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LANDING TRAJECTORY RECONSTRUCTION COMPUTER PROGRAM

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16. Abstract

The Lander Trajectory Reconstruction (LTR) computer program is a tool for analysis of the planetary entry trajectory and atmosphere reconstruction process for a lander or probe.

The program can be divided into two parts -- the data generator and the reconstructor. The data generator provides the "real" environment in which the lander or probe is presumed to find itself. The reconstructor reconstructs the entry trajectory and atmosphere using sensor data generated by the data generator and a Kalman-Schmidt consider filter. A wide variety of vehicle and environmental parameters may be either solved-for or considered in the filter process.

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PREFACE

The *Lander Trajectory Reconstruction (LTR)* program is a computer program developed by the Martin Marietta Corporation to analyze the entry trajectory and atmosphere reconstruction process for the planetary entry of a lander or probe. The program was initially developed in the Viking lander contract, NAS1-9000. In Contract NAS5-11873, the program was modified and expanded to provide for more flexible atmosphere models, a wider variety of measurement types, and an arbitrary entry plane.

The program can be divided into two parts -- the data generator and the reconstructor. The data generator provides the "real" environment in which the lander or probe is presumed to find itself. Thus the data generator integrates the equation of motion from entry to landing using vehicle and atmosphere models that are assumed to model the "real" environment. These data are then used as inputs to the reconstructor.

The reconstructor reconstructs the entry trajectory and atmosphere using the sensor data generated by the data generator and a Kalman-Schmidt recursive estimation algorithm. The estimation algorithm generates an estimate of the state of the vehicle at each measurement time as well as the statistics associated with the estimate. In addition to the basic state of the vehicle, the state vector may be augmented with a wide variety of vehicle and environmental parameters. These augmented parameters may be treated as either solve-for parameters or consider parameters. The solve-for parameters are estimated along with the basic state variable, whereas the consider parameter uncertainties are used in generating the state and solve-for parameters statistics but are not estimated, i.e., their uncertainties are not improved.

The reconstructor can be operated in either of two modes. Mode A operation is designed for high-Mach number high-altitude regions. The principal atmosphere measurements of temperature and pressure are difficult to obtain accurately in these regions. Consequently vehicle acceleration, based on an atmosphere model and measurements of temperature and pressure, tend to be less accurate than direct accelerometer outputs. Therefore in mode A operation, no a priori atmosphere model is assumed and the vehicle acceleration terms in the equations of motion are obtained directly from accelerometer and, if available, gyro data. In low-Mach number regions, particularly as terminal velocity is approached, accurate temperature and pressure measurements are available and accelerometer data yield less useful information. Mode B operation is designed for such regions. The vehicle accelerations are based on an a priori atmosphere model and accelerometer data are processed as observables.

The documentation for the LTR program is contained in two volumes: the *Analytic/Users' Manual* and the *Programmers' Manual*. Each of these manuals is self contained.

The *Analytic/Users' Manual* consists of two parts. The first part provides a unified treatment of the mathematical analysis of the LTR program. The general problem descriptions, formulation, and solution are given in a tutorial manner. This is followed by the detailed analysis of each LTR subroutine. The second part contains the information necessary to operate the program. The input and output quantities are described in detail. Example cases are also given and discussed.

The *Programmers' Manual* provides the reader with the information he needs to effectively modify the program. The overall structure of the program and the computational flow and analysis of the individual subroutines are described in this manual.

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PART I

LTR ANALYTICAL MANUAL

I. INTRODUCTION

The *Lander Trajectory Reconstruction (LTR)* program is a planetary entry trajectory and atmosphere reconstruction program. Currently LTR is a preflight mission analysis tool that is used to perform error analyses and simulations of entry trajectory and atmosphere reconstruction processes. The LTR program can provide answers to questions such as How do modeling errors affect our ability to reconstruct the entry trajectory and planetary atmosphere? Is the reconstruction process convergent? What kind of reconstruction strategy and instrumentation accuracies are required to meet the scientific objectives of the mission?

The LTR program consists of a data generator program and a reconstruction program. The data generator can be run independently as an entry trajectory program, but is used primarily to generate the "actual trajectory and atmosphere" and "actual measurements" for use in the reconstruction program. The reconstruction program is primarily a simulation program that processes these "actual measurements" in an attempt to reconstruct the "actual trajectory and atmosphere." In designing an actual mission, of course, we can never obtain exact values of dynamic and measurement parameters, and our equations of motion always neglect certain dynamical effects and often embody certain simplifications in the interest of computational efficiency. It is important to know the significance of these inherent limitations on our ability to reconstruct the entry trajectory and the planetary atmosphere. This is the basis for the division of the LTR program into two parts. In essence, the mathematical models used in the data generator to compute the "actuals" represent the "real world," while those models used in the reconstruction program represent the "modeled world."

An independent error analysis mode is currently not available in the LTR reconstruction program. However, all the information that would be generated in an independent error analysis mode is always generated by the LTR reconstruction program. An independent error analysis mode could not be defined for the mode A reconstruction process because "actual" accelerometer measurements are required from the data generator. Although an independent error analysis mode could be defined for the mode B reconstruction process, it would not result in a significant reduction in program operation costs. Furthermore, it is always useful to have simulation information available because of the more difficult problems encountered in designing convergent filters for entry missions. The remainder of this chapter will summarize the contents of the remaining chapters in the Analytic section of this manual.

Chapter II presents the dynamic and measurement models that are used in the data generator to compute the "actuals." The equations of motion are written assuming an inverse square gravitational field and Mach number-dependent aerodynamic coefficients. Provision is available for including the dynamic effects of parachute deployment and release. The atmosphere model is a linear breakpoint model defined by temperature and molecular weight profiles and surface pressure. A linear breakpoint horizontal wind model is also available. During the terminal descent phase the dynamic model can be replaced with the quasi-static dynamic model. The quasi-static dynamic model improves computational efficiency and avoids certain integrator instabilities. Measurement models are defined in the data generator for the following measurement types: axial and normal accelerometers, gyro, radar altimeter, stagnation pressure, stagnation temperature, and range and range-rate from three earth-based tracking stations. "Actual" bias and scale factor errors can be incorporated into most of the dynamic and measurement parameters.

Chapter III presents the recursive linear estimation algorithm used in both reconstruction modes. The algorithm is the Kalman-Schmidt algorithm with a consider mode. The consider mode permits the uncertainties in certain parameters to be considered in the algorithm without actually attempting to estimate these parameters. This is a device for combating filter divergence. The state transition matrix computational method is also described in Chapter III. Quasi-linear filtering is discussed and the measurement noise models for all measurement types are summarized.

The two reconstruction modes available in the LTR reconstruction program differ primarily in the method employed for modeling aerodynamic forces. Since the mode A reconstruction process, which is described in Chapter IV, uses accelerometer and gyro data to model aerodynamic forces, it requires no model of the planetary atmosphere for its operation. The mode B reconstruction process, which is described in Chapter V, uses mathematical models similar to those used in the data generator to model aerodynamic forces and the planetary atmosphere. In either mode provision is available for estimating or considering various dynamic and measurement parameters.

II. MODELING OF ACTUAL TRAJECTORY, ATMOSPHERE, AND MEASUREMENTS

A. ENTRY GEOMETRY AND EQUATIONS OF MOTION

Figure II-1 defines the entry geometry modeled in the LTR program. The entry plane is defined relative to the planetocentric ecliptic coordinate system $x_\varepsilon\ y_\varepsilon\ z_\varepsilon$ by the longitude of the ascending node Ω_ε and the inclination i_ε. The reference line from which the downrange angle ϕ is measured, is defined in the entry plane by the angle ϕ_ε. Since only the planar translation and rotational dynamics of the entry vehicle are modeled in LTR, the state of the entry vehicle can be defined by the altitude h, velocity v, flightpath angle γ. downrange angle ϕ, attitude θ, and angular velocity ω. Flightpath angle γ is measured from the instantaneous local horizontal. The position of the entry vehicle relative to the planet center is given by

$$r = h + R_p \tag{II-1}$$

The vehicle body axes are denoted by the xyz coordinate system, where x is aligned with the vehicle longitudinal axis, y is normal to the entry plane, and z completes the orthogonal triad. The vehicle attitude angle θ is measured from the local horizontal (corresponding to $\phi = 0$) to the x body axis. The vehicle angle of attack α is measured from the relative velocity v_r to the x body axis. Velocity v_r is the vehicle velocity relative to the planetary atmosphere, and is defined as the vector difference of the inertial velocity v and the atmosphere velocity v_a, so that

$$v_r = \frac{v - v_a \cos \gamma}{\cos \varepsilon} \tag{II-2}$$

where ε is the angle between v and v_r. The angle ε is given by

$$\varepsilon = \tan^{-1} \left[\frac{v_a \sin \gamma}{v - v_a \cos \gamma} \right] \tag{II-3}$$

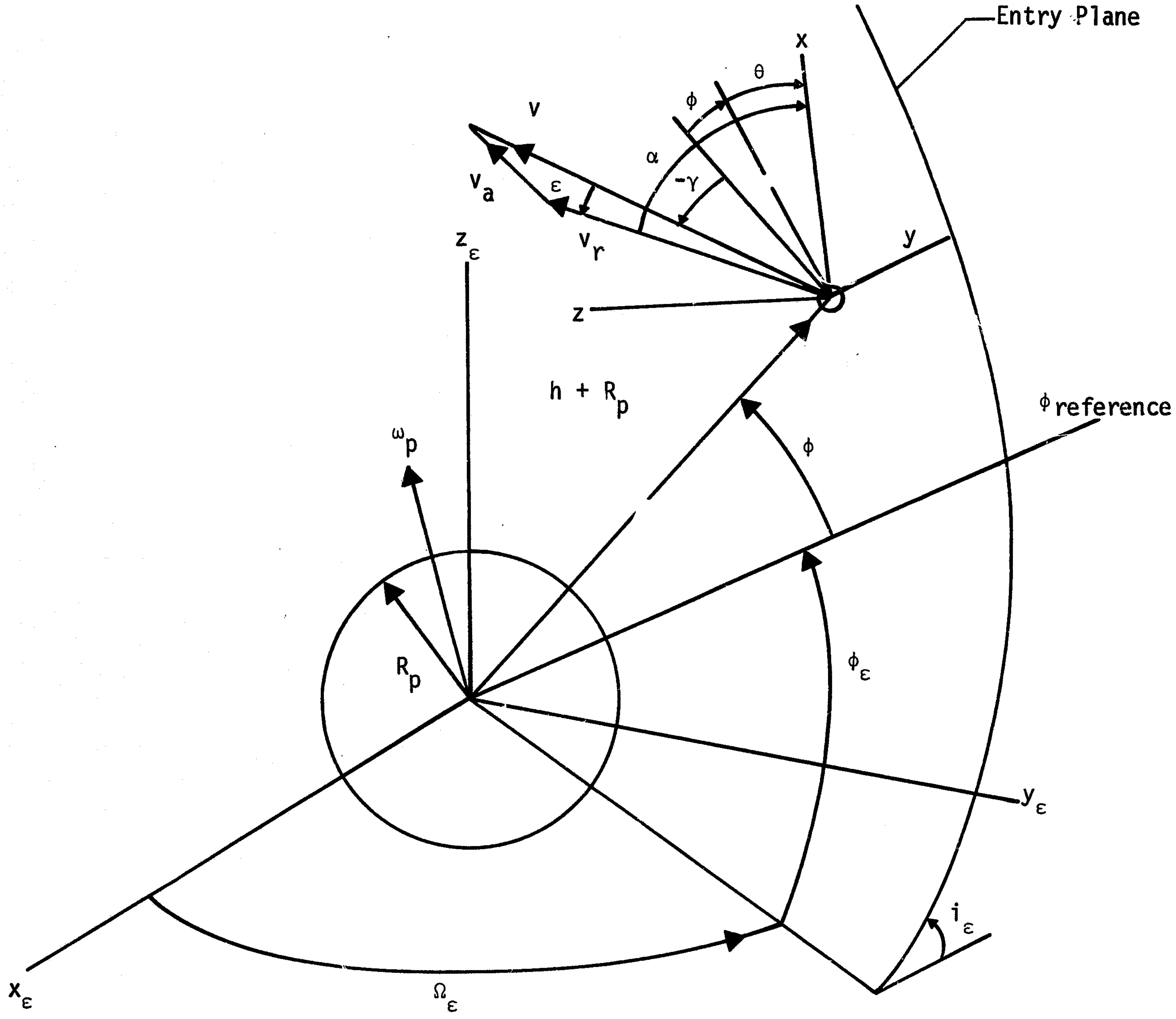

Figure II-1 Entry Geometry

If $\vec{\omega}_p$ denotes the angular velocity vector of the planet, and if $\vec{e}_n$ denotes a unit vector normal to the entry plane, then the atmosphere velocity in the entry plane can be written as

$$v_a = (\vec{\omega}_p \cdot \vec{e}_n)\, r + v_w \qquad \text{(II-4)}$$

where v_w is the horizontal wind velocity. The angle of attack can be related to the other angular quantities according to

$$\alpha = \theta + \phi - \gamma - \varepsilon \quad . \qquad \text{(II-5)}$$

The entry vehicle geometry is defined in Figure II-2. The probe center of gravity (cg) has location (x_p, z_p). When the parachute is deployed, its centerline is assumed to be aligned with the relative velocity vector so that the force F_d exerted by the parachute on the probe is also aligned with the relative velocity vector. The force F_d acts at location $(x_d, 0)$ relative to the body axis system.

Axial aerodynamic force A, normal aerodynamic force N, and aerodynamic (damping) moment M act at the center of pressure and are given by

$$A = - C_A\, q\, S \qquad \text{(II-6)}$$

$$N = - C_N\, q\, S \qquad \text{(II-7)}$$

$$M = C_{M_q}\, \omega\, d^2\, q\, S/v_r \qquad \text{(II-8)}$$

The parachute force is given by

$$F_d = C_D\, q\, S_D \quad . \qquad \text{(II-9)}$$

In these equations C_A, C_N, and C_{M_q} are the axial force, normal force, and damping moment coefficients, respectively, and are tabulated functions of angle of attack α and Mach number M. The parachute drag coefficient C_D is a tabulated function of M only. The quantities S and S_D denote the reference areas of the probe and parachute,

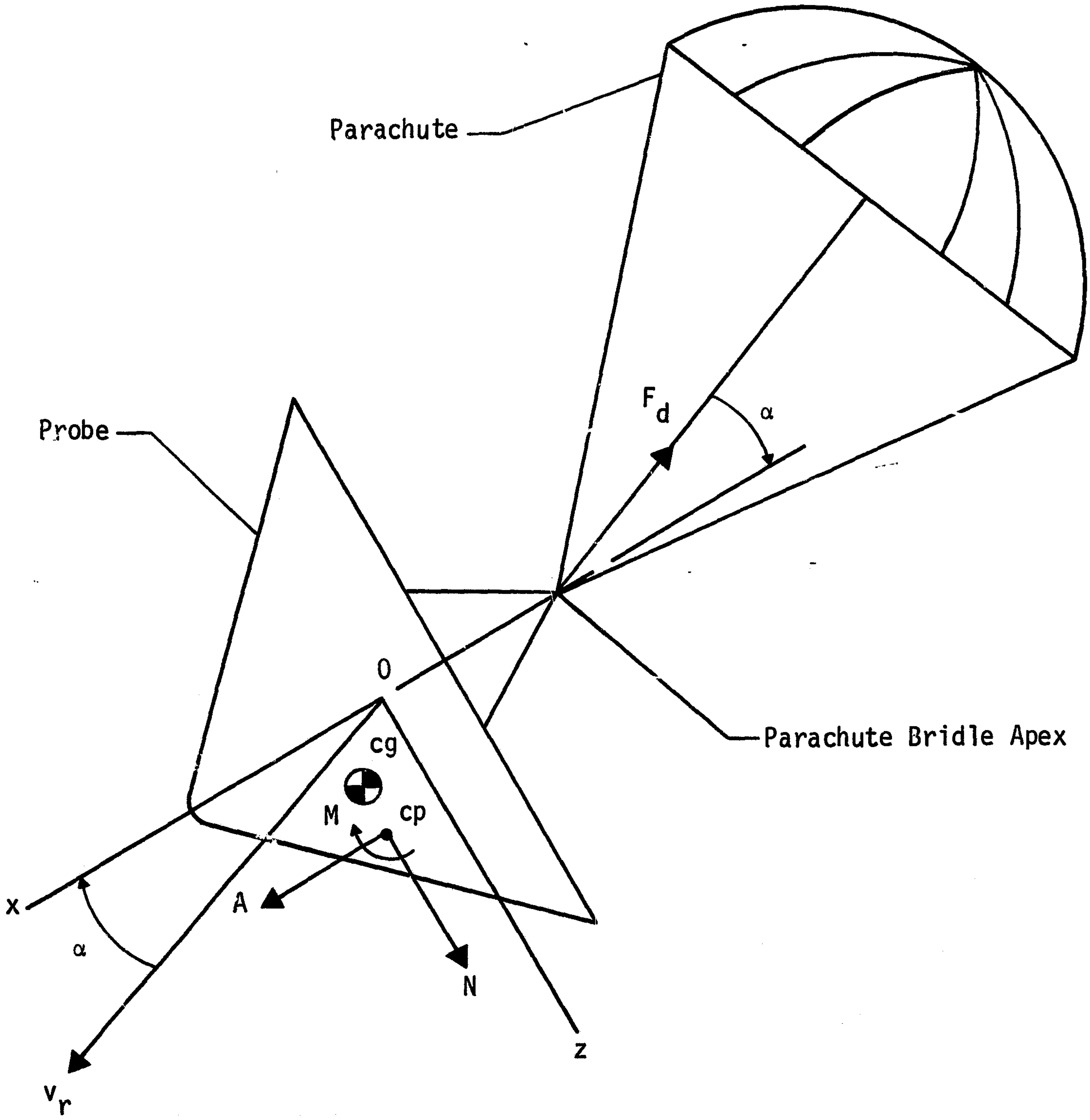

Figure II-2 Entry Vehicle Geometry

respectively; the reference diameter of the probe is denoted by d. Dynamic pressure q is given by

$$q = \frac{1}{2} \rho v_r^2 \tag{II-10}$$

where ρ is the atmospheric density.

Assuming an inverse square gravitational force in addition to the previously discussed aerodynamic forces and moments, the translational and rotational equations of motion of the entry vehicle can be written as

$$\dot{h} = v \sin \gamma \tag{II-11}$$

$$\dot{v} = -g \sin \gamma + \frac{A}{m} \cos (\alpha + \varepsilon) + \frac{N}{m} \sin (\alpha + \varepsilon) - \frac{F_d}{m} \cos \varepsilon \tag{II-12}$$

$$\dot{\gamma} = \left(\frac{v}{r} - \frac{g}{v}\right) \cos \gamma + \frac{1}{v}\left[\frac{A}{m} \sin (\alpha + \varepsilon) - \frac{N}{m} \cos (\alpha + \varepsilon) - \frac{F_d}{m} \sin \varepsilon\right] \tag{II-13}$$

$$\dot{\phi} = \frac{v}{r} \cos \gamma \tag{II-14}$$

$$\dot{\theta} = \omega \tag{II-15}$$

$$\dot{\omega} = \frac{1}{I}\left[(z_p - z_g) A - (x_p - x_g) N + M + z_g F_d \cos \alpha - (x_g - x_d) F_d \sin \alpha\right] \tag{II-16}$$

where I denotes the vehicle (pitch) moment of inertia about the center of gravity, and acceleration of gravity g is given by

$$g = \frac{\mu}{r^2} \tag{II-17}$$

where μ is the gravitational constant. Vehicle mass is denoted by m.

The parachute terms, of course, only appear in the above equations of motion when the parachute is deployed. The parachute can be deployed at a desired altitude, and then released at a lower altitude.

The derivation of the rotational equations of motion assumes that gravity-gradient and attitude control moments are negligible. Out-of-plane rotational dynamics are neglected and are assumed to have negligible coupling with in-plane rotational dynamics.

During certain flight regimes it becomes necessary to modify the equations of motion to avoid excessive computational time. During the terminal velocity regime, for example, it becomes desirable to increase the integration step size, especially when terminal velocities are rather low. Experience has shown, however, that very small step sizes are required during the terminal velocity regime to prevent the onset of an integrator instability. Although the terminal velocity regime is physically characterized by $|\dot{v}| << 1$, an unstable $\dot{v}$ oscillation can occur during this regime if the step size is not chosen small enough. A solution to this problem was obtained by assuming quasi-static motion during the terminal velocity regime. This entails replacing equation (II-12) for $\dot{v}$ with the approximate equation $\dot{v} = 0$, and replacing v in the remaining equations with the terminal velocity v_T, which is computed from

$$v_T = \left[\frac{2\ mg\ |\sin\gamma|}{\rho\ (C_A\ S + C_D\ S_D)}\right]^{\frac{1}{2}} \qquad \text{(II-18)}$$

This equation was obtained by setting $\dot{v}$, α, and ε to zero and v_r to v_T in equation (II-12), and solving for v_T.

Yet another integrator instability can occur during the maximum dynamic pressure (max q) regime if integration step sizes are not sufficiently small. As the max q regime is entered, rotational oscillations with very high frequencies are induced by the aerodynamic moments acting on the entry vehicle. For the integrator to reproduce these oscillations accurately would require an extremely small step size; too large a step size would drive the integrator unstable. The instability normally becomes apparent in the unstable oscillation of the angle of attack during max q. A solution to this problem was devised by approximating the rotational motion during max q so small integration step sizes would not be required. If the actual entry vehicle is aerodynamically stable during max q, it is reasonable to assume that the actual angle of attack oscillations are characterized not only by high frequencies, but very small amplitudes as well. This permits one to set the angle of attack α to zero during max q without significantly disturbing the accuracy of the computed translational motion. Setting $\alpha = 0$ in equation (II-5) yields

$$\theta = \gamma - \phi + \varepsilon \tag{II-19}$$

Differentiating this equation, and assuming $\dot{\varepsilon}$ is negligible, we obtain

$$\omega = \dot{\gamma} - \dot{\phi} \tag{II-20}$$

Thus, during max q we obtain the rotational state from equations (II-19) and (II-20), instead of by integrating equations (II-15) and (II-16). This approximation is also applied during the initial phase of parachute deployment to avoid integration instabilities in the rotational equations.

B. PLANETARY ATMOSPHERE MODEL

The planetary atmosphere modeled in LTR assumes only radial variations in all atmospheric parameters; horizontal gradients are neglected. The hydrostatic equation

$$\frac{dp}{dh} = - \rho g \tag{II-21}$$

and the perfect gas law

$$\rho = \frac{pM}{RT} \tag{II-22}$$

are also assumed to be valid. In these equations p represents ambient pressure; g, acceleration of gravity; ρ, density; M, molecular weight; T, ambient temperature; and R, the universal gas constant.

Combining equations (II-21) and (II-22) yields

$$\frac{dp}{dh} = - \frac{p\,g\,M}{RT} \quad . \tag{II-23}$$

Assuming constant g, the integral of this equation has the form

$$p(h) = p(h_k) \exp \left[- \frac{g}{R} \int_{h_k}^{h} \frac{M(\zeta)}{T(\zeta)} \, d\zeta \right] \quad . \tag{II-24}$$

This integral is evaluated in LTR by assuming piece-wise linear variations of molecular weight M and temperature T with altitude:

$$T(h) = T(h_j) + \left[\frac{T(h_{j+1}) - T(h_j)}{h_{j+1} - h_j} \right] (h - h_j)$$

$$h_j \leq h \leq h_{j+1} \tag{II-25}$$

$$M(h) = M(h_i) + \left[\frac{M(h_{i+1}) - M(h_i)}{h_{i+1} - h_i} \right] (h - h_i)$$

$$h_i \leq h \leq h_{i+1} \tag{II-26}$$

where the set of altitudes h_j define the temperature breakpoints, and the set of altitudes h_i define the molecular weight breakpoints. Details of the evaluation of the integral in equation (II-24) are given in the subroutine ATMSET analysis section.

The molecular weight profile defined by equation (II-26) is computed from a set of mole fraction profiles for the component gases present in the planetary atmosphere. The same breakpoints h_i are used to define these profiles. Letting α_{ji} denote the mole fraction of the jth gas at altitude h_i, the molecular weight at h_i is given by

$$M(h_i) = \sum_j \alpha_{ji} \, m_j \tag{II-27}$$

where m_j is the molecular weight of the jth gas. Up to five gases can be defined in LTR.

