279

EG2

MSC INTERNAL NOTE NO. 67-EG-6

PROJECT APOLLO

A STUDY OF LUNAR MODULE NAVIGATION SYSTEMS ACCURACIES FOR POWERED DESCENT, ASCENT, AND ABORTS

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HOUSTON, TEXAS

January 31, 1967

SUMMARY

A linearized analysis of the navigation accuracy for the Primary Navigation and Guidance System (PGNCS) and Abort Guidance System (AGS) has been made for the Lunar Module (LM) powered descent, aborts off the powered descent, and powered ascent. In this note, the uncertainties are given for (1) the estimated LM inertial state vector, (2) the estimated LM altitude and altitude rate, and (3) the estimated Lunar Module-Command Service Module (LM-CSM) relative range and range rate.

Unitized partial derivatives of the LM state vector errors with respect to each error source are presented for both systems at the end of each trajectory. These matrices can be used for hand calculations of the state vector errors caused by a particular error source (e.g., a gyro drift). Also included are the error models of the systems and the derivation of the equations used to analyze the navigation accuracy of a strapdown inertial navigation system.

INTRODUCTION

The guidance and navigation functions of the LM are performed by two systems - the PGNCS and AGS. An analysis of the guidance and navigation accuracies of these two systems is required to determine monitoring procedures and to estimate system performance. It is the purpose of this note to present the navigation accuracy of both these systems in determining the LM inertial state, LM altitude and altitude rate, and LM-CSM relative range and range rate information for the following trajectories:

a. LM powered descent (50,000 ft. to 2,000 ft. altitude)

b. LM aborts off the nominal descent

   (1) At 25,000 ft. altitude

   (2) At 10,000 ft. altitude

c. LM powered ascent (800 ft. to 50,000 ft. altitude)

Time histories of altitude, altitude rate, relative range, and range rate for these reference trajectories are given in figures 1 through 4. The analysis of the AGS errors required the development of the error equations given in Appendix A. The analysis of the PGNCS errors is available in reference 1.

Most of the results of this study are presented in the form of time histories of the errors considered, and effort is made to explain the underlying trends of these quantities and to indicate the major error contributors.

DISCUSSION

ANALYSIS TECHNIQUES

To perform the linearized analysis of the two onboard navigation systems, it was necessary to use reference trajectories for the lunar powered landings (nominal and two aborts), and the powered ascent. The trajectories were generated in a point mass digital simulation using the guidance equations of the primary system for both descent and ascent (see reference 2).

The a priori navigation uncertainties for the LM and CSM at the start of powered descent are taken to be those resulting from an onboard lunar orbit navigation (3 orbits, 2 landmarks, and 3 measurements) given in reference 3. This initial LM covariance matrix included the errors caused by a 45 second Hohmann descent injection maneuver and is given in figure 5a. All IMU alignments were performed 15 minutes prior to the thrusting maneuvers. The correlation between the LM and CSM errors was considered in determining the relative state errors.

The LM initial covariance matrix for the ascent phase is that resulting from the nominal powered descent for the PGNCS position errors and zero for the velocity errors (see figure 5b).

The specification values for the PGNCS hardware errors were obtained from reference 4; however, the accelerometer bias used in this analysis is one-fourth the specification value. The AGS hardware specification values used are given in Appendix A and reference 5.

A LM instantaneous locally level inertial coordinate system is defined at each point in the trajectory with z axis parallel to the radius vector, y parallel to the angular momentum vector, and x completing the right hand system (see figure 6). This coordinate system is used to express the error data in figures 7a through 10c.

RESULTS

For all four reference trajectories, the AGS out-of-plane velocity error is approximately twice that of the PGNCS at thrust termination. The same ratio is true at termination for the downrange velocity error (except for the 25k abort) and for the altitude velocity error (except for both aborts). In these three excepted cases, the errors in the two systems are approximately equal. For the error sources and error source magnitudes used in this study, the initial misalignment and gyro drifts are the major contributors to the LM state vector errors.

ANALYSIS OF VELOCITY ERRORS

The velocity errors increase linearly (as expected) during LM powered ascent and descent figures (7a and 10a). However, for the abort trajectories, the LM y and z velocity errors (figures 8a and 9a) increase and then start decreasing at the abort point. Because the misalignment of the sensors about the y and z axes are the dominant error source, an explanation of the velocity error caused by misalignments is given.

For both systems, the acceleration error resulting from the misalignments is

$$Ax = |\underline{A}| \; \phi y \sin \gamma$$

$$Ay = -|\underline{A}| \; (\phi x \sin \gamma + \phi z \cos \gamma)$$

$$Az = |\underline{A}| \; \phi y \cos \gamma$$

where

Ax, Ay, Az - are the accelerometer component errors

$|\underline{A}|$ - is the magnitude of the thrust acceleration

ϕ x, ϕ y, ϕ z - are the misalignments abort, x, y, z, respectively

γ - is the angle between the thrust vector and landing site downrange axis

During the powered descent and abort maneuvers, the pitch angle, γ, varies from an initial value of -193 degrees to a final value of + 10 degrees. The thrust is essentially along the x inertial axis (inertial coordinate system is locally level at the landing site), and is approximately - 180 or 0 degrees for a large portion of the trajectory. Therefore, during the trajectory sin $\gamma \approx 0$, cos γ changes sign at the abort point, and

Ax is small

$$Ay \quad \pm \; |\underline{A}| \; \phi z$$

$$Az \quad \pm \; |\underline{A}| \; \phi y \, .$$

The last two expressions explain the negative slope of the y and z velocity error starting at the abort point.

ANALYSIS OF THE ALTITUDE RATE AND RANGE RATE ERRORS (see figures 7c, 8c, 9c, 10c).

The altitude rate and range rate error equations are derived in Appendix B. The mean-squared error for altitude rate can be written

$$\sigma_{\dot{h}}^2 = \left[\frac{Vx}{R}, 1\right] \overset{*}{M} \begin{bmatrix} \frac{Vx}{R} \\ 1 \end{bmatrix}$$

Where Vx/R is the angular rate of change of the unit radius vector (rad/sec)

$$\overset{*}{M} = \begin{bmatrix} \sigma_x^2 & \sigma_{x\dot{z}} \\ \sigma_{x\dot{z}} & \sigma_{\dot{z}}^2 \end{bmatrix}$$ - covariance matrix for down range position error and radial velocity error

The range rate mean squared error is expressed similarly as

$$\sigma_{\dot{\rho}}^2 = \left[\frac{Vx}{}, 1\right] \overset{*}{N} \begin{bmatrix} \frac{Vx}{\rho} \\ 1 \end{bmatrix}$$

where

Vx/ρ is the relative line of sight rate

$\overset{*}{N}$ is the two by two covariance matrix for relative range error and velocity error along the in-plane normal to relative range.

The altitude rate error follows the general shape of the z velocity error, but is smaller in magnitude because the correlation terms reduce the total error.

POWERED FLIGHT PARTIAL DERIVATIVES

Figures 11 through 14 (PGNCS) and figures 15 through 18 (AGS) show the matrices of partial derivatives of the LM state vector with respect to each inertial sensor error. Each matrix element represents the contribution of a particular unit error source to the position and velocity error at thrust termination. The effect of changes in sensor performance or specification can be evaluated rapidly with these matrices.

COVARIANCE MATRICES

Figures 19a through 22b exhibit the LM state covariance matrix at thrust termination of each of the four reference trajectories. The PGNCS covariance matrix is shown in part "a" of each figure, while the AGS covariance matrix is shown in part "b". These covariance matrices are included merely to serve as initial conditions for future analysis of the orbital phasing and rendezvous navigation problem.

CONCLUDING REMARKS

A linearized error analysis for both an inertial platform system and a strapdown inertial system has been performed. Plots comparing the relative accuracy of the PGNCS and AGS are provided, and show that the standard deviation of the position and velocity errors of the two systems propagate similarly.

The misalignment of the inertial sensors with respect to the desired orientation is the dominant error source in the two systems. Gyro drift is also significant error source because the platform is aligned 15 minutes prior to the start of powered descent.

APPENDIX A

DERIVATION OF LM AGS NAVIGATION ERROR EQUATIONS

The basic equations required are those describing a thrusting vehicle in an inverse square central force field, and the matrix differential equation describing the instantaneous orientation of the vehicle with respect to some arbitrarily chosen inertial coordinate system.

These equations are

$$\ddot{\underline{R}} = -\frac{\mu}{|\underline{R}|^3}\underline{R} + T\,\underline{A}_B \tag{A1}$$

and

$$\dot{T} = T\,W \tag{A2}$$

$\underline{R}$ - Position vector of the vehicle in computation coordinates

$\underline{A}_B$ - Thrust acceleration vector in body coordinates

T - Transformation matrix from body to computation coordinates

$$W = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix}$$ - vehicular angular rates in body coordinates

Equation (A2) is derived as follows:

The transformation from computational to body coordinates is

$$T^{-1} = [\underline{u}_1, \underline{u}_2, \underline{u}_3] \tag{A3}$$

where $\underline{u}_i$ are the unit vectors forming the basis for the computational coordinate system. The derivative of $\underline{u}_i$ can be expressed as

$$\left.\frac{d\underline{u}_i}{dt}\right|_C = \left.\frac{d\underline{u}_i}{dt}\right|_B + \underline{\omega} \times \underline{u}_i \tag{A4}$$

Since $\underline{u}_i$ is fixed with respect to the computational system,

$$\left.\frac{d\underline{u}_i}{dt}\right|_C = 0 \tag{A5}$$

Therefore

$$\left.\frac{d\underline{u}_i}{dt}\right|_B = -\underline{\omega} \times \underline{u}_i \tag{A6}$$

or
$$\left.\frac{d\underline{u}_i}{dt}\right|_B = -W\,\underline{u}_i \tag{A7}$$

where W is a cross-product matrix.

Substituting equation (A3) and its derivative

$$\dot{T}^{-1} = -W\,T^{-1} \tag{A8}$$

so that

$$\dot{T} = T\,W$$

since T is orthogonal and W is skew symmetric.

To derive the error equations, equations (A1) and (A2) are perturbed so that

$$\Delta\ddot{\underline{R}} = \mu|\underline{R}|^{-5}(3\underline{R}\,\underline{R}^T - |\underline{R}|^2 I)\Delta\underline{R} + (\Delta T)\underline{A}_B + T\,\Delta\underline{A}_B \tag{A9}$$

and

$$\Delta\dot{T} = (\Delta T)\,W + T\,\Delta W \tag{A10}$$

where

$$\Delta\underline{A}_B = K\,\underline{e}_a \tag{A11}$$

$$\Delta W = \sum_{i=1}^{n} D_i\,e_{gi} \tag{A12}$$

$\underline{e}_a$ - $(n \times 1)$ accelerometer error vector

e_{gi} - i^{th} gyro error source

K - $(3 \times n)$ matrix of partials of acceleration with respect to accelerometer errors

D_i - (3×3) matrices of partials of angular rate with respect to the i^{th} gyro error.

The transformation error ΔT induced by angular rate errors at any time t is

$$\Delta T = \sum_{i=1}^{n} M_i\,e_{gi} \tag{A13}$$

where
$$\dot{M}_i = M_i W + T D_i\,, \quad M_i(0) = 0 \tag{A14}$$

The homogeneous solution of equation (A13) can be written

$$\Delta T = T \Phi \qquad (A15)$$

where Φ is a skew symmetric matrix.

This can be obtained by considering $(T + \Delta T)$ to be an orthogonal transformation; then

$$(T + \Delta T)^T (T + \Delta T) = I \qquad (A16)$$

where $(\quad)^T$ denotes transpose.

Expanding

$$I + \Delta T T^T + T \Delta T^T + \Delta T \Delta T^T = I \qquad (A17)$$

or

$$\left.\begin{aligned} \Delta T T^T &= - T \Delta T^T \triangleq C \\ \Delta T &= C T \end{aligned}\right\} \qquad (A18)$$

$$\Delta T \Delta T^T = C^2 \approx 0 \qquad (A19)$$

This solution satisfies the differential equation (A10) if $\dot{C} = 0$, i.e.

$$\begin{aligned} \Delta \dot{T} &= \dot{C} T + C \dot{T} \\ \Delta \dot{T} &= C T W \\ \Delta \dot{T} &= \Delta T W \end{aligned} \qquad (A20)$$

When $T = I$

$$\Delta T = \begin{bmatrix} 0 & -\phi_z & \phi_y \\ \phi_z & 0 & -\phi_x \\ -\phi_y & \phi_y & 0 \end{bmatrix} \qquad (A21)$$

Since

$$\underline{A}_B \approx |\underline{A}_B| \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$\Phi T \underline{A}_B = \Phi T |\underline{A}_B| \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = |\underline{A}_B| \; \Phi \begin{bmatrix} t_{11} \\ t_{21} \\ t_{31} \end{bmatrix} \qquad \text{(A22)}$$

where t_{i1} are the first column of T.

The product of a skew symmetric matrix and a vector can be written as a vector cross product:

$$\Phi \begin{bmatrix} t_{11} \\ t_{21} \\ t_{31} \end{bmatrix} \triangleq \Phi \underline{z} = \underline{\phi} \times \underline{z} \qquad \text{(A23)}$$

Hence

$$|\underline{A}_B| \; \Phi \underline{z} = |\underline{A}_B| \; \underline{\phi} \times \underline{z} = -|\underline{A}_B| Z \underline{\phi} \qquad \text{(A24)}$$

where Z is the cross product matrix associated with $\underline{z}$.

Equation (A9) can now be written as

$$\Delta \ddot{\underline{R}} = \mu |\underline{R}|^{-5} (3 \underline{R}\underline{R}^T - |\underline{R}|^2 I) \Delta \underline{R} + TK\underline{e}_4 + G\underline{\phi} + H \underline{e}_3 \qquad \text{(A25)}$$

where

$$G = |\underline{A}_B| \begin{bmatrix} 0 & -t_{31} & t_{21} \\ t_{31} & 0 & -t_{11} \\ -t_{21} & t_{11} & 0 \end{bmatrix} \qquad \text{(A26)}$$

$$H = |\underline{A}_B| \left[M_{11}, M_{21}, \ldots M_{n1} \right] \qquad \text{(A27)}$$

where M_{i1} denotes the first column of M_i from (A14).

