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LUNAR NAVIGATION STUDY
FINAL REPORT
(June 1964 to May 1965)

SUMMARY VOLUME

BSR 1134

June 1965

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Authors:

L. J. Abbeduto
M. E. Amdursky
D. K. Breseke
J. T. Broadbent
R. A. Gill
H. C. Graboske
W. G. Green
T. F. King
R. B. Odden
P. I. Pressel
T. T. Trexler
C. Waite

BENDIX SYSTEMS DIVISION
OF
THE BENDIX CORPORATION
Ann Arbor, Michigan

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1. INTRODUCTION

The purpose of the lunar surface navigation and guidance study was to investigate three functional navigation component configurations to determine areas in which technology research and development are required to implement lunar surface vehicle exploration missions through the 1980s. This was accomplished by deriving error models that were then used to evaluate the effects of parameter variations and also to determine navigation errors for typical operating conditions. Data resulting from the studies are applicable for use by system designers and mission planners during vehicle design and optimization phases.

This summary briefly discusses the major areas of the study, but excludes some secondary and supporting tasks which are discussed in the final report (applicable sections are referenced in parentheses).

2. STUDY APPROACH

The block diagram, Figure 1, depicts the approach that was used during the study. Lunar surface exploration mission descriptions were provided in a NASA document: "Post-Apollo Lunar Program Phases and Possible Exploratory Mission Sequence" prepared by David Paul 3rd, MSFC. From the mission objectives described therein, typical navigation requirements were prepared directly, thus bypassing mission and subsystem requirements which normally are intermediate steps. Also, to develop a nominal range of typical requirements, it was necessary to review some of the mission and/or scientific tasks that might be imposed during the program.

State of the art was reviewed for techniques and components that would be applicable to various navigation system concepts. The error models were then used to evaluate the effect of component parameter variations on system performance and to obtain typical accuracy capabilities for each system concept. Comparisons of requirements with capabilities provided an initial evaluation of concepts which, combined with parameter sensitivity studies, presented means for determining areas where technological improvements would be desirable.

One of the basic ground errors under which this study was conducted was that all parameters, errors and requirements, would be 3σ values. In addition, it was stipulated that errors would be combined in a root sum square (RSS) manner.

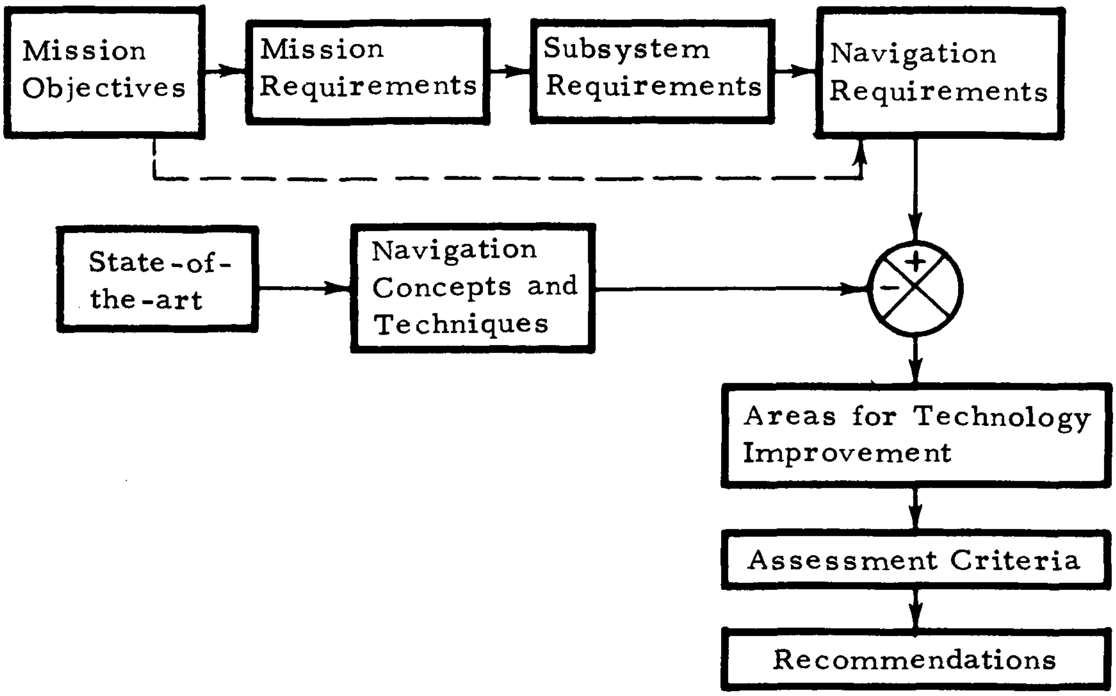

Figure 1 Block Diagram of Study Approach

3. DEFINITIONS OF TYPICAL MISSIONS

The missions defined in the previously referenced NASA document are shown in Table 1. A vehicle for a Type I mission is unmanned and is for vehicle development tests, site surveys, logistics, rescue, and scientific experimentation.

A second mission type for early manned reconnaissance operations is similar to the ALSS MOLAB vehicle. In addition to scientific experiment and survey tasks, the feasibility of utilizing men and equipment in the lunar environment will be investigated.

The Type III mission vehicle is similar to the previous vehicle, except that it will have a larger crew, longer range, and capability of supporting tasks over a complete lunation. Navigation requirements may be more stringent to implement the upgrading of lunar map accuracies.

The Type IV mission vehicle provides a maximum range capability for preliminary exploration of the far side of the moon and potentially over a polar route. These missions may require preliminary route surveys and cached supplies. To provide communications with either lunar bases or earth stations, a communications system comprised of either surface-based or satellite relay stations will probably be required.

TABLE 1

MISSIONS (PER "POST APOLLO LUNAR PROGRAM PHASE AND POSSIBLE EXPLORATORY MISSION SEQUENCE")

Mission	Crew	Duration (days)	Range (km)	Max. Speed (km/hr)	Approx. Time Period
1. Type I - Unmanned	0		240	5	1969 - 1976
2. Type II - Manned	2	14	240	8	1970 - 1985
3. Type III - Manned	4	42	960	16	1975 - 1989
4. Type IV - Manned	6	90	2900	16	1978 -

Notes:

All capable of remote control.
Types II, III, and IV capable of being earth independent.

4. NAVIGATION SYSTEM CONCEPTS

Navigation system concepts that were designated for evaluation during this study were the passive nongyro, inertial, and RF technology systems. Block diagrams of the concepts are shown in Figures 2, 3, and 4.

Each of the three concepts must provide capabilities for functional modes for position fixing, dead reckoning, and piloting. Definitions of these modes are as follows:

1. Position fixing: the process of determining a position and establishing a directional reference using celestial and map references and RF technologies
2. Dead reckoning: the determination of position by advancing a known position for both course and distance
3. Piloting: navigation involving frequent or continuous determination of position relative to geographic points.

An error model of the Command Service Module (CSM) tracking concept was developed, but the use of the technique was not studied in depth. Consideration was also given to radio navigation systems. However, it was basically limited to the use of radio direction finding to increase the homing range parameter.

5. NAVIGATION TECHNIQUE SURVEY

The navigation techniques of interest during the study were for the modes of position fix measurement, dead reckoning, and homing.

5.1 POSITION FIX

Position fix data can be derived by using one of a number of techniques, some of which are dependent upon a local vertical reference. The techniques considered are listed in Table 2 and include celestial and CSM tracking, DSIF and MSFN earth-based tracking, and relative position measurements.