A horizontal wind model is also available in LTR. Since a piece-wise linear variation of wind with altitude is assumed, the wind w at altitude h can be written as

$$w(h) = w(h_n) + \frac{w(h_{n+1}) - w(h_n)}{h_{n+1} - h_n} \quad (h - h_n)$$

$$h_n \leq h \leq h_{n+1} \qquad \text{(II-28)}$$

where the set of altitudes h_n define the horizontal wind breakpoints.

C. ACCELEROMETER AND GYRO MODELS

Two strapdown accelerometers, or velocity reference units, are modeled in LTR. A third accelerometer is not required because of the planar dynamic model assumed by LTR. The two accelerometers are nominally aligned with the x and z body axes of the entry vehicle and have location (x_m, z_m) relative to the origin of the body axes. Although a number of acclerometer error sources could be modeled, LTR assumes only misalignment, bias, and scale factor errors. The actual output from the accelerometer has quantized form and is not available as a continuous function of time. The derivation of the actual accelerometer output equation will be summarized in the following paragraphs.

The actual nongravitational acceleration at the location of the velocity reference unit (VRU) is given by

$$a_x = a_{xg} - \omega^2 \bar{x} + \dot{\omega} \bar{z} \qquad \text{(II-29)}$$

$$a_z = a_{zg} - \omega^2 \bar{z} - \dot{\omega} \bar{x} \qquad \text{(II-30)}$$

where $\bar{x}$ and $\bar{z}$ denote the offset of the VRU relative to the vehicle cg and are given by

$$\bar{x} = x_m - x_g \qquad \text{(II-31)}$$

$$\bar{z} = z_m - z_g \quad , \qquad \text{(II-32)}$$

and where a_{xg} and a_{zg} denote the x and z components of the actual nongravitational acceleration at the vehicle cg.

Because of accelerometer misalignment errors δ_1 and δ_2, the actual nongravitational acceleration experience by the VRU is given by

$$\dot{v}_x = a_x \cos \delta_1 - a_z \sin \delta_1 \tag{II-33}$$

$$\dot{v}_z = a_x \sin \delta_2 + a_z \cos \delta_2 \quad . \tag{II-34}$$

The actual output of the VRU is in quantized form and is corrupted by bias errors C_{bx} and C_{bz} and scale factor errors C_{sx} and C_{sz}. The equations for the quantized output are given by

$$v_{xq}(t_k) = Q \left\{ C_{sx} \int_o^{t_k} \dot{v}_x \, dt + C_{bx} \right\} \tag{II-35}$$

$$v_{zq}(t_k) = Q \left\{ C_{sz} \int_o^{t_k} \dot{v}_z \, dt + C_{bz} \right\} \tag{II-36}$$

where Q denotes the quantizing operator. If we let I denote the modified greatest integer operator, where I(x) is the integer part of x formed by truncating all digits to the right of the decimal, and Δq, the quantum level, then

$$Q(\ ) = I \left\{ \frac{(\ )}{\Delta q} \right\} \times \Delta q \tag{II-37}$$

Note that v_{xq} and v_{zq} are not true velocities. Rather, they represent the contents of the x and z integrating accelerometer registers at time t_k. They would be true velocities only if the inertial orientation of the vehicle had remained constant over the time interval $[0, t_k]$.

A single strapdown gyro, or attitude reference unit, is modeled in LTR. Three gyros are not required because of the planar dynamic model assumed by LTR. Although a number of gyro error sources could be modeled, LTR assumes only misalignment, bias, and scale factor errors. The actual output from the gyro, like that of the accelerometers, has quantized form and is not available as a continuous function of time. Derivation of the actual gyro output equation is summarized in the following paragraph.

The actual angular velocity of the vehicle and the attitude reference unit ARU in the plane of motion is denoted by ω. Because of the gyro misalignment error δ_3, the actual angular velocity experience by the ARU is given by

$$\dot{A}_\theta = \omega \cos \delta_3 \quad . \tag{II-38}$$

The actual output of the ARU is in quantized form and is corrupted by bias error $C_{b\theta}$ and scale factor error $C_{s\theta}$. The equation for the quantized output is given by

$$A_{\theta q}(t_k) = Q \left\{ C_{s\theta} \int_0^{t_k} \dot{A}_\theta \, dt + C_{b\theta} \, t_k \right\} \quad . \tag{II-39}$$

D. PREPROCESSING OF GYRO AND ACCELEROMETER MEASUREMENTS

The quantized accelerometer and gyro data are not processed directly by the navigation filter, but must first be preprocessed. This preprocessing consists of smoothing the quantized data to generate not only smoothed acceleration and attitude angle, but also angular velocity and angular acceleration. The smoothed angular quantities are particularly important for operation of the mode A reconstruction process. The LTR preprocessor employs a five-point central-point smoother, which simply means that five quantized data points are used to determine smoothed data and their derivatives at the center of the five-point interval. The smoothing of $A_{\theta q}$ data will be discussed in more detail in the following paragraph. The same method is used to smooth v_{xq} and v_{zq}.

Suppose we wish to obtain smoothed attitude θ_m, angular velocity ω_m, and angular acceleration $\dot{\omega}_m$ at $t = t_k$. Then, as indicated in Figure II-3, smoothing will be performed using all quantized attitude data over the interval $[t_{k-2}, t_{k+2}]$. We assume $\theta_m(t)$ can be expressed as a quadratic function over this interval, so that

$$\theta_m(t) = C_1 + C_2 (t - t_k) + C_3 (t - t_k)^2 \quad . \tag{II-40}$$

The coefficients C_1, C_2, and C_3 are chosen to obtain a least-squares fit to the data points $A_{\theta q}(t_{k-2})$ through $A_{\theta q}(t_{k+2})$. The solution to this problem is given by the following equations:

$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} = (B^T B)^{-1} B \begin{bmatrix} A_{\theta q}(t_{k-2}) \\ \vdots \\ A_{\theta q}(t_{k+2}) \end{bmatrix} \tag{II-41}$$

where

$$B = \begin{bmatrix} 1 & -2\Delta & 4\Delta^2 \\ 1 & -\Delta & 2\Delta^2 \\ 1 & 0 & 0 \\ 1 & \Delta & 2\Delta^2 \\ 1 & 2\Delta & 4\Delta^2 \end{bmatrix} \tag{II-42}$$

and $\Delta = t_k - t_{k-1}$. Having determined the coefficients C_1, C_2, and C_3, we evaluate equation (II-40) at $t = t_k$ to obtain:

$$\theta_m(t_k) = C_1 \quad . \tag{II-43}$$

Evaluating the first two derivatives of equation (II-40) at $t = t_k$ yields

$$\omega_m(t_k) = C_2 \tag{II-44}$$

$$\dot{\omega}_m(t_k) = 2\ C_3 \quad . \tag{II-45}$$

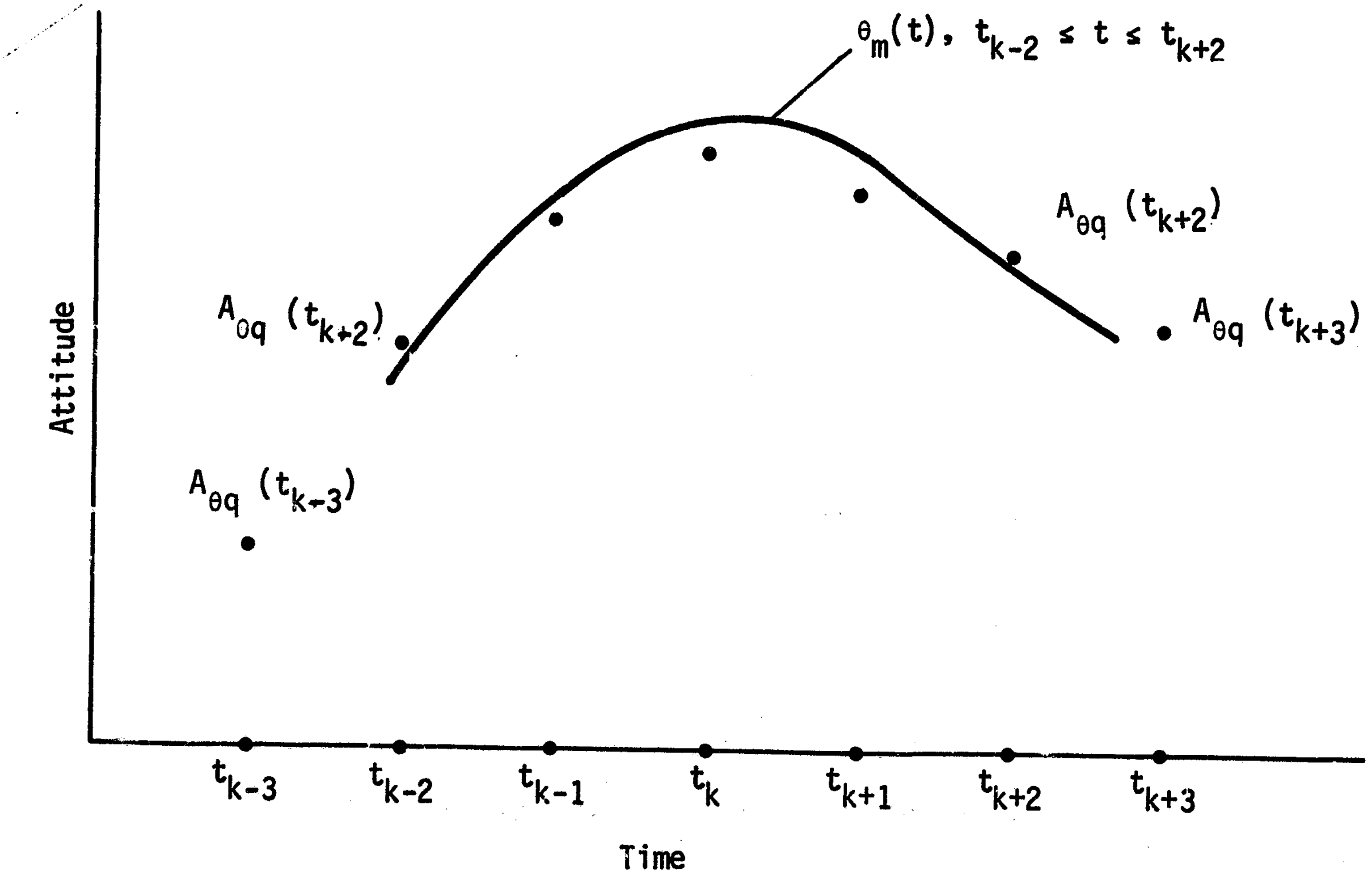

Figure II-3 Smoothing of Quantized Data

Smoothed acceleration data $a_{xm}(t_k)$ and $a_{zm}(t_k)$ are similarly obtained from the quantized accelerometer data. Additional information is available in the subroutine PRPRØS and SMØØT2 documentation.

E. OTHER ONBOARD MEASUREMENT MODELS

In addition to the gyro and axial and normal accelerometers discussed in the previous section, several other onboard measurement types are modeled in the LTR program. These models are summarized below.

1. Stagnation Temperature Measurement

The stagnation temperature measurement is given by

$$T_o = T \left(1 + \frac{\gamma - 1}{2} M^2\right) \tag{II-46}$$

where T is ambient temperature; γ, ratio of specific heats; and M, Mach number. The actual measurement is computed by multiplying the ideal measurement times a scale factor error, and adding on a bias and noise. The noise error is computed by sampling from a gaussian distribution.

2. Stagnation Pressure Measurement

The stagnation pressure measurement is a function of the Mach number regime and is computed using one of the following three equations:

$M \geq 3$:

$$p_o = \frac{1}{2} C_p \rho v_r^2 + p \tag{II-47}$$

$$C_p = 2 - \varepsilon; \tag{II-48}$$

$1 \leq M < 3$:

$$p_o = \frac{1}{2} C_p \rho v_r^2 + p \tag{II-49}$$

$$C_p = \frac{p}{8}\left[\left(\frac{\gamma + 1}{2} M^2\right)^{\gamma/\gamma-1} \times \left(\frac{\gamma + 1}{2\gamma M^2 - \gamma + 1}\right)^{1/\gamma-1} - 1\right] \quad ; \qquad \text{(II-50)}$$

$M < 1$:

$$p_o = p\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/\gamma-1} \qquad \text{(II-51)}$$

where p_o is stagnation pressure; p, ambient pressure; C_p, coefficient of pressure; M, Mach number; γ, ratio of specific heats; and ε, ratio of densities in front of and behind the shock wave. The ratio ε is a tabulated function of v_r. The actual measurement is computed by multiplying the ideal measurement times a scale factor error, and adding on a bias and noise. The noise error is computed by sampling from a gaussian distribution.

3. Radar Altimeter Measurement

The onboard radar altimeter measurement is defined as the shortest distance between the spacecraft and the terrain of the planet within the limits of the altimeter sweep angle. Figure II-4 depicts the relevant radar altimeter and terrain height geometry. The spacecraft has altitude h above the mean planet surface. The altimeter has a symmetrical sweep angle of 2η. Terrain height τ above the mean surface is assumed to have the form

$$\tau = C_1 + C_2 \sin (C_3 \phi' + C_4) + C_5 \cos (C_6 \phi' + C_7) \qquad \text{(II-52)}$$

where constants C_1, C_2, ..., C_7 are chosen to approximate the terrain height profile of the planet, and ϕ' represents the difference between the spacecraft downrange angle ϕ and angular displacement of the terrain due to planet rotation, and is given by

$$\phi' = \phi - \vec{\omega}_p \cdot \vec{e}_n (t - t_o) \quad . \qquad \text{(II-53)}$$

In this equation $\vec{\omega}_p$ denotes the planet inertial angular velocity $\vec{e}_n$ is a unit vector normal to the entry plane (and in the direction of the spacecraft orbit angular momentum). The distance $\tilde{h}$ between the spacecraft and the terrain is given by

$$\tilde{h} = \left[(h + R_p)^2 + w^2 - 2w (h + R_p) \cos (\tilde{\phi} - \phi)\right]^{\frac{1}{2}} \qquad \text{(II-54)}$$

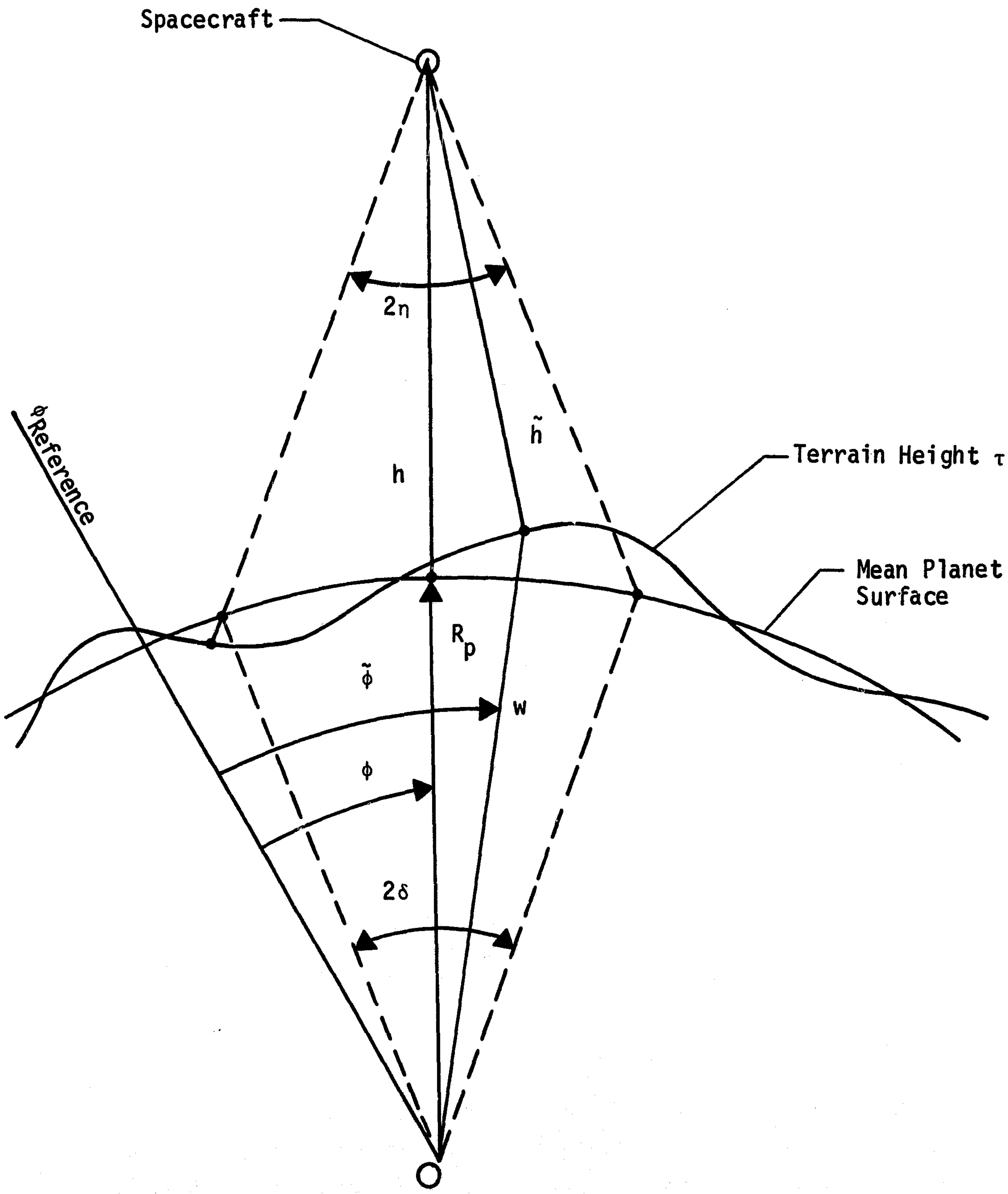

Figure II-4 Altimeter and Terrain Height Geometry where w is the distance from the center of the planet to the actual planet surface. Minimization of $\tilde{h}$ is equivalent to minimization of the function

$$f = w^2 - 2w\,(h + R_p)\cos(\tilde{\phi} - \phi) \qquad \text{(II-55)}$$

The function f is minimized using a direct search over the interval $[\phi-\delta,\ \phi+\delta]$ with respect to $\tilde{\phi}$. The angle δ is given by

$$\delta = \sin^{-1}\left[\frac{(R_p + h)\sin\eta}{R_p}\right] - \eta \qquad \text{(II-56)}$$

The actual radar altimeter measurement is computed by multiplying the minimum $\tilde{h}$ times a scale factor error and adding on a bias and noise. The noise error is computed by sampling from a gaussian distribution.

4. Angle of Attack

The ratio of measured accelerations a_z/a_x can be used to define an angle of attack measurement $\tilde{\alpha}$. The ratio of vehicle lift L and drag D can be related to a_x, a_z, and $\tilde{\alpha}$ according to the equation

$$\frac{L}{D} = \frac{a_z\cos\tilde{\alpha} - a_x\sin\tilde{\alpha}}{a_x\cos\tilde{\alpha} + a_z\sin\tilde{\alpha}} \qquad \text{(II-57)}$$

Solving for $\tilde{\alpha}$, we obtsin

$$\tan\tilde{\alpha} = \frac{\dfrac{a_z}{a_x} - \dfrac{L}{D}}{1 + \left(\dfrac{a_z}{a_x}\right)\left(\dfrac{L}{D}\right)} \qquad \text{(II-58)}$$

The ratio L/D has the form

$$\frac{L}{D} = k\,\tilde{\alpha} \qquad \text{(II-59)}$$

where k is a tabulated function of Mach number. To compute the angle of attack measurement $\tilde{\alpha}$, equation II-58 is solved iteratively using

$$\tilde{\alpha} = \frac{\frac{a_z}{a_x}}{k + 1} \qquad \text{(II-60)}$$

as the initial guess.

F. EARTH-BASED RANGE AND DOPPLER MEASUREMENT MODELS

The geometry of earth-based tracking is shown in Figure II-5. The tracking station is located relative to the geocentric equatorial coordinate system $x_o y_o z_o$ by the latitude θ, longitude λ, Greenwich hour angle GHA of the vernal equinox, earth radius R_o, and altitude h above the mean earth sphere. The spacecraft has position $\vec{r}$ and velocity $\dot{\vec{r}}$ relative to the target planet. These vectors are normally expressed relative to the planetocentric ecliptic coordinate system $x_\varepsilon y_\varepsilon z_\varepsilon$.

The range ρ between the spacecraft and the tracking station is given by

$$\rho = |\vec{r} + \vec{r}_p - \vec{r}_e - \vec{r}_s| \qquad \text{(II-61)}$$

where $\vec{r}_p$ and $\vec{r}_e$ denote the position of the target planet and the earth, respectively, relative to the sun, and $\vec{r}_s$ denotes the position of the tracking station relative to the center of the earth. The heliocentric ecliptic components of $\vec{r}_s$ are given by

$$x_s = (R_o + h) \cos\theta \cos G \qquad \text{(II-62)}$$

$$y_s = (R_o + h) [\cos\theta \cos\varepsilon \sin G + \sin\theta \sin\varepsilon] \qquad \text{(II-63)}$$

$$z_s = (R_o + h) [- \cos\theta \sin\varepsilon \sin G + \sin\theta \cos\varepsilon] \qquad \text{(II-64)}$$

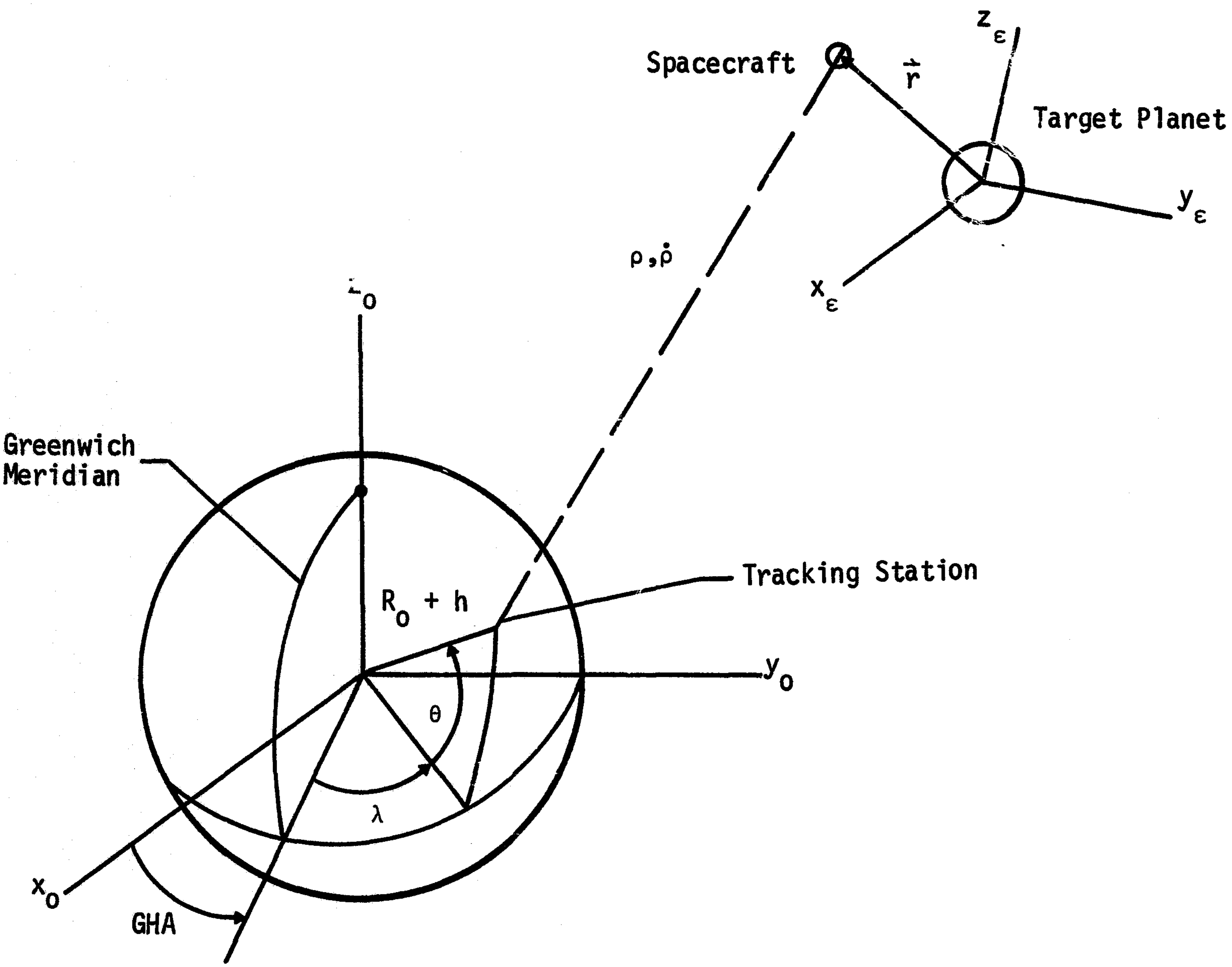

Figure II-5 Earth-Based Tracking Geometry where ε is the obliquity of the ecliptic, and

$$G = \lambda + \omega_e (t - t_o) + \text{GHA}\ (t_o) \quad . \qquad \text{(II-65)}$$

In this last equation, ω_e represents the inertial angular velocity of the earth; $t - t_o$, the time interval since epoch t_o; and GHA (t_o), the Greenwich hour angle at epoch.

