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FACILITY FORM

N66-23737 (ACCESSION NUMBER)

(THRU)

150 (PAGES)

1 (CODE)

CR-74080 (NASA CR OR TMX OR AD NUMBER)

14 (CATEGORY)

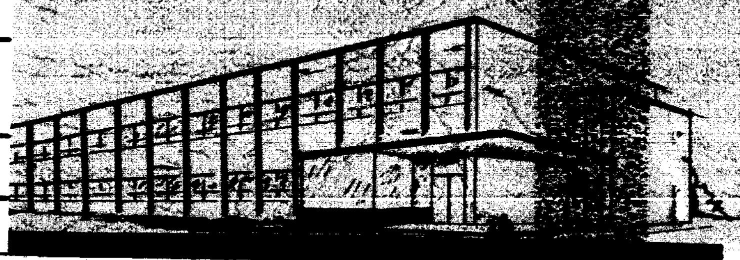
GPO PRICE $ ________

CFSTI PRICE(S) $ ________

Hard copy (HC) 4.00

Microfiche (MF) 1.00

ff 653 July 65



THE Bendix CORPORATION

BENDIX SYSTEMS DIVISION · ANN ARBOR MICHIGAN

CONCEPTUAL DESIGN FOR
MOBILE GEOLOGICAL LABORATORY
POSITION AND HEADING FIX SYSTEM

BSR 1257

March 1966

Submitted to
NASA/MSFC

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SECTION 1

INTRODUCTION AND SUMMARY

At specific intervals throughout a lunar surface exploration traverse, there exists a requirement for accurately determining the vehicle position. Prior to the actual lunar mission the technique, equipment and operation of the position fixing function can be investigated through earth simulation. Such a simulation is valuable in the evolution of the lunar system design as well as the development of astronaut operational proficiency.

A conceptual design of a position fixing system for use on the Mobile Geological Laboratory (MGL) in simulation of the lunar Mobile Laboratory (MOLAB) is contained in this report. The selected position fixing system is based on: (1) the MOLAB system designs presented in conceptual design reports by the Bendix Corporation[1] and the Boeing Company,[2] (2) a consideration of the earth based simulation environment and mobile vehicle, and (3) an equipment survey as an examination of the state-of-the-art and budgetary costs.

The missions, the navigation functions, and the position fixing system requirements for both the lunar MOLAB and the earth MGL were documented in a navigation system description report, Reference 3. This conceptual design report discusses in greater detail the generalities of the position fixing concepts and implementations, both landmark referenced and celestial body referenced.

The prime components of the position fixing system have been identified as: (1) periscopic sextant, (2) clock, (3) reference data, and (4) computation aids. The implementation alternatives for each of the components in the MGL position fixing system are discussed in this report. These alternatives are applicable to both the initially implemented system and systems which might possibly be used as the simulation program advances.

The final section of the report contains a description of the position fixing system recommended for the initial MGL simulation tests. The selection of this system is related to the three criteria previously stated.

SECTION 2

THE GOALS OF LUNAR NAVIGATION SIMULATION

The facility being developed by NASA for simulation of mobile lunar exploration missions is designed to aid in determining the effectiveness of the early exploration missions. The ability to conduct simulated scientific survey experiments using designated astronauts who are operating under realistic equipment and environmental constraints is most valuable not only to the astronaut but also to the equipment designer.

Hence, it is the primary goal of the lunar navigation simulator to guide the development and synthesis of the navigation system best suited to vehicular travel over the lunar surface. This will involve evaluation of hardware performance, data handling efficiency, operational effectiveness and man/machine compatibility.

These evaluations will be made in the light of the governing percepts of the lunar mission, such as:

- the safe return of the astronaut crew to their main base or LEM

- the mission success in terms of performing the planned expedition and acquiring and returning to earth the desired scientific samples and data.

Although the capabilities of the navigation units assembled initially, a land dead-reckoning system, in the Mobile Geological Laboratory may yield a low score in this evaluation, they provide an ideal starting point in the lunar system developmental process. It is anticipated that there may be many steps in this simulation process to arrive at the final system configuration. As mentioned above, the hardware performance will be improved and new functions added, such as for position-fixing and for computation of range and bearing to destination.

The efficiency of the interchange of navigation information between the astronauts and earth will be developed, as will the data handling between astronauts. The simulation facility will be most effective in the area of development of operational techniques best suited to lunar navigation. The best features of present day navigational technology, for example, in such areas as astro-navigation, will be extracted and supplemented by new techniques relevant to the lunar terrain and environment. The feasibility of navigating in a strange land by associating landmark sightings with the features on orbital photographs can be tested. Skillful use of the computational facilities available to the lunar explorer will greatly ease the burden of calculation and coordinate transformation borne by the navigator. These and other operational aspects may be evaluated under controlled conditions in the lunar navigation simulator.

Finally, it will be a goal of this lunar navigation simulation to determine the best balance between system capability and system simplicity. It is always desirable to make navigation as automatic as possible particularly in crew-limited operations. This automaticity invariably increases system complexity at the price of system reliability. Under the controlled conditions of this simulation facility it will be possible to assess the degree of automation to be provided in the navigation system in view of the skill and time available to the astronauts to perform the navigation function.

SECTION 3

POSITION FIX CONCEPTS

The topic of this report is the particular navigation function of determining an instantaneous position of a vehicle. This is called position fixing and is basically the art of relating your position to known surroundings. The axe of the Indian trail-blazer and the astrolabe of the early explorer were instruments of position fixing. Previous analysis has indicated that a periscopic sextant will be the most relevant instrument for use by an astronaut for position-fixing on the surface of the moon. This section describes two methods of using a precision sextant to establish the present position of the observer. These methods are (a) by landmark sighting and (b) by celestial observation.

3.1 Position Fixing by Landmark Sighting

Terrain recognition techniques are applicable to surface navigation under most of the anticipated conditions. These techniques relate principally to the determination of position and heading from observation of local terrain features. The most common example of this type of navigation is termed "pilotage" and historically it predates all other navigation techniques.

The foot soldier with a crude map, trying to locate himself and to establish a direction (heading) to a local objective is practicing a simple form of terrain recognition. Modern tools such as stereoscopic aerial photography and photogrammetrically produced photo maps or photo mosaics have provided today's navigator with powerful aids to the basic problem of orientation with respect to an unfamiliar terrain.

It is obvious that the one condition where this method breaks down completely is in the absence of recognizable terrain features. Examination of maps of the proposed lunar landing site (39^{o} 25'W, 4^{o} 40'N) and of the area of lunar mission simulation indicates that there are significant terrain features which should be visible from any point within the area. It is assumed that good aerial photographs of the proposed areas will have been obtained so that suitable maps with absolute horizontal and vertical accuracies of better than 1 km can be provided to the pilot and navigator of the vehicle. Photogrammetrists have stated that current state-of-the-art techniques utilizing stereo photographs and simple optical instruments, such as a theodolite, should be adequate for navigation in virgin territory with a high order of reliability even under emergency conditions. However, the accuracy with which the vehicle position can be determined will be a function of the time which can be allocated to this task.

It appears that terrain recognition will always be used to some extent in land vehicle navigation. Because of uncertainty about the navigator's ability to orient himself within a reasonable time, this mode of navigation is considered in a backup category. When good and complete horizontal photographic coverage of the mission area is available, then terrain recognition might be considered as the primary navigation mode.

Several procedures are available for locating present vehicle position with respect to lunar surface features. One such procedure as described in Reference 2 requires three identifiable landmarks and the use of azimuth measurements. This is represented in Figure 3-1. The term identifiable landmark implies three criteria: (1) the recognition of the reference landmark, (2) the position of each landmark must be known with respect to some convenient coordinate grid; (3) there should be no confusion as to what point on the landmark will be brought to the center of the field of view for measurement purposes.

From Figure 3-1 it is seen that an estimate of present position is determined with the measurement of the three angles A, B and C relative to a reference line. It is unnecessary to specify the orientation of the reference line as the differences in pairs of angles determine the present position. A pair of landmarks and a difference angle determine a circle of position which passes through the pair of landmarks. The position computation then corresponds to the simultaneous solution of the equations of the resultant circular loci to determine the common intersection point.

Consider a pair of known landmarks separated by a distance 'a'. For convenience a rectangular coordinate system is defined with its x axis passing through both landmarks as shown in Figure 3-2. The observer at point P measures the angle Θ between the known landmarks at points O and A. The intersection of the two straight lines OP, and AP determines the point P.

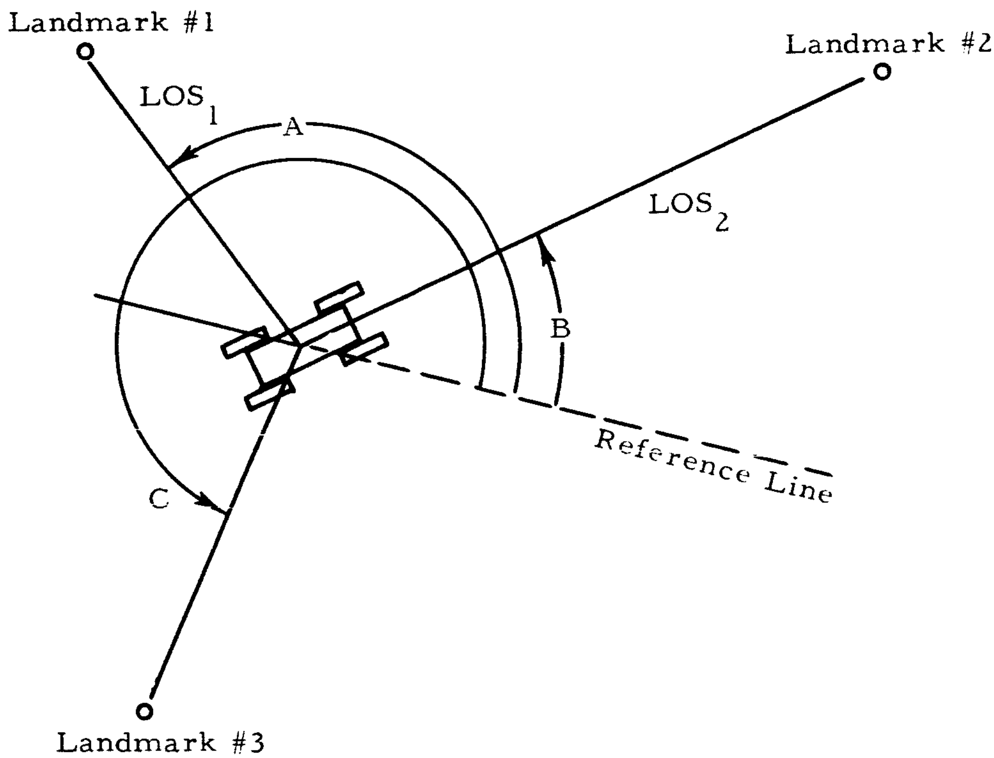


Figure 3-1 Three Landmark Position Fix

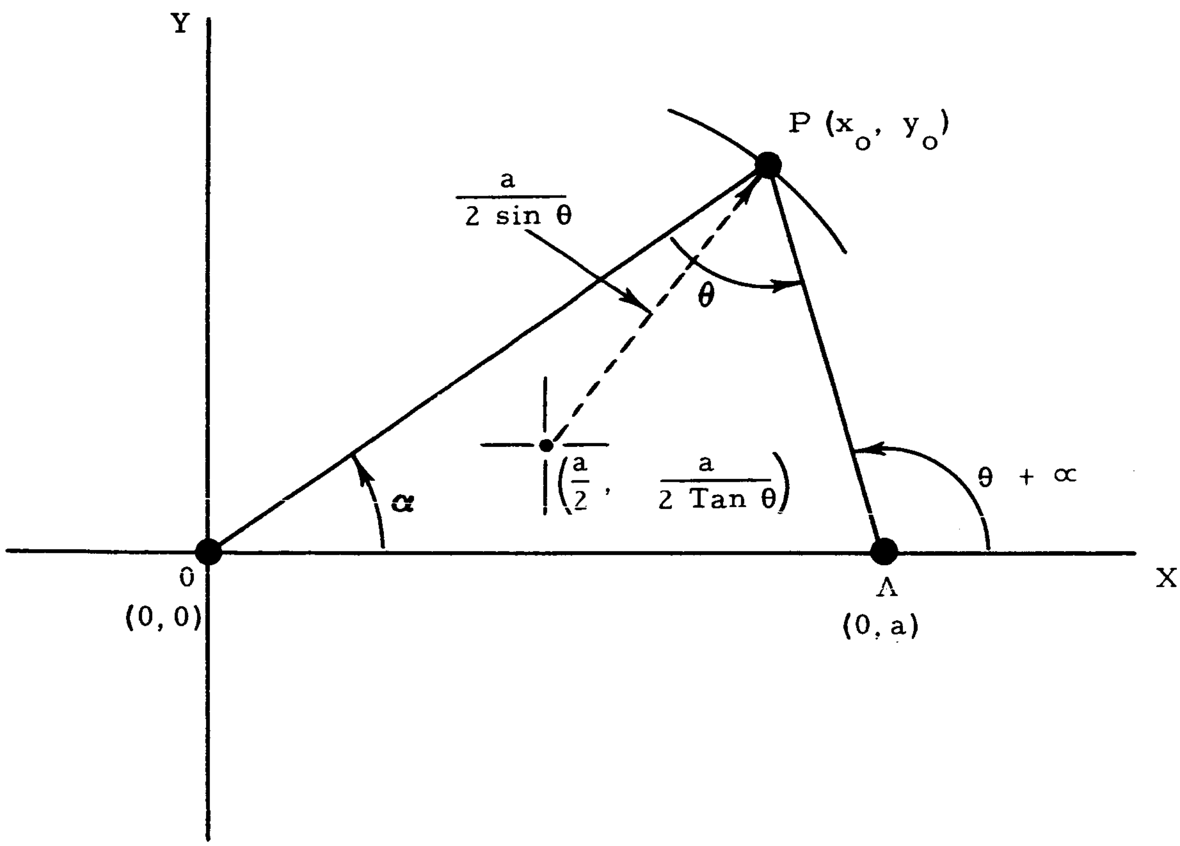


Figure 3-2 Coordinate Definition for Circular Locus Computation

For the straight line OP

$$y = x \tan \alpha ,$$

where

$$\tan \alpha = \frac{y_o}{x_o} .$$

For the straight line AP

$$y = (x - a) \tan (\Theta + \alpha)$$

Solving for x_o and y_o the locus of the point P is found to be a circle as:

$$(x_o - \frac{a}{2})^2 + (y_o - \frac{a}{2 \tan \Theta})^2 = \frac{a^2}{4 \sin^2 \Theta} ,$$

centered at $(\frac{a}{2}, \frac{a}{2 \tan \Theta})$ with radius of $\frac{a}{2 \sin \Theta}$.

Thus, for each pair of known landmarks and measured angle Θ it is possible to construct a circle which is the locus of points of vehicle position. The common intersection of three circles, corresponding to three pairings of three known landmarks, determines position relative to the observed landmarks. Any error in measurement or uncertainty in landmark location results in multiple intersection points, rather than a unique point. More than three landmarks may be used if additional intersection points are required. Position determination accuracy is then improved by using the centroid of the resulting set of intersection points at the position of the vehicle. If the errors in each of the measurements are independent, the use of additional landmarks reduces the standard deviation of the position determination by $\sqrt{n}$ where 'n' is the number of measurements.

An interesting extension of this method is the possibility of fixing landmarks not identified on available maps or of trailblazing. Figure 3-3 presents the geometry applicable to this situation. In the absence of ranging measurements to the remote landmark it is necessary to maneuver the vehicle and use multiple sightings to establish the landmark coordinates. Thus, vehicular motion should be of the same order as distance to the landmark and in such a direction to change the azimuth reading to the landmark. Vehicular position is required at both sighting points, and this may be

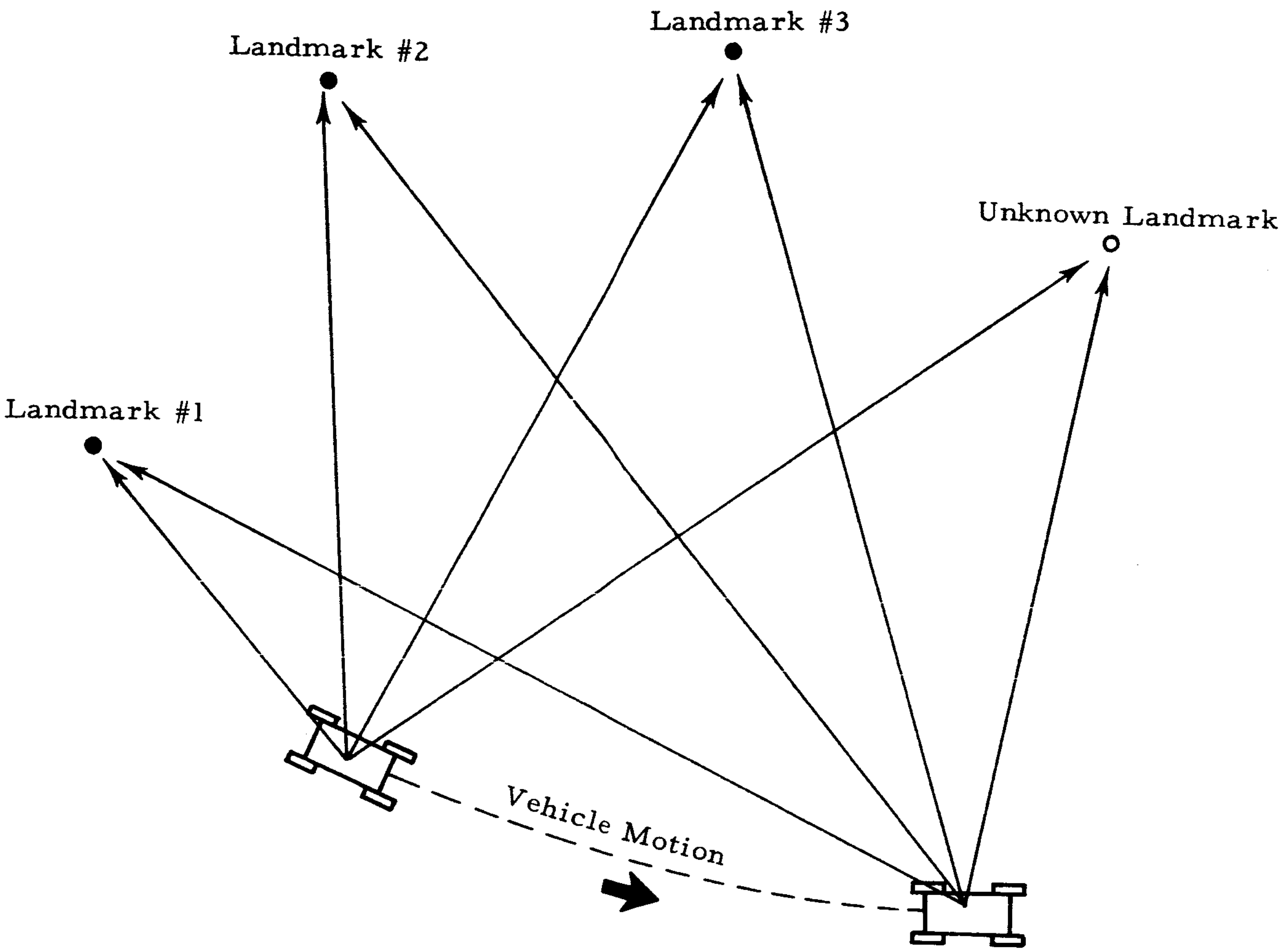


Figure 3-3 Remote Landmark Position Determination

derived from any of several sources. These sources include: two or three landmark sightings, celestial position determination, remote position determination (as accomplished by an earth based or CSM based tracking facility), or position determination through application of the vehicle dead-reckoning navigation system. The intersection of at least two lines of position are then required for the location of the remote landmark. The accuracy of this type of position determination is obviously sensitive to the nominal angle of intersection of the lines of position.

3.2 Position Fixing by Celestial Observation

The use of celestial observation (or astro fixes) is the primary concept of position fixing proposed in the various navigation studies for MOLAB. It is equally relevant for use in fixing the position of the Mobile Geological Laboratory in its simulations of the MOLAB missions. The art of astronomical fixing has been highly developed through extensive usage in marine and air navigation. The concept of celestial navigation is founded on the knowledge of the motion of the earth within the celestial sphere. The stars most commonly used in celestial navigation are at such great distances from the earth that the rays of light observed are virtually parallel. Even the separation of the earth and moon is negligible (light seconds) compared to the distances to the stars (many light years). Hence, with suitable coordinate rotations, the techniques of celestial navigation developed on earth will be applicable on the moon. Also, on the moon's surface, the availability of stars for sighting at all times and the slower apparent movement of the stars reduce some of the limitations of astro fixing implicit in its use on earth. A brief review of the concept of astro fixing is discussed below to emphasize the basic principles involved.

As shown in Figure 3-4 the primary reference in position fixing by astronomical sightings is the "geographical position (GP)" of the body being sighted. This is the point of intersection of the surface of the earth and the line joining the center of the body and the center of the earth. All bodies in the heavens appear to move continuously across the sky from east to west (due to the earth's rotation) but at any given instant each one defines a specific geographic position on the earth's surface. The geographic coordinates (latitude and longitude) of each specific GP for commonly observed stars has been tabulated against Greenwich Mean Time. The latitude of a star's GP is a constant called its declination. The longitude of a star's GP is dependent only on the time of day and the date.

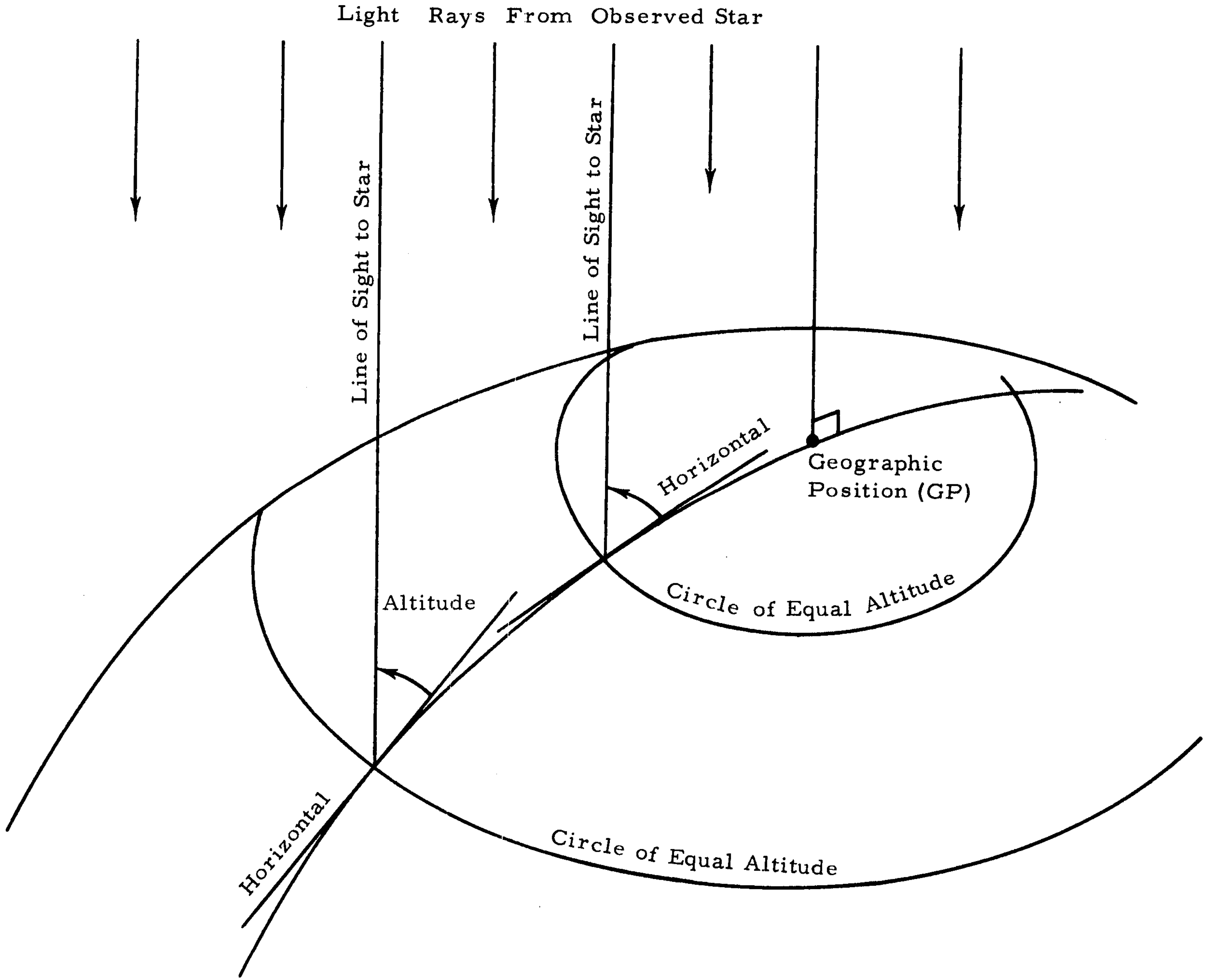


Figure 3-4 Altitude Angle is a Measure of the Observer's Position

Figure 3-4 also illustrates that the altitude angle, which is between the line-of-sight to a particular star and the observer's horizon, is proportional to the distance of the observer from the GP of that star at the time of observation. One such measurement establishes the observer's position on a circle centered on the GP of the observed star. Measurement of the height above the horizon (altitude) of two stars establishes the position of the observer at one or other intersection of two such circles (see Figure 3-5). The general location of the observer is normally known well enough to resolve this ambiguity.

The concept of position fixing by celestial sightings thus resolves to the simultaneous solution of two spherical triangles each comprising:

- a polar distance(b) of the observed star (dependent only on date and time for a particular star)

- a measured co-altitude of the star (a)

- the co-latitude of the observer (c), to be determined.

For the triangles depicted in Figure 3-5, the following relations apply:

$$t_1 = \cos^{-1}\left[\frac{\cos a_1, - \cos b_1 \cos c}{\sin b_1 \sin c}\right] \quad (1)$$

$$t_2 = \cos^{-1}\left[\frac{\cos a_2 - \cos b_2 \cos c}{\sin b_2 \sin c}\right] \quad (2)$$

The sum of these two angles can be determined precisely by subtracting the siderial hour angles (SHA) of the two observed stars. This yields the relation

$$t_1 + t_2 - (SHA_2 - SHA_1) = 0 \quad (3)$$

By selecting various values for "c" and iteratively solving equations (1) and (2) for "t_1" and "t_2", the proper solution may be found to satisfy equation (3). A wide variety of computational techniques and devices have been devised over the years by those who make use of celestial observations for position fixing. Some are applicable to world-wide usage: Others are designed for use in localized geographic areas. The major differences arise from such considerations as the permissible demands on operator time, the positional precision required and the facilities available.

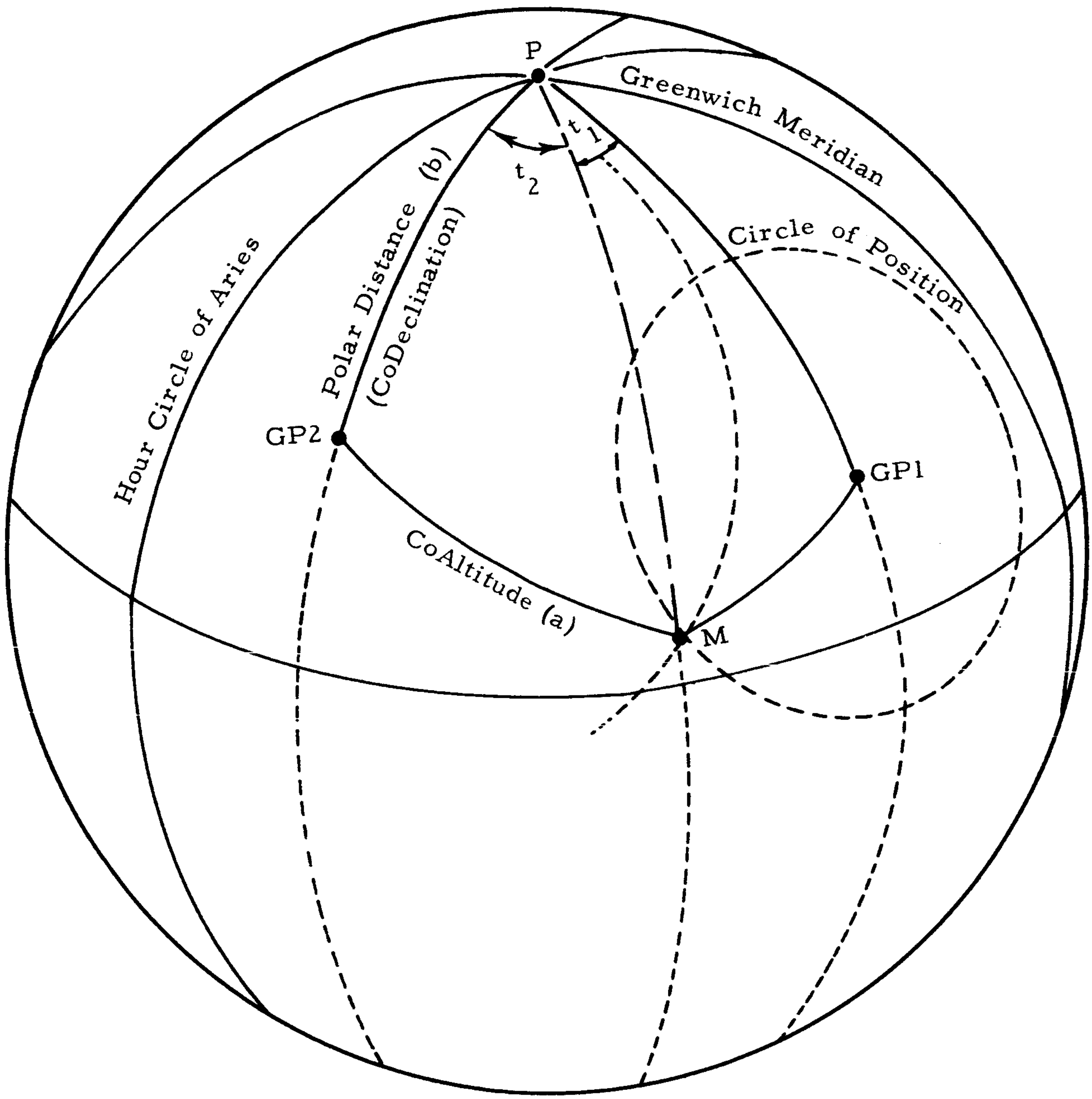


Figure 3-5 Geometry of Celestial Position Fix

SECTION 4

IMPLEMENTATION OF THE POSITION FIX

From Section 3 it is evident that the theory behind position fixing by sighting landmarks and by celestial observations has much in common. It is also apparent that the sighting instrument used in both techniques could be the same. This comparison is continued below in the presentation of the detailed functions involved in each concept. In addition, the mechanics of implementing the astro fix concept, as it is practiced at present by the traditional navigator, is described in more detail.

4.1 FUNCTIONAL DESCRIPTION OF POSITION FIX CONCEPTS

The two proposed concepts of position fixing are very similar in the manner in which the location of the observer is extracted from the available data. Figure 4-1 illustrates the functional flow typical of both concepts. The functions listed vary only in the nature of the data and equations being manipulated. An understanding of these functions in the context of each concept is essential to the design of an effective system for implementing that concept. On the following pages is presented a brief comparative description of the functions (shown on Figure 4-1) involved in the two proposed position fix concepts together with some of the constraints implicit in determining position by each method. Some of the functions are more thoroughly described in Section 6.

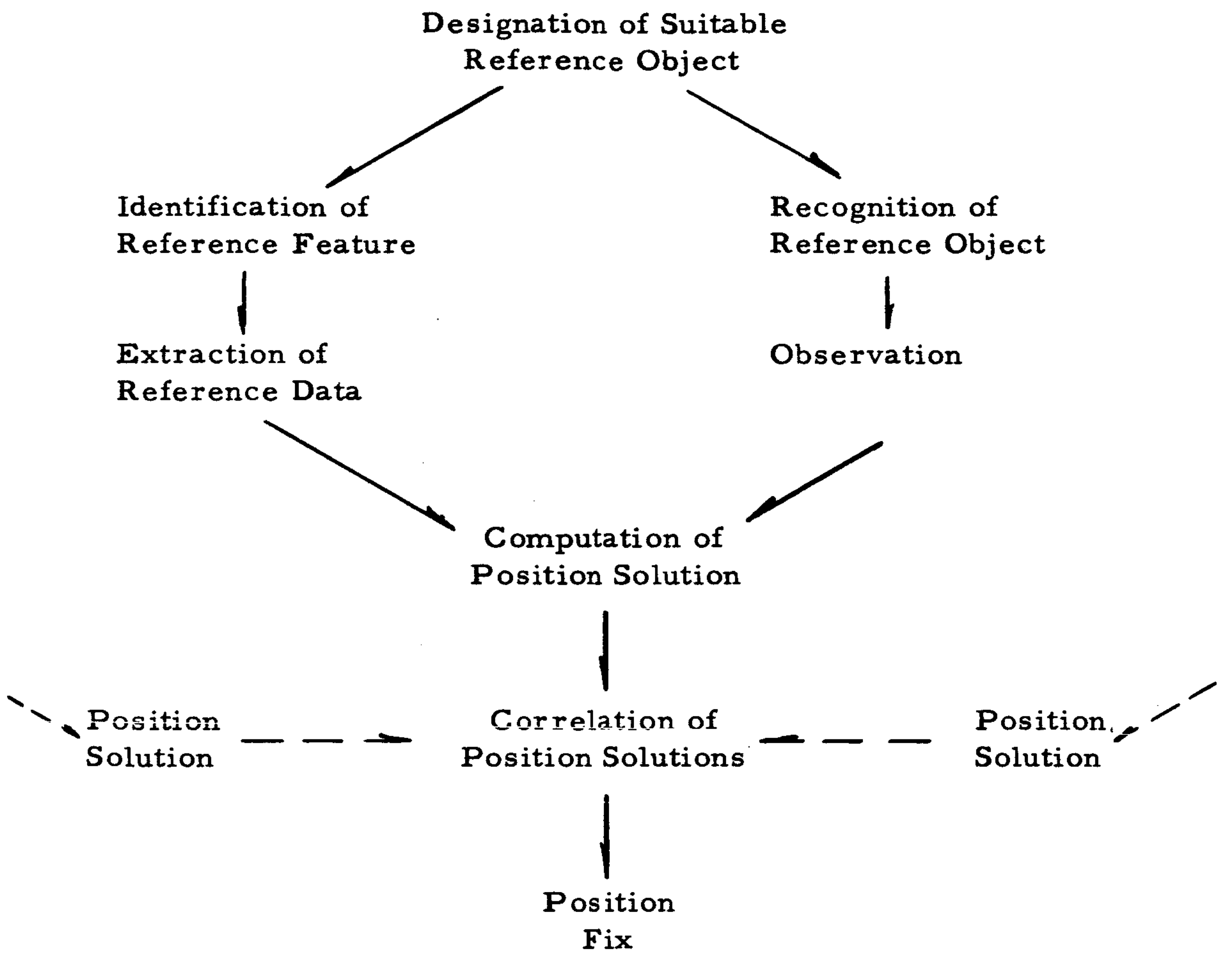


Figure 4-1 Functional Flow in Position Fix Concepts

FUNCTION: Designation of Suitable Reference Object	
Landmark	Celestial
The success or failure of this concept depends on the ability to designate prior to a mission those objects (a) suitable for use as references, (b) which will be recognizable by the observer from his viewpoint. A great deal of work has yet to be done to establish the procedure by which aerial survey data on the features of unexplored terrain can be classified in terms of an observer's ability to recognize those features from various locations on the surface of the terrain and under a variety of light conditions. The simulation operations of MGL should yield valuable information on the techniques of implementing this function.	It is evident from Figure 3-5 that the choice of stars to be observed (i.e., the locations of GP 1 and GP 2 relative to M) has a major influence on the accuracy of the resultant position fix. For example, the two position circles should intersect at approximately a right angle and the two co-altitudes should be approximately the same. The sensitivity of the error in the position fix to the designation of reference object is reported in Reference 4. Since, in both the lunar and earth simulation operations, the location of M is highly constrained, a simple analysis can indicate those stars best suited to positive recognition and accurate position determination at a specified time and date.