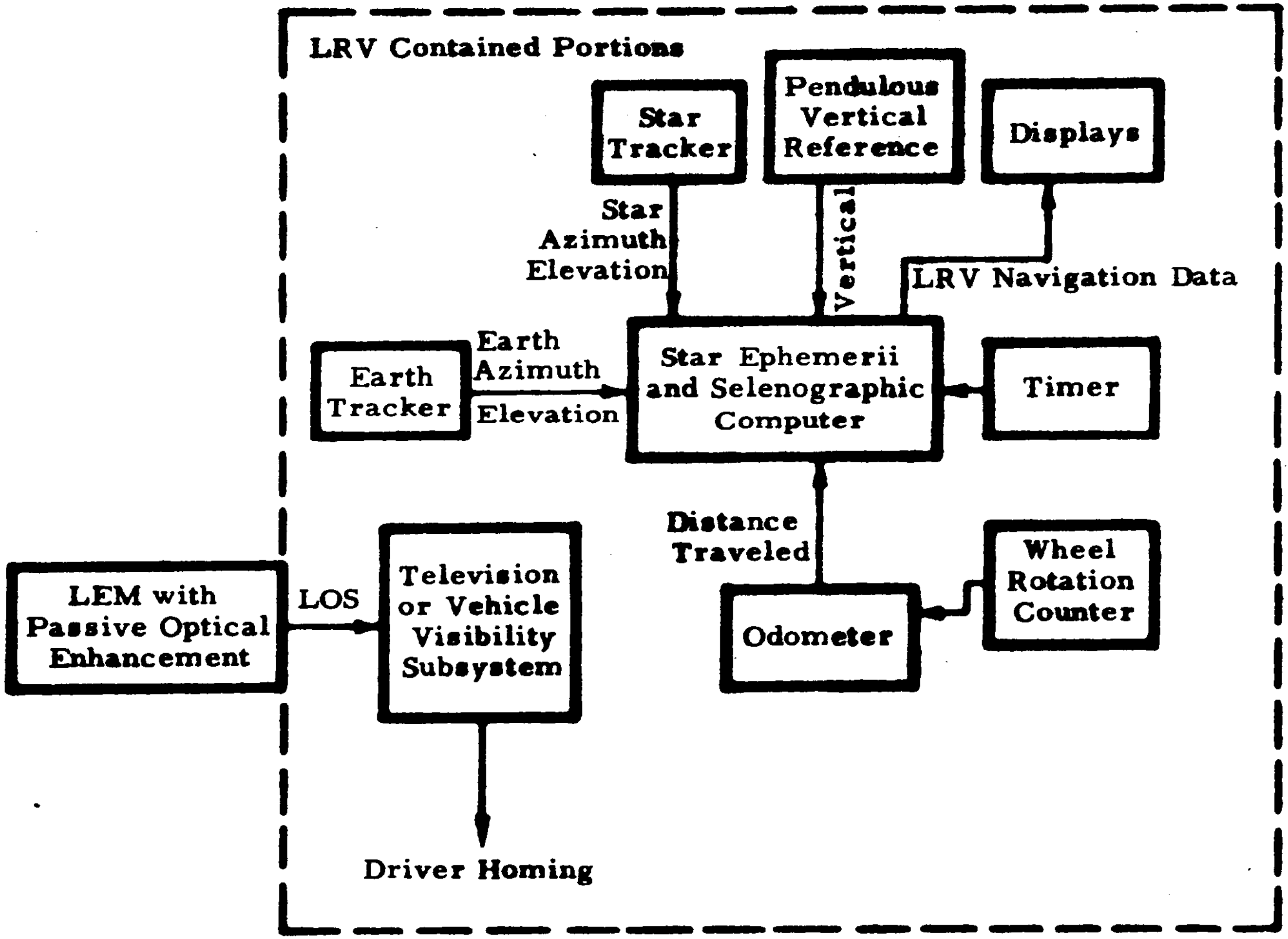

Figure 2 Concept 1—Passive, Nongyro System Block Diagram

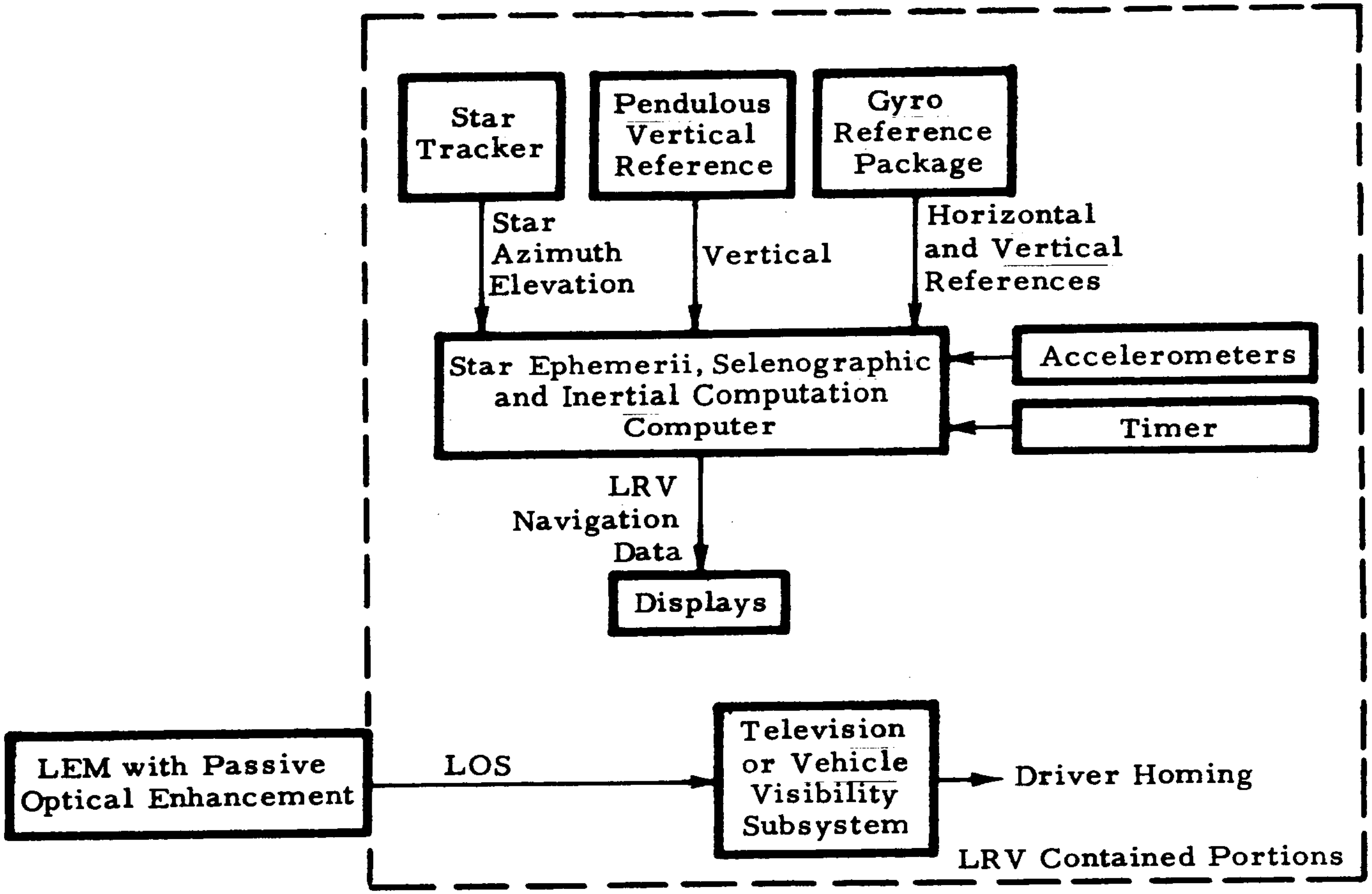

Figure 3 Concept 2—Inertial System Block Diagram

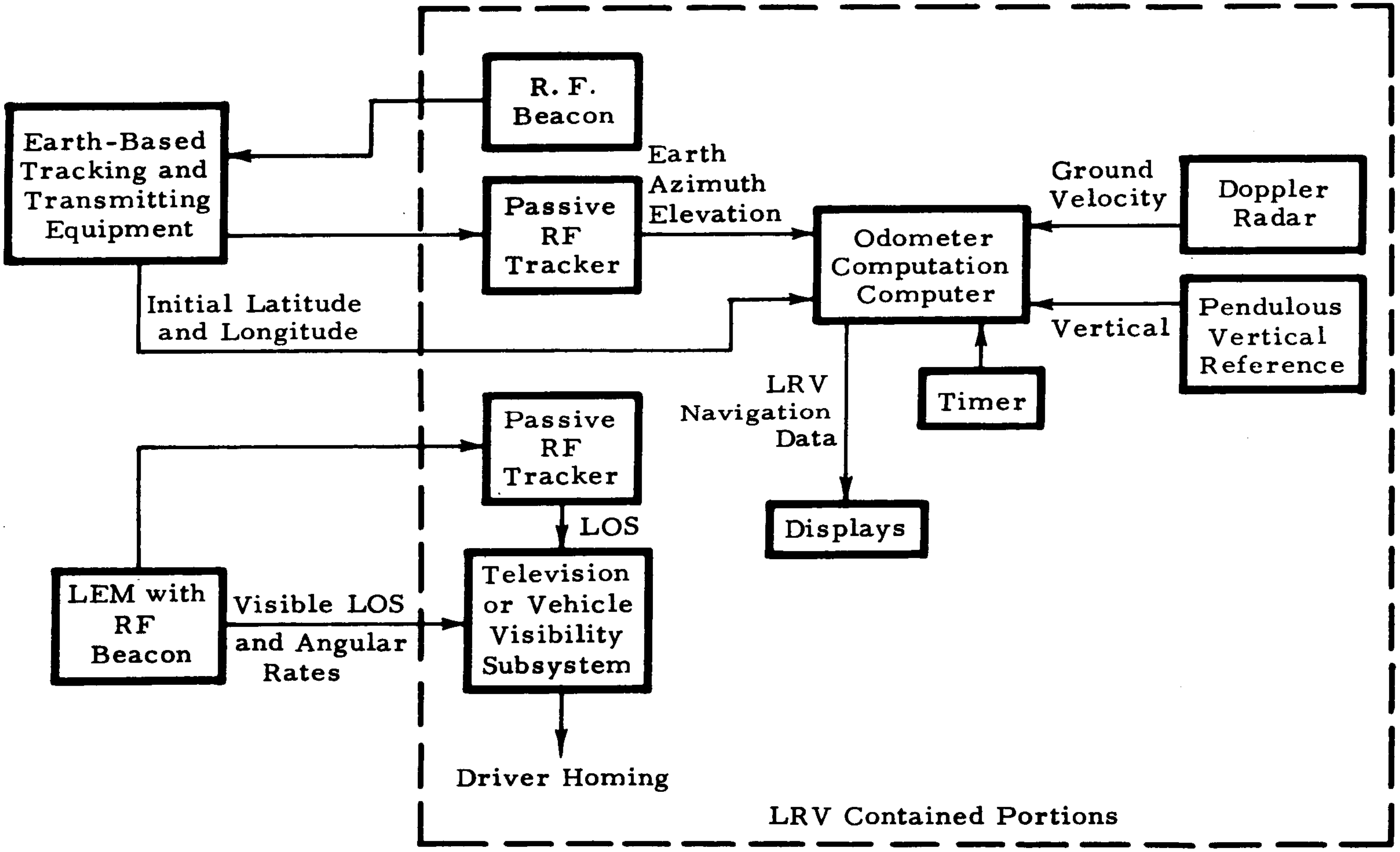

Figure 4 Concept 3—RF Technology System Block Diagram

TABLE 2

POSITION FIX TECHNIQUES

1. Celestial (sun, stars, earth)
   - a. Selection of observables
   - b. Acquisition of observables
   - c. Ephemeris
   - d. Computation (on-board, remote)
   - e. Instrumentation

2. CSM tracking
   - a. Acquisition
   - b. Measurement
   - c. Computation
   - d. Instrumentation

3. DSIF and MSFN

4. Relative position
   - a. Angle measurements to surface features
   - b. Computation of position
   - c. Instrumentation

Celestial navigation techniques include the use of the sun, earth, and other planets and stars for observables. Selection of particular observables requires consideration of visual magnitude, spectral radiance, spatial distribution, background illumination, phase errors (applicable to planets), occultations by the earth, ephemeris, and relative position in space.

The use of solar tracking is limited to the lunar day; earth tracking is limited to the near-side missions. However, each is limited still further by geometric considerations in the vicinity of its subpoints on the lunar surface. Acquisition, selection, and tracking requirements depend upon the particular observable, with the sun and the earth being the easiest to acquire. Others, including the planets, will require techniques for pointing and scanning relative to a specific reference line to obtain the desired tracking. Subsequent computation of position and heading can be done either on-board or at a remote site, but an on-board navigation capability must be maintained for safety.

Instrumentation required for tracking the observables is being used for numerous space applications, and the state of the art is continually progressing. The orbiting CSM and possibly orbiting communications or navigation satellites can be used for position fix purposes. This technique, similar to Transit and potentially similar to SECOR, requires one or more of a combination of angle tracking, range measurement, or frequency measurement in addition to computations in order to derive the necessary position and direction data.

The DSIF and MSFN facilities are capable of very accurate surface position measurements after long-term tracking of a cooperative beacon on a surface vehicle. Predicted position measurement accuracy is a function of time. However, this technique is limited to near-side missions and may require excessive tracking time (up to two weeks) to produce the desired accuracy. Once position is known, the vehicle must establish an azimuth reference using either an observable or a gyrocompass. (Table 8-18.)

Position fix data can also be obtained by making angular measurements to surface features shown on lunar maps. Although the accuracy may be less than required, the technique provides a form of closed-loop system for return to an LEM position marked on the same map. The angle-measuring technique might be used with either a laser or optical range finder to provide an increased capability.

5.2 DEAD RECKONING

Dead reckoning requires a directional reference, some form of distance-measurement equipment, and a suitable computation and display capability. Applicable instrumentation is shown in Table 3. As a directional reference, the gyrocompass would be the most desirable instrument, but it is not applicable to polar navigation. In addition, lunar rotational rate and gravity are low and reasonable accuracy may possibly be achieved only through improved designs. Azimuth gyros can also be used; these being aligned from directional data derived at the time a position fix is made. The use of celestial references for continuous directional data was also considered and is used in the RF technology and passive nongyro concepts.

