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APOLLO LOGISTICS SUPPORT SYSTEMS MOLAB STUDIES

Task Report On

Navigation System Studies

(Preliminary)

Prepared under Contract No. NAS8-5307 by

R. A. Perkins

HAYES INTERNATIONAL CORPORATION
Missile and Space Support Division
Apollo Logistics Support Group

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PREFACE

This report was prepared by the Hayes International Corporation, the Apollo Logistics Support Group, for the George C. Marshall Space Flight Center, under the authorization of task order H-28, contract NAS8-5307. The NASA technical liaison representative was Mr. Jack Harden of the Advanced Studies Office, Astrionics Laboratory.

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For
ADVANCED STUDIES OFFICE
ASTRIONICS LABORATORY

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1.0 SUMMARY

This Task Order sequentially follows Task Order NASA TM-X-52032-9, "Task Report on Navigation Systems Study", and Task Order N-21, "Report on Navigation Systems Studies for a Lunar Mobile Laboratory". These reports define the MOLAB navigational requirements, state-of-the-art navigation techniques which are feasible, and error criteria pertinent to the unique task.

This report is concerned with state-of-the-art hardware that may be used, based on these last two reports; on the heading and vertical orientation; radio frequency navigation equipment; celestial state-of-the-art equipment; optical ranging; and relative navigation.

The best way of obtaining heading and vertical, short of a tuned platform, is to slave a vertical gyro to a roll stabilized directional gyroscope, using friction averaging bearings for the two degree of freedom gyro inertial reference. The absence of a magnetic field precludes the possibility of slaving the directional gyro so that celestial fixes at each station will orient the gyro initially. A two-directional electromagnet pendulum or level represents the best vertical reference under these limiting conditions. Obtainable accuracies in vertical and azimuth demonstrate that the combination of equipment can produce good accuracy, based on operation during the worst leg of the MOLAB traverse. It is thought that this could

be a reliable back-up system in on a system using a stellar-inertial primary unit.

Radio frequency investigations show that using the C/M as a navigation satellite for a three-position range fix from the MOLAB, and using the DSIF as a computer is not feasible. Historically, error of C/M and MOLAB position has been in conflict with respect to accuracy. A recent letter from NASA headquarters shows that the MOLAB and the C/M can both be located within $\pm$ 100 meters after a period of tracking by several DSIF stations.

Since MOLAB error using the C/M is 25 times the C/M error, or 2500 meters, and the DSIF can locate the MOLAB independently within 100 meters, it is not feasible to use this method of navigation. Additionaly, the DSIF would have to contain the range fix computational equipment, and the C/M is available for approximately only eighteen minutes every two hours.

VHF navigation aids for placement at MOLAB stations require minimum power but are voided due to the short distance to which line - of - sight transmission on the lunar surface is limited. High antenna towers are out of the question for the mission, due to limitations on the equipment that may be sent to the moon plus the fact that installation times are too great if it were possible to ship the equipment.

The MOLAB traverse, as limited as it is, then calls for over-the-horizon transmission at medium frequencies. A relatively high powered LEM beacon can provide a homing source for a MOLAB beacon receiver. State-of-the-art beacon systems will have a 10-20 meter extra distance traveled effect for the maximum LEM-MOLAB distance of 93 km.

Optical range finders are available in 3-meter base lengths with a one part in 10^4 resolution. Ranging error is only approximately 5 meters at a minimum sighting range of 1000 yards, and approximately 150 meters at 6700 yards---the maximum expected horizontal sighting distance. Use of shorter than three meter base lenghts means greater error and vice-versa.

Optical and antenna equipment present azimuth errors as they are tilted from the vertical. The effects are shown in graph form. Antenna equipment on the MOLAB, sighting earth, can be off $\pm$ 2 degrees and still make contact with the earth.

Of the many types of gyros that exist today, it is better for the long term MOLAB mission to use a two degree of freedom or a single degree of freedom inertial quality gyro if a stable platform is used. The MOLAB mission is not meant to be a proving ground for newer types of gyros.

If inertial platforms are used, a digital computer will probably be an intergral part of the system. Proven single or double integrating accelerators exist which are useable for the mission. Again, the philosophy is to steer away from newer types on a long mission.

It is felt that a philosophical discussion of the star tracker presents a valid argument for its incorporation in the MOLAB navigation system.

Celestial manual hardware has shown increasing accuracy (chronometers, $\pm$ 0.05 sec/day; theodolites, 0.2 secs. horizontal accuracy). Errors from hardware are smaller than previously thought. Mapping accuracies and lunar extremes data present the higher errors.

MOLAB navigation relative to LEM is a function of a LEM beacon azimuth homing process, and is also accomplished as a function of the dead reckoning process and its errors.

2.0 MOLAB TRAVERSE; VEHICLE FORCING FUNCTIONS

Consideration of vertical and heading reference hardware requires determining the nature of the MOLAB traverse and the vehicle dynamics.

Tables IA and B show the present traverse contemplated[1]. The longest traverse is chosen as the worst case condition, since vertical and heading determing equipment deteriorate as a function of time between corrections. This traverse is travel leg 8-5. The distance covered is 34 kilometers at a speed of 4.85 kilometers per hour for a seven hour time total.

The traverse in each case is a straight line path, but latest evidence shows that a portion of the path will contain obstacles. The astronaut will therefore be turning to avoid these, at random times. (Vertical and heading references can not be set at any time during traverse, to avoid scientific mission interference).

Next, horizontal acceleration must be considered. Table II A[37] shows a maximum acceleration in the roll direction of 3.168 ft/sec^2 before the MOLAB overturns. Table IB shows a maximum acceleration in the pitch direction of 2.148 ft/sec^2 before overturning. Both of these values occur on a level path.

Vertical displacements due to obstacles are considered in Tables III and IV.[36] The median value chosen in Table II for the approximate

MOLAB speed shows that with a 1/4 sine wave, 0.5 cps., one ft. amplitude forcing function, the vehicle will:

a) bounce 1.75 ft.

b) settle within 3" in 6 sec.

c) have a 4 ft/sec^2 acceleration

d) have a pitch angled at 13.4 degrees

Table IV shows a maximum roll angle of 4.2 degrees for a ninty degree steering angle.

Reference 37 is based on MOLAB VII, using Ackermann steering. Reference 36 is based on MOLAB III, but the values are approximately equivalent for MOLAB VII. The values determined are for recommended Ackermann steering, 1000 $pound/ft^2$ spring and tire constants and a 250 pound /ft/sec damping factor.

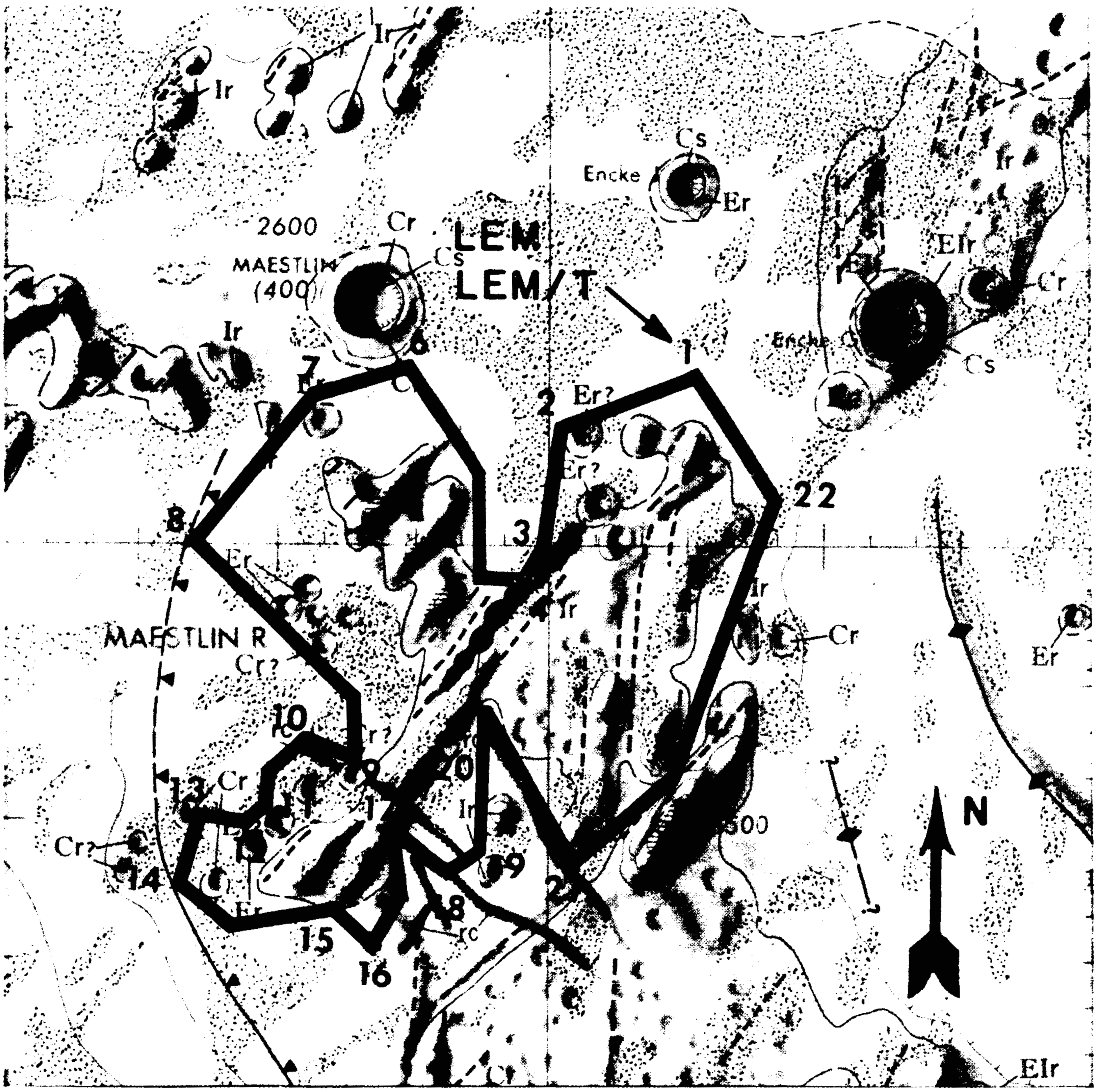


TABLE IA MOLAB TRAVERSE

TABLE IB

MOLAB LUNAR TRAVERSE

Lunar	Travel Leg	Distance to Stations (Kilometers)	Velocity (Kilometers/Hour)	Angular Turn at Leg	Traverse Time (Hours)
Day	1-2	8	4.75	0°	1.75
	2-3	15	4.62	0°	3.25
	3-4	16	5.33	100° cw	3.00
	4-5	11	5.50	60° ccw	2.00
	5-6	20	5.00	30° ccw	4.00
	6-7	37	5.28	60° ccw	7.00
	7-8	21	5.25	150° ccw	4.00
	8-5	34	4.85	10° ccw	7.00
	5-9	12	6.00	60° cw	2.00
	9-1	26	5.20	60° cw	5.00
Night	1-10	14	4.66	60° ccw	3.00
	10-11	12	4.80	80° ccw	2.50
	11-12	12	4.80	30° ccw	2.50
	12-13	18	4.50	80° ccw	4.00
	13-1	18	4.50	100° ccw	4.00

Σ 274 Kilometers Σ 55 Hours

The worst traverse from the navigation standpoint is the longest traverse. This is because the directional gyro, operating unslaved except for moon rate correction, is degraded for this long period of time.

TABLE II ROLL CHARACTERISTICS

A. ROLL CHARACTERISTICS - MOLAB VII

Slope	Limit $V^2/r_c g$ Before Overturn
0°	0.57
10°	0.41
20°	0.22
30°	0.02

The maximum acceleration MOLAB may experience is on a straight and level path. This would be roll produced in a turn, and is 0.59 times the moon gravitational constant (5.37 ft/sec^2) or 3.168 ft/sec^2.

B. PITCH CHARACTERISTICS - MOLAB VII

Slope	Limit $V^2/r_c g$ Before Overturn	
	Downhill	Uphill
0°	0.29	0.40
10°	0.11	0.22
20°	- 0.07	0.04
30°	- 0.25	- 0.15

The maximum longitudinal acceleration MOLAB may experience is on a straight and level path. This is 0.40 times the moon gravitational constant (5.37 ft/sec^2) or 2.148 ft/sec^2.

