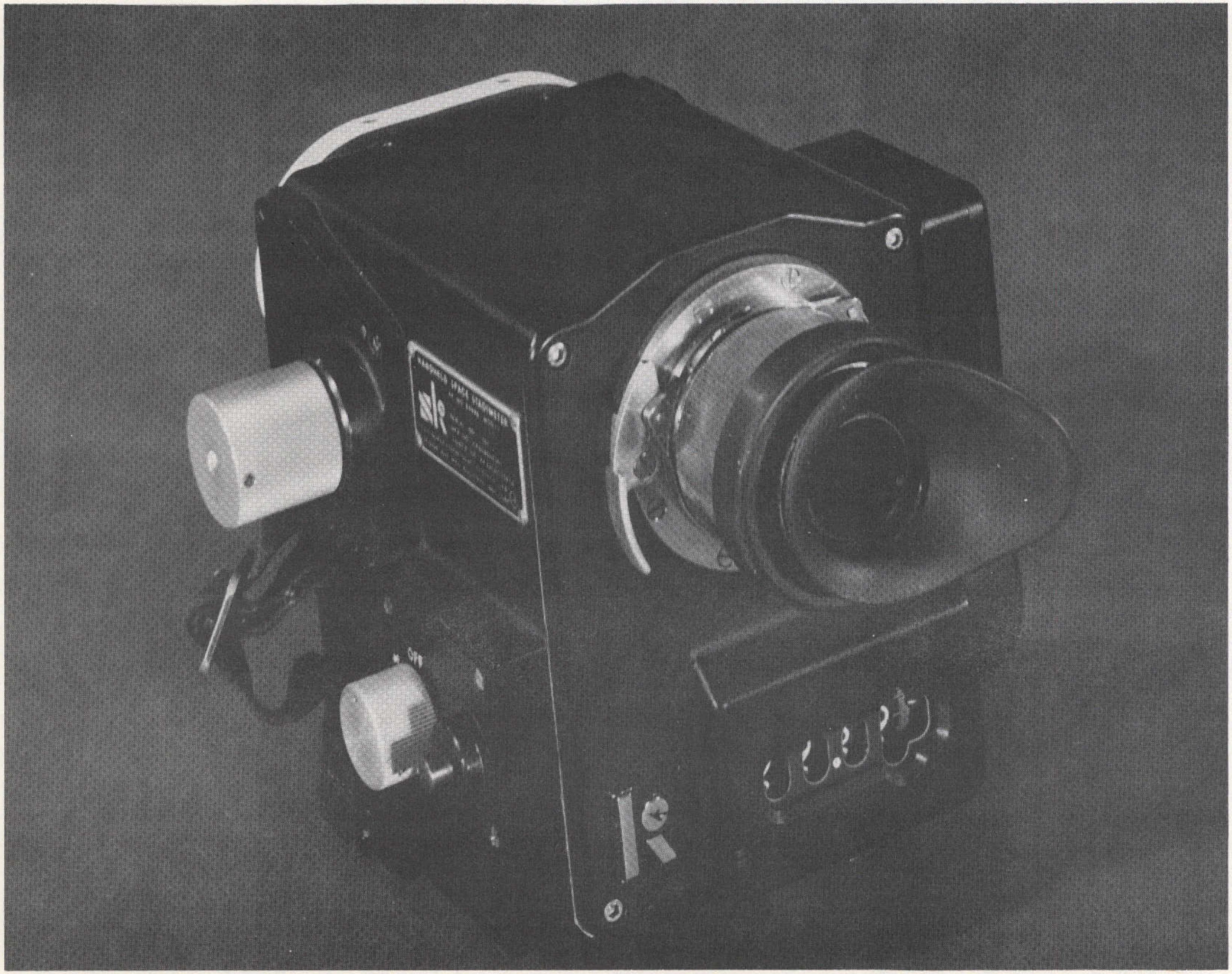

Figure 3.- USAF stadimeter.