TABLE 3

DEAD-RECKONING INSTRUMENTATION

1. Directional reference
    a. Gyrocompass
    b. Azimuth gyro
    c. Celestial tracker

2. Traverse measurement
    a. Distance
        (1) Fifth wheel odometer
        (2) Drive wheel odometer
    b. Velocity
        (1) Tachometer
        (2) Doppler radar
    c. Acceleration

3. Computation and display

Traverse data can be obtained by use of any one of the following type sensors: distance, velocity, or acceleration. Direct distance measurements involve the use of fifth wheel or drive wheel odometers. Other odometric techniques such as infrared and radiation chaining were considered, but not in any detail.

Velocity sensors can be used. However, these require a single integration to get a measure of distance, and mission time may increase range errors. Suitable sensors might be tachometers, either fifth wheel or drive wheel, or doppler systems using RF or optical techniques where the doppler systems would require stabilized sensors for isolation from the vehicle motion. The use of accelerometers might possibly require stabilization of the sensors and double integration of the accelerometer signal. Again, mission time duration and vertical errors may lead to excessive distance errors. The doppler and accelerometer concepts might also suffer from signal-to-noise ratio problems because of the low vehicle velocities and the random motions of the vehicle during a traverse.

5.3 PILOTING

To implement the piloting function, the vehicle operator should be provided with optimum visibility of the lunar surface consistent with vehicle design constraints. Components and parameters associated with the piloting function are shown in Table 4.

TABLE 4

PILOTING

1. Visibility
    a. Surface feature identification
    b. Hazard avoidance

2. Displays
    a. Range-to-go
    b. Map position
    c. Direction
        (1) Computed
        (2) RFDF
    d. Vehicle attitude

3. Homing
    a. Optical/visual
    b. Television

Since the astronauts will be concerned primarily with viewing and interpreting the lunar surface structure directly ahead of the vehicle during a traverse, navigation and guidance data should be conveniently displayed without interfering with that basic task. As a minimum, it is believed that direction to the destination should be provided. Additional displays might then present range-to-go to the destination and current surface position. Although current position could be displayed in selenodetic coordinates, position displayed on a lunar map would probably be preferable.

6. TYPICAL NAVIGATION REQUIREMENTS

Evaluation of the performance of a component, group of components, or a system configuration necessitates a comparison of performance capabilities with typical performance objectives or requirements. To derive realistic recommendations for technological research and development, the performance objectives or ranges of performance objectives should be derived from requirements imposed by the planned use of the equipment. Hence, the missions previously discussed were reviewed to derive typical navigation parameter requirements. (Section 4.1.)

The utilization of navigation capabilities is indicated by a number of lunar surface mission tasks, and those considered in this study are shown in Table 5.

TABLE 5

MISSION TASKS

	Task	Control Mode
1.	Vehicle development tests	Remote
2.	Site selection, survey, and marking	Remote and manned
3.	Rescue and logistics	Remote and manned
4.	LEM/T to LEM	Remote
5.	Scientific measurements	Manned
6.	Precision retrace	Manned and remote
7.	Landmark mapping	Manned
8.	Selenodetic survey	Manned

An initial traverse from the LEM truck to the LEM is assumed to be required at the start of each manned mission. In the event that the separation distance is beyond a visual (TV) line of sight, then the LEM must either be within a radio direction finding homing range or the navigation systems must be capable of measuring vehicle position and direction so that a vehicle traverse can be controlled from a remote location to within a homing range. Other navigation requirements may be imposed by the scientific measurements of gravitational, magnetic, seismic, radiation, etc, parameters where locations of separate surface points or continuous measurements of surface positions during traverse are required along with the scientific data measurements.

One specific navigation requirement associated with the position fix mode is stated by the equation:

$$(E_{VS})^2 + (E_{LS})^2 \leq (H_R)^2$$

where

E_{VS} = vehicle location error in the selenodetic system

E_{LS} = LEM location error in the selenodetic system

H_R = homing range (TV, visual, or radio).

The vehicle location error, E_{VS}, is a combination of initial position fix error and dead-reckoning error or simply position fix error if time permits updating of the navigation data.

Similar equations with errors in a relative position measuring system using terrain map references are also applicable. In fact the latter system might be augmented with path markers that are set up by previous missions. The major contribution to mission success obtained by meeting the previously stated requirements is the assurance of astronaut safety insofar as navigation capabilities or return to the LEM are concerned.

At this point, the requirement and the desirability for being independent of earth support should be recognized. The RF technology system concept relies on: continuous earth tracking of an earth station signal for an azimuth reference, and tracking by an earth station for determination of lunar surface position. To satisfy the earth-independence requirement, this navigation concept should be augmented by either a celestial or surface feature means for returning to the LEM. The backup equipment components of the other concepts must provide similar capabilities. As a minimum during an emergency, the vehicle navigation capability must provide means for sequential fixing of surface positions until the vehicle can be brought within a homing range.

Typical requirements in terms of celestial position measurement accuracies or relative position accuracies based upon mapped surface features can be established for use in evaluating a navigation concept. Examples of some typical requirements are:

1. Static Surface Position Accuracy

    a. 0.7 km: This accuracy would be required to provide a capability for improving map accuracies based upon estimated state of the art after the Lunar Orbiter program has been successful.

    b. 2.3 km: A viewing height of 2 m on one vehicle and 4 m on the other (LEM) results in line of sight (LOS) of 6 km for a smooth moon. This is reduced to about 2.3 km due to intervening marial undulations assumed to be 3 m.

    c. 4 km: Viewing heights of about 4 m on each vehicle increases LOS to 4 km with intervening terrain heights of 3 m.

    d. 10 km: It is assumed that the use of elevated antennas on the vehicles will provide an increased homing range.

    e. 0.45 km: Scientific mission experiments may require this as an accuracy objective. (This is roughly comparable to 65 to 100 m estimated for a probable accuracy of DSIF and MSFN network tracking systems.)

2. Traverse Measurement

    An estimated resolution and short-range accuracy requirement of 1 m may be required for the measurement of gravity, magnetic, and radiation parameter variations. This may also be of importance in gravity surveys where the data would be used to locate subsurface caves for the establishment of lunar bases.

7. NAVIGATION COMPONENT SURVEY

Utilization of the error models to evaluate concept performance capabilities requires the use of representative component parameter errors.

These data were derived by contacting vendors and reviewing technical documents and reports. In addition to available state-of-the-art (SOA) capabilities, predictions of SOA through the 1980s were also requested. Due to proprietary data considerations on the part of the vendors, the latter data were not obtained.

Since it was necessary to establish a realistic range of parameter values, some of the limit values were estimated. These estimates were based upon known SOA capabilities that would be applicable to a component, estimates of what might be feasible if SOA techniques were applied to a particular component, and judgment. These ranges of parameter values were then submitted to NASA for review and comment; after corrections, typical values were used for concept evaluations.

Component parameter data are itemized in Table 6. Data for one parameter in particular, doppler velocity, were difficult to obtain for a number of reasons. First, many of the associated parameters such as vehicle motion, antenna stabilization, and lunar surface characteristics could not be defined. Secondly, the accuracy of the system would be functions of size and power and these parameters were not a part of this study. It was believed by some qualified sources that a comparison of odometers with a doppler system was not realistic because of the low vehicle velocities and the problems that would be encountered implementing a doppler system design. As a result, the doppler accuracy range of 0.1 to 10% was estimated to be a reasonable value for use during the study. If the associated navigation concept merits further consideration, a study of the parameter value would be justified.

8. LUNAR PHYSICAL AND MISSION PARAMETERS

The evaluation of a lunar navigation concept requires either the use of, or the consideration for, uncertainties in lunar environmental parameters and other parameters that may be functions of either mission planning or other associated systems. An example of a lunar environmental parameter is target or feature recognition in the lunar illumination environment. Traverse range, mission duration, and map accuracy are typical parameters imposed by missions and other systems. These parameters are listed in Table 7.

Certain preliminary studies were conducted to establish ranges of typical parameter values. In the area of optics and illumination, prior

TABLE 6

NAVIGATION COMPONENT PARAMETERS

Parameter	Suggest Parameter Range (3σ)	Nominal Value	References
Azimuth ref	Alignment: 0.1 to 5° Drift: 0.005 to 5°/hr		Component vendors
Odometer error	0.1 to 10% of distance traveled	1% of distance traveled	Telecon with US Army Mobility Command, Ft. Belvoir, Va.
Vertical sensor	10 to 160 arc sec	36 arc sec	102 arc min, 26 June 64 Coordination Meeting at MSFC (12 arc sec feasible in lunar gravity environment with state-of-art accelerometers).
Star tracker or periscope sextant	2 to 120 arc sec	36 arc sec	"Working Paper" NSL E30-8, June 1964 or Task Order N-21, Vendor Data.
Timer	0.01 to 10.0 sec	0.1 sec	"Working Paper" NSL E30-8, June 1964 on Task Order N-21 and well within state-of art.
Ephemeris	3 to 120 arc sec	36 arc sec	"Working Paper" NSL E30-8, June 1964 or Task Order N-21 and "Selenographic Coordinates" Kalensher, JPL #32-41.
Earth tracker (IR)	1 arc min to 1°	0.2°	6 arc min state of art from vendors.
Earth tracker (RF)	6 arc min to 2°	0.2°	Depends upon correction for earth station location.
Platform null error	2 to 600 arc sec	36 arc sec	(Accelerometer state of art)
Gyro drift rate	0.01 to 1°/hr	0.08°/hr	
Accelerometer sensitivity	162×10^{-7} cm/sec^2 to 162×10^{-3} cm/sec^2	162×10^{-6} cm/sec^2	
Accelerometer linearity	0.01 to 0.0001%	0.001%	
Computation errors	Hand plot: 0.1 min in elev. (6 arc sec) 0.1° in az. (360 arc sec) Computer: ephemeris data accuracy using digital computer		Bowditch and Dutton. "Working Paper" NSL E 30-8 June 1964 on Task Order N-21.
Doppler velocity	0.1 to 10%		Bendix estimate.
Hand held sextant	10 arc sec to 10 min		12 arc sec in 1965 per vendor.