The range rate $\dot\rho$ between the spacecraft and the tracking station is given by

$$\dot\rho = \dot{\vec\rho} \cdot \vec e_\rho = \frac{\dot{\vec\rho} \cdot \vec\rho}{\rho} \qquad \text{(II-66)}$$

where $\vec e_\rho$ is a unit vector directed along the range vector $\vec\rho$, and $\dot{\vec\rho}$ is given by

$$\dot{\vec\rho} = \dot{\vec r} + \dot{\vec r}_p - \dot{\vec r}_e - \dot{\vec r}_s \qquad \text{(II-67)}$$

where $\dot{\vec r}_p$ and $\dot{\vec r}_s$ denote the velocity of the target planet and the earth, respectively, relative to the sun, and $\dot{\vec r}_s$ denotes the velocity of the tracking station relative to the center of the earth. The heliocentric ecliptic components of $\dot{\vec r}_s$ are given by

$$\dot x_s = - \omega_e (R_o + h) \cos\theta \sin G \qquad \text{(II-68)}$$

$$\dot y_s = \omega_e (R_o + h) \cos\theta \cos\varepsilon \cos G \qquad \text{(II-69)}$$

$$\dot z_s = - \omega_e (R_o + h) \cos\theta \sin\varepsilon \cos G \quad . \qquad \text{(II-70)}$$

Actual range and doppler (range-rate) measurements are computed in LTR by incorporating the effects of various error sources in the range and doppler measurements computed from the previous equations. Three types of range and doppler error sources are modeled in LTR: (1) station location errors, (2) instrument bias and noise, and (3) refractivity effects of the planetary atmosphere. Station location errors are modeled as biases in station latitude, longitude, and altitude. Instrument noise is computed in LTR by sampling from a gaussian distribution.

III. RECURSIVE STATE ESTIMATION

A. RECURSIVE ESTIMATION ALGORITHM

The recursive estimation algorithm refers to the computational procedure that combines the dynamic model and measurement information to generate estimates of the deviation of the basic system state from the nominal and the covariances associated with these estimates. It is also possible to augment the state vector with parameters that are known with some uncertainty. The basic estimation algorithm treats all uncertain parameters as solve-for parameters, i.e., the estimation algorithm generates estimates of these parameters as well as estimates of the basic state. Continued processing of measurements will often reduce state covariances to unrealistically low values, a situation that can induce divergence in the estimation algorithm. One method used to prevent divergence is to incprorate a consider option in the algorithm and divide all uncertain parameters into either solve-for or consider parameters. Consider parameters are not estimated by the algorithm, nor can their covariance be reduced by measurement processing. In essence, by not solving for all parameters in the uncertain parameter set, the algorithm acknowledges that the nominal dynamic and measurement parameter values do not fully describe the real world, and that it is impossible to reduce parameter uncertainties indefinitely.

Thus the basic state vector is augmented with both solve-for parameters and consider parameters. The consider parameters are further categorized into dynamic-consider parameters, measurement-consider parameters, and dynamic/measurement-consider parameters. A dynamic-consider parameter appears in the dynamic equations only, whereas a measurement-consider parameter appears in the measurement equations only. Dynamic/consider parameters appear in both.

Before presenting the estimations algorithm, the dynamic and measurement models will be described. The set of dynamic equations is assumed to have been linearized about a nominal trajectory. The augmented state vector of deviations from nominal may be written in partitioned form as

$$x^A = \begin{bmatrix} x \\ q \\ u \\ v \\ w \end{bmatrix} \qquad \text{(III-1)}$$

where

x = basic state vector,

q = vector of solve-for parameters,

u = vector of dynamic-consider parameters,

v = vector of measurement-consider parameters,

w = vector of dynamic/measurement-consider parameters.

The linearized dynamic model is assumed to have the form

$$x^A_{k+1} = \phi^A_{k+1,k}\, x^A_k + q^A_{N_{k+1,k}} \qquad \text{(III-2)}$$

where $\phi^A_{k+1,k}$ is the augmented state transition matrix over the interval $[t_k, t_{k+1}]$ and $q^A_{N_{k,k+1}}$ represents the effects of dynamic noise over the interval. Since the dynamic noise affects the basic state only,

$$q^A_{N_{k+1,k}} = \begin{bmatrix} q_{N_{k+1,k}} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad \text{(III-3)}$$

The linearized measurement model is assumed to have the form

$$y_k = H^A_k\, x^A_k + \eta_k \qquad \text{(III-4)}$$

where y_k represents the deviation of the observation from the nominal observation at t_k, H^A_k relates changes in x^A_k to changes in the measurement y_k, and η_k represents the measurement noise.

Under the usual assumptions of white noise, the dynamic and measurement noise statistics are described by

$$E\left[q_{N_k}\right] = E\left[\eta_k\right] = 0$$

$$E\left[q_{N_j}\ q_{N_k}^T\right] = Q_{N_k}\ \delta_{jk}$$

$$E\left[\eta_j\ \ \eta_k^T\right] = R_k\ \delta_{jk}$$

The equations constituting the recursive estimation algorithm are of two types -- prediction equations and filtering equation. The prediction equations describe the behavior of the state and covariance matrix as they are propagated forward in time with no measurement processing. The state prediction equation is simply equation III-2 without the dynamic noise term. The filtering equations define the covariance updating procedure whenever a measurement is processed. Details of their derivation may be found in Reference 3.

The covariance of the augmented state is defined as

$$P_k^A = E\left[\left(\hat{x}_k^A - x_k^A\right)\left(\hat{x}_k^A - x_k^A\right)^T\right]$$

where $\hat{x}_k^A$ is the estimated deviation from nominal and x_k^A is the actual deviation from nominal. The covariance prediction equation that relates the covariance following the processing of a measurement at t_k, P_k^{A+}, to the covariance prior to processing the next measurement at t_{k+1}, P_{k+1}^{A-}, is given by

$$P_{k+1}^{A-} = \Phi_{k+1,k}^A\ P_k^{A+}\ \Phi_{k+1,k}^{A\ T} + Q_{N_{k+1,k}} \qquad \text{(III-5)}$$

Before presenting the filtering equations, the measurement residual at t_k must be defined. The measurement residual, ε_k, is the difference between the "actual" measurement y_k^a and the estimated or expected measurement y_k^e. y_k^a is composed of an error-free component, $\underline{y}_k$, based on the actual state deviation, x^A plus a random noise component ν_k and a bias component b

$$y_k^a = \underline{y}_k + \nu_k + b \qquad \text{(III-6)}$$

The estimated or expected measurement, y_k^e, is composed of an error-free component $\tilde{y}_k$ based on the nominal state, plus a measurement deviation based on the estimated state deviation $\hat{x}^A$

$$y_k^e = \tilde{y}_k + H_k^A \hat{x}_k^{A-} \quad . \tag{III-7}$$

The measurement residual is then simply

$$\varepsilon_k = y_k^a - y_k^e \quad . \tag{III-8}$$

The filler equations involve equations for the measurement residual covariance matrix J, the augmented Kalman gain matrix K^A, the covariance update equation, and the state update equation. The first two equations are

$$J_{k+1} = H_{k+1}^A \, P_{k+1}^{A-} \, H_{k+1}^{A\,T} + R_{k+1} \tag{III-9}$$

$$K_{k+1}^A = P_{k+1}^{A-} \, H^{AT} \, (J_{k+1})^{-1} \quad . \tag{III-10}$$

Unfortunately there is no compact formulation for the state and covariance update equations in terms of the above matrices. This is true because the consider parameters and their covariances are not updated and thus require special handling. An artifice that may be used is to partition the rows of K_{k+1}^A corresponding to the partition of the augmented state vector in equation III-12:

$$K_{k+1}^A = \begin{bmatrix} K1_{k+1} \\ K2_{k+1} \\ K3_{k+1} \\ K4_{k+1} \\ K5_{k+1} \end{bmatrix} \tag{III-11}$$

If a modified gain matrix is defined by

$$K_{k+1}^{Am} = \begin{bmatrix} K1_{k+1} \\ K2_{k+1} \\ 0 \\ 0 \\ 0 \end{bmatrix} , \qquad \text{(III-12)}$$

then the estimated state update equation may be written

$$\hat{x}_{k+1}^{A+} = \hat{x}_{k+1}^{A-} + K_{k+1}^{Am} \varepsilon_{k+1} \quad . \qquad \text{(III-13)}$$

The covariance update equation may also be written in terms of K_{k+1}^{Am}; however, only the partitions of P_{k+1}^{A+} on and above the diagonal are valid

$$P_{k+1}^{A+} = P_{k+1}^{A-} - K_{k+1}^{Am} H_{k+1}^{A} P_{k+1}^{A-} \quad . \qquad \text{(III-14)}$$

To take advantage of the sparceness and symmetry of the above equations, they are computed in partitioned form. The partitioned equations are given in the subroutine FILTER analysis.

B. MEASUREMENT NOISE MODELS

This section discusses the measurement noise models used to compute the measurement noise covariance matrix R appearing in equation (III-9).

The measurement noise covariance for an accelerometer, stagnation pressure, angle of attack, range, or doppler measurement is assumed to be a constant. For a stagnation pressure measurement p_o, R is a two-valued function:

$$R_{p_o} = \begin{cases} C_1 , & p_o \geq 20 \text{ millibars} \\ C_2 , & p_o < 20 \text{ millibars} \end{cases} \quad . \qquad \text{(III-15)}$$

The measurement noise covariance for a radar altimeter measurement $\tilde{h}$ can be either set to a constant or computed as a function of the measurement itself. Currently, with the latter option

$$R = \text{maximum} \begin{cases} [.005\,\tilde{h},\ .051] & ,\ \tilde{h} \geq 6 \\ [.015\,\tilde{h},\ .00051] & ,\ \tilde{h} < 6 \end{cases} \quad . \tag{III-16}$$

Although the doppler measurement noise is assumed to be constant, the modeled doppler noise can be adjusted to account for differences between the actual and modeled sample rates using the approximation

$$\sigma_{\dot{\rho}} = \sigma_{\dot{\rho}_{\text{actual}}} \left(\frac{1}{T_s^{1/2}} \right) \tag{III-17}$$

where $\sigma_{\dot{\rho}_{\text{actual}}}$ is the actual or original sample rate (typically 1 mm/s for a 1-minute count time), and T_s is the spacing between successive doppler points used in the model. For additional information concerning this approximation, see Reference 4.

C. COMPUTATION OF STATE TRANSITION AND OBSERVATION MATRICES

The state transition matrices describe the behavior of a dynamic system in the neighborhood of a nominal trajectory. Before presenting the technique used in the LTP program for computing state transition matrices, the deviation of the general form of the dynamic system modeled in LTR will be summarized.

The nonlinear equations describing the motion of the lander or probe have the form

$$\dot{X}^A = f\ (X^A,\ t) \tag{III-18}$$

where X^A denotes the augmented state vector. If equation (III-18) is linearized about a nominal trajectory, it takes the form

$$\dot{x}^A = \frac{\partial f}{\partial X^A}\, x^A \tag{III-19}$$

where x^A represents small deviations from the nominal augmented state $\tilde{X}^A$. The partial derivative is evaluated along the nominal trajectory.

The discrete solution of equation (III-19) over the interval $[t_k, t_{k+1}]$ is given by

$$x^A_{k+1} = \Phi(t_{k+1}, t_k)\, x^A_k \quad . \tag{III-20}$$

If the augmented state vector is partitioned into the basic state vector, x; solve-for parameter vector, q; dynamic-consider parameter vector, u; measurement parameter vector, v; and dynamic/measurement parameter vector, w; it is possible to make a corresponding partition of the state transition matrix Φ. Before writing Φ in partitioned form, it should be observed that all solve-for and consider parameters are assumed to be constant. This means that all partitions of Φ will be either zero matrices or identity matrices except for those associated with the basic state vector. Thus the partitioned form of Φ is

$$\Phi = \begin{bmatrix} \phi & \psi & \theta_u & 0 & \theta_w \\ 0 & I & 0 & 0 & 0 \\ 0 & 0 & I & 0 & 0 \\ 0 & 0 & 0 & I & 0 \\ 0 & 0 & 0 & 0 & I \end{bmatrix} \tag{III-21}$$

The specification of the time interval has been dropped in equation (III-21) and will henceforth be assumed to be $[t_k, t_{k+1}]$ unless shown otherwise.

A numerical differencing technique was chosen for the computation of the partitions of the state transition matrix. This was done because of the resulting ease with which the solve-for/consider parameter set may be changed or expanded. Before describing the numerical differencing technique, let us adopt the following notation. Express the perturbation in the augmented state at time t_{k+1} due to a perturbation in the state at t_k or x_k as $x^A(t_{k+1}; x_k, t_k)$ and let the jth column of Φ be designated by $\Phi_{\cdot j}$. Now consider the special case of equation (III-20) in which x^A_k is a vector whose only nonzero element is the jth element:

$$x_k^A = [0, \cdots, 0, \delta_j, 0, \cdots, 0]^T = d_j \quad . \qquad \text{(III-22)}$$

Equation (III-20) becomes

$$x^A\,(t_{k+1};\, d_j,\, t_k) = \Phi_{.j}\,\delta_j \quad , \qquad \text{(III-23)}$$

from which we obtain the jth column of Φ as

$$\Phi_{.j} = \frac{x^A\,(t_{k+1};\, d_j,\, t_k)}{\delta_j} \; . \qquad \text{(III-24)}$$

The numeration of this expression is evaluated by integrating the state equations over the interval $[t_k, t_{k+1}]$ as follows. Let

$$I_j = \int_{t_k}^{t_{k+1}} f\left(X^A(\tau) + d_j,\ \tau\right) d\tau = X^A\left(t_{k+1};\ X_k^A + d_j,\ t_k\right) - \left(X_k^A + d_j\right) \qquad \text{(III-25)}$$

and

$$I = \int_{t_k}^{t_{k+1}} f\left(X^A(\tau),\ \tau\right) d\tau = X^A\left(t_{k+1};\ X_k^A,\ t_k\right) - X_k^A \quad ; \qquad \text{(III-26)}$$

then

$$x^A(t_{k+1};\, d_j,\, t_k) = I_j - I + d_j \quad . \qquad \text{(III-27)}$$

Thus the state transition matrix is computed by evaluating the integral I once and the integral I_j once for each column of Φ.

The computation of partitions of the state transition matrix is controlled by the subroutine STM.

Observation matrices relate the deviations from nominal in the augmented state variable to deviations in observables from their nominal values. The general nonlinear observation equation has the form

$$Y = Y\ (X^A\ t) \tag{III-28}$$

where Y denotes the observable. The linearized versions of equation (III-28) is

$$y = \frac{\partial Y}{\partial X^A}\, x^A = H^A\, x^A \tag{III-29}$$

where y and x^A represent deviations from the nominal values of $\tilde{Y}$ and $\tilde{X}^A$.

If we partition the augmented state vector as before, equation (III-29) may be written as

$$y = [H \vdots M \vdots 0 \vdots L \vdots G] \begin{bmatrix} x \\ q \\ u \\ v \\ w \end{bmatrix} \tag{III-30}$$

The third partition is zero since the dynamic-consider parameters do not affect the observables.

The columns of the augmented observation matrix H^A are found by numerical differencing just as with the state transition matrix. However, this time the method is more direct since no integration of state equations is required. If we set $x^A = d_j$ as before, equation (III-29) may be written

$$y = Y\left(X^A + d_j,\ t\right) - Y\left(X^A,\ t\right) = H^A_{\cdot j}\ \delta_j \quad . \tag{III-31}$$

Thus

$$H^{A}_{\cdot j} = \frac{Y\left(\overline{X}^{A} + d_{j},\ t\right) - Y\left(\overline{X}^{A},\ t\right)}{j} \quad . \qquad \text{(III-32)}$$

The computation of the partitions of the observation matrix are controlled by the subroutine HMM.

D. QUASI-LINEAR FILTERING EVENT

The quasi-linear filtering event option is included in the LTR program as an additional means to combat filter divergence. One of the several causes of filter divergence is the failure of the linearization assumption on which the entire estimation process is based. If the vehicle or the environment departs markedly from the current nominal value, the linearization assumptions can become invalid. The quasi-linear filtering event overcomes this difficulty by updating the nominal trajectory to correspond to the present estimate of the state. Specifically, updating the nominal trajectory results in better computation of the state transition and observation matrix partitions used in the recursive estimation algorithm.

Letting t_j denote the time of the quasi-linear filtering event, and using the $(\ )^-$ and $(\ )^+$ notations to indicate values immediately before and after the event, respectively, the basic state and solve-for parameter vectors are updated as follows:

$$\begin{aligned} \tilde{X}_j^+ &= \tilde{X}_j^- + \hat{x}_j^- \\ \tilde{Q}_j^+ &= \tilde{Q}_j^- + \hat{q}_j^- \\ \hat{x}_j^+ &= 0 \\ \hat{q}_j^+ &= 0 \end{aligned} \qquad \text{(III-33)}$$

where the superscript ˜ indicates the nominal value and the superscript ^ indicates an estimated value.

IV. MODE A STATE ESTIMATION AND ATMOSPHERE RECONSTRUCTION

A. MODE A DYNAMIC MODEL

A five-dimensional primary state vector is employed in the mode A reconstruction process. This state vector is defined by

$$x = (h, v, \gamma, \phi, p)^T \tag{IV-1}$$

where

h = vehicle altitude

v = vehicle velocity

γ = vehicle flightpath angle

ϕ = vehicle downrange angle

p = ambient atmospheric pressure.

The four vehicle state variables are defined in Figure II-1. These four state variables comprise the entire mode B primary state vector. In mode B, atmospheric pressure is not treated as a state variable.

The fundamental difference between the mode A and mode B reconstruction processes lies in the manner in which nongravitational forces are modeled. The general translational equations of motion can be written symbolically as

$$\dot{x} = g(x) + f(x) \tag{IV-2}$$

where in this case x represents the translational state; $g(x)$, the gravitational acceleration acting on the vehicle; and $f(x)$, the nongravitational acceleration. The mathematical form of $g(x)$ is well known and can be used to accurately model gravitational acceleration. This is not the case for the nongravitational acceleration $f(x)$, particularly when $f(x)$ represents an aerodynamic acceleration as is the case for the planetary entry problem. Nevertheless, mode B does use a mathematical model for $f(x)$, which also requires the selection of a mathematical model of the planetary atmosphere. Mode A, however, dispenses entirely with the attempt to mathematically model $f(x)$. Instead, mode A uses acceleration and gyro data to model f(x). In other words, f(x) is replaced by

$$f\left(a_{x_m}, a_{z_m}, \theta_m\right)$$

where a_{x_m} and a_{z_m} represent (smoothed) axial and normal accelerometer (VRU) data, respectively, and θ_m represents (smoothed) gyro (ARU) attitude data. Except for a nominal molecular weight profile, mode A requires no model of the planetary atmosphere. The axial acceleration a_{x_m}, however, is essential for mode A operation.

The remainder of this section will treat the mode A dynamic model in more detail. The equations of motion are summarized as

$$\dot{h} = v \sin \gamma \qquad \text{(IV-3)}$$

$$\dot{v} = -g \sin \gamma + a_{x_c} \cos (\alpha + \varepsilon) + a_{z_c} \sin (\alpha + \varepsilon) \qquad \text{(IV-4)}$$

$$\dot{\gamma} = \left(\frac{v}{r} - \frac{g}{v}\right) \cos \gamma + \frac{1}{v} \left[a_{x_c} \sin (\alpha + \varepsilon) - a_{z_c} \cos (\alpha + \varepsilon)\right] \qquad \text{(IV-5)}$$

$$\dot{\phi} = \frac{v}{r} \cos \gamma \qquad \text{(IV-6)}$$

$$\dot{p} = - g \rho \dot{h} \qquad \text{(IV-7)}$$

where a_{x_c} and a_{z_c} represent corrected axial and normal accelerometer data, respectively, and $\alpha + \varepsilon$ can be obtained from equation (II-5)

$$\alpha + \varepsilon = \theta_c + \theta_o + \phi - \gamma \qquad \text{(IV-8)}$$

where attitude θ has been represented as the sum of the initial attitude θ_o and the change in (corrected) attitude θ_o since t_o. This permits the mode A filter to treat θ_o as a solve-for or consider parameter. The angle ε is computed from equations (II-3) and (II-4). A nominal wind profile is assumed by mode A to compute the horizontal wind velocity v_w. Equation (IV-7) is just the time-differential form of the hydrostatic equation, where ρ represents atmospheric density.

Accelerations a_{x_c} and a_{z_c} and attitude θ_c are referred to as corrected quantities since the measured accelerations a_{x_m} and a_{z_m} and the measured attitude θ_m have been corrected or calibrated for scale factor, bias, and misalignment errors. The equations relating corrected quantities to measured quantities are summarized as

$$a_{x_c} = \frac{1}{\cos\left(\delta_{1_c} - \delta_{2_c}\right)} \left\{ \frac{a_{x_m} - c_{sx}}{c_{bx}} \cos \delta_{2_c} + \frac{a_{z_m} - c_{sz}}{c_{bz}} \sin \delta_{1_c} \right\} + \omega_c^2 \, \bar{x} - \dot{\omega}_c \, \bar{z} \qquad \text{(IV-9)}$$

$$a_{z_c} = \frac{1}{\cos\left(\delta_{1_c} - \delta_{2_c}\right)} \left\{ - \frac{a_{x_m} - c_{sx}}{c_{bx}} \sin \delta_{2_c} + \frac{a_{z_m} - c_{sz}}{c_{bz}} \cos \delta_{1_c} \right\} + \omega_c^2 \, \bar{z} + \dot{\omega}_c \, \bar{x} \qquad \text{(IV-10)}$$

$$\theta_c = \frac{1}{c_{s\theta}} \left\{ \theta_m - c_{d\theta} \, t \right\} \qquad \text{(IV-11)}$$

where c_{sx}, c_{sz}, and $c_{s\theta}$ represent scale factors; c_{bx}, c_{bz} and $c_{b\theta}$, biases; and $c_{d\theta}$, gyro drift error. Equations (II-31) and (II-32) define the accelerometer offsets $\bar{x}$ and $\bar{z}$. Corrected angular velocity ω_c and angular acceleration $\dot{\omega}_c$ are given by

$$\omega_c = \frac{1}{c_{s\theta}} \left\{ \omega_m - c_{d\theta} \right\} \qquad \text{(IV-12)}$$

$$\dot{\omega}_c = \frac{\dot{\omega}_m}{c_{s\theta}} \qquad \text{(IV-13)}$$

where ω_m and $\dot{\omega}_m$ are measured angular velocity and angular acceleration, respectively. Misalignment angles δ_{1_c} and δ_{2_c} are calibrated using

$$\delta_{1_c} = \delta_1 - c_{b\delta_1} \tag{IV-14}$$

$$\delta_{2_c} = \delta_2 - c_{b\delta_2} \tag{IV-15}$$

where δ_1 and δ_2 are the nominal misalignment angles, and $c_{b\delta_1}$ and $c_{b\delta_2}$ are misalignment biases.

Returning to equation (IV-7), it is apparent that a method for obtaining density ρ must be available before this final state equation can be integrated. Unlike mode B, an atmospheric model cannot be used for generating ρ. Instead, in mode A an approximate relationship between ρ and a_{x_c} is used. Comparing equations (IV-4) and (II-12), neglecting temporarily the parachute term in equation (II-12), and using equation (II-6), we obtain

$$q = -\frac{m}{C_a S} a_{x_c} \quad . \tag{IV-16}$$

The parachute effect can be incorporated approximately by writing

$$q = -\frac{m}{(C_A S + C_D S_D)} a_{x_c} \quad . \tag{IV-17}$$

Having related dynamic pressure q to a_{x_c}, it is a simple matter to relate ρ to a_{x_c} since

$$\rho = \frac{2q}{v_r^2} \tag{IV-18}$$

where v_r is the relative velocity given by equation (II-2). With density ρ available from equations (IV-17) and (IV-18), equation (IV-7) can be integrated to obtain atmospheric pressure p. Atmospheric temperature is then directly available from the equation of state

$$T = \frac{p\,M}{\rho\,R} \qquad \text{(IV-19)}$$

where M is the molecular weight and R is the universal gas constant. Molecular weight M is computed from the nominal mole fraction profiles of the component gases in the planetary atmosphere.