TABLE III

MOLAB VERTICAL DISPLACEMENT STUDY RESULTS

A. PITCH AXIS

MOLAB Speed	Type of Input 1/4 Sine Wave Step 0.5 cps	Bounce Height / Bump Height	Time in Seconds to Settle Within 3 Inches Peak Height
2.6 mph	Ampl. 0.5 ft.	1.6	4
	1.0 ft.	1.75	6
	2.0 ft.	2.2	8

B. VERTICAL ACCELERATION OF CENTER OF GRAVITY

MOLAB Speed	Type of Input 1/4 Sine Wave Step 0.5 cps	Acceleration ft/sec^2
2.6 mph	Ampl. 0.5 ft.	2
	1.0 ft.	4
	2.0 ft.	11

C. MAXIMUM PITCH ANGLE FOR TRANSCENDING HIGH OBJECTS

MOLAB Speed	Type of Input 1/4 Sine Wave Step 0.5 cps	Pitch Angle (Degrees)
2.6 mph	Ampl. 0.5 ft.	6
	1.0 ft.	13.4
	2.0 ft.	38

TABLE III (Cont'd)

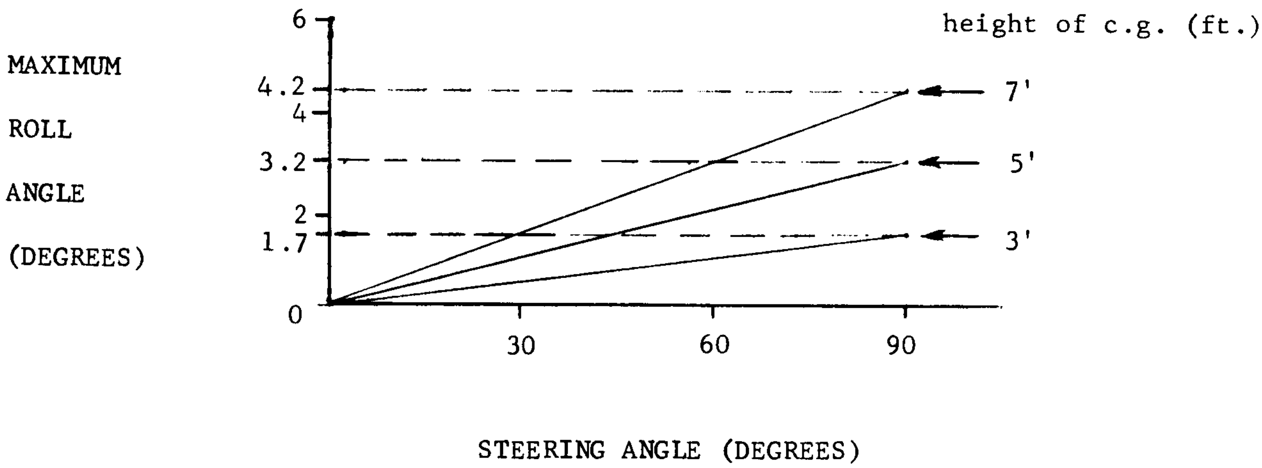
D. PITCH BOUNCE WITH WASHBOARD SURFACE

FORCING FUNCTION IS A 1' P.P. CONTINUOUS SINE WAVE, 0.5 CPS

Bounce	C.G. Displacement	Bounce
1st, +	0.6'	0+'
-	- 0.9'	- 1.4'
2nd, +	+ 1.6'	+ 5.7'

Table IV MOLAB VERTICAL DISPLACEMENT STUDY RESULTS

ROLL VERSUS STEERING ANGLE



MOLAB VELOCITY IS 2.6 MPH

3.0 VERTICAL, HEADING REFERENCES

Based on previous navigation reports (References 1 and 2), possible equipment to be used for heading and vertical indications includes directional gyros, vertical gyros, pendulums, and various types of levelers. This equipment must be considered before the necessity of a stable platform or a stable, Schüler tuned, platform is demonstrated.

3.1 CONVENTIONAL VERTICAL SENSORS

Various types of erectors are considered first, since they may be used by themselves and are used in vertical gyros which are ideally used to slave a directional gyro for this application.

3.1.1 ELECTROLYTIC LEVEL ERECTORS, BUBBLE

This type is in use today. They consist of glass vials filled with a conducting fluid. Electrodes are connected to each end and to the center.

When the fluid is horizontal, the resistance of each end to the center is the same. When the vertical is displaced, the half of the level with the lesser fluid has greater resistence than the half with more fluid.

Effectively, the device operates as a potentiometer. This type is not as linear as a pendulum type, which is explained later. As indicators, these devices have typical verticality alignment errors of ± 6 arc minutes on the moon. One manufacturer has stated that this dead spot in a roll stabilized vertical-directional gyro still allows good operation on the worst traverse, and that redesign will negligibly improve operation.

3.1.2 MERCURY SWITCHES

These are on-off devices used for gyro erection. The output is constent for any angle off vertical, so that the gyro erection rate is a constent. Gyros are easily disturbed when subjected to small accelerations. These switches would be useful for a rapid erection mode only.

3.1.3 EDDY-CURRENT ERECTOR

A permanent magnet is suspended under the gyro. A copper disk is connected to an extension of the gyro shaft. When the gyro tilts, motion of the disk relative to the magnet causes eddy currents, which produce a drag force. This is not an accurate system.

3.1.4 ROLLING-BALL ERECTOR

This type is used on vertical gyros with moderate accuracy. The erector is mounted on top of the gyro. This revolving disk contains steel balls in a banana-shaped slot close to the periphery of the disk. Rotation is much slower than that of the gyro. Gyro erection takes place in a spiral plate. This type is not suitable for the MOLAB.

3.1.5 MERCURY ERECTOR

This is a precision instrument. There is vertially no dead space and the unit responds to minute tilts. Two tanks filled with mercury are connected by a small base pipe. The tanks are mounted on the gyro and revolved at the same rate as the natural frequency of the mercury. The natural period of the mercury is approximately the same as the MOLAB forcing functions, so that it would be disturbed by these motions. It is, therefore, not adequate for the MOLAB operation.

3.1.6 PENDULUM (See Figure 1)

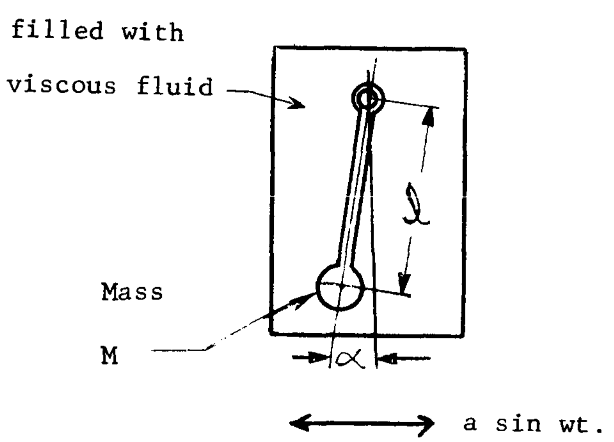


FIGURE 1 VERTICAL PENDULUM

The viscously damped pendulum, with capability of various damping factors, represents the most accurate vertical device. There are two axes electrolytic and two axes electromagnetic versions. The latter is more accurate.

The pendulum may be used to supply roll and pitch or it may be used as an erector. Pendulum action may be derived by using Figure 1. Here the unit is subject to an acceleration, "a sin wt". With the mass "M" off vertical at an angle "α", a torque, $M\,a\,\ell\cos\alpha$, is produced. This is opposed by:

a) gravity couple: $M\,g\,\ell\sin\alpha$

b) damping couple: $C\,d\alpha/dt$

c) angular acceleration couple: $M\,\ell^2\,d^2\alpha/dt^2$

Then: $M\,a\,\ell\cos\alpha = M\,g\,\ell\sin\alpha + C\,d\alpha/dt + M\,\ell^2\,d^2\alpha/dt^2$

With α small: $\sin\alpha = \alpha$, $\cos\alpha = 1$

$\therefore\ M\,a\,\ell = M\,g\,\ell\alpha + C\,d\alpha/dt + M\,\ell^2\,d^2\alpha/dt^2$

In Laplace form, dividing by $M\,g\,\ell$:

$$a/g = (\ell/g\ S^2 + C/Mg\ell \cdot S + 1)$$

a/g = angle of the virtual vertical due to acceleration

$\ell/g = 1/w_m^2$, w_m = pendulum undamped natural frequency

$C/M\,g\,\ell = \tau$, the pendulum damping time constant

The MOLAB will be moving in a straight line, aside from obstacle avoidance. The maximum acceleration along the pitch axis without overturning on a straight slope is 0.4 moon gravity.

Therefore, $a/g = 0.4$ and

$$\therefore \frac{\alpha'}{0.4} = \frac{1}{S^2/w_m^2 + \tau S + 1}$$

or in terms of frequency:

$$\frac{\alpha}{0.4} = \frac{1}{1 - w^2/w_m^2 + J_w \tau}$$

The most accurate pendulum considered has an undamped natural frequency of 2 cps.

$$\ell/g = \frac{1}{w_m^2}$$

Therefore, for the moon, the w_m is modified to be 0.417 times w_m on the earth because $g_{moon} = 1/6\ g_{earth}$.

$\tau = \frac{c}{Mg}$ is increased 6 times because of moon gravity.

MOLAB forcing functions have a 0.5 cps frequency. The period is 2 seconds. The pendulum should have a ten times longer period, or 20 seconds, to isolate it from the disturance frequency.

M, g, and ℓ are fixed; therefore C must be altered by changing the viscous fluid.

The pendulum is subjected to other forces, such as Coriolis. These forces are studied under the vertical gyro. The magnitudes prove to be negligible.

The best available pendulum has a 2 minute of arc, and 2 second of arc repeatability. This may be redesigned for the proper time constant and perform within 3 minutes of arc (1500 meters) with a 3 second (25.36 meters) repeatability.

Other factors enter into the performance, including the fact that moon gravity intuitively would multiply error. Reduced load (g) sensitivity and static (w_m of sensitive components of pivot friction) enter in to reduce error, as shown.

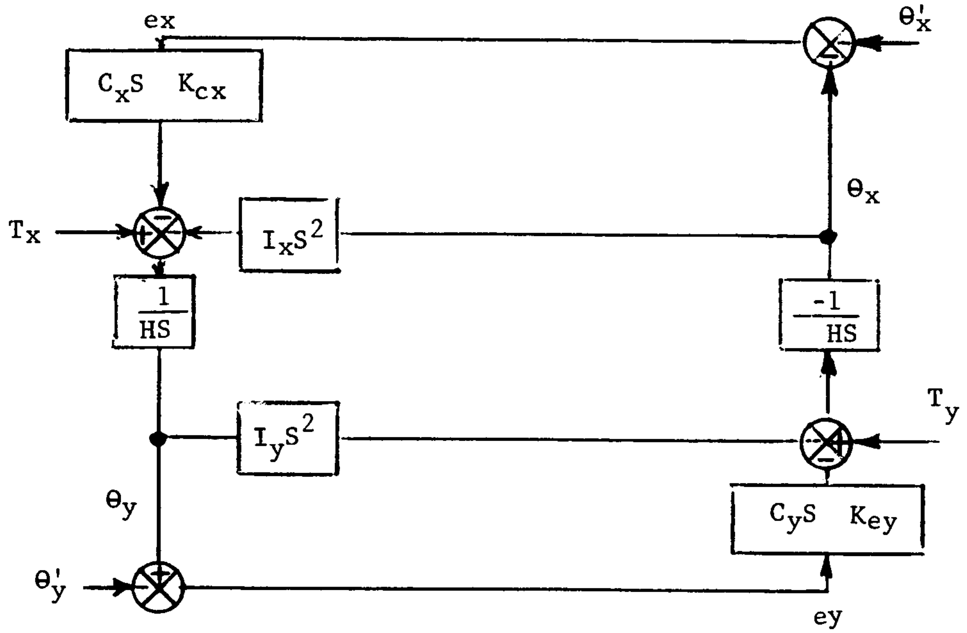
3.2 GYROS

Before discussion of vertical and directional gyros, the subject of gyros is introduced.

Two degree of freedom gyros (Figures 2 and 3) are available with drift rates down to 0.1 degree per hour. Angular rate of change is proportional to the component of torque applied perpendicularly to the spin axis. Gyro gain is one.

The gyro is the ultimate limiting factor in performance of vertical and directional gyros on any platform.

In the true sense, a two degree of freedom gyro has a third degree of freedom, aligned with the spin axis. The steady portion of the torque is counteracted by motor bearings and drag effects. However, A.



$C_x 1 C_y$ = Viscous drag coefficients

K_{ex}, K_{ey} = Elastic resitant constants

I_x, I_y = Flywheel inertias

T_x, T_y = Applied gyro torques

H = Angular momentum

$= I_z W_z = I_z \dot{\theta}_z$

FIGURE 2 TWO DEGREE OF FREEDOM GYRO TRANSFER FUNCTION

a) Neglecting I_x and I_y; C_x, C_y, K_{ex}, K_{ey} results in an ideal free gyro.

b) 1. X and Y inertially stabalized reference axes are provided.

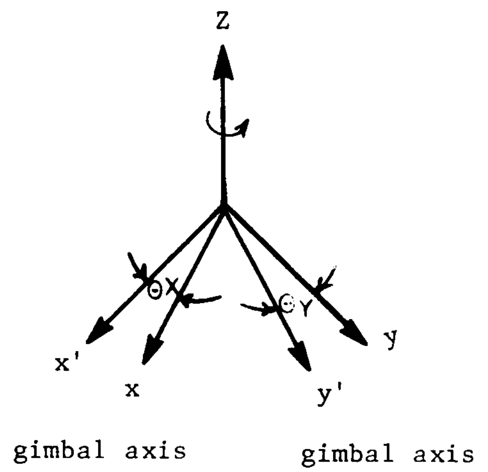
2. Error signals are obtained without gyro precession and without any significant time delay.