To write equation (A25) in state vector form, let

$$\underline{x} \triangleq \begin{bmatrix} \Delta \underline{R} \\ \Delta \dot{\underline{R}} \end{bmatrix} \qquad \text{(A28)}$$

Then

$$\dot{\underline{x}} = F\underline{x} + \overset{*}{M}\underline{e} \tag{A29}$$

where

$$F = \begin{bmatrix} 0 & I \\ \mu|\underline{R}|^{-5}(3\underline{R}\underline{R}^T - |\underline{R}|^2 I) & 0 \end{bmatrix}$$

$$\overset{*}{M} = [TK, H, G]$$

$$\underline{e} = \begin{bmatrix} \underline{e}_a \\ \underline{e}_g \\ \underline{\phi} \end{bmatrix}$$

A solution of equation (A29) is

$$\underline{x} = \psi\underline{x}_0 + P\underline{e} \tag{A30}$$

where

$$\dot{\psi} = F\psi, \quad \psi(0) = I$$

and $$\dot{P} = FP + \overset{*}{M}, \quad P(0) = 0.$$

DERIVATION C" VEHICULAR ANGULAR RATE COMPUTATION

Let $$\underline{u}_a \triangleq \frac{\underline{A}_B}{|\underline{A}_B|} \tag{A31}$$

where $\underline{u}_a$ is the unit

vector in the direction of the thrust acceleration. The rat e of change of $\underline{u}_a$ in the computation coordinate system is

$$\left.\frac{d\underline{u}_a}{dt}\right|_c = \underline{\omega}_c \times \underline{u}_a \tag{A32}$$

Crossing $\underline{u}_a$ into equation (A32),

$$\underline{u}_a \times \frac{d\underline{u}_a}{dt} = \underline{\omega}_c - (\underline{u}_a \cdot \underline{\omega})\,\underline{u}_a \tag{A33}$$

The angular rate in compuational coordinates is

$$\underline{\omega}_c = -\frac{d\underline{u}_a}{dt} \times \underline{u}_a \tag{A34}$$

Numerically, the angular rates are computed by

$$\underline{\omega}_c = \frac{\sin^{-1}|\underline{u}_{a_{n-1}} \times \underline{u}_{a_n}|}{\Delta t}\left(\frac{\underline{u}_{a_{n-1}} \times \underline{u}_{a_n}}{|\underline{u}_{a_{n-1}} \times \underline{u}_{a_n}|}\right) \tag{A35}$$

where $\underline{u}_{a_{n-1}}$ and $\underline{u}_{a_n}$ are the unit accelerations at times t_{i-1} and t_i respectively, and $\Delta t = t_i - t_{i-1}$.

The angular rate, $\underline{\omega}$, in body coordinates is

$$\underline{\omega} = T^T \underline{\omega}_c \tag{A36}$$

ERROR MODEL

Assumptions -

(1) Acceleration is essentially along the X_B(roll) axis.

(2) The error coefficients are constant during a burn.

(3) The error coefficients are statistically independent.

Accelerometer Error Model

$$\Delta \underline{A}_B = K \underline{e}_a$$

$$\begin{bmatrix} \Delta A_{Bx} \\ \Delta A_{By} \\ \Delta A_{Bz} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & A_x & A_x^2 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & A_x & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & A_x \end{bmatrix} \begin{bmatrix} B_x \\ B_y \\ B_z \\ k \\ \kappa \\ C_{yx} \\ C_{zx} \end{bmatrix}$$

Error	Definition	Values Used
$\Delta \underline{A}_B$	Acceleration error vector in body coordinates	
B_x, B_y, B_z	Accelerometer Bias	.00222 ft/sec
k	Accelerometer Scale factor	87 PPM
κ	Accelerometer Scale factor nonlinearity	58 $\frac{\text{PPM}}{\text{ft/sec}^2}$
C_{yx}, C_{zx}	Accelerometer cross axis sensitivities	68 $\widehat{\text{sec}}$

Note the omission of y axis and z axis scale factors and cross axis sensitivities. This is due to there being virtually no acceleration sensed along these axes.

Angular Rate Error Model

$$\begin{bmatrix} \Delta \omega_x \\ \Delta \omega_y \\ \Delta \omega_z \end{bmatrix} \quad \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \end{bmatrix} + \begin{bmatrix} T_x \omega_x \\ T_y \omega_y \\ T_z \omega_z \end{bmatrix} + (XSAU) A_x + (AN) A_x^2 + \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix} \cdot \begin{bmatrix} \phi_{x0} \\ \phi_{y0} \\ \phi_{z0} \end{bmatrix}$$

Error	Definition	Values Used
$\Delta\omega_x$, $\Delta\omega_y$, $\Delta\omega_z$	Angular rate error	
ϵ_x, ϵ_y, ϵ_z	gyro constant drift	.28 deg/hr
T_x, T_y, T_z	gyro torquer scale factor error	.38 PPM
X5AU	x gyro spin axis unbalance	.13 deg/hr/g
AN	x gyro anisoelasticity	0 deg/hr/g
ϕ_{x0}, ϕ_{y0}, ϕ_{z0}	initial misalignment	250 sec

As in the accelerometer model, the acceleration sensitive errors in the y and z gyros were dismissed as zero.

APPENDIX B

DERIVATION OF LM ALTITUDE AND ALTITUDE RATE ERRORS

Let the inertial coordinate system origin be at the center of the moon such that the altitude of the LM (including the mean lunar radius) is given by

$$h = \underline{u}_R^T \underline{R} \tag{B1}$$

where

$\underline{R}$ = LM radius vector

$\underline{u}_R$ = unit vector of $\underline{R}$

The differential for h is given by

$$\Delta h = \Delta \underline{u}_R^T \underline{R} + \underline{u}_R^T \Delta \underline{R} \tag{B2}$$

where

$$\Delta \underline{u}_R^T = \Delta \left(\frac{\underline{R}^T}{h} \right) = \frac{\Delta \underline{R}^T}{h} - \frac{\underline{R}^T}{h^2} \Delta h \tag{B3}$$

so that

$$\Delta h = \underline{u}_R^T \Delta \underline{R} \tag{B4}$$

The mean squared error in h is given by

$$E\left\{ \Delta h^2 \right\} = E\left\{ \underline{u}_R^T \Delta \underline{R} \, \Delta \underline{R}^T \underline{u}_R \right\} \tag{B5}$$

$$\sigma_h^2 = \underline{u}_R \, E\left\{ \Delta \underline{R} \, \Delta \underline{R}^T \right\} \underline{u}_R \tag{B6}$$

$$\sigma_h^2 = \underline{u}_R^T \, \overset{*}{C}_R \, \underline{u}_R \tag{B7}$$

where $\overset{*}{C}_R$ is the covariance matrix for LM position.

A simplification can be made for σ_h^2 is the LM position vector is defined in an instantaneously local level system:

$$\underline{R}^T = [0, 0, R] \qquad \underline{u}_R^T = [0, 0, 1] \tag{B8}$$

Thus

$$\sigma_h^2 = [0, 0, 1] \begin{bmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} \\ \sigma_{xy} & \sigma_y^2 & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z^2 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{B9}$$

$$\sigma_h^2 = \sigma_z^2 \tag{B10}$$

Since altitude rate is the projection of LM velocity on the LM radius vector, it may be written as

$$\dot{h} = \underline{u}_R^T \dot{\underline{R}} \tag{B11}$$

The first order differential for $\dot{h}$ is given by

$$\Delta \dot{h} = \Delta \underline{u}_R^T \dot{\underline{R}} + \underline{u}_R^T \Delta \dot{\underline{R}} \tag{B12}$$

and making the following substitutions,

$$\Delta \underline{u}_R^T = \frac{\Delta \underline{R}^T}{h} - \frac{\underline{R}^T}{h^2} \Delta h$$

$$\Delta h = \underline{u}_R^T \Delta \underline{R} \tag{B13}$$

$$\left[\frac{\dot{\underline{R}}}{h} - \frac{\underline{u}_R^T \dot{\underline{R}}}{h} \underline{u}_R \right]^T = (\dot{\underline{u}}_R)^T$$

the final relation is

$$\Delta \dot{h} = \dot{\underline{u}}_R^T \Delta \underline{R} + \underline{u}_R^T \Delta \dot{\underline{R}} \tag{B14}$$

Hence the mean squared error for altitude rate is

$$E\left\{\Delta\dot{h}^2\right\} = E\left\{\left[\underline{\dot{u}}_R^T, \underline{u}_R^T\right]\begin{bmatrix}\Delta \underline{R} \\ \Delta \underline{\dot{R}}\end{bmatrix}\left[\Delta \underline{R}, \Delta \underline{\dot{R}}\right]\begin{bmatrix}\underline{\dot{u}}_R \\ \underline{u}_R\end{bmatrix}\right\} \quad \text{(B15)}$$

$$\sigma_{\dot{h}}^2 = \left[\underline{\dot{u}}_R^T, \underline{u}_R^T\right] E\left\{\begin{bmatrix}\Delta \underline{R} \\ \Delta \underline{\dot{R}}\end{bmatrix}\left[\Delta \underline{R}, \Delta \underline{\dot{R}}\right]\right\}\begin{bmatrix}\underline{\dot{u}}_R \\ \underline{u}_R\end{bmatrix} \quad \text{(B16)}$$

$$\sigma_{\dot{h}}^2 = \left[\underline{\dot{u}}_R^T, \underline{u}_R^T\right] \overset{*}{C}_{RV} \begin{bmatrix}\underline{\dot{u}}_R \\ \underline{u}_R\end{bmatrix} \quad \text{(B17)}$$

where $\overset{*}{C}_{RV}$ is the LM state covariance.

In the instantaneously local level system

$$\left[\underline{\dot{u}}_R^T, \underline{u}_R^T\right] = \left[\frac{V_x}{R}, 0, 0, 0, 0, 1\right] \quad \text{(B18)}$$

where $\frac{V_x}{R}$ is horizontal velocity divided by radius magnitude.

Thus $$\sigma_{\dot{h}}^2 = \left[\frac{V_x}{R}, 1\right]\begin{bmatrix}\sigma_{\dot{x}}^2 & \sigma_{\dot{x}\dot{z}} \\ \sigma_{\dot{x}\dot{z}} & \sigma_{\dot{z}}^2\end{bmatrix}\begin{bmatrix}\frac{V_x}{R} \\ 1\end{bmatrix} \quad \text{(B19)}$$

LM-CSM RELATIVE RANGE - RELATIVE RANGE RATE ERRORS

Since range and range rate between the LM and CSM are defined in an identical manner to LM altitude and altitude rate, respectively, the relative error equations are identical to the altitude equations:

$$\sigma_{\rho}^2 = \underline{u}_\rho^T \overset{*}{C}_\rho \underline{u}_\rho \quad \text{(B20)}$$

$$\sigma_{\dot{\rho}}^2 = \left[\underline{\dot{u}}_\rho^T, \underline{u}_\rho^T\right] \overset{*}{C}_{\rho\dot{\rho}} \begin{bmatrix}\underline{\dot{u}}_\rho \\ \underline{u}_\rho\end{bmatrix} \quad \text{(B21)}$$

where

$\sigma_\rho^{\,2}$ = mean-squared error in range

$\sigma_{\dot\rho}^{\,2}$ = mean-squared error in range-rate

$\underline{u}_\rho$ = unit relative range vector

$\dot{\underline{u}}_\rho$ = line-of-sight rate vector in the plane of motion

$\overset{*}{C}_\rho$ = relative range covariance matrix

$\overset{*}{C}_{\rho\dot\rho}$ = relative state covariance matrix

A simplification analogous to the altitude locally level transformation can be made if a "relative locally level system" is defined with z along the relative range vector and y is perpendicular to the relative velocity vector.

$$\sigma_{\dot\rho}^{\,2} = \begin{bmatrix} \frac{V_x}{\rho} & , & 1 \end{bmatrix} \begin{bmatrix} \sigma_x^{\,2} & \sigma_{x\dot z} \\ \sigma_{x\dot z} & \sigma_{\dot z}^{\,2} \end{bmatrix} \begin{bmatrix} \frac{V_x}{\rho} \\ 1 \end{bmatrix} , \qquad \text{(B22)}$$

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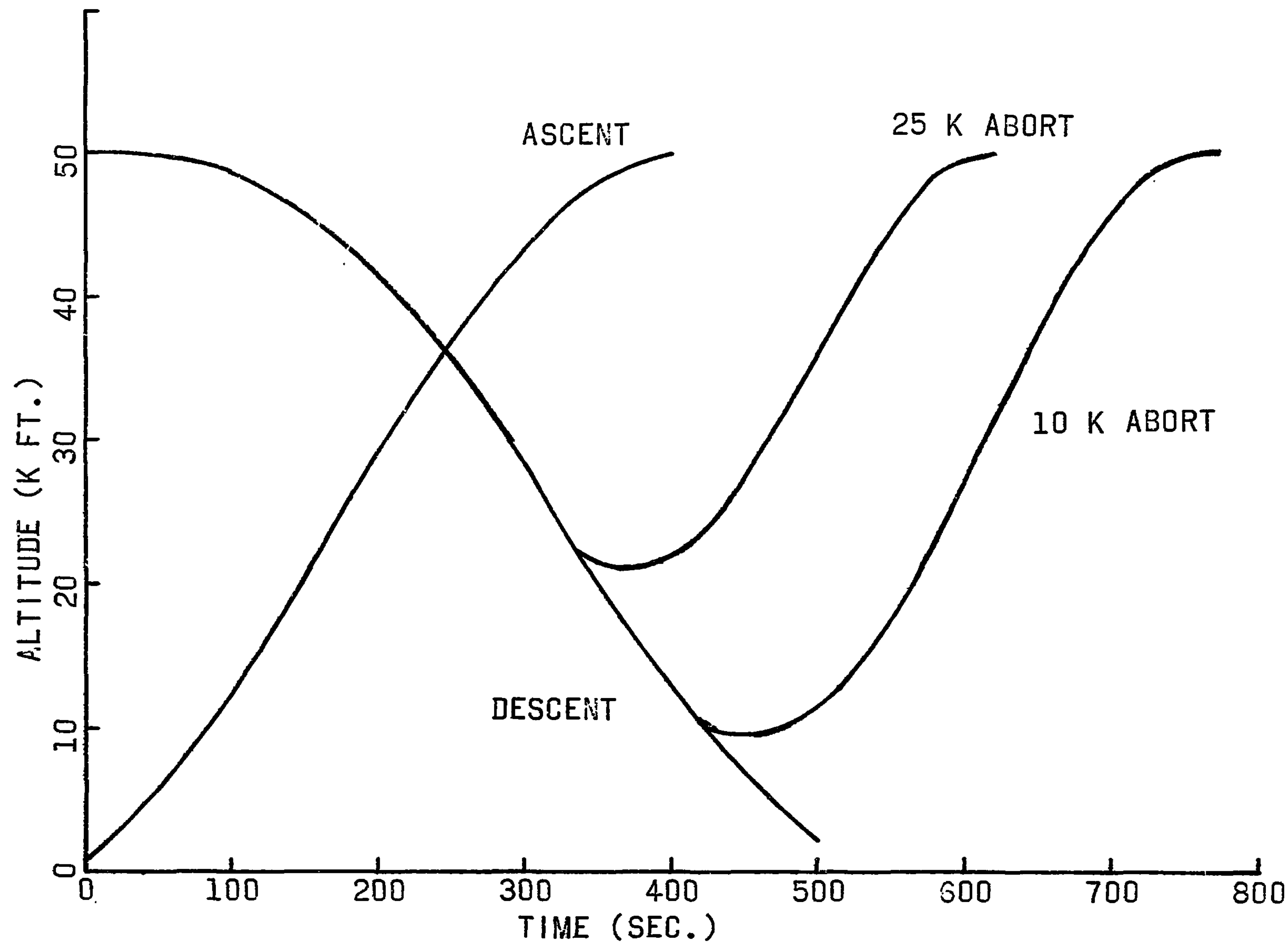