If a normal accelerometer is not available, the following substitutions must be made in the previous equations:

$$\left.\begin{aligned} a_{z_c} &= 0 \\ \delta_{2_c} &= 0 \end{aligned}\right\} \qquad \text{(IV-20)}$$

If a gyro is not available, we assume

$$\left.\begin{aligned} \omega_c &= 0 \\ \dot{\omega}_c &= 0 \end{aligned}\right\} \qquad \text{(IV-21)}$$

and delete equation (IV-11).

A quasi-static dynamic model option is also available in mode A. When quasi-static motion is assumed, equation (IV-4) is deleted and velocity is computed from equation (II-18).

B. MODE A RECURSIVE TRAJECTORY AND ATMOSPHERE RECONSTRUCTION

The equations presented in Section A are used to compute the nominal trajectory and state transition matrices (via numerical differencing) required by the linear recursive estimation process described in Chapter III. Nominal observations and observation matrices are computed using the equations presented in Chapter II.D and II.E (Part I), with "actual" parameter values replaced by nominal parameter values. Since mode A already employs accelerometer data in its dynamic model, accelerometer data are not treated as a (filtered) measurement in mode A as in mode B. Neither are gyro data treated as a (filtered) measurement in mode A.

Parameters listed in Table II-1 (Chapter II, Part I) and checked in the mode A column can be augmented to the mode A primary state vector as either solve-for or consider parameters. Note that accelerometer and gyro scale factors, biases, and misalignments can also be treated as augmented parameters, and can thus influence the propagation and update of estimates and covariance matrices.

Estimates of certain parameters that do not appear in the mode A parameter augmentation list can nevertheless be obtained as derived estimates. These estimates are referred to as derived (or secondary) estimates since they are derived from estimates generated by the recursive estimation process, and in no way influence this recursive process. Derived estimates are presently available for atmospheric density and temperature. The required equations for both the derived estimates and their variances follow.

The nominal density computed from equations (IV-17) and (IV-18), when combined, yield

$$\rho = - \frac{2m\, a_{x_c}}{v_r^2\, (C_A\, S + C_D\, S_D)} \; . \qquad \text{(IV-22)}$$

To obtain a derived estimate of the density deviation from its nominal value, we should, strictly speaking, take the first variation of equation (IV-22) with respect to the primary state variables and all explicit and implicit augmented parameters on which ρ depends through equation (IV-22). Denoting all such parameters as w, we would obtain a first variation of equation (IV-22) having the form

$$\delta\rho = \Gamma_1\, (\delta x,\ \delta w)^T \qquad \text{(IV-23)}$$

where Γ_1 is the Jacobian matrix

$$\Gamma_1 = \left[\frac{\partial \rho}{\partial\, (x,\ w)} \right] \; . \qquad \text{(IV-24)}$$

Then the derived estimated deviation of density would be given by

$$\delta\hat{\rho} = \Gamma_1\, (\delta\hat{x},\ \delta\hat{w})^T \qquad \text{(IV-25)}$$

where estimates $\delta\hat{x}$ and $\delta\hat{w}$ are available from the recursive estimation process (estimates of any elements of w that are treated as consider parameters are, of course, zero). The variance of the derived estimate $\delta\hat{\rho}$ can be found from

$$\sigma_\rho^2 = \Gamma_1 \begin{bmatrix} P & C_{xw} \\ C_{xw}^T & W \end{bmatrix} \Gamma_1^T \tag{IV-26}$$

where P is the primary state covariance matrix, W the augmented parameter covariance matrix, and C_{xw} represents the correlation between x and w.

We could operate on equation (IV-19) in similar fashion to obtain a derived estimate of temperature. Such an estimate would have the form

$$\delta\hat{T} = \Gamma_2 \, (\delta\hat{x}, \ \delta\hat{w})^T \tag{IV-27}$$

where

$$\Gamma_2 = \left[\frac{\partial T}{\partial \, (x, \ w)}\right] \tag{IV-28}$$

The variance of $\delta\hat{T}$ would be given by

$$\sigma_T^2 = \Gamma_2 \begin{bmatrix} P & C_{xw} \\ C_{xw}^T & W \end{bmatrix} \Gamma_2^T \tag{IV-29}$$

Currently, however, derived estimates $\delta\hat{\rho}$ and $\delta\hat{T}$ are computed from considerably simplified expressions. The first variation of ρ is taken only with respect to v_r, and then $\delta\hat{v}_r$ itself is replaced with $\delta\hat{v}$ to obtain

$$\delta\hat{\rho} = \frac{2\rho}{v_r} \, \delta\hat{v} \tag{IV-30}$$

and

$$\sigma_{\rho}^{2} = \frac{4\rho^{2}}{v_{r}^{2}}\,\sigma_{v}^{2} \qquad \text{(IV-31)}$$

The first variation of T is taken with respect to p, M, and v_r (with $\delta\hat{v}_r$ replaced with $\delta\hat{v}$) to obtain

$$\delta\hat{T} = T\left(\frac{\delta\hat{p}}{p} + 2\,\frac{\delta\hat{v}}{v_{r}} + \frac{\delta\hat{M}}{M}\right) \qquad \text{(IV-32)}$$

and

$$\sigma_{T}^{2} = \frac{T^{2}}{p^{2}}\,\sigma_{p}^{2} + \frac{4T^{2}}{v_{r}^{2}}\,\sigma_{v}^{2} + \frac{T^{2}}{M^{2}}\,\sigma_{M}^{2} \qquad \text{(IV-33)}$$

Eventually equations (IV-30) through (IV-33) should be replaced with equations (IV-25), (IV-26), (IV-27), and (IV-29) to obtain improved derived estimates $\delta\hat{\rho}$ and $\delta\hat{T}$ and more realistic variances of σ_{ρ}^{2} and σ_{T}^{2}.

The entire mode A trajectory and atmosphere reconstruction process is based on the method presented in Reference 1.

V. MODE B STATE ESTIMATION AND ATMOSPHERE RECONSTRUCTION

A. MODE B DYNAMIC MODEL

A four-dimensional primary state vector is employed in the mode B reconstruction process. This state vector is defined by

$$x = (h, v, \gamma, \phi)^T \tag{V-1}$$

where

h = altitude

v = velocity

γ = flightpath angle

ϕ = downrange angle.

These variables are defined in Figure II-1.

The fundamental difference between the mode A and mode B reconstruction processes, which was explained fully in Chapter IV.A, consists in the manner in which the nongravitational forces acting on the entry vehicle are treated. Unlike mode A where all information on the aerodynamic forces and planetary atmosphere are imbedded in the accelerometer and gyro data, mode B assumes a mathematical representation for both aerodynamic forces and the planetary atmosphere.

The remainder of this section will treat the mode B dynamic model in more detail. The equations of motion are summarized below:

$$\dot{h} = v \sin \gamma \tag{V-2}$$

$$\dot{v} = -g \sin \gamma + \frac{A}{m} \cos (\alpha + \varepsilon) + \frac{N}{m} \sin (\alpha + \varepsilon) - \frac{F_d}{m} \cos \varepsilon \tag{V-3}$$

$$\dot{\gamma} = \left(\frac{v}{r} - \frac{g}{v}\right) \cos \gamma + \frac{1}{v} \left[\frac{A}{m} \sin (\alpha + \varepsilon) - \frac{N}{m} \cos (\alpha + \varepsilon) - \frac{F_d}{m} \sin \varepsilon\right] \tag{V-4}$$

$$\dot{\phi} = \frac{v}{r} \cos \gamma \qquad \text{(V-5)}$$

where axial aerodynamic force A, normal aerodynamic force N, and parachute drag force F_d are given by

$$A = - C_A \, q \, S \qquad \text{(V-6)}$$

$$N = - C_N \, q \, S \qquad \text{(V-7)}$$

$$F_d = C_D \, q \, S_D \qquad \text{(V-8)}$$

where dynamic pressure $q = \frac{1}{2} \rho \, v_r^2$. These equations of motion have the same form as the translational equations of motion used by the data generator to compute the "actual" entry trajectory. These latter equations are presented in Chapter II.A. However, mode B uses assumed nominal values of all parameters to integrate these equations, whereas the data generator uses "actual" values. In addition, mode B does not model rotational motion, assumes gyro information is not available, and that the nominal angle of attack α is zero.

Before the aerodynamic forces given by equations (V-6) through (V-8) can be evaluated, it is necessary to obtain density ρ. Unlike mode A that extracts density from the axial accelerometer measurement a_{x_c}, mode B assumes that the planetary atmosphere can be modeled by piece-wise linear temperature and molecular weight profiles. In fact, the mathematical atmosphere model employed by mode B has the same form as the model employed by the data generator to compute the "actual" atmospheric properties. The equations that define such an atmosphere model are presented in Chapter II.B. Of course, mode B uses assumed nominal values of all parameters to define its atmosphere model, whereas the data generator uses "actual" values to define its atmosphere model.

A quasi-static dynamic model option is also available in mode B. When quasi-static motion is assumed, equation (V-3) is deleted and velocity is computed from equation (II-18).

B. MODE B RECURSIVE TRAJECTORY AND ATMOSPHERE RECONSTRUCTION

The equations presented in Section A (and related equations in Chapter II.A and II.B) are used to compute the nominal trajectory and state transition matrices (via numerical differencing) required by the linear recursive estimation process described in Chapter III. Nominal observations and observation matrices are computed using the equations presented in Chapter II.D and II.E, with "actual" parameter values replaced by nominal parameter values. Unlike mode A, mode B treats accelerometer data as measurements to be used directly in the recursive estimation process. Mode B uses the following equations to compute nominal accelerometer measurements and accelerometer observation matrices:

$$a_x = \left(\frac{A}{m} \cos \delta_1 - \frac{N}{m} \sin \delta_1\right) C_{sx} + C_{bx} \qquad \text{(V-9)}$$

$$a_z = \left(\frac{A}{m} \sin \delta_2 + \frac{N}{m} \cos \delta_2\right) C_{sz} + C_{bz} \qquad \text{(V-10)}$$

where aerodynamic forces A and N are given by equations (V-6) and (V-7), δ_1 and δ_2 are axial and normal accelerometer misalignment angles, C_{sx} and C_{sz} are scale factors, and C_{bx} and C_{bz} are biases.

Parameters listed in Table II-1 (Chapter II, Part II) and checked in the mode B column can be augmented to the mode B primary state vector as either solve-for or consider parameters. Unlike mode A, which can treat only one atmospheric parameter -- pressure, in the recursive estimation process, mode B can treat several -- surface pressure, temperature profile parameters, and mole fraction profile parameters. If mode B solves for any of these atmospheric parameters, the final estimates can be used to compute pressure and density as a function of altitude. This could be accomplished by rerunning the data generator program with an atmosphere model defined by these new atmospheric parameter estimates.

The mode B trajectory and atmosphere reconstruction process is an adaptation of the method presented in Reference 2.

VI. INDIVIDUAL SUBROUTINE ANALYSES

Individual subroutine analyses are found in Chapter V of the Programmers' Section of the manual.

VII. REFERENCES

1. F. Hopper. *LTR2 Program, Philosophy and Implementation.* 1643-71-31-V. Martin Marietta Corporation memorandum, April 23, 1971.

2. R. Falce and P. Kusinitz. *Mars Entry Trajectory Reconstruction Program, Dynamic and Measurement Equations,* April 1, 1970.

3. R. Falce. *METR Program Simulation Mode Logic.* 1643-71-21-V. Martin Marietta Corporation Memorandum, March 18, 1971.

4. G. Null, H. Gordon, and D. Tito. *The Mariner IV Flight Path and Its Determination from Tracking Data.* JPL TR 32-1108, August 1, 1967.

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PART II

LTR USERS' MANUAL

I. INTRODUCTION

The *LTR Users' Manual* provides the user of the LTR data generator and reconstruction programs with all the information necessary to input these programs and interpret the output.

Chapter II describes the input of the LTR program. This includes a description of the data deck and tape structure, namelist variable definitions, measurement and event scheduling, and restrictions on the use of the programs. Chapter III describes the output of the LTR data generator and reconstruction programs. Chapter IV discusses actual sample cases run using the LTR programs. These sample cases are presented primarily to demonstrate the operation and versatility of the LTR programs and to assist the user in the input/output procedure for these programs.

II. INPUT DESCRIPTION

A. DATA DECK AND TAPE STRUCTURE

The first card of an LTR data deck must have an integer 1 or 2 in CC 10, followed by another card with Hollerith problem identification information, such as case number, landing date, etc. If the first card has set RUNNØ = 1, the data generator namelist section ERAN must be input and the data generator and preprocessor will be executed. If the first card has set RUNNØ = 2, the reconstruction program namelist ERAN must be input and:

1) The data generator must have been executed immediately before, or;
2) The data generator must have written logical units 10 and 16 onto magnetic tape during a previous run;
3) The plotting and summary table namelist PLTVAR must be input before the reconstruction and summary modes can be run.

If the reconstruction program is to be executed, a measurement schedule in fixed-field format must follow the PLTVAR section of data. See Section C.3 for a description of the measurement schedule. If the first card has set RUNNØ = 3, the program terminates execution.

B. DATA GENERATOR INPUT VARIABLE DEFINITIONS

1. Namelist Variable Definitions

The namelist variables appearing in the data generator namelist ERAN and read from subroutine SETUP1 are defined below according to several categories. Most of these variables will be preset by the program if they do not appear in the namelist input; these preset values are the quantities enclosed by parentheses in the namelist variable definitions. The required input units are specified in the last column.

a. Trajectory Variables

XN(1)	Initial nomial vehicle altitude h (0.)	km
XN(2)	Initial nomial vehicle velocity v (0.)	km/s
XN(3)	Initial nominal vehicle flight path angle γ (0.)	deg
XN(4)	Initial nominal vehicle downrange angle ϕ (0.)	deg
XN(5)	Initial nominal vehicle attitude angle θ (0.)	deg
XN(6)	Initial nominal vehicle angular velocity ω (0.)	deg/s
XN(7)	Initial value of integral of axial VRU output (0.)	km/s
XN(8)	Initial value of integral of normal VRU output (0.)	km/s
XN(9)	Initial value of integral of ARU output (0.)	rad
IC00R	Code that defines coordinate system relative to which the entry plane is oriented using the variables ECLINC, ECL0NG, and PHIR (3) = 1, planetocentric ecliptic 2, planetocentric equatorial 3, subsolar orbital plane	--
ECLINC	Inclination of the entry plane relative to xy-plane of IC00R coordinate system (0.)	deg
ECL0NG	Longitude of the ascending node of the entry plane relative to IC00R coordinate system (0.)	deg
PHIR	Angle between the line of nodes and the ϕ reference line. Sum of argument of periapsis and initial true anomaly of vehicle (0.)	deg

TC	Initial trajectory time (0.)	s
TF	Final trajectory time	s
IYR thru SECSI	Initial calendar date corresponding to initial trajectory time TC. IYR = year (integer) IM0 = month (integer) IDAY = day (integer) IHR = hour (integer) IMIN = minute (integer) SECSI = second (floating)	--
DT	Integrator step size (0.1)	s
QSALT	Altitude at which the dynamic model is to be replaced with the quasi-static dynamic model (40.)	km
QSDT	Integrator step size when quasi-static dynamic model is used (1.)	s
0DB	Maximum dynamic pressure permitted for integration of the complete set of equations of motion. Whenever dynamic pressure exceeds 0DB, the motion of the entry vehicle is assumed to be described by the point mass equations of motion. See the last paragraph in Chapter II.A of the *Analytic Manual* for more details (15. x 10^5)	$kg/km \cdot s^2$
HD	Parachute deployment altitude (0.)	km
HR	Parachute release altitude. HR must be less than HD (0.)	km

b. Planet and Atmosphere Variables

NTP	Planet code (3) = 2, Mercury 3, Venus 5, Mars 6, Jupiter 7, Saturn 8, Uranus 9, Neptune 10, Pluto	--

RM	Planet radius (6050.)	km
MU	Planet gravitational constant (3.2486×10^5)	km^3/s^2
G0	Acceleration of gravity at planet surface (8.867×10^{-3})	km/s^2
0MEG	Planet angular velocity (2.997×10^{-7})	rad/s
ATM0S(1)	Surface pressure	$kg/km\text{-}s^2$
ATM0S(18) thru ATM0S(33)	Nominal atmosphere temperature profile. ATM0S(18) through ATM0S(25) define the altitude breakpoints in ascending order. ATM0S(26) through ATM0S(33) define the corresponding temperatures at each of the altitude breakpoints	km °K
NTPTS	Number of altitude breakpoints used to define the temperature profile. NTPTS must not exceed 7 (6)	--
XMFH	Altitude breakpoints (in ascending order) for all mole fraction profiles. XMFH(1) must be set equal to ATM0S(18) (0., 120., 370., 1000., 0.)	km
XMFW	Set of nominal mole fraction profiles for up to five component gases corresponding to the altitude breakpoints appearing in XMFH. Each row of mole fractions corresponds to an altitude breakpoint (.9 , .06, .04, 0. , 0., .9 , .06, .04, 0. , 0., .1 , .1 , .03, .77, 0., .01, .01, .03, .95, 0., 0. , 0. , 0. , 0. , 0.)	--
NMPTS	Number of altitude breakpoints used to define the mole fraction profile in XMFH. NMPTS must not exceed 5 (4)	--
CGMW	Molecular weights of up to five component gases. Order corresponds to order of mole fractions at each altitude breakpoint (44.011, 28.012, 39,948, 2.016, 0.)	--

AR	Universal gas constant (8.31432×10^{-3})	
AGAM	Ratio of specific heats (1.4)	--
WDTBL	Nominal wind profile. WDTBL(1) = n, number of altitude breakpoints WDTBL(2) through WDTBL (1 + n) define the sequence of altitude breakpoints in ascending order WDTBL(2 + n) through WDTBL(1 + 2n) define the corresponding sequence of wind magnitudes. Up to 10 altitude breakpoints can be defined (2., 0., 10., 0., 0.)	 -- km km/s
TH	No[illegible]l terrain height profile coef[illegible]s C_1, C_2, ..., C_7, required to define the profile $\tau(x) = C_1 + C_2 \sin(C_3x + C_4) + C_5 \sin(C_6x + C_7)$. C_1, C_2, and C_5 are expressed in units of km; C_3, C_4, C_6, and C_7 are dimensionless	--
TERHT	Logical variable that indicates whether the data generator is to use the terrain height model defined above: (true) = true, use terrain height model; false, do not use terrain height model	--

c. Entry Vehicle Variables

IPHAS	Code defining entry phase (1) = 1, phase prior to parachute deployment 2, parachute phase 3, phase following parachute release	--
VMASS	Vehicle mass as a function of IPHAS (174., 122., 100.)	kg

VSA	Vehicle reference area as a function of IPHAS (1.474×10^{-6}, 0.292×10^{-6}, 0.292×10^{-6})	km^2
VDIA	Vehicle reference diameter as a function of IPHAS (1.37×10^{-3}, 0.61×10^{-3}, 0.61×10^{-3})	km
VRI	Vehicle rotational inertia as a function of IPHAS (1.76×10^{-5}, 0.5×10^{-5}, 0.5×10^{-5})	$kg\text{-}km^2$
XG	Vehicle cg offset along x-axis (0.)	km
ZG	Vehicle cg offset along z-axis (0.)	km
XD	Parachute bridle apex location along x-axis ($-1. \times 10^{-3}$)	km
SDP	Parachute reference area ($46. \times 10^{-6}$)	km^2
CDTBL	Parachute drag coefficient table as a function of Mach number. CDTBL(1) = n, number of tabulated C_D values; CDTBL(2) through CDTBL(1 + n) define the sequence of tabulated Mach numbers in ascending order; CDTBL(2 + n) through CDTBL(1 + 2n) define the corresponding values of drag coefficients. Up to 24 Mach number/drag coefficient pairs can be defined. (5. , 0. , 0.6, 1.4 , 3.2 , 100., 0.5, 0.5, 0.49, 0.19, 0.19)	--

d. Measurement Variables

XM	Velocity reference unit (VRU) location along x-axis (0.)	km
ZMM	VRU location along z-axis (0.)	km
XSTEP	Quantum level for x-axis VRU (1.5×10^{-5})	km/s

ZSTEP	Quantum level for z-axis VRU (1.5×10^{-5})	km/s
TSTEP	Quantum level for attitude reference unit (0.004)	rad
DELT	Nominal axial accelerometer, normal accelerometer, and gyro misalignment angles (0., 0., 0.)	rad
VXQA	Initial axial accelerometer quantized data for five time points centered about initial time (5 * 0.)	km/s
VZQA	Initial normal accelerometer quantized data for five time points centered about initial time (5 * 0.)	km/s
THTQA	Initial gyro quantized data for five time points centered about initial time (5 * 0.)	rad
ETA	Radar altimeter sweep half-angle (0.7854)	rad
SALT	Array of altitudes above mean earth surface for three tracking stations	km
SLAT	Array of latitudes in degrees north for three tracking stations	deg
SLØN	Array of longitudes in degrees east for three tracking stations	deg

The following tracking station locations are preset:

	SALT	SLAT	SLØN
1. Goldstone	1.031	35.384	-116.833
2. Madrid	.05	40.417	-3.667
3. Canberra	.05	-35.311	149.136

NØFRAC	Refractivity code (true); nonfunctional = false, refractivity model will be used true, refractivity model will not be used	--

e. Other Variables

ICNTR	The Multiple of DT at which time interval prints are to be made. If ICNTR = N, a print occurs every (N * DT) seconds (100)	--
RESTRT	Logical variable that indicates if subroutine RSTART has punched restart cards for this input deck (false)	--

2. Error Definitions

Most of the namelist variables defined in subsection 1 represent nominal values. Actual errors in these variables are specified by inserting the proper C(j) variables in the same namelist. All C(j) variables are defined in Table II-1, along with their required input units. The same table also indicates in which programs the C(j) variables presently have meaning. The use of the C(j) variables in the mode A and mode B reconstruction programs is treated in Section C.2. Room for more than 70 new C(j) variables is still available in the table. All C(j) scale factors are preset to 1., while all C(j) biases are preset to 0.

As an example of the use of the C(j) variables, suppose one wished to define errors in the initial vehicle state, the scale factor in the aerodynamic coefficient C_A, and the altimeter bias. The errors in the initial vehicle state are specified as:

C(101) = 10., altitude error

C(102) = .05, velocity error

C(103) = 1.2, flightpath angle error

C(104) = .5, downrange angle error

C(140) = -2., attitude error

C(106) = -.03, angular velocity error.

If the actual C_A scale factor error were +1%, we would set

C(20) = 1.01,

and if the altimeter bias were 0.75 kilometer, we would set

C(72) = .75 .

Table II-1 C(j) Variables

j	C(j)	Units	Data Generator	Mode A	Mode B
1	Surface pressure p_o bias	kg/km-s^2	✓		✓
2	Altitude h_1 bias Temperature Profile	km		*	
3	Temperature T_1 bias	°K	✓		✓
4	h_2	km	✓		✓
5	T_2	°K	✓		✓
6	h_3	km	✓		✓
7	T_3	°K	✓		✓
8	h_4	km	✓		✓
9	T_4	°K	✓		✓
10	h_5	km	✓		✓
11	T_5	°K	✓		✓
12	h_6	km	✓		✓
13	T_6	°K	✓		✓
14	h_7	km	✓		✓
15	T_7	°K	✓		✓
16	Axial aerodynamic coefficient C_A bias	--	✓	✓	✓
17	Normal aerodynamic coefficient C_N bias	--	✓		✓
18	Damping moment aerodynamic coefficient C_{M_q} bias	--	✓		
19	Center of pressure Xp bias	km	✓		
20	C_A scale factor	--	✓	✓	✓
21	C_N scale factor	--	✓		✓
22	C_{M_q} scale factor	--	✓		
23	Xp scale factor	--	✓		
24					
25					
26	Cg offset in x-direction, Xg	km	✓	✓	
27	Cg offset in z-direction, Zg	km	✓	✓	
28	VRU offset in x-direction, X_m	km	✓	✓	
29	VRU offset in z-direction, Z_m	km	✓	✓	
30	Vehicle mass bias	kg	✓	✓	✓
31	Vehicle rotational inertia bias	kg-km^2	✓		

---

*C(2) may appear in the data generator namelist only if C(151) also appears and is identical to C(2).

