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The design of a celestial navigation microcomputer with thoughts on an integrated information distribution system

Moore, Jon Prichet; Rainsberger, David Brandt

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

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MICROCOMPUTER WITH THOUGHTS ON AN INTEGRATED
INFORMATION DISTRIBUTION SYSTEM

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The Design of a Celestial Navigation

Microcomputer with Thoughts on an Integrated

Information Distribution System

by

Jon Prichet Moore
Lieutenant, United States Navy
B.S., Oklahoma State University, 1968

and

David Brandt Rainsberger
Lieutenant, United States Navy
B.S., Miami University, 1968

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN COMPUTER SCIENCE

ABSTRACT

This report lays the groundwork for further development
of a microcomputer that provides full celestial navigation
capability. The physical design specifications and design
philosophy are investigated. The fix algorithm which
allows determination of position without the use of H.O.
Publications is implemented in the BASIC language.

The application of microcomputer technology to devices
of this nature brings to light the need for an information
distribution system. Thoughts on a system of this purpose
are presented.

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I. INTRODUCTION

This paper deals with two interleaved subjects. The two subjects will be discussed with varying levels of detail and scope. The more specific subject of the two is the conceptual design of a celestial navigation computer. A general approach toward a digital information distribution system is the second subject. The celestial navigation computer is discussed first, as it is an element of the entire system, and the design specifics of this device relate better to the entire system than vice versa.

The celestial navigation computer provides for manual input of information as well as documentation of the output for legal records. The main reason why a computer is beneficial for celestial positioning is that it eliminates errors made in recording, computing and plotting of celestial information. The design efforts attempt to eliminate manual recording of substantive information and manual plotting of lines of position (LOP's) for use in determining position. Automatic information recording is provided.

This paper provides an analysis of the programming language, program I/O requirements and physiological requirements of the device. The initial purpose of this paper was to design the device, then to see how this philosophy and design process could be applied to other building block devices applicable to the information distribution system. Comments to this point will be made in Section VI.

II. NEED FOR A CELESTIAL MICROCOMPUTER PERIPHERAL

It would seem that with all of the fancy new gadgetry
on the market today, the age-old method of navigating by
the stars might just start to fade away. It is conceivable
that this could happen in the civilian world; however, the
military is often more demanding in the constraints placed
upon its ships. The electronic devices which use electro-
magnetic radiation in the position determination loop are
subject to deception, jamming and detection (as in the
case of radar), and support failure, e.g., destruction of
navigational satellites or LORAN stations, etc. The only
other navigation device not subject to standoff disabling
is the ship's inertial navigation system. It must be
pointed out that an inertial navigation system is only as
good as its platform's stability and the stability only
as good as its positional estimates. Thus the longer the
platform goes without being updated, the worse the platform
stability becomes--truly a spiraling decline in accuracy.

With all of the electronic fixing devices out of the
picture, visual sighting or sonar positioning is all that
is left. Visual sighting is passive and includes celestial
position determination, and this is the reason for main-
taining excellence in position determination by the stars.

The microcomputer is a newcomer to this field. This
technology properly applied allows for increased speed and

accuracy and the reduction of human errors. A need to determine position faster simply goes along with the increase in ship speed, e.g., new hydrofoil ships can conceivably reach speeds in excess of 60 knots. The need for increased accuracy is an economic as well as operational benefit. Accurate positioning is needed for proper and efficient deployment of weapons, efficient navigation and maneuvering.

The submarine force has implemented a celestial naviga-tion system in the most complete terms. Completely computer controlled, several "spot shots" are obtained in a moment and the submarine's navigation systems can then be updated. The Air Force has used the ASTRO-TRACKER to aid in celestial navigation.

In January, 1975, Carl Nuese and Dr. Alan Schneider provided the algorithms necessary to create a celestial navigation calculator using the Hewlett Packard Model 65 programmable microcomputer [Ref. 8]. The peripheral device under design in this paper was intended to hit the mark somewhere between the HP-65 calculator and the submarine celestial navigation computer--much closer to the HP-65 side of the spectrum.

The HP-65 calculator solution to navigation problem lacks the same sort of smoothness that placing a square block into a round hole does; with a lot of effort it works but it leaves a lot to be desired. The HP-65 general purpose calculator uses programmable magnetic cards to hold prestored

programs that are executable on the machine. Though the device is relatively inexpensive the following drawbacks are noted:

1.   Storage and maintenance of the program cards are cumbersome.

2.   I/O is nonexistent.

3.   Data format is not "conventional."

4.   Record keeping must still be done manually.

5.   The device is subject to pilferage.

6.   Expansion of programs is difficult in its 100-instruction memory.

The advantages are the following:

1.   Self contained (excluding the magnetic cards).

2.   Easier to operate than most terminals.

3.   Inexpensive.

4.   Good supporting vendor.

5.   Applicable to many other mathematical problems.

III. DESIGN PHILOSOPHY

A. OBJECTIVES

The objectives of the design of the device are simple:

1. Implement Nuese and Schneider's algorithms in a
device that does not have the disadvantages of the HP-65.

2. Maintain the advantages of the HP-65 without appre-
ciably increasing the cost/performance factor.

3. Provide for integration into the overall information
distribution system.

4. Provide the fail safe/soft features and hardcopy
printout capabilities.

Two definitions will be stated at this time.

Microcomputer: A small general purpose computer. It
contains a microprocessor and a small number of (sup-
port) LSI circuits. Usually mounted on one or two
printed circuit boards. May or may not be programmable.

Minicomputer: A computer with larger word sizes and
faster execution times than a microcomputer.

The proposal to specify a microcomputer for the celestial
computer was based on the further observations that the micro-
computer can be exactly specified as to the I/O structure,
memory structure and contents, power supply designs, etc.,
whereas the minicomputer requires adjusting of all of the
above mentioned properties to "fit" the minicomputer. The
cost for a microcomputer is also much less than that of the
minicomputer.

An eight-bit-wide microcomputer consisting of a micro-
processor, a 128 x 8 bit RAM, a 1024 x 8 ROM and peripheral

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adapter cost around $473 in 1974, and by 1976 is estimated
to cost under $100 [Ref. 6]. Though larger than the HP-65
it is still less than ten times as large. An examination
of data equipment suppliers will show that a small mini-
computer will cost around $5,000 and higher.

The device must be self-contained (except for power),
easy to operate and relatively inexpensive. The I/O struc-
ture must allow for keyboard entry, and the formats for data
must be naturalized (36° 15' 33" vice 36.1533°) to the prob-
lem. Note that the algorithm expressed in Appendix A uses
the latter form due to limitations of the BASIC language
I/O structure. As the device would be a small production
lot, vendor support would be minimal or nonexistent; yet
the simplicity of the device should allow for easy onboard
maintenance.

B. PHYSICAL DESIGN SPECIFICS

The device must be housed in one unit. The unit must
allow for connection to power and to the data distribution
system. The unit will have a simple ten-digit keyboard with
a N/E (north or east) and S/W (south or west) key. A 16
element five-by-seven dot LED must be placed above the key-
board for verification of entries as the line printer prints
a completed entry.

A 30 character wide line printer (for printing instruc-
tion, entries and calculation results) must be placed in
the unit. The unit is illustrated in Figure 1, and a
sample output strip is displayed in Appendix B.

Data Verification Readout (LED)

30 Character Line Printer

Program Selectors

Data Entry Keyboard
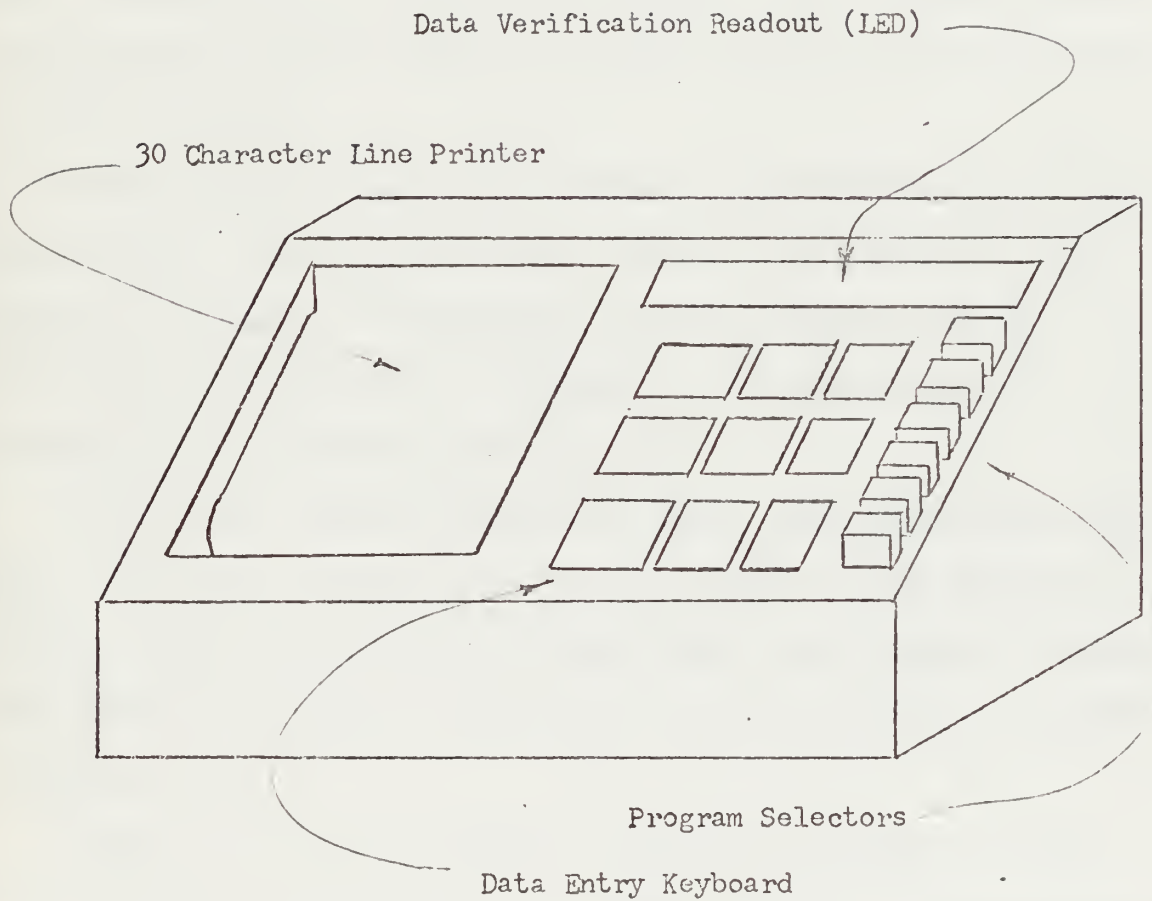
Figure 1-Celestial Navigation Microcomputer

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IV. THE CELESTIAL FIX ALGORITHM

The purpose of the proposed navigational computer is to enhance the speed, accuracy and ease with which calculations such as those used in celestial navigation can be made. The program presented in Appendix A removes the need for the user to depend on the Nautical Almanac [Ref. 13] and other required H.O. publications by computing the values supplied by these tables.

When taking a fix several phases of sight reduction are considered: insertion of user values, correction of the sextant altitude, establishment of the position of the observed celestial body, solution of the navigational triangle and displaying the results.

User values include Greenwich date, day, month and year, the observer's assumed position, the name of the body observed, the time (Greenwich Mean Time), the sextant altitude, the observer's height of eye or dip and the sextant's index of correction.

Correction of the sextant's altitude includes changes in altitude due to refraction, semi-diameter of the sun and moon and parallax for the moon.