FUNCTIONS - Identification of Reference Feature
- Extraction of Reference Data

Landmark

For those objects (mountains, craters, etc.) which are larger than the required precision of the position fix, it is necessary to identify specific features (recognizable prior to the mission) on these objects whose location can be catalogued.

The method of cataloguing will normally be a topographic map, but could take on any number of forms suited to efficient and precise extraction of the location coordinates of those reference features being observed.

A valuable aspect of this concept is the ability of the operator to add to the reference data as his familiarity with the terrain improves. The features he can add on-site can be smaller and hence of much higher potential accuracy.

Celestial

For a given pair of stars the reference data and corrections are catalogued in relation to the features listed below:

Reference Data	Catalogued Under
Declination	Name of star
Sidereal Hour Angle	Date & Time (UT)
Parallax	Apparent Altitude of Star

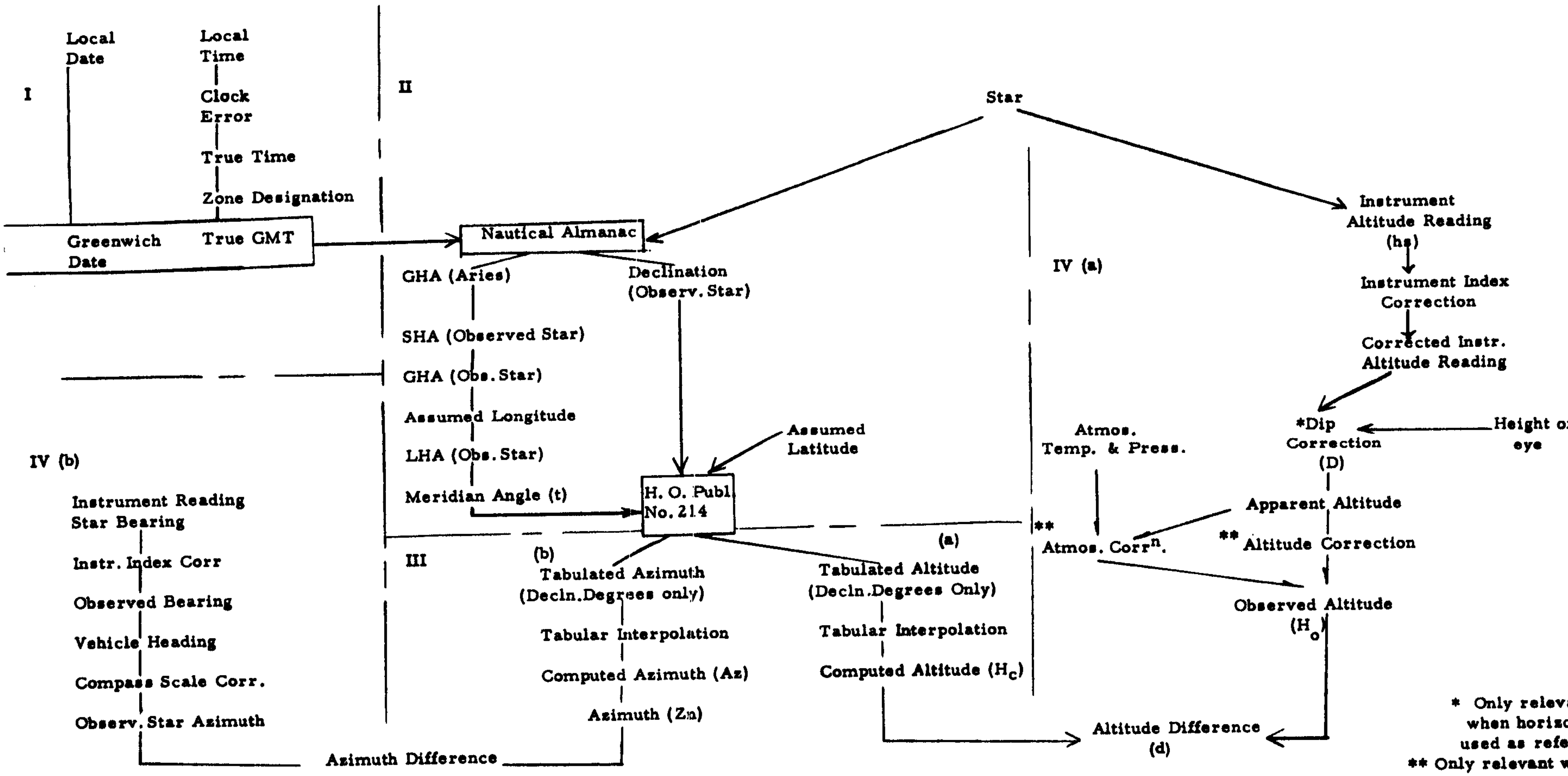
Traditionally this catalogue is published in book form as an almanac (nautical, air, etc.) to suit the needs of the using navigator. The conditions attendant with land navigation are sufficiently unique to warrant a brief task analysis to establish the best form and format for use by this navigator to efficiently and precisely extract the necessary celestial observation reference data.

FUNCTIONS - Recognition of Reference Object
- Observation & Measurement

Landmark	Celestial
Initial recognition of the reference object may be with the unaided eye, but smaller objects/features may require some optical magnification. In any event the reference object/feature being sighted must be recognizable through the sextant/theodolite in order to make the required bearing measurements. The characteristics of the sextant having greatest influence on recognizability are the magnification and the field of view. Magnification is required to ensure adequate resolution of the reference feature. Sufficient field-of-view is necessary that the designated feature is recognizable in its surroundings. The optimum combination for use in lunar vehicular missions should be established during the simulation exercises.	The ability of the astronaut to locate, identify and align a sextant to a particular star is largely a matter of experience. But the optical characteristics of the sextant are very important. The magnification, field-of-view and eyepiece aperture must be carefully balanced. NASA Ames Research Center has done some valuable research[4, 5] on these sextant parameters. A large number of visual aids are available to assist the observer in recognizing the designated reference star. These delineate the approximate altitude and azimuth angles, or the magnitude, or the pattern of adjacent stars, or combinations of these. Knowing the approximate coordinates permits the observer to set up a preliminary alignment of his sextant, thereby narrowing down the search of the sky hopefully within the field of view of his sextant. This search process is assisted by having the altitude and the azimuth of the sextant line-of-sight displayed to the observer as he sights through the eyepiece. The measured value of star altitude must be corrected for atmospheric refraction.

FUNCTION: Computation of Position Solution		
	Landmark	Celestial
Given Data	1. Coordinates of 2 landmarks 2. Separation of two reference landmarks 3. Measured angular separation of landmarks from vehicle location (See Fig. 3-2)	1. Greenwich hour angle (GHA) of Aries 2. Sidereal hour angle (SHA) of designated star 3. Declination of designated star 4. Star altitude reading and relevant corrections
Compute	1. Center of position circle (X_p, Y_p) 2. Radius of position circle (R_p)	1. Polar distance (b) 2. Observed altitude (a) 3. Colatitude (c) 4. Meridian angle See Figure 3-5
Equations	(See Page 3-5)	(See Page 3-9)
Techniques	1. Special slide rule 2. Nomograph 3. Pre-computed graphs prepared as map overlays	1. Table look-up (Figure 4-2) 2. Electro-mechanical analog computer 3. Digital computer 4. Graphical solutions (Weems System of Navigation) 5. Pre-computed graphs prepared as map overlays

FUNCTION: Correlation of Position Solutions	
Landmark	Celestial
The accurate extraction of the fix position from two or more position circles can be performed by numerical solution of the circle intersections by analog or digital computer, or by graphical solution directly on a topographic map of the area. Because of the errors implicit in the measurement, computation and correlation functions, the position of the vehicle will seldom be precisely at the intersection of two position circles. An understanding of the errors in each of the functions is necessary to determine the "most probable position" in relation to the position and arrangement of the various position circle intersections.	The techniques used for correlating the data from two or more star sightings into a position fix depend mostly on the nature of the position solution. Where manual computation and table look-ups methods are used for solving the spherical triangles (Figure 4-2), the most common technique is to plot on a map a small segment of the position circle (called a line of position) separated from the assumed position of the vehicle by a distance equal to the difference between the observed and computed altitude of the star (d) at an angle (Zn) equal to the computed star azimuth. A series of these plots will delineate an area of position, and procedures such as those described in Reference 7 assist in selecting the "most probable position" for the fix. These same procedures can be used when correlating the iterated solutions of the spherical triangles obtained from analog or digital computers. Where sufficient computational facilities exist, it is conceivable that an automated procedure for determination of the most probable position from a set of 3, 4, or 5 position solutions could be established.



* Only relevant when horizon is used as reference
** Only relevant when sighting through an atmosphere.

Figure 4-2 COMPUTATION OF CELESTIAL POSITION FIX BY TABLE LOOK-UP

4.2 TYPICAL CELESTIAL POSITION FIX BY TABLE LOOK-UP

Celestial observations have been the traditional tool of marine and air navigators to "fix" their position and heading. The accuracy of position determination required in this kind of navigation was of the order of a mile or more, and the techniques of measurement and computation developed for these purposes were tailored to this requirement. Recently, the requirements for navigating supersonic transport aircraft, long range submarines and spacecraft have spurred significant advances in sextant technology and in the data processing associated with celestial position fixing. Although the position fix precision requirements for lunar vehicle navigation are more stringent than those for marine navigation, the procedure used by marine navigators (Figure 4-2) provides a good baseline illustration of the technique of position fix determination from celestial references. Since most sextants provide a measure of both the elevation and the azimuth of the star during the same sighting operation, this normal procedure includes a check of the output of the heading reference equipment as well as of the geographic coordinates of the observer. Figure 4-2 illustrates one form of data flow in this process. It must be emphasized that the procedure shown is only one of many and that it is designed to suit a situation where:

- a full-time navigator is available

- the systematic errors relevant to the technique and to the normal environment have been computed and made available in convenient form.

- computational aids (tabular solutions with interpolation features) have been made available at reasonable cost.

- the correlation of position solutions is to be made by special plotting techniques on a map.

Within these qualifications, the following brief description of this procedure provides an indication of the manner of determining vehicle position by celestial observation. The procedure can be considered to be divided into the following activities as blocked out on Figure 4-2:

I - determination of Greenwich Mean Time

II - almanac data extraction

III - sight reduction table look-up

IV - instrument measurements

Not illustrated on Figure 4-2 is the activity of plotting on a suitable map the star azimuth, "Zn", and the altitude difference, "a", adjacent to the assumed latitude and longitude to yield a line of position solutions. Hence, it should be appreciated from the outset that the process depicted on Figure 4-2 must be repeated at least once (preferably 2 or 3 times) before the most probable position of the vehicle can be determined.

4.2.1 Determination of Greenwich Mean Time

Determination of time is shown as the first step in resolving position. Star coordinates are catalogued with reference to Greenwich mean time in the most popular nautical almanacs. Hence, it is necessary for the navigator to maintain a clock indicating the date and local time on the Greenwich meridian or to compute these from the time indicated on the clock he has available. As shown in the diagram, if the clock is indicating local time this has to be corrected for clock errors and time zone difference to obtain Greenwich mean time.

4.2.2 Extraction of Star Coordinates

The motion of the earth relative to the celestial sphere has been observed for years and is very precisely known. This data, for the stars most commonly used for navigation, is tabulated in nautical almanacs and air almanacs in a form suited to the general practices and required frequency of celestial observation. A single value of declination angle is normally given for each star in almanacs that are published annually. For stars in certain portions of the sky this value can change as much as 20 arc seconds per year. The other coordinate of star position which is listed in the almanacs is either sidereal hour angle or right ascension. Both angles relate the star to a position called the "first point of Aries" (or simply "Aries"). Aries is that point in the sky at which the sun crosses the equator as it moves northward on the celestial sphere. This point is not marked by a star but is considered to revolve about the earth at approximately the same rate as do the stars. Since the change of position of Aries relative to the stars is very slow, the sidereal hour angle (SHA) of the stars is constant for comparatively long periods of time. Because of this it is possible to describe the positions of all the stars by tabulating the Greenwich Hour Angle (GHA) of Aries at frequent intervals and the SHA of each star once for a comparatively long period. As stated above, nautical almanacs are normally published annually. Within the limits of the publications a navigator determines the GHA of the star he is observing by summing the SHA of the star and the GHA of Aries at the time of observation. Right ascension (RA) is the explement of SHA, being the angle from Aries eastward to the star, i.e., RA + SHA = 360°.

4.2.3 Sight Reduction Table Look-Up

Most navigational tables used by American navigators today are published by the Hydrographic Office, but a few are published by private sources. Perhaps the most widely used of all such tables are known simply as "HO214" entitled "Tables of Computed Altitude and Azimuth". There are 9 volumes, one for each 10° latitude. In these books the solutions of the navigational triangle are tabulated for celestial altitudes of 5° or greater. Answers are given to an accuracy of 0.1 minutes of altitude and 0.1 degree of azimuth.

Using such tables of solutions, it is possible to obtain a trial solution of the altitude angle associated with: (1) a stated meridian angle, 't', (derived from the GHA of the star and the estimated vehicle longitude); (2) star polar distance, 'b', (co-declination); and (3) the estimated co-latitude, 'c', of the vehicle. This trial solution, when compared with the measured altitude angle, yields a line of position in the vicinity of the estimated vehicle position. This line of position is plotted on an appropriate map as a short straight line at right angles to an azimuth (Zn) line through the estimated position and at a distance equivalent to the value of the altitude difference (d). If the measured altitude is less than the computed altitude this means that the vehicle is actually closer to the substellar point (GP) than was estimated. The line of position, in this case, would be marked on the map on the G.P. side of the estimated position.

The azimuth angle (Zn) value extracted from the sight reduction tables should be equivalent to the measured azimuth angle of the star.

This measured azimuth is determined by combining the sextant azimuth with the vehicle heading. Any difference between the table value and the measured value of azimuth is derived from sighting errors, time errors and/or errors in the heading reference system. If the sighting process is done carefully, the azimuth difference can logically be attributed to the heading system and the system output corrected to reduce the azimuth difference to zero.

A very common operational practice which improves the total procedure of celestial position fixing is the precomputation of the star azimuth and altitude associated with the location and time at which it is planned to make a star sighting. This precomputation can be tailored to suit the operational requirements and where a digital computer is available at the base facility, formats can be generated for the navigator on a particular mission which greatly improve the accuracy and ease of deriving a position fix from celestial observations. These precomputed values of azimuth and altitude also greatly improve the reliability of locating and identifying the designated star. With these values set on the sextant for initial sighting, the designated star should be within the field of view.

4.2.4 Star Observation

The procedure diagrammed in Figure 4-2 is specifically limited to the sighting of stars. The moon or the planets can also be sighted and reduced using almanacs and sight reduction tables in a slightly different procedure. Several additional corrections need to be applied to derive the observed altitude of the moon or the planets. The major corrections applicable to star sightings compensate for the refraction effects of the atmosphere. This is one source of error which will not be of concern to the lunar navigator. On earth it is one of the primary limits to precision position fixing by astro-sightings. Refraction corrections to apparent altitude are included in most nautical almanacs tabulated under values for apparent altitude and for temperature and pressure deviations from standard conditions. The refraction correction ranges from 0 to approximately 5 arc minutes for altitudes from 90° to 10°; and from 5 to 35 arc minutes for altitudes from 10° to 0°. The temperature/pressure correction is within $\pm$ 7 arc minutes over the range of normal surface ambient conditions. Not accounted for are the effects of atmospheric turbulence and layering which can be very severe in warm, desert areas.

Unfortunately only gross approximations of the proper atmospheric corrections can be estimated and applied to the instrument reading. The residual combination of these errors resulting from atmospheric uncertainties have a controlling effect on the ultimate precision of the resulting position fix since they will be at least as great as the instrument errors in a high quality sextant.

SECTION 5

MGL POSITION FIX REQUIREMENTS

The performance required of the position and heading fix system for the Mobile Geological Laboratory is determined from analysis of

- the objectives of the simulation program
- the design reports of the MOLAB navigation system prepared by the Bendix Corporation(1) and the Boeing Company(2)
- the practical considerations of earth-based operation of a lunar system

Position fixing by optical sightings is a very old and highly developed art. As indicated in the previous section, the activities performed by the navigator to fix his position in the traditional settings have been streamlined by cheap, yet effective, reference and computing aids. This vast store of practical experience is a most valuable input to the design of a system suitable for use by an astronaut on the lunar surface to fix his position. But the novelty to the environment, the mission and the vehicle associated with this particular navigation problem give rise to a very unique set of requirements. These requirements will be outlined and briefly discussed in this section.

5.1 SIMULATION APPROACH(3)

The primary purpose in procuring and testing the MGL navigation system is to advance the state-of-knowledge with respect to lunar vehicle navigation systems. From data obtained in simulation tests, the navigation techniques, the implementation design factors, the man-system interfaces, and the general operating procedure which have been defined in MOLAB design studies can be modified or confirmed. The worth of the initial simulation tests is not dependent on the use of a simulation system which is identical to that system designed in a MOLAB study. Useful information can be obtained from testing a simulation system selected in the following manner:

* Assume the simulation navigation techniques are identical to those identified in MOLAB study reports by the Bendix Corporation and the Boeing Company.

* Implement the simulation system with the same types of equipment as identified in the MOLAB reports

* Restrict the gross operating parameters of the simulation system to be on a 1 to 1 scale with the lunar study systems. That is, the position error and distance traveled of the simulation mission should be of the same order of magnitude as the lunar mission so that the navigation function can be performed in a "real lunar world." Line-of-sight is the only gross distance parameter not transformed 1 to 1

* Distribute the allowed simulation system error (defined by the previous statement) among the contributing components, i.e., time uncertainty, ephemeris uncertainty, gravity anomaly uncertainty, sensor measurements errors, etc. This distribution is restricted by: (1) the state-of-knowledge with respect to the physical uncertainties, (2) operator capabilities, and (3) equipment availability and cost.

Modifications of the initial simulation system implementation to evaluate various procedures within the basic position fix and dead-reckoning techniques will be made as the simulation tests proceed. These modifications will be based on the results from the simulation tests, the differences between the MOLAB navigation systems and the simulation navigation system, and the results of further analyses of the MOLAB design.

5.2 OPERATIONAL AND ENVIRONMENTAL REQUIREMENTS

The overriding operational requirements governing the design of the position fix system for the simulation of lunar vehicle navigation is that it provide a realistic simulation of lunar conditions in an earth environment. Unfortunately, in several important aspects, this requirement cannot be met. For example, the parallax and image distortion caused by the earth's atmosphere will always give a false impression of the capability of optical sighting of celestial objects as performed on the surface of the moon. Similarly, the relatively rapid movement of the star field for an earth-based observer imposes an unreal pace of operations for equivalent accuracy and makes it most difficult to retain realism in this important phase of the simulation. But within these limitations the firm requirement remains that of providing a realistic simulation of lunar surface position fixing by celestial and landmark sightings. This need not imply that the system is required to provide the best position fix for an observer in the Mobile Geological Laboratory without support from external systems which can be expected to be available to the lunar explorer.

The system equipment must be compatible with the capabilities and limitations of the man/suit combination, particularly with respect to dexterity, time response and handling limitations.

A single member of the crew must be able to perform all essential functions associated with the operation of the position fix system and be able to extract the position coordinates from the measured data.

Operational constraints and environmental constraints as noted in reference 3 are as follows:

Operational constraints

- Maximum radial range of operation (not less than 80 km)
- Maximum total traverse range (not less than 400 km)
- Both day and night operations are required
- Mission duration of at least 14 days
- System operable by one man while driving vehicle
- Operation by a space-suited astronaut

Environmental Constraints

- Flagstaff, Arizona area
- Seasonal temperature variations
- Earth spin rate
- Earth gravity

- Availability of celestial references (star positions and cloud cover)
- Availability of terrain feature references (feature position and illumination)
- MGL velocity, acceleration and structural characteristics
- Rain, snow, wind and sand
- Soil conditions

5.3 SYSTEM REQUIREMENTS

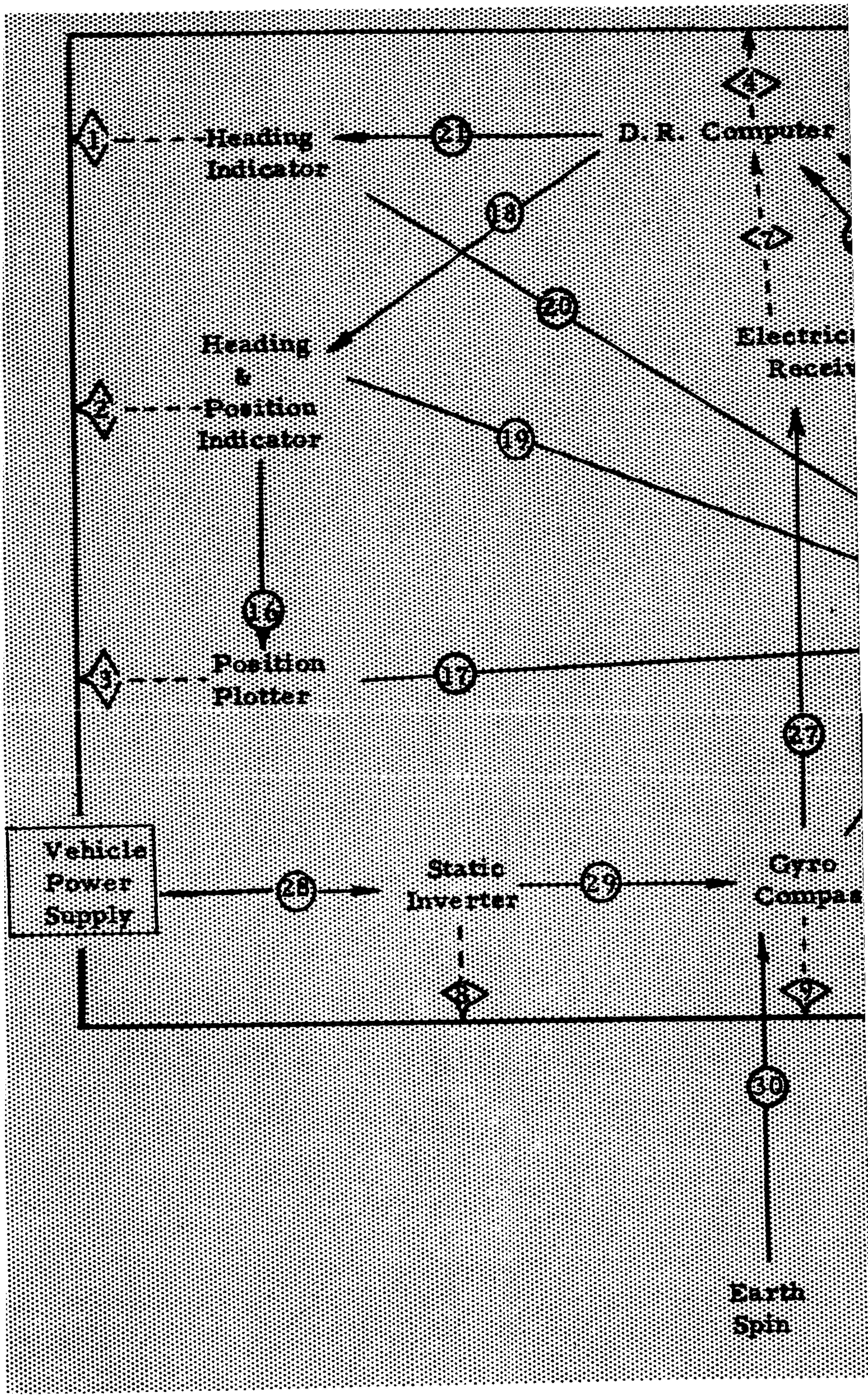
The position fix system must impose a minimum of constraints on the design and/or operation of other systems and functions of the Mobile Geological Laboratory. The MGL navigation system must be compatible with the Flagstaff field test operation. This includes the MGL vehicle, the MGL systems, and the Command Data Reception Analysis (CDRA) center which is located within the offices of the USGS Branch of Astrogeology.

The interfaces of the position fix system and its surrounding elements were detailed in Reference 3. The interface diagram of that report is shown in figure 5-1. Explanatory notes on these position fix system interfaces (as numbered in figure 5-1) are given below:

a. Installation Interfaces (11-15)

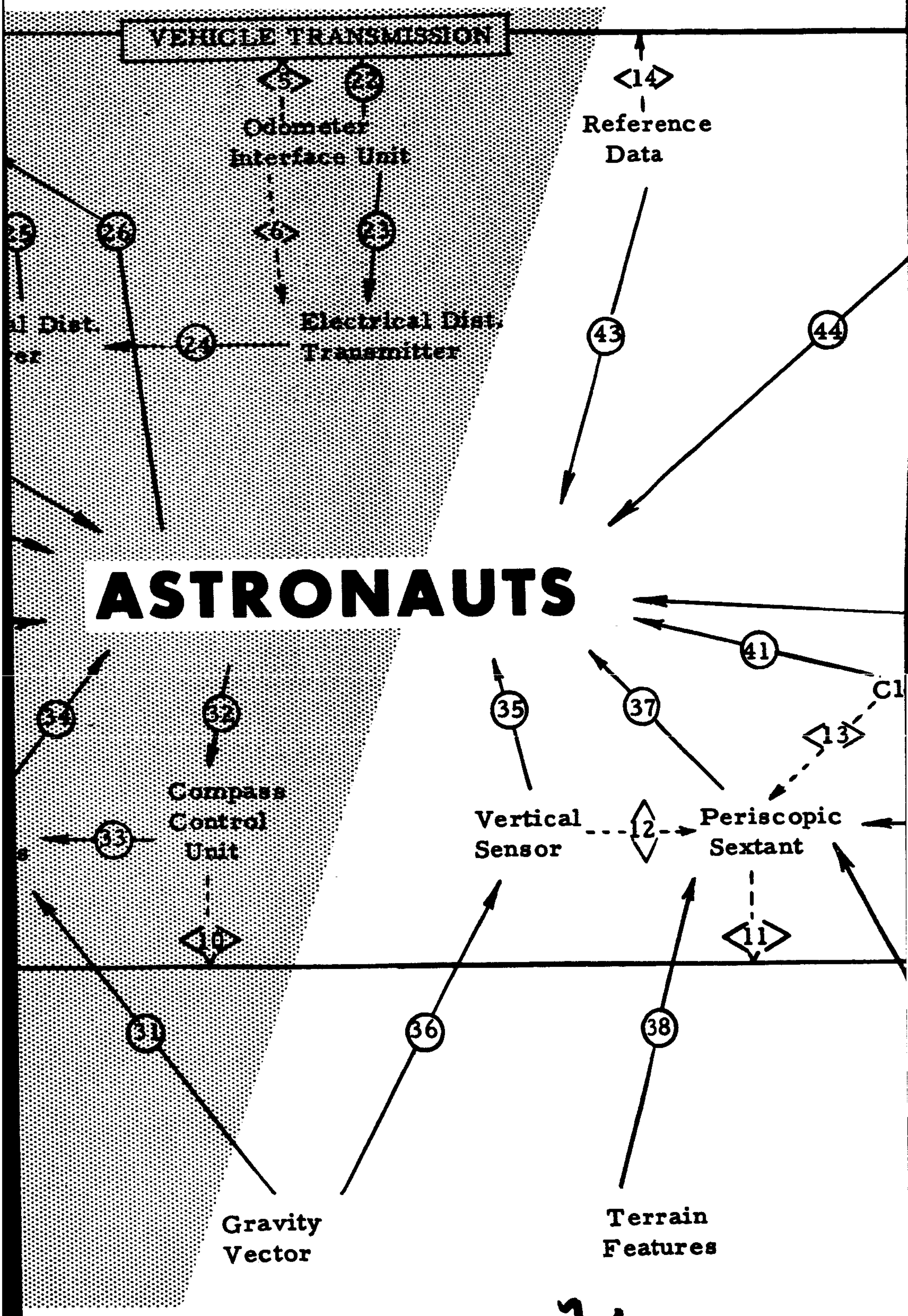
11. Periscopic Sextant

The periscopic sextant is mounted in the roof of the MGL as shown in Figure 5-2. A sufficient portion of the periscope is to be removable from a mount, which is fixed to the vehicle, to reduce the interior obstruction to 5 inches below the roof. A suitable storage facility is to be provided for this removable portion when it is not in use. The general height of the sextant eyepiece above the floor is to be as shown in figure 5-2. It is important that a weather-tight seal be provided on the sextant mount suitable for preventing rain or dust from penetrating the vehicle when the sextant is either in position or removed. Sufficient

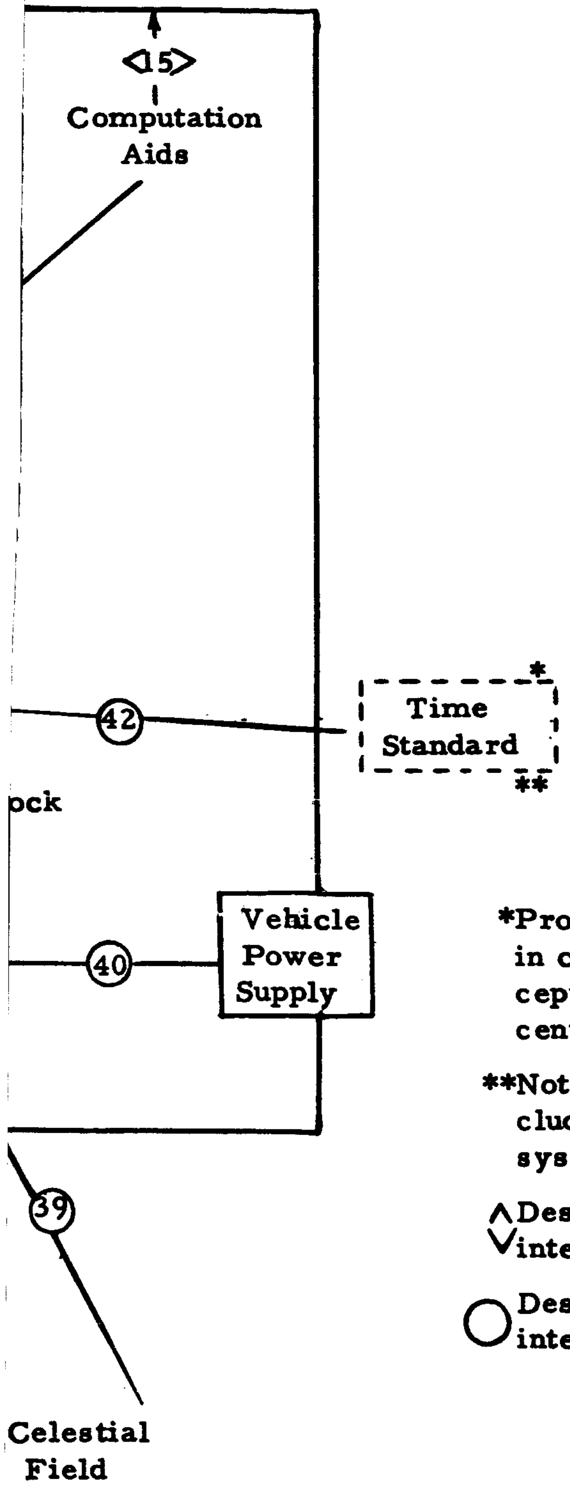


1
Heading Indicator
21
D. R. Computer
4
18
7
20
Heading & Position Indicator
2
19
16
3
Position Plotter
17
27
Vehicle Power Supply
28
Static Inverter
29
Gyro
8
9
30
Earth Spin

Figu



re 5-1 Mobile Geological Laboratory Navigation System Interface



*Proposed for installation in command data reception and analysis center.

**Not proposed to be included in preliminary system.

◇ Designates installation interface.