FIGURE 1 LM ALTITUDE

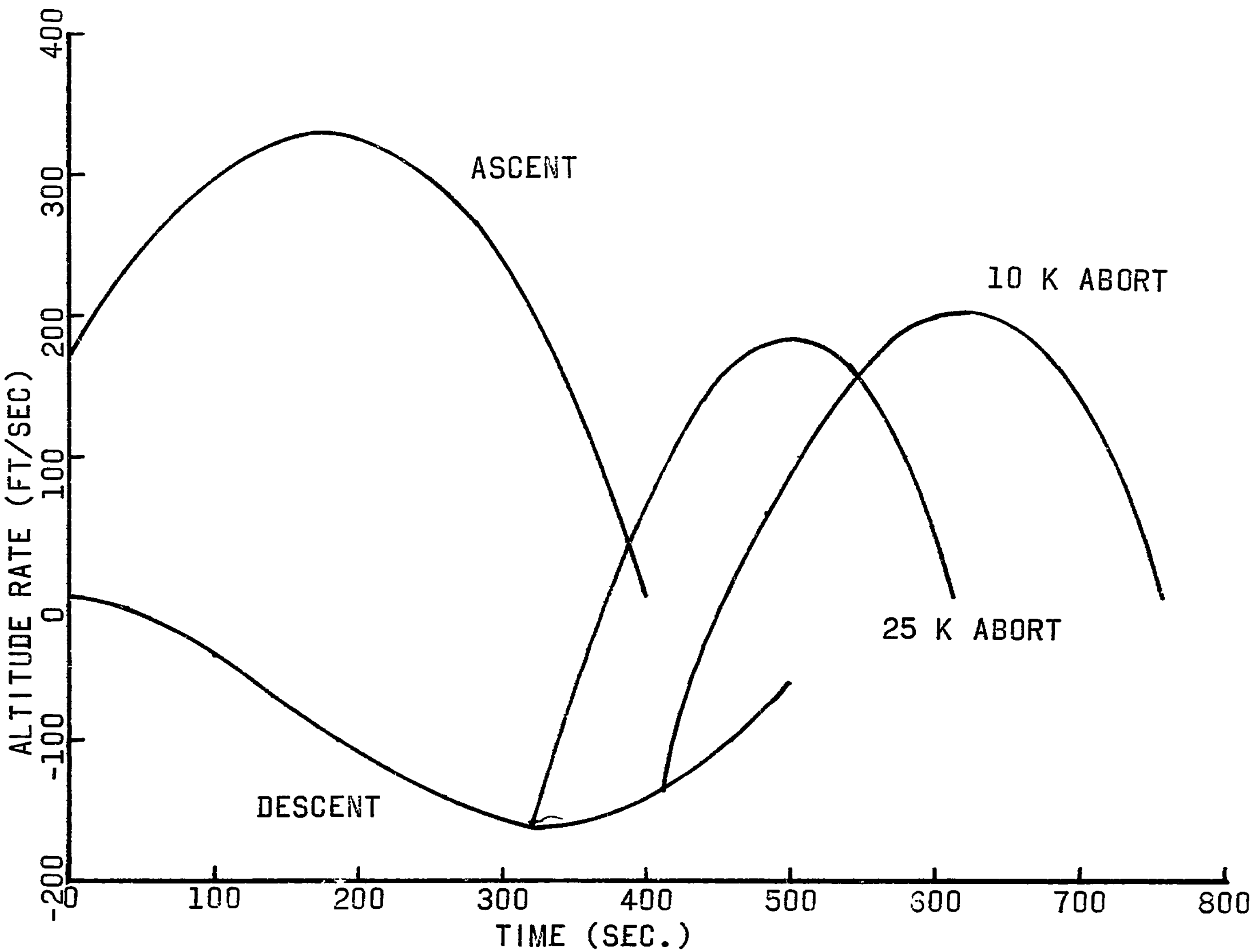

FIGURE 2 LM ALTITUDE RATE

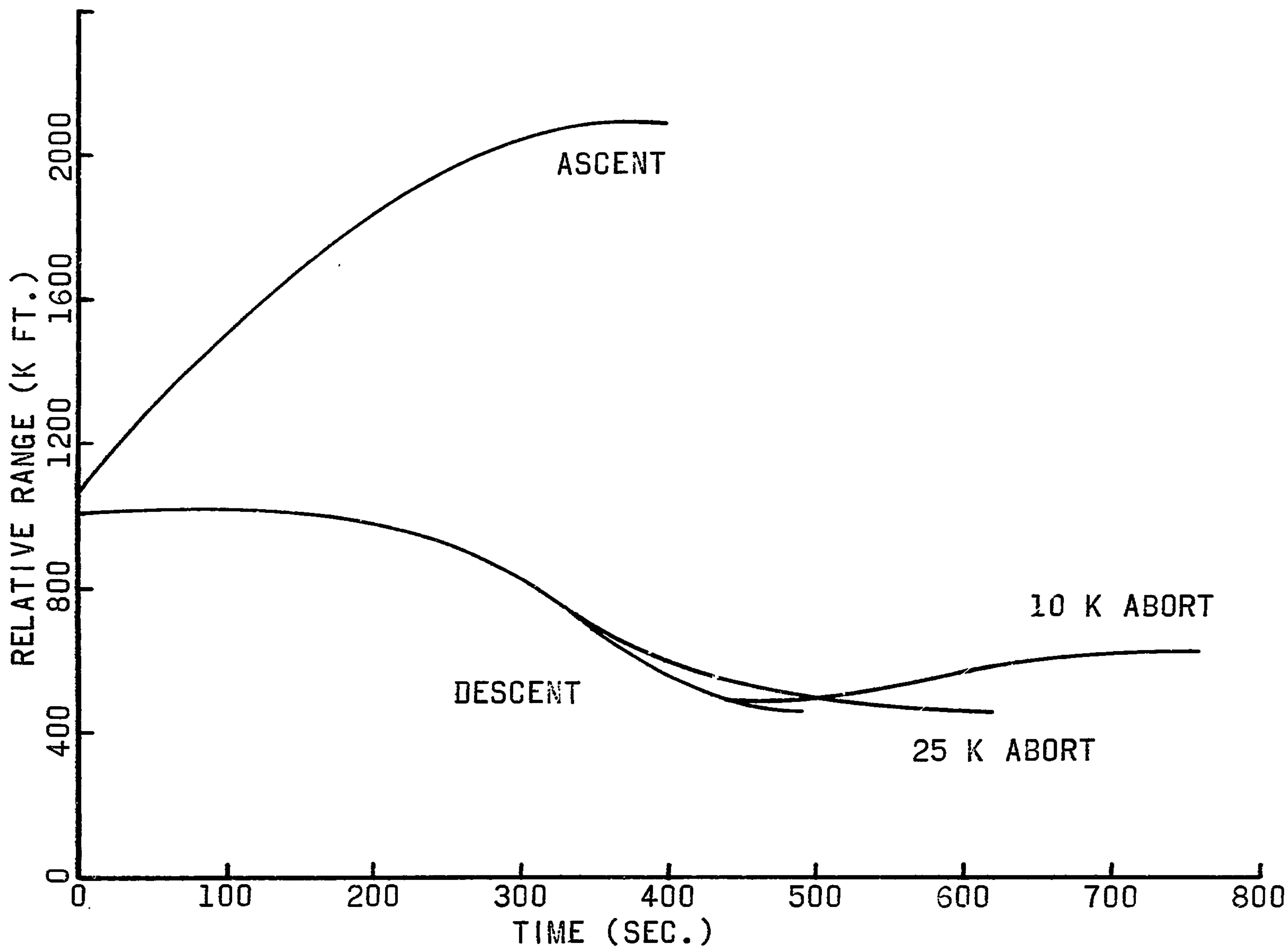

FIGURE 3 LM-CSM RELATIVE RANGE

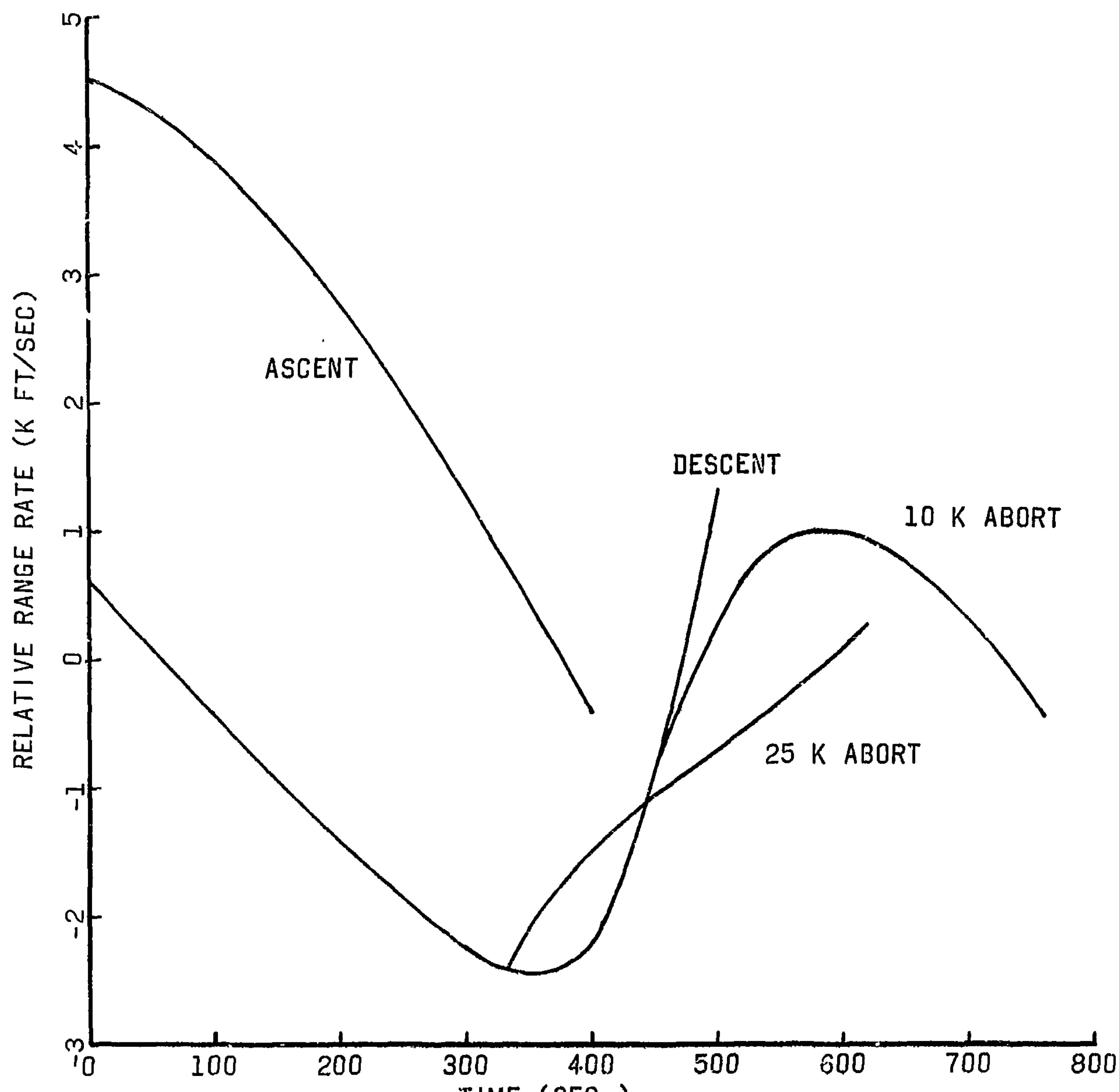

FIGURE 4 LM-CSM RELATIVE RANGE RATE

5600101.	-19857.	-514152.	264.	43.	-5964.
	169367.	- 20108.	19.	-75.	18.
		482981.	-403.	-25.	518.
			0.	0.	0.
(SYMMETRIC)				1.	0.
					7.

(A) NOMINAL DESCENT

6200098.	0.	0.	0.	0.	0.
	2357287.	0.	0.	0.	0.
		3910636.	0.	0.	0.
			0.	0.	0.
(SYMMETRIC)				0.	0.
					0.