Establishment of the position of the observed celestial body on the earth (GP) involves the calculation of the Greenwich Hour Angle (GHA) and declination (Dec) of the body (see Figure 2). Associated with each star are eight

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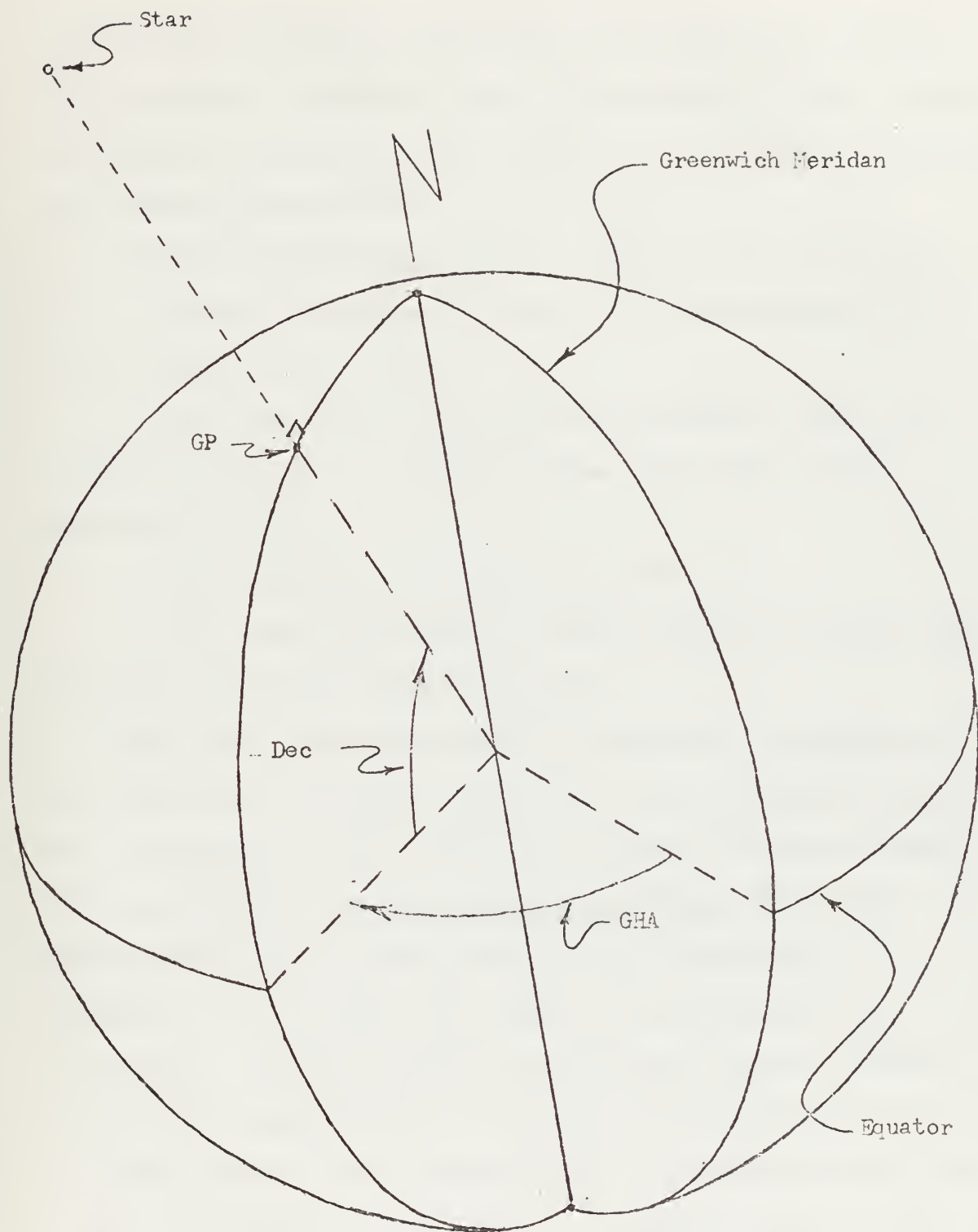
Figure 2-Geographic Position (GP) of a Star

intermediate constants which are calculated and combined
with universal constants (rate of precession of the equinox,
rotation of the earth on its axis and aberration) to produce
the GHA and declination.

Constants which apply to all stars are the following:

1. Rate of rotation of the earth with respect to the
vernal equinox [Ref. 11].

2. The longitude rate of the sun based on the time
between successive crossings by the sun of the vernal
equinox [Ref. 10].

3. The obliquity for epoch 1975 [Ref. 10].

4. The annual precession rates for epoch 1975 in right
ascension and declination [Ref. 10].

With these common constants, particular intermediate
constants associated with each star are developed. Utiliz-
ing the apparent right ascension and declination as found
in Apparent Places of the Fundamental Stars [Ref. 14],
right ascension and declination can be computed to a
reference time through the effects of precession and
aberration. Other constants include the rate of increase
of the mean sun longitude in degrees per day, precession
in right ascension and declination in degrees per day, true
right ascension and declination in degrees, and the time
behavior of the corrections for aberration [Ref. 8].

When the intermediate constants are developed and
applied to the algorithms, the computed GHA and declination
of a star will result. Discussion of the computation of

the constants, GHA and declination is presented in the next section. With the algorithm for computing GHA and declination of a star implemented it now becomes a matter of selecting those stars necessary to perform a sight reduction yielding a navigational fix.

Considering a three-star fix, the GHA and declination for each star is obtained as discussed above. Working with pairs of stars the solution of the associated navigational triangles will produce intersection points on the circles of equal altitudes (see Figure 3).

Three triangles are used to calculate a possible position as shown in Figure 4. The first triangle has vertices N (north pole), A and B. The angle A is either G1-G2 or 360°-(G1-G2). This angle represents the difference in the GHA's. Given the angle A and cosides d1 and d2 (the declinations), the law of cosines is applied to solve the third side t. Given the three cosides the angle B opposite coside d1 is calculated. Given three cosides in the second triangle, H1, H2 and t, the angle B3 opposite H1 is found.

Letting m be the sign of the sin(G1-G2), the angles B(1)=mB-B3 and B(2)=mB+B3 are found. Given angle B(1) and cosides d2 and H2, the third coside L(1) is found. Given the three cosides d2, H2 and L(1) the angle A(1) opposite H2 is found. In the same manner L(2) and A(2) are found. L(i) is equivalent to the latitude and A(i) is equivalent to the longitude of an intersection of the circles of equal altitude.

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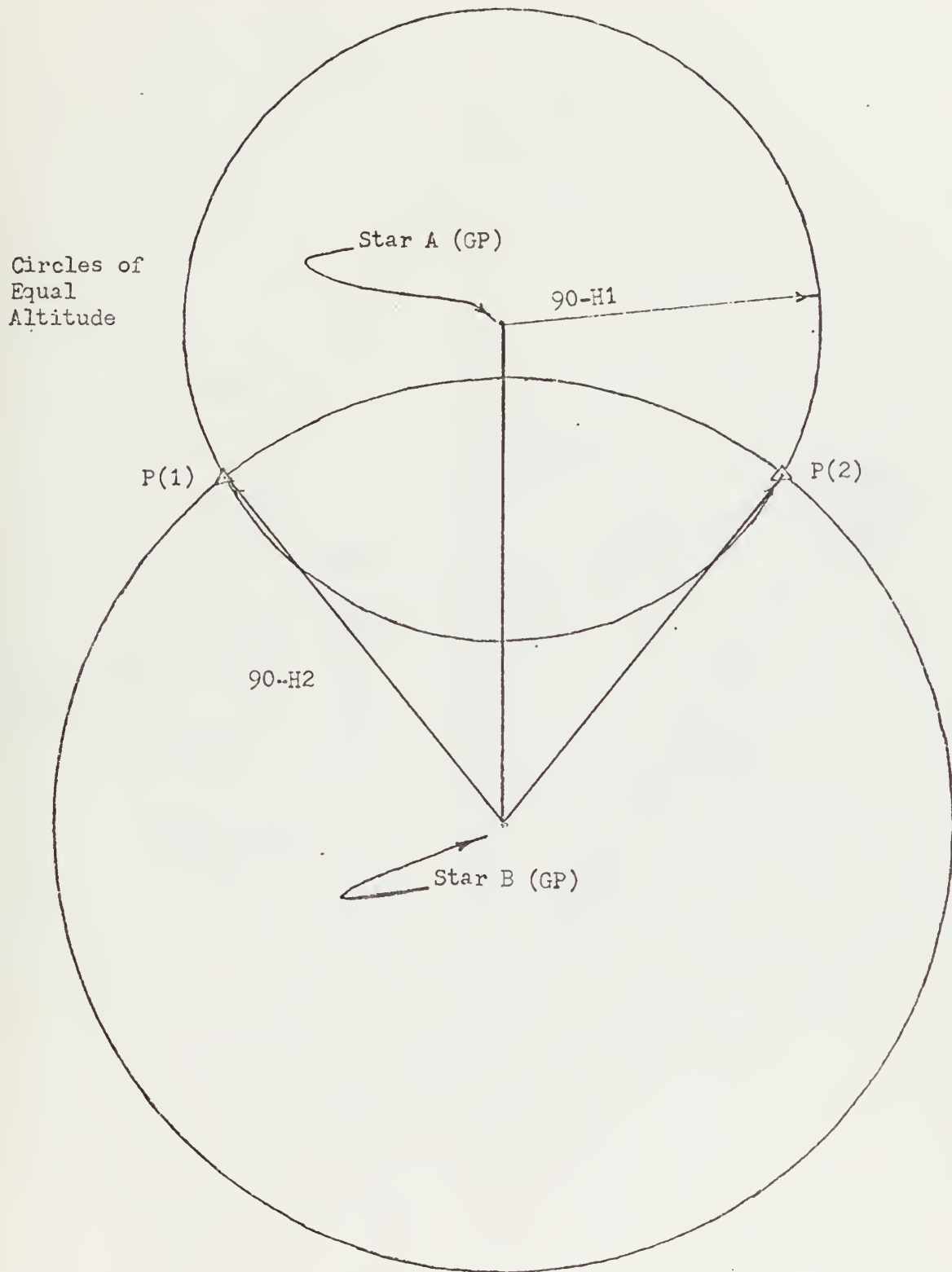
Figure 3--Navigational Fix from Altitudes
of Two Celestial Bodies