○ Designates functional interface

3

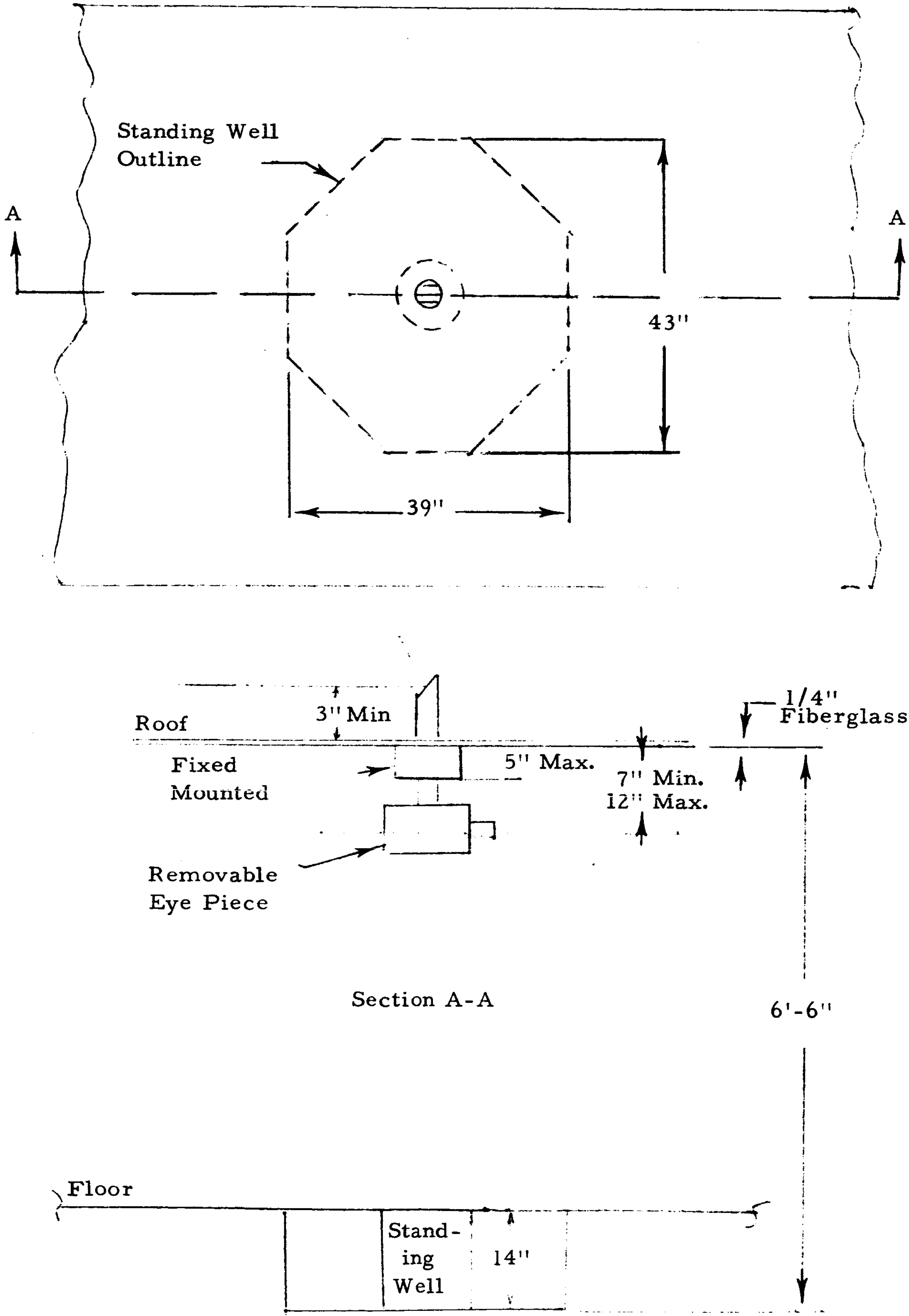


Figure 5-2 MGL Sextant Mounting

clearance is required around the sextant to permit the observer, while he is viewing, to level the instrument to correct for any vehicle attitude up to 15° from horizontal.

12. Vertical Sensor

This item is to be mounted directly on to the sextant periscope.

13. Clock

The clock is to be mounted directly on to the sextant periscope in such a position as to be readily observable with little, or no, eye movement or refocusing while the sextant is being aligned with a reference star at any relative bearing to the vehicle axis.

14. Reference Data

Suitable storage facilities are to be provided for the reference tables and charts of astronomical and terrain data necessary for the identification and location of the navigation reference to be observed and necessary for deriving input data for position determination.

15. Computation Aids

Additional storage facilities are to be provided for the reduction tables, graphs and/or calculators necessary to facilitate the solution of two or more navigation triangles to provide the fix position.

b. Functional Interfaces (35-44)

35. Astronaut: Vertical Sensor

By observing the indicated position of the vertical sensor, as it senses and displays the local vertical vector, the astronaut can properly level the sextant.

36. Gravity Vector: Vertical Sensor

The gravity force actuates the vertical sensor.

37. Astronaut: Periscopic Sextant

The astronaut levels the sextant to properly align its axis with the gravity vector, and adjusts the azimuth and altitude of the line of sight to coincide with the navigation reference.

38. Sextant: Terrain Features

The sextant has the proper magnification and field of view such that the terrain references can be recognized and measured.

39. Sextant: Celestial Field

The sextant has the proper magnification and field of view such that the celestial references can be recognized and measured.

40. Vehicle Power Supply: Periscopic Sextant

Although it has not been established at this time, it is possible that some DC power may be required for the sextant scale illumination or operation of the electrical angle readouts.

41. Clock: Astronaut

The clock displays time to the astronaut continuously.

42. Time Standard: Astronaut

Periodically the clock is to be checked and alter ed, if necessary, to agree with the representation of time presented by a time standard such as a master clock or the transmissions from radio stations such as WWVB. An audible display of time to the astronaut would permit him to more readily time his star sightings without disturbing his visual concentration through the sextant. The WWVB time signals can be made available to the vehicle in the field through the normal communications channel to the base.

43. Reference Data: Astronaut

The basic navigation reference data required by the astronaut are: (a) values of declination, sidereal hour angle and parallax for a variety of suitable stars for use in celestial position fixing, and (b) values of position coordinates for a variety of terrain features for use in landmark position fixing. The form in which this data is best presented to the observer could range from standard reference books and maps presently available, to special charts, nomographs, tables or maps which are designed to:

- Reduce the storage volume
- Reduce the lookup time by improved data retrieval techniques
- Incorporate some pre-computation relevant to navigating in a known (localized) geographic area

The basic reference data will not be altered in any of these presentations, but the specialized nature of navigation for the MOLAB lunar mission and the MGL simulation mission will be best served by an optimally designed reference data storage and method of data retrieval and presentation to the astronaut/navigator.

44. Computation Aids: Astronaut

Because the art of navigation has been practiced for so many years by so many people under so many different circumstances, a wide variety of field-evaluated computational aids are available to the navigator. For example, several compact calculators have been marketed which yield approxmate coordinates of various stars for use in the selection of reference stars observable at a stated time and location. These devices also prove valuable in the initial identification and location of the stars to be observed.

Extraction of the position solution from a navigation triangle formed by a particular set of celestial/time observations can be performed with pencil, paper and a table of trigonometric (sin/cos) functions. Navigators have attempted to streamline this task to reduce both the time involved and the probability of human error. The table look-up method is one of the most popular methods. This method depends on a book published by the U.S. Hydrographic Office entitled H.O. Pub No. 214, "Tables of Computed Altitude and Azimuth". A similar document intended primarily for use in aircraft navigation is H.O. 249. Neither of these documents will yield the accuracy of solution desired for the MGL navigation system, but they make it possible to evaluate the relevance of table look-up techniques (using specially-generated tables for Flagstaff, Arizona) to the operational constraints of a MOLAB simulation.

Another computation aid which demonstrates an alternative approach more relevant to the MGL navigation problem is the Weems System of Navigation. This system is dependent on a set of books entitled "Star Altitude Curves". Each volume in the set presents a series of graphs of the latitude and local sidereal time of an observer associated with a particular altitude reading on a particular star. Computing the position fix with this document requires noting the point of intersection on the graph of two star altitudes and extracting the latitude and local sidereal time of the observer. The difference between the graph value and the navigation system clock value is the observer's longitude. Again, the available publications provide inadequate accuracy for MGL requirements; however an adaption of this technique using graphs generated on a computer-controlled X-Y plotter for the operating latitudes and longitudes of the MGL has many obvious advantages as a computation aid in the simulation of lunar navigation.

5.4 DATA HANDLING REQUIREMENTS

This position fix system must be designed to minimize the time required to derive, from the observations and reference data, the position of the operator to the required precision. Since the system will generally be operated within 200 kilometers of Flagstaff, Arizona, the amount of reference data to be compiled is highly constrained. For any one mission which is limited to a radius of 80 km, the amount of data to be searched and the range of possible position solutions is still further constrained. This constraint makes a major contribution to the speed of data flow through the system.

The system of units used throughout the presentation of reference data, instrument scales and computation aids must be consistent, must be understandable, without excessive training and must be chosen to reduce the possibility of operator error through blunders in data conversion or manipulation.

The output data must be in a form and format consistent with the requirements to (a) immediately advise the navigator of the position solution, and (b) at the operator's choice, up-date the position computed and/or displayed by the dead reckoning system. The implementation of this requirement is dependent on the design of the dead reckoning (D. R.) system and the manner in which it can be up-dated. It is apparent that this interface between the two systems demands serious design considerations to ensure that the inherent precision of the position fix system is fully exploited by the D. R. system to: (1) update its display of computed position and (2) to make suitable corrections to those functions contributing systematic errors.

5.5. EQUIPMENT DESIGN REQUIREMENTS

The equipment associated with this system must be compatible with the requirements to transport and operate the system while mounted in the U. S. G. S. Mobile Geological Laboratory in the vicinity of Flagstaff, Arizona. The mounting and installation of the equipments should not require major structural modifications to the MGL or major additions to the power generation facilities on-board the vehicle.

Since the prime purpose of the vehicle and its systems is to provide a simulation facility, it is to be expected that changes and additions will take place in the equipment. The initial design of the navigation equipment must, therefore, anticipate some of the long range requirements which will enter the simulation for evaluation and permit design modifications to suit these requirements.

The equipment design must reflect the highest reliability possible. Backup and alternate modes of operation must be included in the design. Existing state-of-the-art techniques must be used rather than using unproven, new components and techniques.

The position fix system must permit the operator to perform the functions described in Section 4. 1 and illustrated on Figure 4-1.

5.6 ACCURACY REQUIREMENTS

Position fix system and component accuracy requirements were derived in reference 3. This section contains an accuracy requirements summary.

The order-of-magnitude of the required accuracy of the position and heading fix of the MGL navigation system was established through consideration of three criteria:

1. The MGL mission parameter of distance (distance traveled, position error, terrain feature size, etc.) should be equal to the MOLAB mission parameter of distance

2. The performance of the MGL system units should be similar to the performance of the MOLAB system units

3. The MGL simulation system should be composed of "off-the-shelf" units.

In Table 5-1 the magnitude of the primary errors in the MOLAB position and heading fix systems are noted. These errors are related to the types of units identified for the MOLAB navigation systems and for navigation units investigated in a general study of the lunar navigation problem by Bendix. In general, the data from the three referenced studies is in agreement. The computed error in MOLAB position and heading which results from the tabulated error components as documented in the MOLAB reports is shown on the table. The system errors are based on a 2-star fix: the error fix can be reduced through repeated sightings, but a system comparison point of a 2-star fix was selected.

Table 5-1 also contains the MGL error limits as defined by the criteria statements 1 and 2 with relation to the MOLAB systems' errors. The source of the data on the table is referenced.

The precision of the time measurement was reduced for the MGL implementation from that of the MOLAB designs. The timing error quoted by the MOLAB studies was limited by other vehicle functions which required an extremely accurate time definition. For purposes of navigation on the moon, the knowledge of time is not as critical as indicated by Table 5-1. A value of MGL clock error on the order of 0.5 to 1.0 sec yields an earth position error comparable to the position

TABLE 5-1

POSITION AND HEADING FIX SYSTEM PRIMARY ERRORS

Note: The data presented in this table was reported on the following reference pages:
Ref #1: 3-101
Ref #2: 4-34, 6-4
Ref #4: 5-4, 5-6, 6-56
Ref #8: 2-36

	Error (1 σ)				
	Bendix Corp. Navigation Study [4]		Bendix Corp. [1] MOLAB	Boeing Company [2,8] MOLAB	
Parameter	State-of-the-Art	Nominal Value	MOLAB Report	MOLAB Report	MGL Simulation
Sensors					
Sextant Altitude Angles	1 to 40 sec of arc	12 sec of arc	6 sec of arc	30 sec of arc	3.7 to 18 sec of arc
Sextant Azimuth Angles	1 to 40 sec of arc	12 sec of arc	6 sec of arc	60 sec of arc	33 sec of arc
Static Vertical Sensor	3 to 53 sec of arc	12 sec of arc	5 sec of arc	0.0 sec of arc	5 sec of arc
Clock	0.03 to 3.3 sec of time	0.03 sec of time	0.0 sec of time	0.0 sec of time	0.5 to 1.0 sec of time
Calculation	Manual: 6 sec alt; 360 sec azimuth Automatic: 1 to 40 sec of arc	None	0.0 sec of arc	9 sec of arc	Manual: 6 sec in alt; 360 sec in azimuth; Plotting 1.2 sec [11] Automatic: 0 sec of arc
Physical Uncertainties					
Ephemeris Data	1 to 40 sec of arc	13 sec of arc	18 sec of arc	39 sec of arc	1 sec of arc [11,12,13]
Gravity Anomalies	20 to 200 sec of arc	None	60 sec of arc	30 sec of arc	10 sec of arc [13]
Sighting Tables	Not Applicable	Not Applicable	Not Applicable	30 sec of arc	1 sec of arc
Man					
Celestial Angles	0.0 sec of arc	0.0 sec of arc	0.0 sec of arc	0.0 sec of arc	4.25 sec of arc [9,10]
Vertical Angles	0.0 sec of arc	0.0 sec of arc	0.0 sec of arc	0.0 sec of arc	4.25 sec of arc [11]
Time	0.0 sec of arc	0.0 sec of arc	0.1 sec of arc	0.0 sec of time	0.1 sec of time
Computed Position Error	—	—	0.80 km	0.49 km	0.68 to 1.20 km
Computed Heading Error	—	—	112.6 sec of arc	120 sec of arc	39 to 364 sec of arc

error component dependent on the celestial angle measurement. Further discussion of the time-dependent position error is contained in Appendix D.

The validity of these accuracy requirements, derived in reference 3, must be further investigated with regard to the third criteria statement, that the MGL simulation system must be composed of "off-the-shelf" units. At the time of the interim report, which contained the derivation of the above stated accuracy figures, it had been indicated by optical manufacturers that a sextant of such accuracy and composed of off-the-shelf components could be supplied. The proposed sextants, in response to a Request for Proposal which was based on the above accuracy figures, are summarized in section 6. 1. 1 From the sextant data presented in section 6. 1. 1, it is obvious that the effect of the requirement for off-the-shelf implementation is to increase the error components stated on Table 5-1 and the error flow diagram of figure 5-3.

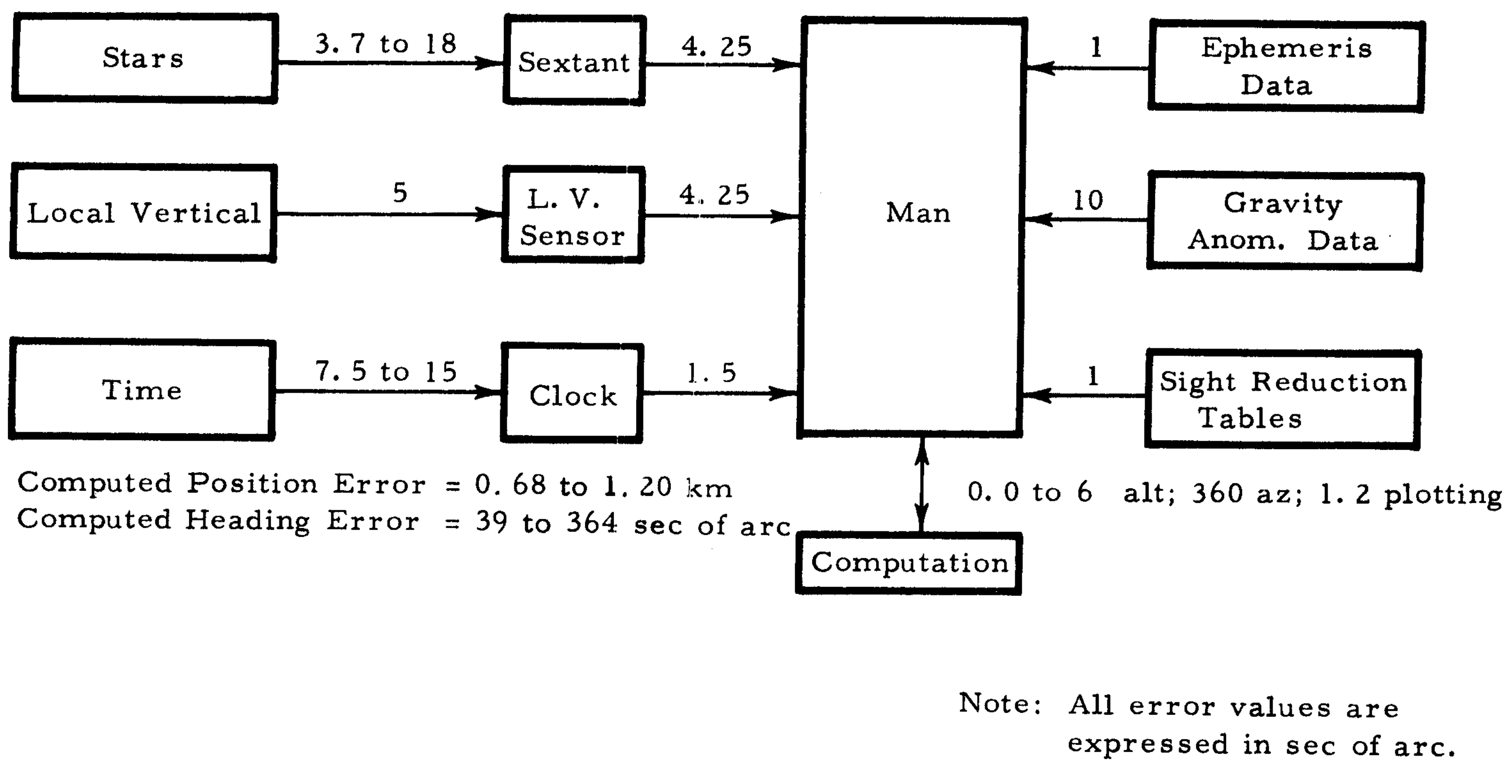


Figure 5-3 MGL Position and Heading Fix System Functional Error Flow Diagram

SECTION 6

MGL POSITION FIX SYSTEM ALTERNATIVES

A survey of existing equipments was conducted to establish the availability of suitable system components with which to implement the position fixing function in accordance with the determined functional and performance requirements. In the following sections the results of this survey are reported under the following headings:

- Optical Measurements
- Time Measurements
- Reference Data
- Computation Aids

These sections include not only the hardware and software available but also the operational variations relevant to each item.

6.1 OPTICAL MEASUREMENTS

The alternative methods of making the optical measurements associated with position fixing become evident not only in the optical characteristics of the sextant instruments but also in the arrangement of the readouts and the controls. Seven instrument suppliers were contacted for preliminary design suggestions regarding a suitable periscopic sextant. The replies received on this survey are summarized below, together with the alternative methods of implementing the transfer of the sextant measurements to the rest of the position fix system. Some operational alternatives associated with the optical measurements are also included.

6.1.1 Instrumentation

Periscopic sextant design data was obtained from seven manufacturers of precision optical instruments by preparing a sextant specification and submitting a request for proposal (RFP) to potential suppliers. The sextant specification was derived from the available data with regard to the MGL vehicle characteristics and the preliminary sextant requirements reported in BSR-1243(3). The RFP Statement of Work and the Sextant Specification are presented in Appendix A.

The recipients of the sextant RFP were: (1) Farrand Optical Company, (2) Itek Corporation, (3) Keuffel & Esser Company, (4) Kollmorgen Corporation, (5) Kollsman Instrument Corporation, (6) Perkin-Elmer Corporation, and (7) R. A. Morgan Company. Responses were received from four of these organizations.

In addition to the sextant designs provided through replies to the RFP, the basic aircraft sextant produced by the Kollsman Instrument Corporation was included in the implementation matrix as a potential MGL sextant. The following sections summarize the data contained in the four submitted proposals and the standard Kollsman aircraft sextant.

6.1.1.1 Itek Corporation Proposed Sextant(14)

The Itek Corporation proposed sextant is composed of available components and employs established observational techniques. The sextant basic units are a theodolite type instrument and precise levels.

The sextant is gimbal mounted to the vehicle roof. Sealing is accomplished at the roof by "O" rings and external to the vehicle is a rotatable dome. The eyepiece of the sextant is removable for storage while not in use: alignment of the eyepiece at time of replacement is accomplished by a ball and groove configuration.

Five optical paths are used for presenting to the observer the sextant measured quantities. These optical paths as shown on the instrument diagrams of Figures 6-1 and 6-2 are: (1) the celestial field, (2) the instantaneous azimuth on the azimuth circle, (3) the instantaneous altitude on the altitude circle, (4) a vertical indicator within the observation eyepiece, and (5) a second vertical indicator.

The light from the observed star enters the sextant through a flat glass of the external dome and is relayed to the observer eyepiece by a system of mirrors and lenses. A large eyepiece of 2-1/2 inches accommodates an observer wearing a space helmet. A 15 degree real field and 45 degree apparent field is provided. It is possible to make observations over the range of altitude angles from 7.5 to 60 degrees, free from vignetting: vignetting occurs beyond these angles but is limited

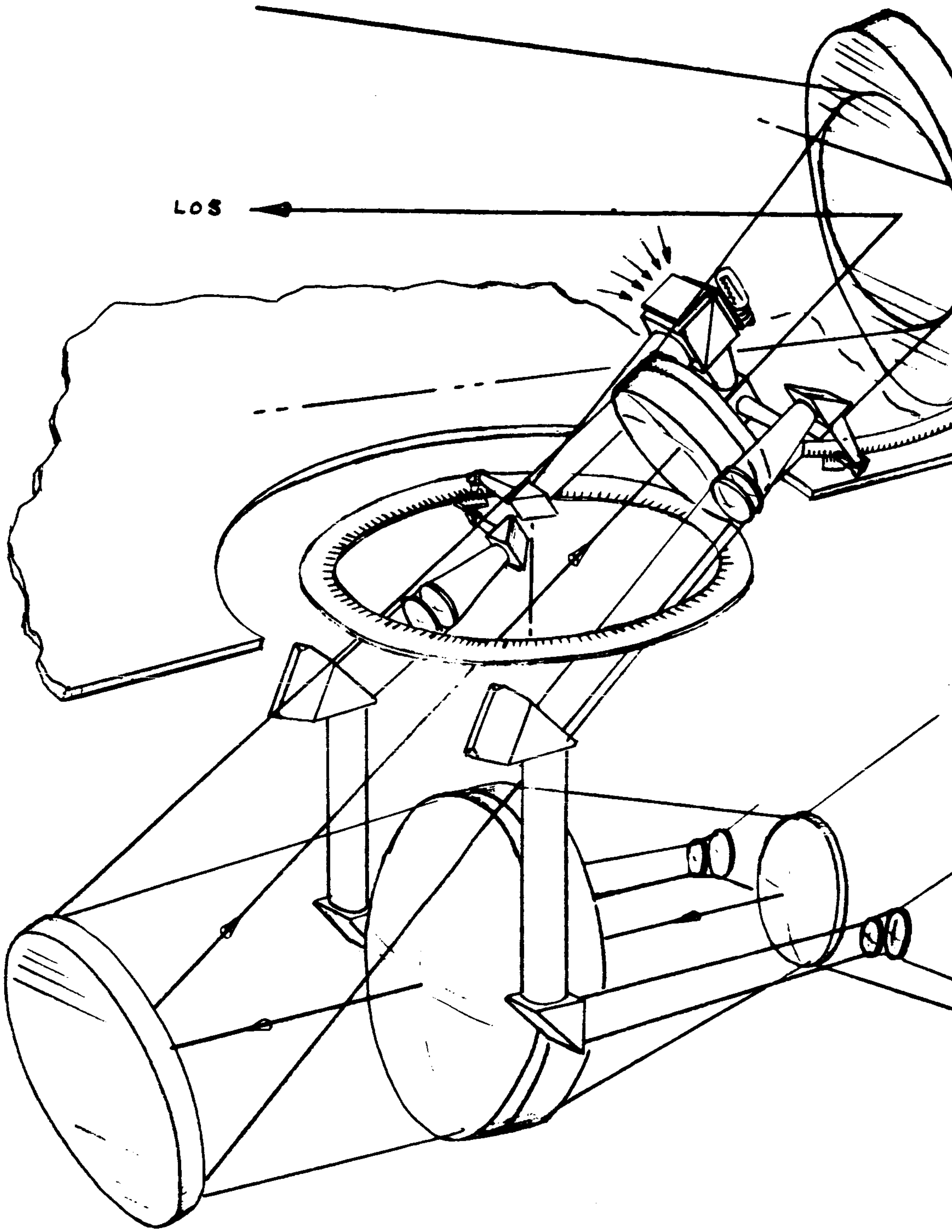


Figure 6-1 Itek, Preliminary Design Layout

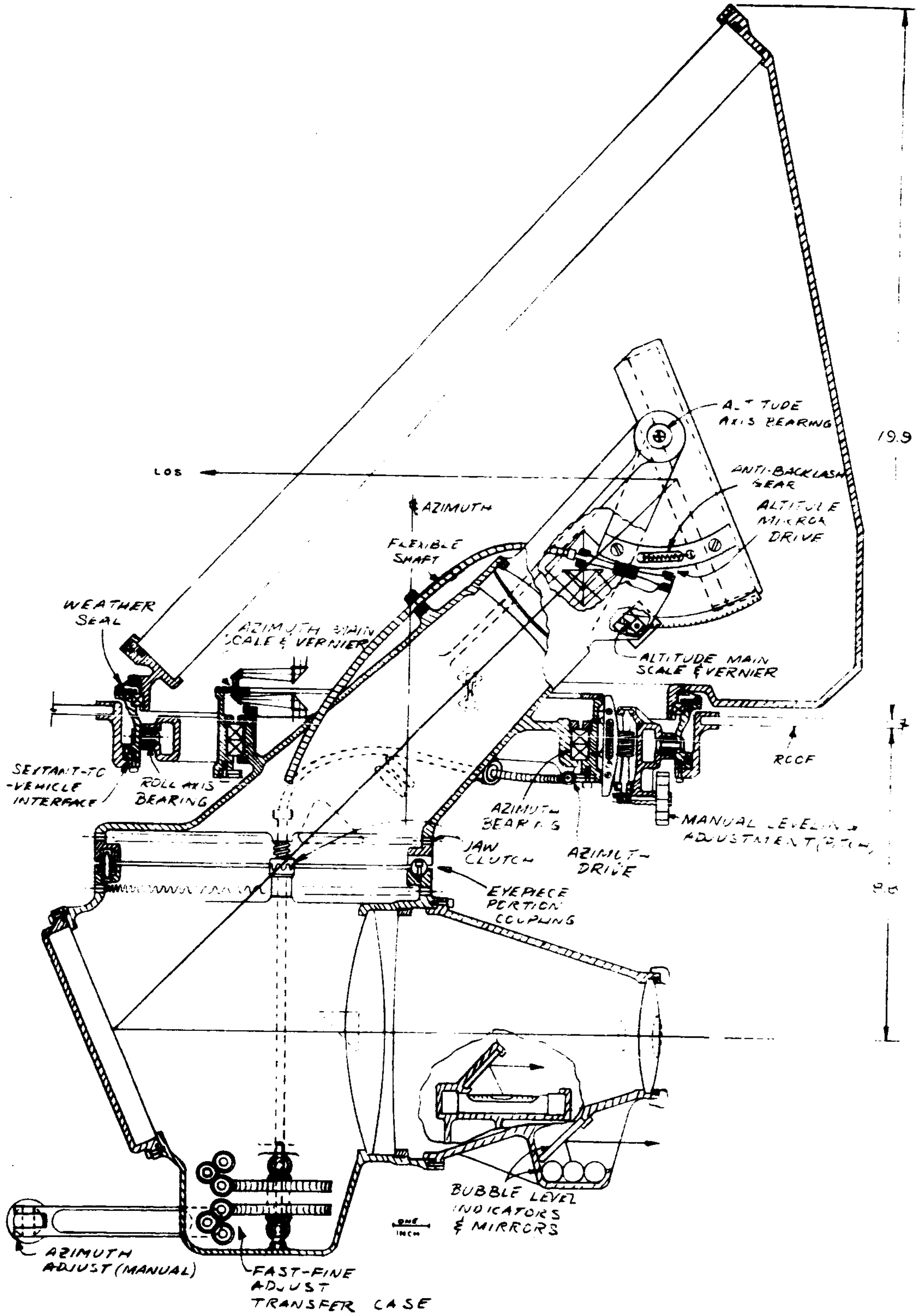


Figure 6-2 Itek, Preliminary Optical Layout

to less than 50 percent at altitude angles of -15 to +80 degrees. The 3x magnification at the normal field of view permits centering of the star image on the reticle to the order of 2 arc seconds. Particular elements within this celestial observation optical path assure that the observed image is erect and correct as to left or right.

Two auxiliary microscopes and prism relay systems provide the observer a view of the altitude and azimuth reading circles. Itek advises that these angle indicators be presented adjacent to, rather than superimposed with, the celestial field due to light transmission and field obstruction properties.

The sextant leveling bubbles are viewed by means of tilted mirrors. Itek recommends viewing the levels directly rather than through the telescopic eyepiece; however, their proposed design indicates that the sextant pitch is observed in the main eyepiece and that the sextant roll is observed external to the eyepiece.

The mirror-theodolite sextant system is mounted in the center of a gimballed mount. The altitude and azimuth movements of the theodolite portion of the system are manually driven by crank handles (both coarse and fine adjust is provided). The pitch and roll gimbal drives are actuated by thumbwheels. Precision worm gear combinations are used in accomplishing the instrument position adjustments.

6.1.1.2 Keuffel & Esser Proposed Sextant[15]

The MGL periscopic sextant proposed by the Keuffel and Esser Company employs many standard techniques as used in precision theodolites but must be considered primarily as a new design instrument.

The entire sextant is mounted as a single unit to the vehicle roof: the eyepiece portion is removable for storage. A bellows type dust cover, a dust seal, and a protective case protect the sextant from dust and rain.

Three optical paths, as shown in the diagrams of Figure 6-3, are noted in the sextant. These are for observation of the celestial body, for observation of the horizontal and vertical glass circles (for reading star altitude and azimuth) and for observation of the instrument vertical sensor. Two of these, the celestial body and the vertical reference along

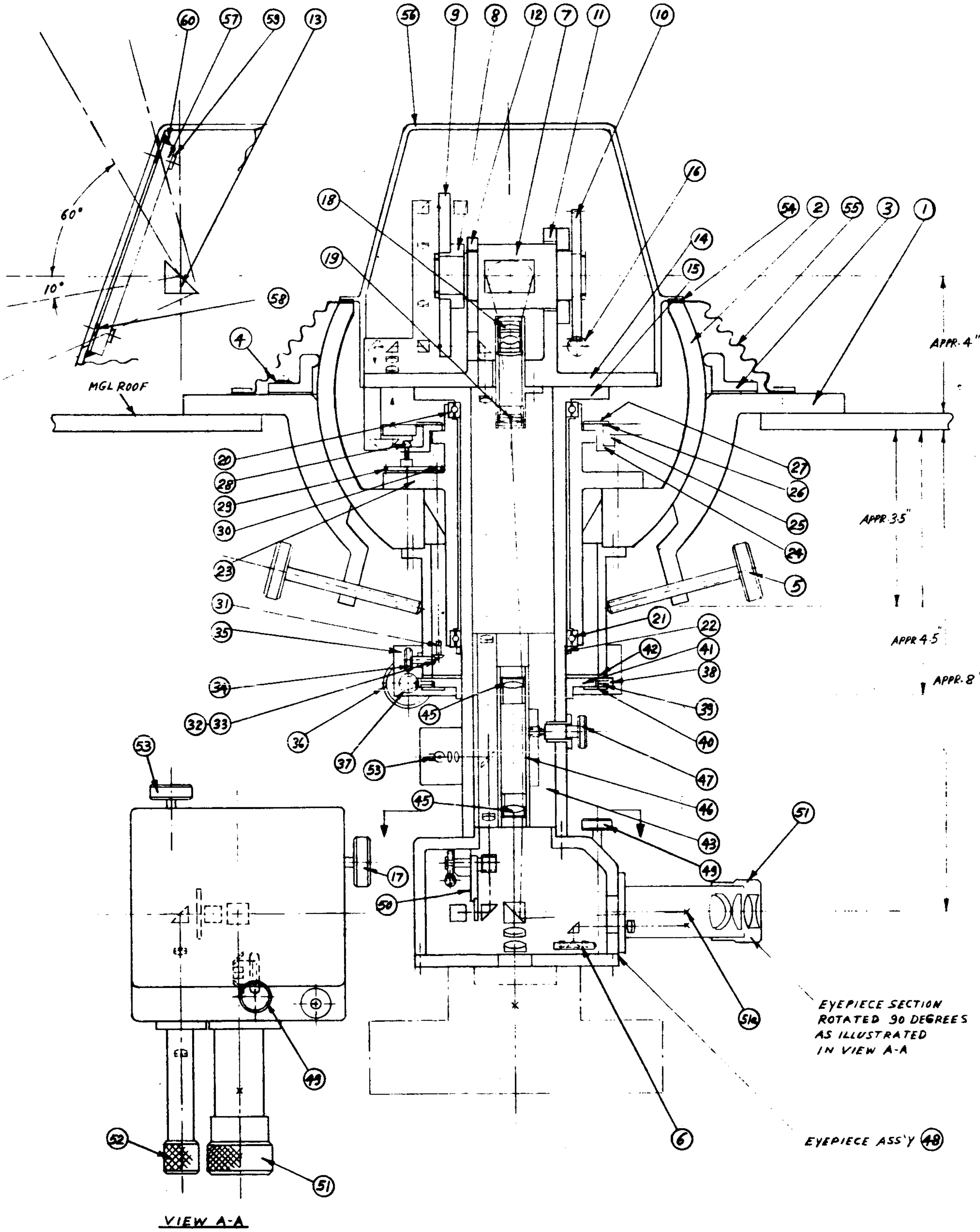


Figure 6-3 Keuffel & Esser, Navigation Periscopic Sextant

with the sextant reticle, are viewed in a single eyepiece; the altitude and azimuth references are presented in a second eyepiece.

The celestial observation optical path is comprised of prisms, lenses, and glass plates. Care is taken in the design to eliminate astigmatism and acromatic effects. A beam splitter is provided at the base of this optical path such that a camera can be attached to the bottom of the sextant unit for simultaneous operator observation and camera photography.

The camera objective covers a 15 degree field of view; the eyepiece covers a 72 degree field. This defines the telescope magnification of 4.8 power (72/15 = 4.8). An optical power selector knob produces a translation of optical components to yield a 6 power magnification with a 12 degree field of view.

A sextant pointing accuracy of 2.5 sec of arc is expected: observer sighting repetition of within 4 sec of arc is expected.

The flat glass window limits the range of the altitude observation angle from -10 to +60 degrees. Continuous rotation about the azimuth axis permits measurement through 360 degrees. Two level units enable the operator to level the sextant for vehicle angles up to 15 degrees from the horizontal. A coarse level, external to the eyepiece, is accurate to approximately 40 sec of arc; the fine level, within the eyepiece, has an accuracy of 5 arc minutes per 2 mm movement.