3. Since there is no significant time constant, H and C calibration is not required and also because gain is independent of H and C values.

4. The gimbals do not coerce the spin vector.

5. Torques will apply ordered precession.

A.



$$ex = \theta_x - \theta_{x'}; \quad ey = \theta_y - \theta_{y'}$$

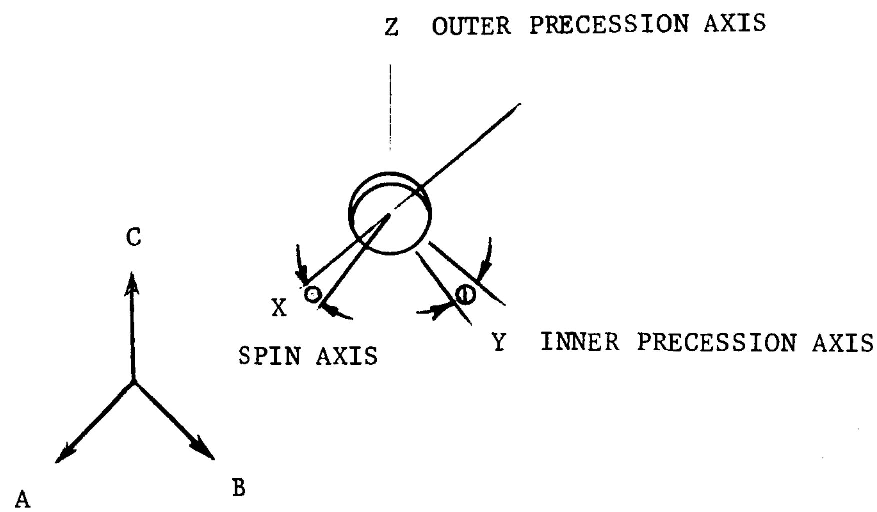
$$T_x = HS\theta_y + I_x S^2 \theta_x + ex\,(C_x S + K_{ex})$$

$$T_y = -HS\theta_x + I_y S^2 \theta_y + ey\,(C_y S + K_{ey})$$

Figure 3

TWO DEGREE OF FREEDOM GYRO

EFFECTS OF MASS SHIFTS AND ACCELERATIONS



ACCELERATIONS

Acceleration Direction Along Axis	Mass Shifts Along	Torque Produced Around	Drift Around
A	X	-	-
	Y	Z	Y
	Z	Y	Z
B	X	Z	Y
	Y	-	-
	Z	X	-
C	X	Y	Z
	Y	X	-
	Z	-	-

$A \parallel X$, $B \parallel Y$, $C \parallel Z$ gyro shown is a directional gyro; a vertical gyro has its input axis vertical so that interchanging X and Z axes will perform the necessary change.

Bearing play along the inner precession axis or gyro gimbal deformation makes it sensctive to accelerations along the spin axis, and it will drift.

The two degree of freedom gyro requires self-balancing, and ginbals around its two output axes.

W_Z = Z axis precessional velocity = $\frac{d\theta}{dt} = \frac{TY}{H}$ where TY is applied X axis torque; H is gyro angular momentum

W_Y = Y axis precessional velocity = $\frac{d\phi}{dt} = \frac{TZ}{H}$

existing weak coupling between the spin axis assembly and gyro housing causes negligible modulation of angular momentum. Reduced gravity means reduced loading on the gyro. Generally, the gyro will perform better on the moon than on the earth.

The general subject of gyros is treated later in the report.

3.3 VERTICAL GYRO, PLATFORM ERRORS

The vertical gyro (Figure 4) is a two degree of freedom unit which has gimbal displacements about each output axis, measuring angular displacement from the local vertical axis.

The gyro spin axis is maintained vertical through sensing of pendulum devices. This gyro serves the same purpose as the pendulum, but maneuvering does not cause oscillation.

3.3.1 ERECTION

Mutually orthorgonal pendulums on the inner or pitch axis feed the gyro (through roll and pitch gimbal torquing) proportional to gyro tilt. The tile, θ, is then expressed as:

$$\frac{d\theta}{dt} \quad \frac{\theta}{\tau} = 0$$

where is the erection system time constant,

$$S\ \theta_s \quad \frac{1}{\tau}\ \theta_s = c$$

$$\theta_s = \frac{c}{S + \frac{1}{\tau}}$$

$$\theta_t = \theta_o \quad {}^{-t/\tau} \qquad \text{where } \theta_o = \text{tilt of } dt = 0$$

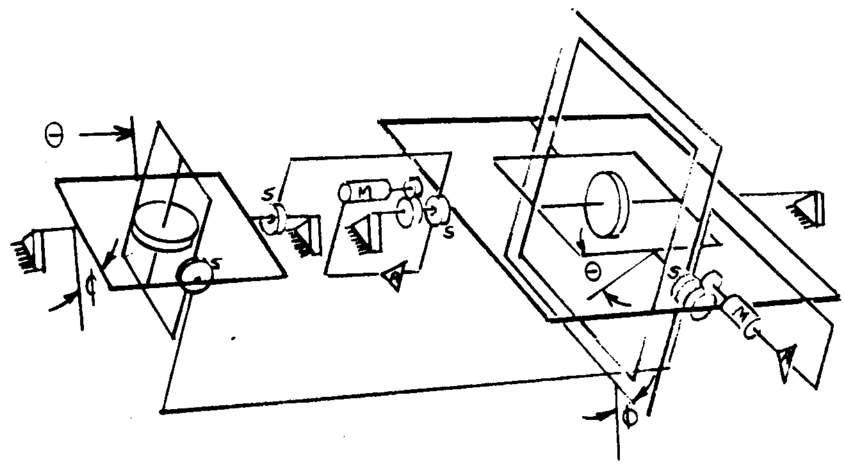


FIGURE 4 CONNECTING THE VERTICAL GYRO TO THE DIRECTIONAL GYRO, ALLOWING BETTER ACCURACY TO BE ACHIEVED

3.3.2 INERTIAL FORCES ACTING ON PLATFORMS IN MOLAB LUNAR REGION MOON RATE OR LATITUDE CORRECTION

The vertical gyro is affected by the horizontal component of moon rate (Figure 5). Without correction the gyro will tilt toward the west by an amount:

$$\theta = w_m \cos \lambda$$

$$w_m = 0.536 \ °/hr = 2.6 \times 10^{-6} \ rad/sec$$

with τ = 20 seconds to isolate vehicle motion, error is:

λ = 4° north latitude in MOLAB traverse of Kepler - Encke region

$$\theta = 20 \times 2.6 \times 10^{-6} \times .996$$

$$\theta = 0.18' \ arc = 10.8 \ secs$$

Although this error is small, it is better to compensate for these because other errors enter which add to the total error. Roll and pitch may be torqued as follows:

$$T_R = H \, w_m \cos \text{latitude} \sin \text{heading}$$

$$T_P = H \, w_m \cos \text{latitude} \cos \text{heading}$$

where H = Angular momentum of the gyro

T_R, T_P = Roll, pitch torque respectively

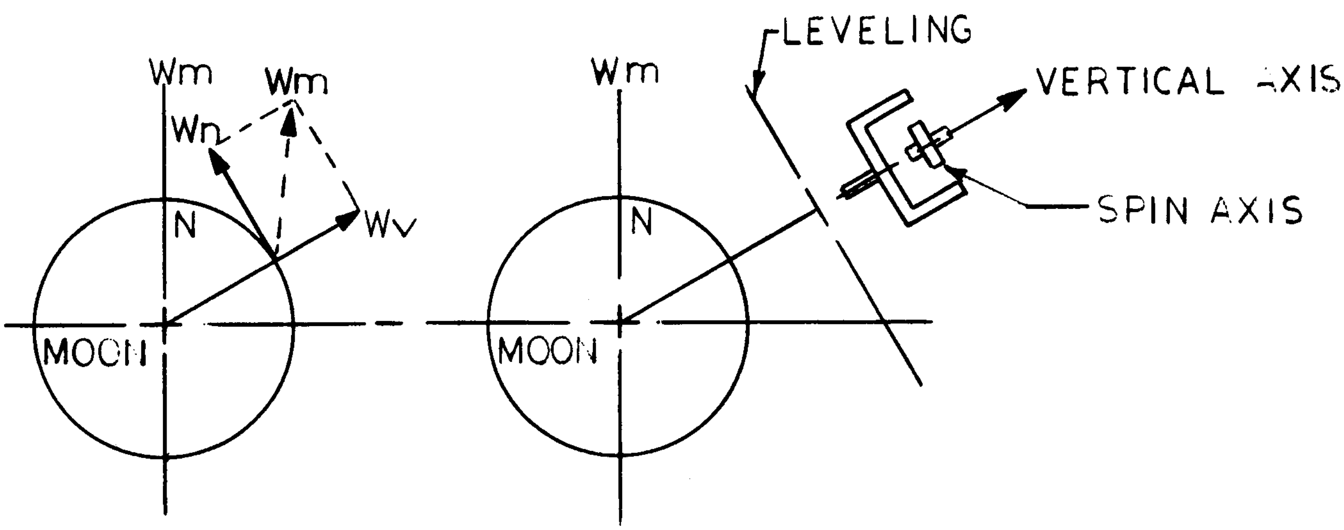


FIGURE 5 NORTH AND VERTICAL COMPONENTS OF MOON RATE AS SEEN BY GYRO

3.3 3 VELOCITY ERROR

The moon is approximately spherical, and, when the MOLAB travels along the lunar surface, it pitches forward, with respect to inertial space, at an angular rate of V/R. V, in this case, is the MOLAB velocity, and R is the radius of the moon.

A vertical gyro in the MOLAB will tend to tilt aft. The following relationship exists:

$$\frac{\theta}{\tau} = \frac{V}{R}$$

where θ/τ is the erection rate. The MOLAB velocity is $\approx$ 5 km/hr, and the moon radius is 1738 km. τ is 20 seconds; the erection time constant to isolate vehicle motions.

$$\theta = \tau V/R = 20 \text{ seconds} \times \frac{5 \text{ km/hr}}{1738 \text{ km} \times 3600 \text{ sec/hr}}$$

$$\theta = 0.000016 \text{ rad.}$$

$$= 0.054 \text{ min.}$$

$$= 3.24 \text{ secs.}$$

This error may be eliminated by applying a torque, H V/R, about the roll axis, where H is gyro angular motion.

3.3.4 CENTRIFUGAL ERROR

A body on the surface of the moon is subject to centrifugal force, due to moon rotation. Therefore,

$$F = M w_m^2 R \cos \text{latitude}$$

where M is the mass.

The horizontal component is:

$$F \sin \text{latitude} = M w_m^2 R \sin \text{latitude} \cos \text{latitude}$$

The angle that the vertical is displaced is with latitude equal to four degrees:

$$\Theta = \tan^{-1} \frac{w_m^{\ 2} R \sin \lambda \cos \lambda}{g}$$

$$\Theta = \tan^{-1} \frac{(2.6 \times 10^{-6})^2 \times 1738000 \text{ meters} \times .06976 \times .99756}{1.6 \text{ meters/sec}^2}$$

$$\Theta = \tan^{-1} 0.514 \times 10^{-6} \approx 0$$

The MOLAB movement in the easterly direction adds to the moon rotation by an amount less than 1/4 the moon rate, which is negligible (assuming 5 km/hr, MOLAB speed according to traverse statistics).

3.3.5 CORIOLIS ERRORS

Coriolis acceleration results from a body moving linearly on a curved surface which is rotating. The Coriolis force is expressed:

$$F = 2 M w_m V \sin \text{latitude}$$

where V = velocity which, in practice, is expressed as V_n for the north velocity component and V_E for the east velocity component.

Total Coriolis is the square root of the sum of the squares of both forces for the east and north velocity.

$$V_n = V \cos \text{heading}$$

$$V_E = V \sin \text{heading}$$

Total force, $F_T = (4\,M^2\,w_m^2\,V^2 \sin^2 \text{heading} \sin^2 \text{latitude}$

$+\,4\,M^2\,w_m^2\,V^2 \cos^2 \text{heading} \sin^2 \text{latitude})^{1/2}$

$$F_T = 2\,M\,w_m\,V \sin \text{latitude}$$

Coriolis acts normal to the MOLAB travel direction in the roll plane, and would result in a right of vertical error. The error,

$$\theta = \tan^{-1} \frac{2\,w_m\,V \sin \text{heading}}{g}$$

When MOLAB $\theta = \tan^{-1} \dfrac{2 \times 2.6 \times 10^{-6} \text{ rad/sec} \times 4.55 \text{ ft/sec} \times .06976}{5.36 \text{ ft/sec}^2}$

$$\theta = \tan^{-1} .27 \times 10^{-6} \approx 0$$

The MOLAB movement on the moon effectively experiences no Coriolis error.