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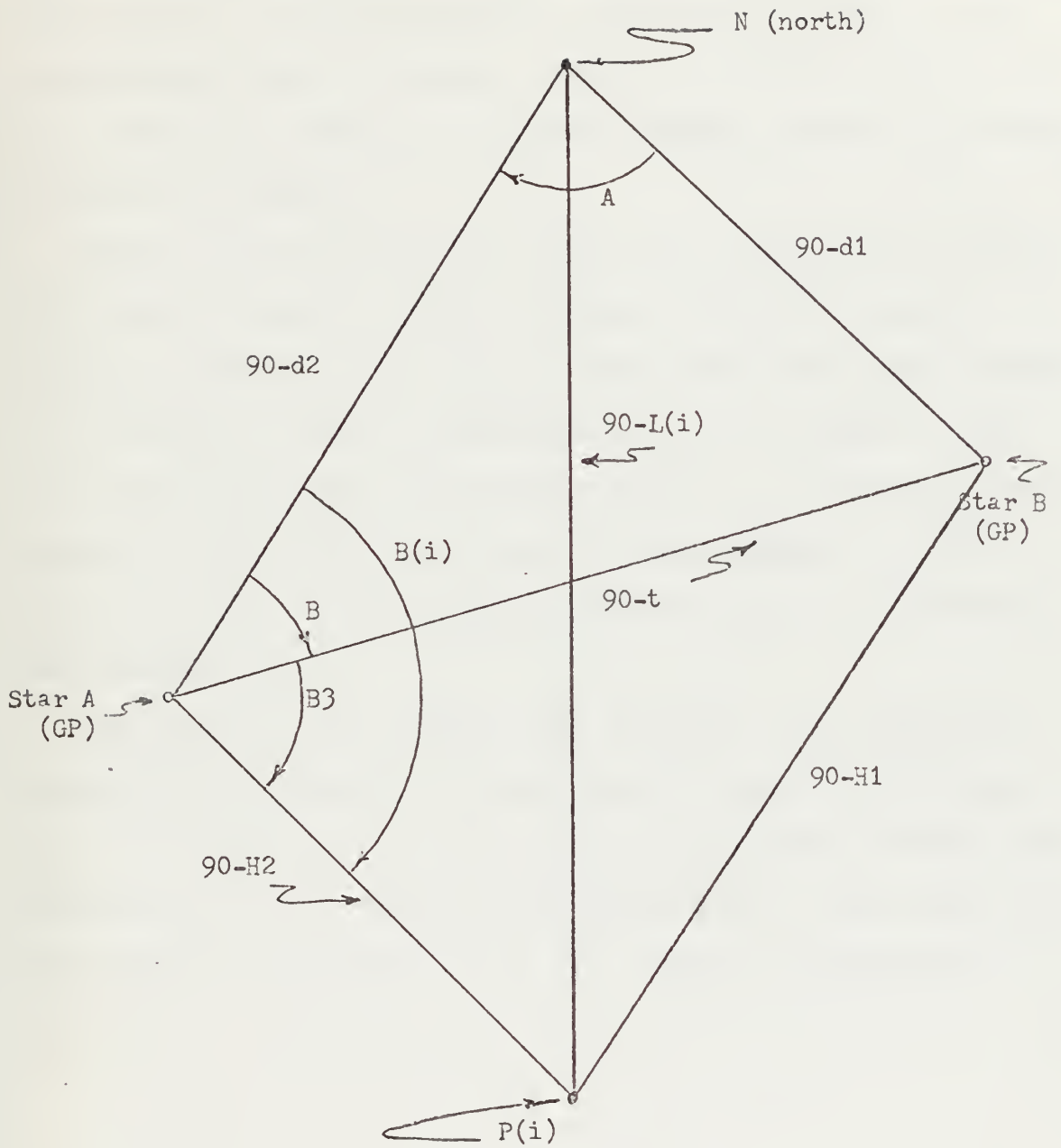
Figure 4-Triangles used for Navigational Fix

Repeating the algorithm considering the third celestial body and one of the previously used bodies, a second pair of positions will be found. A third repetition yields two more positions totaling six (the maximum) possible positions, as shown in Figure 5.

These six positions are then investigated to determine the closest three by determining the shortest distance connecting these three points. With this resulting triangle the location of the two endpoints of a line which is one-third away from any side of the triangle is computed. The center of this line containing the two endpoints is the center of mass of the triangle and therefore is considered the celestial fix.

The program will provide for accuracy in mathematical manipulation of numbers to one part in four billion using the BASIC interpreter at the Naval Postgraduate School and implementing the program on the INTEL 8080. This will provide for the accuracies of .1 or .2 miles as presented in Ref. 8.
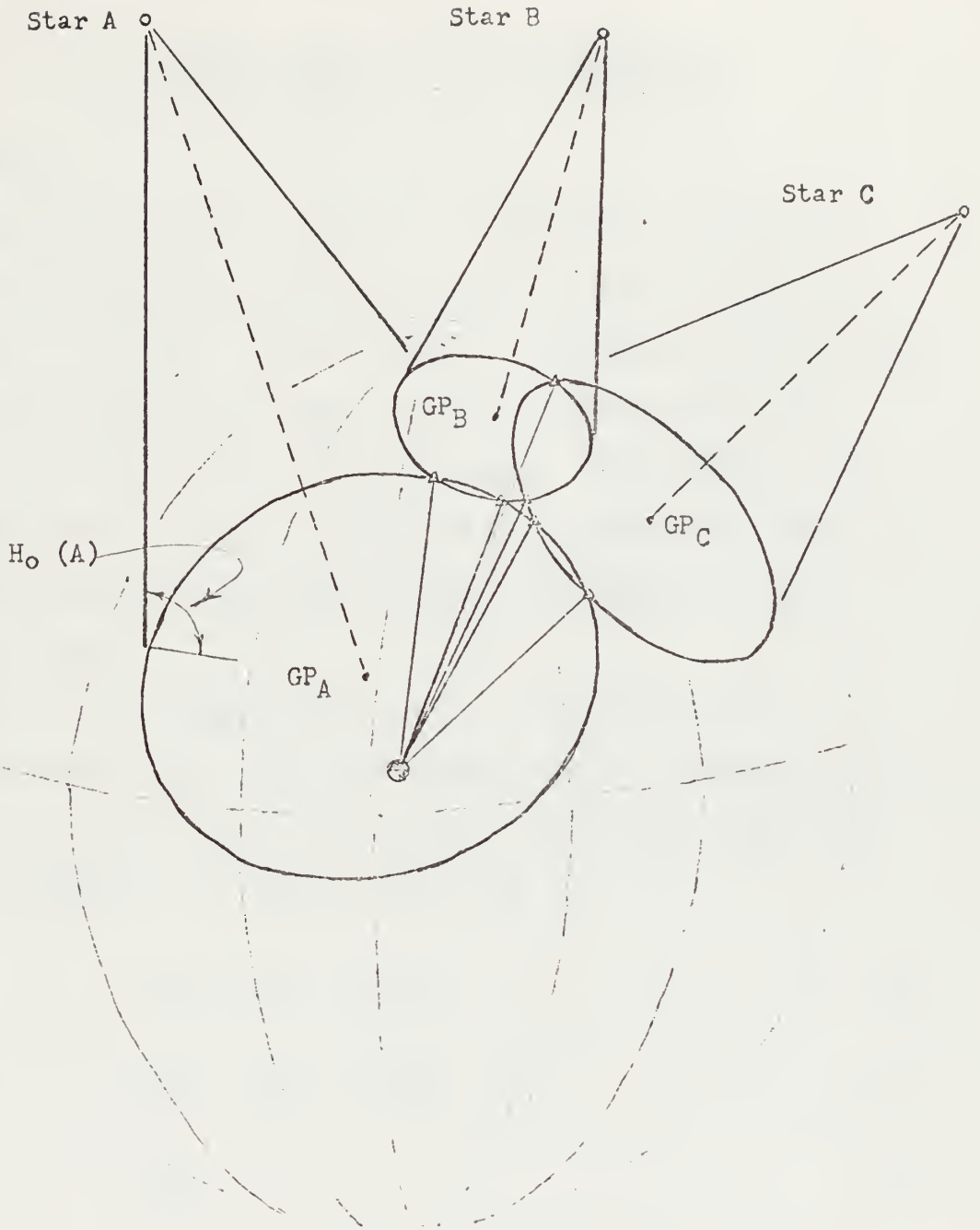
Figure 5-Overall Celestial Situation
with six intersection points depicted

V.   PROGRAM THEORY AND IMPLEMENTATION

A.   THEORY

When computing the constants needed for the program a common reference time is necessary to provide for the accuracy of results. If the data is referenced to the mean equinox and equator of date, or to a fixed epoch then no error is introduced. The reference time employed in the algorithms is 0000 29 Nov 1971 as suggested by Ref. 8. Any data known at some other time is retarded to this reference time.

Note that the GHA of the star is related to the Greenwich Hour Angle of Aries (GHA_γ) and the sidereal hour angle of the star (SHA), the latter being 360° minus the right ascension α. Thus for any time t,

$$GHA = GHA_\gamma + SHA \tag{1}$$

$$GHA = GHA_\gamma + (360 - \alpha) \tag{2}$$

$$GHA = GHA_\gamma - \alpha \tag{3}$$

The GHA_γ increases at a constant rate, namely, the rate of rotation, a, of the earth with respect to the vernal equinox. Knowing GHA_γ at some time t_1, then

$$GHA = a(t - t_1) + GHA_{\gamma 1} - \alpha(t) \tag{4}$$

where t is the present time measured in days and decimal parts of a day from the time t_1, a time in the recent past. Because it will later prove efficient to refer all events to an earlier time (t_0 = 0000 29 Nov 1971) this leads to

$$GHA = a(t - t_0) - a(t - t_1) + GHA_{\gamma 1} - \alpha(t) \qquad (5)$$

$$= a(t - t_0) + GHA_{\gamma 0} - \alpha(t) \qquad (6)$$

where $GHA_{\gamma 0} = GHA_{\gamma 1} - a(t_1 - t_0)$ \qquad (7)

The apparent right ascension α at time t is related to its known true value α' at some previous time t_1 through the effect of precession and aberration.

Therefore (see "Supplement," [Ref. 11, pp. 39-49])

$$\alpha(t) = \alpha'(t_1) + \dot{\alpha}(t - t_1) + \Delta\alpha(t) \qquad (8)$$

where

$\alpha'(t_1)$ = the true right ascension at time t_1

$\dot{\alpha}$ = precession in right ascension (degrees per day)

$\Delta\alpha$ = correction in right ascension at time t for aberration (as defined on p. 47, "Supplement")

In order to refer all data to the common reference time t_0, it is convenient to rewrite (8) as follows:

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$$\alpha(t) = \alpha'(t_1) + \dot{\alpha}(t - t_o) - \dot{\alpha}(t_1 - t_o) + \Delta\alpha(t) \qquad (9)$$

$$= \alpha'(t_o) + \dot{\alpha}(t - t_o) + \Delta\alpha(t) \qquad (10)$$

where

$$\alpha'(t_o) = \alpha'(t_1) - \dot{\alpha}(t_1 - t_o) \qquad (11)$$

Inserting (10) into (6),

$$GHA = GHA_{\gamma o} + a(t - t_o) - \alpha'(t_o) - \dot{\alpha}(t - t_o) - \Delta\alpha(t) \qquad (12)$$

$$= [GHA_{\gamma o} - \alpha'(t_o)] + (a - \dot{\alpha})(t - t_o) - \Delta\alpha(t) \qquad (13)$$

Or,

$$GHA = a_{18} + a_{19}(t - t_o) - \Delta\alpha(t) \qquad (14)$$

where

$$a_{18} = GHA_{\gamma o} - \alpha'(t_o) \qquad (15)$$

$$= GHA_{\gamma 1} - a(t_1 - t_o)$$

$$- \alpha'(t_1) + \dot{\alpha}(t_1 - t_o) \qquad (16)$$

and

$$a_{19} = a - \dot{\alpha} \qquad (17)$$

Now $\Delta\alpha$ must be developed into a usable form. The equation on pages 47 and 48 in "Supplement" [Ref. 8] shows that aberration at time t is given by

$$= -k \sec \delta'[\cos \alpha' \cos \lambda \cos \epsilon + \sin \alpha' \sin \lambda] \qquad (18)$$

where λ is the longitude of the mean sun measured along the

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ecliptic from γ, ε is the obliquity (angle between the mean planes of the ecliptic and equator), k is the constant of aberration defined on page 48 in "Supplement," having a value of 20.47", and α' and δ' are the true right ascension and declination, all values being at time t. Selecting t_1 as a convenient time for determining the mean place of the star and the obliquity, and regarding α', δ' and ε as constants over the interval from t_1 to t, equation (18) becomes:

$$\Delta\alpha = -\left(\frac{20.47}{3600} \sec \delta_1' \cos \alpha_1' \cos \varepsilon_1\right) \cos \lambda$$

$$-\left(\frac{20.47}{3600} \sec \delta_1' \sin \alpha_1'\right) \sin \lambda \tag{19}$$

$$= a_{10}\cos \lambda + a_{11}\sin \lambda \tag{20}$$

where

$$a_{10} = -\frac{20.47}{3600} \sec \delta_1' \cos \alpha_1' \cos \varepsilon_1 \tag{21}$$

$$a_{11} = -\frac{20.47}{3600} \sec \delta_1' \sin \alpha_1' \tag{22}$$

The factor 3600 enters because $\Delta\alpha$ will be computed as fractions of a degree whereas k was given in arc seconds.