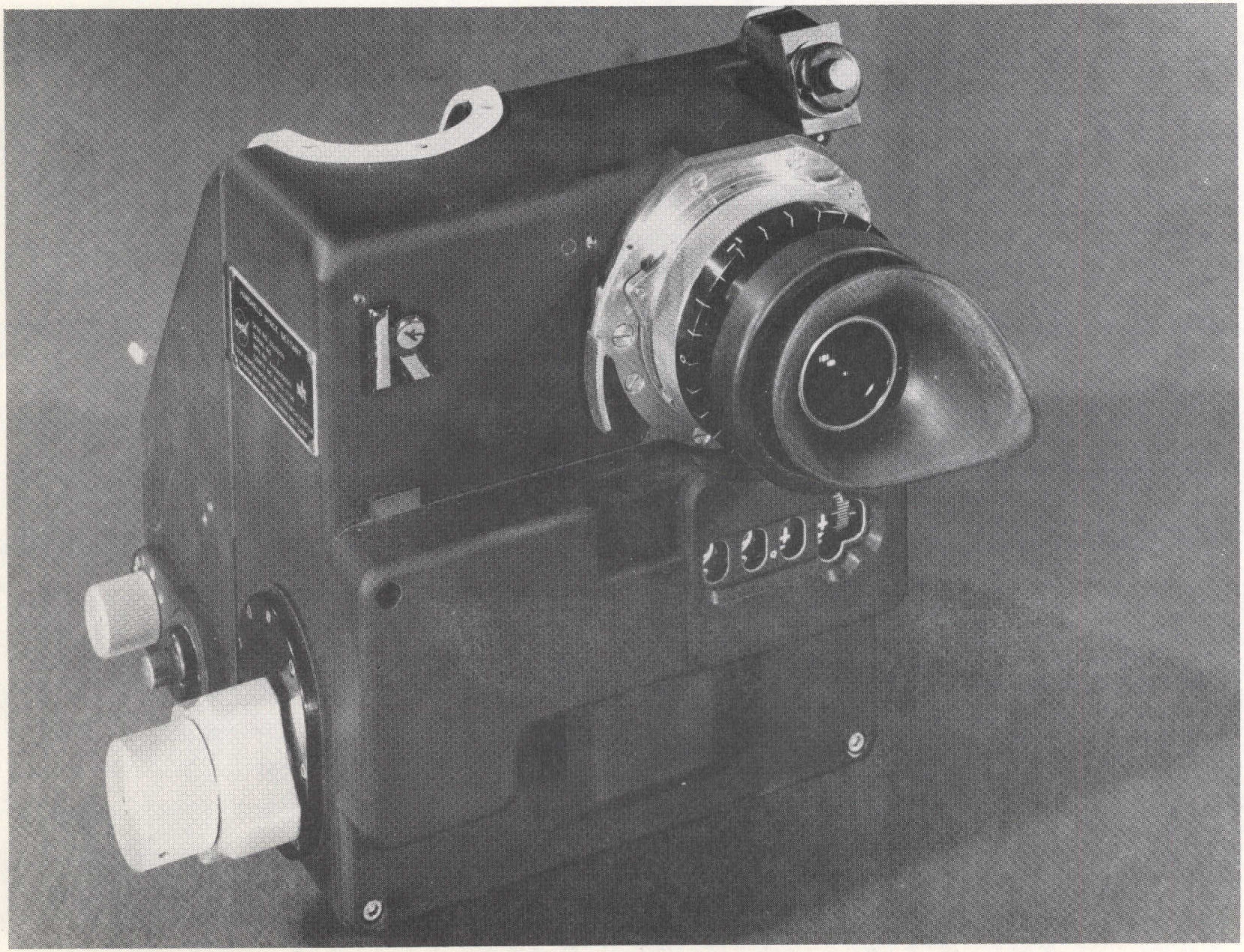

Figure 2.- NASA sextant.