The vertical gyro must then be considered for the effect of MOLAB vehicle acceleration, velocities, and displacements. Thus the equation of motion of the vertical gyro must be presented:

3.3.6 VERTICAL GYRO MOTION EQUATIONS IN TERMS OF TORQUE

1. $\left[A + E + (F + J - E)\cos^2\theta\right]\ddot{\phi} - G\,L\,\dot{\theta}\cos\theta - 2\,(F + J - E)\,\dot{\phi}\,\dot{\theta}\sin\theta\cos\theta$

   $= -D_1\,\dot{\phi} - C_1\,\phi - K_1\,i_1$ (outer or roll gimbal)

2. $(B + J)\,\ddot{\theta} + G\,L\,\dot{\phi}\cos\theta + (F + J - E)\,\dot{\phi}^2 \sin\theta\cos\theta$

   $= -D_2\,\dot{\theta} - C_2\,\theta - K_2\,i_2$ (inner or pitch gimbal)

3. $\dot{\phi} - \dot{\phi}\sin\theta = L =$ constant

When the gimbals are nearly perpendicular ($\theta = 0$), equations 2 and 3 reduce to:

2A. $(A + F + J)\,\ddot{\phi} - G\,L\,\dot{\theta} = -D_1\,\dot{\phi} = C_1\,\phi - K_1\,i_1$

3A. $(B + J)\,\ddot{\theta} + G\,L\,\dot{\phi} = -D_2\,\dot{\theta} - C_2\,\theta - K_2\,i_2$

Where: A = Moment of inertia (I) of outer gimbal about outer gimbal axis:

B = I of inner gimbal about inner gimbal axis.

E = I of inner gimbal about wheel spin axis.

F = I of inner gimbal about an axis perpendicular to inner gimbal and wheel spin axis.

G = I of wheel about wheel spin axis

J = I of wheel about any axis in plane of symmetry of wheel which is perpendicular to spin axis.

t = time

ϕ = Angular position of outer gimbal relative to gyro case (roll)

θ = Angular position in inner gimbal relative to outer gimbal (pitch)

ψ = Angular position of wheel relative to inner gimbal about the spin axis.

D_1 = Damping coefficient about outer gimbal axis

D_2 = Damping coefficient about inner gimbal axis

C_1 = Spring rate about outer gimbal axis

C_2 = Spring rate about inner gimbal axis

K_1 = Torque scale factor for outer gimbal

K_2 = Torque scale factor for inner gimbal

i_1 = Outer gimbal torque current

i_2 = Inner gimbal torque current

Gimbal inertia times MOLAB accelerations (roll and pitch) produce unwanted torques. Therefore, gimbals should be constructed as light as is possible. Inetria remains the same on the moon, even though gravity is 1/16 that of the earth gravity.

Pitch and roll displacement from zero causes interaction about both axes. Actual MOLAB roll motion is limited to below 10° because of the possibility of the vehicle overturning. Pitch motion may be as high as 40°.

The torque factors K_1, i_1, K_2, and i_2 are really overall functions of pendulum gain, servo amplifier gains, and torque transfer function gain. The vertical error is inversely proportional to the product of these three terms.

In stabilized platform, there are two main frequencies of interest.[4] One, the natural frequency of the platform servo system, is a frequency of minimum servo stiffness. Large rotational excursions may be expected at this frequency, which usually is around 100 radians/second. Second, mechanical resonances of platform gibal structure, between 10^2 and 10^3 radians/second, would amplify vibrational disterbances. The MOLAB forcing functions are at 0.5 cps, so that both these factors may be eliminated from error considerations.

MOLAB forcing functions have a very limited effect on the vertical gyro. Manufacturing estimates show that a vertical gyro with a five minute arc accuracy on earth may expect somewhat better performance on the moon, even when considering the worst lunar traverse.

3.4 DIRECTIONAL GYROS

A directional gyro is a two degree of freedom gyro (Figure 1) with horizontal spin axes. The spin axis is preferably aligned north or east, since it has been discovered that maximum residual azimuth error is reduced if the rotor points north-south.[16]

The gyro provides inertial azimuth reference. Since there is no magnetic field on the moon, the gyro cannot be slaved. Since it must be operated free, it must be initially aligned before each leg of the MOLAB traverse. Again, because it is free, the gyro must be counter-torqued to overcome drift from moon rate input.

In order to minimize intercardinal tilt error when the MOLAB undergoes yaw, a roll stabilized directional gyro is desirable. A roll stabilized directional gyro is a conventional directional gyro mounted with an additional outer gimbal which is free to rotate about its roll axis. This roll gimbal will be slaved to a vertical gyro so that the gimbal will maintain the gyro azimuth axis parallel to local vertical through 360^{o} of roll rotation.

Since the gyro will be operating free from leg to leg of the traverse, it is important to obtain the highest quality two degree of freedom displacement gyro.[5]

Important gyro characteristics include bearing play and gyro balance. References 22,27, and 29 show that high accuracy, directional gyros have

0.1^{o} to 1^{o} per hour drift rates, and that bearing friction averaging gyros provide less drift. An average drift rate of 0.5^{o} per hour is assumed for calculation purposes. For the maximum seven hour lunar traverse, this amounts to 3.5 degrees. However, a false latitude correction may be fed to the gyro to offset steady state drift, leaving only random drift, which should be approximately 0.2^{o}/hr maximum. Statistically, gyro drift over a long period is not in the same direction, and therefore averages less.

Reference 2, Appendix A, developes the equation in terms of EDT (extra distance traveled) for a heading reference with gyro tilt.

$$EDT = a\left[\frac{\theta}{\tan\theta} \quad \frac{1}{\sin\theta} - \frac{1}{\tan\theta} - 1\right]$$

where a = straight line course and θ = drift angle

See Figure 6 for geometry.

For a 0.2^{o}/hr random drift, the EDT is 0.225 km, which is 0.643% additional distance. These are pessimistic figures, since better gyros are available, and drift rate is random in reality.

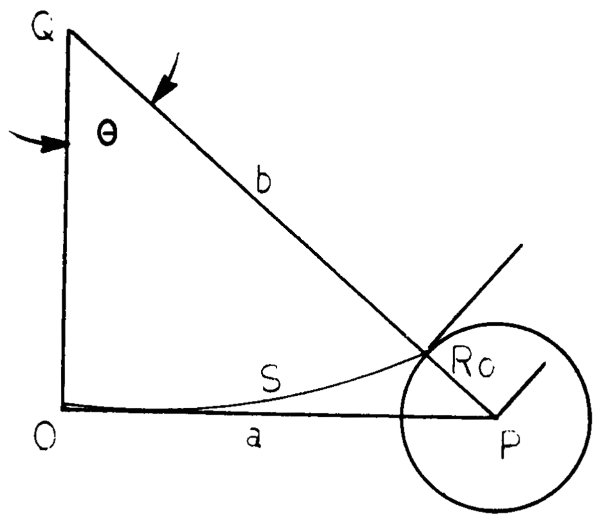
Equations 1 and 2 of the vertical gyro motion are the same for the dir-directional gyro; however, equation 3 becomes:

$$\psi - \dot{\theta}\sin\theta = L = \text{constant}$$

where ψ = angular position of wheel relative to inner gimbal

Nutational conical oscillation of the gyro spin axis has a frequency which is a function of rotor momentum, gimbal inertia, and torque angle. An azimuth gyro in a level travel path has a typical 167 cps

FIGURE 6 GEOMETRY FOR DIRECTIONAL GYRO WITH DRIFT FROM STATION TO STATION



OP $=$ a $=$ Station to station minimum distance

S + R_o $=$ Actual distance traveled

EDT $=$ Extra distance traveled $=$ S + R_o - a

θ $=$ Direct angle

value and about 72 cps when banked about 65°. In the MOLAB, a forcing frequency of 0.5 cps can not cause the gyro to drift, since a gimbal gyro resonance can not take place at this frequency.[42]

MOLAB forcing functions have a second order effect on the roll-stabilized directional gyros, as determined by state-of-the-art gyro manufacturers.

3.5 COMBINED VERTICAL DIRECTIONAL GYRO RESULTS

With the best roll stabilized vertical-directional gyro available (directional gyro drift is 0.1°/hr), and considering inertial force and MOLAB forcing functions, the system, on the largest MOLAB leg (7 hours; 35 km), can have a 560 meter error, and a 0.92° error from the terminal leg of the path.

One manufacturer states that performance of a friction averaging non-roll stabilized directional gyro is 0.5 degrees per hour on the moon. For the worst , or seven-hour, traverse, the three sigma error is:

$$3\sigma \text{ error} = \int_0^{7\text{hr}} \text{vel} \times \sin(7 \times 0.5^{\circ})\, dt$$

$$\approx 2.1 \text{ km}$$

The CEP error is about one half of the 3σ error, or approximately 1 km.

4.0 RADIO FREQUENCY NAVIGATION

Radio frequency navigation encompasses the following possibilities:

a) Using the C/M as a navigation satellite for a three position range-fix, identifying MOLAB position.

b) Dropping radio beacons at each MOLAB station reached for use in ranging on two or more stations.

c) Using the LEM with a beacon for homing on the MOLAB.

The first method is available for 18 minutes of every 126 minutes that the C/M is over the horizon. This means that this method would necessarily be a backup method.

LEM rendezvous radar could be used for ranging; the C/M has a transponder for this radar. Extensive computer equipment is needed to solve the range equations for particular C/M range coordinates when interrogated. This means the DSIF should house this equipment, and the equipment limited C/M would act as a relay for the MOLAB. Task Report 2A shows that accuracy increases as the time between range interrogations increases. This is not a problem. But the same report shows that for a C/M orbit approximating the actual orbit, error in C/M range coordinates are reflected 25 times as great in the solution of this navigation problem. Conflicting reports exist on the accuracy with which DSIF can provide C/M range fixes.

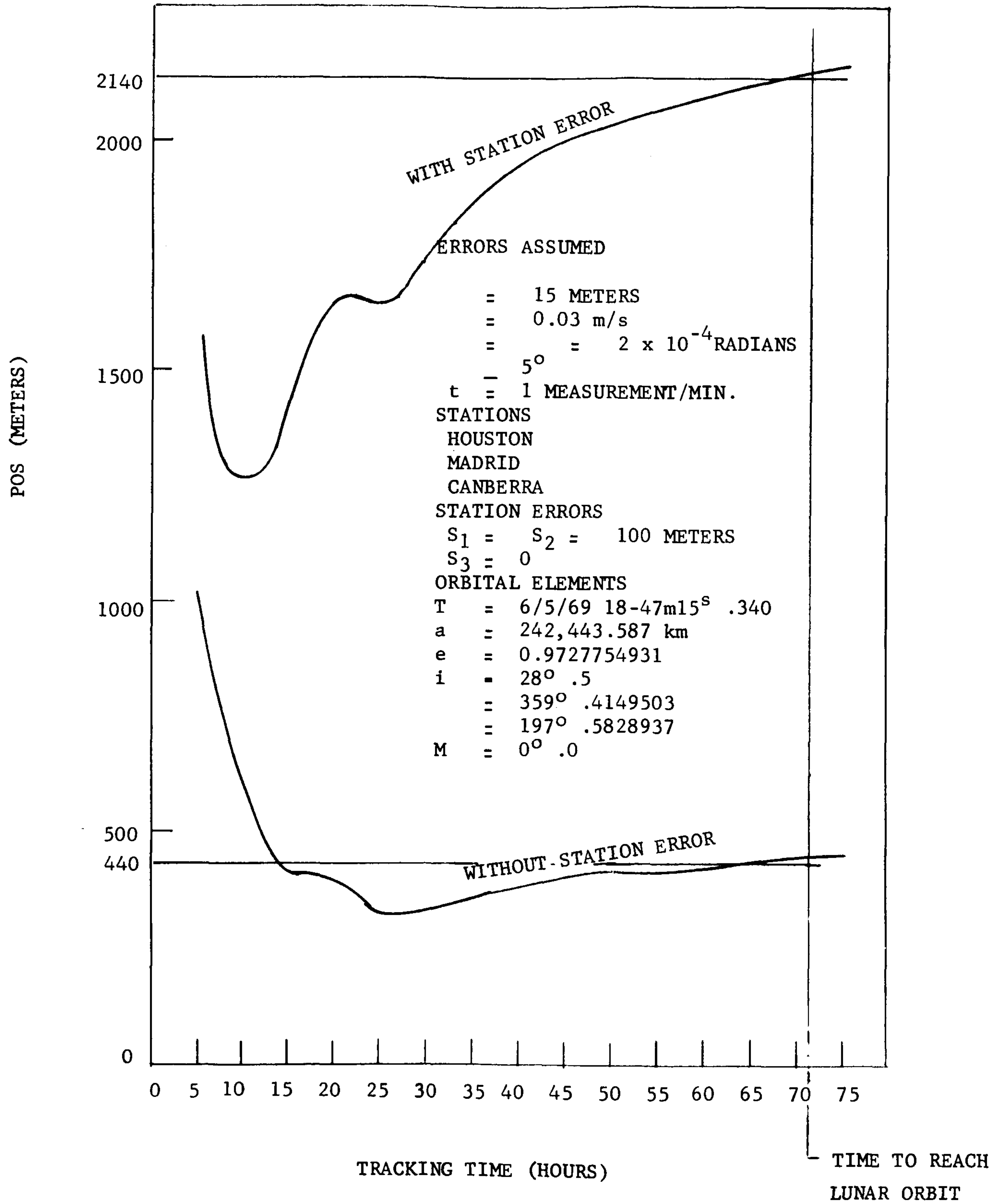
Figure 7 shows a 2400 meter error in C/M position at a lunar distance which is out of the question for this operation. However, a report "Capabilities of MSFN for Apollo Guidance and Navigation" by Bessett-Berman, Reference 63, with cover letter dated May 20, 1964 by Mr.S. Mardyce of the Manned Lunar Mission Studies, NASA, Washington, D.C., claims $\pm$100 meters positional accuracy, assuming the same DSIF errors as Goddard. A recent letter by Mr. S. W. Mardyce of NASA Headquarters to Mt/1 William B. Taylor, dated September 10, 1964, shows that several DSIF stations, after a period of tracking, can locate both the MOLAB and the C/M at $\pm$100 meters error. Since the MOLAB error, using the C/M as a satellite, is 25 times greater at $\pm$2500 meters, it is not feasible to install equipment on the MOLAB and at the DSIF to solve this type of position fix.