(B) NOMINAL ASCENT

FIGURE 5 LM INITIAL COVARIANCE MATRICES

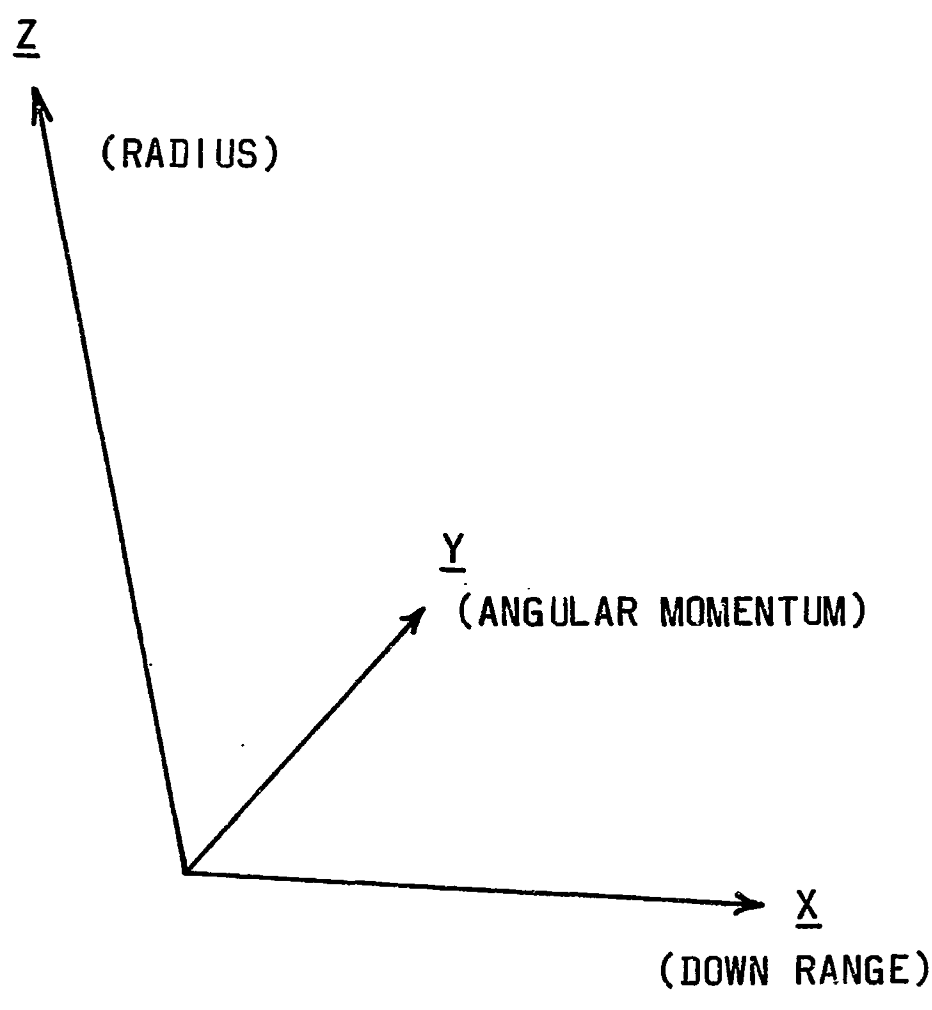

FIGURE 6 LOCALLY LEVEL COORDINATE SYSTEM

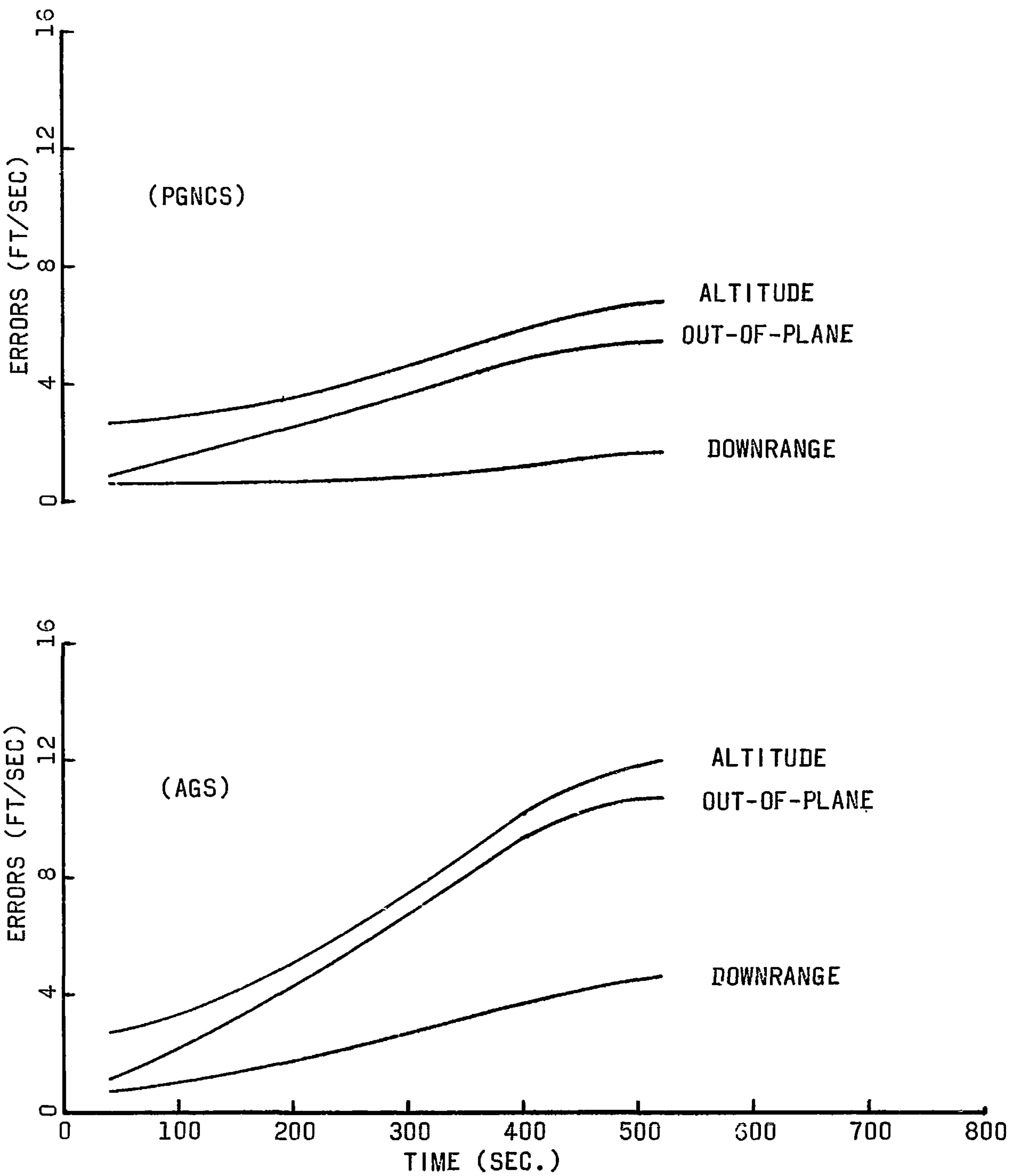

FIGURE 7A LM VELOCITY ERRORS (NOMINAL DESCENT)

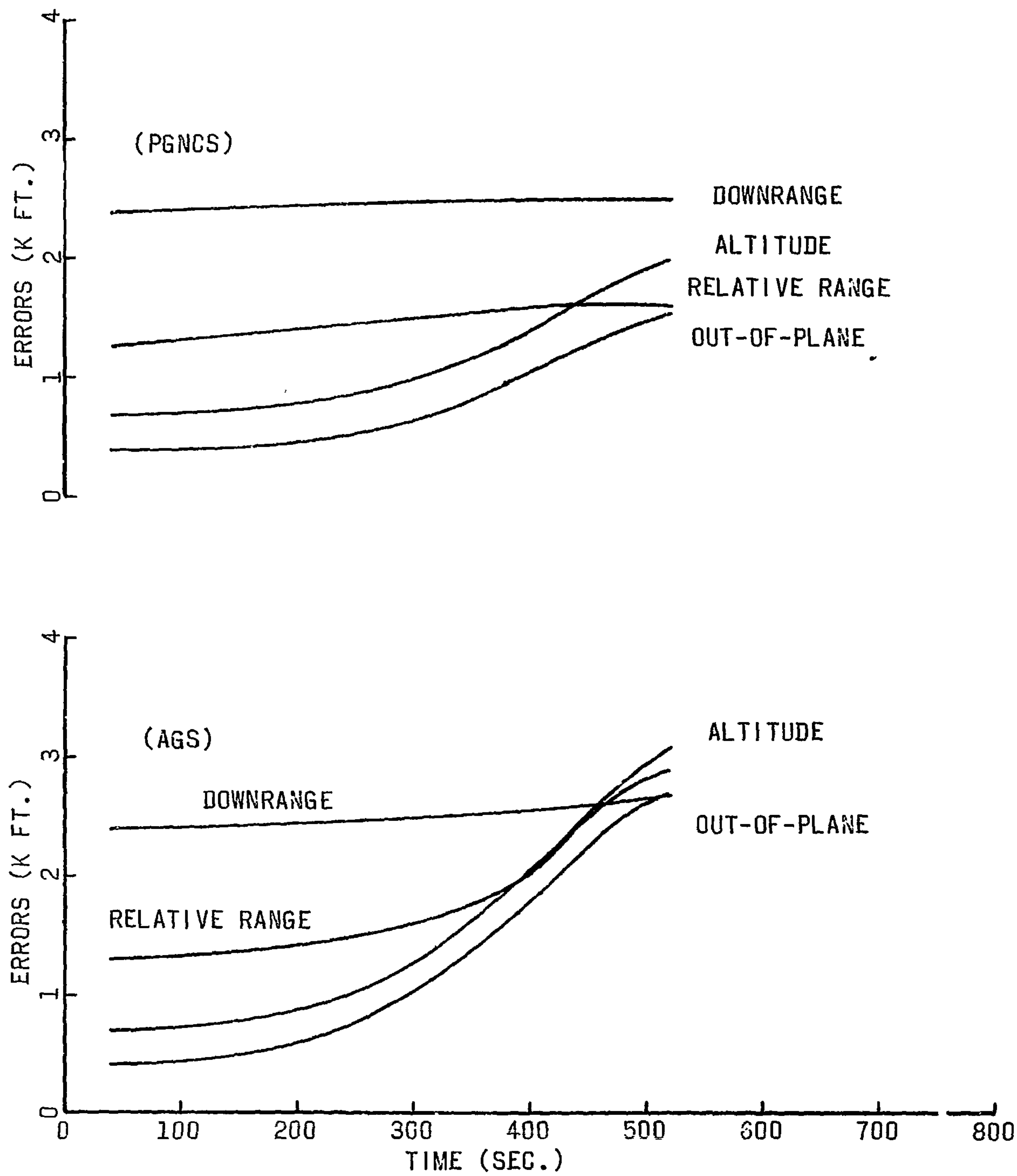

FIGURE 7B LM POSITION AND RELATIVE RANGE ERRORS

(NOMINAL DESCENT)

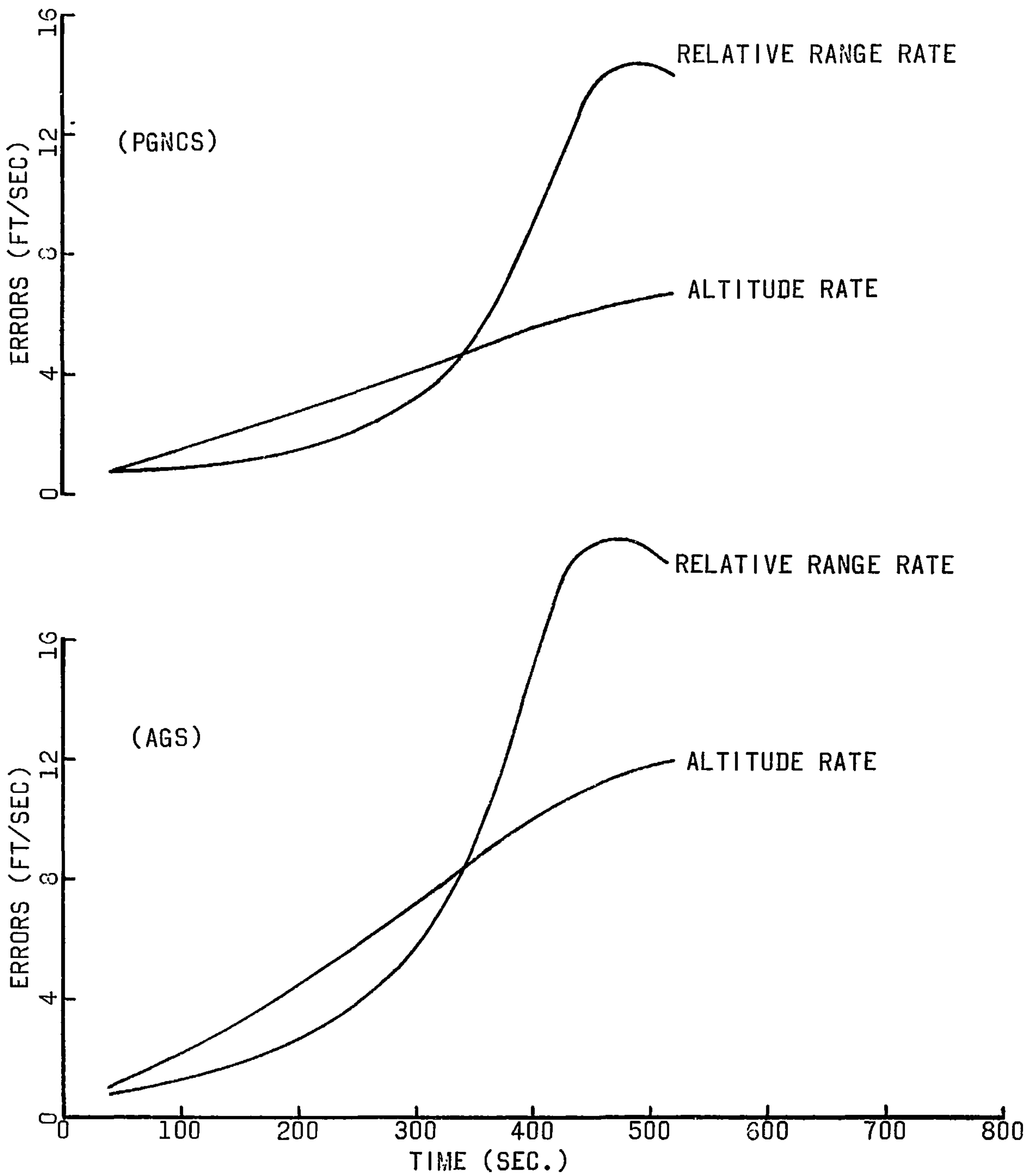

FIGURE 7C RELATIVE RANGE RATE AND ALTITUDE RATE ERRORS (NOMINAL DESCENT)