TABLE 7

PHYSICAL AND MISSION PARAMETERS

Parameter	Suggested Parameter Range (3σ)	Nominal Values	References
LEM Location	0.5 km to 5 km		0.455 km. Coordination Mtg., 26 June 1964, DSIF Tracking; NASA Memorandum, MT-1, dated 22 Sept. 1964. 100 m. probable error converted to 3σ. 974 meters (3σ). 63-261-778, "Primary Mission Definition Apollo-LEM Landing Surface Requirements-10 Dec., 1963". 2 km. Lunar Logistic System, Vol. VI-Tracking & Mission Control, MTQ-M-6-1, March 15, 1963 MSFC CEP of 800 meter radius - MOLAB RFQ Question & Answer #62.
		0.91 km CEP	LEM-Landing Accuracy Objective Specification. Personal communication from Mr. S. W. Fordyce, NASA Hqs., to Mr. J. W. Harden, Jr., NASA MSFC, dated 28 Dec. 1964.
Map Accuracy Horizontal	0.5 km to 10 km	1 km	3.56 km & 1 km to 2.5 km per MSC as of 4 Aug. 64' 1.2 km per ACIC as of 28 Aug. 64. 1 km in "Considerations on Lunar Surface VehicleNavigation" Harden & Doyle from NSL E30-8 references.
Vertical	0.3 km to 3 km		
LEM/LRV Landing Separation	1 km to 10 km	5 km	10 km - ALSS 402, Trip Report, NASA (CEP for each is 0.91 km. See first parameter).
Scientific Instr. Homing Range	1 km to 10 km	2 km	Bendix Estimate.
Surface Position Markers	Active - 2 km to 10 km Passive - (0.5 km to 2 km)	2 km	Bendix Estimate..
LRV to LEM or Base	5 km to 3000 km		"Post-Apollo Lunar Program Phases & Possible Exploration Mission Sequence" by David Paul III, MSFC.
Deflection of Vertical	0 to 600 arc sec		"Working Paper" NSL E30-8, June 1964 or Task Order N-21, Bendix Report BSR 1016, 17 Sept. 1964; Bowditch "American Practical Navigator". W. Kaula-letter to F. Digesu-Max. of 180 to 600 arc sec RMS.
Visual & TV Homing Range	0.5 km to 5 km	2 km	1 km (Bendix Estimate; Doyle Thomas).
RFDF Homing Range	5 km to 50 km	10 km	Bendix Estimate.
Vehicle Velocity (Ave.)	1 km/hr to 15 km/hr	10 km/hr	Bendix Estimate; Fost-Apollo Lunar Program Phases, etc., by D. Paul III, MSFC.
Traverse Day	2 hr to 24 hr		Bendix Estimate based upon "Post-Apollo Lunar Program Phases, etc. ," by D. Paul III, MSFC.
DSIF & MSFN Position Measurement	3.3 km to 185 m (2 days to 2 wks tracking time)	2 km	JPL IOM 312.7-93 dated 3 March 1965 by T.H. Elconin.
Relative Map Accuracy	0.01% to 1% of feature separation distance		Personal communication from Mr. J. A. Downey to Contracting Officer's Rep. R-ASTR-AN, dated 15 Dec 1964.

company-sponsored work was extended to define further the problems associated with visual detection of man-made and natural objects on the lunar surface. The illumination conditions included direct solar radiation and radiation reflected from the earth. Results have indicated that curvature and intervening surface features rather than illumination tend to determine the visibility limits.

RF systems were of interest for direction finding to extend the homing range parameter. Studies by Vogeler and others at the National Bureau of Standards indicate that a surface communications range in excess of 10 km may be feasible. However, calculations have been based upon assumed values of surface conductivity, dielectric constant, and attenuation by intervening surface obstacles. As a result, the feasibility of the systems is not conclusive.

Deflection of vertical is one parameter that may be of great importance to navigation system accuracy if an absolute lunar coordinate system is used. An error of 600 arc sec 3 σ might potentially cause a very large position error. However, from the safety standpoint, the gradient or rate or change of deflection error may be equally important if it is such that surface position ambiguities could be caused by instrument sensitivity and repeatability parameters.

Data on parameters associated with other lunar programs such as Apollo and Lunar Orbiter were derived from available documentation. References are listed in the table.

9. ERROR MODELS

The purpose of the models is to provide an analytic means for evaluation of: (1) component accuracy requirements, and (2) performance of total navigation concepts. The analytical technique employed for the error models was basically the covariance technique in which 3 σ values of component errors, lunar physical parameters, and typical mission parameters are related to a 3 σ vehicle position error ellipsoid. Steady-state geometrical relationships were used to evaluate partial derivative error sensitivity coefficients. These coefficients then relate input errors to vehicle position errors.

The form of the vehicle position error is shown in Figure 5 where the vehicle center of gravity is located at the origin of a generalized coordinate system, X_1, X_2, X_3. The magnitudes of the vehicle position error components are σ_{X_1}, σ_{X_2}, and σ_{X_3}.

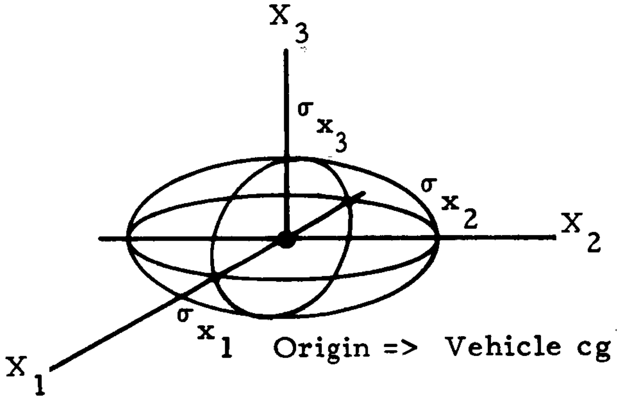

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Figure 5 Vehicle Position Error Ellipsoid

As the vehicle traverses the lunar terrain, the vehicle error ellipsoid is rotated and translated accordingly about some traverse path to the destination coordinates. A homing device is located, possibly with a position error, at the destination coordinates, and it has an associated range of detection or homing range. The combination of these parameter values, which are dependent upon the type of homing device and the typical navigation requirements, establishes the typical accuracy requirement for the concept. A comparison of total concept error with homing range then provides a concept accuracy criteria.

The error models were developed to provide maximum flexibility in their applications. As a result, a complete navigation concept can be evaluated in its entirety or a subconcept such as position fix or dead reckoning can be evaluated separately.

10. POSITION FIX ERROR MODEL

Position determination is obtained from celestial tracker angle measurements for the passive nongyro concept and inertial concept. The RF technology system uses DSIF/MSFN tracking networks to provide the vehicle position on the lunar surface; the errors are used in the form of north and east error components, ΔR_N and ΔR_E.

Generally, vehicle position in latitude and longitude is determined through an iterated solution of the equation:

$$\sin \epsilon_i^* = \sin u_i \sin x + \cos u_i \cos x \cos (w_i - y) \tag{10-1}$$

where

i = 1, 2 index designation of observable

u_i = ith observable, latitude subpoint

w_i = ith observable, longitude subpoint

ϵ_i^* = ith observable, measured true altitude

x = vehicle latitude

y = vehicle longitude.

If total differentials of the previous equation are taken, the matrix form for the differentials as 3 σ values of error random variables is as follows:

$$\begin{bmatrix} \sigma_x^2 \\ \sigma_y^2 \end{bmatrix} = \begin{bmatrix} C_1^2 & C_2^2 & C_3^2 & C_4^2 & C_5^2 & C_6^2 \\ C_7^2 & C_8^2 & C_9^2 & C_{10}^2 & C_{11}^2 & C_{12}^2 \end{bmatrix} \begin{bmatrix} \sigma_{\epsilon_1}^{*2} \\ \sigma_{u_1}^{*2} \\ \sigma_{w_1}^{*2} \\ \sigma_{\epsilon_2}^{*2} \\ \sigma_{u_2}^{*2} \\ \sigma_{w_2}^{*2} \end{bmatrix} \tag{10-2}$$

The position fix model inputs from the mission model are:

x vehicle latitude at fix

y vehicle longitude at fix

$\epsilon^*_{1,2}$ observable true altitude; from Equation 10-1

$u_{1,2}$ observable subpoint latitude

$w_{1,2}$ observable subpoint longitude.

The transformed sensed error inputs are:

$\sigma^*_{\epsilon_{1,2}}$ altitude measurement error

$\sigma^*_{u_{1,2}}$ observable declination error

$\sigma^*_{w_{1,2}}$ observable right ascension error.

The quantity which is of interest is error in position. Thus,

$$\Delta R_N \vec{1}_N = R \sigma_x \vec{1}_N \tag{10-3}$$

$$\Delta R_E \vec{1}_E = R \cos(x) \sigma_y \vec{1}_E . \tag{10-4}$$

Then position error due to position fix error is given as

$$(PE)_{PF} = \sqrt{(R \sigma_x)^2 + (R \cos(x) \sigma_y)^2} \tag{10-5}$$

11. INITIAL AZIMUTH ERROR MODEL

The azimuth alignment error is derived from the solution of the astronomical triangle using a lunar-based ephemeris. See Figure 6.

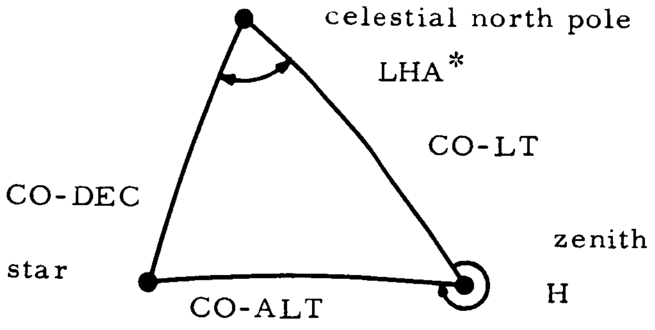


Figure 6 Astronomical Triangle

The following definitions apply:

LHA* = local hour angle of celestial reference

CO-DEC = co-declination

CO-LT = co-latitude

CO-ALT = co-altitude

H = celestial tracker true azimuth referenced north.

Applying the Law of Sines to the astronomical triangle results in the equation:

$$\sin(360^\circ - H) = \frac{\sin(LHA^*)}{\sin(CO\text{-}ALT)} \sin(CO\text{-}DEC) \qquad (11\text{-}1)$$

Star azimuth is measured relative to the vehicle body axis in the local horizontal plane. Then, from Figure 7, the vehicle heading from true north is related by:

$$H = A + \alpha^* . \qquad (11\text{-}2)$$

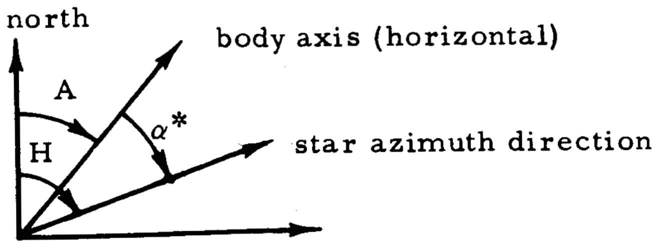


Figure 7 Star Azimuth Definition

The initial azimuth alignment error, σ_{AO}, is expressed as follows:

$$\sigma_{AO}^2 = [C_{17}^2 \; C_{18}^2 \; C_{19}^2 \; C_{20}^2 \; C_{21}^2] \begin{bmatrix} \sigma_{xn}^2 \\ \sigma_{\alpha i}^{*2} \\ \sigma_{ui}^{*2} \\ \sigma_{wi}^{*2} \\ \sigma_{yn}^2 \end{bmatrix} \qquad (11\text{-}3)$$

Symbols and coefficients are either derived or defined in the final report.

12. DEAD-RECKONING ERROR MODEL

The dead-reckoning function is required for navigation from an initial point, P_O, to a destination, P_D. Ideally, the best route would be an arc of a great circle between the points, but due to surface obstacles and hazards, the actual traverse will have a considerable amount of azimuthal variation. A similar condition exists for vehicle pitch angle variations and the associated altitude changes. During these maneuvers, the operator will try to minimize the path deviations in order to minimize time to destination and to limit the vehicle roll and pitch angles to safe conditions. Thus, some form of model is needed to define the paths.