Equation (20) can be rewritten as

$$\Delta\alpha = a_{12} \sin (\lambda + a_{13}) \tag{23}$$

where

$$a_{12} = \sqrt{a_{10}^2 + a_{11}^2} \tag{24}$$

and

$$a_{13} = \tan^{-1} \left(\frac{a_{10}}{a_{11}}\right) \tag{25}$$

The longitude of the mean sun increases linearly with time according to the equation

$$\lambda(t) = \dot{\lambda}(t - t_1) + \lambda_1 \tag{26}$$

where λ_1 is the known longitude at some convenient reference time t_1. As has previously been done, it is best to refer to a common reference time t_o by rewriting (26) as follows:

$$\lambda(t) = \dot{\lambda}(t - t_o) - \dot{\lambda}(t_1 - t_o) + \lambda_1 \tag{27}$$

$$= \dot{\lambda}(t - t_o) + \lambda_o \tag{28}$$

where λ_o is defined as follows:

$$\lambda_o = \lambda_1 - \dot{\lambda}(t_1 - t_o) \tag{29}$$

Substituting (28) into (23), the results are

$$\Delta\alpha = a_{12} \sin[\dot{\lambda}(t - t_o) + \lambda_o + a_{13}] \tag{30}$$

$$= a_{12} \sin[\dot{\lambda}(t - t_o) + a_{14}] \tag{31}$$

where a_{14} is defined as follows:

$$a_{14} = \lambda_o + a_{13} \qquad (32)$$

Using (31) in (14) the substitution yields

$$GHA = a_{18} + a_{19}(t - t_o) - a_{12} \sin [\dot{\lambda}(-t_o) + a_{14}] \qquad (33)$$

Because a_{19} includes earth rate, roughly 360° per day, and that $t - t_o$ may be on the order of 30,000 days, to preserve accuracy in the computation it is worthwhile to separate a_{19} into two parts, one of which, a_{21}, is 360° and the other a_{22}, is the remainder. Let

$$a_{19} = a_{21} + a_{22} \qquad (34)$$

where

$$a_{21} = 360 \qquad (35)$$

and

$$a_{22} = a_{19} - 360. \qquad (36)$$

In similar fashion, denote the number of days from the reference t_o to the time t to be D.d where D is a whole number of days since 0000 Nov 29, 1971, and d a fractional part. That is

$$t - t_o = D.d \qquad (37)$$

Then it is obvious that the product of the angular rate times the time yields an angle modulo 360° which can be expressed

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as follows:

$$a_{19}(t - t_o) = (360 + a_{22})(D + d) \tag{38}$$

$$= 360D + a_{22}(D + d) + 360d \tag{39}$$

$$= a_{22}(D + d) + 360d \tag{40}$$

$$= a_{22}(D.d) + 360d \tag{41}$$

Substituting this result and (37) into (33) yields

$$GHA = a_{18} + a_{22}(D.d) + 360d - a_{12}[\dot{\lambda}(D.d) + a_{14}] \tag{42}$$

The constants $\dot{\alpha}$ and $\dot{\delta}$, precession in right ascension and declination, for a particular star are obtained using the formulas on page 39 in "Supplement," except that the values of the constants have been taken for epoch 1975 from the American Ephemeris and Nautical Almanac [Ref. 10]. Conversion to degrees per day is

$$\dot{\alpha} = \frac{1}{3600 \times 365.24219418} [46.1060 + 20.0404 \sin \alpha_1' \tan \delta_1'] \tag{43}$$

$$\dot{\delta} = \frac{1}{3600 \times 365.24219418} [20.0404 \cos \alpha_1'] \tag{44}$$

This now completes the derivation for the Greenwich Hour Angle of a star at time t.

Turning attention to the derivation of declination, it is noted that the derivation is similar to those just carried out. Declination of a star changes because of precession and parallax. Letting δ be the apparent

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declination at time t, δ' be the true declination at some specified time, $\dot{\delta}$ be the rate of precession of this star in declination, $\Delta\delta$ be the correction to declination for aberration, the result is

$$\delta(t) = \delta'(t_1) + \dot{\delta}(t - t_1) + \Delta\delta(t) \qquad (45)$$

where t_1 is the reference time of which the true right ascension and declination are known. The numerical value of $\dot{\delta}$ is given in (44). This form is converted to the standard reference time t_o by the same method which has been used above. The result is

$$\delta(t) = \delta'(t_o) + \dot{\delta}(t - t_o) + \Delta\delta(t) \qquad (46)$$

where

$$\delta'(t) = \delta'(t_1) - \dot{\delta}(t_1 - t_o) \qquad (47)$$

From pages 47 and 48 in "Supplement" the time behavior of the correction for aberration is

$$\Delta\delta = -k(\sin \epsilon_1 \cos \delta_1' - \cos \epsilon_1 \sin \alpha_1' \sin \delta_1') \cos \lambda$$

$$-k \cos \alpha_1' \sin \delta_1' \sin \lambda \qquad (48)$$

$$= a_{15} \cos \lambda + a_{16} \sin \lambda \qquad (49)$$

where

$$a_{15} = \frac{20.47}{3600} (\sin \epsilon_1' \cos \delta_1' - \cos \alpha_1' \sin \alpha_1' \sin \delta_1') \qquad (50)$$

$$a_{16} = \frac{20.47}{3600} \cos \alpha_1' \sin \delta_1' \qquad (51)$$

The constants a_{15} and a_{16} are in degrees. Simplifying further

$$\Delta\delta = a_{17} \sin (\lambda + \tan^{-1} \frac{a_{15}}{a_{16}}) \tag{52}$$

where

$$a_{17} = \sqrt{a_{16}^2 + a_{15}^2} \tag{53}$$

Substituting (52) and (28) into (46),

$$\delta(t) = \delta'(t_o) + \dot{\delta}(D.d) + a_{17} \sin[\dot{\lambda}(t - t_o) + a_{20}] \tag{54}$$

where

$$a_{20} = \lambda_o + \tan^{-1} \frac{a_{15}}{a_{16}} \tag{55}$$

and

$$t - t_o = D.d \tag{56}$$

The final equations of importance which lead to GHA and declination are (42) and (54). Note that eight star-particular constants are involved in these two equations, plus $\dot{\lambda}$, a constant which appears in all calculations of GHA and declination of the stars.

The equations involving reference times have been set up in such a way as to maximize freedom in their selection. Reference time t_o was selected to be 0000 Nov 29, 1971, to facilitate the calculation of time in days with a minimum number of entries as suggested by Ref. 8.

The reference time t_1 is any convenient time, presumably in the recent past, at which the GHA of Aries is precisely given in some reference tabulation. The time t_1 is referenced to true right ascension and declination as listed in some reference almanac. The true right ascension and declination at $\alpha'(t_1)$ and $\delta'(t_1)$ can be obtained from the apparent values $\alpha(t_1)$ and $\delta(t_1)$ by setting $t = t_1$ in equations (8) and (45) and solving for α' and δ'.

The reference time t_1 is also the time, again in the recent past, at which obliquity ε_1, α_1', δ_1' and λ_1 are accurately known. The reference time for λ_1 is such that the accuracy of the sun's mean longitude is known from some almanac data. It will minimize the errors due to (a) eccentricity of the earth's orbit, and (b) the leap year cycle, if t_1 is chosen at or near the time of earth perihelion, in the midpoint of a leap year cycle.

It should be noted that t_1 for the known value of GHA of Aries may be different from the t_1 for the known values of true right ascension and declination. Likewise t_1 may be yet another time for the known sun's mean longitude. Since all the values (constants) associated with t_1 are retarded to t_0 no difference in t_1 is objectionable.

B. IMPLEMENTATION

The program presented in Appendix A is the result of several conversions. The first conversion consisted of taking algorithms expressed in Ref. 8 with the HP-65

programs to produce a debugged FORTRAN IV program. The HP-65 programs deal with degrees as a unit of angular measure vice radians. A conversion of all data from degrees to radians was made for use in the FORTRAN IV and BASIC programs. General routines 0010 and 0020 provide for I/O conversion of radians to degrees, and hours, minutes, and seconds to hours (and vice versa). These conversions were needed for ease of data entry and data output.

The HP-65 programs are compact due to the limited number of registers used for intermediate storage. This efficiency of memory was carried through to the FORTRAN IV programs and then to the BASIC programs for the routines that determine the GHA and declination of the star and the subroutine that determines the azimuth (Zn) and distance (subroutine 0300 and 0400, respectively). It was felt that this level of efficiency need not be continued in the remainder of the program due to the need for self-documentation.

FORTRAN IV was selected as the intermediate step in the conversion due to the amount of core memory allocated to the FORTRAN compiler. The BASIC interpreter is limited in memory on the IBM 360 installation and would not hold the completed BASIC program.

The reduced precision of the FORTRAN IV version of the program (as it was not programmed in double precision) was attributable to the internal formatting of the variables. High precision was not of great concern at this stage of development.

As the goal of this process was to provide a program that would implement the algorithms necessary to complete a celestial fix on a microprocessor, the FORTRAN IV version was converted to BASIC. The BASIC program allows for much greater precision in computation as the values are expressed in 32 bit floating point, when interpreted by the available BASIC interpreter in the Microcomputer Laboratory at the Naval Postgraduate School. The BASIC interpreter at the W. C. Church Center was not of sufficient size to run the entire program. Therefore, the main subroutines and all required support routines were run and debugged separately, and required information was transferred manually from routine to routine. Because the BASIC language does not provide for scopal variables and due to the limited types of identifiers available much of the self-documentation of the FORTRAN IV program was lost. Table I correlates variables in subroutine 0100 in the program listing (Appendix A) to those variables previously discussed during the theory presentation.

Subroutine 0100 computes the eight constants associated with a star and places them in array C (elements $C(2)-C(9)$). Element $C(1)$ is the rate of increase of the mean sun longitude (common to all stars).

In order to organize the variables as much as possible a scheme was invoked as explained below. Since there were a number of subroutines in the program, a method of passing variables was constructed. The variables R1-R9 and P1-P9

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TABLE I

Identifier Correlation of Variables in Subroutine

0100 and Equation Variables

Subroutine Variable	Equation Variable
C(1)	$\dot{\lambda}$
C(2)	a_{20}
C(3)	a_{17}
C(4)	$\dot{\delta}$
C(5)	$\delta'(t_o)$
C(6)	a_{22}
C(7)	a_{12}
C(8)	a_{18}
C(9)	a_{14}
I3	α_1
I4	δ_1
I5	$\dot{\alpha}$
I6	a_{19}
I7	a_{10}
I9	a_{11}
J0	a_{15}
J1	a_{16}
C5	ε_1

are passing variables. Variables used in three or more
non-general routines were considered as global and were
selected to be as self-documenting as possible. For example,
the two constants for each star are placed in the array
$S(X,X)$. The constants used by routine 0300 to determine
GHA and declination which are created from the S array are
placed in the C vector. All other constants were repre-
sented by the format C1-C9.

Several routines use intermediate variables while calcu-
lating the object variables. These variables are repre-
sented by I1-I9, J1-J9 and M1-M9. All logical values are
represented by L1-L9. Note that this scheme was invoked
to eliminate problems created by not having scopal varia-
bles. This must be considered in the selection of a
language for other peripherals used in the system. Points
to be considered in selecting a final programming language
for such a system and the peripherals attached to it are
discussed in Section VII.