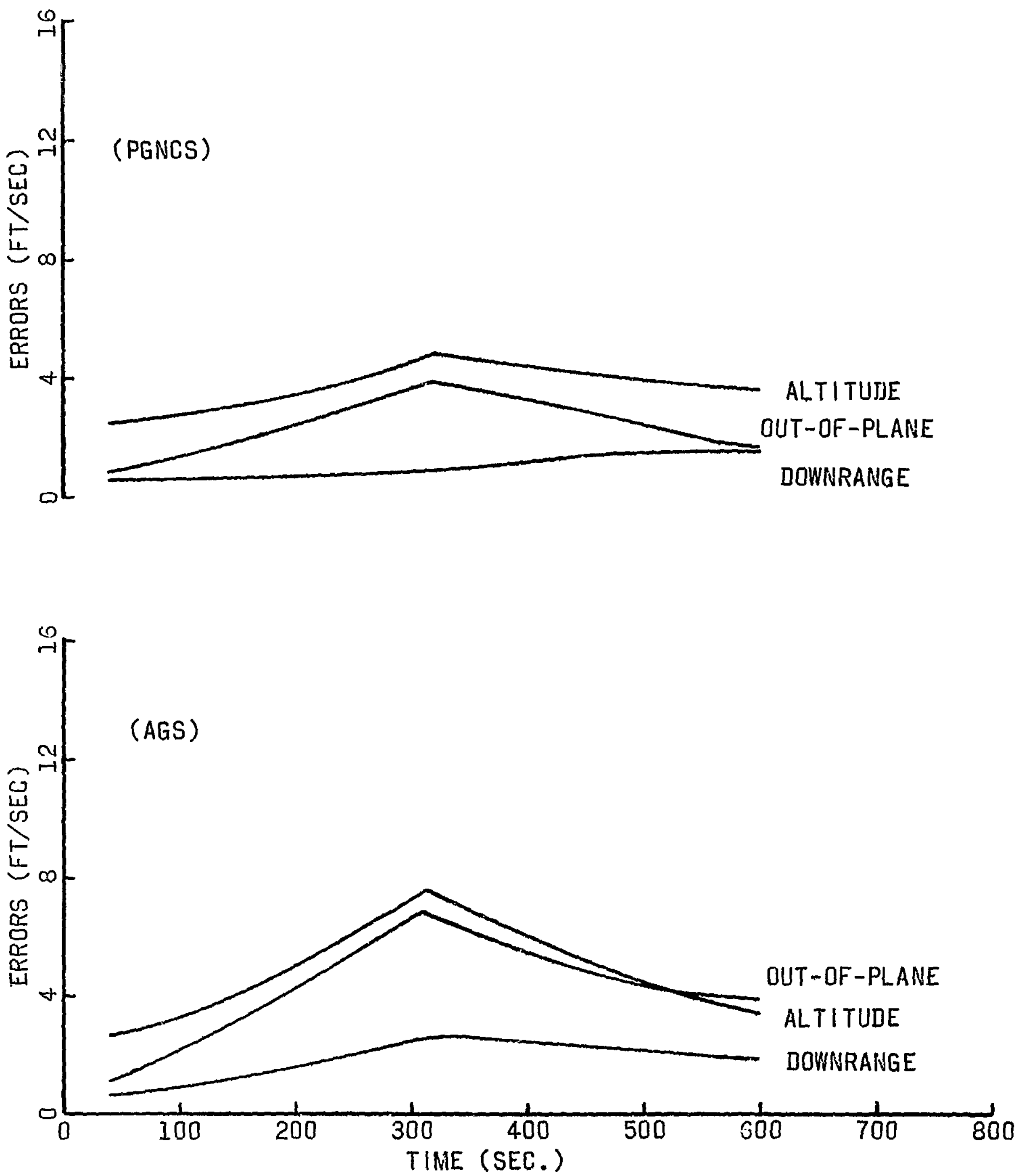

FIGURE 8A LM VELOCITY ERRORS (25,000 FT ABORT)

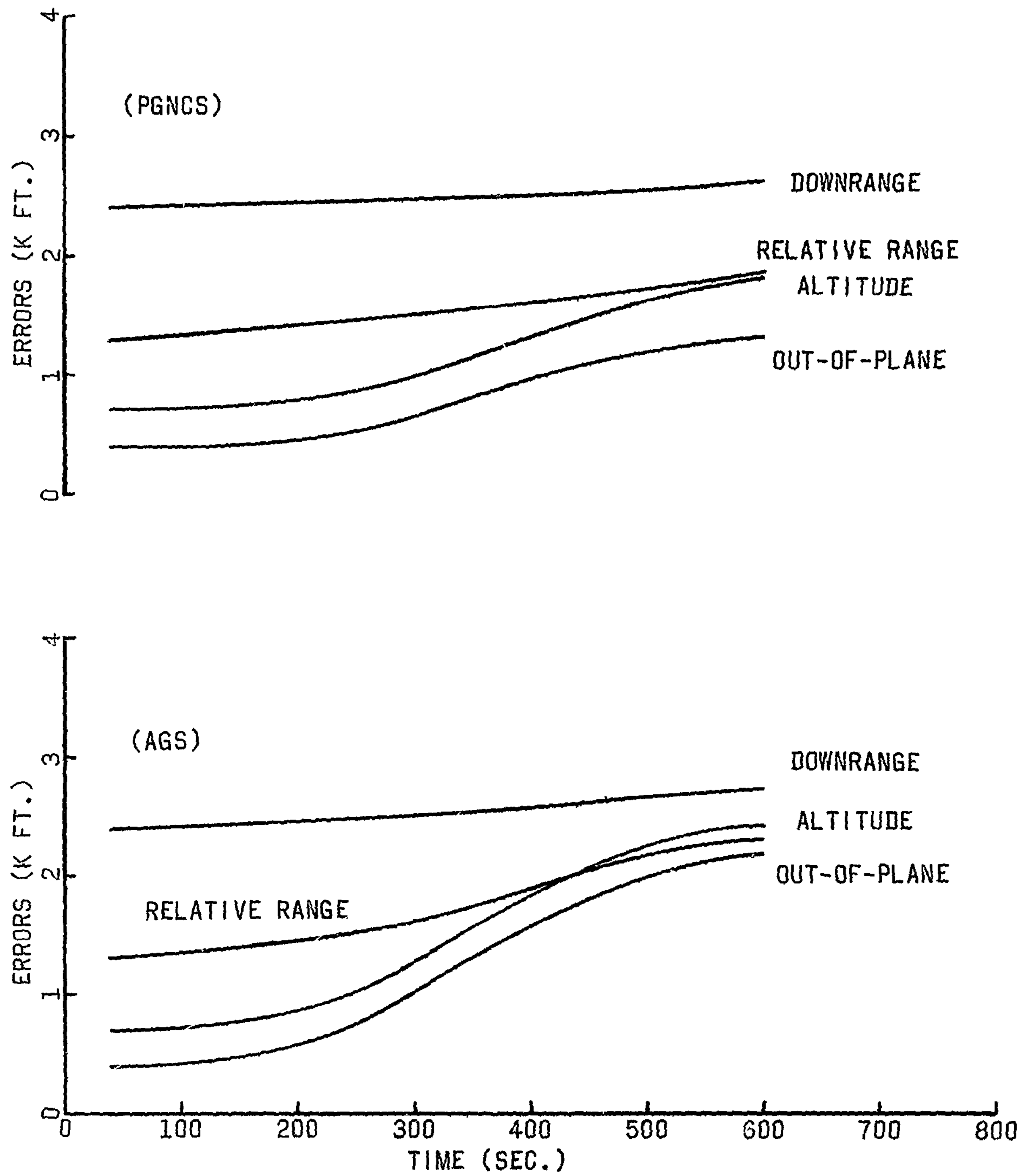

FIGURE 8B LM POSITION AND RELATIVE RANGE ERRORS
(25,000 FT ABORT)

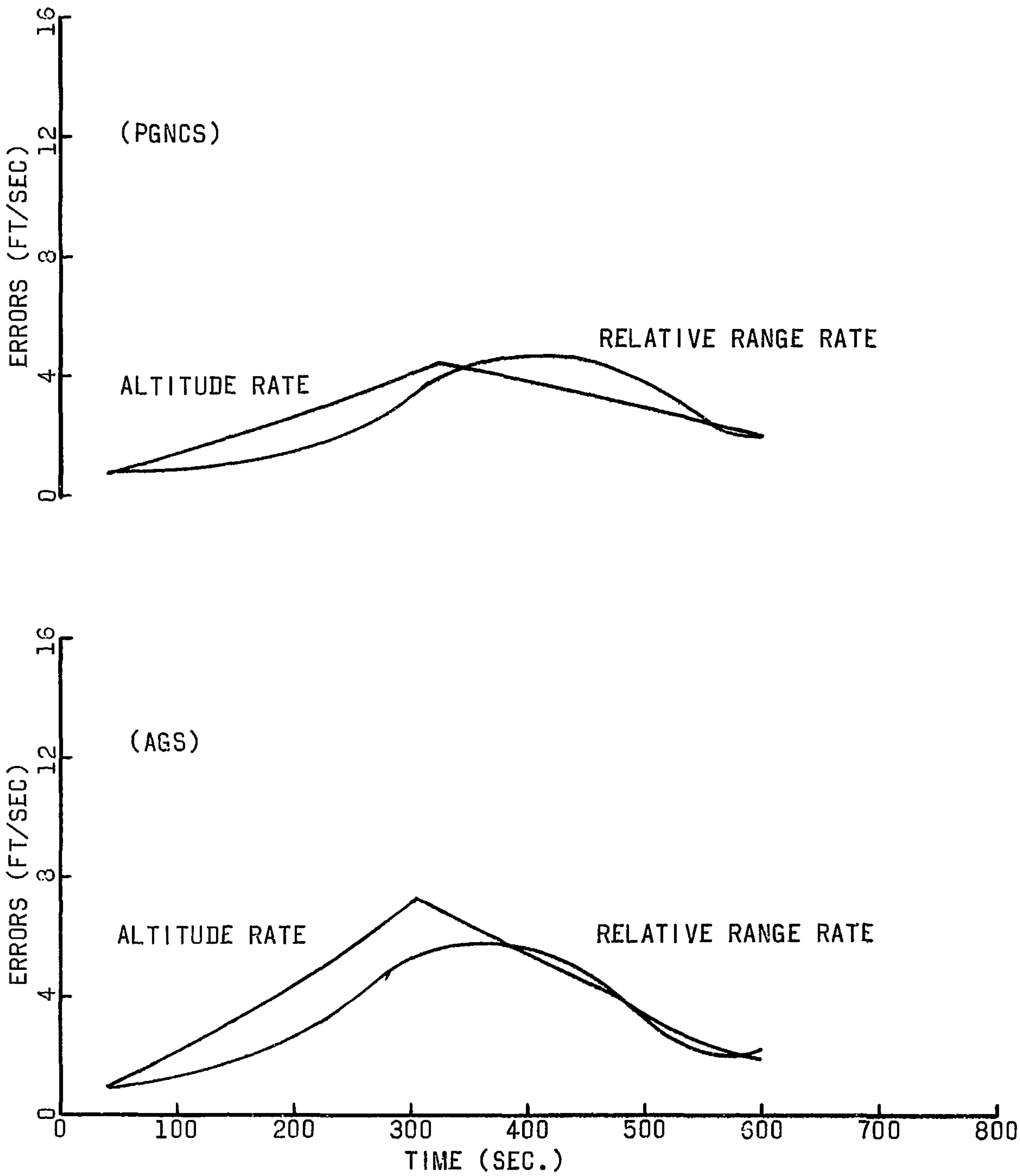

FIGURE 8C RELATIVE RANGE RATE AND ALTITUDE RATE ERRORS
(25,000 FT ABORT)

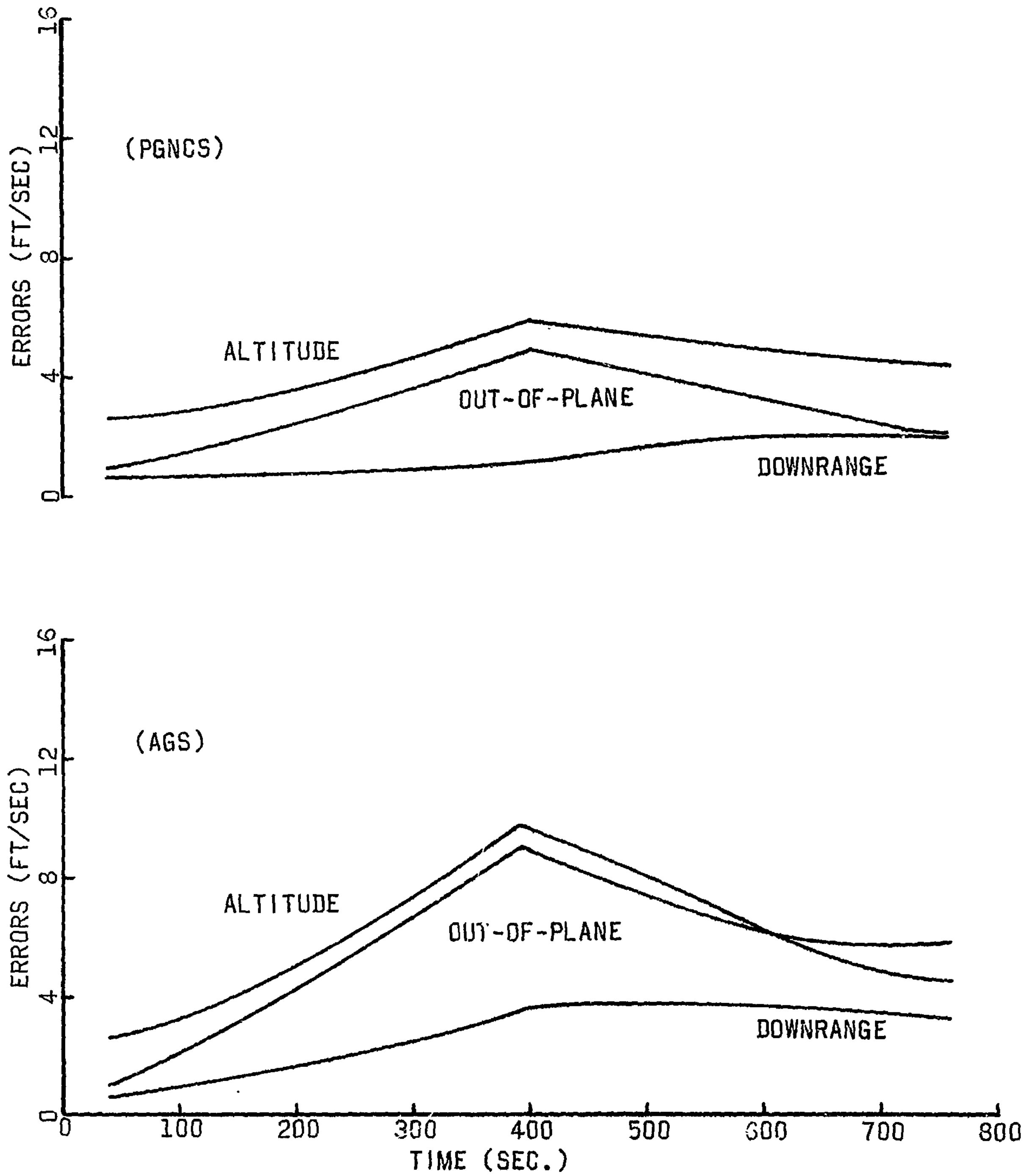

FIGURE 9A LM VELOCITY ERRORS (10,000 FT ABORT)