Table II-1 (Cont)

j	C(j)	Units	Data Generator	Mode A	Mode B
32					
33					
34					
35					
36					
37					
38					
39					
40					
41	C_1 bias	km	✓	✓	✓
42	C_2 bias	km	✓	✓	✓
43	C_3 bias	--	✓	✓	✓
44	C_4 bias Terrain Height Profile	--	✓	✓	✓
45	C_5 bias	km	✓	✓	✓
46	C_6 bias	--	✓	✓	✓
47	C_7 bias	--	✓	✓	✓
48					
49					
50					
51	Axial accelerometer scale factor	--	✓	✓	✓
52	Axial accelerometer bias	*	✓	✓	✓
53	Normal accelerometer scale factor	--	✓	✓	✓
54	Normal accelerometer bias	*	✓	✓	✓
55	Accelerometer misalignment δ_1 bias	rad	✓	✓	✓
56	Accelerometer misalignment δ_2 bias	rad	✓	✓	✓
57					
58					
59					
60					
61					
62					
63	Gyro (ARU) misalignment δ_3 bias	rad	✓	✓	
64	Range bias (station 1)	km	✓	✓	✓
65	Range bias (station 2)	km	✓	✓	✓
66	Range bias (station 3)	km	✓	✓	✓
67	Doppler bias (station 1)	km/s	✓	✓	✓
68	Doppler bias (station 2)	km/s	✓	✓	✓
69	Doppler bias (station 3)	km/s	✓	✓	✓

---

*Accelerometer bias has units of km/s in data generator and units of km/s^2 in modes A and B.

Table II-1 (Cont)

j	C(j)	Units	Data Generator	Mode A	Mode B
70					
71	Altimeter scale factor	--	✓	✓	✓
72	Altimeter bias	km	✓	✓	✓
73					
74					
75					
76					
77					
78					
79					
80					
81	Pressure measurement scale factor ($M \geq 1$)	--	✓	✓	✓
82	Pressure measurement bias ($M \geq 1$)	kg/km-s^2	✓	✓	✓
83	Pressure measurement scale factor ($M < 1$)	--	✓	✓	✓
84	Pressure measurement bias ($M < 1$)	kg/km-s^2	✓	✓	✓
85					
86					
87					
88					
89					
90					
91	Temperature measurement scale factor	--	✓	✓	✓
92	Temperature measurement bias	°K	✓	✓	✓
93					
94					
95					
96	Parachute C_D scale factor	--	✓	✓	✓
97	Parachute C_D bias	--	✓	✓	✓
98					
99					
100					
101	Initial altitude h_0 error	km	✓		
102	Initial velocity v_0 error	km/s	✓		
103	Initial flightpath angle γ_0 error	deg	✓		
104	Initial downrange angle ϕ_0 error	deg	✓		
105	*				

---

*C(105) is used as an internal variable for computing sensitivity matrices associated with the 5th state variable in mode A.

Table II-1 (Cont)

j	C(j)	Units	Data Generator	Mode A	Mode B
106	Initial angular velocity ω_0 error	deg/s	✓		
107					
108					
109					
110					
111	Station 1 altitude bias	km	✓	✓	✓
112	Station 1 latitude bias	rad	✓	✓	✓
113	Station 1 longitude bias	rad	✓	✓	✓
114	Station 2 altitude bias	km	✓	✓	✓
115	Station 2 latitude bias	rad	✓	✓	✓
116	Station 2 longitude bias	rad	✓	✓	✓
117	Station 3 altitude bias	km	✓	✓	✓
118	Station 3 latitude bias	rad	✓	✓	✓
119	Station 3 longitude bias	rad	✓	✓	✓
120					
121					
122					
123					
124	Gyro (ARU) scale factor	--	✓	✓	
125	Gyro (ARU) drift error	rad/s	✓	✓	
126					
127					
128					
129					
130					
131					
132					
133					
134					
135					
136					
137					
138					
139					
140	Initial attitude θ_0 error*	deg	✓	✓	✓
141					
142					
143					
144					
145					

---

*C(140) may only appear in data generator namelist; index 140, however, may appear in any parameter augmentation list in modes A and B.

Table II-1 (Cont)

j	C(j)	Units	Data Generator	Mode A	Mode B
146					
147					
148					
149					
150					
151	Altitude h_{α_1} bias } Mole Fraction Altitude Breakpoint	km	See	C(2)	
152	Altitude h_{α_2} bias	km	✓		✓
153	Altitude h_{α_3} bias	km	✓		✓
154	Altitude h_{α_4} bias	km	✓		✓
155	Altitude h_{α_5} bias	km	✓		✓
156	Mole fraction $\alpha(1,1)$ bias } at h_{α_1}	--	✓		✓
157	$\alpha(2,1)$	--	✓		✓
158	$\alpha(3,1)$	--	✓		✓
159	$\alpha(4,1)$	--	✓		✓
160	$\alpha(5,1)$	--	✓		✓
161	$\alpha(1,2)$ } at h_{α_2}	--	✓		✓
162	$\alpha(2,2)$	--	✓		✓
163	$\alpha(3,2)$	--	✓		✓
164	$\alpha(4,2)$	--	✓		✓
165	$\alpha(5,2)$	--	✓		✓
166	$\alpha(1,3)$ } at h_{α_3}	--	✓		✓
167	$\alpha(2,3)$	--	✓		✓
168	$\alpha(3,3)$	--	✓		✓
169	$\alpha(4,3)$	--	✓		✓
170	$\alpha(5,3)$	--	✓		✓
171	$\alpha(1,4)$ } at h_{α_4}	--	✓		✓
172	$\alpha(2,4)$	--	✓		✓
173	$\alpha(3,4)$	--	✓		✓
174	$\alpha(4,4)$	--	✓		✓
175	$\alpha(5,4)$	--	✓		✓
176	$\alpha(1,5)$ } at h_{α_5}	--	✓		✓
177	$\alpha(2,5)$	--	✓		✓
178	$\alpha(3,5)$	--	✓		✓
179	$\alpha(4,5)$	--	✓		✓
180	$\alpha(5,5)$	--	✓		✓

Table II-1 (Concl)

j	C(j)		Units	Data Generator	Mode A	Mode B
181	Altitude h_1 bias	Wind Profile	km	✓	✓	✓
182	Wind w_1 bias		km/s	✓	✓	✓
183	h_2		km	✓	✓	✓
184	w_2		km/s	✓	✓	✓
185	h_3		km	✓	✓	✓
186	w_3		km/s	✓	✓	✓
187	h_4		km	✓	✓	✓
188	w_4		km/s	✓	✓	✓
189	h_5		km	✓	✓	✓
190	w_5		km/s	✓	✓	✓
191	h_6		km	✓	✓	✓
192	w_6		km/s	✓	✓	✓
193	h_7		km	✓	✓	✓
194	w_7		km/s	✓	✓	✓
195	h_8		km	✓	✓	✓
196	w_8		km/s	✓	✓	✓
197	h_9		km	✓	✓	✓
198	w_9		km/s	✓	✓	✓
199	h_{10}		km	✓	✓	✓
200	w_{10}		km/s	✓	✓	✓

Any number of actual errors can be defined in the data generator namelist.

The C(j) variables can also be used to alter the nominal aerodynamic characteristics of the entry vehicle. Currently all aerodynamic tables are defined in the BLØCK DATA subroutine. One could, of course, remove the existing aerodynamic tables from BLØCK DATA and replace them with the desired aerodynamic tables. This, however, is a cumbersome task that is not really required until the aerodynamic characteristics of a particular vehicle have been finalized. For preliminary studies it is far easier to manipulate certain C(j) variables in such a way that the existing BLØCK DATA aerodynamic tables approximate the desired aerodynamic tables. For example, the C_A table can be modified by using the C_A scale factor C(20) and the scale factor bias C(16). Suppose that C(20) = .9 and C(16) = -.1 would transform the existing C_A table to the desired C_A table. Then if there were no actual C_A errors, one would simply insert C(20) = .9 and C(16) = -.1 in the data generator (and reconstructor) namelist. If, however, actual errors are defined, say a +1% C_A scale factor error and a C_A bias of .03, then one would insert

$$C(20) = .9\ (1.01) = .909$$

and

$$C(16) = -.1 + .03 = -.07$$

in the data generator namelist. C(20) = .9 and C(16) = -.1 would still appear in the reconstructor namelist.

3. Restrictions

A successful data generator run depends on selection of proper values for namelist variables DT, QSALT, QSDT, and ØDB. Improper values can lead to integrator instability in the data generator. Since integrator step size DT is used to integrate both translational and rotational equations of motion, DT must be chosen small enough to prevent instability or inaccuracies in the integration of the rotational equations, but large enough to avoid exorbitant computational time. High-frequency rotational oscillations, which are likely to occur in the maximum dynamic pressure regime, would require extremely small values of DT. To circumvent this problem, the variable ØDB has been defined. This variable represents the maximum dynamic pressure permitted for the integration of the complete set of equations of motion. Whenever dynamic pressure exceeds 0DB, the motion of the entry vehicle is assumed to be described by the point mass equations of motion so the rotational equations of motion need not be integrated. This same approximation is currently employed whenever the parachute is deployed.

Another type of integrator instability can occur during the terminal velocity regime when $|\dot{v}| \ll 1$. To avoid using very small integration step sizes to prevent this instability, an option for using the quasi-static dynamic model has been developed. When the quasi-static model is used, the $\dot{v}$ equation is not integrated and velocity is computed using equation (II-18). The user sets QSALT to the altitude at which the quasi-static model is to be used, and QSDT to the step-size to be used in the integration of the quasi-static equations of motion. QSDT can be chosen up to 10 times larger than DT, depending, of course, on DT and the particular entry problem. The user should be certain that QSALT is chosen so the quasi-static assumptions are satisfied over the entire altitude range from 0. to QSALT. The quasi-static assumptions are (1) $|\dot{v}| << 1$, and (2) $\gamma \doteq -90°$. Since the vehicle motion normally violates the quasi-static assumptions for a few minutes after parachute release, it is recommended that the restriction QSALT < HR < HD be applied.

C. RECONSTRUCTION PROGRAM INPUT VARIABLE DEFINITIONS

1. Namelist Variable Definitions

The namelist variables appearing in the reconstruction program namelist ERAN and read from subroutine SETUP are defined in the following subsections according to several categories. Many of these variables that are identical to those appearing in the data generator namelist are not defined. Refer to Section B.1 for their definitions. As in Section B.1, preset values of namelist variables are enclosed in parentheses, and required input units are specified in the last column.

a. Trajectory Variables

XN(1) thru XN(4)	See Section B.1	
XN(5)	Initial nominal ambient pressure; required only for mode A (0.)	millibars
THETI	Initial nominal vehicle attitude angle θ; required only for mode A (0.)	deg
XO(1) thru XO(5)	Initial original nominal vehicle state. XO(I) corresponds to XN(I) above for I = 1, 2, ..., 5	--
ICØØR	See Section B.1	
ECLINC	See Section B.1	
ECLØNG	See Section B.1	
PHIR	See Section B.1	
TC	See Section B.1	
TF	See Section B.1	
IYR thru SECSI	See Section B.1	
EDN(1)	Initial vehicle altitude estimate $\delta\hat{h}$ (0.)	km
EDN(2)	Initial vehicle velocity estimate $\delta\hat{v}$ (0.)	km/s
EDN(3)	Initial vehicle flightpath angle estimate $\delta\hat{\gamma}$ (0.)	rad
EDN(4)	Initial vehicle downrange angle estimate $\delta\hat{\phi}$ (0.)	rad
EDN(5)	Initial ambient pressure estimate $\delta\hat{p}$ required only for mode A (0.)	kg/km-s^2

QEDN	Initial solve-for parameter vector estimate. Order of elements must correspond to order of elements in LISTQ. Units are the same as internal units (10 * 0.)	--
DT	Nonfunctional	--
QSDT	Integration step size used after time QST; input only if data generator is not run	s
SDT	Integration step size used in the data generator; should be input only if data generator is not run	s
QST	Time at which dynamic model is changed to quasi-static model. Computed in data generator and transmitted to reconstruction program if these two programs have been run in sequence. Should be input only if data generator is not run	s
TD	Time of parachute deployment as determined by the data generator. Should be input only if data generator is not run	s
TR	Time of parachute release as determined by data generator. Should be input only if data generator is not run	s
TEND	Time of next event. Should be input only if data generator is not run	s

b. Planet and Atmosphere Variables - All planet and atmosphere variables defined in Section B.1 for the data generator namelist are also defined for the reconstruction program namelist, with the exception that variables NTPTS, ATMOS(1), and ATMOS(18) through ATMOS(33) are not used when the reconstruction program is run in mode A. The following variable, which is not defined for the data generator namelist, appears in the reconstruction program namelist:

GAMTBL	Table of specific heat ratios as a function of molecular weight. GAMTBL(1) = n, number of molecular weight breakpoints; GAMTBL(2) through GAMTBL(1 + 2n) define the corresponding sequence of specific heat ratios. Up to four breakpoints can be defined (2., 0., 1000., 1.4, 1.4)	--

c. Entry Vehicle Variables - All entry vehicle variables defined in Section B.1 for the data generator namelist are also defined for the reconstruction program namelist. The following variable, which is not defined for the data generator namelist, appears in the reconstruction program namelist:

BKTBL	Table of k (see equation (II-59)) as a function of Mach number; required only if angle of attack measurements are scheduled. BKTBL has same structure as GAMTBL; up to nine breakpoints can be defined (2., 0., 1000., -.922, -.922)	--

d. Measurement Variables - Most measurement variables defined in Section B.1 for the data generator namelist are also defined for the reconstruction program namelist. Those not defined for the reconstruction program namelist are XSTEP, ZSTEP, TSTEP, VXQA, VZQA, THTQA, and N0FRAC. The following variables, which are not defined for the data generator namelist, appear in the reconstruction program namelist:

CDEL	Logical variable that indicates if misalignment errors are to be treated (true) = true, misalignment errors will be treated false, misalignment errors will not be treated	--
NACCEL	Logical variable that indicates if the normal accelerometer is to be deleted (false) = true, normal accelerometer deleted false, normal accelerometer not deleted	--

NGYRO	Logical variable that indicates if gyro is to be deleted; applies only to mode A (false) = true, gyro deleted false, gyro not deleted	--

e. Parameter Augmentation Variables - Parameters appearing in the C(j) table of Section B.2 can be augmented to the entry vehicle state vector as either solve-for, dynamic-consider, measurement-consider, or dynamic/measurement-consider parameters. This is accomplished by inserting the index j associated with parameter C(j) in one of the parameter lists defined below. Although the order of indices in a given list is arbitrary, once the order has been defined the related covariance matrix partitions (to be defined subsequently) must correspond to this order.

NQ	Number of solve-for parameters; must not exceed 10 (0)	--
NU	Number of dynamic-consider parameters; must not exceed 20 (0)	--
NV	Number of measurement-consider parameters; must not exceed 20 (0)	--
NW	Number of dynamic/measurement-consider parameters; must not exceed 10 (0)	--
LISTQ	List of augmented solve-for parameters	--
LISTU	List of augmented dynamic-consider parameters	--
LISTV	List of augmented measurement-consider parameters	--
LISTW	List of augmented dynamic/measurement-consider parameters	--

f. Initial State and Augmented Parameter Covariance Matrices

P	State covariance matrix. Structure of (square) matrix must correspond to the order of state variables XN(1), XN(2), ..., XN(n), where n = 5 for mode A, and n = 4 for mode B. Units for P and all remaining covariance variables are appropriate combinations of internal units (km, kg, s, rad). All covariance variables are preset to zero	--
Q	Solve-for parameter covariance matrix. Structure of (square) matrix must correspond to the order of parameter indices appearing in LISTQ	--
DU	Dynamic-consider parameter covariance matrix. Since matrix is assumed diagonal, DU is a one-dimensional array of variances whose order must correspond to the order of indices appearing in LISTU	--
DV	Measurement-consider parameter covariance matrix (diagonal). DV is a one-dimensional array of variances whose order must correspond to LISTV	--
DW	Dynamic/measurement-consider parameter covariance matrix (diagonal). DW is a one-dimensional array of variances whose order must correspond to LISTW	--
CXQ	State/solve-for parameter covariance matrix. Dimension n x NQ	--
CXU	State/dynamic-consider parameter covariance matrix. Dimension n x NU	--
CXV	State/measurement-consider parameter covariance matrix. Dimension n x NV	--
CXW	State/dynamic/measurement-consider parameter covariance matrix. Dimension n x NW	--

CQU	Solve-for parameter/dynamic-consider parameter covariance matrix. Dimension NQ x NU	--
CQV	Solve-for parameter/measurement-consider parameter covariance matrix. Dimension NQ x NV	--
CQW	Solve-for parameter/dynamic-measurement-consider parameter covariance matrix. Dimension NQ x NW	--
SDMWT	Molecular weight standard deviation used in mode A derived estimation process (this variable will be deleted when the option for augmenting mole fraction parameters in mode A has been developed)	--

g. Measurement Noise Statistics

REDRR2	Logical variable used to compute altimeter noise (false) = true, use user-specified measurement noise false, compute measurement noise in subroutine ØBSM	--
RR	Three-dimensional measurement noise variance array: 1st index I, indicates measurement type; 2nd index J, measurement component; 3rd index K, regime. Only the accelerometer measurement currently requires more than one component (axial and normal). Only the pressure measurement currently depends on the (Mach number) regime. RR values represent variances whose units are assumed to be internal units. The correspondence between index I and measurement type is indicated: I = 1, accelerometer (mode B only) 2, gyro (nonfunctional currently) 3, altimeter 4, stagnation pressure 5, stagnation temperature	--

	6, angle of attack (mode A only) 11, doppler, station 1 12, range, station 1 13, doppler, station 2 14, range, station 2 15, doppler, station 3 16, range, station 3	
SD	Two-dimensional actual measurement noise standard deviation array: 1st index I, indicates measurement type; 2nd index J, measurement component. Only the accelerometer measurement currently requires more than one component (axial and normal). SD values represent standard deviations whose units are assumed to be internal units. The correspondence between index I and measurement type is identical to that for the preceding RR array	--

h. Other Variables

LTR2	Logical mode A variable (true) = true, mode A false, not mode A	--
LTR1	Logical mode B variable (false) = true, mode B false, not mode B	--
ICNTR	Measurement print code. Print will occur after every ICNTR measurements or groups of simultaneous measurements	--
MCNTR	Counter on the TMN and MC0DE event arrays. Whenever MCNTR reaches 250, another batch of 250 events is read from tape 20 into these arrays and MCNTR is reset to 1. Should be input only if restarting	--
RESTRT	See Section B.1	--
NMEAS	Counter on the number of measurements taken up to the current time. Nonfunctional currently	--

2. Use of C(j) Table in Reconstruction Program

Just as the C(j) variables defined in Table II-1 I can be used to specify actual errors to be incorporated in nominal values of the variables in the data generator, so can the C(j) variables be used in the reconstruction program to change previously defined nominal values to new nominal values. Normally this option is not employed, however, since nominal scale factors are usually set to 1. and nominal biases are usually set to zero, if the C(j) associated with the aerodynamic coefficients are selected in the data generator to alter the nominal aerodynamic tables appearing in BLOCK DATA, the same C(j) variables must be used in the reconstruction program to change the existing aerodynamic tables in BLOCK DATA to the desired nominal values (see Section B.2 for an example).

The primary use of the C(j) table in the reconstruction program lies in parameter augmentation. The final two columns in Table II-1 indicate which parameters can be augmented to the state vector in each of the two reconstruction modes. Augmentation is accomplished by inserting the index j of the appropriate parameter C(j) in one of the four parameter lists. For example, if the user wished to treat the C_A scale factor as a solve-for parameter, the C_N scale factor and the vehicle mass bias as dynamic-consider parameters, doppler biases for all three tracking stations as measurement-consider parameters, and the axial accelerometer scale factor as a dynamic/measurement-consider parameter, the following should appear in the namelist:

```
LISTQ = 20,              NQ = 1
LISTU = 21, 30,          NU = 2
LISTV = 67, 68, 69,      NV = 3
LISTW = 51,              NW = 1 .
```

Whether a consider parameter is to be treated as a dynamic-, measurement-, or dynamic/measurement-consider parameter is a function of the measurement types scheduled and the reconstruction mode. If in doubt, it is always safe to treat the questionable parameter as a dynamic/measurement-consider parameter and insert the associated index j in LISTW. If NACCEL is true (i.e., when the normal accelerometer is deleted), C(53) and C(54) cannot be treated as solve-for parameters although it is still meaningful to treat them as consider parameters. If NGYR0 is true (i.e., when the gyro is deleted in mode A), C(124), C(125), and C(140) can only be treated as consider parameters.

3. Measurement/Event Types and Schedules

Measurements and events are input with fixed field formats immediately after the PLTVAR namelist section. Each card contains the following formats and information:

F10.3	F10.3	F10.3	I10
START	TIMEND	TIMDIF	CØDE

where

START is the time (in seconds) to start a measurement or event,

TIMEND is the time (in seconds) to end a measurement or event,

TIMDIF is the time (in seconds) between measurements or events,

CØDE is the type of measurement or event to be processed, and can take on any of the following values,

= 1 accelerometer measurement

= 2 gyro measurement (not functional)

= 3 altimeter measurement

= 4 pressure measurement

= 5 temperature measurement

= 6 angle of attack measurement

= 7 to 10 not used

= 11 prediction event (not functional)

= 12 quasi-filtering event

= 13 print increment set event

= 14 set internally

= 15 set internally

= 16 set internally

= 17 print without measurement

= 18 set internally

= 19, 20 not used

= 21 range-rate measurement from station 1

= 22 range measurement from station 1

= 23 range-rate measurement from station 2

= 24 range measurement from station 2

= 25 range-rate measurement from station 3

= 26 range measurement from station 3.

The last card of the measurement schedule must have a START value of 100000. to signify the end of measurement input.

4. Restrictions

Restrictions on the use of the quasi-static dynamic model and the selection of integration step sizes and measurement schedules in the LTR reconstruction program are discussed in this section.

The use of the quasi-static dynamic model in the reconstruction program is subject to the same restrictions that apply in the data generator program. In fact, the values selected for DT and QSDT in the data generator must be small enough that the step sizes of 2*DT and 2*QSDT do not lead to integrator instabilities in the reconstruction program because the step sizes used in the reconstruction program must be twice the size of the corresponding step sizes used in the data generator.

The quasi-static dynamic model should be used with care when a wind model has been defined since the quasi-static assumptions are not always satisfied when the entry vehicle encounters winds of sufficient magnitude. This restriction applies to the data generator as well as to the two modes of the reconstruction program.

Since the LTR program performs trajectory reconstruction utilizing data already generated (by the data generator), the user cannot arbitrarily select integration step sizes. Since the present integrator is a two-step Runge-Kutta package, the basic step size in the reconstructor must be an even multiple of the basic step size used in the data generator. In addition, the use of the quasi-static dynamic model introduces more problems:

1) The switch to the quasi-static model in the data generator must occur at a time that corresponds to an even multiple of the basic integration step size so the two-step Runge-Kutta integrator can be used in the reconstructor;

2) The data generator quasi-static integration step size QSDT must be a multiple of the basic data generator step size DT to insure proper measurement processing in the reconstructor;

3) The switch to the quasi-static model in the data generator must occur at a time that corresponds to an even multiple of the quasi-static model step size to be used by the data generator to prevent improper measurement sequencing in the reconstructor.

The user must also sequence measurements in the reconstructor with care. If, for example, the user wished to process altimeter measurements from 5 seconds to 100 seconds every 1 second, the reconstructor could not integrate with a step size of 0.75 seconds, either before or after a change to the quasi-static model. The reconstructor step size of 0.75 seconds would require a data generator step size of 0.375 seconds for the same time period and therefore no altimeter data would be available to the reconstructor at 5.000 seconds. The user could choose a reconstructor step size for the quasi-static model of 1.0 second and a basic step size of 0.1 second, thereby requiring step sizes in the data generator of 0.5 second and 0.05 second for the quasi-static and basic models, respectively. This would ensure that all necessary data had been calculated in the data generator. The general rule, then, is that the measurement times must be at even multiples of the data generator quasi-static model step size.

An additional user problem concerns state transition matrices. The assumption of linearity is not valid for all integration step sizes. The user, for example, could not expect linear matrices over an interval of 60 seconds but can assume linearity over a 1-second interval. Given the integration step sizes used by the data generator, the measurement sequencing subroutine SCHED will allow an interval between measurements or events of no more than 10 times the step size used at a given time point. The user must therefore determine what step sizes can be used in both the basic and quasi-static dynamic models that will not violate linearity assumptions.

The user restrictions on integration step sizes are summarized as:

1) The integration step size in the reconstructor must be an even multiple of the step size used in the data generator, regardless of the dynamic model chosen. The program currently sets the step sizes internally in the reconstructor to twice the step sizes used in the data generator;

2) In the data generator the quasi-static step size QSDT must be a multiple of the basic integration step size DT;

3) Measurement and/or event times (see subroutine SCHED) must be at even multiples of the data generator quasi-static model integration step size QSDT;

4) Integration step sizes must be chosen so the linearity assumption used in the computation of state transition matrices in the reconstructor is not violated.