The second method involves placement of radio beacons at the twelve stations other than the initial station. Practical considerations show that minimum equipment can be carried for this purpose. This calls for line-of-sight or VHF equipment which is small in size and power requirements.

Line-of-sight transmission on the moon is limited, since the small diameter of the moon means a short horizon distance. The MOLAB traverse distances are such that high antennas would be needed. Considering that two emplanted beacons might service several stations also shows that antenna heights are too large to be considered. Figure 8 shows transmitting antenna and receiving antenna heights versus lunar line-of-sight distance in kilometers.

FIGURE 7

THE EFFECT OF TRACKING STATION LOCATION ERRORS ON SPACECRAFT POSITION UP TO LUNAR DISTANCE



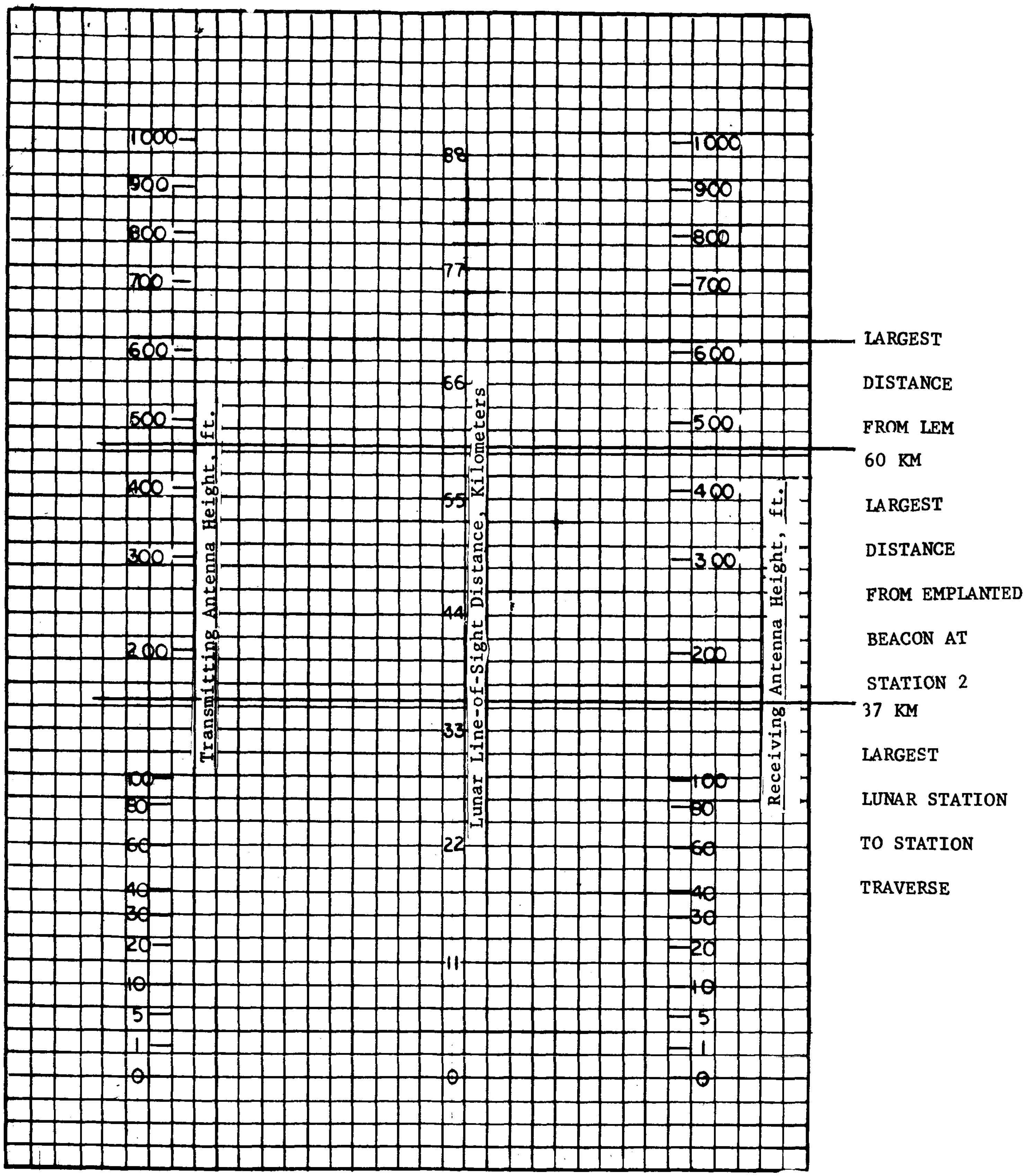


FIGURE 8 LUNAR LINE-OF-SIGHT NOMOGRAPH

The third method involves homing on a LEM beacon. At the average horizontal distances involved in the MOLAB traverse, medium frequencies are feasible. A 1000 W, 1500 mc, vertically polerized, pulsed carrier wave beacon transmitter with a 65 ft, retractable antenna can transmit 120 km. Maximum MOLAB range is 70 km. The 1000 Watts is for a peak pulse output. Pulse modulation techniques extend the beacon range over that obtainable with pure carrier waves. A MOLAB receiver using fixed crossed field loops and a vector sensing antenna would have a 20 kc bandwidth and approximately - 100 dbm sensitivity. Absolute angular error is in the neighborhood of one degree.

The above cases assume that the moon dielectric constant equals two and that the moon conductivity is 3.4×10^{-4} mhos per meter.

Another factor which may affect the operation is solar wind. This is an electron protron stream emanating from the sun and traveling to the moon. The electron density is such that at 700 kc and below, radio propagation is effectively lost. This solar wind could act as an ionosphere (close to the moon's surface during noontime). This effect is unknown, but it is known that June, July, January and December have minimum solar wind. These are also the times for the most favorable earth launch period. There is a smaller probability that the solar wind will be minimum during the lunar mission time.[40]

With a 1° absolute heading accuracy and a maximum MOLAB distance from the LEM, the MOLAB will travel a greater distance than that of an ideal path.

Reference 2 developed the following formulas for extra distance traveled by the MOLAB with LEM homing error (See Figure 9).

$$EDT = R - R_o \ (\sec \theta - 1)$$

where R = Distance from MOLAB to LEM

(the greatest distance from the LEM is 93 km)

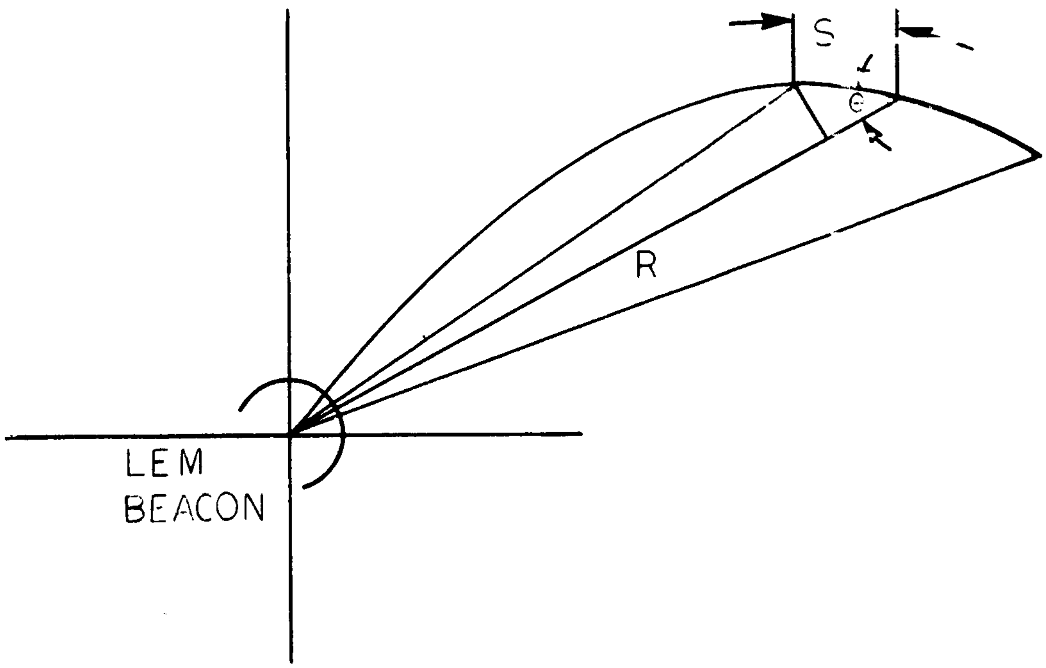
R_o = The sighting distance radius which may be ignored at the 93 km range.

θ = The fixed angular error of the beacon equipment, which is one degree absolutely

$$EDT = 93 \text{ km } (\sec. 1.0^\circ - 1) = 18.6 \text{ meters}$$

As the range decreases, EDT decreases. Thus, EDT is insignificant.

FIGURE 9 MEDIUM FREQUENCY HOMING BEACON GEOMETRY



R = Range to LEM from MOLAB

θ = Constant offset bias of equipment

5.0 OPTICAL RANGE FINDING

Optical range finders are an aid to MOLAB navigation. Lunar points, known from terrestrial investigations, may be ranged on to provide position by triangulation techniques.

From Reference 2, a minimum optical range of 1000 yards is cited. Line-of-sight horizon distance, with the optics approximately nine feet above the lunar surface, is estimated to be 6700 yards.

An optical range finder solves the surveyor's problem, shown in Figure 10.

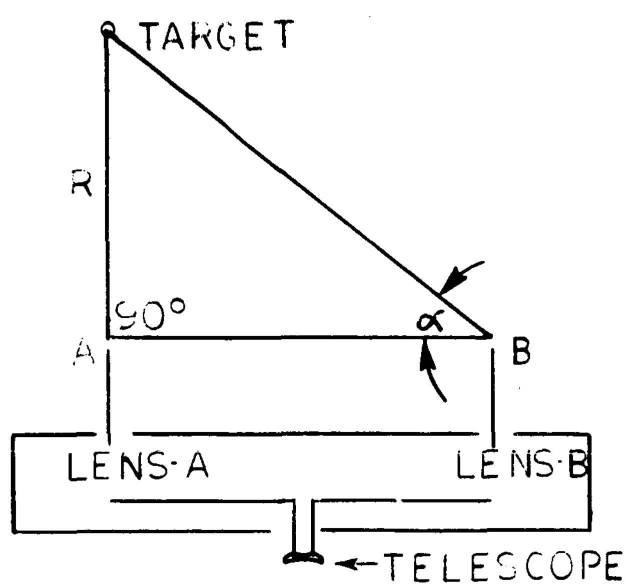


FIGURE 10 OPTICAL RANGE FINDER, WITH BASE LENGTH AB, SOLVES RANGE, R, WITH EQUATION $R = AB \tan \alpha$

Range finders are either stereoscopic or coincidence type. A stereoscopic type example contains a scale in each ocular. The scale appears as a zigzag row of dots receding to infinity. The dots superimpose on the scene, and each object in the scene appears to lie in the same plane as one of them. The acute stereoscopic sense of humans allows quick determination of which dot is coincidental with an object. This type is useful for operation at high vehicle speeds, which is not typical of MOLAB operation.

A second type of range finder, which is quite adequate for MOLAB operation, is a coincidence type. Referring to Figure 10, the image in one half of the field is formed by one objective, lens A, and that in the other half is formed by the other objective, lens B. Prism angular movement of lens B is required to bring the image in the two halves of the field into coincidence. This movement is then converted into range of the object.

Range finder accuracy depends, then, on angle measurement accuracy, which is a function of the optical system magnification. The higher the magnification, the greater the accuracy. The brighter the optical target, the greater the magnification that may be used.

The lunar atmosphere has no effect on the ranging equation, since this atmosphere is only one ten thousanth that of the earth.

Three meter base length range finders are available with resolution of one part in ten thousand.