The optical path from the altitude circles contains lenses, beam splitters, and prisms. Particular care is taken to assure optimum light transmission. Sources contributing to the total error in altitude reading are:

. Pointing accuracy of the telescope	4 sec
. Maximum accuracy obtainable with leveling unit	2 sec
. Circle accuracy (parallax and bearings)	3 sec
. Zero calibration capability	2 sec
Total	11 sec

Eccentricity which would contribute about 6 sec of arc is eliminated by taking 2 readings which are 180 degrees apart. The two circle readings form double lines which are oriented with a fixed index line.

The performance parameters of the sextant are:

Field of View	15 to 12 degrees (a function of magnification)
Magnification	4.8 x to 6 x
Altitude Range (Center of Field)	-10 to +60 degrees
Azimuth Range	360 degrees
Altitude Accuracy	11 sec of arc
Azimuth Accuracy	30 sec of arc

The azimuth circle, as well as the altitude circle, are read on a second sextant eyepiece. Because of the less restrictive accuracy in the azimuth measurement, the effect of circle eccentricity is not compensated. A single circle scale line is oriented with respect to a double line fixed index. The observed circles are separated by proper masking which identify the individual light paths.

Keuffel and Esser recommend that a zero calibration capability be included in the instrument design. Two vertical gravity mirror assemblies placed 180 degrees apart on top of the MGL would be used in this calibration.

A manual control knob and altitude worm gear drive the altitude prism located in the periscopic head. The azimuth drive is accomplished by manually rotating the sextant in its mount and by a control knob which drives the sextant via gears, shaft, and bevel gears.

6.1.1.3 Kollmorgen Proposed Design[16]

The Kollmorgen proposed sextant employs some of the techniques which are standard in Kollmorgen submarine periscopic sextants.

The instrument is mounted to the MGL by means of a gimballing system which allows 15 degrees of altitude variation in any direction.

The periscope is hermetically sealed and internally pressurized with an inert gas at a dew-point sufficiently low to prevent condensation of moisture on the optical surfaces.

The periscope head window forms a part of the sealed system. The periscope consists of a rotating inner section and a stationary outer section. The eyepiece housing which contains the telescope eyepiece and the altitude and azimuth readout eyepieces can be removed for storage (see Figure 6-4).

Four optical paths are used in performing the celestial measurements: (1) to observe the celestial field, (2) to observe the vertical indicator, (3) to readout the azimuth angle, and (4) to readout the altitude angle. These are shown in Figure 6-5.

The optical path for observing the celestial field is composed of prisms and lenses. A high power lens system is rotated in and out of this path for instrument magnification variation. The indication of verticality is reflected into the same optical path such that the star and vertical reference can be viewed simultaneously.

The altitude and azimuth glass circle angles which are transmitted by fiber optics are read in auxiliary eyepieces. Eccentricity errors are eliminated by reading both halves of the setting circles.

Two level references are employed. A coarse level is obtained by a bubble level external to the periscope. The fine level is obtained by autocollimation from the surface of a floated mirror which will reflect, reversed, the image of the telescope reticle back on itself.

Altitude viewing changes are accomplished by rotating the head prism. The spindle or prism carrier is similar in design to that of the Polaris navigation periscope, utilizing a thrust bearing flatted and polished to optical specifications. Azimuth training is both coarse and fine: coarse, by simply manually pointing, fine by a bull gear and pinion.

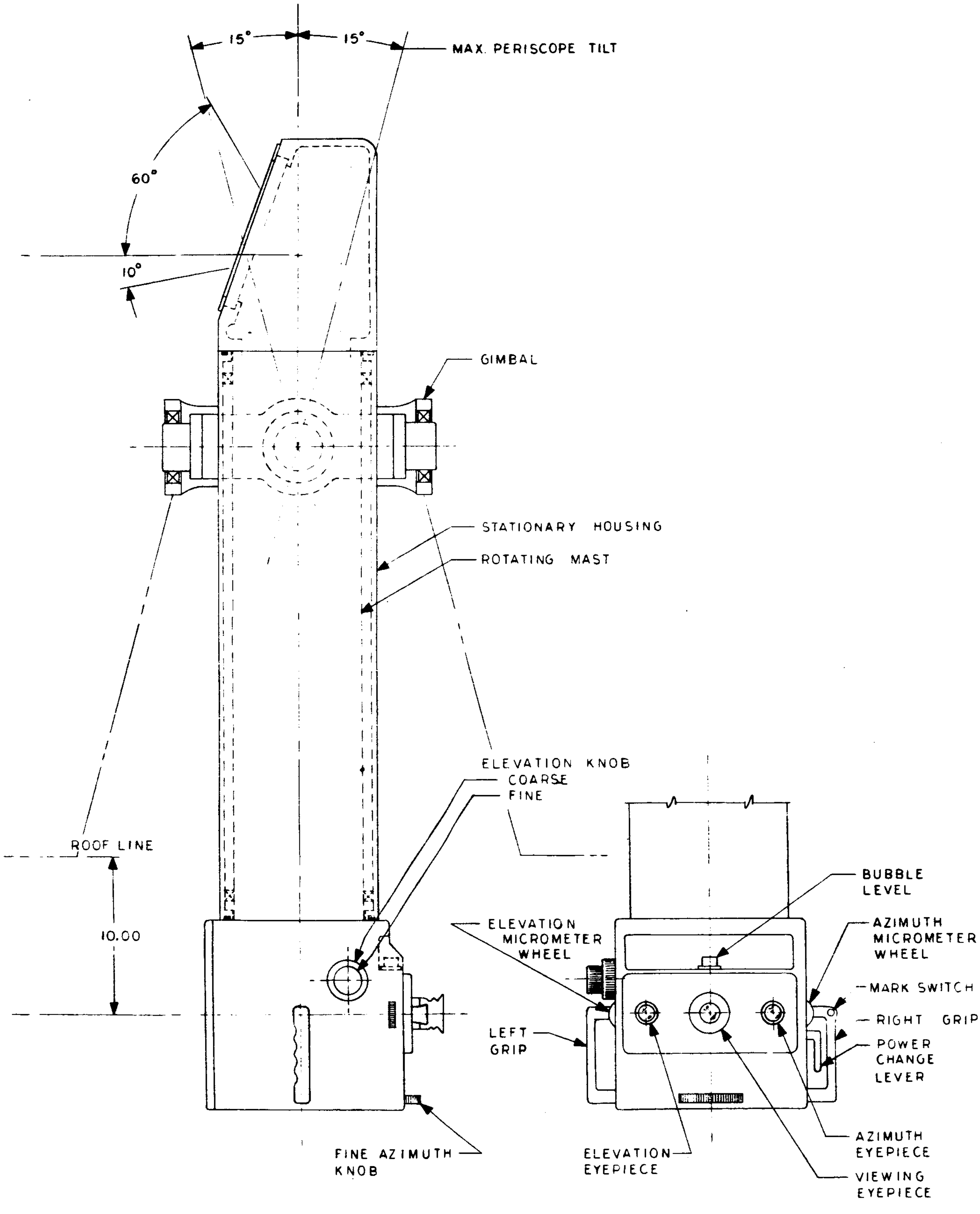


Figure 6-4 Kollmorgen, Periscope Outline

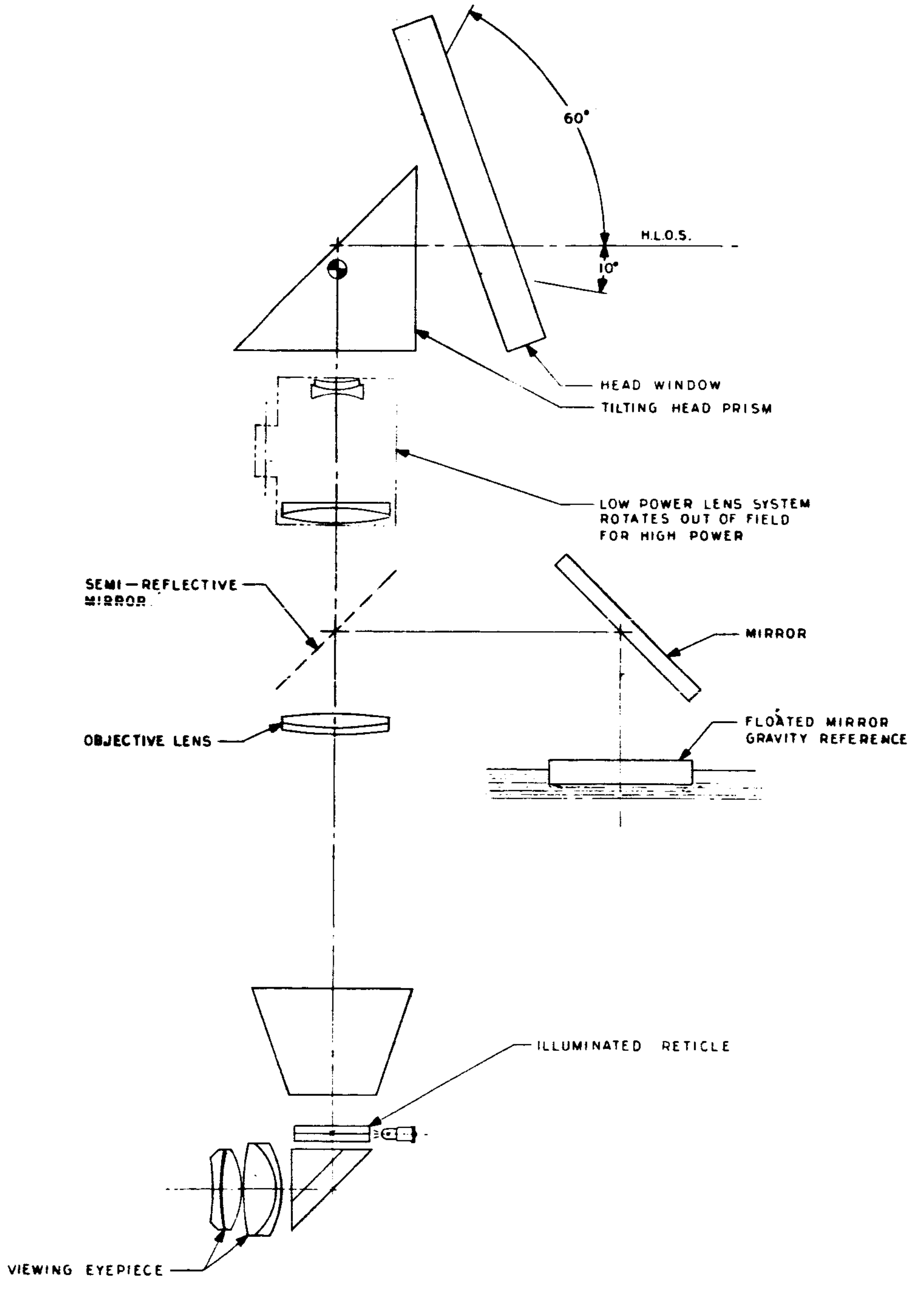
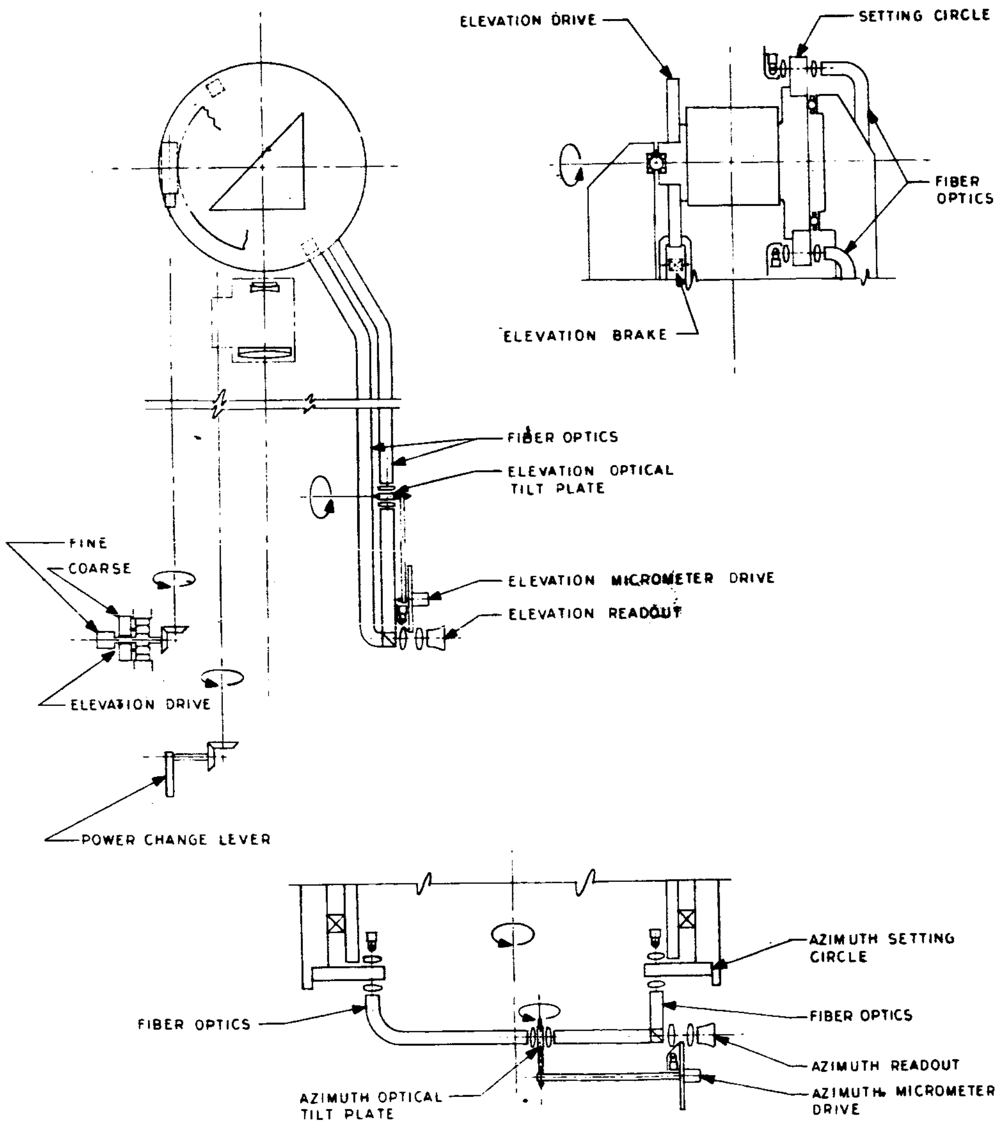


Figure 6-5 Kollmorgen,



lechanical Schematic

Sextant error components are tabulated below. The totals are taken as a vector sum representing the worst case conditions.

Instrument Error Allotment (peak to peak)

Elevation

Leveling, error effect 1:1 max;	2 sec
Nitrogen wedge due to differential pressure at 1.5 atm	44 sec *
Prism wedge (tol = 15 sec)	4.5 sec
Head window wedge (tol = 5 sec)	1.5 sec
Readout error 1:1	5 sec
	57 sec
*Can be calibrated, chart to be supplied	-44
Maximum Total Elevation Error	13 sec

Azimuth

Non-orthogonality of Gimballing 3' at 15^{o} tilt	5 sec
Prism pyramidal (tol 10 sec)	6 sec
Head window pyramidal (5 sec)	3 sec
Cross-level prism to spindle (5 sec)	3 sec
Leveling (2 sec x level error)	7 sec
Readout 1:1	5 sec
Maximum Total Azimuth Error	29 sec

6.1.1.4 Kollsman Standard Aircraft Instrument(17)

The Kollsman standard sextant and mount have been proven capable of celestial angular measurement through use in commercial and military aircraft for many years. Two variations of the sextant are available: One obtains the local vertical reference by means of a bubble level, the second by means of a pendulous mirror. The Kollsman proposed sextant of Section 6.1.1.5 incorporates the pendulous mirror reference: this vertical reference is discussed in that section. Therefore, the discussion of the standard sextant presented in this section is limited to the details with regard to the functioning of only the bubble level reference.

The true heading mount unit is attached to the roof of the MGL vehicle and aligned to the longitudinal axis of the vehicle. The sextant unit is attached to and through the true heading mount to provide a celestial view external to the vehicle. Two optical trains (for the bubble level reference sextant) are utilized in performing the measurements of celestial altitude and celestial azimuth. This is illustrated by the simplified diagram of Figure 6-6.

The celestial body is observed through the optical path shown on the left side of the diagram. The celestial light is reflected from an index prism located in the periscope head through the objective system, a field lens, and an erecting system; then directed by a prism to the operator's eye forming a real image at the focal plane of the erecting system. A reticle of vertical and horizontal lines which indicate center of field are on the focal plane.

The optical path to the right side of the diagram transmits the verticality indication and the true heading scale. The artificial horizon of the sextant is an air bubble located at the top of the body of the sextant. The image of the bubble passes through a lens and reflector system which directs a portion of the light to the eyepiece where a real image is formed at the focal plane of the telescope. An optical system supported on the bubble chamber transmits the true heading scale from the heading mount to the same plane as that of the bubble.

The view presented to the operator by these two optical paths of the sextant is also shown in Figure 6-6. Shown are the artificial horizon, the star position relative to the instrument reticle, and the azimuth scale. The azimuth scale is shuttered from view by the operator as desired.

The rotation of the index prism (for altitude pointing variation) is controlled by a worm gear and sector in the sextant. The motion is transformed to the prism by means of a rod and levers from the control knob. Geared to the control knob is a counter which indicates the instantaneous altitude angle. The average altitude angle as determined over a 0.5 to 2.0 min interval by a ball integrator, is read on the altitude counter at the end of the integration period.

The performance parameters of the sextant (either the bubble level or pendulous mirror reference system) and mount are:

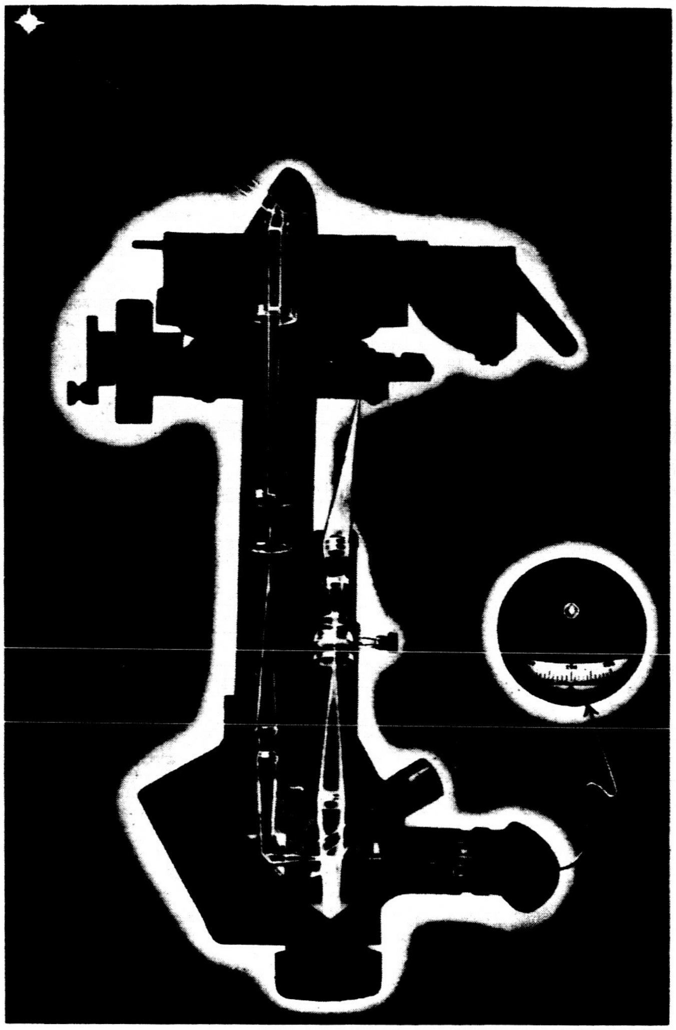


Figure 6-6 Kollsman, Schematic, Bubble Type with True Heading Mount

Field of View	15 degrees
Magnification	2 x
Altitude Range (Center of Field)	-2.5 to +84.5 degrees
Azimuth Range	360 degrees
Altitude Accuracy	2 min of arc
Azimuth Accuracy	15 min of arc

The heading mount gimbals allow for rotation of the sextant through 360 degrees in azimuth and a 15 degree movement in pitch and roll about the normal sextant and mount orientation. A weather seal is provided by an operated shutter when the periscope is removed from the mount. The standard periscopic sextants and mount described above are illustrated in Figure 6-7.

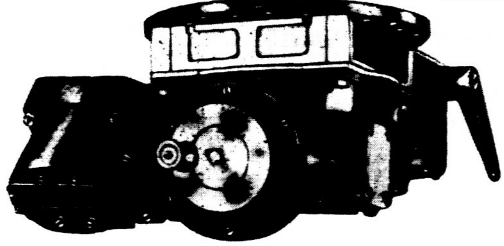
6.1.1.5 Kollsman Proposed Design[17]

The Kollsman proposed MGL sextant is a modified version of their standard aircraft sextant and true heading mount which were described in Section 6.1.1.4.

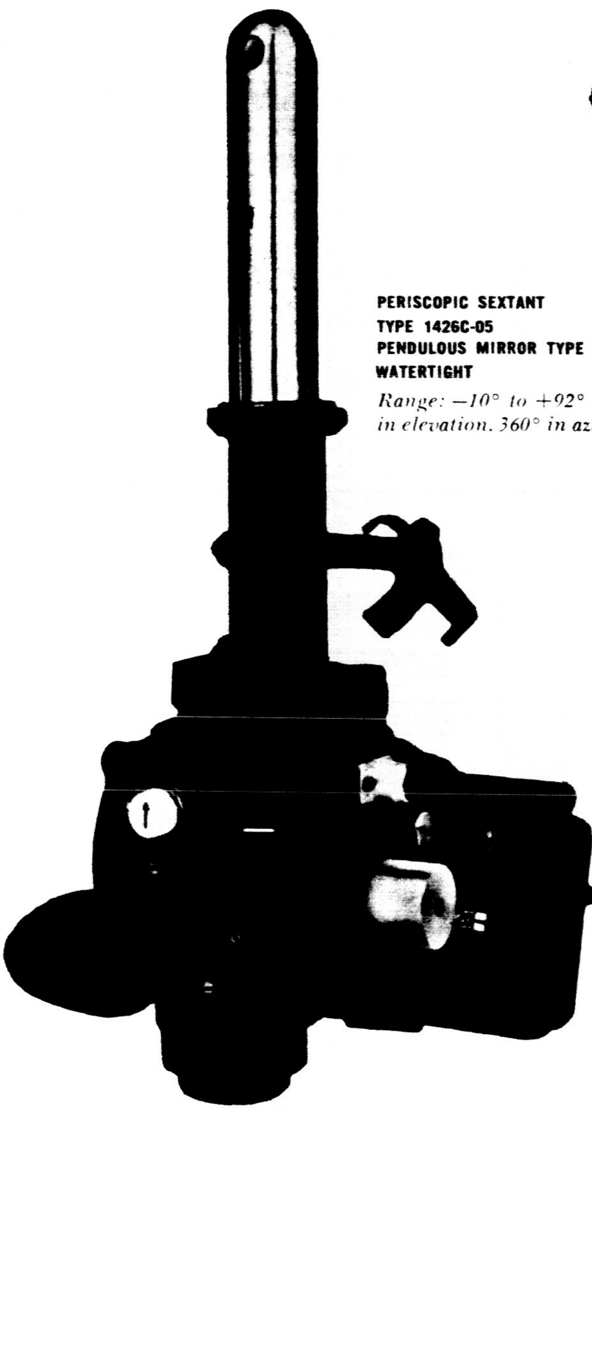
The modified version utilizes a pendulous element, suspended in a fluid damping chamber, to position the image of an illuminated line in the eyepiece focal plane. This line serves as an artificial horizon.

This sextant has three optical paths as shown in Figure 6-8. They are the celestial body sighting path, that associated with illuminating the pendulous mirror and relaying the artificial horizon indication, and that provided for transmitting the azimuth scale from the true heading mount.

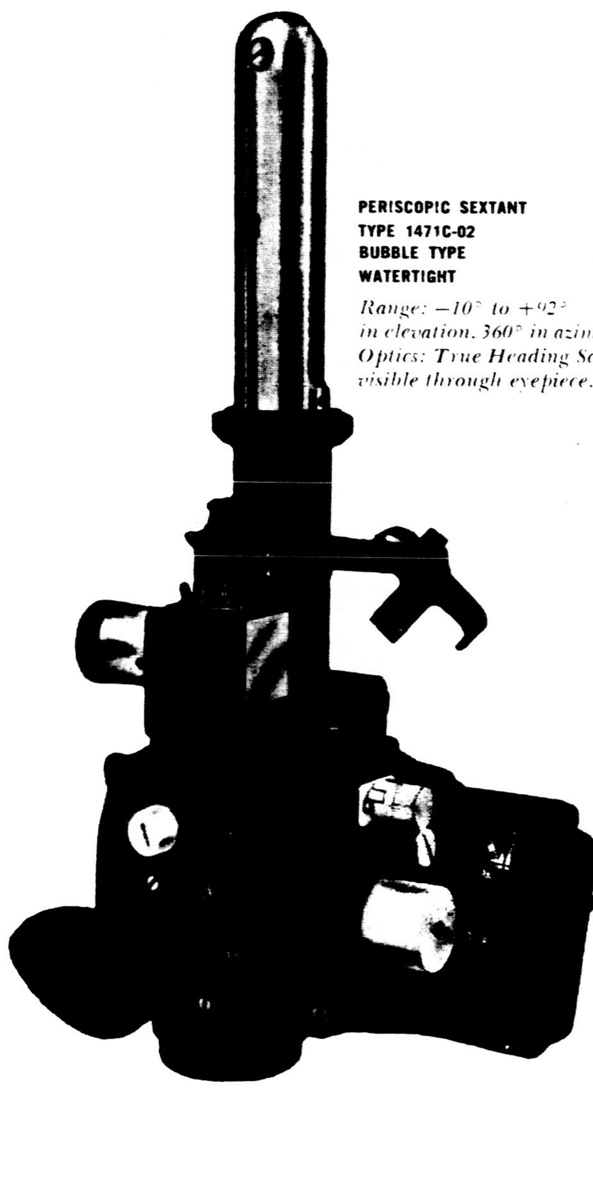
The celestial sighting optical path, that shown on the left of the diagram of Figure 6-8, is identical to that described with regard to the standard Kollsman sextant. The altitude angle is measured by means of trunnion mounted prism in the periscopic head. The rotational position of the index prism is controlled by a manual knob. The angular precision of prism location is improved over that of the standard Kollsman sextant



SEXTANT MOUNT
TYPE 1708-01
Contains True Heading Scale.



PERISCOPIC SEXTANT
TYPE 1426C-05
PENDULOUS MIRROR TYPE
WATERTIGHT
Range: −10° to +92° in elevation. 360° in azimuth.



PERISCOPIC SEXTANT
TYPE 1471C-02
BUBBLE TYPE
WATERTIGHT
Range: −10° to +92° in elevation. 360° in azimuth. Optics: True Heading Scale visible through eyepiece.

Figure 6-7 Kollsman, Standard Aircraft Sextants and Mount

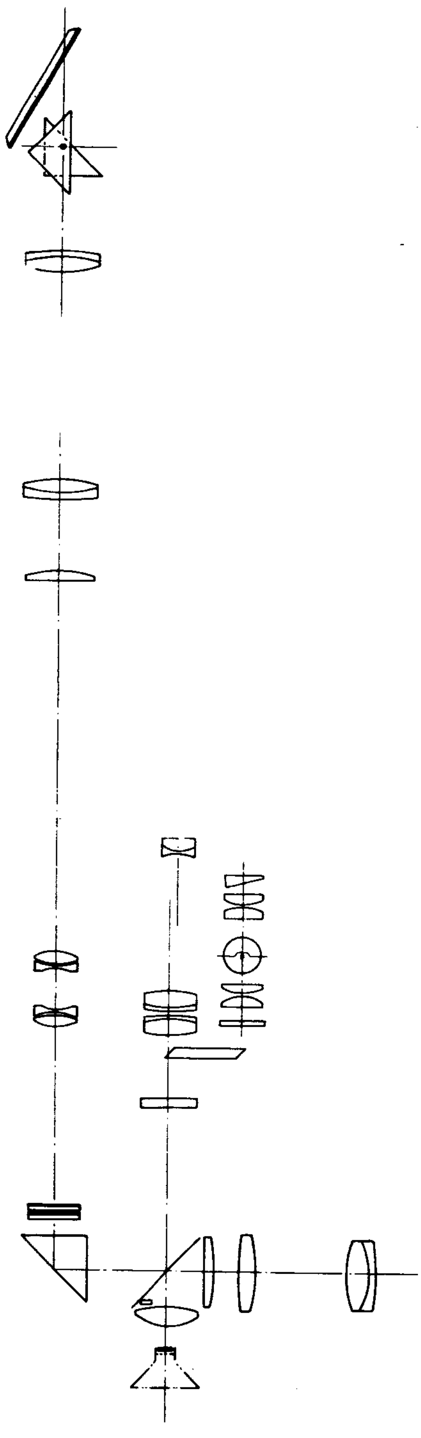


Figure 6-8 Kollsman, Optical Schematic

by the utilization of more accurate control components. The measured altitude is indicated on a time averaged counter which is driven by the control knob.

The verticality indicator optical path is contained within the sextant unit. The pendulous element, located in the lower portion of the sextant, is a stainless steel mirror pivoted at its center on a concave jewel. The mirror is maintained horizontal by the pendulous action of a conical skirt attached to its periphery. A narrow slit of light is directed down toward this mirror, reflected by the mirror, and then directed toward the eyepiece. A lens system forms a real image of the horizontal reference at the focal plane of the main optical system. The altitude angle of the celestial body is obtained when the index prism of the periscope head has been rotated to bring the image of the star into coincidence with the horizontal line.

The third optical path, shown in the center of the diagram is for the purpose of relaying the true heading scale from the sextant mount to the operator's eyepiece. The function of this optical system is similar to that described for the standard Kollsman sextant.

The performance parameters of this modified sextant and mount are:

Field of View	14.5 to 14.75 degrees
Magnification	2 x
Altitude Range (Center of Field)	-2.5 to +84.5 degrees
Azimuth Range	360 degrees
Altitude Accuracy	30 sec rms 60 sec max.
Azimuth Accuracy	1.5 min rms 5 min max.

The sextant mount is provided with a flange to assure a tight weather seal with the MGL vehicle roof. A shutter can be closed at times of sextant removal to close the periscope opening.

The true azimuth scale is manually rotated in the true heading mount. Azimuth relative position is indicated by a counter and an image of the true azimuth scale is projected to the operator's eyepiece. The true azimuth scale assembly and receptacle are mounted by a pressure sealed gimbal. The gimbal mount allows for leveling of the sextant over a 15 degree range. The form of the Kollsman proposed sextant is identical to that of the standard aircraft sextant as shown in Figure 6-7.

6.1.1.6 Sextant Instrumentation Summary

Each of the proposed MGL sextants, as described in the previous sextions, appears capable of performing the required simulation navigation functions. The accuracy, the operational ease, and the similarity to the MOLAB designs[1, 2] of these instruments varies considerably. This, and the instrument development status, are reflected in the delivery prices quoted by the manufacturers. The instrument characteristic parameters which were identified in the sextant specification (Appendix A) and the fundamental program parameters which were identified in the sextant statement of work (Appendix A) are listed in Table 6-1, for each of the presented sextants.

Performance

Referring to Table 6-1, the performances of the various sextants are quite similar: the major difference appears in the accuracy of the angular measurements. The altitude errors range from a few seconds of arc to 2 min of arc: the azimuth errors range from approximately 30 sec of arc to 15 min of arc. The allowable errors stated in the sextant specification were 15 sec of arc and 30 sec of arc for altitude and azimuth respectively. These were derived as simulation goals; however, the proposed sextants whose errors exceed this goal do offer an accuracy acceptable for initial simulation tests.