VI. THE INFORMATION DISTRIBUTION SYSTEM

A. OBJECTIVES

This subject will primarily be concerned with the
integration of a general purpose computer into the existing
shipboard information flow. The "system" in the spotlight
is the navigation suite aboard U.S. Navy ships. The phil-
osophy for this approach is simple and is best stated by
Joseph Weir [Ref. 1]:

> "Good systems can be designed only in the presence of
> potential users and applications. By using the system
> in numerous applications and assiduously watching its
> performance, it gradually can be adopted to the (actual)
> needs of the application and the user. Ingenious ivory
> tower solutions frequently do not work or they solve
> problems that don't exist."

A close examination of this statement while relating
it to the navigation suites will show that in fact the
"system" has been designed both as far as it need and can
be with the existing equipment. Note that the "system"
comprises geographically dispersed equipment and telephones
for communication links.

The application and needs of the navigation system have
been defined as will be discussed later in this section. If
all this is true then why rock the boat by imposing a
system, apparently complex, on an existing "system"?

Discussion with crewmen aboard the USS Hancock indi-
cated that the existing system is cumbersome, subject to
human frailties and is not timely enough for the devices

on board. OMEGA radio navigation sets are capable of
providing information for navigational fixes every few
seconds, yet this information is only used hourly. In
this case the communication link is the "weak" link, and
to eliminate this weak link an information distribution
system must be imposed. The distribution system must
appear translucent and straightforward to the user, for as
Weir mentions,

> "The more complex the system, the more likely it is
> that it won't get used or will be misunderstood or
> misused." [Ref. 1]

All systems have sensors and effectors, and some
communication constraints placed on them. Although most
of these sensors for the navigation system in fact exist,
there are always new devices being created.

For example, ten years ago operational OMEGA navigation
sets did not exist. If a system had been created and imple-
mented on the ships at that time without forethought with
regard to new devices, then the information system would
not have been able to integrate the new device into the
network.

In order to fully utilize an information distribution
system there must be "terminals" with which to input informa-
tion and query the system. For example, suppose the bridge
wants to know the average RPM of the four propulsion shafts.
Engineering would have a terminal (either automated or manual)
that would accept certain required data, e.g., tachometer
inputs, transform it into its varied forms and relay the

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data to the central processor. The processor would then transfer the required information to the terminal at the bridge.

B. DESIGN PHILOSOPHY

The question might be asked, "Why try to integrate an information distribution system with the existing peripherals?" The answer should be obvious--cost of implementation. Existing equipment must be fully exploited until it is not wise to continue using it.

By integrating existing equipment into a network instead of creating all of the component parts of the system anew, the cost of research and development of all the new sensors and effectors in the system can be elided [Ref. 2]. Of course, the use of current equipment will demand the design of interfacing equipment such as analog to digital converters, digital to analog converters, fault sensing networks, etc. However, the cost of these units should be relatively inexpensive when compared to the redesign of any one sensor or effector in the system. The application of the same item (A/D or D/A, etc.) to many peripherals is a cost savings when design efforts are considered.

As distribution of existing data is the concern of the central system and since there is a multiplicity of like data, the question of which source's information should be distributed must be handled. A rather trite answer is "the best." Again a question, "Which sensor is providing 'the best' information?"

A definition of the term "best" is recursive and must include words like timeliness, accuracy and statistical validity. As each sensor in the system is operating at pre-system design rates, some periodic (auto track LORAN C) and others at non-periodic rates (celestial sightings), timeliness takes on a meaning associated with the quality of the source. For example, if the only peripheral capable of input to the system is the celestial navigation unit, an output of ship's position would only be considered timely if the last celestial position had been updated with inputs from the "best" heading and speed information to provide an estimate of the current position.

The word "accuracy" when associated with "best" means most accurate on a timely basis. A position based on a ten-hour old OMEGA position is usually not as accurate as a five-minute old celestial position.

This is all well and good, yet how are these descriptors compiled? A central machine is obviously the device that will have to provide the software to meet problems based on statistical properties.

Statistical properties of each measuring device must be taken into account. The proper error probabilities must be applied to each input; then based on the result of the combined statistics, the "best" source is selected to represent that class of input. It is this source's information (corrected for time) that must be distributed.

Along with statistical constraints imposed on the data, a status check must also be imposed on the device. If the data is apparently correct yet the device has failed, then the data is obviously of no use. The status determination system must be as nearly fail-safe as possible. Since this paper is proposing a centralized star network vice a fully connected or ring network [Ref. 2], all the status checks must be initiated at the central computer (see Figure 6). In order to design a fail-safe status monitor, the following considerations must be employed:

1. Notice of failure of the central computer must be distributed to all peripheral stations.

2. Failure of each peripheral must affect only that peripheral and, at worst, place the system in a degraded mode.

3. Status of selected peripherals might have to be recorded for legal records.

4. Failure of the peripheral must not cause failure of the status check mechanism.

There are several reasons for designing an information distribution system. Many operations aboard a ship are dependent on the same source of information. For example, the Combat Information Center and radar stations need true course and speed information. These are parallel operations and their information must be based on the same source. A distribution system would be the answer to this problem.
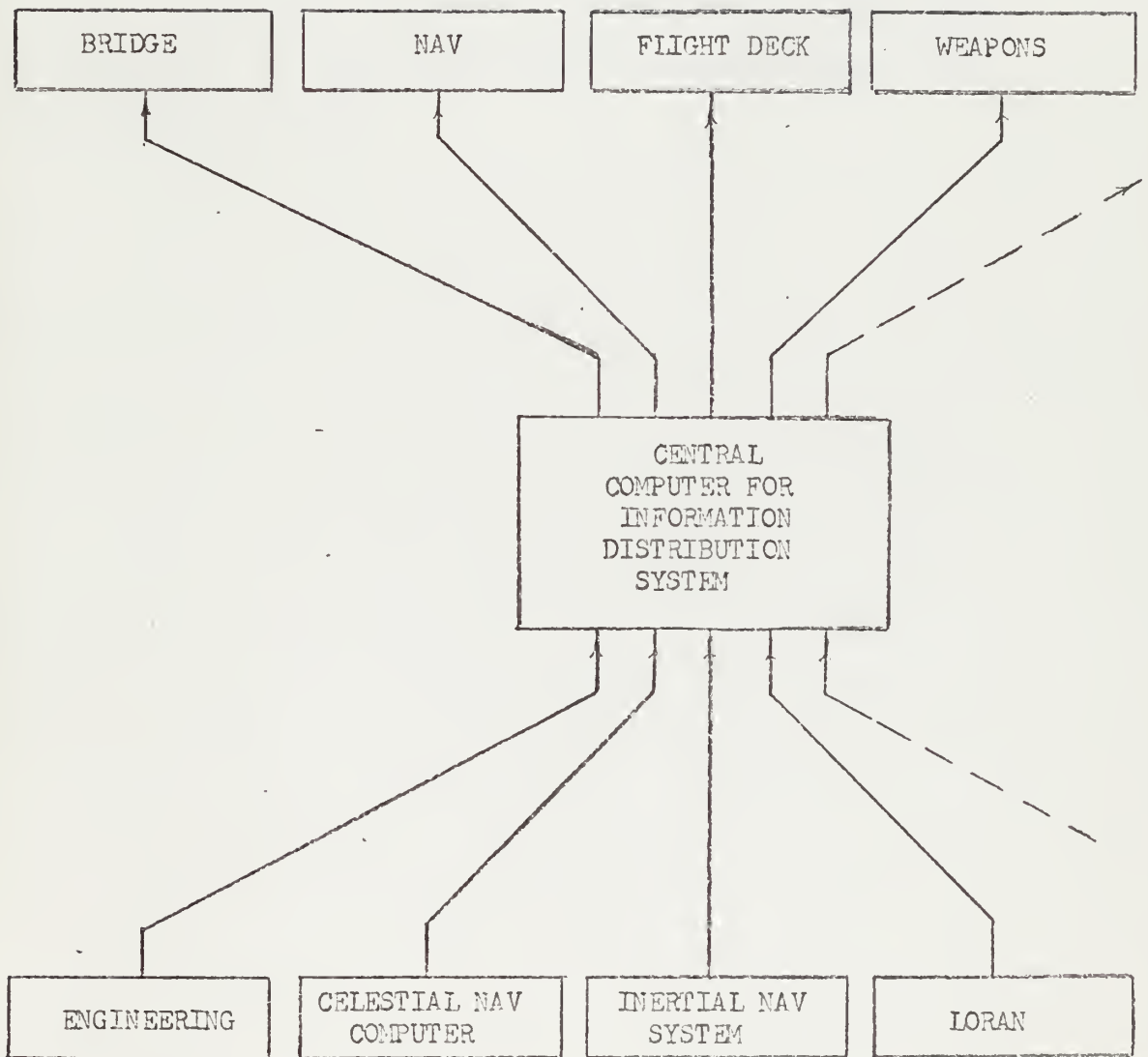
Figure 6-Information Distribution System

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All of the discussion thus far has been about distribution
of information gathered from sensors, so where is all this
fine information used? An example may best describe the
answer. Suppose the navigator updates the current ship's
position with the celestial navigation computer. If the
Captain desires to proceed to a desired point, the point
could be placed into the system and the system would pro-
vide proper steering information (great circle steering)
to the Helmsman, or this data could be transmitted to an
auto-pilot upon request.

VII. LANGUAGE SELECTION

The subject of language selection is placed at this
point in the paper due to its applicability to both the
celestial navigation microcomputer and an information
distribution system as described within. The considerations
in selecting a programming language for these two devices
have much in common, the most important of which is the
microprocessor.

There are two main considerations in selecting a pro-
gramming language for a microcomputer. The first and most
important consideration is that of efficiency; efficiency of
both memory utilization and program execution speed. The
second point concerns the cosmetics of the language (i.e.,
is the language easy to read and is it self-documenting?).

In consideration of the first property, that of
efficiency, the language must be chosen in the light of
cost/availability of volatile memory. Even though the
addressing schemes of some microprocessors provide for
large memories there may be physical and/or cost limita-
tions placed on the microcomputer design that make very
efficient use of the available memory imperative. For
peripherals operating with unmodifiable code the number of
memory locations can be optimized and placed with a high
degree of efficiency. For processors using programs which
have subroutines with arrays of data created during the

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execution of the program, the placing of these arrays
on a metal mask chip or fixing and reserving the addresses
of these arrays is an inefficient use of memory.

The best way to program in an efficient manner is to
use block structured programming techniques utilizing
"scopal" variables. Block structured languages like Algol
60 and PLM [Ref. 12] allow for scopal variables to include
arrays which provide for efficient use of random access
memory and reduce the amount of programmable/read only
memory. By creating arrays as needed, common random
access memory may be used very efficiently allowing for
lower investment in space and cost.

The second area of concern, that of cosmetics, is a
growing concern with all languages. It may be a seemingly
unimportant aspect until the prospects of non-volatile
runtime modifiable LSI memories (e.g., ferroelectric
memories [Ref. 15]), multiplicity of similarly constructed
peripherals and common maintenance support are considered.
The celestial navigation microcomputer program bases
all of the calculations for geographical positioning
of the body constants which vary from year to year.
In order for the device to enjoy extended longevity,
the constants must be alterable. The language must
allow for the documentation to help provide this support.
An assembler program is not a self-documenting
program no matter how efficient it is. Its logic and

meaning are often forgotten with the loss of the programmer. Indeed, the programmer may lose the logic to his own program if he has been away from it for a length of time. For example, the statement below is obvious in its intent:

NO$YEARS = NO$DAYS / 365.

Yet even though the next statement provides for the same efficiency of calculation it does not connote as clear a meaning:

LIT DAYS; LIT 365; DIV; LIT YRS; STO; .....

The assembler language form of this statement loses the easily conceived meaning of the first statement.

Though the celestial fix program in Appendix A was written in the BASIC language due to the precision attainable through its use, the program itself would not be understandable without the comment statements and extra documentation.