The traverse from P_O to P_D can be broken up into incremental traverses of length D. An initial azimuth angle, A_{OD}, between P_O and P_D defines the direction of the ideal path. However, an obstacle avoidance maneuver will require a change in the azimuth angle, ΔA, for an incremental distance between points P_O and P_1. As a result, the path traversed from P_O to P_1 will be at an angle, $A_{OD} + \Delta A$. Similarly, the traverse from P_1 to P_2 would be at an angle, $A_{1D} + \Delta A$. Thus, a traverse from P_O to P_D can be accomplished dynamically by a series of incremental line segments defined by length D and random azimuth variations from a prescribed probability density function as in Figure 8. This procedure can also be used for terrain slope and vertical anomaly variations.

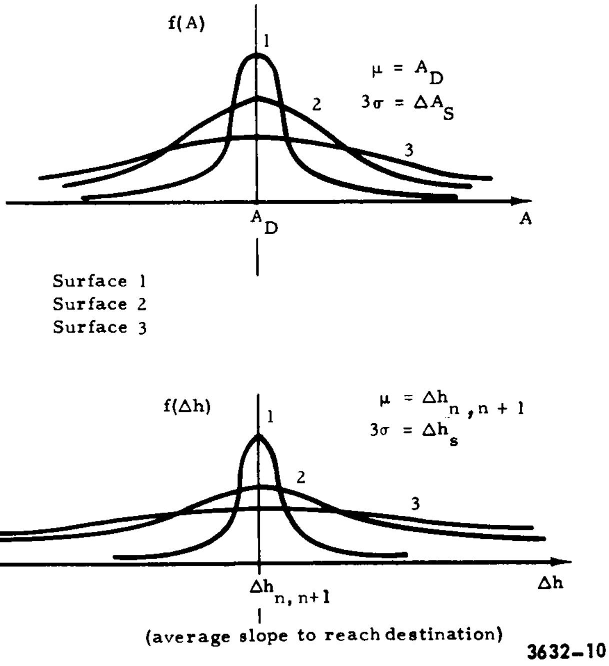


Figure 8 Path Density Functions

The figure shows sets of gaussian density functions for azimuth, A, and altitude, h. The means of the functions are always defined as either the angle or the altitude between the starting point of an increment and the destination. The three curves for each function might be typical of three different terrain characterizations that range from smooth maria for Surface 1 to rough highlands for Surface 3.

Procedures used in developing the dead-reckoning error model are similar to those previously described. The capabilities provided by the programmed models include:

1. **An analysis of a selected concept on a postulated mission. Given the system, terrain characterizations, mission's initial and destination points, vehicle paths are dynamically altered by the program. Hence, evaluation is not restricted to a fixed path analysis and an infinite number of paths are actually available.**

2. A path can be retained as a datum trajectory and used to evaluate other system concepts.

3. The program is capable of determining the maximum dead-reckoning distance prior to system realignment or updating by performing a position fix. If the position fix is not required, the program will operate without this capability.

4. The program's main flexibility is its not being constrained to the three specific concepts described.

The computer program also includes the capability for direct digital print-out of data that might ordinarily be done by hand plotting. Examples of these are shown in Figures 9, 10 and 11.

In Figure 9, the incremental traverse distance between adjacent points in the latitude-longitude plot is 2 km. The total straight-line traverse distance is 58.2 km, and the path proceeds in the north-west direction to the 5-km homing range where the navigation problem is terminated. The total distance of the traverse was 63.7 km or an extra distance traveled of 9.2%. The 3σ limit of the azimuthal variation was 90°.

Figure 10 shows altitude, H, vs distance traveled and there is a 10:1 slope magnification that exaggerates the peaks. The altitude difference between the initial and final points was 0.4 km, and the 3σ limit of vehicle pitch angle variation was 20°.

Figure 11 depicts total position error vs time; this example is for Concept 3 or the RF technology system. The 2.8-km initial error is due to the position fix error, and as the dead-reckoning process continues along a path as indicated by the previous figures, the position error increases as shown. The convenience of this data plotting capability in minimizing data reduction time is obvious. Other examples are included in the final report.