5.1 ERROR CALCULATIONS

Again, the range equation is:

$$R = AB \tan\alpha$$

Differentiating for error:

$$dR = AB \sec^2\alpha \, d\alpha$$

where $d\alpha$ is in radians

$$dR = AB \sec^2 \left(\text{arc} \tan \frac{R}{AB}\right) \frac{d\alpha}{57.3}$$

α has a maximum of ninety degrees, and for a minimum range R_{min}:

$$\alpha \min = \tan^{-1} \frac{R_{min}}{AB}$$

α then ranges through:

$$90^{\circ} - \tan^{-1} \frac{R_{min}}{AB}$$

The rotating lens system, or mirror system, at B actually moves through a small angle, while the 360° readout is engaged through a gear train of ratio N. The ratio N is:

$$\frac{360}{90 - \tan^{-1} \frac{R_{min}}{AB}}$$

Readout angle, α_R, is related to α and N as follows:

$$\alpha_R = \alpha \cdot \frac{360}{90^{\circ} - \tan^{-1} \frac{R_{min}}{AB}}$$

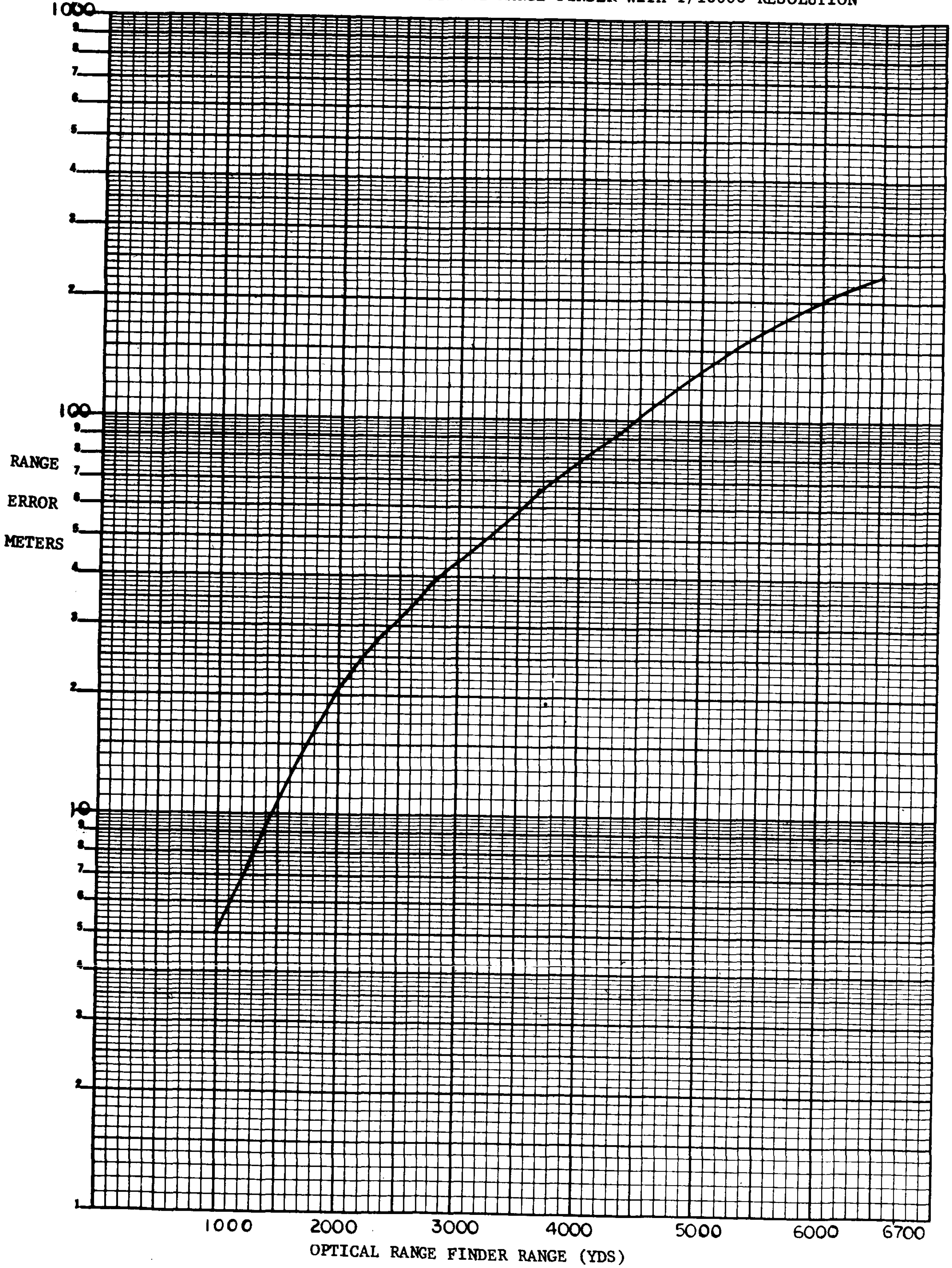
The range error equation then becomes (in terms of readout angle):

$$dR = \sec^2\left(\tan^{-1}\frac{R}{AB}\right)\frac{90 - \tan^{-1}\frac{R_{min}}{AB}}{360 \times 57.3}\, d\alpha_R$$

where R and AB are in meters.

Assume a minimum range of five meters, a three meter base length, and a maximum visible distance of 6700 yards. Error is 235 meters. At a minimum expected sighting distance of 1000 yards, error is 5.3 meters. Figure 11 gives the error for the whole sighting range distance to be expected.

FIGURE 11 RANGE ERROR VS RANGE FOR OPTICAL RANGE FINDER WITH 1/10000 RESOLUTION



6.0 AZIMUTH DEVIATION DUE TO TILT OF OPTICAL OR ANTENNA EQUIPMENT

Where vertical deviation occurs, the tilt results in an azimuth error which increases both with tilt and elevation. The geometry of the situation is seen in Figure 12. The equation for A, azimuth error, is:

$$\Delta A = \tan^{-1}\left\{ \left[\sin^2 \left(\tan^{-1} \frac{\tan E}{\cos A} + L\right) + \frac{\cos^2 E \sin^2 A}{1-\cos^2 E \sin^2 A} \right]^{1/2} \right.$$

$$\left. \times \frac{\cos\left(\tan^{-1}\left[\dfrac{(1-\cos^2 E \sin^2 A)^{1/2} \sin\left(\tan^{-1} \dfrac{\tan E}{\cos A} + L\right)}{\cos E \cos A}\right] - CL\right)}{\cos\left(\tan^{-1} \dfrac{\tan E}{\cos A} + L\right)} \right\} - A$$

where A = Azimuth

A = Azimuth error

CL = Cross level axis error

E = Elevation angle

L = Level axis error

A plot of azimuth error versus elevation angle for various tilts in level and cross level is shown in Figure 11.

With their 5° radiation cone, MOLAB antennas may be ± 2 degrees off center and still make contact with the earth. With a maximum earth declination angle relative to the moon, and a MOLAB pitch of 30°, the plot shows that a 0.25° tilt will give 2° azimuth error. If the antennas were slaved to an earth tracker inertial platform, the coordinated would be the same, and tilt could be kept to a minimum. If not, a coordinate converter slaved to roll and pitch would be necessary.

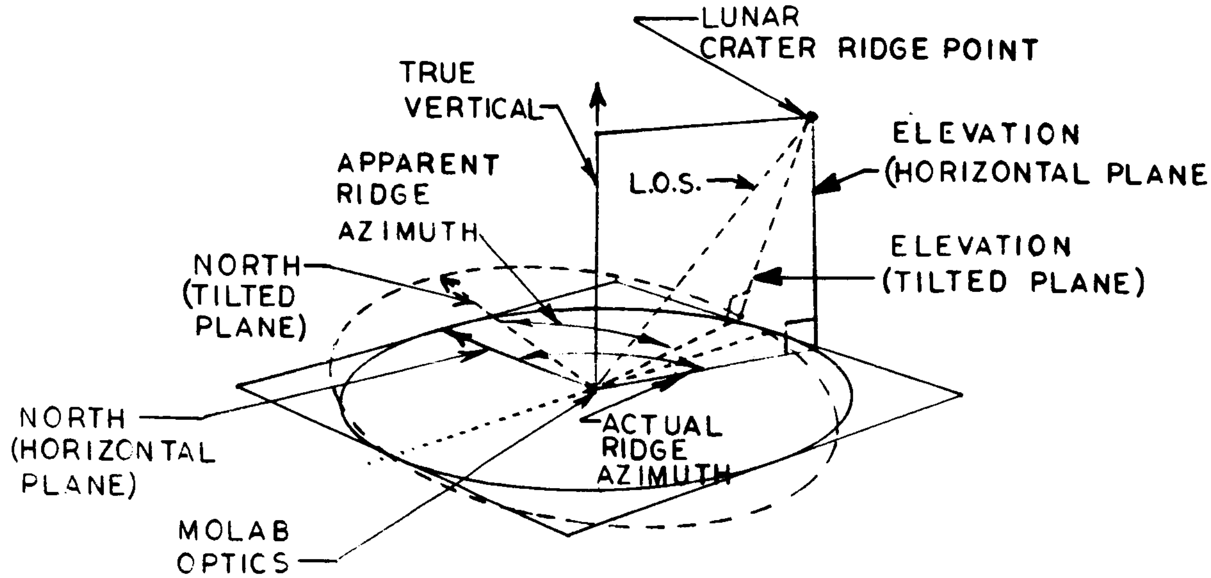


FIGURE 12 HEADING ERROR DUE TO VERTICAL DEVIATION

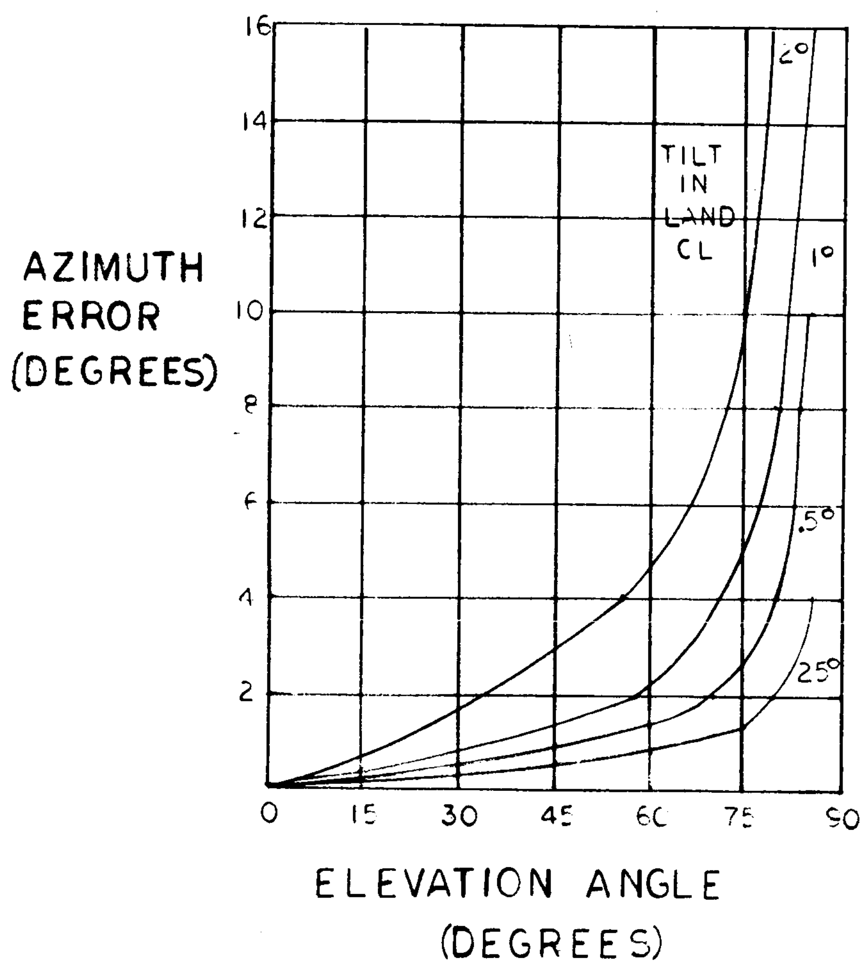


FIGURE 13

AZIMUTH ERROR VERSUS ELEVATION ANGLE

7.0 GYROS

The gyro field has expanded rapidly in the last decade. The race has been toward extremely low drift rates. Drift rate needs vary with application as follows: (MOLAB possibilities)

Intertial measurement unit - 0.001°/hr - 0.1°/hr

High accuracy directional gyro - 0.1°/hr - 1.0°/hr

Vertical gyro - 5 - 50°/hr

The 0.001°/hr drift rates are available in gyros with 20,000 hour life expectancy. These gyros would be used in stable platforms, where signals are controlled by servo motors which, in turn, are controlled by the gyro pickoff. The gyro angular momentum is effectively multiplied by servo gain. Small servo signals control the gimbals, so that the gyro has movement limited to less than a degree. The platform allows vehicle motion isolation. Thus the gyro operates best in this environment.

There are essentially five types of gyros:

a) Gimballed rotor gyros, which are widely used.

1. two degree of freedom gyro (displacement)
2. one degree of freedom gyro (displacement rate)

b) Free rotor gyros(used since the mid 1950's): These contain spherical bearing support for the rotor allowing three degrees of freedom about a point(displacement). There are three kinds of support:

1. Autolubricated gas bearing

2. Electrostatic support

3. Magnetic support (super conductive body under cryogenic conditions).

Electronics are very critical in this type gyro, and special fabrication and gaging techniques are needed.

c) Fluid rotor gyros: This type has a spinning fluid body or a fluid stream, which is the inertial element (displacement, rate). Forces are measured by pressure differential. Complex hydrodynamic effects occur.

d) Vibrating gyros: The inertial element in this type gyro oscillates rather than rotates (displacement, rate). This gyro has too high a drift rate.

e) Particle gyros : This type of gyro has angular momentum of atomic nucelli, lesser frequency difference properties, or translational momentum of electrons. It provides gyroscopic action.