Specifically, there are primarily two high level languages available to the microprocessor programmer; BASIC as implemented at the Naval Postgraduate School and PLM. BASIC, as the name implies, provides for the basic needs of a programmer. BASIC has subroutines, iterative and logical capability, the full range of mathematical manipulators and limited I/O. A quick glance at the program in Appendix A provides the evidence of a major drawback: lack of variable scope and identifiers. There are no local

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variables; all variables are global. This property coupled with the limited identifier schemes causes a programmer of a large program to run out of variables quickly. His attention is turned to efficient use of identifiers instead of efficient programming techniques.

PLM, on the other hand, provides for scopal variables and identifiers that allow for self-documentation. The following statements are equivalent; however, the second connotes more meaning:

$$\text{LET J1} = G(Q) - G(R)$$

$$\text{DIFF} = \text{GHA1} - \text{GHA2}.$$

The array used in the determination of the three intersections used to calculate the fix (subroutine 0600 ... ARRAY V(6,6)) is a temporary array. In BASIC the array is permanently allocated space. Using PLM and scopal variables the array would be created by the program during execution (indeed, could be of variable size) and be destroyed or written over upon exit from the subroutine. There are a few drawbacks with the use of PLM. The primary drawback in the execution of the program in Appendix A is the word size. Sixteen bits do not provide the accuracy needed for the celestial navigation problem. Though this problem can be solved, it is not easily solved.

Special mathematical routines like trigonometric functions are not available in PLM, yet they can be programmed. The point is that PLM can be tailored to the needs of the

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programmer with a little extra work while the BASIC language cannot be tailored to the user at all. PLM provides a much more versatile language yet the detail required in programming is greater than that of BASIC.

A final comment on the selection of a language deals with the multiplicity of processors on an information distribution system. If each processor were programmed at a different level with a different language the maintenance and design problems would be horrible. For example, suppose one processor is to provide a second processor information. If the first processor is programmed in BASIC then it would probably transmit its data in 32 bit floating point form. The second processor (programmed in PLM) would have to have an I/O routine to convert that processed data to a local format. If there were a third language then the PLM-programmed processor may need yet another I/O processing routine. This situation is the grounds for selection of a single programming language for a system of microprocessors.

VIII. CONCLUSIONS

Currently, the proposed computer is capable of developing a navigational fix (without use of the Nautical Almanac and H.O. Publications) utilizing only the 57 navigational stars. Because of this limitation it is obvious that numerous and known applications are yet to be incorporated. Among these include methods which employ the attributes of the sun, moon and planets so that positioning with these bodies can be performed. Considering functional aspects for future development of programs, suggested programs are closest point of approach (CPA), great circle calculations, star location utilizing estimated altitude and azimuth and fix triangulation routines.

The sun, moon and planets present special problems because of their proximity to earth. They do not appear fixed in the sky as do stars. Stars do move across the sky due to the earth's rotation but their great distances impart a constant relationship to their neighboring stars. The planets and moon, being closer to earth, possess no fixed relation in the evening sky with the stars.

The size of the sun and moon requires a special consideration termed semi-diameter. More accurate sight reductions can be performed by aiming the sextant at the upper and lower limb of these bodies; corrections for the radius of the body can be programmed.

For lunar observations horizontal parallax is a parameter required to be considered. It is the apparent difference in the position of a body when viewed from two different locations. Horizontal parallax is significant for the moon because it is the closest body to earth.

The celestial lines of position are included to give the navigator the option of plotting LOP's. This method should provide the navigator with an azimuth, a distance and a toward/away indication in reference to the assumed position of the observer with which the LOP should be plotted. This is the backup routine to the fix calculation algorithm.

The proposed celestial navigation computer was used as a vehicle for the approach to a design of a dedicated microcomputer. Other devices of similar construction used as peripherals in the information distribution system would be approached in the same manner. Approaching the design of each device on its own merits will allow for the system to grow in a manner that "fits" the situation, i.e., a single "ivory tower" system would not result.

Indeed, the development of the central processor (assuming enough ports are planned for) would grow with the system as each new unit would simply add length to the polling routines and interrupt structures. Following along with Weir's natural growth concept, each processor's programs would be designed and built (or at least the algorithms be provided for) as needed by cognizant individuals, from

current literature, as done in the case of the celestial navigation computer. The only restraint placed on the design/designer would be that of language and interface specifications. As delineated earlier, the authors believe that of the two languages examined PLM would be the most efficient language and would provide for much needed self-documentation.

The central processor in the information distribution system may very well be a minicomputer or a microcomputer depending on its functions. It need only be a distribution device designed along the same lines as the peripherals it supports. The level of computation provided by the central processor must be established early in the design phase because the peripherals would need to "take up the slack" for the computational capabilities not provided by the central processor. For example, the averaging of the revolutions per minute may be accomplished at the peripheral (which is recommended) or at the central processor on the request of the inquirer. Again, keeping this device simple (only the necessary switching and monitoring routines) will provide for more independence and faster information transfer.

```basic
DIM B(2),L(6),E(5),V(6,6),D(3),H(3),G(3)
DIM C(9),Z(3),A(3),O(3),S(2,57)
REM DEFINE LOGICAL VALUES AND CONSTANTS
LET T=0
LET C1=5
LET C2=.01745329252
LET C3=57.29577951
LET C4=3
REM LOAD THE STAR CONSTANTS INTO THE ARRAY S
LET S(1,1)=
LET S(1,2)=
LET S(1,3)=
LET S(1,4)=
LET S(1,5)=
LET S(1,6)=
LET S(1,7)=
LET S(1,8)=
LET S(1,9)=
LET S(1,10)=
LET S(1,11)=
LET S(1,12)=
LET S(1,13)=
LET S(1,14)=
LET S(1,15)=
LET S(1,16)=
LET S(1,17)=
LET S(1,18)=
LET S(1,19)=
LET S(1,20)=
LET S(1,21)=
LET S(1,22)=
LET S(1,23)=
LET S(1,24)=
LET S(1,25)=
LET S(1,26)=
LET S(1,27)=
LET S(1,28)=
LET S(1,29)=
LET S(1,30)=
LET S(1,31)=
LET S(1,32)=
LET S(1,33)=
LET S(1,34)=
LET S(1,35)=
LET S(1,36)=
LET S(1,37)=
LET S(1,38)=
```

LETS(1,39)=3.8...
LETS(1,40)=3.8...
LETS(1,41)=4.8...
LETS(1,42)=4.3...
LETS(1,43)=4.3...
LETS(1,44)=4....
LETS(1,45)=4....
LETS(1,46)=4....
LETS(1,47)=4....
LETS(1,48)=4....
LETS(1,49)=5....
LETS(1,50)=5....
LETS(1,51)=5....
LETS(1,52)=5....
LETS(1,53)=5....
LETS(1,54)=5....
LETS(1,55)=5....
LETS(1,56)=6....
LETS(1,57)=-....
LETS(2,1)=-....
LETS(2,2)=-....
LETS(2,3)=-....
LETS(2,4)=1....
LETS(2,5)=-....
LETS(2,6)=-....
LETS(2,7)=-....
LETS(2,8)=-....
LETS(2,9)=-....
LETS(2,10)=-....
LETS(2,11)=1....
LETS(2,12)=-....
LETS(2,13)=-....
LETS(2,14)=-....
LETS(2,15)=-....
LETS(2,16)=-....
LETS(2,17)=-....
LETS(2,18)=1....
LETS(2,19)=-....
LETS(2,20)=-....
LETS(2,21)=-....
LETS(2,22)=1....
LETS(2,23)=-....
LETS(2,24)=-....
LETS(2,25)=-....
LETS(2,26)=-....
LETS(2,27)=-....
LETS(2,28)=-....
LETS(2,29)=-....

```
LET S(2,30)=-1.09886909
LET S(2,31)= .9943723495
LET S(2,32)=-1.97904671035
LET S(2,33)= .19253497255
LET S(2,34)=-1.862849282
LET S(2,35)= .0516157071
LET S(2,36)=-1.632644689
LET S(2,37)= .3570574519
LET S(2,38)=-1.335951739
LET S(2,39)= .27818386018601
LET S(2,40)= 1.296040778
LET S(2,41)=-1.467771362381
LET S(2,42)= .45037975603
LET S(2,43)=-1.20399317403174
LET S(2,44)= .64729147177
LET S(2,45)= .21951282352235
LET S(2,46)= .8986928665
LET S(2,47)= .6003580652204
LET S(2,48)= .676483203083
LET S(2,49)= .4534822018574
LET S(2,50)=-.15361617094
LET S(2,51)= .99163770941
LET S(2,52)= .787218521
LET S(2,53)=-.1703400141
LET S(2,54)= .82174978441
LET S(2,55)=-.51932480036
LET S(2,56)= .2630294571
LET S(2,57)= GOSUB 0200  REM RUN STAR FIX PROGRAM
PRINT 'PROGRAM COMPLETE'
STOP
```

```
REM ***********************************************************************
REM **                                                                   **
REM ** GENERAL SUBROUTINE (0010) CONVERTS DEG.MINSEC TO RADIANS OR        **
REM **    IF HOUR INDICATOR IS SET (L1=T) THEN HRS.MINSEC TO HRS.         **
REM **    PASSING VARIABLE IS (P1).                                       **
REM **                                                                   **
REM ***********************************************************************
0010 LET I1=INT(P1)
     LET I2=P1*100-I1*100
     LET I3=P1*10000-INT(I2)*100-I1*10000
     LET P1=I1+(I3+60*INT(I2))/3600
     REM CONVERT DEGREES TO RADIANS
     IF L1=T THEN 0011
     LET P1=P1*C2
0011 LET L1=F
     RETURN
REM ***********************************************************************
REM **                                                                   **
REM ** GENERAL SUBROUTINE (0020) CONVERTS RADIANS TO DEG.MINSEC           **
REM **    IF HOUR INDICATOR IS SET (L1=T) THEN HRS. TO HRS.MINSEC         **
REM **    PASSING VARIABLE IS P1                                          **
REM **                                                                   **
REM ***********************************************************************
0020 IF L1 = T THEN 0021
     LET P1=P1*C3
0021 LET I1=INT(P1)
     LET I2=(P1-I1)*60
     LET I3=(I2-INT(I2))*60
     LET P1=I1+(INT(I2)*100+I3)/10000
     LET L1=F
     RETURN
REM ***********************************************************************
REM **                                                                   **
REM **    GENERAL SUBROUTINE (0030) NORMALIZES ALL RADIAN MEASUREMENT     **
REM **       TO 2*PI RADIANS                                              **
REM **                                                                   **
REM ***********************************************************************
0030 LET P1=P1/C1
     LET P1=(P1-INT(P1))*C1
RETURN
```

```
REM *************************************************
REM *                                               *
REM *   GENERAL SUBROUTINE 0040 DETERMINES THE INVERSE SIN AND
REM *   INVERSE COS OF THE PASSED ARGUMENT (P1). THE VARIABLE
REM *   P2 IS USED TO DETERMINE WICH FUNCTION WILL BE IMPLEMENTED.
REM *   IF P2=1 THEN THE ARCSIN OF THE ARGUMENT IS DETERMINED
REM *   IF P2=2 THEN THE ARCCOS OF THE ARGUMENT IS DETERMINED
REM *   AND APPLIED TO THE POSITIVE RANGE 0-180 DEGREES.
REM *                                               *
REM *************************************************
0040 IF P2 NE 2 THEN 0041
     LET P1=ATN(SQR(1-P1**2)/P1)
     IF P1 GT 0 THEN 0042
     LET P1=P1+C4
0041 IF P2 NE 1 THEN 0042
     LET P1=ATN(P1/SQR(1-P1**2))
0042 LET P2=0
RETURN
```

```
REM ***********************************************************
REM **  GENERAL SUBROUTINE 0100 CREATES THE VECTOR OF EIGHT  **
REM **  CONSTANTS USED TO CALCULATE THE GHA AND DECLINATION OF **
REM **  THE SELECTED BODY (SUBROUTINE 0300).                  **
REM ***********************************************************

0100 LET I0=360.9856473*C2
     REM CONVERT EARTH ROTATION RATE TO RADIANS
     LET I1=.75
     REM EPOCH 1975 IN CENTURIES SINCE 1900
     LET I2=1.745765584
     REM GHA OF ARIES 0000 01JAN 1975
     LET I8=365.2421987 8-.00000614*I1
     LET C(1)=C1/I8
     REM OBLIQUITY EPOCH 1975
     LET C5=-.4091494033
     REM RIGHT ASCENSION OF BODY EPOCH 1975
     LET I3=S(1,R9)
     REM DECLINATION OF BODY EPOCH 1975
     LET I4=S(2,R9)
     REM RATE OF CHANGE OF RIGHT ASCENSION
     LET C6=.0022352331
     REM RATE OF CHANGE OF DECLINATION
     LET C7=.0000971586
     LET I5=(C6+C7*SIN(I3)*TAN(I4))/I8
     LET C(4)=C7*COS(I3)/I8
     REM CONSTANT OF ABERATION EPOCH 1975
     LET I6=10-15
     LET C8=.0000992+I3
     LET I7=C8/COS(I4)*COS(I3)*COS(C5)
     LET I9=C8/COS(I4)*SIN(I3)
     LET C(7)=SQR(I7*2+I9*2)
     LET J0=C8*(SIN(C5)*COS(I4)-COS(C5)*SIN(I3)*SIN(I4))
     LET J1=C8*COS(I3)*SIN(I4)
     REM CORRECT FROM 4.5 JAN 74 TO BASE DATE 29.0 NOV 71
     LET C(3)=SQR(J0*2+J1*2)
     LET P1=C(11)*767.5
     REM NORMALIZE RADIAN MEASURE TO 360 DEGREES
     GOSUB 0030
     LET J2=4.951771598-P1
     LET P1=J2+ATN(I7/I9)
     GOSUB 0030
     LET C(9)=P1
     LET P1=J2+ATN(J0/J1)
     GOSUB 0030
     LET C(2)=P1
     REM CORRECT FROM 0.0 JAN 75 TO BASE DATE 29.0 NOV 71
```

```
LET P1=I6*1128
GOSUB 0030
LET C(8)=I2-P1-I3
IF C(8) GE 0 THEN 0101
LET C(8)=C(8)+C1
LET C(6)=I6-C1
0101 REM CORRECT FROM 0.0 JAN 75 TO BASE DATE 29.0 NOV 71
LET C(5)=I4-C(4)*1128
RETURN
```