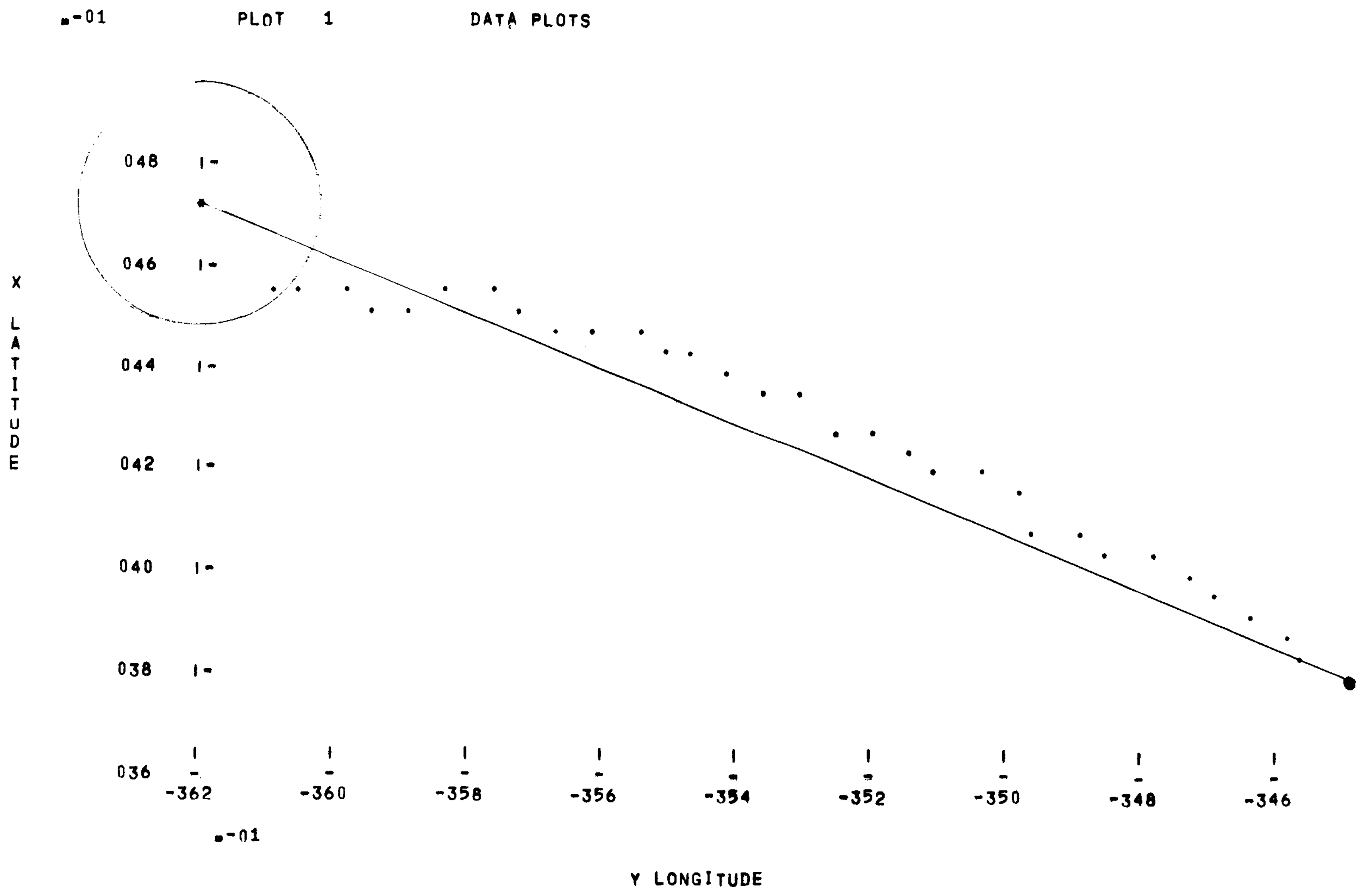


Figure 9 Vehicle Path, Latitude and Longitude

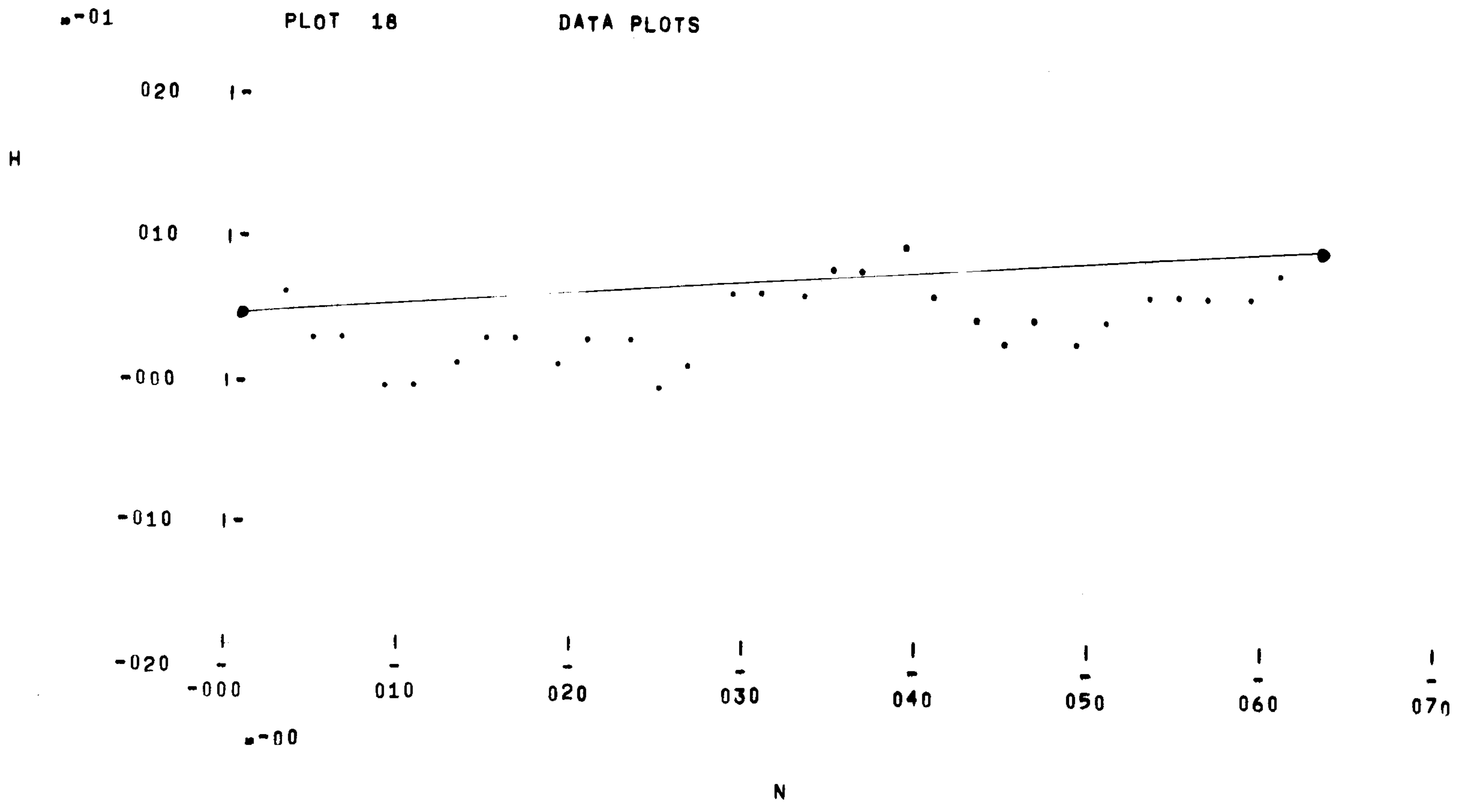


Figure 10 Altitude vs Distance Traveled

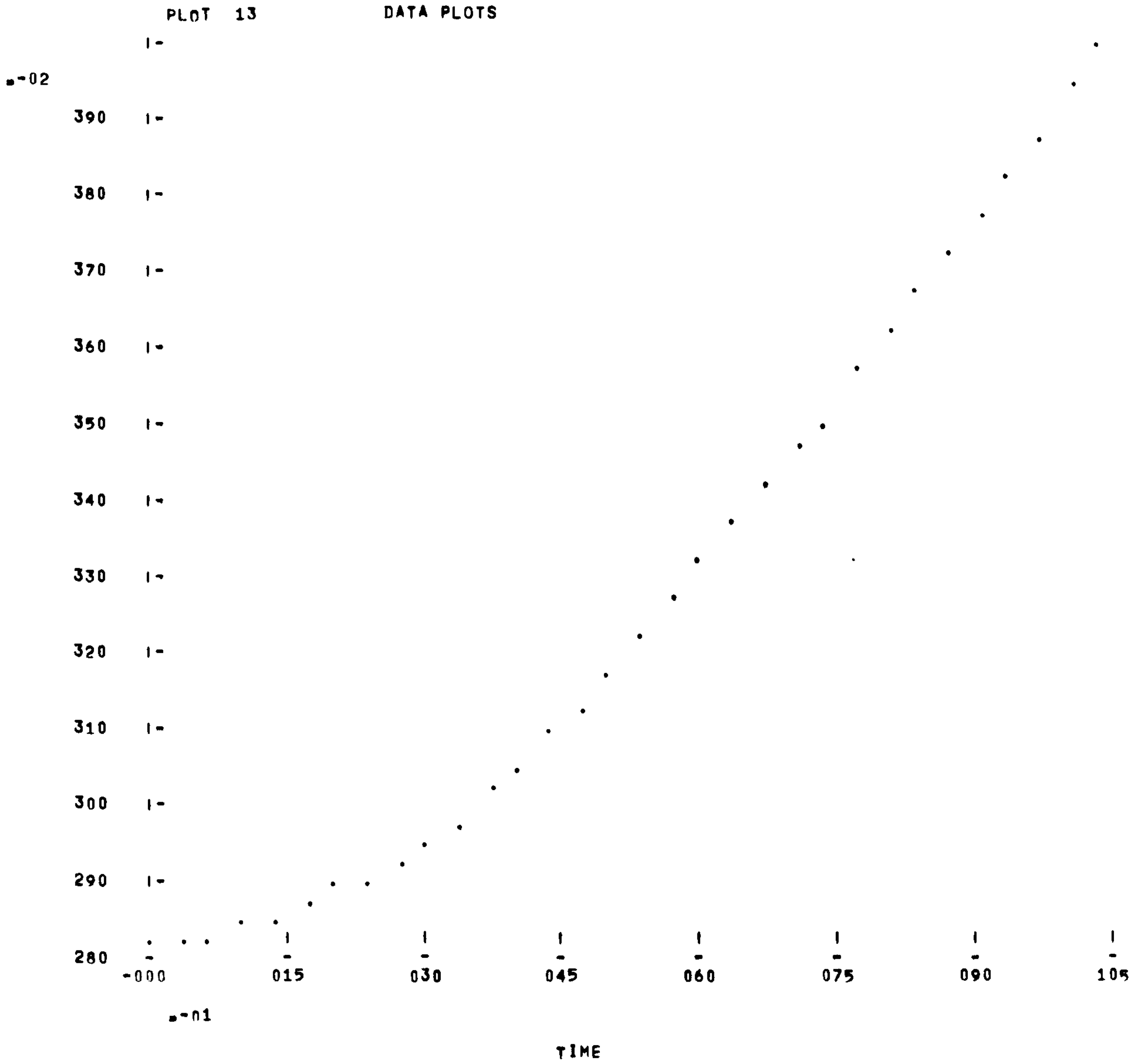


Figure 11 System Error vs Time

13. ERROR MODEL DIAGRAM - CONCEPT 1

The error model diagram of the passive, nongyro system is shown in Figure 12. The model forcing functions or input error terms (σ_i), the 3 σ error measures of equipment errors and physical uncertainties, are identified below the diagram. These error sources are identical to those discussed in Sections 7 and 8. Through the use of partial derivative error sensitivity coefficients, the error model transforms the input errors to a vehicle position error and a vehicle azimuth error on the lunar surface. The total vehicle position error, as shown by the summing notation, is an RSS combination of the position fix error and the dead-reckoning error.

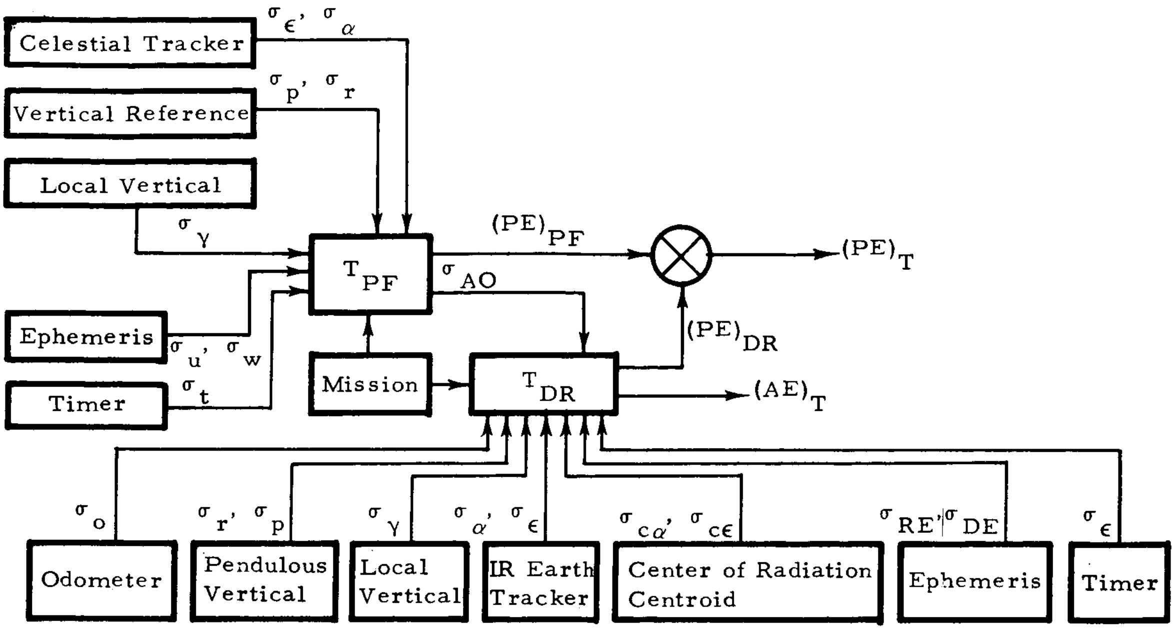
To initiate the position fix program, the required inputs are: vehicle position and attitude, celestial reference positions relative to the vehicle, and the magnitude of the technique input errors. The position fix model supplies the initial alignment errors in azimuth and vehicle position.

The categories of the inputs required for dead reckoning are: vehicle state, which includes initial vehicle position, attitude, and velocity; vehicle destination; the 3 σ limits of the statistical terrain characteristics; the lunar mechanics parameters of rotational rate, radius, and earth subpoint position; and the magnitudes of the input errors. With these parameters, the statistical vehicle path and dead-reckoned computed path, including system errors, are calculated. The total navigation system error ellipsoid, position fix and dead reckoning, is determined and translated across the surface terrain.

14. ERROR MODEL DIAGRAM - CONCEPT 2

The error model diagram of the inertial system is shown in Figure 13. In a manner similar to the previously discussed system analysis, an error model transforms the inertial system input errors to a vehicle position error and a vehicle azimuth error on the lunar surface. A total vehicle position error is determined by an RSS combination of the position fix error and the dead-reckoning error.

The position fix program inputs are identical to those of the previous system: vehicle position and attitude, celestial reference positions relative to the vehicle, and the magnitude of the technique input errors.



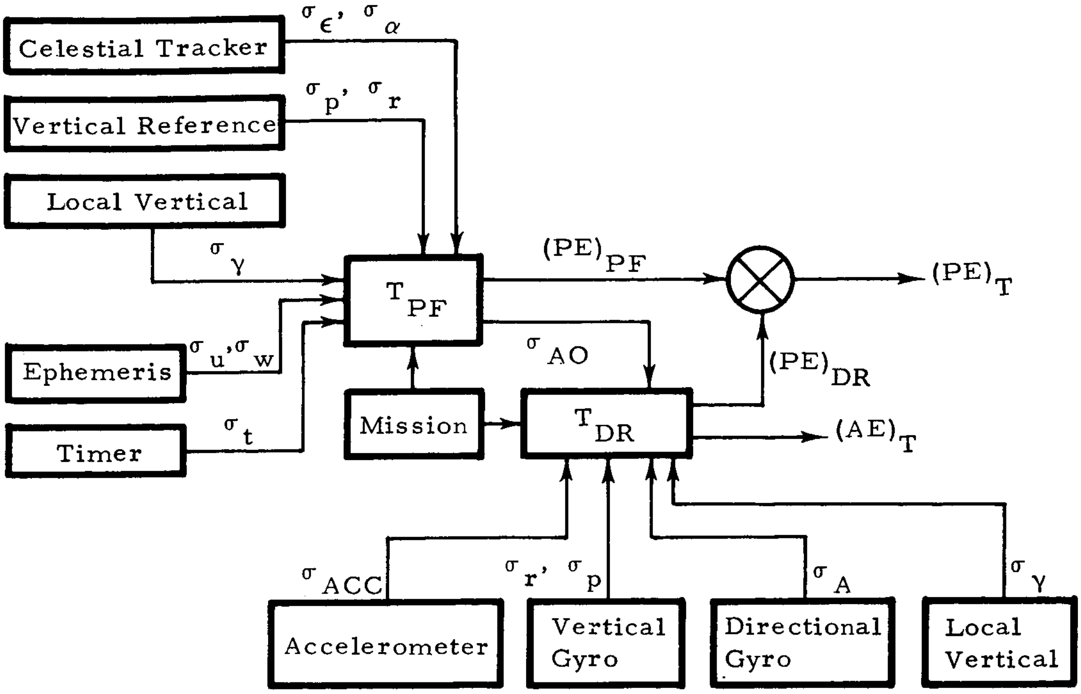
Symbol Identification

$(PE)_{PF}$ = Error in position fix
$(PE)_{DR}$ = Error in dead reckoning
$(PE)_{T}$ = Total position error
$(AE)_{T}$ = Total azimuth error
T_{PF} = Position fix transformation
T_{DR} = Dead-reckoning transformation
σ_i = Component error or physical uncertainty