Controls and Displays

The controls and displays of the listed sextants are functionally identical; however, the implementation varies among the various instruments. All sextant controls are manual: some are actuated by knobs, some by thumbwheels, some by cranks, and some by simply movement of the sextant. All proposed angular readouts are visual; however, vary among circle projections to eyepieces, scale projection to eyepieces, and

Table 6-1

PROPOSED SEXTANTS: DESIGN AND PROGRAM CHARACTERISTICS

Parameter	Section Number	Periscopic Sextant Designs				
		Itek	Keuffel & Esser	Kollmorgen	Kollsman (Standard)	Kollsman (Proposed)
Specification Performance	(3.0)					
Field of View	(3.2)	15 degree	15 degree	16 degree & 4 degree	15 degree	14.5 to 14.75 degrees
Magnification		3 power	4.8 power	3 power & 12 power	2 power	2 power
Alt. Accuracy	(3.3.1)	<15 sec RMS; 30 sec max	11 sec of arc	13 sec of arc	2 min or arc	30 sec RMS; 60 sec max.
Azimuth Accuracy	(3.3.2)	<30 sec RMS; 90 sec max	<30 sec of arc	29 sec of arc	15 min of arc	1.5 min RMS; 5 mm max.
Altitude Range	(3.4.1)	-15 to + 80 degree	- 10 to + 60 degrees	- 10 to + 60 degrees	-2.5 to 84.5 degrees	-2.5 to 84.5 degrees
Azimuth Range	(3.4.2)	0 to 360 degree	0 to 360 degrees	0 to 360 degrees	0 to 360 degrees	0 to 360 degrees
Image Orientation	(3.5).	Erect & correct for right and left	Erect and correct for right and left	Erect and correct for right and left	Erect and correct for right and left	Erect and correct for right and left
Control & Displays	(4.0					
Altitude Adjust	(a)	Manual	Manual	Manual	Manual	Manual
Azimuth Adjust	(b)	Manual	Manual	Manual	Manual	Manual
Alt. Readout	(d)	Scale projected to reading eyepiece	Scale projected to reading eyepiece	Scale projected to reading eyepiece	Counter	Counter
Azimuth Readout	(e)	Scale projected to reading eyepiece	Scale projected to reading eyepiece	Scale projected to reading eyepiece	Scale projected to eyepiece	Scale projected to eyepiece
Mechanical Design	(5.0)					
Height	(5.2)					
Exterior		~7 inches	~4 inches	~3.5 inches	~4.5 inches	4.5 inches
Interior (permanent)		~4.3 inches	~6.4 inches	~8.3 inches	~3.5 inches	~3.5 inches
Removable eyepiece	(5.3)	Yes	Yes	Yes	Yes	Yes
Eyepiece	(5.4)					
Location(from roof)		8.8 inches	~8 inches	10 inches	~10.25 inches	10.25 inches
Adjustable focus		Yes	Yes	Yes	Yes	Yes
Exit pupil/alti angle		Yes	Yes	Yes	Yes	Yes
Leveling to 15°	(5.5)	Yes	Yes	Yes	Yes	Yes
Weather Seal	(5.6)	Yes	Yes	Yes	Yes	Yes
Weight 15 lbs	(5.7)	Not stated	Not stated	Not stated	12.2 lbs	Not stated
Power	(5.8)	Flashlight Battery	6V; 0.5 amp	Not stated	28 volt	3 volt; AC or DC
Lighting	(5.9)	Alt. & Az. circles	Ref. Reticle; level vial Alt. & Az. circles	Reticle	Horiz. line, Az. scale	Horiz. line, dials, scales
Design Options	(6.0)					
Az. Readout in FOV	(1)	} $5,000	Not Recommended	Not Recommended	Yes	Included in Design
Alt. Readout in FOV	(2)		Not recommended	Not Recommended	No	Redesign
6X Magnification	(3)	$10,000	$2,400	12 X Included in Design	No	Redesign
Azimuth to North	(4)	Included in Design	$3,600	Not included	Yes	Included in Design
Elect. Alt. & Ar. Readouts	(5)	$20,000	$62,900	Not included	No	Redesign
Alt. Angle Avg.	(6)	$10,000	$15,700	Not included	Yes	Included in design
Camera Attach.	(7)	$500	$2,400	Not included	No	9,000
Laser Attachment	(8)	$20,000	$2,400	Not included	No	Not known
Filters	(9)	$200	$600	Not included	Yes	Included in design
Zero Calibration	(10)	Included in Design	$6,000	Not included	No	Not recommended
Statement of Work						
Program Length		10 months	12 months	10 months	6 months	10 months
Develop. Status		Estab. Tech. Avail. Comp.	Standard Theodolite Tech.	Sub. Periscopic sextant tech.	Existing units	Modif. of Existing Units
Cost with included design options						
Sextant Design & Manufacture		230,000	126,800	220,000	~6,000	12,700
Document. & shipment		6,000	6,700	10,100	*2,000	3,700
Acceptance Test		11,000	14,500	22,000	*8,000	18,600
Field Service (1 wk)		1,200	1,000	~1,000	*1,000	1,375
Total		248,200	149,000	253,100	*17,000	36,375

* Estimated Costs

simply digital counters. The projection of the vertical reference varies also. In some instances the vertical indication is displayed within the same field as the celestial field, but in others it must be viewed from a slightly different observer position. All of these control and display configurations are acceptable for the initial simulation instrument since one of the desired tasks of the simulation investigation is to examine these and other instruments - operator interfaces.

Mechanical Design

The mechanical designs of the 5 sextants are quite different, yet each functionally is capable of meeting the sextant requirements. The general size and operationally critical dimensions are acceptable; each provides a removable eyepiece; focusing and an altitude independent exit pupil position are provided; instrument leveling up to 15 degrees can be achieved; and a weather seal and an illumination source are implemented.

Design Options

In general, a wide variation in the advisability of the various design options was expressed in the four RFP responses. In an effort to evaluate the worth and cost of the design options, they were classified into three groups: favorable, questionable, and unfavorable. The class of the ten RFP options are shown in Table 6-2.

Only four of the ten design options can be immediately resolved with regard to inclusion in the initial simulation sextant: the azimuth to North and filters will be included, the electrical readout of altitude and azimuth angles and the laser ranger compatibility will not be included. The inclusion of the other design options is a function of the selected design points with regard to the sextant's accuracy and development status. The criticality of these other options is not significant in the determination of this design point; they will simply result from the design point selection.

Statement of Work

The MGL periscopic sextant programs proposed by the four optical instrument manufacturers are all of approximately the same duration, that is, 10 to 12 months from contract award to hardware delivery. However, the costs associated with these programs varies greatly due to the present development status of the sextant and the sextant design sophistication.

TABLE 6-2

DESIGN OPTION SUMMARY

Design Option	Class	Comments
1. Azimuth Readout in FOV	Questionable	There are difficulties with illumination and FOV blockage.
2. Altitude Readout in FOV	Questionable	There are difficulties with illumination and FOV blockage.
3. 6 x Magnification	Questionable	This is easily designed into "new" instruments, not included in "modified" instruments.
4. Azimuth to North	Favorable	Recommended as a capability of an instrument.
5. Electrical Azimuth & Altitude Readouts	Unfavorable	Not recommended; produces significant system complexity.
6. Altitude Angle Average	Questionable	This appears costly for compatibility with instruments of higher accuracy.
7. Camera Attachment	Questionable	This appears a worthwhile option but is costly to incorporate into simpler instruments.
8. Laser Attachment	Unfavorable	Not recommended; not enough laser information is presently available; will probably place undue penalties in optics implementation.
9. Filters	Favorable	Recommended; relatively easy to implement and useful during terrain sighting.
10. Zero Calibration	Questionable	This appears required only for the sextants of higher accuracy.

The range of sextant complexity, from an off-the-shelf production item to that approaching a MOLAB design (functionally), is described in the sextant proposals. It appears that this results from the fact that all manufacturers could not meet the request for an off-the-shelf or modification of an off-the-shelf implementation. The current status of the development of the proposed sextants are described as established techniques, available components, and modification of existing units.

The approximate range of costs quoted for the sextant programs was $36, 000 to $250, 000. This cost is broken down as follows (approximately):

Program Item	Range of Cost (K$)
Sextant Hardware	13-230
Documentation	3-10
Acceptance Test	11-22

For an initial simulation periscopic sextant it is not practical to employ the most accurate instrument and all of the desired design options at the costs indicated by these RFP responses. Figure 6-9 is a plot of sextant cost vs. sextant accuracy for the proposed and the standard aircraft sextants. A very sharp rise in sextant costs exists for units of altitude error less than 20 sec of arc.

The quoted costs associated with the documentation of the proposed sextants of $3, 000 to $10, 000, appears to be a reasonable number. This magnitude of effort should provide the degree of documentation required to efficiently operate and maintain the sextant and yet not incur documentation costs beyond the scope of the navigation simulation program.

Acceptance tests costs ranging from $11, 000 to $22, 000 were quoted in the proposals. For highly accurate instruments, elaborate tests and test equipment are required; however, if a sextant on the lower end of the accuracy scale is selected for the MGL, the acceptance tests effort and required facilities should be substantially reduced.

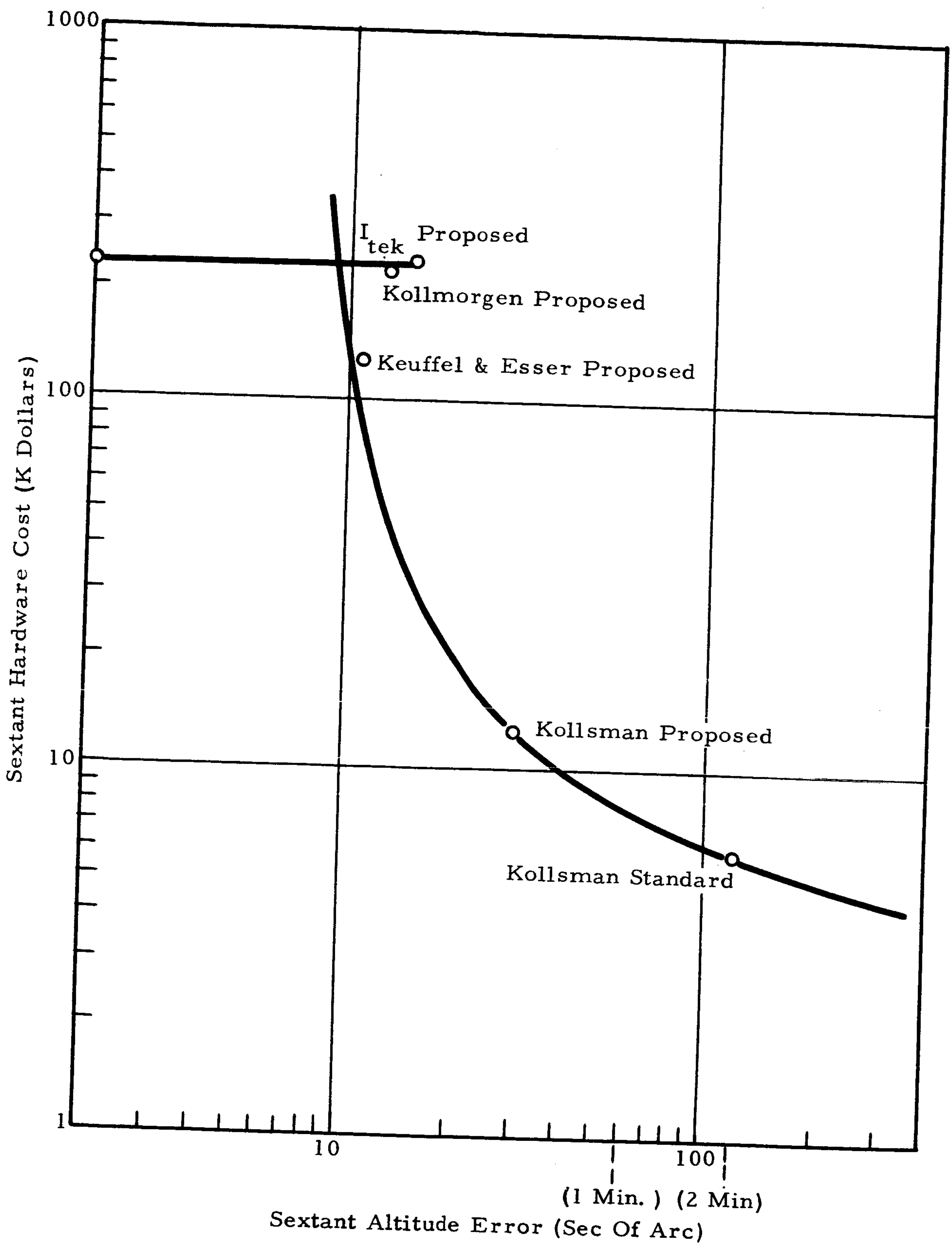


Figure 6-9 Sextant Altitude Error vs Sextant Hardware Cost

The program costs of documentation and acceptance tests for the standard aircraft sextant must be estimated since this implementation was not included as a part of a sextant program proposal. It seems reasonable to assume, because of production standardization and quality assurance, that the cost associated with these programs tasks would be less than the lowest of the four proposed programs. This criterion was used in estimating the standard sextant program costs. The program length to manufacture and deliver such a production item has been quoted at 6 months.

6.1.2 Sextant Data Storage/Transfer

It is important that the integrity of the output data from the sextant be preserved and in a form of most use to the mission. Many alternative forms of sextant data storage and transfer can be conceived but for purposes of this preliminary design only two aspects will be discussed. These are: (a) the nature of the display of azimuth and altitude, and (b) coupling of the azimuth scale and the heading system.

6.1.2.1 The Display of Azimuth and Altitude Angles

The readibility of precision scales of the types included in the above sextants is an exceedingly important factor. The angle display must enable the operator to read the angles repeatedly and quickly to the required precision. Much human factors information is available for the design of effective angle readouts. In addition, there are operational advantages to having one or both of the sextant angles visible to the observer while sighting the star. Normal procedures for astro-fixing call for precomputation of the sextant coordinates based on approximate values of observer location, time of observation and the stars to be observed. These preliminary values can be set on the sextant at the right time and the relevant star should be in the field of view. If at least the azimuth angle (or some significant number on the azimuth scale) can be seen in the sextant field of view with the star, serious misidentification of stars are likely to be averted.

An alternative concept, which is intended to alleviate the timing problem discussed in Section Appendix D.2., provides a remote readout of the sextant angles by use of angle transducers. By converting the appropriate shaft rotation angle into a suitable form of digital notation, the reading can be transferred to a number of locations without loss of precision. Some of the obvious alternatives are as follows:

The sextant angles could be displayed on unambiguous, numerical indicators of suitable size and readibility to eliminate scale reading error. The display could be "frozen" at the appropriate time to hold the correct values for the operator's convenience.

The signals could be applied to a suitable recorder which, at a time signaled by the observer, could provide a permanent record for use in later computation and for insertion in the mission log book. This record could include not only the sextant angles but also the time, the date and any other information of interest to the operator at the time of position fixing. An additional recording device, a camera, could be used to record the "true" star-reticle orientation at the time the observer indicates star-reticle coincidence.

Electrical readouts of the sextant angles could be transmitted through the available telemetry channels back to mission control for a check computation of vehicle position. It is not recommended that this link be used for the primary position fix computation, but, for little added complexity in the vehicle it could provide a valuable back-up facility.

6.1.2.2 Coupling of Sextant and Gyro Heading System

The data transfer from the sextant to the dead-reckoning heading system must also be considered. The importance of maintaining an accurate heading reference for computation of dead-reckoning (DR) position must not be underestimated. Typical of the effect of heading error are the results of field trails performed by the U. S. Army on a vehicle DR navigation system similar to that being installed in the Mobile Geological Laboratory. A summary to the results of five such tests runs is given in Figure 6-10. Each plotted point represents the recorded differences, for each leg of the test course, between the output of the DR computer and the surveyed values for the check points. To normalize the results each error vector is resolved (a) along track, i. e., along the direction of a line between adjacent check points and (b) across track. The most obvious feature of Figure 6-10 is that the across track errors are generally five times larger than the along track errors demonstrating the importance of accurate heading data for use in the DR computer.

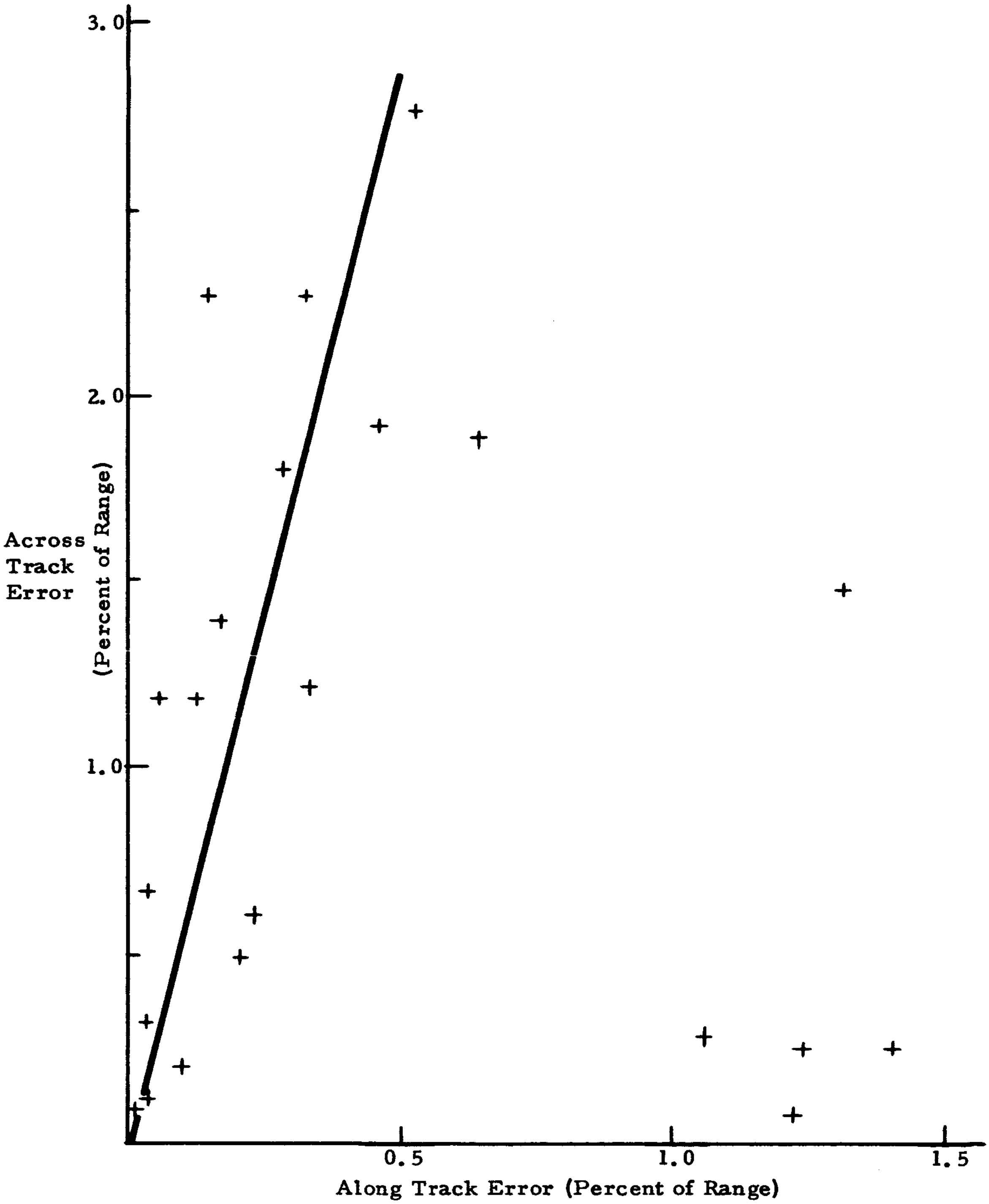


Figure 6-10 Results of Dead Reckoning System Field Trials

Considering another aspect of the heading error problem it is possible, by making a number of broad generalizations, to determine how often it is necessary to stop and update the DR position computation for a given error in heading data. The results of this computation are given in Figure 6-11 for maximum track-keeping errors of 0.5 and 1.0 kilometers. Superimposed on this data are curves giving the time between heading system updates to ensure that the average errors in a directional gyro heading system, having drift, are kept within the stated values. The directional gyro discussion is significant with relation to the MOLAB implementation. Typical of the data presented by this figure is:

(1) For a maximum track-keeping error of 0.5 km (utilizing the gyro compass of the initial MGL DR system, which has a stated error of 0.75 degrees), it is necessary to stop every 40 kilometers to perform a position fix.

(2) At the same time, if this gyro had a drift rate of 1 deg./hour it would be necessary to stop every 1.5 hours to perform a heading fix.

The purpose of Figure 6-11 is to illustrate the relation between the operational activities (position and heading fixes) and the heading system performance for a given navigation accuracy requirement. Since it is most likely that it will be necessary to stop the vehicle to perform the position and heading fixes, it is essential to keep the time between fixes as long as possible and the time required to perform each fix as short as possible. There is, on the other hand, a trade-off to be made between low drift rate of the heading system (which adversely affects cost and reliability) and an auxiliary facility (at extra cost) for making celestial heading fixes rapidly and reliably to a lower quality gyro system. It is not possible within the scope of this report to perform this trade-off; however, two such auxiliary facilities are discussed below.

<u>Servo Coupling</u>

The Synchronous Astro Compass (SAC), manufactured by Computing Devices of Canada (a Bendix subsidiary) is used on many military and commerical aircraft with the standard Kollsman periscopic sextant to assist the navigator in easily and precisely calibrating the heading reference system. The form of the Synchronous Astro Compass

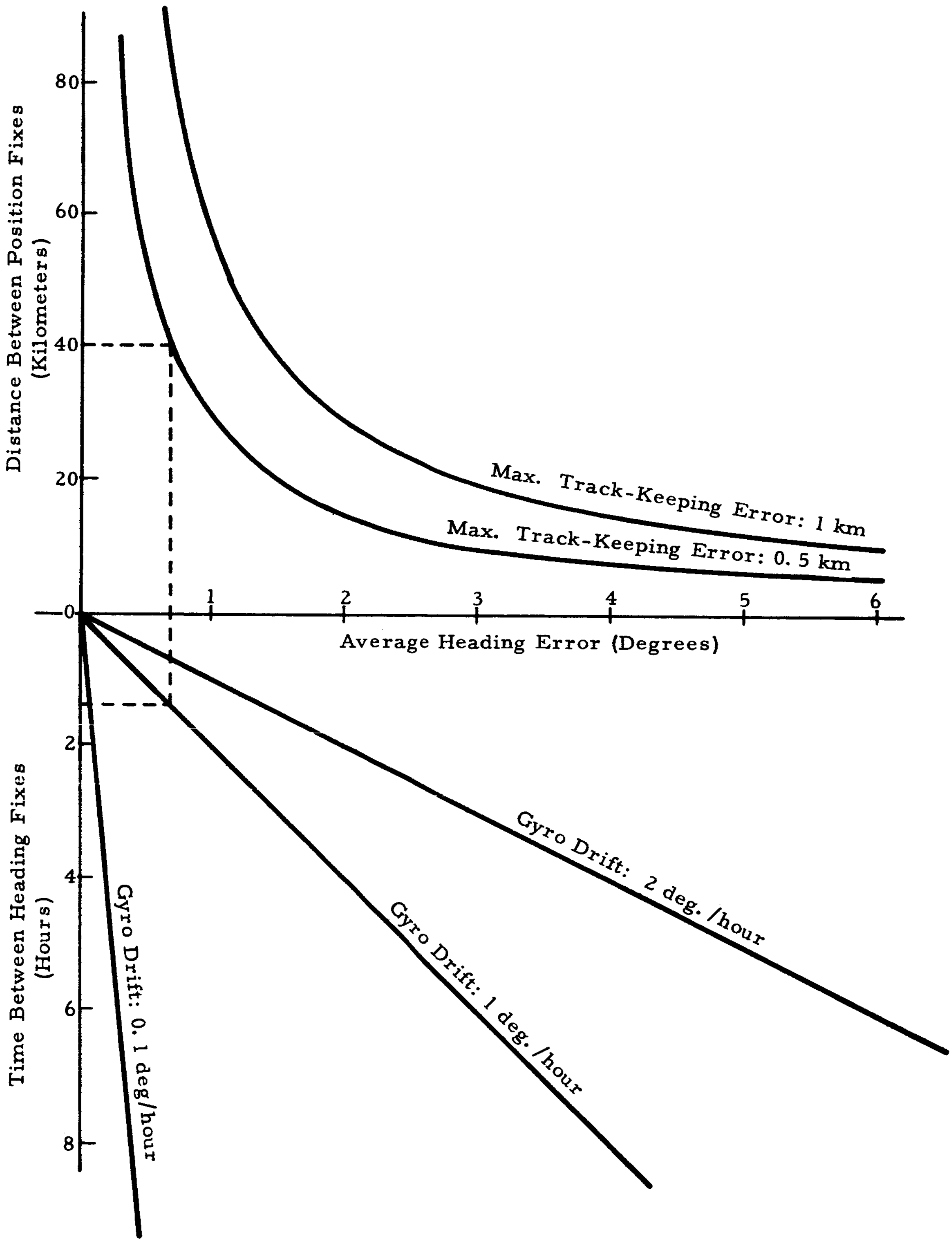


Figure 6-11 Heading Error Effects

can be adapted to a wide variety of sextants, gyros and DR systems. In general, the data flow is as shown in Figure 6-12. The azimuth scale on the sextant is servo driven to agree with the combined signals of gyro heading (supposedly true heading) and pre-computed star azimuth to yield a reading of star relative bearing under the azimuth scale index. If the operator now turns his sextant until an azimuth reading of 0° appears in the field of view, the star to be sighted should appear at that azimuth by scanning in elevation. When the star is sighted and the sextant azimuth aligned to it, the azimuth scale reads heading error. If the gyro-slewing controls are placed within reach of the observer at his sighting station he can immediately slew the gyro to reduce this error to zero, thus restoring the gyro output signal to signify true heading. The time required for this operation is very short, and it makes use of the many accuracy advantages of a null-reading instrument.

Typical specifications for the SAC are:

Number of Units	2
Total Weight	.....5.5 pounds
Total Power	.....D.C.: 9 watts
	400 cps: 17 volt-amps
Mean Power	.....3500 hours
Heading Accuracy	.....$\pm$ 0.25° (std. deviation)

Optical Coupling

A second coupling of the sextant and the DR heading system can be accomplished optically. This coupling provides a high degree of accuracy but imposes operational requirements on the astronaut. The need for a coupling of the accuracy obtainable by this system may arise due to vehicle flexure between the sextant mount and the DR heading mount.

Implementation of this coupling system is accomplished by: (1) providing within the periscopic sextant a rotatable prism/mirror system which will allow viewing inside of the vehicle, in viewing directions contained in the vertical plane, and (2) providing a mirror system within the DR heading system through which alignment orientation can be determined from the sextant viewing position. The DR heading system would most probably be located directly beneath the sextant, below a door in the vehicle floor. This heading system location is compatible with the c.g. location requirement.

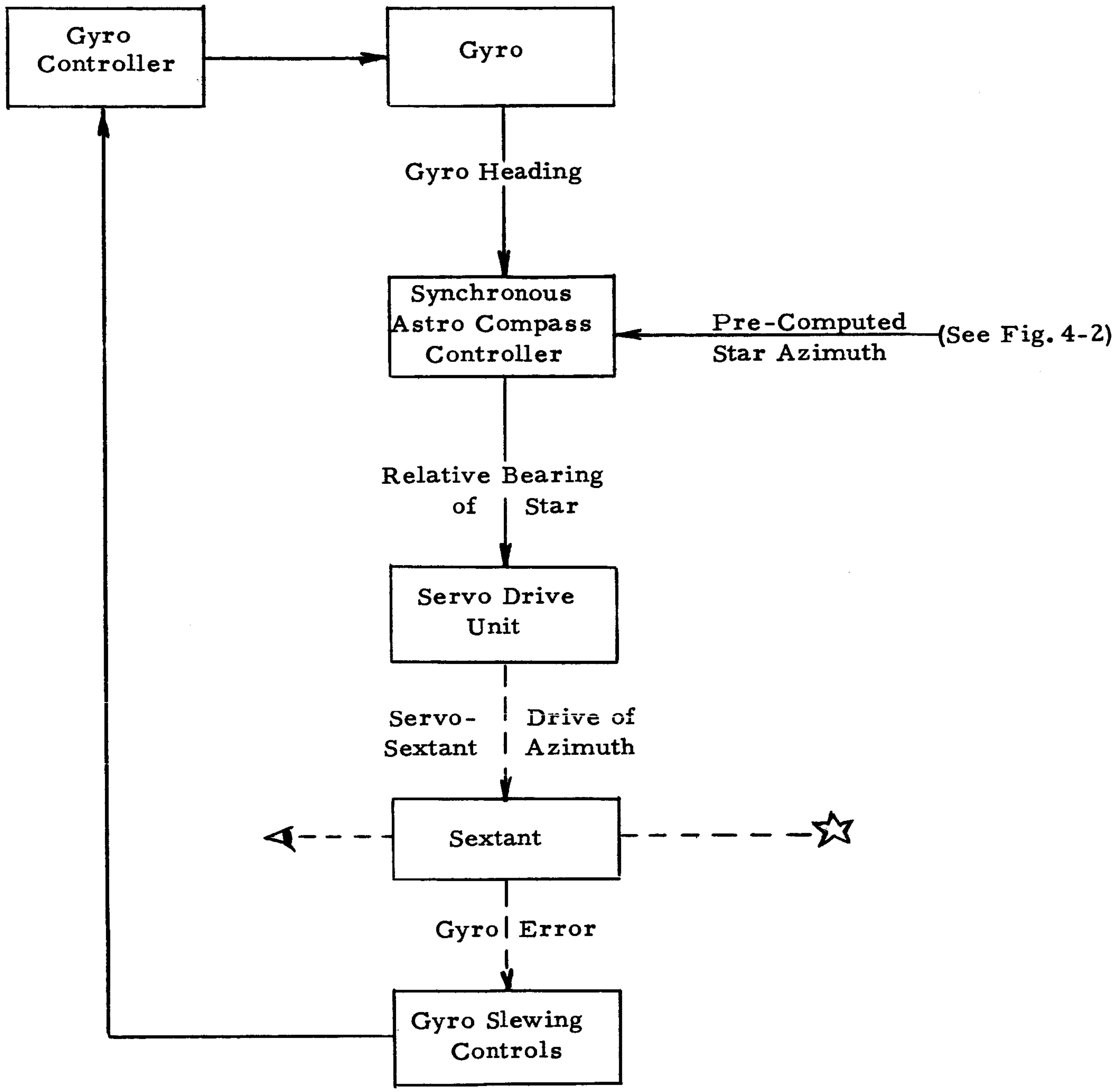


Figure 6-12 Synchronous Astro Compass Data Flow

6.1.3 Operational Considerations in Taking Optical Measurements

A number of alternative operational constraints must be considered in connection with the taking of the optical measurements associated with position fixing. These pertain specifically to the constraints placed upon the vehicle and the personnel during the time this precision sextant is being used. A number of such considerations are associated with the stability and attitude of the vehicle when it is parked. The following notes are presented to identify certain potential problem areas without seriously attempting to propose solutions.

6.1.3.1 Vehicle Stability

Neither the Bendix nor the Boeing MOLAB reports analyzed the suitability of the MOLAB as a stable sighting platform. Movements of the astronauts within the vehicle will undoubtedly cause pitch and roll movements which could have an appreciable affect on sighting accuracy. Vehicle movement will have an associated angular acceleration which will disturb the local vertical-seeking sensor in the sextant. This vehicle movement will also present a difficult ("impossible", according to one sextant manufacturer) star-tracking problem for the observer. Not only is movement of the chassis of concern, but also flexure of the cabin roof. This latter concern is particularly relevant in the MGL. Several possible solutions to this stability problem have been identified. The problem can be virtually eliminated by using jacks to support the vehicle and a rigid cabin structure for sextant mounting. This is a "brute force" approach and the jacks are not especially desirable operationally. Another approach is to measure the sighting offset deviations of the star-reticle coincidence and deviation of the local vertical-sextant orientation at the time of observation and use this to calculate the true angles.

If the vehicle oscillations have a natural frequency of a few cycles per minute, the operator is able to maintain the alignment of the sextant line-of-sight with the star. In this case, an integrator such as is used to provide an indication of the average deviation of scale reading from its initial value during a stipulated time period. The algebraically averaged deviation is applied to the initial scale reading and is assumed to be relevant at the mid-point of the integration time interval. If the stability problem is less than anticipated it may be sufficient to mount the sextant over the vehicle c. g. and to restrict operator movement thus preventing disturbing vehicle motions.

The approximate magnitude of this stability problem should be investigated prior to procurement of a sextant for MGL. With the MGL parked on a flat surface and with an operator standing in the sighting position cabin movements can be observed. A movement of a few hundredths of an inch at either end of the cabin indicates a problem to be reckoned with. Possible solutions should be discussed with the selected sextant supplier. If the frequency oscillations is low, serious consideration should be given to inclusion of the error averaging option on the initial sextant procurement. After delivery and installation, this problem should receive thorough investigation. A part of the investigation should be an analytical comparison of MGL suspension characteristics with those of a MOLAB on the lunar surface. If large differences exist then the MGL problem should be solved separately and a fixed-base simulator should be constructed to investigate the MOLAB problem.

Although Bendix has not observed the MGL while operating, it is anticipated that engine vibrations could affect the precision of sextant observations. If it is necessary to stop the engines during sightings, the implications of such an operational constraint on such other systems as environmental control, life support, power, communications, and data processing will have to be investigated.

6.1.3.2 Vehicle Leveling

A MOLAB design requirement was that the vehicle should have the ability to traverse 15 degree slopes. This requirement was interpreted in both the Bendix and Boeing studies as a requirement for celestial sighting measurements with the vehicle parked at any slope angle up to 15 degrees. Accommodation of this requirement requires either a sextant leveling capability over a 15 degree range or accurate measurement of vehicle pitch and roll and calculation of the desired angles from measurements of elevation and train. The requirement to perform scientific work within the vehicle while parked on a 15 degree slope apparently was not imposed as a requirement on either the mobility or life support subsystems since no consideration of a cabin-leveling mechanism is evident. Basic life support activity, let alone useful work, will be difficult, if not impossible, with the vehicle parked on a 15 degree slope.

A self-leveling pendulous sextant is recommended for initial use in the MGL and is a possibility for MOLAB. The leveling and cabin seal units of such a sextant would be significantly simplified if leveling within a range of only ± 2 or ± 3 degrees rather than ± 15 degrees were required. Two factors related to this matter should be investigated during MGL simulations; (1) the maximum vehicle inclination at which the crew can comfortably work, and (2) the probability of finding a relatively level surface on which to park the vehicle at required position fix points on a typical mission. Crew comfort might be dependent upon vehicle heading with respect to the slope. This factor should be controlled and its effects observed. While jacks might be used to level a vehicle parked on a steep slope, they would be considerably more complicated than jacks used only to stiffen the suspension. They should be considered only if the requirement to park on a steep slope is strongly justified.

6.2 TIME MEASUREMENTS

The only factor which prevents the stars from appearing in a fixed location in the sky is the rotation of the earth on its axis. The manner in which we measure earth rotation is in terms of time. Astronomers have at least 8 different definitions of time including the various categories of siderial, solar and ephemeris times. The most common time used by the traditional navigator is Greenwich Mean Time (Universal Time). This is defined as the hour angle, for an observer on the Greenwich meridian, of a fictitious, or mean, sun which is assumed to move at a uniform rate eastward along the equator, making a complete circle from vernal equinox to vernal equinox in the same time it takes the real sun to make the same circuit along the ecliptic. Since this is the time used to synchronize the world-wide operations of modern space missions it is most appropriate that Universal Time (Greenwich Mean Time) be used for the coordination of lunar-based celestial position fixes and for simulations of these operations. A time standard displaying Universal Time can be used or, as shown in Figure 4-2, the time can be derived from a clock displaying local zone time.

In addition to the importance of knowing precisely what time it is (in terms of the sun's hour angle at Greenwich), the moment of time which is important to celestial position fixing is that instant at which the observer establishes the measured altitude of the star. It is evident that an error is introduced into the position solution if the wrong time is associated with the observed altitude. A lack of simultaneity in the observation of time and altitude angle has the same effect as an equivalent clock error. The seriousness of this error varies with the configuration of the navigation triangle (Figure 3-5).

Based on the time error analysis presented in Appendix D, it is proposed that the timepiece to be selected for the MGL position fix system should not have a drift in clock rate greater than 1 second per day. Assuming it will be operationally feasible to perform a timecheck once a day, this constrains the absolute time error to 1 second. It is also proposed that the timepiece be readable reliably by an operator standing at the sextant sighting position.

The following sections discuss the alternative instruments, together with the variations of time display and operational usage, which are suited to the specific timing requirements of MGL position fixing.

6.2.1 Instrumentation

A great variety of suitable timepieces which generally comply with the same MGL position fix specification are currently available. A timepiece specification was generated, which was purposely general in the area of physical and readout characteristics, but which stated the primary requirements of rate stability (1 second drift per day) and environment. This specification is reproduced in Appendix B.