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```
REM **********************************************************
REM **
REM **    SUBROUTINE (0200) REQUEST ALL INITIAL DATA REQUIRED
REM **    FOR FIX. CONSTANT DEFINITIONS FOLLOW:
REM **    L2:....=LEAP YEAR   T=LEAP YEAR
REM **    D:....=DAY OF THE MONTH
REM **    M:....=MONTH
REM **    Y:....=YEAR (LAST TWO DIGITS 19XX )
REM **
REM **    SET LOGICAL FLAG 2 (LEAP YEAR) TO TRUE
REM **********************************************************
0200 LET L2=T
     REM FROM THIS POINT TO 0204 DETERMINE THE DAYS SINCE REF
     REM DATE 29 NOV 1971
     PRINT 'ENTER DAY'
     READ D
     PRINT 'ENTER MONTH'
     READ M
     PRINT 'ENTER YEAR'
     READ Y
     LET R8=M
     LET R6=30*M+D
     LET R7=Y-72
     LET R6=R6+365*R7
     LET R7=R7/4
     LET R6=R6+INT(R7)
     IF (R7-INT(R7)) NE 0 THEN 0201
     REM INDICATE THIS YEAR IS LEAP YEAR
     LET L2=F
0201 IF M LE 2 THEN 0203
     IF M LE 8 THEN 0202
0202 LET M=M+1
     LET M=INT(M/2)
     GO TO 0204
0203 IF L2=F THEN 0204
     LET M=M+1
0204 LET R3=R6+M
     PRINT 'ENTER ALTITUDE (FT MSL)'
     READ A
     PRINT 'ENTER TEMPERATURE (DEG CENTIGRADE)'
     READ T1
     LET L1=F
     PRINT 'ENTER COURSE (D.MS)'
```

```
READ P1
PRINT P1
GOSUB 0010
LET C=P1
PRINT "ENTER SPEED (KNOTS TRUE)"
READ K
PRINT K
REM CONVERT SPEED (KTS) TO RADIAL VELOCITY
LET K=.0002908820087*K
PRINT "ENTER ASSUMED LAT (N/S) +/-(D.MS)'"
READ P1
GOSUB 0010
LET R1=P1
PRINT "ENTER ASSUMED LONG(E/W) +/-(D.MS)'"
READ P1
PRINT P1
GOSUB 0010
LET R2=P1
PRINT "ENTER NUMBER OF BODIES THIS FIX"
READ N1
PRINT N1
PRINT . = 1 TO N1
FOR N = 1 TO N1
PRINT "ENTER STAR/BODY NUMBER"
READ R9
IF R9 NE 44 THEN 0214
PRINT "CONSTANTS UNAVAILABLE"
LET N1=N1-1
GO TO 0209
0214 PRINT "ENTER GMT OF OBS (H.MS)'"
READ P1
PRINT P1
LET L1=T
REM CONVERT GMT (H.MMSS) TO GMT (HRS.)
GOSUB 0010
LET R4=P1
PRINT "GMT (HRS)=",R4
IF N=1 THEN 0206
IF (O(N-1)-INT(O(N-1))) LT R4 THEN 0206
LET R3=R3+1
LET O(N)=R3+R4/24
0206 PRINT "ENTER HS (D.MS)'"
READ P1
PRINT P1
GOSUB 0010
LET H=P1
```

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```
        PRINT 'ENTER IC (D.MS)'
        READ P1
        PRINT P1
        GOSUB 0010
        LET I=P1
        REM COMPUTE 1A=HS+IC
        LET R8=H+I
REM   ****************************************************************
REM   *** CORRECT FOR ALTITUDE, TEMPERATURE AND CORIOLIS EFFECT   ***
REM   *** IF USED IN AIRCRAFT OR HIGH SPEED CRAFT                 ***
REM   ****************************************************************
REM   ****************************************************************
        IF A GT 200 THEN 0207
        REM DETERMINE THE DIP IN MINUTES OF ARC
0207    LET P1=.97*SQR(A)
        REM CONVERT MINUTES OF ARC TO RADIANS
        LET P1=P1*.0002908882
        REM REMOVE THE EFFECT OF DIP FROM THE OBSERVED ALTITUDE
        LET R8=R8-P1
        LET R5=R8
        LET H(N)=R5
        LET P1=R8
        GOSUB 0020
        PRINT 'HA=',P1
        LET P1=I
        GOSUB 0020
        LET P1=H
        GOSUB 0020
        REM DETERMINE THE CONSTANTS NEEDED FOR THIS BODY
        GOSUB 0100
        REM DETERMINE GHA AND DEC FOR THIS BODY
        GOSUB 0300
        LET G(N)=P3
        LET D(N)=P4
        REM DETERMINE ZN ZND DISTANCE TOWARD THIS BODY FOR LOP
        GOSUB 0400
0209    NEXT N
        IF N1=1 THEN 0208
        REM CORRECT THE OBSERVED ALTITUDES FOR PLATFORM MOVEMENT
        GOSUB 0500
0208    GOSUB 0600
        REM DETERMINE THE FIX IF POSSIBLE
        LET P1=O(D1)-INT(O(D1))
        PRINT 'TIME OF FIX (.DAY)',P1
        RETURN
```

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```
REM ****************************************************************
REM **                                                            **
REM **      STARCARD/BODYCARD (USES STAR CONSTANTS C(X) )          **
REM **                                                            **
REM **  THIS ROUTINE DETERMINES THE GHA AND DECLINATION OF THE BODY **
REM **  R3 DAYS SINCE REFERENCE DATE                              **
REM **  R4 HOURS GMT THEN GHA                                     **
REM **  R6 DECLINATION                                            **
REM **  R7 LONGITUDE OF MEAN SUN                                  **
REM **  R8 DAYS.DAY SINCE REFERENCE                               **
REM **  P3 GHA                                                    **
REM **  P4 DEC                                                    **
REM ****************************************************************
0300 LET R8=(R4/24)+R3
     REM DETERMINE THE LONGITUDE OF THE MEAN SUN
     LET R7=R8*C(1)
     REM COMPUTE THE DECLINATION OF THIS BODY
     LET P1=SIN(R7+C(2) )*C(3) +(R8*C(4) )+C(5)
     GOSUB 0030
     LET R6=P1
     REM COMPUTE THE GHA FOR THIS BODY
     LET P1=C(8)+C(6)*R8+C1*R4/24-C(7)*SIN(R7*C(9))
     GOSUB 0030
     LET P4=P1
     LET P3=P1
     GOSUB 0020
     PRINT 'GHA  OF BODY=',P1
     LET P1=R6
     LET P4=P1
     GOSUB 0020
     PRINT 'DEC OF BODY (D.MMSS)',P1
RETURN
```