Subscripts (σ)

ϵ = Celestial reference elevation angle
α = Celestial reference azimuth angle
p = Vehicle pitch angle
r = Vehicle roll angle
γ = Angle between gravity vector and geometric radius
u = Celestial reference subpoint latitude angle
w = Celestial reference subpoint longitude angle
t = Time
o = Odometer distance
$c\alpha$ = Center of radiation centroid error, azimuth
$c\epsilon$ = Center of radiation centroid error, elevation
RE = Right ascension angle
DE = Declination angle
AO = Initial azimuth alignment

Figure 12 Concept 1 – Passive, Nongyro System Flow Diagram



Symbol Identification

$(PE)_{PF}$ = Error in position fix
$(PE)_{DR}$ = Error in dead reckoning
$(PE)_T$ = Total position error
$(AE)_T$ = Total azimuth error
T_{PF} = Position fix transformation
T_{DR} = Dead-reckoning transformation
σ_i = Component error or physical uncertainty

Subscripts (σ)

ϵ = Celestial reference elevation angle
α = Celestial reference azimuth angle
p = Vehicle pitch angle
r = Vehicle roll angle
γ = Angle between gravity vector and geometric radius
u = Celestial reference subpoint latitude angle
w = Celestial reference subpoint longitude angle
t = Time
ACC = Vehicle accelerations
A = Dead-reckoning azimuth error
AO = Initial azimuth alignment

Figure 13 Concept 2-Inertial System Flow Diagram

An additional model input (vehicle acceleration) is required along with those previously discussed: vehicle state, which includes initial vehicle position, attitude, accelerations, and velocity; vehicle destination; the 3 σ limits of the statistical terrain characteristics; the lunar mechanics parameters of rotational rate and radius; and the magnitudes of the input errors. With these parameters, computations are accomplished as described for the previous concept.

15. ERROR MODEL DIAGRAM - CONCEPT 3

The error model diagram of the RF technology system is shown in Figure 14, In a manner similar to the previously discussed systems analyses, the error model transforms the RF technology input errors to a vehicle position error and a vehicle azimuth error on the lunar surface. A total vehicle position error is determined by an RSS combination of the position fix error and the dead-reckoning error.

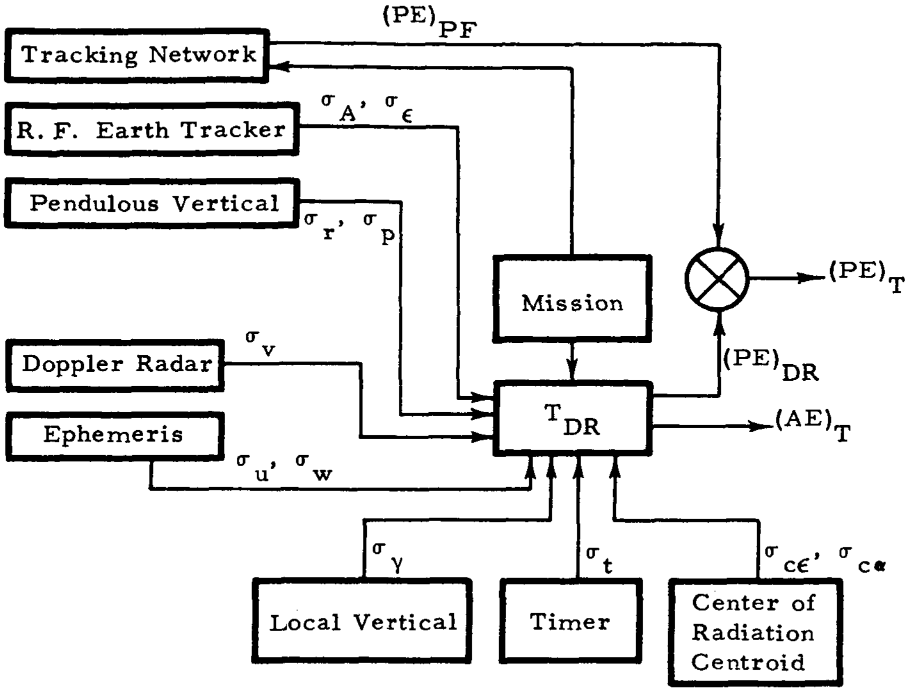
The position fix program requires vehicle position and the magnitude of the technique input errors.

The categories of the inputs required for dead reckoning are identical to those discussed for the passive, nongyro system: vehicle state, which includes initial vehicle position, attitude, and velocity; vehicle destination; the 3 σ limits of the statistical terrain characteristics; the lunar mechanics parameters of rotational rate, radius, and earth subpoint position; and the magnitudes of the input errors. With these parameters, computations are accomplished as previously described.

16. SUMMARY OF RESULTS

Inherent to the problem of lunar surface navigation is the necessity for astronaut safety. Within the guidelines and framework of this study, safety is directly equated with navigation concept accuracy. Resolving this equation into analytical terms expresses a "safe" navigation system as that concept which allows the guidance or pilotage mode of homing to be effected.

Thus, the navigation error must be less than or equal to a homing range associated with each navigation concept. This navigation error may or may not fulfill one or more typical terminal requirements imposed by mission tasks, and it is at this point that tradeoff studies can be initiated.



Symbol Identification

$(PE)_{PF}$ = Error in position fix
$(PE)_{DR}$ = Error in dead reckoning
$(PE)_T$ = Total position error
$(AE)_T$ = Total azimuth error
T_{DR} = Dead-reckoning transformation
σ_i = Component error or physical uncertainty

Subscripts (σ)

ϵ = Celestial reference elevation angle
α = Celestial reference azimuth angle
p = Vehicle pitch angle
r = Vehicle roll angle
v = Vehicle velocity
u = Celestial reference subpoint latitude angle
w = Celestial reference subpoint longitude angle
t = Time
γ = Angle between gravity vector and geometric radius
$c\alpha$ = Center of radiation centroid error, azimuth
$c\epsilon$ = Center of radiation centroid error, elevation

Figure 14 Concept 3—RF Technology System Flow Diagram

Figure 15 shows plots of ranges of component accuracies required for the nongyro, inertial, and RF concepts to satisfy the lunar surface navigation accuracy requirements for the years from 1972 to 1984. The design point or accuracy type systems of the dead reckoning and position fix subconcepts of the selected surface navigation systems are plotted as a function of mission era, and represent the accuracy type concept required to meet the most demanding, but typical, navigation requirement of the era. The accuracy type systems are defined as nominal (NOM), state of the art (SOA) and projected state of the art (Proj. SOA). The definitions of these accuracy type or design point systems are:

NOM:	The nominal accuracy type system is comprised of components with accuracies corresponding to the component accuracies of present-day state-of-the-art instrumented concepts. These components are the types which have been used in operational navigation systems.
SOA:	The state-of-the-art accuracy-type system consists of components with accuracies corresponding to state-of-the-art laboratory-tested components. These components have generally an order of magnitude less error than the NOM components but represent components which are functional in a tightly controlled, ideal, laboratory-type environment.
Proj. SOA:	The projected state-of-the-art accuracy components are representative of future attainable accuracies and are approximately an order of magnitude more accurate than the SOA type.

The position fix design point accuracy requirements are constant throughout the lunar exploration era. However, since ranges and durations increase with each lunar exploration mission, the dead reckoning requirements become more stringent. The nongyro dead reckoning subconcept requires no component state-of-the-art advancement, but by 1980 present-day ideal SOA accuracy-type components must be capable of functional system implementation in an uncontrolled environment. By 1980, however, the inertial dead reckoning concept will require operational projected state-of-the-art accuracy components, while the RF concept requires functional

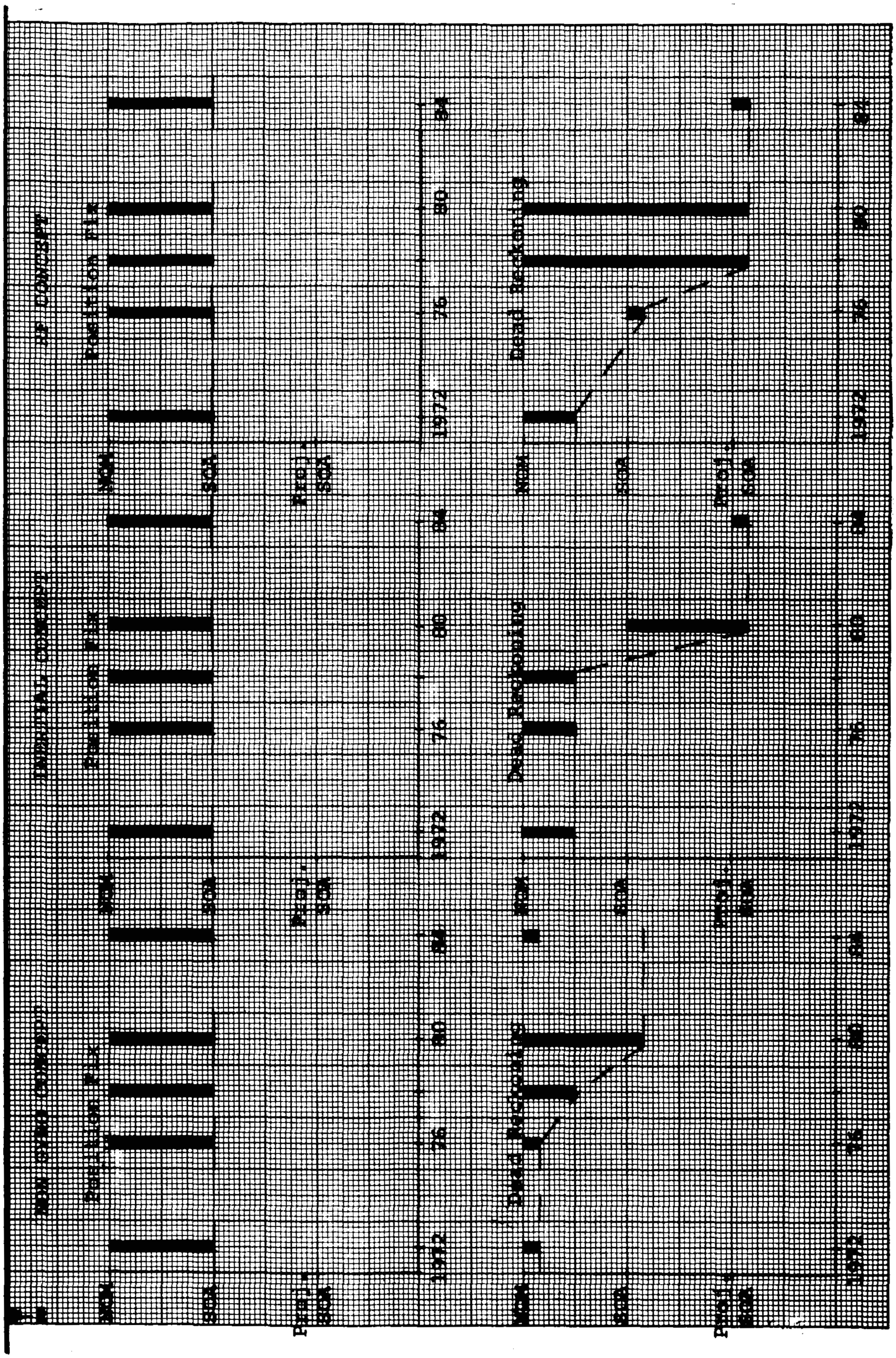


Figure 15 Accuracy Type/Design Point Requirements

projected state-of-the-art components by 1978. The typical component error requirements for each concept and component are listed in Tables 8, 9, and 10. The asterisk notation indicates component accuracy requirements which cannot be met by NOM components.