If the quasi-static dynamic model is not used, the restrictions are fewer:

1) Reconstructor step sizes are still even multiples of data generator step sizes;

2) Measurement/event times must occur at even multiples of the data generator integration step size DT;

3) State transition matrix linearity must still be considered when choosing step sizes.

III. OUTPUT DESCRIPTION

A. DATA GENERATOR OUTPUT DESCRIPTION

The initial data generator output consists of the following:

1) Namelist ERAN;
2) Initial actual state vector -- altitude, velocity, flightpath angle, downrange angle, attitude angle, angular velocity, unquantized axial VRU output, unquantized normal VRU output, unquantized ARU output, ambient pressure;
3) Planet and vehicle constants;
4) Initial and final trajectory times in seconds;
5) Actual planet atmosphere model.

At each trajectory printout time, the following output is printed:

1) Trajectory time and integration step size in seconds -- entry phase;
2) Actual state vector;
3) Actual state vector derivatives;
4) Actual trajectory, atmosphere, and aerodynamic parameters, i.e.,
    a) Vehicle relative velocity,
    b) Horizontal wind velocity,
    c) Dynamic pressure,
    d) Molecular weight of atmosphere,
    e) Ambient temperature of atmosphere,

    f) Ambient pressure of atmosphere,

    g) Density of atmosphere,

    h) Angle of attack,

    i) Aerodynamic coefficient, C_A,

    j) Aerodynamic coefficient, C_N,

    k) Mach number,

    l) Axial aerodynamic force (does not include parachute effect),

    m) Normal aerodynamic force (does not include parachute effect),

    n) Center of pressure location along x body axis,

    o) Aerodynamic damping moment acceleration (does not include parachute effect),

    p) Angle between inertial and relative velocity vectors,

    q) Aerodynamic coefficient, C_{M_q},

    r) Aerodynamic damping moment (does not include parachute effect),

    s) Local acceleration of gravity,

    t) Total axial aerodynamic acceleration,

    u) Total normal aerodynamic acceleration;

5) Actual measurements,

    a) Axial accelerometer (km/s^2),

    b) Normal accelerometer (km/s^2),

    c) Stagnation pressure ($kg/km\text{-}s^2$),

    d) Rate gyro (rad/s),

    e) Radar altimeter (km),

    f) Stagnation temperature (°K),
    g) Range from three earth-based tracking stations,
    h) Range-rate from three earth-based tracking stations,
    i) Refraction effects on range and range-rate measurements (not functional currently);
6) Auxiliary trajectory information (computed in subroutine AUXIL),
    a) Communication angle,
    b) Angle between entry plane and plane of the sky,
    c) Latitude/longitude ground trace relative to the planetocentric equatorial, subsolar orbital plane, and planetocentric geographic coordinate systems.

B. RECONSTRUCTION PROGRAM OUTPUT DESCRIPTION

The initial reconstruction program output consists of the following:

1) Namelist ERAN;
2) Array of measurement noise variances for all measurement types;
3) Initial nominal vehicle state vector -- altitude, velocity, flightpath angle, downrange angle;
4) Planet and vehicle constants;
5) Initial and final trajectory times in seconds;
6) Number and list of solve-for parameters (appear only if $NQ \neq 0$);
7) Number and list of dynamic-consider parameters (appear only if $NU \neq 0$);
8) Number and list of measurement-consider parameters (appear only if $NV \neq 0$);

9) Number and list of dynamic/measurement-consider parameters (appear only if $NW \neq 0$);

10) Primary state covariance matrix -- primary state refers to the unaugmented state used in the recursive estimation process;

11) Solve-for parameter covariance matrix (appears only if $NQ \neq 0$);

12) Vector of dynamic-consider parameter variances (appears only if $NV \neq 0$);

13) Vector of measurement-consider parameter variances (appears only if $NV \neq 0$);

14) Vector of dynamic/measurement-consider parameter variances (appears only if $NW \neq 0$);

15) Array of nominal C_j's;

16) Initial original nominal, most recent nominal, and actual vehicle state vectors;

17) Initial most recent nominal and actual atmosphere state vectors -- ambient pressure, density, ambient temperature molecular weight (appear only in mode A);

18) Initial actual and reconstructed VRU and ARU data -- attitude angle, angular velocity, axial nongravitational acceleration, normal nongravitational acceleration, normal nongravitational acceleration (appear only in mode A);

19) Entry parameters based on most recent nominal trajectory;

20) Initial estimated and actual vehicle state deviations from most recent nominal and initial vehicle state estimation errors;

21) Initial estimated and actual atmosphere state deviations from most recent nominal and initial atmosphere state estimation errors (appear only in mode A);

22) Initial estimated and actual solve-for parameter deviations from most recent nominal and initial solve-for parameter estimation errors;

23) Initial estimated solve-for parameter deviations from original nominal;

24) Additional entry parameters based on most recent nominal trajectory;

25) Initial primary state, solve-for parameter, and consider parameter correlation matrix partitions. Standard deviations appear along diagonals of the symmetric partitions and correlation coefficients comprise the remaining elements;

26) Measurement and event data cards;

27) Measurement schedule;

28) Event schedule;

29) Number of measurements to be processed for each measurement type;

30) Number of events to be executed for each event type.

When measurement information is to be printed, the output summarized below will be available. Items 1 through 20 also appear for a type 17 or when a "print without measurement" event occurs:

1) Measurement type and trajectory time;

2) Message "quasi-static model" if quasi-static dynamic model is being used at current trajectory time;

3) Original nominal, most recent nominal, and actual vehicle state vectors;

4) Most recent nominal and actual atmosphere state vectors (appear only in mode A);

5) Actual and reconstructed VRU and ARU data (appear only in mode A);

6) Entry parameters based on most recent nominal trajectory;

7) Estimated and actual vehicle state deviations from most recent nominal and vehicle state estimation errors immediately before processing the measurement;

8) Estimated and actual atmosphere state deviations from most recent nominal and atmosphere state estimation errors immediately before processing the measurement (appear only in mode A);

9) Estimated and actual solve-for parameter deviations from most recent nominal and solve-for parameter estimation errors immediately before processing the measurement;

10) Estimated solve-for parameter deviations from original nominal immediately before processing the measurement;

11) Additional entry parameters based on most recent nominal trajectory;

12) State transition matrix for primary state vector;

13) Remaining state transition matrix partitions and lists of all solve-for and consider parameters. The order of elements in each parameter list corresponds to the order of columns in each state transition matrix partition;

14) Diagonal of dynamic noise covariance matrix;

15) Primary state, solve-for parameter, and consider parameter correlation matrix partitions immediately before processing the measurement. Standard deviations appear along diagonals of the symmetric partitions and correlation coefficients comprise the remaining elements;

16) Measurement noise covariance matrix;

17) Primary state and solve-for parameter gain matrices;

18) Density and temperature estimation error standard deviations immediately before processing the measurement (appear only in mode A and then only if MACHN0 is true. MACHN0 is an internally set logical that is set true when sufficient aerodynamic decelerations have been attained to make density and temperature estimation feasible);

19) Measurement residual covariance matrix;

20) Nominal measurement;

21) Observation matrix partitions;

22) Estimated and actual measurement deviations from nominal and actual measurement residuals;

23) Estimated and actual vehicle state deviations from most recent nominal and vehicle state estimation errors immediately after processing the measurement;

24) Estimated and actual atmosphere state deviations from most recent nominal and atmosphere state estimation errors immediately after processing the measurement (appear only in mode A);

25) Estimated and actual solve-for parameter deviations from most recent nominal and solve-for parameter estimation errors immediately after processing the measurement;

26) Primary state, solve-for parameters, and consider parameter correlation matrix partitions immediately after processing the measurement. Standard deviations appear along diagonals of the symmetric partitions and correlation coefficients comprise the remaining elements;

27) Measurement noise covariance matrix (redundant; identical to item 17);

28) Primary state and solve-for parameter gain matrices (redundant; identical to item 18);

29) Density and temperature estimation error standard deviations immediately after processing the measurement (appear only in mode A and then only if MACHN0 is true);

30) Actual measurement noise;

31) Actual measurement noise standard deviations.

Quasi event output consists of the following:

1) Original nominal, most recent nominal, and actual vehicle state vectors immediately after quasi event has been executed;

2) Most recent nominal and actual atmosphere state vectors immediately after quasi event has been executed (appear only in mode A);

3) Estimated and actual vehicle state deviations from most recent nominal and vehicle state estimation errors;

4) Estimated and actual ambient pressure deviation from most recent nominal and ambient pressure estimation error (appear only in mode A);

5) Most recent nominal solve-for-parameters immediately after quasi event has been executed;

6) Estimated and actual solve-for parameter deviations from most recent nominal and solve-for parameter estimation errors immediately after quasi event has been executed;

7) Estimated solve-for parameter deviations from original nominal.

IV. SAMPLE CASES

A. LTR MODE A SAMPLE CASE

The sample case presented here demonstrates the application of the mode A reconstruction process to a Venusian entry problem, and is primarily presented to aid the user in defining the required input data and interpreting the resulting output. Before the reconstruction program can be run, the "actual" trajectory, atmosphere, and measurements used in the reconstruction program must be available from a previous data generator run. For this reason, the input and output for the associated data generator run is presented first.

1. Data Generator

a. Input Discussion - The input data for the data generator consist of the following namelist ERAN cards:

```
XN=248., 11.08, -38.8, 0., -38.8, 0.,
DT=.1, TF=500.,
IYR=1977, IMØ=5, IDAY=16, IHR=23, IMIN=54,
SECSI=41.,
ICØØR=3, PHIR=0., ECLINC=140.61, ECLØNG=68.2,
ØDB=15.E+5,

GØ=8.867E-3, RM=6050., ØMEG=2.997E-7, MU=3.2486E5,
ATMØS(1)=1.104E10,
ATMØS(18)=0., 60., 115., 125., 137., 175., 2*0.,
ATMØS(26)=738., 260., 170., 2*210., 710.,
NTPTS=6, NMPTS=4,
WDTBL=2., 0., 10., 0., 0.,
TERHT=.FALSE., AGAM=1.4,

VMASS=174., 122., 100.,
VSA=1.474E-6, .292E-6, .292E-6,
VDIA=1.37E-3, .61E-3, .61E-3,
VRI=1.76E-5, .5E-5, .5E-5,
XG=0., XM=0., ZG=0., ZMM=0.,
XSTEP=1.5E-5, ZSTEP=1.5E-5, TSTEP=.004,
ICNTR=20,
RESTRT=.FALSE.,
```

```
C(101)=-10., .025, .4, .5, C(140)=1.5,
C(16)=-.1, C(20)=1.034, 2.1, 4., .23,
C(51)=1.00066, C(53)=1.00066,
C(64)=.25, C(67)=1.E-6, C(71)=1.001, C(81)=1.01,
C(83)=1.01, C(91)=.99, C(96)=.97,
C(111)=1.2E-3, -1.3E-7, 5.E-7,
C(152)=6., C(156)=.03, -.03, C(161)=.01, -.01,.
```

The first group of cards defines the nominal entry conditions and certain integration variables. The initial nominal entry state is specified by the XN vector and the variables ICOOR through ECLONG. These latter variables define the orientation of the entry plane, while XN defines the vehicle state in that plane. An integration step size of .1 second will be used in generation of the "actual" trajectory. Point-mass motion will be assumed whenever dynamic pressure q exceeds 15 millibars, as is indicated by ODB. This is necessary to maintain integrator stability through the max q regime.

Planetary physical characteristics are specified by the next group of cards, including the planetary atmosphere model. This planetary atmosphere model is defined by the surface pressure ATMOS(1), a sequence of six temperature breakpoints defined by the ATMOS(18) vector, and the six corresponding temperatures defined by the ATMOS(26) vector. Mole fraction profiles are also required to complete definition of the atmosphere model. Since the desired mole fraction profiles are preset by the program, they need not appear in the above namelist.

The third group of cards specifies vehicle and certain instrumentation characteristics. The mass (VMASS), reference area (VSA), etc are given as three vectors, which correspond to the three available phases of entry in LTR--aeroshell, parachute, and terminal (with parachute released). However, since variables HD and HR do not appear in the above namelist, the entire sample case deals with only the aeroshell phase.

The final group of cards defines the "actual" dynamic and measurement errors and other differences between the "actual" and nominal models. Elements C(101) through C(104) define initial errors in the vehicle translational state and C(140) defines an initial vehicle attitude error. Use of the aerodynamic coefficient C(J)s to alter preset nominal aerodynamic coefficient tables, as well as to define "actual" errors in the vehicle aerodynamic coefficients, has been explained in Chapter II of this section. In this particular sample case C(16), C(22), and C(23) are used only to alter the preset nominal coefficient tables; C(20) is used only to specify an "actual" error; while C(21) performs both functions. To convert the preset C_N table to the desired table requires that the preset table be multiplied by a factor of 2. We also desire to introduce a 5% "actual" C_N scale factor error into this table. Thus we set

$$C(21) = 2\ (1.05) = 2.1$$

The remaining C(J) elements are used to specify "actual" errors in certain sensors and in the nominal mole fraction profiles.

b. Output Discussion - Selected pages from the output of the data generator portion of this sample case appear in section D, where it is referred to as case A-1. The selected pages show the "actual" state and state derivatives, various vehicle and atmosphere parameters corresponding to this state, and "actual" values of all measurement types available in the LTR program at selected trajectory times. A trajectory time of 24. seconds corresponds to max q. Since dynamic pressure obviously exceeds ØDB, the point-mass dynamic model was used to generate the information shown at 24. seconds. This also explains why ALPHA and the normal acceleration are zero at this point. The output for this sample case was generated at the CDC 6400/6500 computer at the Martin Marietta Corporation.

2. Reconstruction Program

a. Input Discussion - The input data for the reconstruction program consist of a namelist and a measurement/event schedule. The namelist, which is also entitled ERAN, consists of the following cards:

```
XN=248., 11.08, -38.8, 0., 5.4E-9,
XØ=248., 11.08, -38.8, 0., 5.4E-9,
THETI=-38.8, TF=500.,
IYR=1977, IMØ=5, IDAY=16, IHR=23, IMIN=54, SECSI=41.,
ICØØR=3, PHIR=0., ECLINC=140.61, ECLØNG=68.2,

GØ=8.867E-3, RM=6050., ØMEG=2.997E-7, MU=3.2486E-5,
WDTBL=2., 0., 10., 0., 0.,
TERHT=.FALSE.,

VMASS=174., 122., 100.,
VSA=1.474E-6, .292E-6, .292E-6,
VDIA=1.37E-3, .61E-3, .61E-3,
```

```
VRI=1.76E-5, .5E-5, .5E-5,
XG=0., XM=0., ZG=0., ZMM=0.,
ICNTR=1, RESTRT=.FALSE.,
NGYR0=.TRUE., LTR2=.TRUE.,

C(16)=-.1, C(21)=2., 4., .23,

P=200.,      0.,        0.,        0.,          0.,
    0.,      2.5E-4,    0.,        0.,          0.,
    0.,      0.,        1.22E-3,   0.,          0.,
    0.,      0.,        0.,        3.234E-4,    0.,
    0.,      0.,        0.,        0.,          25.E-10,

NV=9, LISTV=67, 64, 111, 112, 113, 81, 83, 91, 71,
DV=2.E-12, .08, .15E-5, .19E-13, .33E-13, 1.E-4, 1.E-4, 1.E-4, 1.E-6,

NW=5, LISTW=140, 20, 96, 51, 53,
DW=.25E-2, 2.78E-4, .006, .1E-6, .1E-6,

SDMWT=3.,

REDRR2=.TRUE.,
RR(11,1,1)=1.E-12, .001,
RR(3,1,1)=.01, 1.E+8, 1., RR(4,1,2)=1.3E+10,
SD(11,1)=1.E-7, .02,
SD(3,1)=.05, 1.E+5, .5,.
```

The first group of cards defines the initial nominal primary state used in the mode A reconstruction process. The first four elements of the XN vector define the vehicle translational state and are identical to the first four elements of the XN vector appearing in the data generator namelist. The fifth element of the primary state and the fifth element of XN is the ambient pressure. The variable THETI defines the initial nominal vehicle attitude.

Planetary physical characteristics are specified by the next group of cards. Note that an atmosphere model does not appear since the mode A reconstruction process does not employ such a model.

The third group of cards is essentially the same as the third group appearing in the data generator namelist except for the addition of NGYR0 and LTR2. Setting NGYR0 true indicates that gyro measurements will not be processed. Setting LTR2 true indicates that the mode A reconstruction process will be used.

The four C(J) elements appear next and are used solely to alter the preset nominal aerodynamic coefficient tables.

The remaining cards define the statistics of the error sources acknowledged in the design of the filter. The P-array is the initial covariance matrix for the primary state XN. The filter considers nine measurement-consider parameters and five dynamic/measurement-consider parameters. These parameters are defined in LISTV and LISTW, respectively, and their variances are given in the DV and DW vectors, respectively. The assumed molecular weight standard deviation is given by SDMWT. Measurement noise variances assumed by the filter are defined by the RR variables while the "actual" measurement noise standard deviations are defined by the SD variables.

The measurement/event schedule cards used in this sample case are listed.

1800.	2000.	20.	3
60.	2000.	50.	4
80.	2000.	100.	5
1.	2000.	30.	21
10.	100.	30.	22
150.	2000.	200.	22
200.	200.	10.	12
350.	350.	10.	12
700.	700.	10.	12
1200.	1200.	10.	12
1400.	1400.	10.	12
100000.			

Not all these measurements and events will be processed in the sample case since TF was set to 500. in the previous namelist.

b. Output Discussion - Selected pages from the reconstruction program portion of this sample case appear in section D, where it is referred to as case A-2. The measurement output for a range measurement at 10. seconds and a doppler measurement at 121. seconds is shown. The range measurement at 10. seconds reduced altitude errors from 8.718 to 8.171 kilometers, flightpath angle errors from -.943 to -.515° and downrange angle errors from -.38 to .090°. The velocity error increases slightly. Reconstructed ARU data are zero, and will remain zero since NGYR0 was set true in the namelist. Reconstructed VRU data are zero since sufficient axial aerodynamic deceleration has not yet developed. According to the data generator output at 10. seconds, the axial aerodynamic deceleration is only on the order of 10^{-7}. However, a reconstructed axial acceleration appears in the doppler measurement at 121. seconds. The reconstructed normal acceleration is still zero, and will remain so since the integrated normal acceleration never exceed the normal accelerometer quantum level ZSTEP. The output for this sample case was generated on the CDC 6400/6500 computer at the Martin Marietta Corporation.

B. LTR MODE B SAMPLE CASE

The sample case presented here demonstrates the application of the mode B reconstruction process to a Venusian entry problem, and is presented primarily to aid the user in defining required input data and interpreting the resulting output. As in Section A, the input and output of the associated data generator run is presented first.

1. Data Generator

a. Input Discussion - The input data for the data generator consists of the following namelist ERAN cards.

```
XN=248., 11.06, -74., 0., -65., 0.,
DT=.1, QSDT=.5, QSALT=55., TF=500.,
IYR=1977, IMØ=5, IDAY=16, IHR=23, IMIN=54, SECSI=41.,
ICØØR=3, PHIR=-14.624, ECLØNG=137.82,
ECLINC=89.36,
ØDB=15.E+5,

GØ=8.867E-3, RM=6050., ØMEG=2.997E-7, MU=3.2486E+5,
ATMØS(1)=1.104E+10,
ATMØS(18)=0., 60., 115., 125., 137., 175., 2*0.,
ATMØS(26)=738., 260., 170., 2*210., 710.,
NTPTS=6, NMPTS=4,
AGAM=1.4,
WDTBL=2., 0., 10., 0., 0.,
TERHT=.FALSE.,

VMASS=22.6, VDIA=.448E-3, VSA=.158E-6,
VRI=1.085E-6,
XG=0., XM=0., ZG=0., ZMM=0.,
XSTEP=1.5E-5, ZSTEP=1.5E-5, TSTEP=.004,
ICNTR=20,
RESTRT=.FALSE.,
```

```
C(101)=-10., .025, .4, .5, C(140)=1.,
C(16)=-.1, C(20)=1.034, 2.1, 4., .23,
C(67)=1.E-4, C(81)=1.01, C(83)=1.01, C(91)=.99,
C(111)=1.2E-3, -1.3E-7, 5.E-7,
C(1)=5.E8, C(3)=5., 2.5, -4., 3.5, 2., -4., -7., 6., -4., 8., 6.,
C(152)=6., 8., C(156)=.03,-.03, C(161)=.01, -.01,
C(166)=.01, .015, -.015, -.01,.
```

Since these data are very similar to the data presented for the mode A sample case (data generator) in Section A, only the differences will be explained here.

The first difference concerns the appearance of the variables QSDT and QSALT in the above namelist. These variables indicate that the quasi-static dynamic model will be used when the vehicle descends to an altitude of 55. kilometers. The integration step size will be increased from .1 second to .5 second. The second difference concerns the physical characteristics of the entry vehicle. The mode A sample case involves an entry vehicle representative of the Planetary Explorer main probe, while the mode B sample case involves an entry vehicle representative of the Planetary Explorer miniprobe. This accounts for the different values used for the variables VMASS through VRI in each case.

b. Output Discussion - Selected pages from the output of the data generator portion of this sample case appear in section D, where it is referred to as case B-1. The data at the trajectory time of 40. seconds were generated with the standard dynamic model, although the point-mass assumption was employed since the dynamic pressure exceeded the input value of 0DB. This is still true at the trajectory time of 228. seconds. In addition, the data at this latter time were generated using the quasi-static dynamic model since the vehicle altitude is less than the input value of QSALT. The fact that the derivative of the velocity is zero is a consequence of using the quasi-static dynamic model. The output for this sample case was generated in the CDC 6400/6500 computer at the Martin Marietta Corporation.

2. Reconstruction Program

a. Input Discussion - The input data for the reconstruction program consist of a namelist and a measurement/event schedule. The namelist, which is also entitled ERAN, consists of the following cards.

```
XN=248., 11.06, -74., 0.,
X0=248., 11.06., -74., 0.,
```

```
IYR-1977, IMØ=5, IDAY=16, IHR=23, IMIN=54, SECSI=41.,
ICØØR=3, PHIR=-14.624, ECLØNG=137.82, ECLINC=89.36,
TF=500.,

GØ=8.867E-3, RM=6050., ØMEG=2.997E-7,
MU=3.2486E+5,
ATMØS(1)=1.104E+10,
ATMØS(18)=0., 60., 115., 125., 137., 175., 2*0.,
ATMØS(26)=738., 260., 170., 2*210., 710.,
NTPTS=6, NMPTS=4,
AGAM=1.4,
TERHT=.FALSE.,
WDTBL=2., 0., 10., 0., 0.,

VMASS=22.6, VDIA=.448E-3, VSA=.158E-6,
VRI=1.085E-6,
XG=0., XM=0., ZG=0., ZMM=0.,
ICNTR=1,
RESTRT=.FALSE.,
NACCEL=.TRUE., NGYRØ=.TRUE.,
LTR1=.TRUE.,

C(16)=.1, C(21)=2., 4., .23,

P=200.,          0.,            0.,          0.,
   0.,           2.5E-4,        0.,          0.,
   0.,           0.,            1.22E-3,     0.,
   0.,           0.,            0.,          3.234E-4,

NQ=4, LISTQ=3, 5, 7, 9,

Q=25.,           0.,            0.,          0.,
  0.,           10.,            0.,          0.,
  0.,            0.,            1.5,         0.,
  0.,            0.,            0.,         40.,

NU=2, LISTU=20, 140,
DU=2.78E-4, .25E-2,

NV=7, LISTV=67, 111, 112, 113, 81, 83, 91,
DV=12.E-8, .15E-5, .19E-13, .33E-13, 1.E-4, 1.E-4, 1.E-4,

NW=8, LISTW=4, 6, 8, 152, 153, 156, 161, 1,
DW=4., 8., 14., 25., 50., 6.E-4, 1.E-4, 2.E+9,

SDMWT=3.,
```

```
RR(4,1,1)=1.E8, RR(4,1,2)=1.3E10, SD(4,1)=1.E5,
RR(5,1,1)=1., SD(5,1)=.5,
RR(11,1,1)=1.E-8, SD(11,1)=1.E-5,.
```

Since these data are very similar to the data presented for the mode A sample case (reconstruction program) in part A, only the differences will be discussed here.