The task of measuring and displaying time is a very common one. For this reason it was not expected that any special development would be required to provide a suitable timepiece for the MGL position fix system. The survey of available timepieces was conducted in two phases, (a) available clocks consistent with the accuracy requirement and (b) available components from which a clock of suitable accuracy could be assembled and possibly giving more flexibility in the human engineering of the display of time to the sextant operator. The results of these two surveys are given in the following sections.

6.2.1.1 Available Clocks

Both escapement-type and electronic clocks were surveyed for compliance with the timepiece specification. Only one escapement-type clock met the accuracy and power supply requirements, whereas a number of electronic clocks could be considered applicable. One version of Accutron clock, manufactured by Bulova Watch Company, meets all the basic requirements for a position fix system timepiece and provides an adequate readout in a very small integrated package. The preliminary characteristics for this class of timepiece is given in Figure 6-13. A

Figure 6-13

SPECIFIC CHARACTERISTICS OF ACCUTRON CLOCKS, TIMERS AND SWITCHES

[illegible]	[illegible]	DESCRIPTION	WT. GRAMS	[illegible]	[illegible]	[illegible]	[illegible]	ACCURACY	CONTACT OR OUTPUT	TRANSISTOR (a)
CLOCK 1 in. Dial	10-10 10-11 10-12 10-13	Ge. Trans. Si. Trans. 360 cps Output Stop & Start	33g	1 5/16 x 1 5/16	.58	Hour, Min. & Sec.	12 or 24 hr., hr. & min. (sec.) graduations	±1.8 sec. per day	— — 0.3v(b) —	Ge. Si. Si. Si.
CYCLE TIMER	11-10 11-11 11-12 11-13 11-14 11-15 11-16 11-17	Second Contact Minute Contact Hour Contact Second & Minute Contacts Second & Hour Contacts Minute & Hour Contacts Second, Minute & Hour Minute, Minute & Hour	42g	1 5/16 x 1 5/16	.68	Second only (c)	Unnumbered 5 or 15 sec. graduations (c)	Seconds ±0.3 sec. Minutes ±3 sec. Hours ±2 min. (d)	SPDT 50ma. 6v resistive 10ma. 6v inductive. (e)	Ge.
5 YEAR SWITCH (2 mo.-5 yr.)	12-10 12-11 12-12 12-13	1 Switch Time. Preset 12-10w. External Setting 12-11w. 2-3 yr. cell 12-12w. 2 switch times	82g 97g 97g 97g	1 5/16 x 1 5/16	2.00 2.35 2.35 2.35	Year, Month & Second	Year & Month grad. indicates time remaining.	±2 days	2 SPDT 7 amps 28v resistive, 3 amps 28v inductive	Si.
CLOCK 1⅞ in. Dial	13-10 13-11	Rear Setting Front Setting	82g	2 3/8 x 2 3/8	.53 .99	Hour, Min. & Sec.	12 or 24 hr., hr. & min. (sec.) grad.	±1.5 sec. per day		Ge.
CALENDAR CLOCK	14-10 14-11	1-31 Day Date 0-999 Days	48g	1 5/16 x 1 5/16	.68	Hr. Min. & Sec.	24 hr., hr. & min. (sec.) grad.	±1.5 sec. per day		Ge.

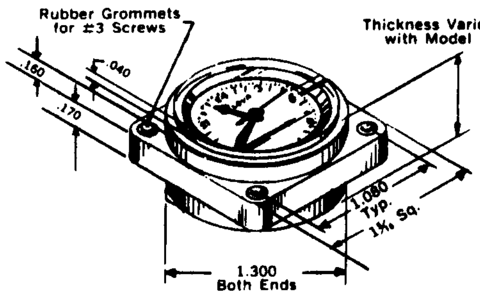
(a) Si. transistors available to substitute for Ge.

(b) Thru 47K ohm resistor & 0.1 uf capacitor

(c) Available with hour and minute hands and 12 or 24 hour dial

(d) Duration of Contacts: 1 to 60 second pulses — ±.3 seconds; ½ second minimum
1 to 60 minute pulses — ±5 seconds; ½ minute minimum
1 to 24 hour pulses — ± 10 minutes; 12 minutes minimum

(e) Contacts: Contacts can be obtained every 1, 2, 3, 4, 5, 6, 10, 12, 15, 20, 30 or 60 seconds and/or 1, 2, 3, 4, 6, 8, 12 or 24 hours. The duration of the contact can be varied but the sum of the make-break (on-off) periods must be divisible into one of the above units.



more detailed technical description is given in Appendix C. The Systems and Instruments Division of Bulova Watch Company has expressed interest in this timepiece requirement and has quoted an approximate price of \$450.00 for a newly-developed chronometer having three Accutron movements in a case 1.25" thick, weighing 100 grams. The 3-movement configuration ensures the required accuracy over the stated environment range. This was the only electromechanical timepiece which was found to fulfill the requirement.

On the other hand, there are a number of companies which offer electrical and electronic clocks having almost any desired precision. The characteristics of four applicable models chosen to illustrate the spectrum of features available are summarized in Table 6-3: specification data sheets are attached as Appendix C. The cost and precision data from Table 6-3 have been plotted in Figure 6-14 to yield the "rule of thumb" conclusion that the cost of a digital clock triples for each order-of-magnitude increase in required drift rate stability. One unfortunate aspect of the statements of precision of electronic clocks is that the stated stability is in terms of the drift of the basic oscillator used. This makes it difficult to directly relate "parts per million" precision to "seconds per day" requirements. The stability of an oscillator, including the tuning fork of the Accutron clock, can be affected by a wide variety of factors. Some of these factors yield short term drifts and others affect the long term stability. Hence, to compare timepieces it is necessary to compare their stability over the same time period and not assume that drift rates are linear.

TABLE 6-3

Summary of Digital Clock Characteristics

	Digital Clock Make and Model				
	Tymeter	Chrono-Log Model 2600	WANG 2000 Series	Chrono-Log Model 12100	EECO Model 804
Stated Precision (Parts/10^6)	10 (Estimated)	3 to 10	3 to 10	1 ppm/week	0.03
Display Resolution (Second)	0.5	1	1	0.001	1
Volume (cu. in)	300	900	1400	1500	2300
Weight (lbs)	10	23		30	30
Cost (Dollars)	650 (Estimated)	900	1050	1825	8000

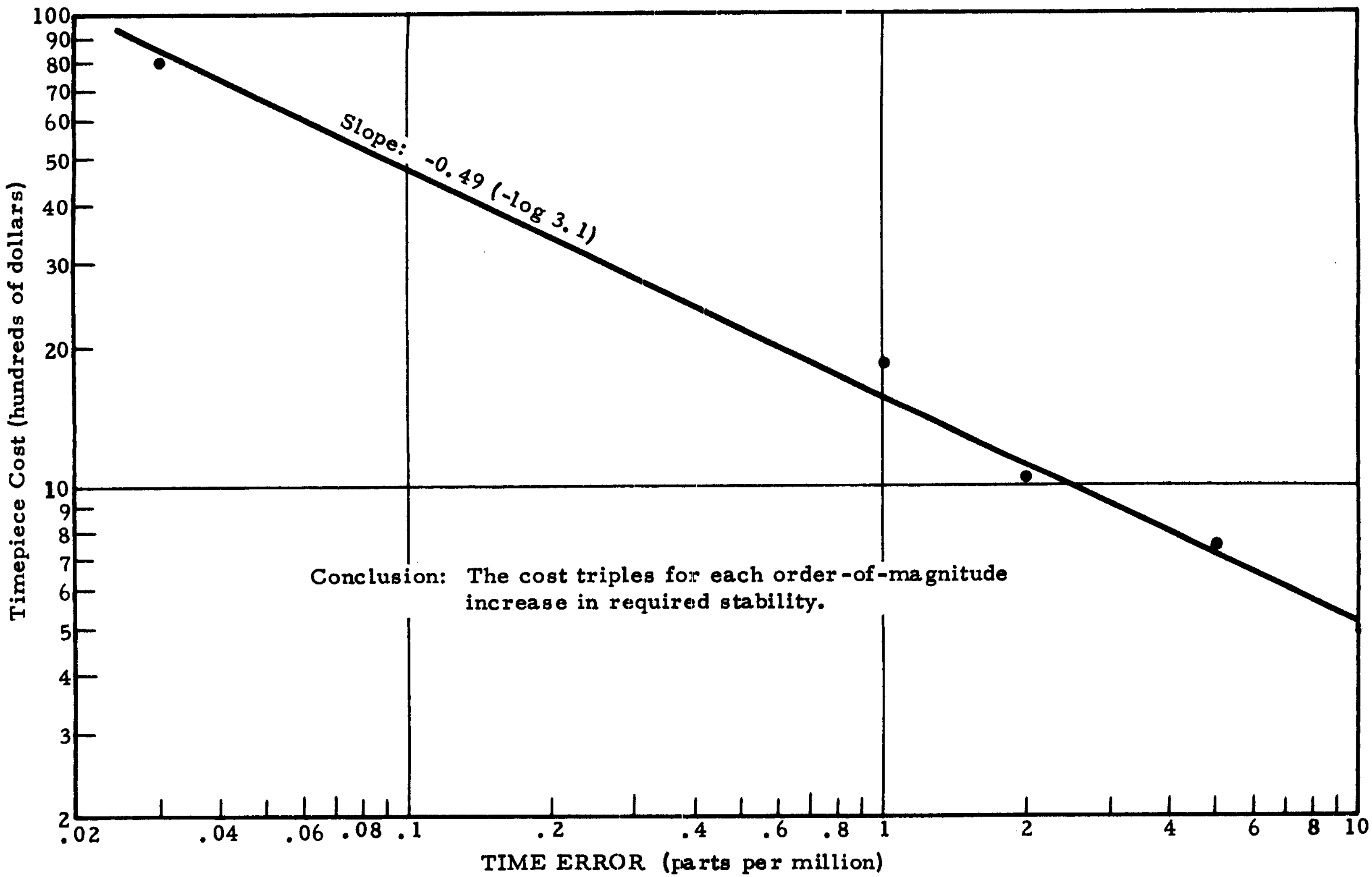


Figure 6-14 Relationship of Timepiece Cost to Drift-Rate Stability

For example, Bulova Watch Company guarantees "that the Accutron wristwatch will not gain or lose more than one minute per month". At the same time they are very hesitant to suggest that the same watch will not gain or lose 2 seconds per day. Provisionally, the specification shown in Appendix B states the accuracy on a daily basis since it is anticipated that a time check would be performed daily and any error noted or corrected. This time interval over which the total drift of one second is required to apply may be lengthed or shortened, if the need arises, in accordance with operational constraints established during the simulation trials.

6.2.1.2 Available Timepiece Components

In addition to the clock survey discussed above, a preliminary survey was made of available components suitable for assembling a device capable of meeting the drift rate and environment requirements of the specification and tailored to the installation and operational requirements of the MGL. The internal functions of a clock were first delineated as shown in Figure 6-15. It then appears feasible, if circumstances warrant, to assemble from available components a timepiece having exactly the characteristics of precision, range and readability desired. The precision is established by selecting an oscillator of the required stability from the large number of available frequency standards. The selection between solar or sidereal time for the earth or the moon is a matter of scaling the basic oscillator frequency down to yield a time interval between pulses equivalent to the shortest increment of displayed time in the chosen units. Depending on the types of scaler and display selected, the integration function may be provided as a part of that equipment. Electromechanical counters provide the pulse summation and display in the same unit. Many electrical and electronic displays require a separate pulse counter to generate a display-actuating signal. The display device should be chosen from considerations of the most reliable transfer of information to the sextant operator under actual celestial sighting conditions. An excellent review of present-day digital readout devices is given in the Systems Designer's Handbook[18] (January 1966) issued by the publishers of the periodical Electromechanical Design.

It is not intended to imply by the above discussion that a custom-designed timepiece is considered necessary at this time. It is intended to indicate that, if after considerable operational experience with the

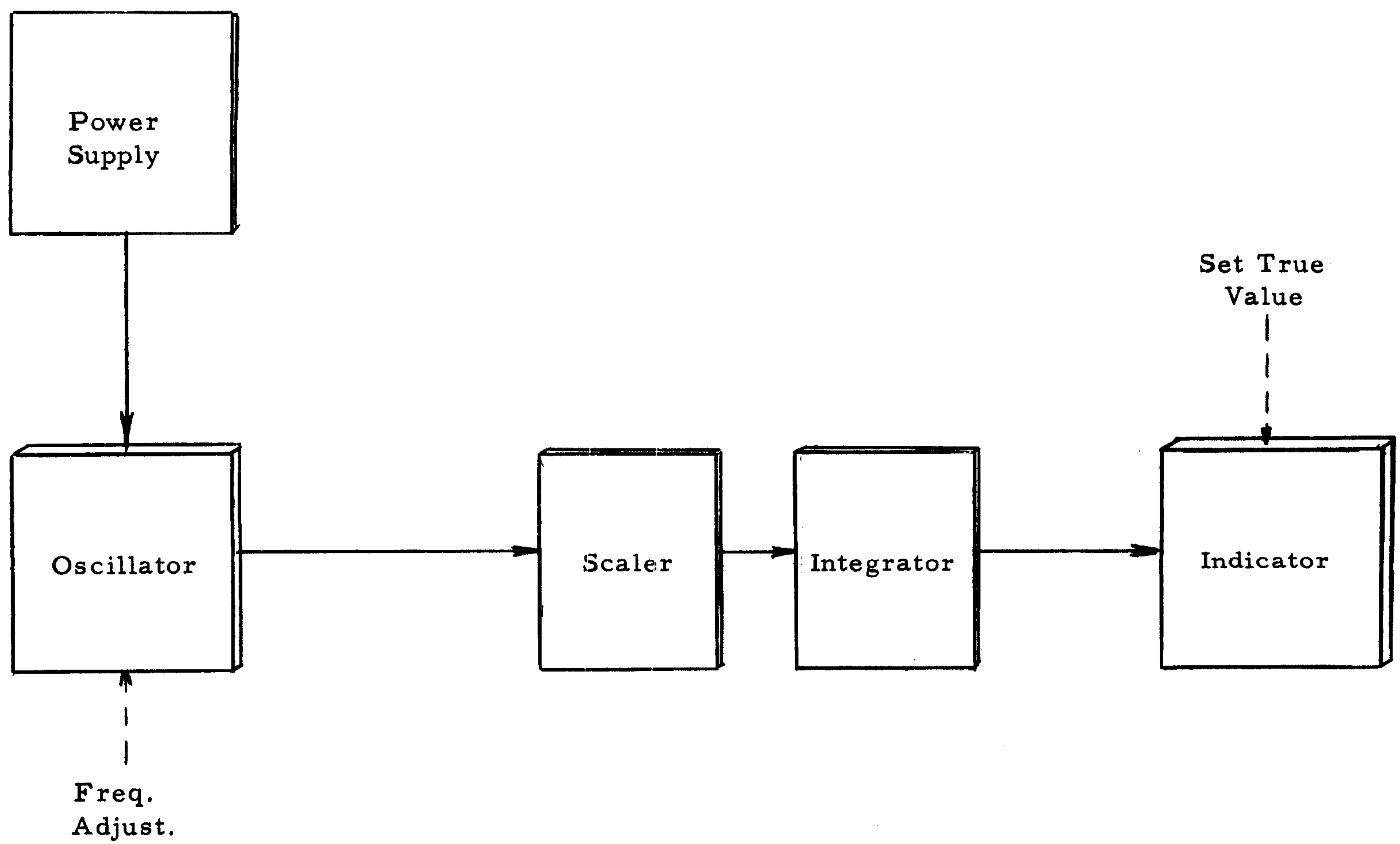


Figure 6-15 Timepiece Functional Diagram

position fix system, system performance could be improved with a customized display of time, such a clock can be provided. As shown in Appendix D. 2, the readability of the timepiece is as important to position fix accuracy as its primary precision. It is most difficult at this time to state what form of display is optimum for the MGL installation.

6.2.2 Time Data Storage and Transfer

There are several relevant alternatives which can be considered in the design of the time display for reliable data transfer to the astronaut. The advantages and disadvantages of three of these alternatives will be discussed in this section. It is suggested that each technique may be operationally tested during the system evaluation phase of MGL simulation trials and a final judgment made as to that which is best suited to consistent position fix precision. The three alternatives are described as:

- Analog display
- Digital display
- Audio/visual display

It can be assumed that at the instant most critical to the position fix accuracy, the observer's attention and preoccupation will be focused on the proper alignment of the sextant. The answer to the time display problem then hinges on the best method of either

A. Calibrating, prior to final sextant alignment, the operator's sense of the rate of change of time (in the units he is using) so that he can make short-term extrapolations to ensure proper sextant alignment at a pre-designated time.

B. Holding the display of time, by a manual signal, long enough to permit the observer to divert his attention from the sextant to the clock and take note of the time.

The crucial difference between these two operational principles is the dependence on the operator. The first operation depends heavily on the operator's skill; the second depends on extra equipment.

The analog display of time is typified by the standard clock face with hour, minute and second hands. The readability of this display benefits from its familiarity to any observer. It is best suited to type A operation because of the compact nature of this kind of clock and because the second hand provides the operator, at a glance, a convenient indication both of time rate and of time remaining to a pre-specified hour. If the timepiece is mounted directly on the sighting portion of the sextant so that the navigator may simultaneously monitor the clock and sight through the sextant, the best conditions for data transfer are achieved. Attempts were unsuccessful in finding a chronometer which incorporated some of the features of a stop watch (see Appendix B, para 5.1). The construction of the Bulova Accutron does not permit such a modification. It must be concluded that the analog display is not feasible for type B operation.

The electronic clocks described in section 6.2.1.2 provide digital displays integral with the electronic package. These displays tend to be large for good readability at a distance. The prime advantage in digital displays is the positive readability with little possibility of misinterpretation. However, they have little advantage over the analog displays in indicating fractions of a second. Although the indicator can display in milliseconds, the eye will not reliably read the 1/10-second numeral. The numerical display provides a trained observer with a measure of the rate of change of time and of the time remaining to a specified hour. Thus, if the operator is able to see the display conveniently while doing the preliminary alignments of the sextant, the digital display can be used in type A operation. For type B operation, with the addition of a data storage register of suitable capacity, most electronic digital clocks can be provided with a temporary "display hold" feature. The clock manufacturers contacted preferred to have the duration of "hold" to be constant for purposes of circuit simplicity. This could be expected to impose only minor operational inconvenience.

The third mode of time display is called audio/visual because it proposes to use an additional human sensor to achieve input of time data without diverting his attention from sextant alignment. This is done by generating in a head set tone pulses at one second intervals. If desirable, the tone of each fifth pulse can be different from the rest, to help in long countdowns. It is recommended that a standard clock (either analog or digital display) be provided as described in the above paragraphs, but that this clock be used only for gross time keeping (reducing the accuracy requirement). The tone in the headset could be provided over the normal communications channel between the vehicle and base from a standard receiver tuned to WWVB[19]. This would tie up this channel for a maximum of 2 to 5 minutes during each position fix, but it is hard to conceive of a more accurate display of time being made available to the astronaut in more efficient and convenient form. The effectiveness of this audio/visual time display can be tested during the MGL simulation trials by using equipment which will most likely exist in the vehicle and in the command center. For early trials, the Accutron clock having a 360 cps. audio output could be used (see Figure 6-13).

To summarize, the conclusions as to the suitability of these three modes of time display are presented in Table 6-4.

6.2.3 Operational Considerations

Two items directly relevant to the time measurement and display for the position fix system are presented in this section because of the effect they can have on the operation of the position fix and other MGL systems. The first one centers around the fact that in the MOLAB designs, a high-precision clock was included as part of the communications system. The second one considers the effects of using sidereal time for position fixing.

As presented in the preliminary design reports, the drift rate of a time standard in the MOLAB communications system meets the clock requirements for purposes of position fixing. It is conceivable that a remote display from that clock could be provided at the sextant operating position either in digital form or as an audible tone signal. In integrating the time requirements of the position fix system into the time standard requirements of the communications system it will be necessary to take into account

- the units requirements (e.g., universal or sidereal time)
- the resolution (e.g., seconds or fractions of a second) requirements
- the stop watch features
- the required display modes.

The timepiece considerations presented in this report have, of necessity, been constrained to the requirements for position fixing. It is obvious

TABLE 6-4

Suitability of Time Display Modes

Time Display	Suitability for Operation	
	Type A (Extrapolation)	Type B (Holding)
Analog	Good	Unfeasible
Digital	Fair	Good
Audio/Visual	Excellent	Unnecessary

that precise time is an essential parameter to many aspects of manned lunar operation. During the scientific mission simulation phase of MGL operation it will be possible to evaluate the possibility of integrating the displays of time as required by various subsystems from a central time standard. Operational simulation is the best way to bring to light the real advantages and disadvantages of such centralization.

It is recommended in Section 6.4.1 that a modified version of the Weems system of navigation be included as a computation aid during the system evaluation phase of MGL simulation tests. This would require altering the clock rate to yield a display of Greenwich sidereal time. This is very easily done on any of the clocks described earlier. Operating on sidereal time drastically simplifies the position computation but has the effect of isolating the position fix activity from every other function performed by the astronaut. Since this activity is intermittent, this isolation need not be a disadvantage. It is strongly recommended that, during the MGL simulation tests, an evaluation be made of the effects on the total MOLAB mission of operating the position fix system on sidereal time.

6.3 REFERENCE DATA

To complete the data requirements for position fixing, the navigator must have available suitable reference data relative to the star or landmark being sighted. This section discusses briefly the alternate forms in which is reference data can be provided to the navigator. Since the astronomical and landmark requirements are quite independent, they are treated separately.

6.3.1 Astronomical Data

Having observed a celestial body at a given time, the navigator must determine the Greenwich hour angle (GHA) and declination of the body at that time. This data is presently made available in the American Ephemeris and Nautical Almanac[20] published annually and containing data for a specific year. This document tabulates the Greenwich hour angle of Aries to(0.001 second),and the mean places of 1078 stars in terms of right ascension (to a resolution of 0.1 second) and declination (to a resolution of 1 arc-second). This document is available from the U.S. Government Printing office in Washington, D. C. (Price $3.75).

6.3.2 Landmark Data

Landmark reference data will most conveniently be presented directly on the maps used by the astronauts. The precision of this data is largely dependent on the quality of the maps. It is feasible to imprint the position coordinates of outstanding landmarks directly on the maps. In most cases the coordinates of identified landmarks will be interpolated from the reference grid superimposed on the map features. The U. S. Geological Survey is at present having prepared ortho-mosaic maps of the simulation test area. A major item in the simulation tests will be that of determining the ability of an astronaut to correlate the features on these maps with the identifiable landmarks.

6.4 COMPUTATION AIDS

The method used to compute the position coordinates from the sextant observations and the reference data has the greatest single influence on the accuracy and effectiveness of this system. A cost-effectiveness criteria becomes evident as soon as an attempt is made to evaluate the miriad techniques available to ease the computation. If the astronaut's time is costed in with the hardware and software costs, it is seen that the "trigonometry table, pencil and paper" method is equally as expensive as many of the automated techniques. The effectiveness can be measured in terms of the <u>fastest solution</u> with the <u>least error</u> derived <u>consistently</u> by typical operators.

It is not possible to list all the methods available to the MGL and MOLAB navigator. But in the following sections a number of relevant techniques are summarized in terms of (a) those which can be carried within the MGL vehicle and (b) those which make use of new or existing computing facilities external to the vehicle but available through telemetry or other communications links.

6.4.1 On-Board Facilities

A wide variety of computational aids are applicable to on-board use by the navigator for extraction of the position solution. In addition, there are slide-rule type star finders which are useful for the preliminary calculations associated with the selection of the stars best suited to accurate position finding at a particular time and place.

In proposing a design for the computation facility associated with the position fix system, it soon becomes apparent that there is one of two directions to proceed: (a) integrate the facility with those computational equipments required in other phases of the total mission; or (b) generate special-purpose hardware (or software) suitable for position finding only. In the first category, for example, a hand or desk calculator of the Curta or Freiden/Marchant type could be useful in many scientific calculations during the mission, as well as performing the 8-figure computations associated with the navigation triangle. It was beyond the scope of this present study to assess the value of a general purpose computing capability to the total MOLAB mission, but it is an item for consideration during the simulation tests.

Among the special purpose aids for use in the MGL are, of course, the sight reduction tables used by air and marine navigators (references 21 and 22). These, in general, have insufficient resolution for MGL navigation because they must be valid anywhere on the earth's surface. If the particular format of these publications is desirable, the solutions could be recomputed at a higher resolution for specific times and latitudes. However, an alternative format is available in the Weems System of Navigation[23] which offers a number of advantages. As presently published, these charts are also of insufficient resolution. But recomputed and replotted for the specific geographic area of operation, the technique drastically reduces manual computation. The following is an extract from one of the books of star altitude charts:

STAR ALTITUDE CURVES

The "Star Altitude Curves" is a short, easy method for fixing positions by means of selected stars. These curves have the following essential features:

1. Each page is a "grid" formed by the respective equal altitude curves (lines of position) of three stars, in a distinctive color .

2. Heavy, numbered curves show each degree of altitude, with light intermediate curves representing increments of 10'.

3. Scales of Latitude, with 5' divisions, appear along the left and right edges of the grid.

4. Scales of Local Sidereal Time (L. S. T.), in hours and minutes, appear across the top, and in degrees with 10' subdivisions across the bottom, of each page.

5. Above the top (L. S. T.) scale are shown the names of the stars used on that page, each with lines indicating the general direction and color of the respective curves.

6. The small figure below the star's name is the correction to be applied for annual change in altitude, the sign showing how it is applied to the sextant altitude for a date later than the epoch for which the curves are computed and positioned. Examples of the use of this annual altitude correction are given in the sample problems.

The principle on which the Star Altitude Curves are constructed is that for any time and place there is only one altitude of any fixed star; for any place and sidereal time, the circle of altitude remains nearly the same from year to year. Intersecting circles of equal altitude for two bodies taken at the same time determine two positions, but usually these two positions are so far apart that one of them can be dismissed as impossible. The circles of equal altitude are plotted on a Mercator chart against latitude and local sidereal time (L. S. T.).

With a bubble sextant in proper adjustment, the only correction normally made to the altitude of a star is that for refraction; with the Star Altitude Curves even this correction is unnecessary, since, in drafting, the curves of altitude are shifted by this amount. When using a marine sextant, a correction is made for the "Dip of the Horizon" as given in a convenient table in each volume of the curves. The observer uses a watch giving the Greenwich sidereal time (G. S. T.), or else converts Greenwich civil to Greenwich sidereal time.

A fix may be obtained from the altitude curves of two or of three stars in about two minutes and without reference to right ascension, declination, hour angle, azimuth, or dead-reckoning position and without the use of the almanac or other tables.

For convenience, the curves are constructed for ten-degree bands of latitude, covering L. S. T. 0 to 24 hours, with an overlap in latitude of 30' between adjacent bands and with overlap in L. S. T. of one or more minutes between the pages.

A valuable aspect of the Weems System is the pre-selection of the most suitable stars for observation during a particular local sidereal time period (see Table 6-5). A sample page is reproduced in Figure 6-16.

6.4.2 Base-Facility Assisted

If a major computing facility is accessible to the central control complex from which the MGL vehicle is operating, it is conceivable that the computational activity associated with position fixing could make use of this capability. The following suggested alternatives can be incorporated as required to

- verify the result of the astronaut's position fix computation
- relieve him of all computational load
- evaluate the need for an on-board general-purpose computer
- simulate the MOLAB (Bendix) digital computer.

With the normal general-purpose digital computer the iterative solution of the two navigation triangles to produce precise fix coordinates is performed in a matter of seconds. The U. S. Geological Survey is presently using the computing facilities of both the Bureau of Standards at Boulder and at Arizona State College at Flagstaff. These computing centers will be available presently to prepare any precomputed solutions required by the astronaut/navigator for preliminary sighting coordinates. A computing facility is scheduled to be in operation at the U.S.G.S. center by May 1967, and this will be suitable for any real-time computational support called for in the simulation trials.

In its simplest form, this base-computer could be called into service by the MGL operator reporting his sextant readings on two stars back to base over the communication link. To more closely simulate the MOLAB operation, a computer entry console similar to that described in Reference 1 could be placed in the MGL with telemetry of the input data back to the base computing center. The computed position could be telemetered back and displayed on the same panel. The equipment response from the

L. S. T.	Star	Altitude	
0 -1:00	Capella	$29^{\circ}-44^{\circ}$	Rising
	Vega	$29^{\circ}-15^{\circ}$	Setting
1:00–3:00	Capella	$40^{\circ}-65^{\circ}$	Rising
	Deneb	$42^{\circ}-18^{\circ}$	Setting
3:00–5:00	Pollux	$30^{\circ}-55^{\circ}$	Rising
	Sirius	$13^{\circ}-37^{\circ}$	Rising
5:00–5:30	Regulus	$18^{\circ}-25^{\circ}$	Rising
	Procyon	$41^{\circ}-52^{\circ}$	Rising
5:30–7:00	Regulus	$25^{\circ}-43^{\circ}$	Rising
	Aldebaran	$70^{\circ}-49^{\circ}$	Setting
7:00–8:00	Regulus	$42^{\circ}-55^{\circ}$	Rising
	Rigel	$43^{\circ}-29^{\circ}$	Setting
8:00–9:00	Capella	$59^{\circ}-44^{\circ}$	Setting
	Rigel	$34^{\circ}-19^{\circ}$	Setting
9:00–10:00	Capella	$48^{\circ}-34^{\circ}$	Setting
	Sirius	$32^{\circ}-18^{\circ}$	Setting
10:00–11:00	Capella	$38^{\circ}-24^{\circ}$	Setting
	Procyon	$48^{\circ}-33^{\circ}$	Setting
11:00–13:00	Regulus	$67^{\circ}-47^{\circ}$	Setting
	Arcturus	$45^{\circ}-70^{\circ}$	Rising
13:00–15:00	Vega	$23^{\circ}-48^{\circ}$	Rising
	Antares	$9^{\circ}-30^{\circ}$	Rising
15:00–17:00	Altair	$20^{\circ}-45^{\circ}$	Rising
	Spica	$42^{\circ}-19^{\circ}$	Setting
17:00–18:00	Altair	$42^{\circ}-56^{\circ}$	Rising
	Deneb	$45^{\circ}-60^{\circ}$	Rising
18:00–19:00	Arcturus	$37^{\circ}-26^{\circ}$	Setting
	Antares	$29^{\circ}-15^{\circ}$	Setting
19:00–20:00	Arcturus	$26^{\circ}-17^{\circ}$	Setting
	Caph	$32^{\circ}-47^{\circ}$	Rising
20:00–21:00	Vega	$73^{\circ}-60^{\circ}$	Setting
	Fomalhaut	$10^{\circ}-23^{\circ}$	Rising
21:00–23:00	Vega	$62^{\circ}-37^{\circ}$	Setting
	Altair	$62^{\circ}-38^{\circ}$	Setting
23:00–24:00	Vega	$40^{\circ}-25^{\circ}$	Setting
	Capella	$20^{\circ}-34^{\circ}$	Rising
		x	
0–24:00	Polaris	$29^{\circ}-41^{\circ}$	

Table 6-5 Stars Suitable for Observation[23]

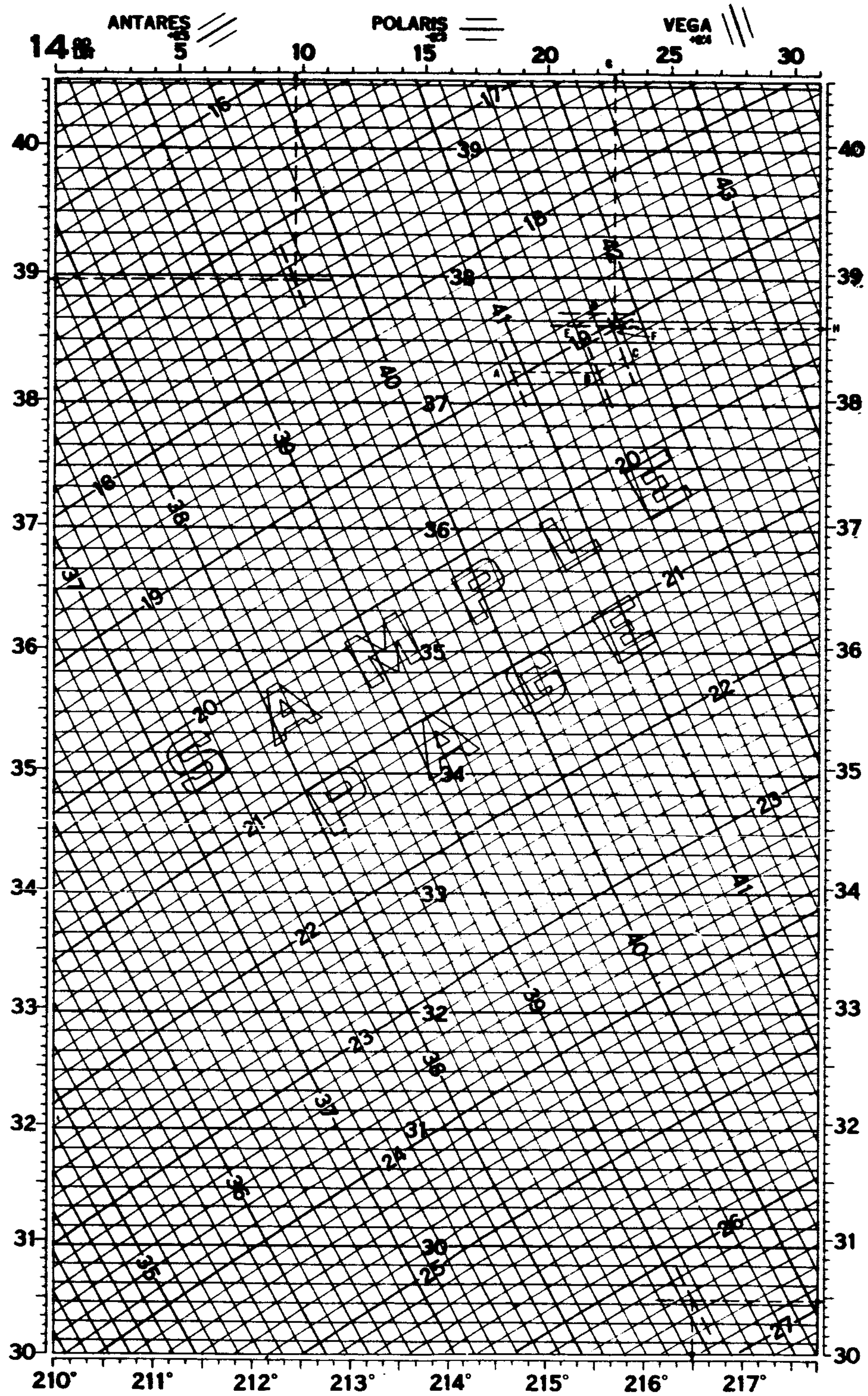


Figure 6-16 Sample of Star Altitude Curves

astronaut's point of view, would be identical with that called out for lunar operation.