```
REM **************************************************************
REM **                                                          **
REM ** THIS SUBROUTINE 0400 DETERMINES THE ZN AND DISTANCE FROM THE **
REM ** ASSUMED LATITUDE AND LONGITUDE THAT THE LINE OF POSITION  **
REM ** FOR EACH BODY SHOULD BE PLACED. THIS DATA (ZN & DIST)     **
REM ** IS PLACE IN A VECTOR Z(N) AND A(N) RESPECTIVELY FOR USE LATER. **
REM **                                                          **
REM ** R0  SCRATCH REGISTER/ASSUMED LONGITUDE                   **
REM ** R1  ASSUMED LATITUDE                                     **
REM ** R2  ASSUMED LONGITUDE                                    **
REM ** R3  NUMBER OF DAYS SINCE REFERENCE DAY                   **
REM ** R4  CHA OF BODY                                          **
REM ** R5  OBSERVED ALTITUDE HO                                 **
REM ** R6  DECLINATION OF BODY (DEC)                            **
REM ** R7  ASSUMED LATITUDE FOR ASSUMED LAT/LONG                **
REM ** R8  COMPUTED ALTITUDE                                    **
REM ** R9  STAR NUMBER                                          **
REM **                                                          **
REM **************************************************************
0400 LET L3=F
     IF SIN(R2+R4) GE 0 THEN 0401
     LET L3=T
0401 LET R0=COS(R2+R4)*COS(R1)*COS(R6)+SIN(R1)*SIN(R6)
     REM DETERMINE THE SIN OF THE COMPUTED ALTITUDE HC
     REM DETERMINE THE HC
     LET P1=R0
     LET P2=1
     GOSUB 0040
     LET R8=P1
     REM DETERMINE THE COSINE OF THE ZN
     LET R0=(SIN(R6)-SIN(R1)*SIN(R8))/(COS(R1)*COS(R8))
     REM DETERMINE THE ZN
     LET P1=R0
     LET P2=2
     GOSUB 0040
     IF L3=T THEN 0402
     LET P1=C1-P1
0402 GOSUB 0030
     LET Z(N)=P1
     LET L1=F
     GOSUB 0020
     PRINT "ZN OF BODY (D.MMSS)",P1
     LET A(N)=(R5-R8)
     LET P1=A(N)
     GOSUB 0020
     LET L1=T
     GOSUB 0010
     LET P1=P1*60
```

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```
PRINT 'DISTANCE' TOWARD BODY (NM)',P1
LET P1=R.8
GOSUB 0020
PRINT 'BASED ON HC (D.MMSS)',P1
PRINT ' '
PRINT ' '
RETURN
```

```
REM *************************************************************
REM **   SPECIAL ROUTINE (0500) CORRECTS LINES OF POSITION FOR MOVEMENT** **
REM **       OF PLATFORM **
REM *************************************************************
0500 PRINT "ENTER SHOT OF DESIRED FIX TIME"
     READ D1
     PRINT D1
     IF D1 GT N1 THEN 0500
     IF D1 LT 1 THEN 0500
     FOR S=1 TO N1
     LET A(S)=A(S)+COS(Z(S)-C )*(O(D1)-O(S))*K*24
     LET P1=A(S)
     LET H(S)=H(S)+P1
     REM CONVERT THE RADIAN DISTANCE TO MILES
     LET P1=P1*60*C3
     PRINT P1 "CORRECTED DIST TOWARD BODY",S
     LET P1=H(S)
     GOSUB 0020
     PRINT "BASED ON CORRECTED HO (D.MMSS)"
     PRINT P1
     NEXT S
     RETURN
```

```
REM ****************************************************************
REM * SPECIAL ROUTINE 0600 RECEIVES THE GHA'S AND DEC'S FOR ALL   *
REM * OF THE BODIES USED IN THE STAR FIX AND DETERMINES THE THREE *
REM * INTERSECTIONS OF THE RESPECTIVE CIRCLES OF EQUAL ALTITUDES  *
REM * THAT ARE APPLICABLE TO THE FIX (OR TWO INTERSECTIONS FOR A  *
REM * TWO BODY FIX). IN THE CASE OF THREE BODIES, THE THREE INT-  *
REM * ERSECTIONS WITH THE SMALLEST SOLID ANGLE ARE USED TO DEFINE *
REM * THE VERTICES OF THE TRIANGLE OF WHICH THE CENTER OF MASS    *
REM * IS USED TO DEFINE THE TWO BODY FIX.                         *
REM * IN THE CASE OF A TWO BODY FIX, THE CLOSEST INTERSECTION TO  *
REM * THE ASSUMED POSITION IS THE FIX.                            *
REM ****************************************************************
0600 IF N1 NE 2 THEN 0601
     REM WITH TWO BODIES GO TO THE INTERSECTION ROUTINE 0700
     REM ONLY ONCE
     LET I1=1
     GO TO 0602
0601 LET I1=3
0602 IF N1 NE 1 THEN 0613   IF ONLY ONE BODY USED THEN 'FIX' NOT POSSIBLE
     REM CAUSE THE INTERSECTION ROUTINE TO ITERATE ON ALL
     REM COMBINATIONS OF BODIES
     FOR Z=1 TO I1
     LET Q=Z+1
     LET P=Z+1
     LET R=1
     IF R NE 4 THEN 0603
0603 LET S=2*Z-1
     REM DETERMINE THE INTERSECTIONS OF EQUAL ALTITUDES FOR THIS PAIR
     GOSUB 0700
     NEXT Z
     IF N1 NE 2 THEN 0605
     REM IN THE CASE OF TWO BODIES SELECT THE CLOSEST INTERSECTION
     REM AS THE FIX
     LET I2=SQR((L(1)-R1)**2+(E(1)-R2)**2)
     LET I3=SQR((L(2)-R1)**2+(E(2)-R2)**2)
     IF I2 GT I3 THEN 0604
     LET I8=L(1)
     LET I9=E(1)
     GO TO 0612
0604 LET I8=L(2)
     LET I9=E(2)
     GO TO 0612
     REM IN THE CASE OF THREE BODIES DETERMINE THE INTERNAL ANGLE
     REM BETWEEN ALL PAIRS OF INTERSECTIONS
0605 LET V1=999999
```

```
      FOR S=1 TO 5
      FOR J=(S+1) TO 6
      LET P1=(COS(ABS(L(S)-L(J)))*COS(ABS(E(S)-E(J)))
      LET P2=2
      REM DETERMINE THE ARC COS OF THE INTERIOR ANGLES
      GOSUB 0040
      LET RO=P1
      REM SELECT THE SMALLEST INTERIOR ANGLE
      IF V1 LT RO THEN 0606
      REM STORE THE INTERIOR ANGLE AND THE PARTICIPATING BODIES
      LET V1=RO
      LET M1=S
      LET M2=J
0606  LET V(S,J)=RO
      NEXT J
      NEXT S
      LET R=1
      REM DETERMINE THE SMALLEST SOLID ANGLE OF THE TRIANGLES THAT
      REM INCLUDE THE TWO INTERSECTIONS THAT PRODUCE THE SMALLEST
      REM INTERIOR ANGLE
      FOR Q=1 TO 6
      IF Q GE M1 THEN 0607
      LET D1=V(Q,M1)+V(Q,M2)
      GO TO 0609
0607  IF Q GE M2 THEN 0608
      LET D1=V(M1,Q)+V(Q,M2)
      GO TO 0609
0608  IF Q = M2 THEN 0610
      LET D1=V(M1,Q)+V(M2,Q)
0609  LET V(R+1,R)=Q
      LET V(6,R)=R+1
      LET R=R+1
0610  NEXT Q
      FOR Q=2 TO 5
      IF V(Q,1) GT D1 THEN 0611
      LET D1=V(Q,1)
      LET R=Q-1
0611  NEXT Q
      REM DETERMINE THE CENTER OF MASS OF THE TRIANGLE USING
      REM THE THREE SELECTED SIDES
      LET I1=V(6,R)
      LET I2=M1
      LET I3=M2
      LET I4=L(I1)-2*(L(I1)-L(I2))/3
      LET I5=E(I1)-2*(E(I1)-E(I2))/3
      LET I6=L(I1)-2*(L(I1)-L(I3))/3
```

```
LET I7=E(I1)-2*(E(I1)-E(I3))/3
LET I8=I4+(I6-I4)/2
LET I9=I5+(I7-I5)/2
    REM CONVERT COORDINATES TO DEGREES.MINSEC
LET P1=I8
GOSUB 0020
LET I8=P1
LET P1=I9
GOSUB 0020
LET I9=P1
0612 PRINT 'FIX (LAT/LONG D.MMSS)='
     PRINT I8,I9
0613 RETURN
```

```
REM ***********************************************************
REM **  SPECIAL SUBROUTINE 0700 DETERMINES THE INTERSECTION  **
REM **  OF TWO CIRCLES OF EQUAL ALTITUDE BASED ON THE HEIGHT  **
REM **  OBSERVED (HO), GHA AND DECLINATION OF EACH OF THE TWO **
REM **  BODIES.                                               **
REM **  THE FOLLOWING VARIABLES ARE PASSED AND DEFINED:       **
REM **                                                        **
REM **  G(Q)....GHA OF BODY 1                                 **
REM **  G(R)....GHA OF BODY 2                                 **
REM **  D(Q)....DECLINATION OF BODY 1                         **
REM **  D(R)....DECLINATION OF BODY 2                         **
REM **  H(Q)....HEIGHT OBSERVED OF BODY 1                     **
REM **  H(R)....HEIGHT OBSERVED OF BODY 2                     **
REM **                                                        **
REM **  S...INDEX INTO LATTITUDE AND LONGITUDE ARRAYS         **
REM ***********************************************************
0700 LET L2=F
     LET J1=G(Q)-G(R)
     IF SIN(J1) GE 0 THEN 0701
     LET L2=T
0701 LET J2=P1=COS(D(Q))*COS(D(R))+SIN(D(Q))*SIN(D(R))
     LET P2=1
     GOSUB 0040
     LET J3=P1
     LET P1=(SIN(D(Q))-SIN(D(R))*J2)/(COS(D(R))*COS(J3))
     LET P2=2
     GOSUB 0040
     LET J2=P1
     IF L2=F THEN 0702
     LET J2=-J2
0702 LET P1=(SIN(H(Q))-SIN(H(R))*SIN(J3))/(COS(H(R))*COS(J3))
     LET P2=2
     GOSUB 0040
     LET J3=P1
     LET B(2)=J2+J3
     LET B(1)=J2-J3
     FOR I=1 TO 2
0703 LET L2=T
     IF SIN(B(I)) GE 0 THEN 0704
0704 LET L2=F
     LET P1=COS(B(I))*COS(D(R))+SIN(D(R))*SIN(H(R))
     LET P2=1
     GOSUB 0040
     LET R8=P1
     LET J6=S+I-1
     LET L(J6)=R8
     LET P1=(SIN(H(R))-SIN(D(R))*SIN(R8))/(COS(D(R))*COS(R3))
```

```
      LET P2=2
      GOSUB 0040
      IF L2=F THEN 0705
      LET P1=-P1
0705  LET E(J6)=P1-G(R)
      LET J=1
      IF ABS(E(J6)) LT C4 THEN 0707
      IF E(J6) GT 0 THEN 0706
      LET J=-1
0706  LET E(J6)=E(J6)-2*C4*J
0707  NEXT I
0708  RETURN


END
```

APPENDIX B   SAMPLE PROGRAM RUN

```
ENTER DAY
 20
ENTER MONTH
 6
ENTER YEAR
 75
ENTER ALTITUDE (FT MSL)
 60
ENTER COURSE (D.MS)
 270
ENTER SPEED (KNOTS TRUE)
 5
ENTER ASSUMED LAT (N/S) +/-(D.MS)
 40
ENTER ASSUMED LONG(E/W) +/-(D.MS)
 15.2224
ENTER NUMBER OF BODIES THIS FIX
 3

ENTER STAR/BODY NUMBER
 1
ENTER GMT OF OBS (H.MS)
 .56
GMT (HRS)=        .944443
ENTER HS (D.MS)
 37.04
ENTER IC (D.MS)
 0
HA=              36.5709
GHA OF BODY=     280.043
DEC OF BODY (D.MMSS)            28.5728
ZN OF BODY (D.MMSS)             80.4231
DISTANCE TOWARD BODY (NM)       8.25071
BASED ON HC (D.MMSS)            36.4854


ENTER STAR/BODY NUMBER
 46
ENTER GMT OF OBS (H.MS)
 1
GMT (HRS)=        1
ENTER HS (D.MS)
 48.39
ENTER IC (D.MS)
 0
HA=              48.3209
GHA OF BODY=     19.1425
DEC OF BODY (D.MMSS)            12.3436
ZN OF BODY (D.MMSS)             237.462
DISTANCE TOWARD BODY (NM)       -30.9003
BASED ON HC (D.MMSS)            49.0303


ENTER STAR/BODY NUMBER
 40
ENTER GMT OF OBS (H.MS)
 1.04
GMT (HRS)         1.07778
ENTER HS (D.MS)
 42.11
ENTER IC (D.MS)
 0
HA=              42.0409
GHA OF BODY=     61.1234
DEC OF BODY (D.MMSS)            74.1533
ZN OF BODY (D.MMSS)             339.153
DISTANCE TOWARD BODY (NM)       14.4483
BASED ON HC (D.MMSS)            41.4942
```

```
ENTER SHOT OF DESIRED FIX TIME
 2
CORRECTED DISTANCE TOWARD BODY 1
 7.92129
BASED ON CORRECTED HO (D.MMSS)
 36.4834

CORRECTED DISTANCE TOWARD BODY 2
-30.9003
BASED ON CORRECTED HO (D.MMSS)
 49.0303

CORRECTED DISTANCE TOWARD BODY 3
 14.3302
BASED ON CORRECTED HO (D.MMSS)
 42.0402

FIX (LAT/LONG D.MMSS)=
 40.3313        15.3354
TIME OF FIX (.DAY)=                    .0415666
PROGRAM COMPLETE
```

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