The mode B primary state vector consists of only four components. This explains why the XN vectors in the two cases have different dimensions. Since the mode B reconstruction process, unlike mode A, requires an atmosphere model, the pertinent ATM0S variables must appear in the above namelist.

Both NACCEL and NGYR0 are set true to remove both the normal accelerometer and the gyro from the reconstruction process. Setting LTR1 true indicates that the mode B reconstruction process will be employed.

The 4x4 P-array defines the initial covariance matrix corresponding to the primary mode B four-dimensional state vector. The mode B filter in this sample case also solves for the temperatures at the first four temperature breakpoints. The second, third, and fourth temperature breakpoints are treated as consider parameters by the filter. Certain of the component mole fraction profile parameters are also considered by the filter.

The measurement/event schedule cards used in this sample case are listed.

```
    30.        2000.       100.      4
    40.        2000.       150.      5
    10.        2000.        60.     21
    60.          60.        10.     12
   200.         200.        10.     12
   600.         600.        10.     12
  1500.        1500.        10.     12
100000.
```

Not all these measurements and events will be processed in the sample case since TF was set to 500. in the previous namelist.

b. Output Discussion - Selected pages from the reconstruction portion of this sample case appear in section D where they are referred to as case B-2. The output for a temperature measurement at 40. seconds, a quasi-event at 200. seconds, and a pressure measurement at 230. seconds is shown. The temperature measurement at 40. seconds reduces the velocity and downrange estimation errors, although the altitude and flightpath angle errors have increased. The temperature estimation errors at the temperature breakpoints of 0. and 60. kilometers have been reduced, while those at the higher temperature breakpoints have not been significantly affected. This is to be expected since the vehicle is at an altitude of 66.6 kilometers when this temperature measurement was made. The nominal trajectory is updated at the quasi-event at 200. seconds, but only the altitude and downrange angle components of the nominal trajectory have been improved as a result. Examining all estimation errors at this quasi-event shows that all initial errors, except for the temperature error at the third temperature breakpoint, have been reduced at 200. seconds. The pressure measurement at 230. seconds, which is the first measurement following the previous quasi-event, does not have much of an effect on the temperature solve-for parameters, although altitude and velocity estimation errors are reduced. Note that all state and solve-for parameter estimation errors at this point easily fall within the $\pm 3\sigma$ range predicted by the filter. For example, compare the altitude error of -.751 kilometer with the predicted $1-\sigma$ standard deviation of .823 kilometer, and the surface temperature error of -4.55°K with the predicted $1-\sigma$ standard deviation of 4.97°F. This indicates that the filter is convergent at this point in the reconstruction process. The output for this sample case was generated on the CDC 6400/6500 computer at the Martin Marietta Corporation.

C. QUASI-STATIC DYNAMIC MODEL SAMPLE CASE

The results of a study performed to establish the validity of the quasi-static dynamic model in the terminal descent phase of a Vernusian entry mission are presented here. The assumptions and equations defining the quasi-static dynamic model are given in Chapter II of the Analytic Section of this manual. The LTR data generator program was used to compute the true vehicle velocity. The quasi-static velocity, of course, was computed from the analytic terminal velocity solution.

Vertical motion ($\gamma = -90°$) was assumed for this study. The initial vehicle velocity was 863 m/s at an 85-kilometer altitude. A ballistic coefficient of 30.01×10^6 kg/km^2 was assumed until the parachute was deployed at the 50-kilometer altitude, after which the ballistic coefficient was changed to 25.539×10^6 kg/km^2.

The Venusian atmosphere model used in this study was based on the GSFC No. 3609 Venusian model. In LTR, atmosphere models are approximated with a surface pressure and linear temperature and molecular weight breakpoint models. The validity of the hydrostatic equation and the perfect gas law is also assumed. The temperature profile used in the study is defined.

Altitude (km)	Temperature (°K)
0.	738.
13.5	640.
42.	387.
60.	256.
115.	170.
125.	210.

A constant molecular weight of 43.2 over the altitude range under consideration was assumed. Surface pressure was set to 1.104×10^5 millibars.

The results of the study are summarized. True velocity (computed by LTR) and quasi-static velocity (computed analytically) are shown as functions of altitude

Altitude (km)	Quasi-Static Velocity (m/s)	True Velocity (m/s)
80.	190.	406.
70.	80.3	83.4
60.	32.7	32.9
50.	15.55	15.87
40.	9.14	9.15
30.	6.06	5.86
20.	4.30	4.30
10.	3.17	3.21

The initial disagreement at the 80-kilometer altitude is due to the fact that the initial velocity at the 85-kilometer altitude was chosen to be 863 m/s, which is much greater than the terminal velocity at that altitude. However, after 70 kilometers, the agreement between the quasi-static and true velocities is quite good.