All of these types are in a research stage.

Approximately 100 new kinds of gyros have been studied recently. The vibrating type gyro, described in (d), is not considered for the MOLAB because it is too high in drift, and the particle gyro described in (e) is still in a research state. Requirements of inertial sensors are increasing from 10^{-4} degrees per hour in 1964 to 10^{-7} degrees per hour in 1968. For this reason, exotic gyro designs are being studied.

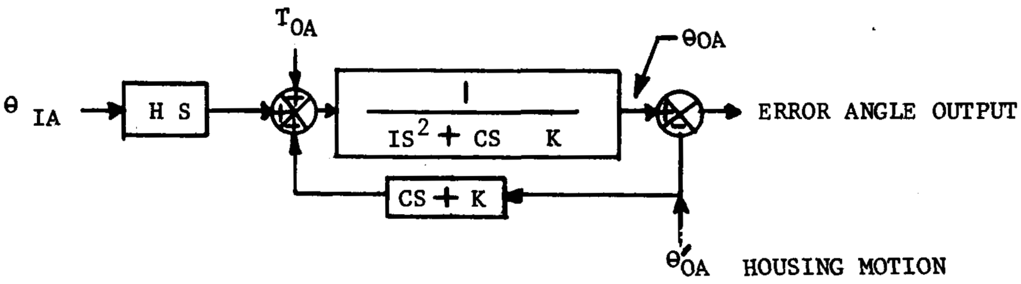
For completeness, the following is a list of gyros (types described in c, d, and e), with present and potential drift rates:

GYROS	DEGREES/HOUR DRIFT
	Potentially
Electrostatic	0.01
Electromagnetic	0.001
Cryogenic Electromagnetic	0.0001
Nuclear Spin	0.001
Cryogenic Nuclear Spin	0.0001
Fluid, Compressible	0.2
Fluid, Incompressible	0.8
Loser	0.001
Vibrating	4.0

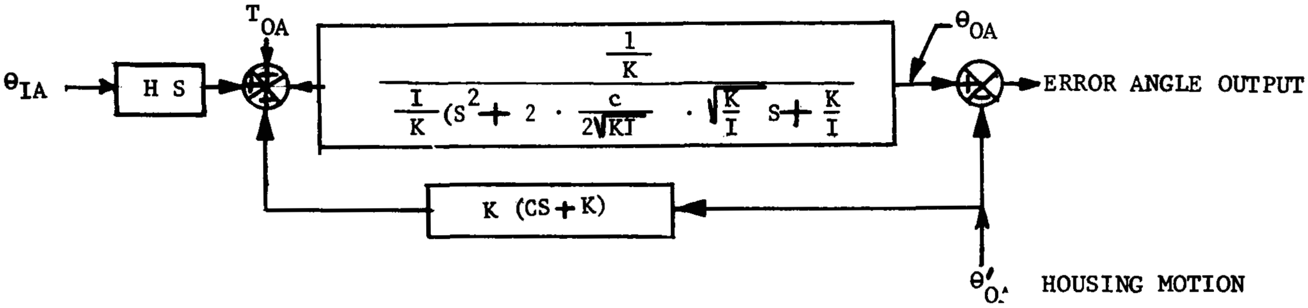
The cryogenic magnetic (rate, displacement) and cryogenic nuclear spin (rate, displacement) offer the best hope for future use.

Two degree of freedom displacement gyros were discussed earlier in the report with respect to vertical and directional gyro applications. The free rotor gyro is presently displaying good results, but it has not been sufficiently proven for use in the MOLAB mission.

The gyro may be considered as a black box, so that a transfer function may be developed for it, and design may proceed by modification of transfer function parameters as shown in Figure 14.



A. SINGLE DEGREE OF FREEDOM GYRO TRANSFER FUNCTION

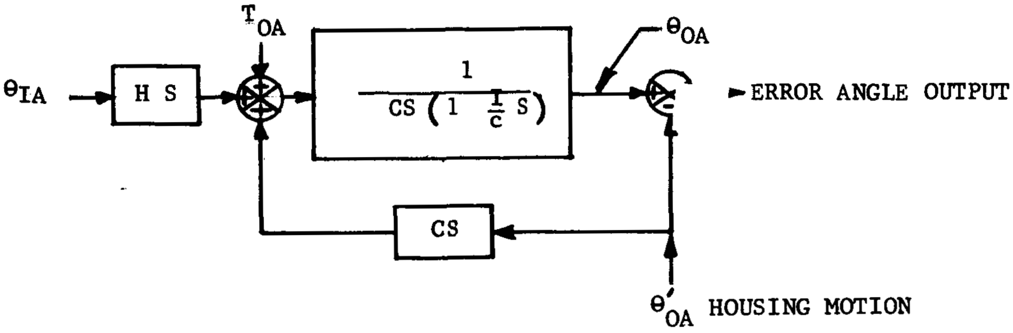


B. SINGLE DEGREE OF FREEDOM GYRO BECOMES RATE GYRO

WITH ADDITION OF HIGH SPRING RESTRAINT, K.

THE SECOND ORDER FORWARD LOOP EQUATION IS IN THE

FORM OF $S^2 \quad 2 \quad W_n S \quad W_n^2$



C. SINGLE DEGREE OF FREEDOM GYRO BECOMES RATE INTEGRATING

GYRO BY HAVING NEGLIGIBLE SPRING RESTRAINT, K, AND A

HIGH VISCOUS COEFFICIENT, C.

INPUT AXIS (IA) OUTPUT AXIS (OA)

T = TORQUE, I = MOMENT OF INERTIA

FIGURE 14 TRANSFER FUNCTIONS - SINGLE DEGREE OF FREEDOM GYROS

Gyros of even 0.001 degree per hour drift possess mass unbalance, assymetrical suspension, static friction, unbalanced torques, disturbing torques from pickoffs, thermal transients plus error sources that are not yet identified. The rate integrating type, floated, is used mainly on stable platforms. A 10^{-6} inch mass drift of a 10^{6} gm-cm^{2}/sec gyro wheel results in a 0.1 degree per hour drift rate in a one g environment. The 0.001°/hr drift has been a difficult task to achieve.

Two degree of freedom inertial type gyros (TDF) exist with non-removable drift rates of less than 0.01 degrees per hour.

Gyro drift over a long term period cannot be said to be continuous in one direction, so that statistically some averaging takes place. The longest traverse of the MOLAB is seven hours, and the shortest is 1.75 hours. Drift rates of 0.01 degrees per hour have negligible effect on dead reckoning performance.

A question of two degree of freedom or single degree of freedom (SDF) gyro stable platforms must be considered, then, in terms of drift. In terms of azimuth drift rate, horizontal accelerations are sensed 70 percent in the SDF platform arrangement, while the TDF platform senses 100 percent, but averaging circuitry can reduce this to 70 percent. Azimuth drift under vertical acceleration is smaller for a TDF platform than for a SDF platform.

TDF gyros are much less susceptible to drift with rotary at the outer case of the gyro than are the SDF gyros. The larger the damping rate, C/H of the SDF gyro, the less the effect of rotary vibrations.

MOLAB 0.5 cps, step, and sinusoidal disturbances considered with gyro drift rates are parameters to be considered overall. The lower drift rate of SDF gyros, but higher vertical acceleration error and higher drift rate of TDF gyros with lower vertical acceleration error indicate that either may be used in the MOLAB on a tradeoff basis.

8.0 ACCELEROMETERS

Accelerometers are inertial systems transducers which obey Newton's second law for translation or rotation. The accelerometer has been improved, mainly for missile application, to have very low g sensing (approximately 10^{-10} to 10^{-12} g), and to withstand high g loading.

The MOLAB requires accelerometers which act with horizontal accelerations limited to less than one moon g. The newer types (electrostatic and electromagnetic) are not applicable here, but certain older designs (pendulous types) can adequately fit the task.

Accelerometers obey a law of equivalency. If the transducer is tilted, it will sense both horizontal and gravitational accelerations.

In the design, both open loop and elastic restraints are used to oppose the force sensed. The latter is preferred since, with feedback, there is vertually no error caused by off neutral deflection of the test mass.

Practical design of the accelerometer requires that a trade off be made between sensitivity plus linearity,and range.

8.1 ERRORS

Bias errors are caused by unwanted fixed torques. Attempts are made to compensate for this. These errors are also called null uncertainty, and, in present day pendulous type, are in the order of $\pm 10^{-4}$ g.

Threshold errors are due to static support friction and other factors which are insignificant. Today's pendulous type have threshold error in the order of 2×10^{-7} g.

Rectification errors are caused by structural resonance from vibration. MOLAB forcing functions are at least 100 times removed (in the lower direction) from accelerometer resonance and, therefore, there is no problem.

Linearity or scale error is in the order of 5×10^{-6} g/g^2 for present day pendulous accelerometers.

Accelerometers probably would be used in an IMU associated with a digital computer. Analog computers are limited in practice to one part in 1000 accuracy, which is not considered adequate, while digital accuracy is theoretically unlimited as a function of the number of bits employed. Also, the digital computer is smaller in size, and MOLAB space is at a premimum. An integrating (velocity meter) or double integrating (distance meter) is preferred, since this eases the digital computer calculations.

Accelerometer accuracy is most important in short term operation, such as in missile flight, while the gyro error is most important in long term operation such as MOLAB mission.

From Reference 55, accelerometer errors can be described as follows:

Error	Error Transform	Distance Error-Transform	Distance Error-Time Function
Accelerometer Scale - Impulse	$\Delta V \cdot \mathcal{E}_s$ (Velocity Change x Scale Error)	$\frac{\Delta V \cdot \mathcal{E}_s}{(S^2 + w^2)}$	$\frac{\Delta V \cdot \mathcal{E}_s}{w}$ sin wt
Accelerometer Bias - Step	$\frac{\Delta a}{S}$ (a = acceleration)	$\frac{\Delta a}{S(S^2 + w^2)}$	$\frac{\Delta a}{w^2}$ (1 - cos wt)

For short term errors (in the vicinity of five minutes) the distance error time function for an accelerometer scale - impulse error is approximately $\Delta V \cdot \mathcal{E}_s \cdot t$. For short time errors, the distance error time function for an accelerometer bias - step error is approximately $1/2 \cdot \Delta a \cdot t^2$.

MOLAB velocity is in the vicinity of 5 kilometers/hour, according to traverse information. This is 4.55 feet/second.

In Reference 55, curves are given for peak error versus velocity change in feet per second for long term and short term errors for specific accelerometer scale and bias errors. For long term errors, an accelerometer scale error of one part in 1000 has approximately a 0.5 nautical mile error for a velocity change of 4000 feet per second. Interpolated, a four foot/second velocity change would give a peak error of approximately one meter. Again for long term errors, an accelerometer bias error of approximately 1.0×10^{-4} g results in a peak error of approximately 0.7 nautical miles.

Thus, accelerometer bias error is important in the overall accuracy in long term errors, while accelerometer scale error has negligible effect for long term operation. An accelerometer bias error of slightly more than one order of magnitude has approximately 0.06 nautical miles error.

For short terms (five minutes) errors, an acceleration scale error of one part in ten thousand for a four foot/second velocity change is interpolated as 0.1245 feet --- a negligible quantity.

Accelerometer bias error of 1×10^{-4} g leads to a 150 foot error, while a bias error of 0.1×10^{-4} g leads to a 15 foot error.

For the sake of completeness, accelerometer types are listed.

8.2 TYPES OF ACCELEROMETERS

a) Elastic Constraint Accelerometer

The principle of stress proportional to stain is used in a spring supported mass system or the electrical equivalent. The transfer function for the mechanical system is:

$$\frac{X}{a} = \frac{M/K}{M/K\,S^2 + 2 \cdot \frac{C}{2\sqrt{KM}} \cdot \sqrt{\frac{M}{K}}\,S + 1}$$

where X = Accelerometer test mass displacement with respect to the case.

a = Space Acceleration

M = Mass

K = Spring Constant

The M/K ratio is the steady state displacement response to unit acceleration, and the $(M/K)^{1/2}$ equals $1/w_m^2$. The damping coefficient is C.

The factors of S in the denominator are two times the damping factor times $1/w_m$.

With damping close to critical, the accelerometer responds uniformly from zero to resonant frequency. Gain and resonant frequency must be traded off in practice since both are related to M and K. This design was most predominant in the earlier days of accelerometer design.

b) Viscous Shear Accelerometer (integrating type)

Here, stress is proportional to the shear rate of a liquid.

c) Inertial Constraint Accelerometer

1. Reaction Rotor:

   Sensed acceleration is balanced by the acceleration of the rotor.

2. Gyropendulum:

   Sensed acceleration causes precession of the gyro in a manner proportional to rate.

3. Balanced Centrifugal Force:

   Sensed acceleration is balanced by the accelerometer centrifugal force.