The principal error contributors of each concept are listed in Table 11. The primary dead reckoning error contributors are the distance sensors and heading reference. Vertical error contributions to horizontal or planar dead reckoning error are secondary.

17. CONCLUSIONS AND RECOMMENDATIONS

The data presented in Section 8 of the final report and Section 16 of this summary indicate that the principal component error sources for which research and development are required are the distance sensing devices. These are comprised of the odometer, accelerometers, and doppler radar of the dead reckoning subconcepts. Also, since celestial position fix error is a heavily weighted function of the deflection of lunar local vertical, a study should be undertaken to define, analyze, and derive compensation for this error source. With the preceding general recommendations as a background, the more specific recommendations are as follows:

1. Solution of the lunar navigation problem for the posulated era requires the implementation of concepts utilizing SOA components with the accuracy capabilities emphasized throughout the study. However, in most applications SOA accuracies are attainable in ideal environments and usually over limited ranges of measurement with typical low reliability, high cost, high weight, and high volume. In addition to the accuracy/safety aspect, to fully assess the lunar surface navigation problem, the additional weighting factors of cost, reliability, weight, volume, and power must be considered. Sophistication of the present error models to evaluate the additional weighting factors is recommended to ensure compatible feasibility with accuracy/safety requirements. Generally though, component miniaturization and particularly extended measurement ranges are needed.

2. The effect of lunar local vertical anomalies upon the horizontal or planar dead reckoning error is negligible. For the vertical component of dead reckoning error, this error input is of secondary importance. Hence, relative navigation utilizing a dead

TABLE 8

NONGYRO CONCEPT, 3 σ REQUIREMENT TABLE

	Component or Aid	Error	Units	Requirement vs Mission Era				
				1972	1976	1978	1980	1984
Position Fix	Star Tracker	Null	deg	0.004*	0.004*	0.004*	0.004*	0.004*
	Static Pendulous Vertical	Null	deg	0.001*	0.001*	0.001*	0.001*	0.001*
	Ephemeris	Uncertainty	deg	0.005	0.005	0.005	0.005	0.005
	Timer	Null	hr	0.00003	0.00003	0.00003	0.00003	0.00003
	Allowable Vertical Anomaly		deg	0.005	0.005	0.005	0.005	0.005
Dead Reckoning	Odometer	(1) Slip (2) Calibration	—	0.01	0.01	0.005*	0.001*	0.005*
	Pendulous Vertical	Null	deg	0.01	0.01	0.01	0.01	0.01
	Ephemeris	Uncertainty	deg	0.01	0.01	0.01	0.01	0.01
	IR Earth Tracker	Null	deg	0.2	0.2	0.2	0.2	0.2
	Timer	Null	hr	0.00003	0.00003	0.00003	0.00003	0.00003

TABLE 9

INERTIAL CONCEPT, 3 σ REQUIREMENT TABLE

	Component or Aid	Error	Units	Requirement vs Mission Era				
				1972	1976	1978	1980	1984
Position Fix	Star Tracker	Null	deg	0.004*	0.004*	0.004*	0.004*	0.004*
	Static Pendulous Vertical	Null	deg	0.001*	0.001*	0.001*	0.001*	0.001*
	Ephemeris	Uncertainty	deg	0.005	0.005	0.005	0.005	0.005
	Timer	Null	hr	0.00003	0.00003	0.00003	0.00003	0.00003
	Allowable Vertical Anomaly		deg	0.005	0.005	0.005	0.005	0.005
Dead Reckoning	Accelerometers	Null	Earth g's	$*10^{-7}$	$*10^{-7}$	$*10^{-7}$	$*10^{-8}$	$*10^{-8}$
	Directional Gyro	Null	deg	0.1	0.1	0.1	*0.0001	*0.0001
		Drift	deg/hr	0.08	0.08	0.08	*0.001	*0.001
	Vertical Gyro	Null	deg	0.1	0.1	0.1	*0.001	*0.001
		Drift	deg/hr	0.05	0.05	0.05	*0.001	*0.001

TABLE 10

RF CONCEPT, 3σ REQUIREMENT TABLE

	Component or Aid	Error	Units	Requirement vs Mission Era				
				1972	1976	1978	1980	1984
Position Fix	Earth-Based RF Tracking (DSIF, MSFN)	Vehicle Position	km	0. 300	0. 300	0. 300	0. 300	0. 300
Dead Reckoning	Doppler Radar	Null		*0. 01	*0. 005	*0. 003	*0. 001	*0. 001
	Doppler Radar Antenna	Null	deg	1. 0	*0. 5	*0. 1	*0. 1	*0. 1
	Pendulous Vertical	Null	deg	0. 01	*0. 0006	*0. 0001	*0. 0001	*0. 0001
	RF Earth Tracker	Null	deg	0. 2	*0. 02	*0. 002	*0. 002	*0. 002
	Ephemeris	Uncertainty	deg	0. 01	*0. 001	*0. 001	*0. 001	*0. 001
	Timer	Null	hr	0. 00003	0. 00003	0. 00003	0. 00003	0. 00003

TABLE 11

CRITICAL ERROR SOURCE

Subconcept	Position Fix		Dead Reckoning		
			Planar		Vertical
Weighting / Concept	Primary	Secondary	Primary	Secondary	Equally
Nongyro	Vertical Anomaly Vertical Sensor	Celestial Tracker Ephemeris	Odometer IR Earth Tracker	Pendulous Vertical	Pendulous Vertical Odometer Vertical Anomaly
Inertial	Vertical Anomaly	Celestial Tracker	Accelerometers Directional Gyro	Vertical Gyro	Vertical Gyro Accelerometers Vertical Anomaly
	Vertical Sensor	Ephemeris			
RF	Celestial Mechanics Tracking Equipment		Doppler Radar RF Earth Tracker		Pendulous Vertical Doppler Radar Vertical Anomaly

reckoning process is little affected by the local vertical anomaly. However, position fix error is a heavily weighted function of the anomalies, and absolute navigation to an extremely precise degree is significantly hindered regardless of the quality of the position fix navigational components unless compensation is provided to negate the anomaly effects.

3. For each navigation concept, a selenographic restriction exists. Concepts 1 and 3, the nongyro and RF systems, determine vehicle heading through earth azimuth measurement. These concepts are restricted to near-side operation. Also, vehicle operation must remain in a selenographic location where the locus of the earth subpoint does not approach the vehicle zenith, at which point the azimuth measurement becomes indeterminant. Due to error sensitivity coefficients, the vehicle selenographic locus should be constrained exterior to a 10° great circle arc of the earth subpoint. Polar navigation by the inertial concept is restricted, but this concept is operational at all longitudes, both far and near side. If 10^{-6} earth g accelerometers are used, the Coriolis and centripetal accelerations must be considered.

   Conventional pole shifting techniques will eliminate the polar singularity for the inertial concept. Similarly, for extremely precise dead reckoning navigation, pole shifting of the latitude-longitude grid to the earth subpoint minimizes error sensitivity coefficients of the earth tracking subsystems.

4. To relax both dead reckoning and position fix component accuracy requirements, homing range extension through the use of passive and active RF and optical beacons is needed. Therefore, the design and performance of experiments should be conducted to verify assumptions regarding optical beacon detection within line of sight and RF propagation beyond the line of sight on the lunar surface.

5. Distance sensor errors are the prime contributors to dead reckoning error. In most instances, one and two orders of magnitude accuracy improvement are required to satisfy concept requirements. Alternate techniques to solve the relative navigation problem requireing benchmark mapping might be hybrid distance-sensing techniques; e. g., short-term accelerometer data coupled with long-term odometer measurement. Also laser, RF, and optical ranging and angular

measurement devices performing trilateration and triangulation might be feasible substitutes for mapping tasks. An error analysis of these techniques is recommended for research and development forecasting.

6. In many instances of the current study, particular component errors were obscured by the presence of a large error source in the concept. The doppler radar, an extremely inaccurate land vehicle navigation sensor, largely negated the performance of the remaining RF concept components. Hence, recommendations for components research are hindered since component requirements are a function of total concept functioning. However, analysis directed to the formation of a set of concepts from a matrix of navigation sensors would avert the problem and remove the concept constraint. Since the error models were constructed in generalized hybrid form, the extension of analysis to a matrix of sensors is simplified and this study is strongly recommended.

7. Due to center of radiation/earth centroid error, and large component errors, position fixing utilizing an RF or IR earth tracker measurement on the earth is not recommended.

8. Due to the adverse lunar environment, time independent navigation concepts should be stressed to prevent error growth during performance of auxiliary exploration functions.

9. To minimize position fix errors, and to substantially reduce position fix component requirements, adherence to the optimal celestial/vehicle geometry is recommended. Minimization of time required of the position fix operation should be considered, and complete digital computation with automation is beneficial. In comparing celestial tracking and earth-based RF tracking, an error analysis of a nominal accuracy type position fix system shows that, for comparable position fix accuracies, vertical anomalies as large as 0.1° can be traded off with one to two days of DSIF tracking time. Therefore, a primary mode of on-board position fixing is deemed a necessity.

   A study to investigate the feasibility of using an on-board optical sight with intervening space suit masks should be performed since an emergency mode of navigation may require vehicle operation without internal pressurization. Additionally, television and its boresight axis reference may have to serve as backup either for a theodolite or a celestial tracker.

10. Due to the importance of minimum position fix error and the inherent ramifications upon all other subconcept requirements and component development, vertical independent techniques such as navigational satellites using range and range rate measurements must be analyzed.

11. In summary, the more important recommendations resulting from the analysis of three navigation system concepts are as follows:

    a. Develop and analyze sets of navigation concepts derived from a matrix of navigation sensors. This would provide a greater selection range for system optimization.

    b. Expand the error models to include other important weighting factors such as reliability, weight, volume, power, and cost.

    c. Develop odometers or odometric systems that will provide 3σ errors that are less than 0.1% of distance traveled.

    d. Develop accelerometers with a null threshold of 10^{-8} (earth g's).

    e. Review present estimates of lunar local vertical deflections. If these estimates (large position errors) are confirmed, applications of navigational satellites and landmark recognition (triangulation) techniques should be analyzed to determine more accurate means for measuring static surface positions.