As the simulation tests progress it is envisioned that the use of the base computing facility in real-time or in other ways will enhance the effectiveness of the MGL navigation system.

SECTION 7

RECOMMENDED INITIAL POSITION FIX SYSTEM

The functional requirements for the position fix system have been outlined in Section 5 and the alternative equipments available for implementing these functions have been described in Section 6. This section contains recommendations as to the equipments which can be readily procured to comprise the first MGL position fix system.

The fact that this system is to be the starting point of a development process had an important bearing on the choice of units. An initial screening of alternative equipments was made to rank them in order of increasing cost for adequate performance. Availability was then noted for each item, as well as development status and field experience. Finally, the remaining items were rated for compatibility with each other as a system and with anticipated system developments. The items which rated highest after this evaluation process are shown in Figure 7-1. The recommended initial position fix system would be comprised of only three items, as follows:

A. Periscopic Sextant:

The Kollsman proposed MGL sextant has been selected as the proper instrument for use on the initial MGL simulation tests. The Kollsman standard aircraft sextant might also be a favorable selection, but due to accuracy limitations is not as well suited as that proposed by Kollsman for position and heading fixing of the MGL. The periscopic sextants of the type approaching the MOLAB class of instrument are far too costly (refer to Figure 5-11) for MGL implementation at this early point in the MOLAB sextant definition.

The Kollsman-proposed sextant is described in Section 6.1.1.5.

B. Timepiece: - Bulova Watch Company

- Accutron Chronometer

- Clock rate drift less than 1 sec. per day

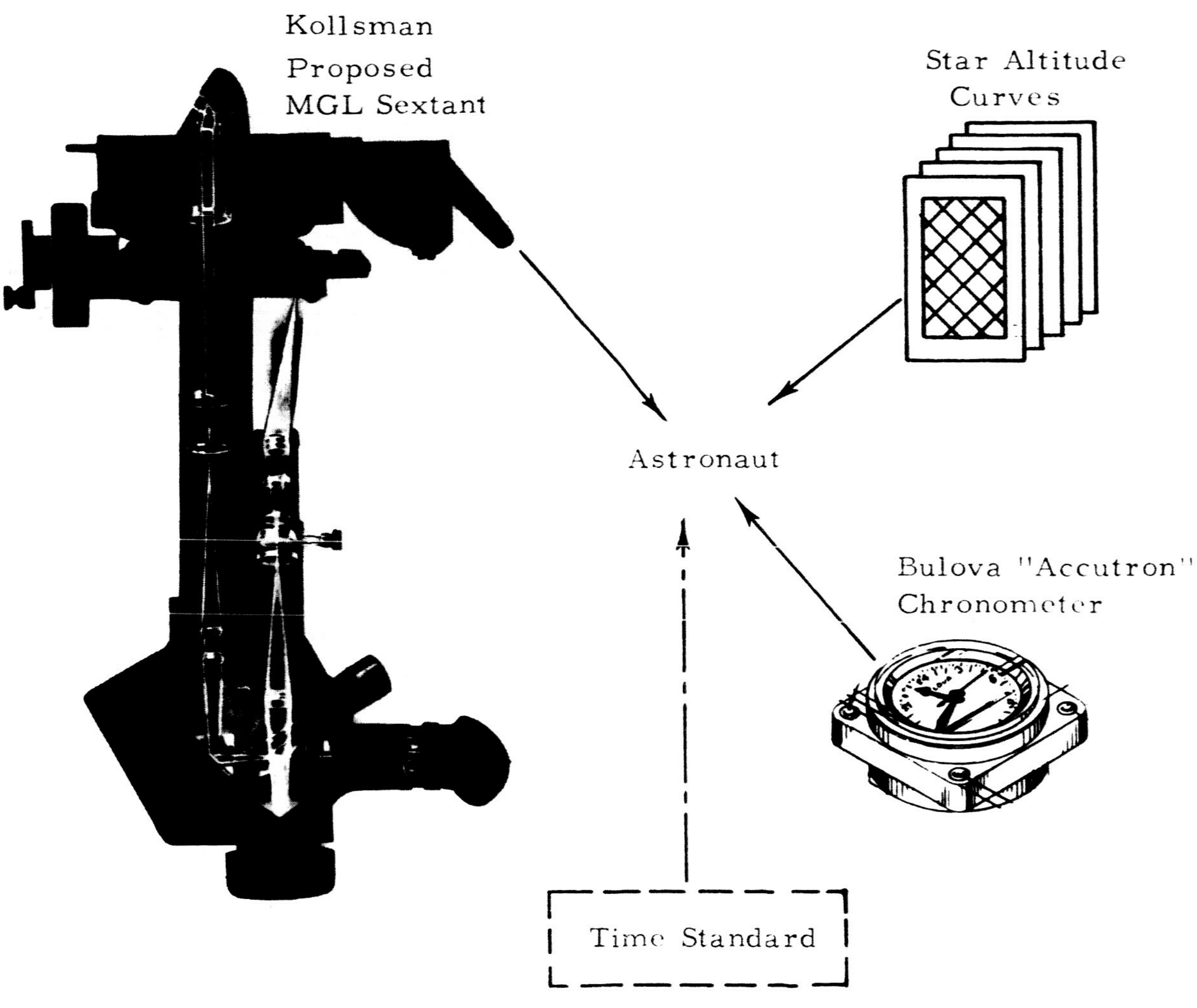


Figure 7-1 Position & Heading Fix System: Equipment Diagram

- 24-hour dial, reading in Greenwich sidereal time

- 360 cps tone burst @ one burst per second

- Budgetary Price: $525 - (plus cost of special case)

C. Position Coordinate Computer

Star altitude curves, having the general format produced by Weems System of Navigation, Inc. (see Figure 6-17) but modified as follows:

- latitude range: 34.5° N to 36.0° N.

- Resolution: Constant altitude plots at 1 arc minute increments

These charts can be generated to adequate precision on a computer controlled X-Y plotter. As in the Weems System the plotted values of altitude will be corrected for atmospheric refraction ensuring direct entry to the curves in terms of the sextant scale reading. The time required to compute and publish these charts is less than the stated delivery time for the sextant. Hence all units of the system can be made to have compatible deliveries.

In conclusion, the probable error in the resulting position as determined with this system based on celestial observations can be summarized as follows:

(a) Position Error Due to Sextant Reading

The RMS error of a sextant altitude sighting is stated as 0.5 arc minutes. If it is assumed that the two stars sighted subtend an angle of 90° at the observer, this yields a square area of position uncertainty with sides 1 arc minute in length. This is shown in Figure 7.2.

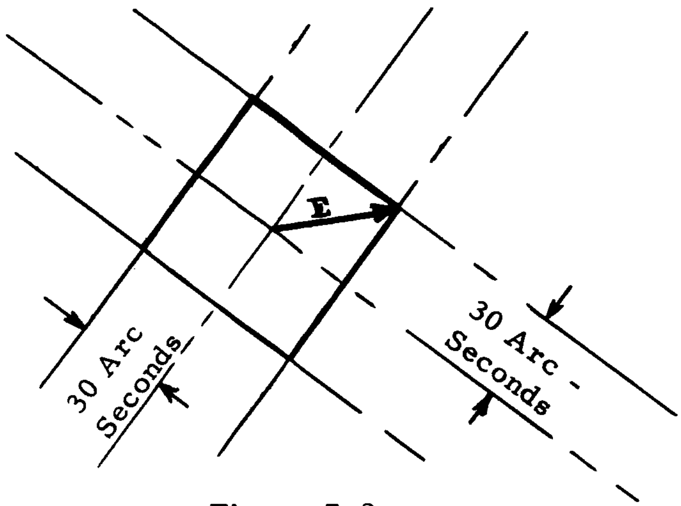


Figure 7-2
Position Error Due to Sextant Reading

As explained in Figure 3-4, a 0.5 arc minute angle is equivalent to a distance on the earth of 0.9 kilometers. This yields a 2-star position fix RSS error, E, of 1.3 kilometers.

(b) Position Error Due to Time Reading

As stated in Appendix D, the maximum probable error in position due to errors in recording the time of the sextant observations is 0.47 kilometers.

(c) Position Error Due to Computation

There is little reason to suspect that properly-prepared star altitude curves would contribute an error greater than $\pm$ 0.3 kilometers.

(d) Position Fix System Probable Error

Position Error	Due To:
1.3	Sextant readings
0.5	Time readings
0.3	Coordinate Computer
1.4	Total System (RSS)

The basis for selection of the MGL position fixing system was stated in Section 1 as:

(1) The MOLAB system designs presented in conceptual design reports by the Bendix Corporation[1] and the Boeing Company[2]

(2) A consideration of the earth-based simulation environment and mobile vehicle

(3) An equipment survey including an examination of the state-of-the-art and budgetary costs.

The position error of the selected system for the initial MGL implementation is of greater magnitude than that established for the position fix systems in the MOLAB studies (refer to Table 5-1); however, this error is within the target performance stated for the MGL system in Table 5-1. The difference between the MGL system error and the MOLAB systems errors is sufficiently small to assure that significant simulation tests can be performed.

The earth-based environmental factors and the navigation system's relation to the MGL vehicle were identified in the system requirements section, Section 5. At a conceptual level, the interfaces associated with the position fix system presented no difficulties.

Section 6 presented alternate system implementations. Throughout this section emphasis was placed on identifying the state-of-the-art and relating the various implementations with regard to budgetary costs. State-of-the-art and costs were a primary factor considered in the sextant selection.

The selected MGL position fix system thus represents the best trade-off in the areas of concern in providing an appropriate system for the initial simulation tests.

APPENDIX A

STATEMENT OF WORK FOR A NAVIGATION PERISCOPIC SEXTANT FOR USE ON THE MOBILE GEOPHYSICAL LABORATORY (MGL)

1.0 SCOPE

This Statement of Work covers the design, manufacture, test, and delivery of one (1) Navigation Periscopic Sextant and associated documentation to be installed in the MGL.

2.0 APPLICABLE DOCUMENTS

1. Bendix Systems Division Specification, AES-832, "Specification for a Navigation Periscopic Sextant for Use on the Mobile Geophysical Laboratory (MGL)", dated 22 December 1965.

3.0 TASKS

1. Design and manufacture one (1) Periscopic Sextant in accordance with the requirements of the specification; AES-832 .

2. Prepare an Acceptance Test Procedure to demonstrate the functional performance and accuracy of the periscopic sextant in accordance with Section 7.0 of the Specification, AES-832. This test procedure shall be submitted for approval at least 30 days prior to the schedule test.

3. Conduct an acceptance test in accordance with the approved test procedure at the contractor's facility. All test instrumentation and test personnel to be supplied by the contractor. The acceptance test shall be completed no later than 10 months after contract award .

4. Prepare the periscopic sextant for shipping by government bill of lading immediately after acceptance testing .

5. Provide documentation to include instllation, calibration, operation, and maintenance instructions at least 60 days prior to delivery .

6. Provide one (1) man-week of technical assitance during installation and calibration of the periscopic sextant in the MGL at Flagstaff, Arizona.

SPECIFICATION FOR A NAVIGATION PERISCOPIC SEXTANT FOR USE ON THE MOBILE GEOPHYSICAL LABORATORY (MGL)

1.0 SCOPE

This specification covers the requirements for a Navigation Periscopic Sextant to be installed in the MGL. The MGL is an earth based land vehicle designed to simulate the operation of the Mobile Laboratory (MOLAB) lunar surface vehicle. The periscopic sextant specified herein will be used in initial simulations of vehicle navigation operations. Specifically, the periscopic sextant is intended to be used for celestial star sightings and surface landmark sightings in support of vehicle position and heading fixing.

2.0 ENVIRONMENT

The MGL will be operated in areas within approximately a 100 mile radius of Flagstaff, Arizona. The periscopic sextant shall be designed to operate with external temperatures of -20° to $+100^{\circ}$F, with an internal MGL temperature of $+60^{\circ}$ to $+80^{\circ}$F, and shall be sealed against rain and dust. The periscopic sextant shall not be damaged or lose calibration when exposed to temperature extremes of -30° to $+140^{\circ}$F internal and external to the MGL.

3.0 PERFORMANCE

3.1 GENERAL

The periscopic sextant shall provide a capability for measuring the altitude of a star or landmark with respect to the local vertical and the azimuth of a star or landmark with respect to the MGL longitudinal axis.

3.2 FIELD OF VIEW

A true field of view of at least 15° shall be provided with magnification consistent with the dual requirement of star finding and accurate angular measurement.

3.3 ACCURACY

3.3.1 Altitude

No more than 50% of the sightings shall be in error by more than 15 arc seconds and no sighting shall be in error by more than 30 arc seconds.

3.3.2 Azimuth

No more than 50% of the sightings shall be in error by more than 30 arc seconds and no sighting shall be in error by more than 1.5 arc minutes.

3.4 RANGE

The center of the field of view shall be adjustable within the following limits:

3.4.1 Altitude

-10° to $+60^{\circ}$ minimum, -15° to $+80^{\circ}$ desired.

3.4.2 Azimuth

360° continuous rotation.

3.5 IMAGE ORIENTATION

An erect image shall be provided and it shall be correct as to right and left.

4.0 CONTROLS AND DISPLAYS

Controls and displays provided for shall include at least the following:

1. Altitude adjust; manual

2. Azimuth adjust; manual

3. Mark Time Control; manually actuated electrical switch. This switch shall be compatible with marking time to 0.1 second.

4. Altitude readout; visual

5. Azimuth readout; visual.

5.0 MECHANICAL DESIGN

5.1 GENERAL

The periscopic sextant shall be designed for installation in the roof of the MGL, see Figure A-1, and for operation by a standing operator. The roof of the MGL will be reinforced as necessary to support the periscopic sextant.

5.2 PERISCOPE HEIGHT

The periscope tube shall be of sufficient length to satisfy the exterior and interior requirements shown in Figure A-1. An adjustable height periscope is not required.

5.3 REMOVAL

The eyepiece portion, Figure A-1, of the periscopic sextant shall be removable from a mount fixed to the roof of the MGL. A storage case shall be provided for the removable portion of the sextant.

5.4 EYEPIECE

The centerline of the eyepiece shall be not less than 7 inches nor more than 12 inches below the roof of the MGL. An adjustable focus monocular eyepiece shall be provided. The exit pupil region shall be independent of altitude sighting angle but may rotate with the periscope for adjustment of the azimuth sighting angle.

5.5 LEVELING

A means shall be provided to level the periscopic sextant for any vehicle attitude up to 15° from horizontal. The sextant shall be pendulous to aid in this operation. An indication of level or an artificial horizon line shall be provided in the field of view.

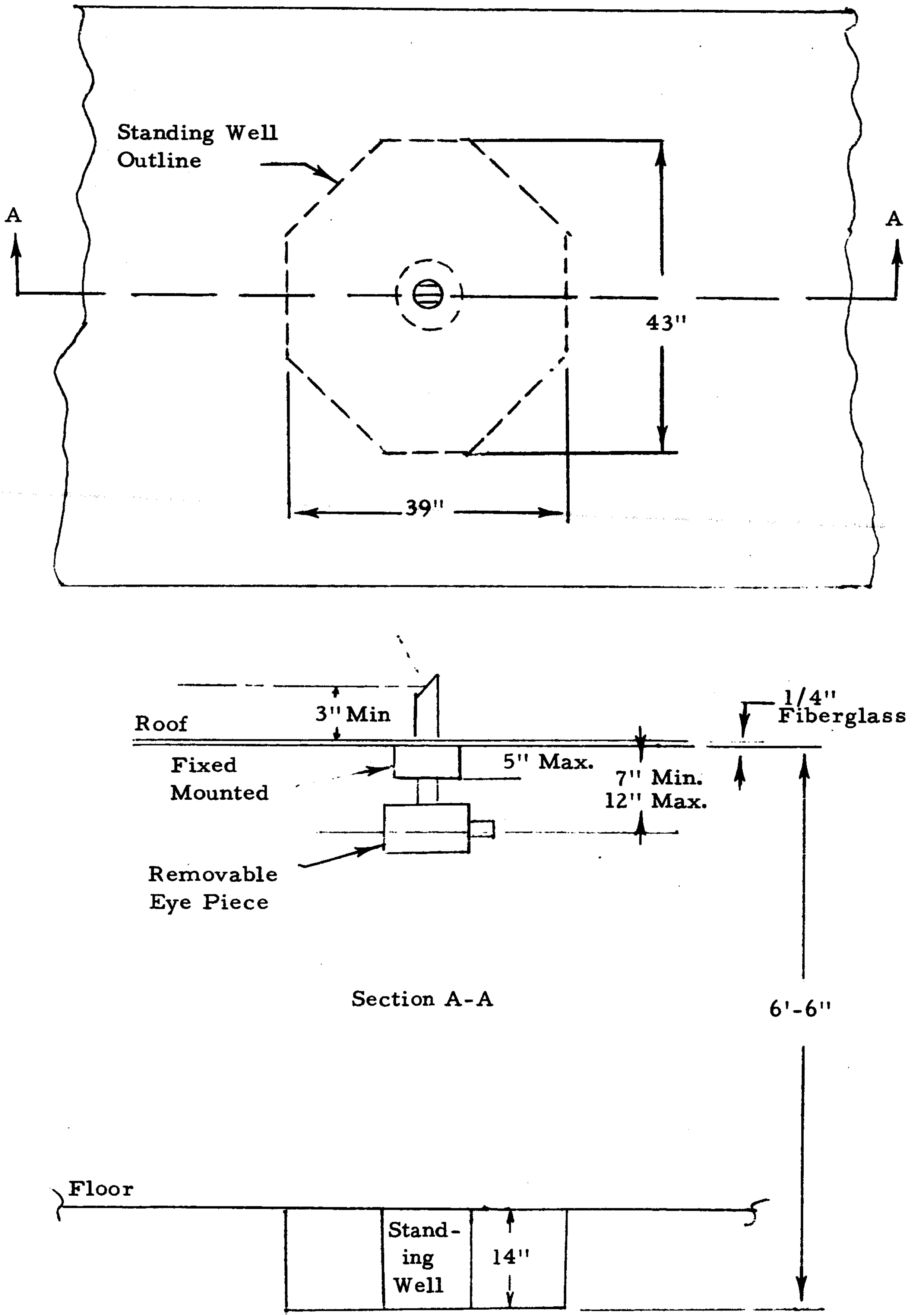


Figure A-1 MGL Sextant Mounting

5.6 WEATHER SEAL

A weather seal shall be provided as a part of the mount to prevent rain and dust from entering the vehicle with the eyepiece unit either installed or removed. This requirement does not have to be met during the act of installing or removing the eyepiece unit.

5.7 WEIGHT

The weight of the removable portion of the periscopic sextant shall not exceed 15 lb.

5.8 ELECTRICAL POWER

24 v ± 4 VDC power will be supplied if required, however, flashlight batteries in the periscopic sextant are preferred for internal ighting.

5.9 LIGHTING

Altitude and azimuth readouts shall be illuminated for night operation.

6.0 DESIGN OPTIONS

Consideration shall be given to incorporation of the following features in the original unit or as a later field modification:

1. Presentation of azimuth angle readout in field of view

2. Presentation of altitude angle readout in field of view

3. Addition of a second optical magnification of 6 X or use of zoom optics. It is intended that the field of view would be reduced in proportion to the increased magnification. Reference reticles or an artificial horizon should not increase in apparent size with increased magnification.

4. Manual rotation of the azimuth scale to permit azimuth readout to be referenced with respect to North. (Vehicle heading will be obtained manually from a gyro compass already installed in the MGL.)

5. Electrical readout of altitude and azimuth angles in parallel binary-coded-decimal format in degrees, minutes, and seconds in addition to the visual readout.

6. An integrating mechanism to average altitude angle over a period of 1 or 2 minutes. An electrical switch output shall be provided to signal the beginning and end of the integration period.

7. A camera attachment to photograph the image. A Polaroid camera is preferred.

8. A means for adding a laser ranging unit boresighted on the optical axis of the periscopic sextant.

9. Optical filters to enhance visibility of landmarks during daylight.

10. A zero calibration capability.

7.0 TESTING

7.1 TEST PROGRAM

An acceptance test program shall be conducted to demonstrate the accuracy capability of the delivered unit. The test procedure shall include at least 50 sightings of point source objects randomly distributed in azimuth and altitude. During test the sextant shall be mounted for standup operation but, otherwise, simulation of operation in the MGL is not required.

7.2 TEST INSTRUMENTATION

Test instrumentation used to determine true angles during the test program shall have an error not greater than 10% of the allowable error of the unit under test.

8.0 DEFINITIONS

8.1 ANGULAR ACCURACY

Sextant errors include the instrument random errors and the systematic errors which are not "easily" compensated for. Sextant error shall include human induced error associated with alignment of a star on a reticle or horizon line and manual readout error as produced by an experienced operator as well as errors introduced by manufacturing tolerances.

APPENDIX B

SPECIFICATION FOR A TIMEPIECE FOR USE ON THE MOBILE GEOPHYSICAL LABORATORY (MGL)

1.0 PURPOSE AND SCOPE

To present the required characteristics of a timepiece suitable for displaying Greenwich mean time.

The timepiece is to be observed by an astronaut/navigator to determine the precise time of celestial sightings made with a periscopic sextant.

The timepiece will be mounted to a bulkhead or panel in a land roving vehicle.

2.0 ENVIRONMENT

2.1 TEMPERATURE

The timepiece shall display Greenwich mean time to the precision stated in Section 3.3 over an ambient temperature range of 60°F to 80°F.

The timepiece shall not be permanently damaged nor shall its operational lifetime be significantly reduced due to storage or operation within the temperature range -30°F to 140°F.

2.2 HUMIDITY

The timepiece shall display Greenwich mean time to the precision stated in Section 3.3 under sustained ambient conditions of 100% humidity.

2.3 DUST

The performance of the timepiece shall not be degraded when operating in a dust-laden atmosphere.

2.4 MAGNETIC FIELDS

External magnetic fields

The degradation of performance when operating in an external magnetic field shall be minimized.

Residual magnetic field

After exposure to external AC or DC fields of up to 100 gauss, the change in the indicated GMT due to residual magnetic fields shall not exceed 2 seconds per day.

2.5 SHOCK

The timepiece shall be resistant to shock impulses of up to 20 g in any direction.

2.6 MOUNTING ATTITUDE

The timepiece shall display Greenwich mean time to the precision stated in Section 3.3 when rotated 20° about either horizontal axis and 360° about vertical axis.

3.0 PERFORMANCE REQUIREMENTS

This timepiece shall present an unambiguous display of Greenwich mean time having the following characteristics:

3.1 Separate indications of hours (0 to 24), minutes and seconds (clearly readable to 0.5 second at a distance from 8 to 24 inches) shall be provided.

3.2 Facilities shall be provided for easily and consistently synchronizing, to within 0.2 second, the display of time with a time standard such as WWVB.

3.3 Provided that the indicated time corresponds with true Greenwich mean time at a particular instant, the indicated time shall not differ from true Greenwich mean time by more than one second over the following 24-hour period.

4.0 DESIGN REQUIREMENTS

4.1 SIZE

The timepiece shall be packaged as compactly as possible consistent with the performance requirements of Section 3.

4.2 POWER SOURCE

The timepiece must operate unattended for a minimum of 14 days. It is preferable that the timepiece derive its operating power from some electrical source and that this source be self-contained. However, alternate types of power, either internal or external, are acceptable if the minimum unattended operating time can be provided.

5.0 DESIGN OPTIONS

The following features are not included in the required characteristics but shall be provided where possible.

5.1 DISPLAY HOLD

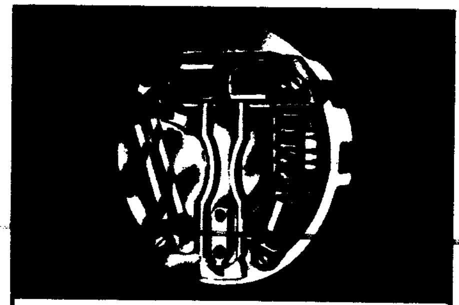
Upon activation of an electrical or mechanical signal, the displayed time at the instant of the signal shall be frozen. As a minimum requirement the "seconds" display shall stop and be able to hold the value for up to 60 seconds without losing the ability to resynchronize with the timing mechanism upon release of the "Hold". It is desirable for all three displays to freeze upon receipt of the signal and to hold for a longer period, but this need only be provided if the design to yield the primary requirements renders it feasible.

APPENDIX C

MANUFACTURER DATA SHEETS FOR TIMEPIECE

This appendix contains specification data sheets for the Bulova electromechanical chronometer and for four makes of electronic digital clocks. The electronic clocks are not the only ones available but are representative of the range of performance and capability available in this kind of equipment. The data sheets presented are as follows:

BULOVA
ACCUTRON*
Timers, Clocks, Switches



GENERAL SPECIFICATIONS APPLICABLE TO ALL ACCUTRON* CLOCKS, TIMERS AND SWITCHES

CASE
Aluminum meter-type, dull black anodized with flat non-reflecting glass crystal. Four rubber grommeted holes in flange for No. 3 mounting screws.

DIAL AND HANDS
Dull black dials with white numerals and graduations. All hands white and coaxial. Hands rotate clockwise.

SETTING
Hour and minute hands settable from rear of timer in all clock models except TE 13-11 which has front setting. Hack feature for stopping second hand for exact setting.

MOVEMENT ACCURACY
Rate 0 ±1.5 sec/day in customer specified attitude at 25°C. Other regulation such as for sidereal time or to correct for special environmental conditions, i.e., operation at reduced pressures, available to customer specification.

POWER SOURCE
Special internal power cell provides extended life at fixed voltage. Voltage 1.32. Current 6 ±1 microamperes at 25°C. Operating life 12 months minimum at temperatures up to 32°C. Current increases rapidly with temperature above 25°C for germanium transistor but only very slightly with silicon transistor. Special 2 year minimum life battery available for 2-3 year switch. Beyond 3 years external source required.

TORQUE
Max. torque output of mechanism 5 gm cm. at 1 rev/hr. Friction clutch on center shaft for setting hands must be altered to provide this torque.

PRESSURE
Rate will be faster 0.71 seconds per day for every 1.0" mercury decrease in pressure. Timers used at high altitudes can be readily regulated to compensate for lower pressure. Continuous exposure to high vacuum is permissible.

ACCUTRON based timers employ a simple mechanism that is almost foolproof: a precision tuning fork. Subsequently, there's a minimum of moving parts, a minimum position error, and an absence of isochronal error. This mechanism can be used as a pulse counter, as an elapsed timer indicator, or to sense changes in temperature, pressure, acceleration, etc. The table on page 2 indicates a few of ACCUTRON timers currently in use.

MAGNETISM
In a 60 gauss A.C. or D.C. external magnetic field, the rate can be a maximum of 60 seconds a day slower than before exposure to such a field. The residual effect after exposure to fields of 100 gauss A.C. or D.C. can be a maximum of 4 seconds a day. Avoid exposure to A.C. or D.C. fields in excess of 200 gauss because they may demagnetize the magnets on the tuning fork.

ACCELERATION
Rate changes 5 seconds per day per g parallel to axis of fork. Rate is faster when force due to acceleration is directed from base towards tines. Rate is slower when force due to acceleration is directed from tines toward base. Acceleration does not affect timing rate on other axes. Timer will not operate above approximately 20 g perpendicular to plane of tines or 10 g in plane of tines, perpendicular to axis of tines. No permanent damage will result if these forces are exceeded.

TEMPERATURE
Operating range 0°C to 50°C with germanium transistor, —40°C to 80°C with silicon transistor. Rate change with temperature ±.25 sec/day °C max. Safe range for storage —55°C to 55°C with germanium transistor, —55°C to 100°C with silicon transistor.

MOISTURE
Accutron timers are normally supplied in housings which are dust proof and moisture proof but not immersion proof under severe environmental conditions.

NUCLEAR RADIATION
Avoid exposure to nuclear radiation — operation of circuit may be affected and transistor permanently damaged by exposure to radiation. Tolerance limits have not been established.

R. F. FIELDS
Dial and case provide complete shielding of movement from strong R. F. fields.

SHOCK
Resistant to shock, any direction, to at least 1,000 g. Extreme limit not established.

VIBRATION
Vibration isolation mounting recommended if accurate operation required at 300-400 cps. Rate increases with increasing g. Withstands 100 g at 5-2000 cps sinusoidal and 25 g rms random vibration on all three axes without permanent damage. Withstands 50 g rms random vibration on 2 axes.

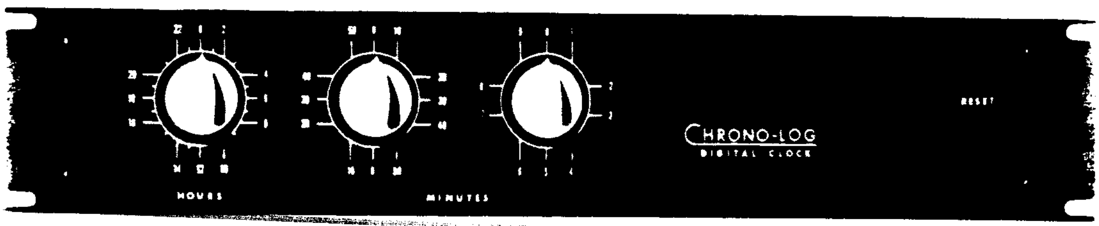
*Registered, U.S. Patent Office. The ACCUTRON movement is covered by U.S. Pat. No. 2,971,323 and other U.S. and foreign patents issued and pending.

BULOVA
INDUSTRIAL & TIMER PRODUCTS

Series 1000-9000

CHRONO-LOG

DIGITAL CLOCKS



The Chrono-log Series 1000-9000 Digital Clocks provide time, date and count inputs to digital computers, data handling systems, data loggers, digital time displays, telemetering systems and checkout equipment. The units can also be used as program controllers, providing unique contact closures for each time interval.

Outputs of the Series 1000-9000 Digital Clocks are in the form of parallel, non-ambiguous, decimal or 8-4-2-1 binary coded decimal contact closure patterns. Up to three independent outputs can be provided in a single unit; decimal or BCD outputs can be combined in one unit.

In most cases, rhodium plated etched circuit commutators are used for the digital circuitry. Precious metal brushes are driven by rotary solenoids operating at less than 10% of their rated duty cycle. All solenoids are suitably suppressed and RF filters and line filters are furnished in all units to eliminate RF propagation.

MODEL 2500 DIGITAL CLOCKS

Model 2500 Digital Clocks provide time-of-day readings in 24 hour or 12 hour time with a resolution of one minute. Time setting and adjustment are made by means of three knobs on the front panel, one each for hours, tens of minutes and minutes. The knobs also provide an indication of the time.

MODEL 2600 & 2700 DIGITAL CLOCKS

Similar to the Model 2500 Digital Clocks, the Model 2600 and 2700 Digital Clocks provide time resolutions of one second and tenths of minutes, respectively. Timing is synchronous with the AC supply frequency or with an external precision frequency source.

MODEL 2800 DIGITAL CALENDARS

The Model 2800 Digital Calendars provide date readings in months and days, i.e. 10/26 for October 26. An external contact closure actuates the Calendar; this contact closure can be obtained from a Chrono-log Digital Clock. The Digital Calendar automatically corrects for 30 and 31 day months and in conjunction with a front panel switch, for the length of February (Leap Year Correction).

MODEL 8000 DIGITAL COUNTERS

Designed for slow speed counting applications, the Model 8000 Digital Counters are widely used as Days Counters or frame counters in data systems. Three, four and five digit models are available with ranges of 000 to 999, 0000 to 9999 and 00000 to 99999. An external contact closure, which can be obtained from a Chrono-log Digital Clock, actuates the Counter.

MODEL 9000 DIGITAL TIMERS

Similar to the Digital Counters, the Model 9000 Digital Timers are actuated from an internal time base and generate time readings in the ranges 000 to 999, 0000 to 9999 and 00000 to 99999. Various time resolutions can be furnished including seconds, minutes, hours, hundredths of hours, tenths of minutes and millidays.

GENERAL SPECIFICATIONS

OUTPUT. Parallel decimal or 8-4-2-1 BCD contact closure patterns with an externally wired lead for each digit position; this permits easy conversion to a serial output by means of an external scanning switch.

OUTPUT CONNECTORS. Cannon miniature connectors are used for input and output data connections. The following connectors on the rear of the chassis are furnished for EACH OUTPUT in the unit; mating connectors and junction shells are available when ordered:

EACH OUTPUT OF:	Cannon DD-50P	Cannon DB-25P
HOURS and MINUTES	one	—
HOURS, MINUTES and SECONDS	one	one
HOURS, MINUTES and 0.1 MIN.	one	one
MONTHS and DAYS	one	—
999	one	—
9,999 or 99,999	one	one

INHIBIT CONTACT. (Not furnished in Models 2600 and 2800.) One (1) SPDT INHIBIT CONTACT is supplied in each unit, for preventing ambiguous readings by delaying the start of any readout which cannot be completed before an output change occurs. The INHIBIT CONTACT is rated for 2 amps. at 110 V, AC or DC, non-inductive. The INHIBIT CONTACT transfers at least one second before a change in output and returns about 50 ms. after the change is completed.

LOAD SWITCHING CIRCUIT. (Not furnished in Model 2800.) One (1) SPST N.C. LOAD SWITCHING Circuit is supplied for each output. This circuit can be used to interrupt the power to an output circuit which would be energized during an output change, such as parallel light displays. Use of the LOAD SWITCHING circuit eliminates switching at the etched circuit boards and increases the current carrying capacity of the output circuits.

The LOAD SWITCHING contact can also be used to inhibit high speed readouts during an output change, to avoid ambiguous readings. The LOAD SWITCHING contact opens about 40 ms. before a change in output and closes about 50 ms. after the change is completed. The output change sequence requires a total of about 100 ms.

OUTPUT LOAD RATINGS. Output circuits are rated for 100 ma. per digit at 110 V, AC or DC, non-inductive, when switching of load currents is done by the output. When the LOAD SWITCHING circuit is used or no load currents are switched by the output, the circuits are rated for 0.5 amps. per digit at 110 V, AC or DC, non-inductive.

SETTING. Setting of hours and minutes, months and days, and the three most significant digits in 8000/9000 Counters—Timers is done by means of direct reading indicating knobs on the front panel. Setting of other digits is done by means of an on-off switch on the front panel. For example, in a Model 2600 Clock, timing is stopped at 00 seconds, indicated by the stepping of the minutes knob; the time at which the Clock will be restarted is then set on the knobs. At the proper instant, the switch is turned on to start timing.