4. Vibrating Strings (Integrating type):

   Sensed accelerations cause one string on one side of the mass to increase tension and therefore increase frequency, while the second string decreases tension and lowers frequency. (frequency $\propto$ tension $^{1/2}$).

d) Balanced Electrostatic Force Accelerometer

1. The test mass is constrained by electrostatic force. A high performance servo is used in conjunction with it.

2. This version has an acceleration reaction or suspended macroscopic particles in an electric field. It is now in the research stage. When developed, these sensors will cost one-forth that of other inertial sensors, and will have about one-third the size and weight.

The particles (2.5 to 250 microns) are shot into an evacuated ring chamber containing an electrical force field from balancing electrodes. Acceleration causes these particles to displace. Open or closed loop operation is possible.

e) Kinematic Accelerometer

1. Transit Time Principle:

Operation depends on the passage of unconstrained particles through fixed points.

2. Pendulum Principle (integrating type) :

The pendulum oscillates freely in a plane containing the acceleration vector. Errors are associated with cross coupling from acceleration normal to the sensing axis and a rectification error torque where compliance can allow defection from vibration forcing. (Viscous damping is normally used.)

For small angles, the ratio of the pendulum angle with respect to the case, α to space sensed acceleration a is:

$$\frac{\alpha}{a} = \frac{\frac{ML}{K}}{\left(\frac{1}{w_n}\right)^2 S^2 + 2 \cdot \zeta \cdot \frac{1}{w_n} \, S + 1}$$

$$= \frac{\frac{ML}{K}}{\frac{ML^2}{K} \, S^2 + 2 \cdot \frac{C}{2L\sqrt{KM}} \cdot \left(\frac{K}{ML}\right)^{\frac{1}{2}} S \quad 1}$$

where L = Pendulum Length

M = Pendulum Mass

K = Spring Constant

C = Damping Constant

The ML/K ratio determines the steady state angular displacement to acceleration.

3. Rotating Pendulum (integrating, double integrating):
Sensed acceleration is developed by angular velocity modulations of the mass unconstrained motion, and measured from time and angular position. Slow variation, low level accelerations can be sensed.

The pendulous gyro version integrating type is a single axis, floated, damped system with a fixed unbalanced gyro type gimbal. A servo system modifies the pickoff information to drive the gyro, to null the pickoff. Servo gain is high to reduce pendulous crosstalk.

A double integrating version has a bearing supported pendulous gimbal in the accelerometer case. The motor rotor is free to turn. Gimbal motion restraining torque is transferred across the motor air gap when the servo amplifier responds to pickoff error.

Motor angular acceleration is a function of the linear acceleration and motor angular velocity is a function of linear velocity. Motor angular position is a function of linear distance travelled or the double integral of the sensed acceleration.

f) <u>Electromagnetic Accelerometer (integrating type)</u>

Force is proportional to current carrying conductor effect in a magnetic field.

9.0 MOLAB NEED FOR STAR TRACKERS

Several arguments favor the use of star trackers for MOLAB navigation. Celestial observations from a steady platform on the moon will have accuracy comparable with that on the earth. In the initial six-month unmanned MOLAB lunar storage period, an automatic star tracker appears ideal for automated navigation information.

A star tracker is a long term accurate device, while gyro stabilized platforms are short term accurate devices; therefore, a tracker has the ability to provide corrections to inertial references. Automatic celestial fixes cut down on mission delay time. The work load of the astronaut should idealistically be cut down in the normal work function areas, to allow maximum possible time for concentration on scientific assignments.

A star tracker gives azimuth and elevation outputs which, when the tracker seeks earth, gives outputs directly to stabilize communication antennas that feed information to earth. Without an earth seeking star tracker, extra equipment would be needed to convert normal roll and pitch platform information to the requirements of the azimuth and elevation antenna. Star tracker power requirements are a minimum, as is the physical size.

Few companies have been highly involved with star tracking equipment; therefore, information is somewhat limited. Trackers have been built which are unique for different applications. An earth-sun tracker would be a possible modification of existing sun-star trackes. Latest star-tracker information[66] indicates accuracies to a less than 5 seconds of arc.

10.0 LEM/MOLAB RELATIVE NAVIGATION

MOLAB navigation includes long time periods out of the sight range of the MOLAB in the lunar day, and in the latter quarter of the mission, during the lunar night. It is desirable to relate course and distance to the LEM in case of danger. A MOLAB/LEM medium frequency process provides relative bearing within one degree. Dead reckoning computations fed to a computer (preferably digital, because of accuracy and readout ease) can continuously provide distance and bearing relative to the MOLAB.

Pitch modified odometer data (5% accuracy) can be fed to an azimuth resolver on a star tracker stable platform and/or directional gyro. The heading of LEM from true north is known by the IMU. The MOLAB heading is celestially determined at the LEM site, station number one. The resolvers on the platforms can be rotated to make heading relative to the LEM(platform drift, pessimistically, is 0.5^{o}/hr). The digital computer will contain LEM coordinates, and MOLAB direction and distance will be continuously displayed relative to the LEM through A/D converted dead reckoning information.

For phychological purposes, it is good to have a plotter with a moon traverse region map which is fed by the dead reckoning data, so that the astronaut will have a visual fix of his track, realtive to the LEM, from station to station. This data could be relative to the LEM, or using a platform north oriented azimuth resolver, relative to the north. Map accuracies are in the order of one km or approximately two minutes of arc.

Relative navigation errors are then almost all accounted for by dead reckoning errors.

It is desirable to have periscopic optics to look at objects such as the LEM while the MOLAB is traversing. Azimuth and elevation relative to the desired object must be accounted for to keep the object tracked.

Since map accuracies are ± one kilometer, the object to be tracked must have a manual differentially added tracking ability to initially find-set the optics on the target. A computer (analog or digital) will contain settable counters for initial positioning of the MOLAB, and map coordinates of the object to be tracked. The MOLAB dead-reckoning mode would have integrated odometer velocity information (5% accurate) times cosine pitch, which, when resolved about the azimuth, would give the distance traveled, north and east. This will be added to or subtracted from the initial computer counter, MOLAB north and east starting fix, to give a running account of the MOLAB position all along the traverse. This information can, in turn, be subtracted from the optics target object set in coordinates.

This information then can be resolved to give azimuth relative to the LEM. The optics azimuth can then position the LEM on the target within the limit of map accuracies.

A differential manual optics tracking handle could finely set the optics in the azimuth on the targets (one km equals two minutes) if this is desired. The problem of elevation or declination remains.

Again, dead reckoning integrated velocity times the sin of pitch gives a running account of altitude with initial MOLAB elevation set in analog or digital counters. This can be subtracted from the optics target elevation (predicted elevations are to be known within ± 150 meters by 1968). The information can drive the optics declination servo and again a differential manual track handle can finely position it for an exact elevation fix.

Errors are mainly from the dead-reckoning equipment. The three-sigma error would be the odometer error times the sin of the azimuth drift integrated over the time period. One optics target can be considered to be tracked for no more than one hour.

$$\int_0^1 \frac{5}{100} \times 5 \text{ km/hr} \times \sin 0\ 1^{\circ} dt$$

is the error for a combined odometer-roll stabilized, unslaved, directional gyro considered in this report. The error is negligible.

11.0 CELESTIAL NAVIGATION HARDWARE

Celestial navigation errors are independent random errors which combine in a root sum square manner. Error sources are:

a) Reading or tracking

b) Vertical deflection

c) Timing

d) Ephemeris

e) Computation

f) Plotting

11.1 READING

The astronaut is hardware, in a sense. It has been determined that uncorrected personal error amounts to ± one minute on manual instruments.[36]

Since there is no lunar free liquid surface to serve as an elevation datum on the lunar surface, there is no visible and natural horizontal reference. Although there are complicated techniques for using a modified sextant without a vertical reference, it is better to use a bubble sextant than a conventional or modified conventional sextant. Bubble sextants are not as accurate as the original sextant. Dip or height of eye correction does not apply, but still error amounts to 2'.

Gravity anomalies will add to the error. Based on 10 seconds error (Reference 67), the moon will have 60 seconds error. Based on both gravity factors, one minute may be assumed.

The transit is gradually being replaced by the theodolite, which is capable of first order accuracy in geodetic surveying (one part in 25,000). Theodolites have been considered as part of the scientific mission in conjunction with a chronometer for celestial position fixes, as well as for other purposes. Theodolites exist with accuracies of 0.2 seconds of arc. They also are designed for compactness, light weight, and are faster and easier to read.

Considering uncorrected personal error in conjunction with the 0.2 second of arc, an accurate theodolite can be considered to give a one minute error in reading.

11.2 VERTICAL ERRORS

Moon gravity is stated as 1/6 earth gravity. However, nothing is known concerning lunar vertical deflections and anomalies. Lunar topography irregularities, coupled with the low value of gravity, seems to indicate that large anomalies may exist. The proposed MOLAB traverse shows that the majority of traverse stations are by craters and areas of sharp contrast to the Mare and ray material. It is in areas of sharp contrast that gravity anomalies are likely to be the worst.

A gravimeter is necessary to determine gravity deviation. This instrument has been planned as part of the scientific mission. The vertical may then be corrected by this amount. If uncorrected, reference is made to the earth's gravity for comparison with moon gravity. Bowditch states a 1.1 minute maximum earth error for a region of high slope mountains bordering on a sea.

11.3 TIMING

On a rotating moon, as well as on a rotating earth, timing of sun or star fixes is of concern. Chronometers are presently available with a daily error of ± 0.05 seconds. An error of 0.05 seconds on the lunar surface, considering a spin rate of 0.536 degrees per hour, is then 0.0268 arc seconds. One second equals 8.42 meters on the moon. The error is negligible. Timing is set with respect to the terrestrial or Greenwich mean time. Chronometers must be checked daily to keep a record of time lost or gained in order to maintain the high accuracy of the chronometer.

Navigational watches are available with ± two seconds error per day. These watches may be referenced to the chronometer for calculation purposes.

11.4 EPHEMERIS

Operation on the moon requires that a lunar ephemeris be generated. The ultimate obtainable accuracy is limited by the accuracy of the physical librations of the moon in latitude and longitude. The latitude motion is 0.04 degree sine wave motion with a six year period. The longitude motion is a 0.02 degree sine wave motion with a one year period. The accuracy at present, according to Reference 35, is limited to hundreths of a degree as indicated. No information has been obtained which condtradicts this as yet; no persons or organizations queried on the subject have answered.

Considering that earth ephemeris is accurate to one second of arc or less, conversions from earth coordinates to lunar coordinates must take into account one second earth error and the error due to libration, which is known to hundreths of a degree.[64] The error, then, is approximately 36 seconds of arc.

11.5 COMPUTATION ERRORS

As defined in Reference 2, manual computation accuracies of 0.1 minute for altitude and 0.1 degree for azimuth are realistic. A latitude error gives equivalent error in LOP's; computation is then given as 0.1 minute RMS.

11.6 PLOTTING, MAP ERRORS

Plotting errors are listed at 1.2 seconds, while mapping errors account for 3.0 seconds. Lunar mission maps are stated as 1 kilometer or 118.7 seconds.

Reference 40 presents a present table of horizontal and vertical accuracies of the moon, which shows that the greatest accuracy is at the zero latitude and longitude point on the moon, and degrades as latitude and longitude increase. For a lunar traverse at 4° N latitude and 39° 40' longitude, a present accuracy of 2270 kilometers exists. However, as stated in Reference 40, the USAF Aeronautical Charts and Information Center predicts a 0° latitude and longitude accuracy of 800 meters CEP (1968) horizontally and 150 meters vertically. (As a result of a lunar optical ranging experiment, R. L. Hiff, MS Travenner, Air Force Cambidge Research Laboratories states that optical radar is being developed for vertical ranging on the moon to 150 meter RMS.).

Interpolation of the 1968 predictions for the MOLAB traverse region stated means one km horizontal accuracy, or 118.7 seconds (2 minutes for practical purposes) with an RMS error of 0.67 minutes of arc.

System Accuracy

LOP errors	One Sigma (Minutes)	One Sigma (Squared)
Reading, Instrument	0.50	0.25
Vertical	1.00	1.00
Timing	0.0047	0.000022
Ephemeris	0.51	0.26
Computation	0.10	0.01
Plotting	0.02	0.0004
Map	0.67	0.4489

Standard deviation = $\sqrt{1.969}$ = 1.4 minutes of arc = 707.28 meters.

12.0 RECOMMENDATIONS

In view of findings made in this report, it is recommended that we:

1. Study gyrocompasses in terms of the possibility of using a fast settling gyrocompass for initial fixes. This possibility does not appear to be probable, but it should be absolutely discounted.

2. Study platforms and star trackers (sun/earth) with reference to use as prime automatic dead reckoning equipment.

3. Keep the idea of radio frequency navigation alive, referring to state-of-the-art techniques and equipment for possibilities in aiding MOLAB navigation.

4. Study lighting conditions on the moon as determined in MOLAB TV studies for use in conjunction with optical navigation techniques.

5. Attempt to come up with non-standard ideas for navigation which may be applicable to the MOLAB task.

6. Study the moon in all aspects for visualization of the actual mission.

7. Examine the astronauts involved in the Apollo navigation, obtaining their ideas on MOLAB navigation (technical and human factors).

8. Study strapdown inertial systems. These are now being used as backup systems in the LEM and C/M.

9. Devise conceptual designs.

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