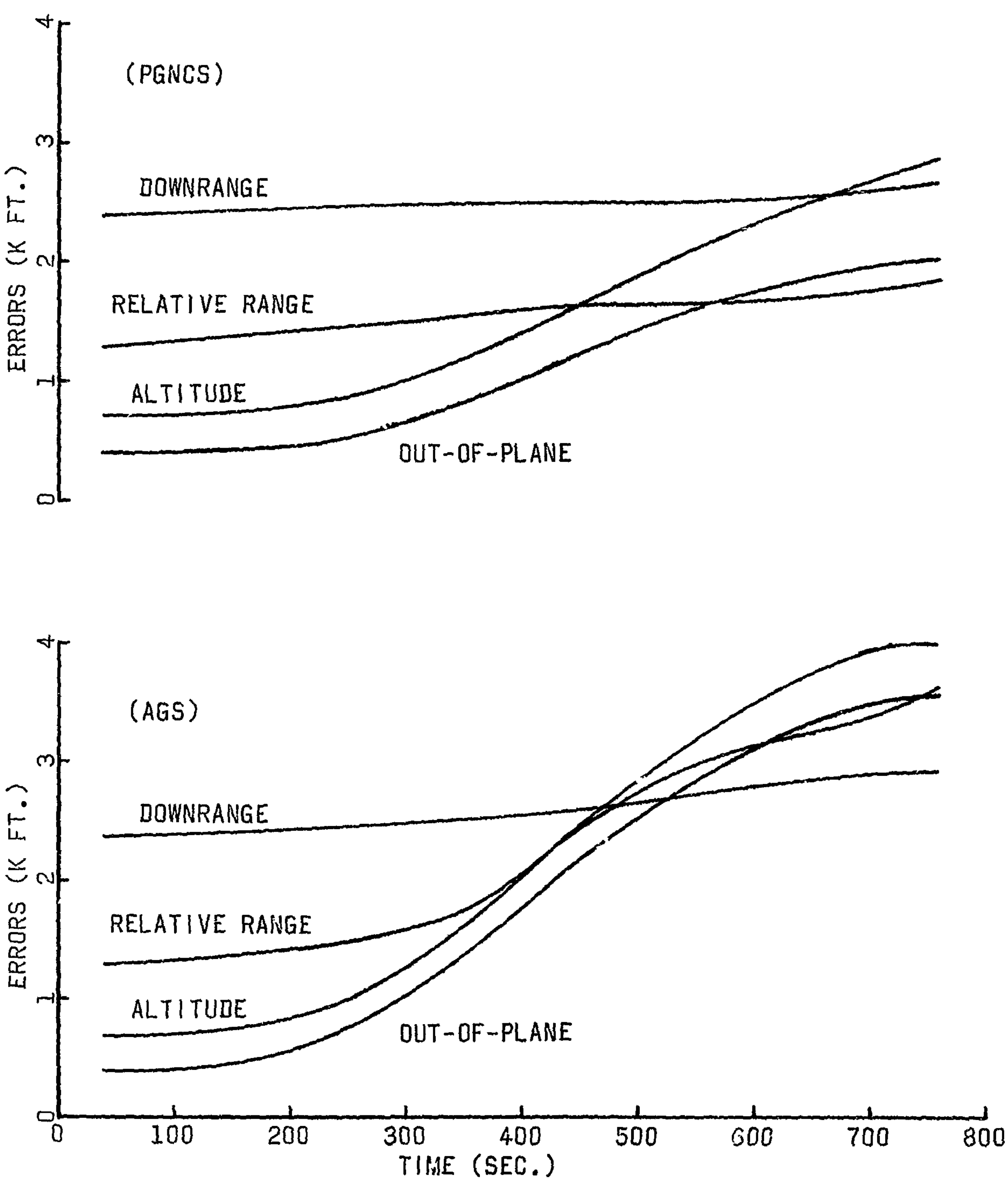

FIGURE 9B LM POSITION AND RELATIVE RANGE ERRORS (10,000 FT ABORT)

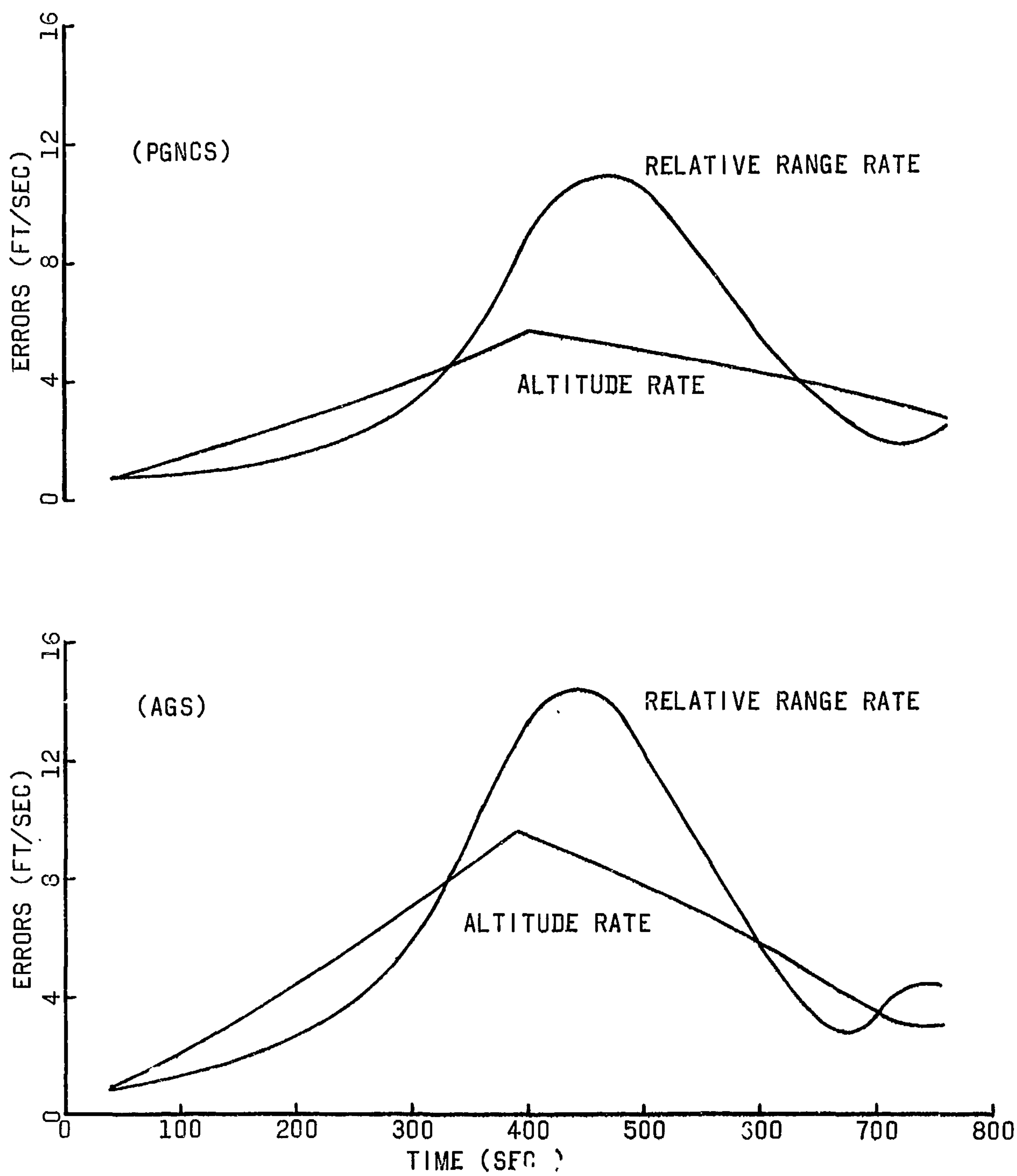

FIGURE 9C RELATIVE RANGE RATE AND ALTITUDE RATE ERRORS
(10,000 FT ABORT)

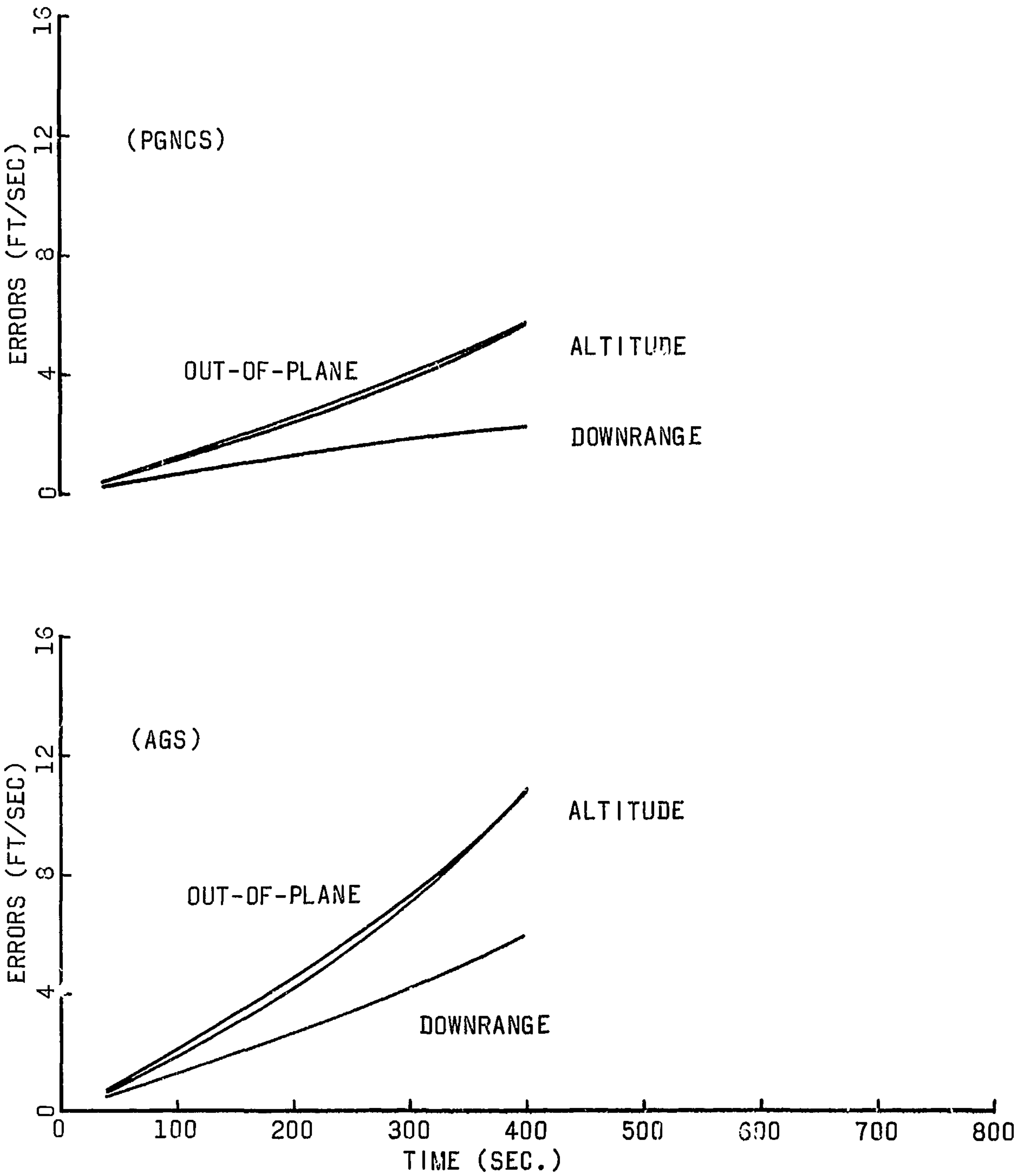

FIGURE 10A LM VELOCITY ERRORS (NOMINAL ASCENT)