MODEL 2800 DIGITAL CALENDAR ACTUATION. The Digital Calendar is actuated by an external contact closure of approximately one second duration, which breaks at midnight. The Calendar changes output when the external contact opens. The external contact carries 115 volts AC, 3 amperes max. Chrono-log Digital Clocks can provide the necessary contact closure for actuating the Calendar.

MODEL 8000 DIGITAL COUNTER ACTUATION. Model 8000 Counters are actuated by an external contact closure. When the external contact closes, the rotary solenoids prime but do not change the count. When the external contact opens, the count changes. The external contact should operate on a duty cycle of 25% or less with a recommended pulse length of 0.5 seconds and a maximum pulse length of one second. The external contact must handle 3 amps., 115 V, AC. When used as a Days Counter, the Counter can be actuated from a Chrono-log Digital Clock, in the same manner as the Model 2800 Digital Calendar.

POWER REQUIREMENTS. Standard supply voltage is 115 V, 60 cycles. Other frequencies and voltages are available. Peak power requirement is 300 watts. Average power required is 25 watts or less.

POWER FAILURE. Indicated on front panel when failure occurs. A SPDT contact is also provided for remote power failure indication. Timing restarts on power resumption but the power failure indications remain until reset.

RF NOISE FILTERING. RF noise filters and a line filter are included in the units to eliminate RF noise propagation.

ACCESSORIES. Instruction manual and line cord.

HOLD CIRCUIT (OPTION). A HOLD circuit can be furnished on any Chrono-log Digital Clock or Timer to prevent time change from occurring while external equipment is reading out the time. A normally open contact in the customer's equipment is used to actuate the HOLD circuit. This N.O. contact should close approximately 80 milliseconds prior to the start of readout and should open immediately after readout is completed. The external N.O. contact should be capable of switching 3 amps. at 115 volts, 60 cycles, AC, and should remain closed no more than 3 seconds.

FUSE. Accessible from front panel.

DIMENSIONS. 3½" high by 12" deep by 19" wide. Standard relay rack mounting.

COLOR. Standard color is light grey.

WEIGHT. Net weight approximately 23 pounds. Shipping weight, approximately 28 pounds.

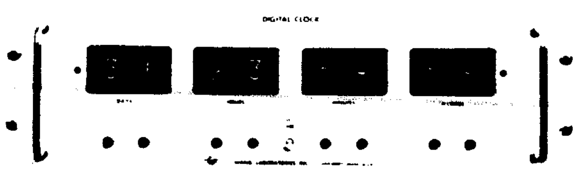
CHRONO-LOG CORP., 2583 West Chester Pike, Broomall, Penna. (ELgin 6-6771)

Wang Laboratories, Inc.

836 NORTH STREET

Tel. 617-851-7311 **TEWKSBURY, MASSACHUSETTS** TWX 617-851-7047

2000 SERIES DIGITAL CLOCKS



*** All solid-state.

*** **Available to your** exact specifications.

*** Attractively priced.

*** Generate timing pulses, provide time data for recording, display time in easily-read NIXIE tube decimal numbers.

DESCRIPTION

These all solid-state highly reliable Digital Clocks are precision instruments for both laboratory and systems applications requiring accurate time-of-day, elapsed time, or system timing control. The standard model provides visual display on six in-line NIXIE tubes, with a range of 00:00:00 to 23 hours:59 minutes:59 seconds. Other ranges are available. The clock is constructed from a wide line of proven Logibloc plug-in circuit modules, offering outstanding flexibility for adaptation to special requirements.

Electrical output is provided as Binary-Coded Decimal voltage levels in 1-2-4-8 code. Other formats are available, or electrical output may be omitted. Timing pulses of one pulse per second are provided, and an external one pps source may be used as a time base.

Time is derived from the 60 cps power line. Experience indicates instantaneous line frequency accuracy of ± 0.1% is maintained within the United States, and long term accuracy is excellent. High accuracy crystal controlled internal time bases are also available: A 100 Kc oscillator of ± 3 ppm short-term stability and ± 10 ppm drift per week is available at a surcharge of $150.00, and oscillators of higher accuracy have been provided on special order. With the internal 100 Kc oscillator option the Digital Clock may be synchronized with an external 100 Kc source, and time-base dividers for use with 1 Mc, 2.5 Mc, or 5 Mc frequency standards are available as modifications.

Front panel push-buttons are provided so that each digit of time may be manually set without disturbing other digits or all digits may be simultaneously reset to 00:00:00. Thumbwheel switches are available on special order for addition of date and month to the electrical output, or date may be advanced automatically by a calendar clock (photo).

Bulletin No. 32

The standard Digital Clock is available in a choice of enclosures: Relay rack mounting (19" wide enclosure, requires 5½" panel height), or bench mounting. The latter is a compact unit in a portable carrying case 9½" high, 7½" wide, and 6" deep, with a convenient carrying handle. Operation is from a 115 VAC 60 cps power line, and 400 cps or 50-400 cps operation is available on request.

Wang Laboratories, Inc., has supplied Digital Clocks for emergency operation from an internal rechargeable nickel-cadmium battery supply. A unique change-over circuit avoids loss of drive while switching to batteries. Clock power requirements are minimized by the economical use of all solid-state NOR circuitry.

Output pulses at selected times, or at switch-selected time intervals, may be provided for systems application. Other features may be added at customer request. These include:

1. 0.1 second time increments, or others as specified.
2. Split ranges, for count down or count down/count up applications, such as T-1000 seconds to T + 1000, and change to 23:59:59.
3. Phase advance controls for precise synchronization of high accuracy time base. Advances or retards phase at selected rate when button depressed.
4. Serial output. Most or least significant bit first, 10-line decimal, BCD, or natural binary output.
5. IRIG, NASA, or other format input or output for range display or time code generation.
6. Thumbwheel switch presets for starting or stopping, or recording from ancillary equipment at selected times.
7. Remote display.
8. Display on projection type units (specify).
9. Chassis sharing. The Digital Clock may be combined with a counter, multiplexer, punch driver, etc., to provide a complete system or sub-system on one chassis.

SPECIFICATIONS

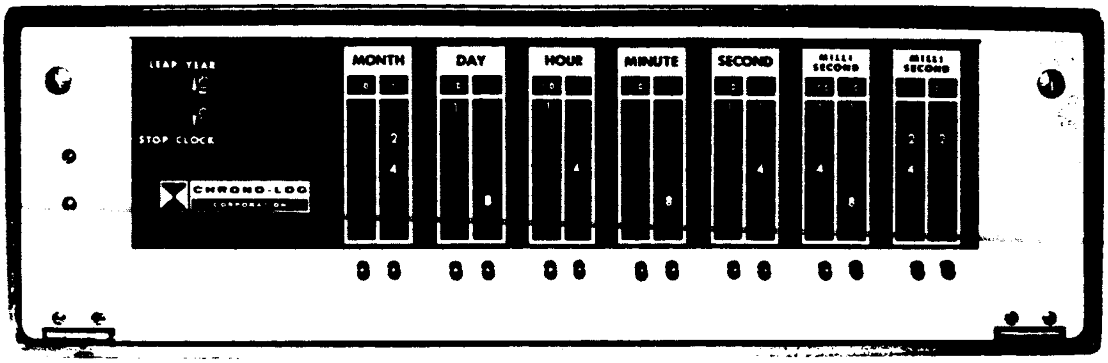
RANGE:	00:00:00 to 23 hours:59 minutes:59 seconds in standard models. Other ranges available on special order.
VISUAL DISPLAY:	Time of day or elapsed time is displayed on 6 in-line NIXIE tubes, with an appropriate filter.
ELECTRICAL OUTPUT:	Time data given in parallel 1-2-4-8 BCD form, binary "0" = -1 ± 0.5 volts, binary "1" = -9 ± 3 volts. Other outputs on special order.
TIMING OUTPUT:	1 pulse per second (-6 volts or more behind 10 kilohms, duration 0.2 sec.).
TIME SET/RESET:	Push-buttons provided to set each digit of time, and one to reset all digits to 00:00:00.
TIME BASE:	60 cps power line. Internal crystal oscillator available.
TIME INTERVALS:	Available for system control. Consult factory.
DIMENSIONS:	Relay-rack enclosure 19" W x 5½" H x 14" D. Bench (portable) case 9½" H x 7½" W x 6" D.
PRICE:	Standard models, $900.00. Delete $150.00 for omission of electrical output. Consult factory for prices on modifications, or on custom designed clocks. Inquiries are invited.

Series

10,000-19,000

CHRONO-LOG

DIGITAL CLOCKS



The Chrono-log Series 10,000-19,000 Solid State Digital Clocks provide digital time inputs to digital computers, data handling systems, data loggers, time displays, telemetering systems and checkout equipment. Either decimal, binary-coded decimal (with or without parity) or straight binary code can be provided. A wide variety of time ranges, resolutions and outputs are available.

The Series 10,000-19,000 Solid State Digital Clocks are compatible with modern, high-speed transistorized digital systems. Flexible output options permit use of the Clocks in either parallel or serial systems. Modular design and construction insure that the Chrono-log Solid State Clocks will meet exact system requirements at minimum cost.

Germanium semiconductors, operating in "worst-case" design circuits, are used in the Clocks. Plug-in glass-epoxy card construction is used throughout, with all cards accessible from the hinged front panel. Standardized cards are used to reduce the number of different cards per Clock. Since the Clocks utilize solid state logic, there is no generation of either electrical transients or audible noise.

Clocks can provide elapsed time or real-time, including the date in months and days, or day of the year. The minimum time resolution is 100 microseconds. Gated outputs are provided where the Clock must share an input register with other digital devices; external "interrogate" lines are used to read the Clock into the register through gates in the Clock. Outputs can be serial or parallel. Internal serializing can also be provided in the Clock to read the time serially at the desired data rate.

Nominal signal levels in the Clocks are —10 volts with an 860 ohm source impedance, and zero volts. Normal maximum output current is 5 ma. (Lamp driver outputs for incandescent decimal displays also can be furnished.)

An attractive illuminated front panel display of the coded Clock reading is provided. A pushbutton per digit on the front panel allows each digit to be set manually to any initial value. The Clock will reset to zero upon receipt of an external electrical "reset" signal, and remain reset until the external signal is removed.

When the Clock includes the date (Clock/Calendar), the date is automatically corrected for 30 and 31 day months and, in conjunction with a front panel switch, for the length of February (Leap Year correction). When the Clock includes a Days Counter, the days output automatically resets to 001 after 365 or 366 days, depending upon the setting of the front panel switch (Leap Year correction).

The Series 10,000-19,000 Clocks require less than 5 microseconds for time change. During time change, an Inhibit bit is generated to signal to the external system that a transition is occurring. An external HOLD signal can also be used to prevent time change from occurring during a readout cycle.

The Clock is designed for either bench or standard 19" relay rack mounting. It requires only 5¼" of panel height and 15" of depth behind the panel, including mating connectors.

GENERAL SPECIFICATIONS

SIGNAL LEVELS: Zero volts; and —10 volts through an 860 ohm source impedance.

OUTPUTS: Digital output of time (and date). Output options are as follows:

> **PARALLEL READOUT:** With parallel readout, all bits of all characters and the complement of all bits are available on the output lines at all times. Output code is either BCD (4 bits per decimal digit) or BCD plus parity (5 bits per decimal digit). Either odd or even parity is available.
>
> **GATED PARALLEL READOUT:** With internal gating, the complete output word is read at one time, under external control. All bits are at logical "O" except during the time a "Read Clock" signal is received from the external system. Output transistors are cut-off except during readout. (Normally, complement is not provided with this option.)
>
> **SERIAL READOUT:** Digits are read character-by-character on a common 4 line (if BCD) or 5 line (if BCD plus parity) data bus. Output transistors are cut-off except during readout. Readout starts on receipt of a "Read Clock" signal and proceeds until the entire message has been read out. Clock automatically HOLDS to prevent time change during readout cycle. Typical data rates are 10 KC to 100 KC. A typical 13 digit time/date message requires approx. 280 microseconds at a 50 KC data rate.

TIME FORMAT: A great variety of formats are available. A typical thirteen digit Clock/Calendar has Months, Days, Hours, Minutes, Seconds, Milliseconds. Other formats utilizing millidays, deciminutes, etc. are available.

DISPLAY: An attractive front panel display of all digits in binary-coded-decimal, (or BCD plus parity) is provided for checkout and time setting.

TIME SETTING: A pushbutton per digit, mounted on the front panel below each digit's display, allows each digit to be manually advanced step-by-step. The Stop-Go switch on the front panel may be used to stop the clock while setting.

TIME BASE ACCURACY: One part per million per week after initial three months of operation if internal oscillator is provided. If line frequency is used as the time base, the Clock is as accurate as the line frequency.

AMBIGUITY: Time change takes less than five microseconds.

INHIBIT: The clock generates a 6 microsecond Inhibit signal spanning the five microseconds required for time change. This signal may be used to flag any time readings made during the transition time.

HOLD: An external HOLD signal can be used to prevent time change during readout. As long as the external HOLD signal is present, the clock will not change time. The HOLD signal must be shorter than the smallest time increment in order to prevent accumulation of a timing error. The HOLD signal should start at least five microseconds before read-out is requested.

REMOTE RESET & START: For those applications where the clock is used to measure elapsed time, rather than time of day, remote RESET of all digits to zero from an external signal is provided. The clock will start keeping time when the external RESET signal is removed.

DESIGN STANDARDS: "Worst-case" design procedures used. Ultra-reliable germanium transistors produced in high volume for major computer programs are used. Circuits use standard transistors; no specially selected transistors are required. Resistor-transistor-logic (RTL), diode-transistor-logic (DTL) and direct-coupled-transistor-logic (DCTL) in common-emitter circuits are used.

CONSTRUCTION: Glass-epoxy plug-in cards, gold plated contacts.

ACCESS: Hinged front and rear doors allow complete access to all plug-in cards and power supply components.

FUSES: On Rear.

ON-OFF SWITCH: On Rear.

SIZE: 19" Relay Rack mounting, 5¼" panel height. 17" wide if bench mounted. ⅝" maximum protrusion in front of panel. Maximum of 15" from rear of panel to rear of mating connector (cable clamp on side of mating connector).

LINE VOLTAGE: 115 V, 60 cycle is standard — other voltages and frequencies on special order.

POWER SUPPLY: Power supply voltages (internally generated) are +12 V and —12 V. In applications where loss of time-keeping during power-line outages cannot be tolerated, provisions can be made to feed these voltages directly from batteries.

MATING CONNECTORS: 75 Pin mating connectors can be furnished by the customer or ordered from Chrono-log. Specify:

> Winchester XMRA-75P-C-1A-406 (where one connector is used).
> Winchester XMRA-75P-C-1B-406 (where second connector is required).

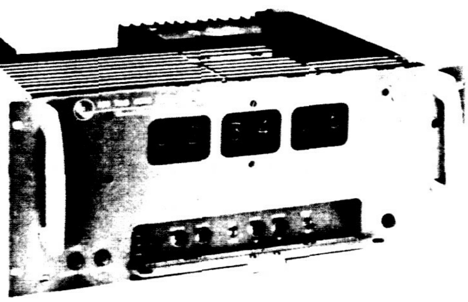
POWER CONNECTOR: Three wire (grounded) connector.

ACCESSORIES: Instruction manual and line cord.

CHRONO-LOG CORP., 2583 West Chester Pike, Broomall, Pa. (215 ELgin 6-6771)

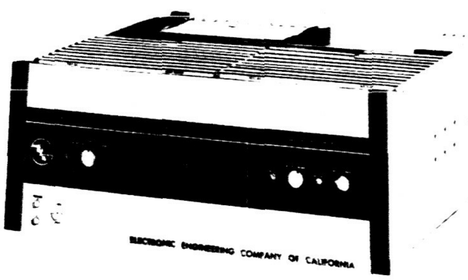
EECO 806, 807, 808

TIME CODE GENERATORS



FEATURES

- **Designed for high reliability** under varied environmental conditions, circuit cards used in 806, 807, and and 808 Time Code Generators are EECO's time-proven standard units.
- **Rugged, light-weight** EECO time code generators are ideally suited for mobile operations in instrumentation vans, aircraft, and in seaborne vehicles. Unit weight is less than 39 lbs.
- **Low power consumption** makes EECO time code generators highly practical for ground checkout and mobile or airborne instrumentation vehicles. Power consumption is less than 100 watts. Battery back-up can be provided.
- **Magnetic core scanning** to reduce power consumption.
- **Printed circuit card connectors** are tested to meet requirements of MIL-C-21097A.
- **Maintenance is simplified.** Readily accessible test points are provided.
- **Frequency setting accuracy** is 1 x 10^{-8}; stability is 5 x 10^{-8} per day under usual laboratory conditions.
- **Normalized outputs** permit direct input to instrumentation type magnetic tape recorders, oscillographs, strip charts, distribution amplifiers, auxiliary timing equipment and some digital time printout systems and radio transmitters.
- **Short-proof parallel time** outputs protect both data and equipment.



APPLICATIONS

Precision output signals from EECO 806, 807, 808 time code generators provide:

- Time bases on test ranges and at special facilities.
- Time data source for computers and data processing systems.
- Coordination and recovery of analog information stored on magnetic tape and chart recorders.
- Time standards for satellite tracking.
- Correlation of data acquired at sites by many types of instrumentation.
- Time references for astronomical observations.
- Simulated precision test range timing source for checkout of missile and space vehicles.

EECO 806, 807, 808
GENERAL SPECIFICATIONS

CONTROLS: To minimize the possibility of accidental switch movement, all switches effecting the calibration, set-up, and synchronization of a unit are interlocked in such a way that accidental operation is impossible. Switches are provided to set a desired time into the unit, advance or retard the basic 1 pps pulse, and to select (806 and 807 only) output pulse rates.

ACCURACY AND STABILITY: Crystal-controlled internal 1 mc frequency standard maintains a stability of 5×10^{-9} per day at normal ambient temperatures. The time accuracy is better than 0.1 second over a 30-day period.
The stability is better than 3×10^{-8} per day over the specified −20°C to +55°C ambient temperature range.

EXTERNAL FREQUENCY STANDARD: A 1 mc or 100 kc external frequency standard may be substituted for the internal oven-controlled crystal oscillator on the EECO 806, 807, or 808. The accuracy of the TCG is determined by the stability and frequency setting accuracy of the external standard used.

SIZE AND WEIGHT:
Height. . . . . 7"
Chassis Depth. . . . . .17" (EECO 808, 18 inches)
Standard Panel Width. . .19"
Weight. . . . . .39 pounds (EECO 807; others slightly less)

POWER REQUIRED: 117 VAC ±10%, 50-400 cps, 1 amp (maximum).
All EECO time code generators employ EECO solid state regulated power supplies mounted directly on the chassis.

OUTPUT SIGNAL CHARACTERISTICS

DC Level Shift Serial Code. . . . . Adjustable 0.5V to 11V base line to peak, code "0" is 0.0V
100 ohms source impedance

Modulated Serial Code. . . . . Adjustable 0V to 12V peak to peak
Max. load is 600 ohms.
Single ended output.

Parallel Code. . . . . "1" = 0.0V to −0.5V
"0" = −11V ± 1V
1000 ohms source impedance

Pulse Rates (806 and 807 only). 9.5V to 12V positive pulses
Pulse width 20% or 50% or pulse period depending upon rate
1000 ohms source impedance

SYNCHRONIZING SIGNAL CHARACTERISTICS

1MC or 100 KC (Depending upon Frequency Standard) . . . . .5 V ±1 V Peak to Peak Square Wave
1000 ohms impedance

1 PPS .8 V min. pos. going, 1000 ohms source imp.
(Pulse width at 50% point = 800µsec)

VISUAL DISPLAY: Time in hours, minutes, and seconds is displayed on the front panel. The EECO 806 and 808 decimal displays contain long-life Nixie indicator tubes. The EECO 807 coded binary display employs incandescent lamps.

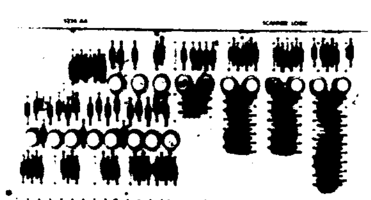
OPTIONS

1. The EECO 807 can be supplied with less than a full complement of codes at a lower price.
2. (a) If an external frequency standard is used with the EECO 806, 807, or 808, an EECO 880 VLF Receiver may be used to phase lock the external frequency standard to stabilized VLF transmissions to maintain excellent frequency stability (in the order of 2 parts in 10^{10} per week). A phase-locked 100 kc output signal from the EECO 880 is then used as the external frequency standard input to the EECO 806, 807, or 808 to yield extremely accurate time. No modifications to the EECO 806, 807, or 808 are required.

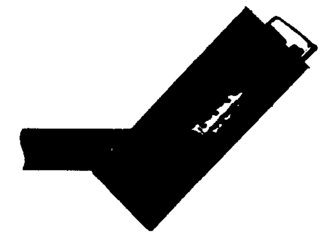
   (b) A minor modification can be made to the EECO 806, 807, or 808 to bring out a 100 kc signal, derived from the internal frequency standard, for use with the EECO 880 VLF Receiver to phase lock the internal frequency standard to stabilized VLF transmissions and will yield the same frequency stability and time accuracy in 2 (a).

DETAILED SPECIFICATIONS

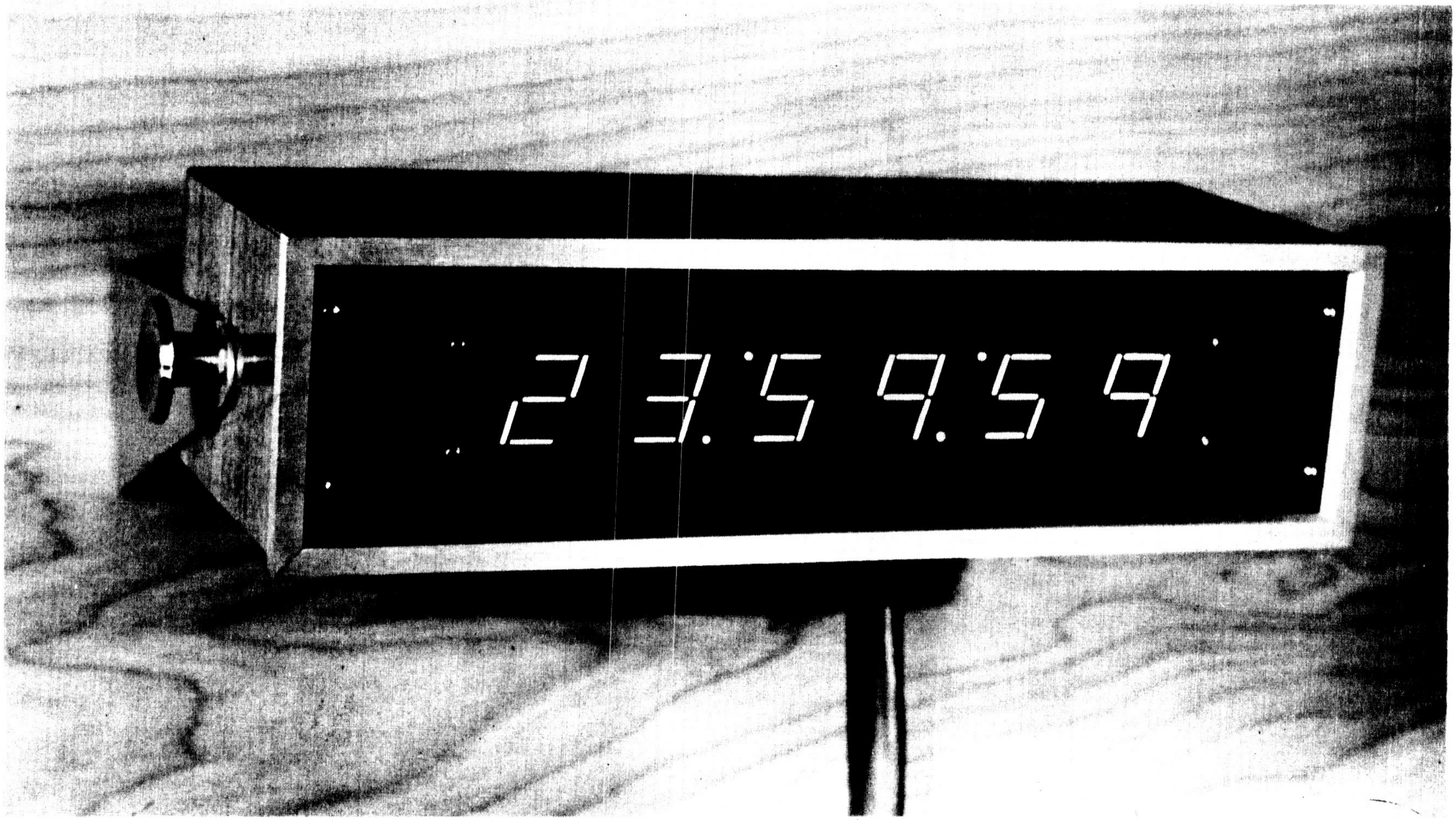
Time Code Generator	Time Code Format	Code Frame Length (sec)	Code Scan Rates (pps)	Code Carrier Frequency (cps)	Pulse Rates (pps)
EECO 806	24-bit BCD	1	25, 50, or 100 (switch selectable)	1000	100,000 10,000 1,000 100 50 25 10 1
EECO 807	17 bit binary (AMR) B_1 —B_n C_1 —C_n D_1 —D_n	 20 1 1	 1 20 100	1000	100,000 10,000 1,000 100 20 10 1
EECO 808	20-bit BCD	1	25	250	NONE



New EECO-series circuit cards are used throughout in the construction of the 806-807-808 series of time code generators. Printed circuit card connectors are tested to meet the requirements of MIL-C-21097A.



All EECO Time Code Generators and auxiliary equipment are drilled and tapped for Chassi-Trak CTD-120 tilt and detent chassis sliders. These can be supplied as an optional item to facilitate inspection of the equipment and routine service and maintenance.



Remote Digital Time Display

APPENDIX D

TIME ACCURACY REQUIREMENTS

In general, errors in the measurement of time enter the position computation in two ways described, arbitrarily, as:

- Absolute errors
- Relative errors.

They both arise from the same activity of recording the time at which a particular set of sextant readings are stated to be valid observations of a given star. But because they have somewhat different effects on the position error they are described separately. The absolute errors are introduced entirely by the timepiece available to the navigator. The relative errors are more a function of restraints on the navigator in the use of the timepiece.

D.1 ABSOLUTE TIME ERRORS

Time is expressed in a wide variety of ways depending on the frame of reference of the observer. The passage of time is most often observed by the movement of the sun or the stars relative to a stated line of sight. These are the origins of solar and sidereal time respectively. Where operations in different time zones must be coordinated (as in the space program) Universal Time has become a widely accepted standard.

Universal Time is the Greenwich mean solar time, expressed in the 24-hour system, beginning with 0^h at midnight. Thus, at a given instant, Universal Time (U.T.) is the hour angle of the mean sun $+12^h$ for an observer on the Greenwich meridian. This time standard is used regardless of the location of the observer. Since most observers are not on the Greenwich meridian to check their clocks by observation, and since the mean sun has no physical reality anyway, the problem of how to regulate precisely a clock keeping mean solar time is a major one. However, from a great many observations of the true sun's position among the stars, formulas have been developed that yield the position of the mean sun as a function of sidereal time. In determining Universal Time, one observes the sidereal time and then converts to U.T. by means of the established formulas. This defines the fundamental time cycle, and the time displayed by any clock (a device which integrates the oscillations of some mechanism) can be evaluated by its agreement with this computed value.

The tabulated values of declination and sidereal hour angle for the observable stars can be derived from this computed value of time to practically any desired accuracy. It is evident that any error in the time displayed by the navigator's clock contributes an equivalent error to the value of Greenwich hour angle (and hence longitude) of star position extracted from such a reference table. If this absolute error in time contributed by the clock is the only error in determination of the longitudes of GP1 and GP2 (Figure 3-5), identical angular errors are introduced into each of these longitudes. Since the sides 'a' and 'b' of the navigation triangles are independent of time, the effect of this absolute error in time is to shift the whole spherical quadrilateral in longitude relative to the Greenwich meridian. And since the rate of rotation of the earth is 0.2506842 arc-minutes per second, this is also the sensitivity of longitude position error to absolute time error. The rotation of the moon (is approximately $1/27^{th}$ that of the earth, hence the equivalent sensitivity of the longitude coordinate of lunar fix position to an absolute error in time is 0.009150 arc-minutes per second. The longitude lines on Figure D-1 represent these relations.

D.2 RELATIVE TIME ERRORS

A second type of error arises in the measurement of time which is considered to be independent of the absolute precision of the timepiece. This error is introduced by a multitude of factors having to do with the navigator's ability to observe the time simultaneously with the sextant sightings. Many human factors contribute to the nature of this error. The installation of the sextant and timepiece should permit the navigator to synchronize his sextant alignment activities with time without:

- Major body movements

- Frequent refocusing of the eyes

- Interruption of the sextant alignment activity once the referenced star has been identified.

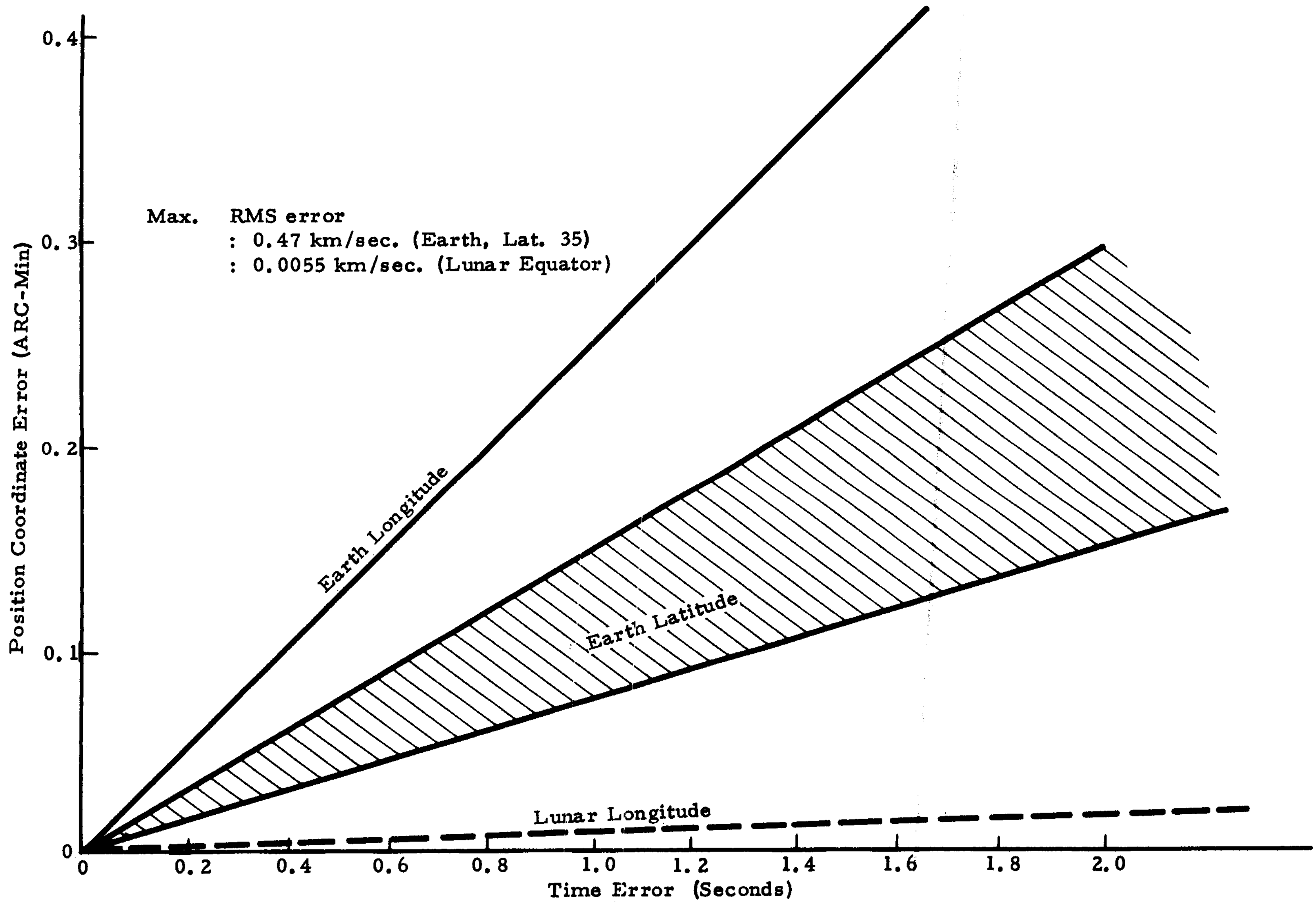


Figure D-1 Error in Fix Position as a Result of Time Errors

It is interesting to note that, if the navigator is uniformly sloppy in recording the times of observation of two successive star sightings, this error has the same effect as a timepiece error. As described in the previous section, this type of error effects only the longitude value of the fix position.

In the more probable cases this error will be random, resulting in erroneous values of Greenwich hour angle and a possible error in the value of total meridian angle ($t_1 + t_2$). This error does change the shape of the spherical quadrilateral (Figure 3-5) and can result in a net error in the latitude coordination of the position fix. The sensitivity of latitude errors to an error in ($t_1 + t_2$) is strongly dependent on the shapes and relative arrangement of the two navigation triangles(4). In Figure D-1 this latitude error has been assumed to be from 1/3 to 2/3 of the magnitude of the longitude error.

It is not possible to make a simple generalization as to the sensitivity of position latitude and longitude errors to errors in time. The many sensitivity coefficients computed in Reference 4 indicate the complexity of the problem and even that analysis leaves one of the star positions relatively fixed (within a few degrees of the observer's meridian). Based on the results presented in that document, it has been established that the error in fix position should seldom exceed a value derived from the RMS of the longitude and maximum latitude error curves given in Figure D-1. This results in a stated possible maximum error sensitivity in fix position of:

1. 0.47 km/second for an observer on earth at latitude 35° (Flagstaff, Arizona)

2. 0.0055 km/second for an observer on the lunar equator.

These sensitivity figures serve to emphasize one of the limitations to realistically simulating lunar astro-fix techniques on earth. On earth standard timepieces and operator reaction times are strained to provide the required position fix accuracy. On the moon the star movements are such that a relatively simple timepiece and unhurried observations will provide very reliably the needed precision.

APPENDIX E

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3. BSR 1243; Mobile Geological Laboratory Navigation System Description; Bendix Corporation, February 1966.

4. Lunar Navigation Study Final Report; BSR 1134; Bendix Corporation, June 1965.

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