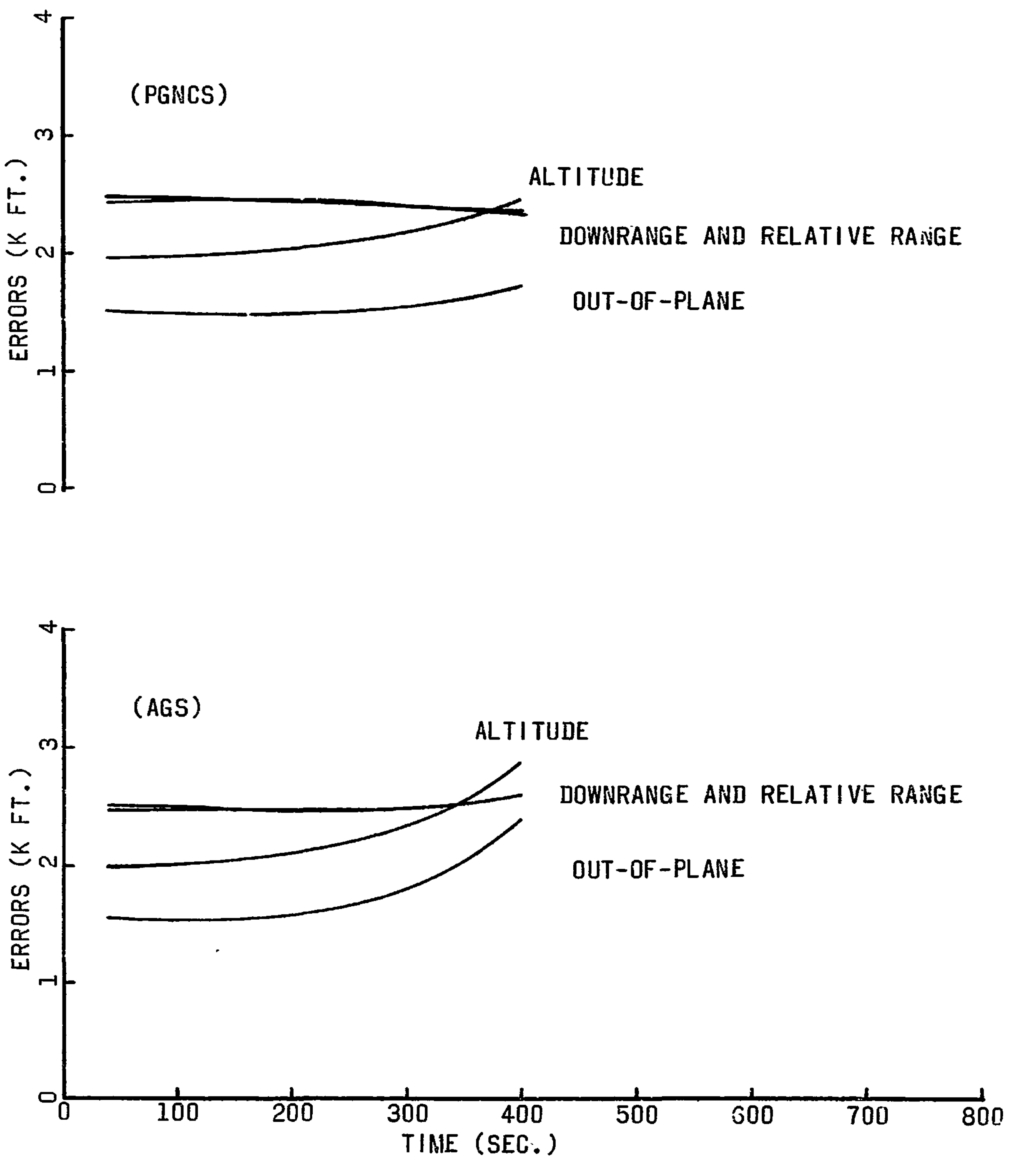

FIGURE 10B LM POSITION AND RELATIVE RANGE ERRORS
(NOMINAL ASCENT)

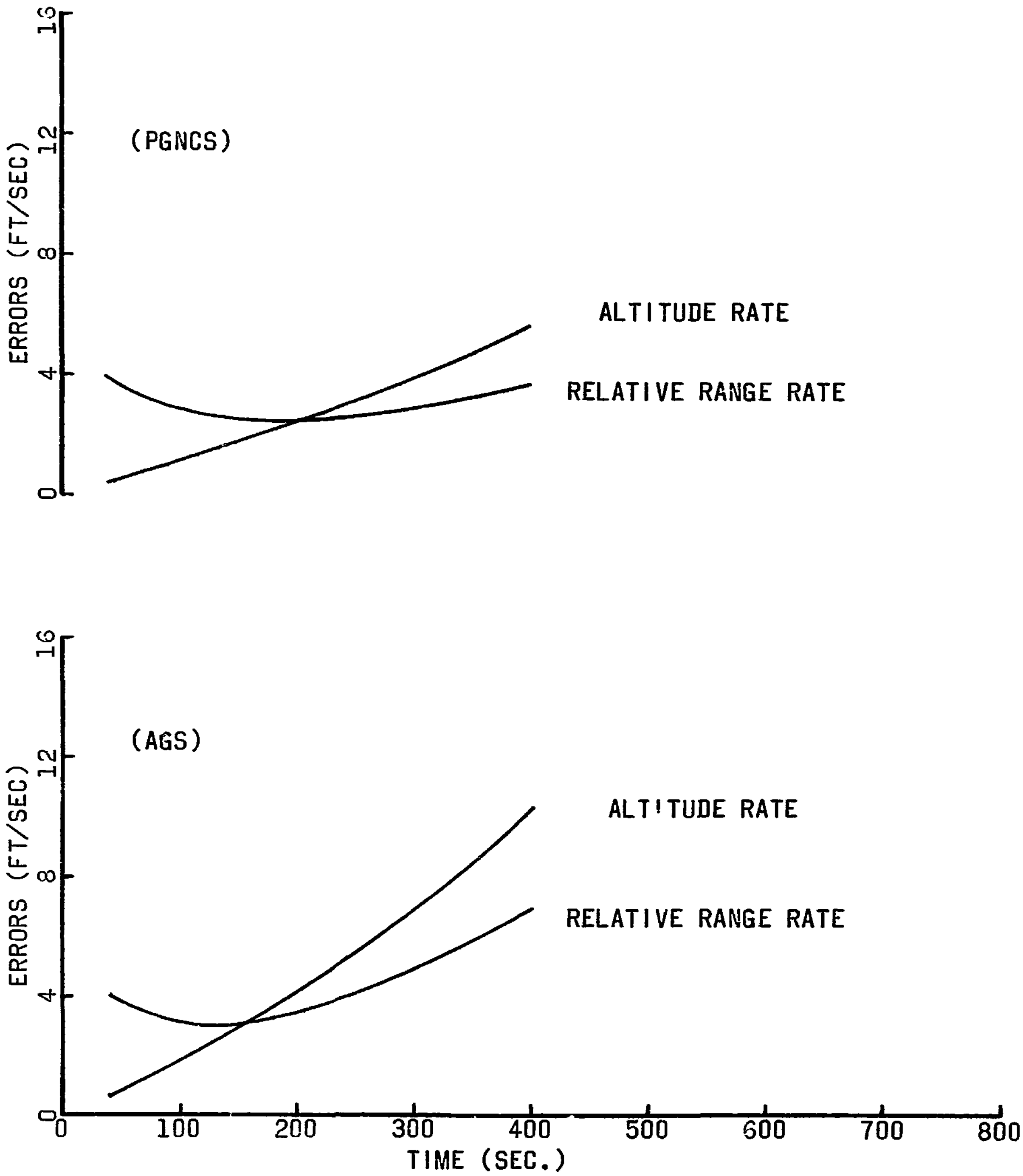

FIGURE 10C RELATIVE RANGE RATE AND ALTITUDE RATE ERRORS (NOMINAL ASCENT)

ERROR SOURCES:

	x(ft)	y(ft)	z(ft)	$\dot{x}$(ft/sec)	$\dot{y}$(ft/sec)	$\dot{z}$(ft/sec)
INITIAL MISALIGNMENT						
ϕ_x = 1 arc sec	0.0	2.15	0.0	0.0	1.18/-2	0.0
ϕ_y = 1 arc sec	-5.17	0.0	-7.29	-6.02/-3	0.0	-[illegible].83/-2
ϕ_z = 1 arc sec	0.0	6.55	0.0	0.0	2.29/-2	0.0
GYRO ERRORS						
DRIFT						
E_x = 1 meru	0.0	36.9	0.0	0.0	.218	0.0
E_y = 1 meru	-10.9	0.0	-116.	- .11[illegible]	0.0	- .479
E_z = 1 meru	0.0	104.	0.0	0.0	.388	0.0
MASS UNBALANCE						
x-Spin = 1 meru/g	0.0	- 2.80	0.0	0.0	-1.98/-2	0.0
y-Input= 1 meru/g	.475	0.0	1.48	4.97/-3	0.0	9.97/-3
z-Spin = 1 meru/g	0.0	1.29	0.0	0.0	8.09/-3	0.0
CROSS AXIS SENSITIVITY						
x to z = 1 arc sec	2.08	0.0	.522	1.15/-2	0.0	2.96/-3
y to x = 1 arc sec	0.0	-6.55	0.0	0.0	-2.29/-2	0.0
y to z = 1 arc sec	0.0	2.15	0.0	0.0	1.18/-2	0.0
z to x = 1 arc sec	1.57	0.0	-6.77	5.48/-3	0.0	-[illegible].54/-2
ACCELEROMETER ERRORS						
x - Bias = .1 cm/sec^2	384.	0.0	-52.6	1.41	0.0	- .181
y - Bias = .1 cm/sec^2	0.0	362.	0.0	0.0	1.34	0.0
z - Bias = .1 cm/sec^2	-97.3	0.0	419.	- .379	0.0	1.73
x - Scale Factor = 100 PPM	-131.	0.0	-33.6	- .459	0.0	- .1[illegible]
z - Scale Factor = 100 PPM	- 10.5	0.0	44.6	-5.80/-2	0.0	.253
x - Non Linearity = 10^{-5}/g	4.53	0.0	1.16	1.50/-2	0.0	4.14/-3
z - Non Linearity = 10^{-5}/g	- .170	0.0	.716	-1.14/-3	0.0	4.89/-3

FIGURE 11 PGNCS POWERED FLIGHT PARTIALS (NOMINAL DESCENT)

ERROR SOURCES:

	x(ft)	y(ft)	z(ft)	$\dot{x}$(ft/sec)	$\dot{y}$(ft/sec)	$\dot{z}$(ft/sec)
INITIAL MISALIGNMENT						
ϕ_x = 1 arc sec	0.0	2.63	0.0	0.0	4.65/-3	0.0
ϕ_y = 1 arc sec	- .328	0.0	-6.62	-4.53/-3	0.0	-4.63/-3
ϕ_z = 1 arc sec	0.0	5.17	0.0	0.0	-2.14/-3	0.0
GYRO ERRORS						
DRIFT						
E_x = 1 meru	0.0	44.5	0.0	0.0	6.77/-2	0.0
E_y = 1 meru	-12.3	0.0	-94.6	-9.94/-2	0.0	1.12/-2
E_z = 1 meru	0.0	70.4	0.0	0.0	- .119	0.0
MASS UNBALANCE						
x-Spin = 1 meru/g	0.0	-3.18	0.0	0.0	-8.82/-3	0.0
y-Input= 1 meru/g	1.011	0.0	- .237	4.71/-3	0.0	-8.28/-3
z-Spin = 1 meru/g	0.0	- .661	0.0	0.0	-9.71/-3	0.0
CROSS AXIS SENSITIVITY						
x to z = 1 arc sec	2.43	0.0	1.05	4.23/03	0.0	2.18/-3
y to x = 1 arc sec	0.0	-5.17	0.0	0.0	2.14/-3	0.0
y to z = 1 arc sec	0.0	2.63	0.0	0.0	4.62/-3	0.0
z to x = 1 arc sec	2.09	0.0	-5.57	-2.95/-4	0.0	-2.45/-3
ACCELEROMETER ERRORS						
x - Bias = .1 cm/sec^2	562.	0.0	245.	1.76	0.0	.828
y - Bias = .1 cm/sec^2	0.0	609.	0.0	0.0	1.91	0.0
z - Bias = .1 cm/sec^2	-241.	0.0	617.	- .704	0.0	2.11
x - Scale Factor = 100 PPM	- 98.2	0.0	- 44.4	4.34/-2	0.0	-8.34/-3
z - Scale Factor = 100 PPM	- 21.2	0.0	54.2	-3.91/-2	0.0	.117
x - Non Linearity = $10^{-5}/g$	6.82	0.0	2.96	2.38/-2	0.0	1.10/-2
z - Non Linearity = $10^{-5}/g$	- .331	0.0	.836	-1.38/-3	0.0	3.65/-3

FIGURE 12 PGNCS POWERED FLIGHT PARTIALS (25 K ABORT)

ERROR SOURCES:

	x(ft)	y(ft)	z(ft)	$\dot{x}$(ft/sec)	$\dot{y}$(ft/sec)	$\dot{z}$(ft/sec)
INITIAL MISALIGNMENT						
ϕ_x = 1 arc sec	0.0	9.70	0.0	0.0	7.49/-3	0.0
ϕ_y = 1 arc sec	4.37	0.0	-27.0	-6.65/-3	0.0	-3.86/-2
ϕ_z = 1 arc sec	0.0	9.72	0.0	0.0	-1.09/-2	0.0
GYRO ERRORS						
DRIFT						
E_x = 1 meru	0.0	204.	0.0	0.0	.172	0.0
E_y = 1 meru	20.6	0.0	-446.	- .312	0.0	- .496
E_z = 1 meru	0.0	140.	0.0	0.0	- .406	0.0
MASS UNBALANCE						
x-Spin = 1 meru/g	0.0	-14.8	0.0	0.0	-1.77/-2	0.0
y-Input= 1 meru/g	7.48	0.0	.872	2.36/-2	0.0	-1.37/-2
z-Spin = 1 meru/g	0.0	-4.73	0.0	0.0	-2.70/-2	0.0
CROSS AXIS SENSITIVITY						
x to z = 1 arc sec	6.06	0.0	9.86	3.67/-3	0.0	1.71/-2
y to x = 1 arc sec	0.0	-9.71	0.0	0.0	1.09/-2	0.0
y to z = 1 arc sec	0.0	9.70	0.0	0.0	7.49/-3	0.0
z to x = 1 arc sec	10.4	0.0	-1.71	-2.97/-3	0.0	-2.15/-2
ACCELEROMETER ERRORS						
x - Bias = .1 cm/sec^2	1645.	0.0	2684.	1.62	0.0	5.33
y - Bias = .1 cm/sec^2	0.0	2631.	0.0	0.0	2.94	0.0
z - Bias = .1 cm/sec^2	-2271.	0.0	3200.	-2.81	0.0	6.69
x - Scale Factor = 100 PPM	- 112.	0.0	- 247.	.208	0.0	- .193
z - Scale Factor = 100 PPM	- 173.	0.0	244.	- .164	0.0	.459
x - Non Linearity = 10^{-5}/g	21.4	0.0	34.4	2.47/-2	0.0	7.19/-2
z - Non Linearity = 10^{-5}/g	- 3.93	0.0	5.29	-5.90/-3	0.0	1.19/-2

FIGURE 13 PGNCS POWERED FLIGHT PARTIALS (10 K ABORT)

ERROR SOURCES:

INITIAL MISALIGNMENT	x(ft)	y(ft)	z(ft)	x(ft/sec)	y(ft/sec)	z(ft/sec)
ϕ_x = 1 arc sec	0.0	-1.75	0.0	0.0	-5.39/-3	0.0
ϕ_y = 1 arc sec	2.49	0.0	-4.37	9.62/-3	0.0	-2.60/-2
ϕ_z = 1 arc sec	0.0	-4.57	0.0	0.0	-2.57/-2	0.0
GYRO ERRORS						
DRIFT						
E_x = 1 meru	0.0	-2.62	0.0	0.0	-7.99/-2	0.0
E_y = 1 meru	37.9	0.0	-69.2	.152	0.0	- .440
E_z = 1 meru	0.0	-72.3	0.0	0.0	- .436	0.0
MASS UNBALANCE						
x-Spin = 1 meru/g	0.0	..827	0.0	0.0	2.03/-3	0.0
y-Input= 1 meru/g	- .724	0.0	1.61	-3.48/-3	0.0	1.22/-2
z-Spin = 1 meru/g	0.0	-1.67	0.0	0.0	- 1.22/-2	0.0
CROSS AXIS SENSITIVITY						
x to z = 1 arc sec	-1.73	0.0	- .290	-5.31/-3	0.0	-9.46/-4
y to x = 1 arc sec	0.0	4.57	0.0	0.0	2.57/-2	0.0
y to z = 1 arc sec	0.0	-1.75	0.0	0.0	-5.39/-3	0.0
z to x = 1 arc sec	7.61/-1	0.0	-4.66	4131/-3	0.0	-2.69/-2
ACCELEROMETER ERRORS						
x - Bias = .1 cm/sec^2	-259.	0.0	-43.5	-1.27	0.0	- .219
y - Bias = .1 cm/sec^2	0.0	-263.	0.0	0.0	-1.289	0.0
z - Bias = .1 cm/sec^2	-43.9	0.0	269.	- .217	0.0	1.37
x - Scale Factor = 100 PPM	93.0	0.0	15.6	.524	0.0	8.99/-2
z - Scale Factor = 100 PPM	-6.08	0.0	37.3	-1.93/-2	0.0	.125
x - Non Linearity = 10^{-5}/g	-3.53	0.0	- .591	-2.31/-2	0.0	-3.93/-3
z - Non Linearity = 10^{-5}/g	- .100	0.0	.615	-3.54/-4	0.0	2.29/-3

FIGURE 14 PGNCS POWERED FLIGHT PARTIALS (NOMINAL ASCENT)

ERROR SOURCES:	x(ft)	y(ft)	z(ft)	$\dot{x}$(ft/sec)	$\dot{y}$(ft/sec)	$\dot{z}$(ft/sec)
INITIAL ALIGNMENT						
ϕ_x = 100 arc sec	0	-4.40/-1	0	0	-5.96/-3	0
ϕ_y = 100 arc sec	4.22/-1	0	7.15	5.89/-3	0	2.81/-2
ϕ_z = 100 arc sec	0	-6.76	0	0	-2.49/-2	0
GYRO ERRORS						
DRIFT						
E_x = 1 meru	0	3.26/1	0	0	1.95/-1	0
E_y = 1 meru	9.42	0	1.14/2	1.17/-1	0	4.73/-1
E_z = 1 meru	0	1.04/2	0	0	3.96/-1	0
GYRO SCALE FACTOR						
T_x = 100 PPM	0	0	0	0	0	0
T_y = 100 PPM	1.01/1	0	4.48/1	1.10/-1	0	2.50/-1
T_z = 100 PPM	0	0	0	0	0	0
MASS UNBALANCE						
x-Spin = 1 meru/g	0	4.51/-2	0	0	3.71/-4	0
x-Anisoelasticity = 1 meru/g^2	0	0	0	0	0	0
CROSS AXIS SENSITIVITY						
x to y = 1 arc sec	0	5.21/-1	0	0	4.31/-3	0
x to z = 1 arc sec	0	0	0	0	0	0
y to x = 1 arc sec	0	0	0	0	0	0
y to z = 1 arc sec	0	0	0	0	0	0
z to x = 1 arc sec	0	0	0	0	0	0
z to y = 1 arc sec	0	2.12	0	0	1.20/-2	0
ACCELEROMETER ERRORS						
x - Bias = 10^{-5} g	-3.79/2	0	2.20/1	-1.40	0	3.69/-1
y - Bias = 10^{-5} g	0	3.91/2	0	0	1.54	0
z - Bias = 10^{-5} g	-2.15/1	0	-4.01/2	-3.65/-1	0	-1.58
x - Scale Factor = 100 PPM	-1.39/2	0	8.93	-5.14/-1	0	1.23/-1
x - Nonlinearity = 10^{-5}/g	-5.15	0	3.79/-1	-1.92/-2	0	4.36/-3
x to y Cross Axis = 1 arc sec	0	6.95	0	0	2.70/-2	0
x to z Cross Axis = 1 arc sec	-4.22/-1	0	-7.15	-5.89/-3	0	-2.81/-2

FIGURE 15 AGS POWERED FLIGHT PARTIALS (NOMINAL DESCENT)

ERROR SOURCES:

INITIAL MISALIGNMENT	x(ft)	y(ft)	z(ft)	$\dot{x}$(ft/sec)	$\dot{y}$(ft/sec)	$\dot{z}$(ft/sec)
ϕ_x = 100 arc sec	0	-9.52/-1	0	0	-4.35/-3	0
ϕ_y = 100 arc sec	2.26	0	5.30	5.25/-3	0	2.69/-3
ϕ_z = 100 arc sec	0	-5.04	0	0	1.01/-4	0
GYRO ERRORS						
DRIFT						
E_x = 1 meru	0	3.71/1	0	0	9.51/-2	0
E_y = 1 meru	3.74/1	0	7.33/1	7.80/-2	0	-3.24/-2
E_z = 1 meru	0	7.13/1	0	0	-1.60/-2	0
GYRO SCALE FACTOR						
T_x = 100 PPM	0	0	0	0	0	0
T_y = 100 PPM	3.13/1	0	-9.10/1	-2.74/-2	0	-9.69/-1
T_z = 100 PPM	0	0	0	0	0	0
MASS UNBALANCE						
x-Spin = 1 meru/g	0	9.11/-2	0	0	4.55/-4	0
x-Anisoelasticity = 1 meru/g^2	0	1.05/-3	0	0	5.99/-6	0
CROSS AXIS SENSITIVITY						
x to y = 1 arc sec	0	4.67	0	0	3.42/-2	0
x to z = 1 arc sec	0	0	0	0	0	0
y to x = 1 arc sec	0	0	0	0	0	0
y to z = 1 arc sec	0	0	0	0	0	0
z to x = 1 arc sec	0	0	0	0	0	0
z to y = 1 arc sec	0	2.19	0	0	4.18/-3	0
ACCELEROMETER ERRORS						
x - Bias = 10^{-5} g	-2.72/2	0	1.15/2	-1.63/-2	0	2.44/-1
y - Bias = 10^{-5} g	0	5.21/2	0	0	1.76	0
z - Bias = 10^{-5} g	-1.24/2	0	-3.08	-3.04/-1	0	-2.36/-1
x - Scale Factor = 100 PPM	-9.63/1	0	4.36/1	2.37/-2	0	8.77/-2
x - Nonlinearity = 10^{-5}/g	-3.40	0	1.65	2.14/-3	0	3.11/-3
x to y Cross Axis = 1 arc sec	0	9.32	0	0	3.30/-2	0
x to z Cross Axis = 1 arc sec	-2.26	0	-5.30	-5.25/-3	0	-2.69/-3

FIGURE 16 AGS POWERED FLIGHT PARTIALS (25 K ABORT)

ERROR SOURCES:	x(ft)	y(ft)	z(ft)	$\dot{x}$(ft/sec)	$\dot{y}$(ft/sec)	$\dot{z}$(ft/sec)
INITIAL MISALIGNMENT						
ϕ_x = 100 arc sec	0	-2.27	0	0	-7.16/-3	.0
ϕ_y = 100 arc sec	4.48	0	8.77	8.95/-3	0	4.71/-3
ϕ_z = 100 arc sec	0	-7.95	0	0	1.43/-3	0
GYRO ERRORS						
DRIFT						
E_x = 1 meru	0	7.46	0	0	1.61/01	0
E_y = 1 meru	7.73/1	0	1.22/2	1.39/-1	0	-4.91/-2
E_z = 1 meru	0	1.14/2	0	0	-4.19/-2	0
GYRO SCALE FACTOR						
T_x = 100 PPM	0	0	0	0	0	0
T_y = 100 PPM	6.46/1	0	-1.34/2	-2.48/-3	0	-1.25
T_z = 100 PPM	0	0	0	0	0	0
MASS UNBALANCE						
x-Spin = 1 meru/g	0	2.14/-1	0	0	8.88/-4	0
x-Anisoelasticity = 1 meru/g^2	0	0	0	0	0	0
CROSS AXIS SENSITIVITY						
x to y = 1 arc sec	0	7.80	0	0	4.53/-2	0
x to z = 1 arc sec	0	0	0	0	0	0
y to x = 1 arc sec	0	0	0	0	0	0
y to z = 1 arc sec	0	0	0	0	0	0
z to x = 1 arc sec	0	0	0	0	0	0
z to y = 1 arc sec	0	4.19	0	0	6.57/-3	0
ACCELEROMETER ERRORS						
x - Bias = 10^{-5} g	-4.07/2	0	2.15/2	5.31/-2	0	3.85/-1
y - Bias = 10^{-5} g	0	8.07/2	0	0	2.14	0
z - Bias = 10^{-5} g	-2.36/2	0	-4.99/2	-4.99/-1	0	-3.90/-1
x - Scale Factor = 100 PPM	-1.48/2	0	8.51/1	6.67/-2	0	1.46/-1
x - Nonlinearity = 10^{-5}/g	-5.35	0	3.38	4.69/-3	0	5.43/-3
x to y Cross Axis = 1 arc sec	0	1.49/1	0	0	4.21/-2	0
x to z Cross Axis = 1 arc sec	-4.48	0	-8.77	-8.95/-3	0	-4.71/-3

FIGURE 17 AGS POWERED FLIGHT PARTIALS (10 K ABORT)

ERROR SOURCES:

INITIAL MISALIGNMENT	y(ft)	y(ft)	z(ft)	$\dot{x}$(ft/sec)	$\dot{y}$(ft/sec)	$\dot{z}$(ft/sec)
ϕ_x = 100 arc sec	0	1.80	0	0	5.69/-3	0
ϕ_y = 100 arc sec	-1.79	0	-4.71	-5.54/-3	.0	-2.72/-2
ϕ_z = 100 arc sec	0	-4.56	0	0	-2.57/-2	0
GYRO ERRORS						
DRIFT						
E_x = 1 meru	0	-1.70/1	0	0	-1.59/-1	0
E_y = 1 meru	-2.68/1	0	-7.41/1	-8.24/-2	0	-4.56/-1
E_z = 1 meru	0	-7.50/1	0	0	-4.14/-1	0
GYRO SCALE FACTOR						
T_x = 100 PPM	0	0	0	0	0	0
T_y = 100 PPM	-4.95	0	-2.27	-1.26/-2	0	-2.16/-1
T_z = 100 PPM	0	0	0	0	0	0
MASS UNBALANCE						
x-Spin = 1 meru/g	0	0	0	0	0	0
x-Anisoelasticity = 1 meru/g^2	0	0	0	0	0	0
CROSS AXIS SENSITIVITY						
x to y = 1 arc sec	0	-2.12/-1	0	0	-2.72/-3	0
x to z = 1 arc sec	0	0	0	0	0	0
y to x = 1 arc sec	0	0	0	0	0	0
y to z = 1 arc sec	0	0	0	0	0	0
z to x = 1 arc sec	0	0	0	0	0	0
z to y = 1 arc sec	0	-1.10	0	0	-9.89/-3	0
ACCELEROMETER ERRORS						
x - Bias = 10^{-5} g	-2.34/2	0	1.04/2	-1.19	0	3.63/-1
y - Bias = 10^{-5} g	0	-2.57/2	0	0	-1.26	0
z - Bias = 10^{-5} g	9.8 /1	0	2.42/2	3.05/-1	0	1.27
x - Scale Factor = 100 PPM	-9.4 /1	0	3.90/1	-5.32/-1	0	1.36/-1
x - Nonlinearity = 10^{-5}/g	-3.85	0	1.47	-2.44/-2	0	5.03/-3
x to y Cross Axis = 1 arc sec	0	-4.99	0	0	-2.72/-2	0
x to z Cross Axis = 1 arc sec	1.79	0	4.71	5.5 /-3	0	2.72/-2

FIGURE 18 AGS POWERED FLIGHT PARTIALS (NOMINAL ASCENT)

6211394	23268	-2447789	-305	52	-6839
	2049248	- 35779	26	7321	- 30
		3430849	1568	- 32	11451
			3	0	7
(SYMMETRIC)				29	0
					43

A. PGNCS

7038398	228359	-2171995	3194	56	-6251
	6420632	- 35483	26	25726	- 29
		8157123	5892	- 32	32109
			20	0	24
(SYMMETRIC)				108	0
					134

B. AGS

FIGURE 19 LM FINAL COVARIANCE MATRICES
(NOMINAL DESCENT)

6974139	40370	-2769528	156	57	-8353
	1828700	- 39941	27	518	44
		3484641	1116	- 28	5208
			2	0	1
(SYMMETRIC)				3	0
					13

A. PGNCS

7380860	36349	-2340524	127	58	-8679
	4800286	- 37437	28	3898	- 38
		5857795	3653	- 27	493
			4	0	1
(SYMMETRIC)				17	0
					13

B. AGS

FIGURE 20 LM FINAL COVARIANCE MATRICES
(25 K ABORT)

7162318	52546	-3621703	110	52	-9312
	4147226	- 51315	24	855	- 69
		81619.7	3562	-32	10548.
			4	0	4
(SYMMETRIC)				5	0
					19

A. PGNCS

8630827	49977	-2471448	504	54	-10736
	12788644	- 47773	25	8576	- 61
		16037641	11600	-31	11363
			11	0	4
(SYMMETRIC)				34	0
					21

B. AGS

FIGURE 21 LM FINAL COVARIANCE MATRICES
(10 K ABORT)

5600233	0	-383365	-815	0	-3313
	3063747	0	0	4764	0
		6040307	-2416	0	8398
			6	0	- 11
(SYMMETRIC)				31	0
					32

A. PGNCS

6688517	0	-1281533	4682	0	-9505
	5621477	0	0	19249	0
		8204857	-5441	0	21781
			35	0	- 3
(SYMMMETRIC)				114	0
					116

B. AGS

FIGURE 22 LM FINAL COVARIANCE MATRICES (NOMINAL ASCENT)