D. SELECTED PAGES FROM LTR SAMPLE CASES

Case A-1: LTR Mode A Data Generator Sample Case

```
         DATA GENERATOR PROBLEM    PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-3M

  ACTUAL STATE VECTOR AT     10.00 SECONDS     INTEGRATION STEP SIZE =       .10     PHASE=  1

         H  =  1.6921663914170E+02   KM            V =  1.1156334181572E+01  KM/SEC           GAMMA = -3.7934412160168E+01  DEGREES
       PHI =  1.3017819706034E+00   DEGREES   THETA = -3.7301131418811E+01  DEGREES          OMEGA = -4.9415274812280E-04  DEGREES/SEC
       VX = -4.2255292754460E-07    KM/SE         VZ = -2.7665354886475E-09 KM/SEC           THTQ = -1.1314188220029E-03DEGREES/SEC
  PRES2 =  2.93[illegible]9744450846E-07MILLIBARS


      STATE DERIVATIVES

            H DOT = -6.8584570405358E+00              V DOT =  5.1631404479111E-03          GAMMA DOT =  4.7043150714520E-02
          PHI DOT =  8.1064099398858E-02          THETA DOT = -4.9415274812280E-04            OMEGA DOT = -2.2992247512274E-04
              DVX = -1.8836435736657E-07                DVZ = -1.2877259846811E-09                 DTHT = -8.6245924625211E-06
           DPRES2 =  1.3102150226326E-02

      RELATIVE VELOCITY     =   1.1157423817439E+01  KM/SEC             PRESSURE    =   3.2236860003164E-07  MILLIBARS
      WIND VELOCITY         =   0.                   KM/SEC             DENSITY     =   2.2745279735908E-01  KG/KM**3
      DYNAMIC PRESSURE      =   1.4157594001333E-04  MILLIBARS          ALPHA       =   1.9307014515740E+00  DEGREES
      MOLECULAR WEIGHT      =   3.7186747277807E+01  KG-MOL             CA          =   1.5705846403379E+00  UNIT FREE
      TEMPERATURE           =   6.3390314560135E+02  DEGREES K          CN          =  -1.0737077230424E-02  UNIT FREE
      MACH NUMBER           =   2.5047776932942E+01  UNIT FREE          CMQ         =  -5.5411155496466E-01  UNIT FREE
      AXIAL FORCE           =  -3.[illegible]5398181784E-05  KG-KM/SEC**2       MOMENT      =   1.6776432892351E-17  KG-KM/SEC**2
      NORMAL FORCE          =  -2.2406432133451E-07  KG-KM/SEC**2       GRAVITY     =   8.3989475570490E-03  KM/SEC**2
      CENTER OF PRESSURE    =  -3.1520917986304E-04  KM                 AXIAL ACCEL=  -1.8836435736657E-07  KM/SEC**2
      MOMENT ACCELERATION   =   9.6416280990524E-20 KM/SEC**2           NORMAL ACCEL=  -1.2877259846811E-09  KM/SEC**2
         EPSILON              =   4.3612603921270E-03


      MEASUREMENT VALUES

           ACCELEROMETERS =        -1.8836436E-07                       RATE GYRO   =        -8.6245925E-06
                                   -1.2877260E-09                       ALTIMETER   =         1.6938586E+02
           PRESSURE       =         2.6413347E+01                       TEMPERATURE =         7.9373196E+04


      DSN TRAKING FOR        STATION 1        STATION 2        STATION 3
      RANGE =             7.07706263E+07  7.07733562E+07  7.07650515E+07       KM
      RANGE RATE =        2.30803786E+01  2.25059150E+01  2.27705017E+01       KM/SEC

      REFRACTIVITY VALUES
      DELTA RANGE =     0.               0.               0.                    KM
      DELTA R-RATE =    0.               0.               0.                   KM/SEC


           COMMUNICATION ANGLE IS        4.61810635E+01


           ANGLE BETWEEN ENTRY PLANE AND SKY IS  6.55079225E+01


      REFFRENCE PLANE   LATTITUDE         LONGITUDE

  PLANETO-EQUATORIAL -2.98883157E+00  3.86733508E+01
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      DATA GENERATOR PROBLEM    PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-3M

ACTUAL STATE VECTOR AT    24.00 SECONDS     INTEGRATION STEP SIZE =      .10    PHASE=  1

      H  =  7.9055510934476E+01  KM              V =  4.6126983333427E+00  KM/SEC         GAMMA = -3.7386323563832E+01  DEGREES
     PHI =  2.3873543655747E+00  DEGREES     THETA = -3.9763412103315E+01  DEGREES        OMEGA = -9.0499521023880E-02  DEGREES/SEC
      VX = -6.6165068126475E+00   KM/SE        VZ =  2.4593992873688E-06 KM/SEC         THTQ = -3.2942483091380E+00DEGREES/SEC
 PRES2 =  6.9921409448945E+00MILLIBARS


     STATE DERIVATIVES

          H DOT = -2.8007667569590E+00             V DOT = -2.3085914431981E+00          GAMMA DOT = -5.6237687718228E-02
        PHI DOT =  3.4261833305652E-02        THETA DOT = -9.0499521023880E-02            OMEGA DOT =  2.4700173026663E-01
            DVX = -2.3138423473662E+00              DVZ =  0.                               DTHT = -1.5795146133445E-03
         DPRES2 =  3.9462553662688E+05

     RELATIVE VELOCITY    =   4.6137801719457E+00  KM/SEC              PRESSURE    =   7.1805405223274E+00  MILLIBARS
     WIND VELOCITY        =   0.                   KM/SEC              DENSITY     =   1.6292927013319E+07  KG/KM**3
     DYNAMIC PRESSURE     =   1.7341350370286E+03  MILLIBARS           ALPHA       =   0.                   DEGREES
     MOLECULAR WEIGHT     =   4.3167746647707E+01  KG-MOL              CA          =   1.5750800000000E+00  UNIT FREE
     TEMPERATURE          =   2.2881825483449E+02  DEGREES K           CN          =   0.                   UNIT FREE
     MACH NUMBER          =   1.8574360391822E+01  UNIT FREE           CMQ         =  -7.2000000000000E-01  UNIT FREE
     AXIAL FORCE          =  -4.0260856844173E+02  KG-KM/SEC**2        MOMENT      =   7.5873484742452E-08  KG-KM/SEC**2
     NORMAL FORCE         =   0.                   KG-KM/SEC**2        GRAVITY     =   8.6478695618112E-03  KM/SEC**2
     CENTER OF PRESSURE   =  -3.1825100000000E-04  KM                  AXIAL ACCEL=  -2.3138423473662E+00  KM/SEC**2
     MOMENT ACCELERATION =   4.3605451001409E-10 KM/SEC**2             NORMAL ACCEL=   0.                    KM/SEC**2
        EPSILON            =   1.0265826091150E-02


     MEASUREMENT VALUES

         ACCELEROMETERS =        -2.3138423E+00                     RATE GYRO    =        -1.5795146E-03
                                  0.                                ALTIMETER    =         7.9134566E+01
         PRESSURE       =         3.4262549E+08                     TEMPERATURE =          1.5857416E+04


     DSN TRAKING FOR        STATION 1        STATION 2        STATION 3
     RANGE =           7.07709420E+07  7.07736638E+07  7.07653628E+07       KM
     RANGE RATE =      1.72548812E+01  1.66803888E+01  1.69452523E+01       KM/SEC

     REFRACTIVITY VALUES
     DELTA RANGE =     0.              0.              0.                    KM
     DELTA R-RATE =    0.              0.              0.                   KM/SEC

         COMMUNICATION ANGLE IS       4.70728715E+01

         ANGLE BETWEEN ENTRY PLANE AND SKY IS  6.55079025E+01


     REFERENCE PLANE   LATITUDE         LONGITUDE

  PLANETO-EQUATORIAL -3.71604664E+00  3.94807315E+01

   SUB-SOLAR ORBITAL  1.51474276E+00  6.63540755E+01
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```
        DATA GENERATOR PROBLEM     PRELIMINARY MAIN PROBE-MODE A-VENUS-P 45 IN 2-3M


ACTUAL STATE VECTOR AT     90.00 SECONDS      INTEGRATION STEP SIZE =       .10     PHASE=  1

       H  =  6.4406990956366E+01   KM            V =  9.9665561865505E-02  KM/SEC           GAMMA = -8.9418225419331E+01  DEGREES
     PHI =  2.4993615338130E+00   DEGREES    THETA = -9.1125535952857E+01  DEGREES          OMEGA = -1.2027221671209E-01  DEGREES/SEC
     VX = -1.1637736625625E+01   KM/SE         VZ = -6.0876902466085E-06 KM/SEC           THTQ = -5.4985840893599E+01DEGREES/SEC
 PRES2 =  1.1598274035503E+02MILLIBARS


     STATE DERIVATIVES

           H DOT = -9.9660424084234E-02             V DOT = -8.4459712860407E-04          GAMMA DOT = -1.2639898282240E-01
         PHI DOT =  9.4828319137806E-05         THETA DOT = -1.2027221671209E-01            OMEGA DOT = -1.7701195503899E-02
             DVX = -9.5344135021361E-03               DVZ = -1.4120408530933E-07                 DTHT = -2.0991461802981E-03
          DPRES2 =  2.1105407221025E+05

     RELATIVE VELOCITY    =    9.9688604702238E-02  KM/SEC              PRESSURE    =    1.1855889082400E+02  MILLIBARS
     WIND VELOCITY        =    0.                   KM/SEC              DENSITY     =    2.4371566884435E+08  KG/KM**3
     DYNAMIC PRESSURE     =    1.2110009690873E+01  MILLIBARS           ALPHA       =    1.1438993695759E-02  DEGREES
     MOLECULAR WEIGHT     =    4.3204946912966E+01  KG-MOL              CA          =    9.2939698052163E-01  UNIT FREE
     TEMPERATURE          =    2.5278856025322E+02  DEGREES K           CN          =   -1.3764312875083E-05  UNIT FREE
     MACH NUMBER          =    3.8199366580222E-01  UNIT FREE           CMQ         =   -7.9542440252168E-02  UNIT FREE
     AXIAL FORCE          =   -1.6599879493717E+00  KG-KM/SEC**2        MOMENT      =    5.6115028075556E-09  KG-KM/SEC**2
     NORMAL FORCE         =   -2.4569510843824E-05  KG-KM/SEC**2        GRAVITY     =    8.6893552641850E-03  KM/SEC**2
     CENTER OF PRESSURE   =   -4.4970043547206E-04  KM                  AXIAL ACCEL=   -9.5344135021362E-03  KM/SEC**2
     MOMENT ACCELERATION =    3.2250016135377E-11 KM/SEC**2            NORMAL ACCEL=   -1.4120408530933E-07  KM/SEC**2
        EPSILON              =    7.8061200659047E-01


     MEASUREMENT VALUES

          ACCELEROMETERS =          -9.5344135E-03                        RATE GYRO    =          -2.0991462E-03
                                    -1.4120409E-07                        ALTIMETER    =           6.4471398E+01
          PRESSURE       =           1.3242831E+07                        TEMPERATURE =           2.5756424E+02


     DSN TRAKING FOR          STATION 1         STATION 2         STATION 3
     RANGE =             7.07718261E+07  7.07745100E+07  7.07662265E+07        KM
     RANGE RATE =        1.32033006E+01  1.26279709E+01  1.28957168E+01        KM/SEC

     REFRACTIVITY VALUES
     DELTA RANGE =     0.                0.                0.                     KM
     DELTA R-RATE =    0.                0.                0.                   KM/SEC

          COMMUNICATION ANGLE IS        4.71656709E+01

          ANGLE BETWEEN ENTRY PLANE AND SKY IS  6.55075855E+01


     REFERENCE PLANE   LATITUDE         LONGITUDE

  PLANETO-EQUATORIAL -3.79103976E+00  3.95641068E+01
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      DATA GENERATOR PROBLEM    PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-3M

ACTUAL STATE VECTOR AT   122.00 SECONDS     INTEGRATION STEP SIZE =       .10    PHASE=  1

        H  =  6.1583533622867E+01  KM              V =  7.8565146440541E-02  KM/SEC         GAMMA = -9.0933564056037E+01  DEGREES
      PHI =  2.4991657483931E+00  DEGREES     THETA = -9.2445013485686E+01  DEGREES          OMEGA = -7.3319777691400E-03  DEGREES/SEC
       VX = -1.1937049951321E+01   KM/SE        VZ = -6.5025115706780E-06 KM/SEC          THTQ = -5.6305318426460E+01DEGREES/SEC
  PRES2 =  1.9332507520212E+02MILLIBARS


      STATE DERIVATIVES

          H DOT = -7.8554717665486E-02             V DOT = -5.1326338562429E-04          GAMMA DOT = -1.2478105191805E-02
        PHI DOT = -1.2000547981083E-05         THETA DOT = -7.3319777691400E-03            OMEGA DOT =  7.2803524073953E-03
            DVX = -9.2108637155212E-03               DVZ =  2.3374277372928E-08                 DTHT = -1.2796715275452E-04
         DPRES2 =  2.7236933157538E+05


      RELATIVE VELOCITY     =    7.8554755912707E-02  KM/SEC               PRESSURE    =    1.9744298844269E+02  MILLIBARS
      WIND VELOCITY         =    0.                   KM/SEC               DENSITY     =    3.9865490324116E+08  KG/KM**3
      DYNAMIC PRESSURE      =    1.2300199871854E+01  MILLIBARS            ALPHA       =   -2.3871572553874E-03  DEGREES
      MOLECULAR WEIGHT      =    4.3212117150090E+01  KG-MOL               CA          =    8.8397493884055E-01  UNIT FREE
      TEMPERATURE           =    2.5740876316258E+02  DEGREES K            CN          =    2.2432505842376E-06  UNIT FREE
      MACH NUMBER           =    2.9832263501198E-01  UNIT FREE            CMQ         =   -7.9904513709784E-02  UNIT FREE
      AXIAL FORCE           =   -1.6026902865007E+00  KG-KM/SEC**2         MOMENT      =    4.4294328557210E-10  KG-KM/SEC**2
      NORMAL FORCE          =    4.0671242628895E-06  KG-KM/SEC**2         GRAVITY     =    8.6973858149840E-03  KM/SEC**2
      CENTER OF PRESSURE    =   -4.4095540590386E-04  KM                   AXIAL ACCEL=   -9.2108637155213E-03  KM/SEC**2
      MOMENT ACCELERATION =    2.5456510665063E-12 KM/SEC**2               NORMAL ACCEL=    2.3374277372928E-08  KM/SEC**2
         EPSILON               =    ).9010347600023E-01


      MEASUREMENT VALUES

           ACCELEROMETERS =          -9.2108637E-03                    RATE GYRO     =          -1.2796715E-04
                                      2.3374277E-08                    ALTIMETER     =           6.1645117E+01
           PRESSURE       =           2.1211949E+07                    TEMPERATURE =             2.5937055E+02


      DSN TRAKING FOR          STATION 1         STATION 2         STATION 3
      RANGE =             7.07722483E+07  7.07749138E+07  7.07666389E+07        KM
      RANGE RATE =        1.31874007E+01  1.26116119E+01  1.28808861E+01        KM/SEC

      REFRACTIVITY VALUES
      DELTA RANGE =     0.              0.              0.                     KM
      DELTA R-RATE =    0.              0.              0.                    KM/SEC

           COMMUNICATION ANGLE IS       4.71657221E+01

           ANGLE BETWEEN ENTRY PLANE AND SKY IS  6.55074295E+01


      REFERENCE PLANE   LATITUDE         LONGITUDE

   PLANETO-EQUATORIAL -3.79090863E+00  3.95639611E+01
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```
        DATA GENERATOR PROBLEM    PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-3M


  ACTUAL STATE VECTOR AT    200.00 SECONDS     INTEGRATION STEP SIZE =       .10    PHASE=  1

        H  =  5.6551268231716E+01   KM               V =  5.4740069601004E-02  KM/SEC          GAMMA = -9.1420096769027E+01  DEGREES
      PHI =  2.4981787969445E+00   DEGREES      THETA = -9.2498338384194E+01  DEGREES         OMEGA =  6.4126499096196E-05  DEGREES/SEC
      VX = -1.2639869707362E+01   KM/SE           VZ = -6.5174385127280E-06 KM/SEC          THTQ = -5.6358643325049E+01DEGREES/SEC
   PRES2 =  4.5908371526973E+02MILLIBARS


      STATE DERIVATIVES

            H DOT = -5.4723256658393E-02              V DOT = -1.8818386976282E-04          GAMMA DOT = -4.8697732113918E-03
          PHI DOT = -1.2728663648431E-05          THETA DOT =  6.4126499096196E-05            OMEGA DOT = -1.1567453640475E-05
              DVX = -8.8999674167073E-03                DVZ =  2.9180580642419E-11                 DTHT =  1.1192185470058E-06
          DPRES2 =  4.0360239323714E+05

      RELATIVE VELOCITY    =    5.4723256658594E-02  KM/SEC             PRESSURE    =    4.6813409283365E+02  MILLIBARS
      WIND VELOCITY        =    0.                   KM/SEC             DENSITY     =    8.4659865292781E+08  KG/KM**3
      DYNAMIC PRESSURE     =    1.2676269020245E+01  MILLIBARS          ALPHA       =   -4.3861363128632E-06  DEGREES
      MOLECULAR WEIGHT     =    4.3224896707866E+01  KG-MOL             CA          =    8.2879807570890E-01  UNIT FREE
      TEMPERATURE          =    2.8747489642067E+02  DEGREES K          CN          =    2.7174042276947E-09  UNIT FREE
      MACH NUMBER          =    1.9668061985717E-01  UNIT FREE          CMQ         =   -7.9999824554547E-02  UNIT FREE
      AXIAL FORCE          =   -1.5485943305071E+00  KG-KM/SEC**2       MOMENT      =   -5.7380200732552E-12  KG-KM/SEC**2
      NORMAL FORCE         =    5.0774210317810E-09  KG-KM/SEC**2       GRAVITY     =    8.7117263439054E-03  KM/SEC**2
      CENTER OF PRESSURE  =   -4.3028801091216E-04  KM                 AXIAL ACCEL=   -8.8999674167074E-03  KM/SEC**2
      MOMENT ACCELERATION =   -3.2977126857789E-14 KM/SEC**2           NORMAL ACCEL=    2.9180580642419E-11  KM/SEC**2
         EPSILON              =    1.4199415679134E+00


      MEASUREMENT VALUES

           ACCELEROMETERS =          -8.8999674E-03                        RATE GYRO    =          1.1192185E-06
                                       2.9180581E-11                        ALTIMETER    =          5.6607819E+01
           PRESSURE        =           4.8574276E+07                        TEMPERATURE =          2.8680200E+02


      DSN TRAKING FOR         STATION 1        STATION 2        STATION 3
      RANGE =            7.07732761E+07  7.07758967E+07  7.07676430E+07       KM
      RANGE RATE =       1.31707447E+01  1.25938480E+01  1.28668416E+01       KM/SEC

      REFRACTIVITY VALUES
      DELTA RANGE =      0.               0.               0.                   KM
      DELTA R-RATE =     0.               0.               0.                  KM/SEC


           COMMUNICATION ANGLE IS          4.71654264E+01


           ANGLE BETWEEN ENTRY PLANE AND SKY IS  6.55070486E+01


      REFERENCE PLANE   LATITUDE          LONGITUDE

    PLANETO-EQUATORIAL -3.79024791E+00  3.95632264E+01
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Case A-2: LTR Mode A Reconstruction Program Sample Case

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RANGE MEASUREMENT FROM STATION  1                              AT TRAJECTORY TIME   10 00SEC
    PROBLEM    PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-3M


 TRAJECTORY
                      ORIGINAL NOMINAL                  MOST RECENT NOMINAL          ACTUAL                  UNITS
   H                  1.7875831848536E+02              1.7875831848536E+02      1.6921663914170E+02       KM
   V                  1.1131630848014E+01              1.1131630848014E+01      1.1156334181572E+01       KM/SEC
   GAMMA             -3.8339720316418E+01             -3.8339720316418E+01     -3.7934412160168E+01       DEGREES
   PHI                7.9431193263621E-01              7.9431193263621E-01      1.3017819706084E+00       DEGREES


 ATMOSPHERE
                                                       MOST RECENT NOMINAL          ACTUAL                  UNITS
   PRESSURE                                            6.2740266824954E-08      3.2236860003164E-07       MILLIBRS
   DENSITY                                             1.0000000000000E-02      2.2745279735908E-01       KG/KM**3
   TEMP                                                3.0000000000000E+02      6.3390314660135E+02       DEGREE K
   MOL. WT                                             3.5892540874251E+01      3.7186747277807E+01


VRU-ARU DATA
                         ACTUAL                           RECONSTRUCTED                 UNITS

   THETA           -3.7301131418811E+01           0.                           DEGREES
   OMEGA           -4.9415274812280E-04           0.                           DEGREES/SEC
   AXC             -1.8836435736657E-07           0.                           KM/SEC**2
   AZC             -1.2877259846811E-09           0.                           KM/SEC**2


 ENTRY PARAMETERS BASED ON MOST RECENT NOMINAL
   WIND VELOCITY       =    0.                  KM/SEC           DYNAMIC PRESSURE    =    1.3448418402448E+01MILLIBARS
   RELATIVE VELOCITY   =    1.1132716112061E+01KM/SEC            MACH NUMBER         =    1.0000000000000E+01 UNIT FREE
   EPSILON             =    4.4172658172132E-03 DEGREES          CA                  =    7.7116235865525E-01 UNIT FREE
   ALPH                =    0.                  DEGREES          GRAVITY             =    8.3732349902621E-03KM/SEC**2


DEVIATIONS FROM MOST RECENT NOMINAL
 TRAJECTORY
             ESTIMATED                          ACTUAL                  (ERROR EST-ACT)               UNITS
   H      -8.2363247454919E-01          -9.5416793436580E+00        8.7180468691087E+00        KM
   V       1.3922044387907E-03           2.4703333557966E-02       -2.3311129119175E-02        KM/SEC
   GAMMA  -5.3796774737613E-01           4.0530815624970E-01       -9.4327590362583E-01        DEGREES
   PHI     1.2723889611897E-01           5.0747003797218E-01       -3.8023114185321E-01        DEGREES


 ATMOSPHERE
             ESTIMATED                         ACTUAL                  (ERROR EST-   ACT)              UNITS
   PRESSURE 6.8863291636041E-10         2.5962833320669E-07       -2.5893970029033E-07        MILLIBRS
   DENSITY  0.                          0.                         0.                         KG/KM**3
   TEMP     0.                          0.                         0.                         DEGREE K

  SOLVE FOR PARAMETERS
            0.                          0.                         0.

  ESTIMATED DEVIATIONS FROM ORIGINAL NOMINAL OF SOLVE FORPARAMETERS
         0.


 ENTRY PARAMETERS BASED ON MOST RECENT NOMINAL


   RELATIVE VELOCITY   =   1.1132716112061E+01   KM/SEC             PRESSURE   =   6.2740266824954E-08  MILLIBARS
```

```
    WIND VELOCITY       =  0.                    KM/SEC          DENSITY    =  1.0000000000000E-02  KG/KM**3
    DYNAMIC PRESSURE    =  1.3448418402448E+01   MILLIBARS       ALPHA      =  0.                   DEGREES
    MOLECULAR WEIGHT    =  3.5892540874251E+01   KG-MOL          CA         =  7.7116235865525E-01  UNIT FREE
    TEMPERATURE         =  3.0000000000000E+02   DEGREES K       CN         =  0.                   UNIT FREE
    MACH NUMBER         =  1.0000000000000E+01   UNIT FREE       CNQ        =  0.                   UNIT FREE
    AXIAL FORCE         =  0.                    KG-KM/SEC**2    MOMENT     =  0.                   KG-KM/SEC**2
    NORMAL FORCE        =  0.                    KG-KM/SEC**2    GRAVITY    =  8.3732349902621E-03  KM/SEC**2
    CENTER OF PRESSURE  =  0.                    KM              EPSILON    =  4.4172658172132E-03  DEGREES


 STATE TRANSITION MATRIX PARTITIONS
        PHI        MATRIX
  1.0000004E+00  -6.1986052E-01   8.7588190E+00   0.               0.
 -1.6629084E-06   9.9993993E-01  -6.5883421E-03   0.               0.
 -3.5786741E-08   1.7879538E-04   1.0006380E+00   0.               0.
 -2.2453707E-07   1.2598215E-04   1.1015770E-03   1.0000000E+00    0.
 -1.8510873E-07   5.1902417E-05  -7.3338817E-04   0.               1.0000000E+00


DYNAMIC-MEASUREMENT CONSIDER PARAMETERS =  140   20   96   51   53
        THW        MATRIX
  0.             0.              0.              0.               0.
  0.             0.              0.              0.               0.
  0.             0.              0.              0.               0.
  0.             0.              0.              0.               0.
  0.             0.              0.              0.               0.


DIAGONAL OF DYNAMIC NOISE MATRIX
  0.             0.              0.              0.               0.


         STATE
         PP        MATRIX
  1.4208805E+01   3.6926249E-03   9.5871129E-02   8.9840918E-02  -2.8741853E-01
  3.6926249E-03   1.5294533E-02   2.5925316E-01  -1.3844639E-01  -1.7068817E-01
  9.5871129E-02   2.5925316E-01   9.2540509E-01   9.2059198E-01  -8.9651806E-01
  8.9840918E-02  -1.3844639E-01   9.2059198E-01   9.3976710E-01  -8.4887805E-01
 -2.8741853E-01  -1.7068817E-01  -8.9651806E-01  -8.4887805E-01   1.2835235E-09
        CXV CORR   MATRIX
  3.1655320E-06   0.              1.5794790E-07  -8.0744827E-08  -3.3795047E-08   0.              0.              0.
  0.
 -4.9709295E-06   0.             -2.4803030E-07   1.2679602E-07   5.3069372E-08   0.              0.              0.
  0.
  3.1746450E-05   0.              1.5840260E-06  -8.0977277E-07  -3.3892337E-07   0.              0.              0.
  0.
 -7.3938472E-06   0.             -3.6892460E-07   1.8859860E-07   7.8936310E-08   0.              0.              0.
  0.
 -2.9299134E-05   0.             -1.4619143E-06   7.4734784E-07   3.1279596E-07   0.              0.              0.
  0.
        CXW CORR   MATRIX
  0.             0.              0.              0.               0.
  0.             0.              0.              0.               0.
  0.             0.              0.              0.               0.
  0.             0.              0.              0.               0.
  0.             0.              0.              0.               0.

       ACTUAL DYNAMIC NOISE
          R        MATRIX
```

```
  1.0000000E-03


        UNMODELED DYNAMIC NOISE COVARIANCE MATRIX
        0.              0.              0.              0.              0.

GAIN MATRICES
          K1        MATRIX
 -1.7893898E-02
 -3.5534010E-05
  2.4414950E-04
  2.6997264E-04
 -1.7185631E-06


          RESIDUAL UNCERTAINITY MATRIX
                    MATRIX
  3.5908378E+03
```

```
    RANGE MEASUREMENT =    7.07705870E+07  KM


        OBSERVATION MATRIX PARTITIONS
           H         MATRIX
 -6.9750309E-01  0.            0.            3.6577581E+03  0.


        DYNAMIC-MEASUREMENT CONSIDER PARAMETERS
           G         MATRIX
  0.             0.            0.            0.             0.


        MEASUREMENT CONSIDER PARAMETERS
           L         MATRIX
  0.             9.9999973E-01  1.2536616E-01  -1.3007120E+03  5.0503118E+03  0.             0.             0.
  0.

 MEASUREMENTS
                              ESTIMATED                     ACTUAL                       RESIDUALS
                          7.0770595736001E+07          7.0770626328030E+07          -3.0592028617859E+01


      DEVIATIONS FROM MOST RECENT NOMINAL
         TRAJECTORY
                      ESTIMATED                     ACTUAL                  (ERROR EST-ACT)            UNITS
          H        -1.3710431164544E+00        -9.5416793436580E+00       8.1706362272036E+00      KM
          V         3.0514699762439E-04         2.4703333557966E-02      -2.4398186560341E-02      KM/SEC
          GAMMA    -1.1002394443263E-01         4.0530615624970E-01      -5.1533210068233E-01      DEGREES
          PHI       6.0044535640197E-01         5.0747003797218E-01       9.297[illegible]8429790E-02      DEGREES

        SOLVE FOR PARAMETERS
                     0.                          0.                          0.


            STATE
            EP          MATRIX
  1.4168288E+01  -6.9003944E-03  3.8876038E-01  9.9958568E-01  -5.8465922E-01
 -6.9003944E-03   1.5145584E-02  9.1856973E-01 -6.9168265E-03  -4.7777763E-01
  3.8875038E-01   9.1856973E-01  3.9204907E-01  3.8889563E-01  -6.7125941E-01
  9.9958568E-01  -6.9168265E-03  3.8889563E-01  1.5488484E-01  -5.8460680E-01
 -5.8465922E-01  -4.7777763E-01 -6.7125941E-01 -5.8460680E-01   7.6608956E-10
          CXV CORR  MATRIX
  2.5747212E-06   3.5721727E-04  3.2238465E-07 -2.9211073E-07   1.1311903E-06  0.             0.             0.
  0.
 -6.1341694E-06   6.6359494E-04  5.4162036E-08 -2.6417802E-07   2.2179394E-06  0.             0.             0.
  0.
  9.1882719E-05  -1.0092132E-02 -8.9393446E-07  4.0535901E-06  -3.3715999E-05  0.             0.             0.
  0.
  2.5725975E-06  -2.8247391E-02 -1.5205778E-05  1.7840084E-05  -9.1651334E-05  0.             0.             0.
  0.
 -5.9743351E-05   6.3449381E-03  4.6342275E-07 -2.4981128E-06   2.1218562E-05  0.             0.             0.
  0.
          CXW CORR  MATRIX
  0.             0.            0.            0.             0.
  0.             0.            0.            0.             0.
  0.             0.            0.            0.             0.
  0.             0.            0.            0.             0.
  0.             0.            0.            0.             0.

        ACTUAL DYNAMIC NOISE
```

```
              R         MATRIX
  1.0000000E-03

          UNMODELED DYNAMIC NOISE COVARIANCE MATRIX
          0.                0.                0.                0.                0.

GAIN MATRICES
             K1         MATRIX
 -1.7893898E-02
 -3.5534010E-05
  2.4414950E-04
  2.6997264E-04
 -1.7185631E-06

             RESIDUAL UNCERTAINITY MATRIX
                        MATRIX
  3.5908378E+03

          ACTUAL MEASUREMENT NOISE
        2.0606645999998E-02

          MEASUREMENT COVARIANCE MATRIX
        2.0000000000000E-02
```

```
DOPPLER MEASUREMENT FROM STATION  1                              AT TRAJECTORY TIME  121.00SEC
    PROBLEM    PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-3M

  TRAJECTORY
                    ORIGINAL NOMINAL              MOST RECENT NOMINAL          ACTUAL              UNITS
    H             7.3000690547543E+01           7.3000690547543E+01      6.1662346266752E+01      KN
    V             4.9961921135524E-02           4.9961921135524E-02      7.9081973389546E-02      KM/SEC
    GAMMA        -9.1554833498257E+01          -9.1554833498257E+01     -9.0920587591225E+01      DEGREES
    PHI           1.9720070532197E+00           1.9720070532197E+00      2.4991777056531E+00      DEGREES

  ATMOSPHERE
                                                 MOST RECENT NOMINAL          ACTUAL              UNITS
    PRESSURE                                    2.6632843168221E+02      1.9467594165644E+02      MILLIBRS
    DENSITY                                     1.0470131331500E+09      3.9326328024518E+08      KG/KM**3
    TEMP                                        1.3211517800296E+02      2.5727979701804E+02      DEGREE K
    MCL. WT                                     4.3183123008242E+01      4.3211917003504E+01

VRU-ARU DATA
                     ACTUAL                            RECONSTRUCTED             UNITS

    THETA       -9.2434940732901E+01          0.                            DEGREES
    OMEGA       -1.1433582106660E-02          0.                            DEGREES/SEC
    AXC         -9.2178174750768E-03         -9.2250000003560E-03           KM/SEC**2
    AZC         -1.1625497438391E-08          0.                            KM/SEC**2

  ENTRY PARAMETERS BASED ON MOST RECENT NOMINAL
    WIND VELOCITY      =   0.                   KM/SEC            DYNAMIC PRESSURE   =   1.3058116411079E+01MILLIBARS
    RELATIVE VELOCITY  =   4.9943526115285E-02KM/SEC              MACH NUMBER        =   2.6465644962714E-01 UNIT FREE
    EPSILON            =   1.5599626068924E+00 DEGREES            CA                 =   9.3394537345388E-01 UNIT FREE
    ALPH               =   0.                  DEGREES            GRAVITY            =   8.6649811672799E-03KM/SEC**2

DEVIATIONS FROM MOST RECENT NOMINAL
  TRAJECTORY
                 ESTIMATED                         ACTUAL                  (ERROR EST-ACT)              UNITS
   H        -5.0489984252398E+00          -1.1338344280792E+01       6.2893458555519E+00       KM
   V         3.1563133075245E-02           2.9120052254022E-02       2.4430808212228E-03       KM/SEC
   GAMMA    -7.2164713276593E+00           6.3424590703198E-01      -7.8507172346913E+00       DEGREES
   PHI       5.9964651431821E-01           5.2717065243338E-01       7.2475861884822E-02       DEGREES

  ATMOSPHERE
                 ESTIMATED                        ACTUAL                   (ERROR EST-   ACT)            UNITS
   PRESSURE-9.0684408565250E+01          -7.1652490025768E+01      -1.9031918539482E+01       MILLIBRS
   DENSITY -1.3233753170274E+09          -6.5374985290477E+08      -6.6962546412262E+08       KG/KM**3
   TEMP      1.2200235772552E+02           1.2516461901508E+02      -3.1622612895526E+00       DEGREE K

   SOLVE FOR PARAMETERS
            0.                             0.                         0.

   ESTIMATED DEVIATIONS FROM ORIGINAL NOMINAL OF SOLVE FORPARAMETERS
          0.


  ENTRY PARAMETERS BASED ON MOST RECENT NOMINAL


    RELATIVE VELOCITY   =    4.9943526115285E-02   KM/SEC              PRESSURE   =    2.6632843168221E+02  MILLIBARS
```

```
          WIND VELOCITY         =   0.                     KM/SEC               DENSITY     =   1.0470131331500E+09  KG/KM**3
          DYNAMIC PRESSURE      =   1.3058116411079E+01    MILLIBARS            ALPHA       =   0.                   DEGREES
          MOLECULAR WEIGHT      =   4.3183123008242E+01    KG-MOL               CA          =   9.3394537345388E-01  UNIT FREE
          TEMPERATURE           =   1.3211517800296E+02    DEGREES K            CN          =   0.                   UNIT FREE
          MACH NUMBER           =   2.6465644962714E-01    UNIT FREE            CMQ         =   0.                   UNIT FREE
          AXIAL FORCE           =   0.                     KG-KM/SEC**2         MOMENT      =   0.                   KG-KM/SEC**2
          NORMAL FORCE          =   0.                     KG-KM/SEC**2         GRAVITY     =   8.6649811672799E-03  KM/SEC**2
          CENTER OF PRESSURE    =   0.                     KM                   EPSILON     =   1.5599626368924E+00  DEGREES


 STATE TRANSITION MATRIX PARTITIONS
          PHI          MATRIX
  1.0000014E+00  -9.9964088E-01   1.7101101E-03  -2.0501800E-06   0.
 -2.8263199E-06   1.0000009E+00   1.2360266E-05   2.3304725E-04   0.
 -1.5362928E-06   6.6601822E-03   1.0099667E+00  -1.6858250E-01   0.
  3.6121098E-11  -4.3771470E-06   8.2375263E-06   9.9999929E-01   0.
 -1.3431218E+02  -8.8805822E+06  -3.6582419E+04  -6.3874311E+03   1.0012767E+00


DYNAMIC-MEASUREMENT CONSIDER PARAMETERS =  140   20   96   51   53
          THW          MATRIX
 -5.1636535E-05   0.              0.             -4.6117719E-03   0.
  3.4360313E-04   0.              0.              9.2201257E-03   0.
 -1.6849091E-01   0.              0.              5.0270001E-03   0.
 -7.0916555E-07   0.              0.              7.5653736E-11   0.
 -6.4595425E+03  -4.6257519E+05   0.             -4.5815800E+05   0.


DIAGONAL OF DYNAMIC NOISE MATRIX
  0.              0.              0.              0.              0.


          STATE
          PP           MATRIX
  8.4029630E+00  -5.4846817E-01   1.6377953E-01   9.9864434E-01  -3.7789077E-02
 -5.4846817E-01   1.0325922E-03  -6.2217679E-01  -5.5563250E-01  -1.2002277E-01
  1.6377953E-01  -6.2217679E-01   1.4526209E+01   1.8067182E-01  -8.6785530E-02
  9.9864434E-01  -5.5563250E-01   1.8067182E-01   9.0223853E-02  -3.9786560E-02
 -3.7789077E-02  -1.2002277E-01  -8.6785530E-02  -3.9786560E-02   2.7011888E+00
         CXV CORR  MATRIX
 -9.3243304E-05   9.4898714E-03   5.4107560E-06  -9.2469046E-06   3.2389631E-05   0.              2.0115874E-01   1.5708002E-02
  0.
  2.4553557E-04  -1.1042227E-02  -1.1622519E-05   1.3037087E-05  -3.4367343E-05   0.              1.5976698E-02  -4.8398517E-01
  0.
 -1.1935480E-04   1.0821265E-03  -6.9768248E-06   4.2615543E-06   5.8624460E-06   0.             -5.6926694E-03   5.2898478E-02
  0.
 -1.0506425E-04  -3.9482699E-02  -2.2467125E-05   2.2517578E-05  -1.2615641E-04   0.              2.0079502E-01   1.5755994E-02
  0.
  6.3905508E-05   3.3865545E-03   1.3553299E-05  -8.6374870E-06   7.7743196E-06   0.             -6.9852084E-01   2.7509548E-01
  0.
         CXW CORR  MATRIX
 -2.0616520E-01  -3.5784709E-01  -2.5091499E-06   9.2675990E-02  -4.5043896E-08
  6.0120694E-01  -5.2965872E-02   3.4688924E-06   4.1169786E-02   6.2273055E-08
 -9.9572003E-01   1.1921598E-02  -1.4595007E-07  -5.3297482E-03  -2.6200745E-09
 -2.2296605E-01  -3.5721444E-01  -2.5014297E-06   9.2430545E-02  -4.4905305E-08
  1.1280193E-01  -5.1782654E-01  -1.7408803E-06  -3.7198216E-02  -3.1252031E-08

        ACTUAL DYNAMIC NOISE
           R         MATRIX
```

```
  1.0000000E-12


        UNMODELED DYNAMIC NOISE COVARIANCE MATRIX
        0.              0.              0.              0.              0.

GAIN MATRICES
          K1        MATRIX
  1.3681434E+02
 -8.3757771F-02
  3.6919767E+01
  2.9592784E-02
 -4.1004767E+06


          RESIDUAL UNCERTAINITY MATRIX
                    MATRIX
  4.6830578E-05

       STANDARD DEVIATIONS ON DENSITY AND TEMPERATURE
         DENSITY              4.3294405840480E+07          TEMPERATURE            1.0764771073417E+01
```

```
     RANGE-RATE MEASURMENT =   1.31681900E+01  KM/SEC


        OBSERVATION MATRIX PARTITIONS
           H       MATRIX
  8.4913239E-08   6.6894077E-01   2.8627543E-02  -3.0577591E-02   0.


        DYNAMIC-MEASUREMENT CONSIDER PARAMETERS
           G       MATRIX
  0.              0.              0.              0.              0.


        MEASUREMENT CONSIDER PARAMETERS
           L       MATRIX
  1.0000080E+00   0.              5.7512460E-05  -2.6073156E-01  -8.6254392E-02   0.              0.              0.
  0.


MEASUREMENTS
                                ESTIMATED                      ACTUAL                      RESIDUALS
                          1.3185377760577E+01           1.3187763104700E+01          -2.3853441234110E-03


    DEVIATIONS FROM MOST RECENT NOMINAL
       TRAJECTORY
                     ESTIMATED                       ACTUAL               (ERROR EST-ACT)            UNITS
         H       -4.7226491505354E+00          -1.1338344280792E+01        6.6156951302563E+00    KM
         V        3.1363341968245E-02           2.9120052254022E-02        2.2432897142235E-03    KM/SEC
         GAMMA   -2.1706412392143E+00           6.3424590703198E-01       -2.8048871462463E+00    DEGREES
         PHI      6.0369096455678E-01           5.2717065243338E-01        7.6520312123396E-02    DEGREES


       ATMOSPHERE
                     ESTIMATED                      ACTUAL               (ERROR EST-  ACT)            UNITS
         PRESSURE-9.0782219046080E+01          -7.1652490025768E+01       -1.9129729020312E+01    MILLIBRS
         DENSITY -1.3149984990818E+09          -6.5374985290477E+08       -6.6124864617701E+08    KG/KM**3
         TEMP     1.2089682637227E+02           1.2516461901508E+02       -4.2677926428050E+00    DEGREE K

        SOLVE FOR PARAMETERS
                  0.                            0.                       0.


          STATE
          PP        MATRIX
  8.3506410E+00  -5.8869172E-01   6.3844001E-01   9.9877640E-01  -2.6522168E-02
 -5.8869172E-01   8.5890231E-04  -9.9800187E-01  -5.8704716E-01  -2.1478128E-01
  6.3844001E-01  -9.9800187E-01   1.2076088E+00   6.3697231E-01   2.0243263E-01
  9.9877640E-01  -5.8704716E-01   6.3697231E-01   8.3474646E-02  -2.6793127E-02
 -2.6522168E-02  -2.1478128E-01   2.0243263E-01  -2.6793127E-02   2.6865741E+00
         CXV CORR  MATRIX
 -1.0566536E-04   9.5143594E-03   5.2339935E-06  -9.3524403E-06   3.2441203E-05   0.              2.0307130E-01   1.5005630E-02
  0.
  3.6564838E-04  -1.3067064E-02  -1.2718969E-05   1.5956796E-05  -4.0416250E-05   0.              1.3325769E-02  -5.7709178E-01
  0.
 -2.7013629E-03   9.2777199E-03  -1.0644697E-04   4.6172820E-05   5.4334922E-05   0.              1.2511905E-03   5.5069290E-01
  0.
 -1.1963605E-04  -3.9853753E-02  -2.2898913E-05   2.2651073E-05  -1.2738785E-04   0.              2.0323068E-01   1.4961700E-02
  0.
  7.5281122E-05   3.4375565E-03   1.3823279E-05  -8.6401323E-06   7.9576252E-06   0.             -7.0292828E-01   2.7733798E-01
  0.
         CXW CORR  MATRIX
```

```
-9.6031236E-02  -3.6118506E-01  -2.5487173E-06   9.3496352E-02  -4.5754204E-08
 5.9568919E-02  -5.7154332E-02   4.3123162E-06   4.8068618E-02   7.7414078E-08
-6.4204936E-02   2.6242000E-02  -4.3051413E-06  -3.8484363E-02  -7.7285275E-08
-9.5954045E-02  -3.6147302E-01  -2.5499563E-06   9.3481737E-02  -4.5776448E-08
 9.6127395E-03  -5.1962260E-01  -1.7281359E-06  -3.7623862E-02  -3.1023245E-08

       ACTUAL DYNAMIC NOISE
          R        MATRIX
 1.0000000E-12


       UNMODELED DYNAMIC NOISE COVARIANCE MATRIX
       0.             0.             0.             0.             0.

GAIN MATRICES
          K1       MATRIX
 1.3691434E+02
-8.3757771E-02
 3.6919767E+01
 2.9592784E-02
-4.1004767E+06


         RESIDUAL UNCERTAINITY MATRIX
                   MATRIX
 4.6830578E-05

      STANDARD DEVIATIONS ON DENSITY AND TEMPERATURE
        DENSITY            3.6011954849657E+07          TEMPERATURE           1.0327883539926E+01

       ACTUAL MEASUREMENT NOISE
    -5.8866690000010E-08

       MEASUREMENT COVARIANCE MATRIX
     1.0000000000000E-07
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Case B-1: LTR Mode B Data Generator Sample Case

```
      DATA GENERATOR PROBLEM    PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-3M


ACTUAL STATE VECTOR AT    40.00 SECONDS     INTEGRATION STEP SIZE =      .10    PHASE=  1

      H  =  6.6592872491646E+01  KM           V =  1.2327865119756E-01  KM/SEC         GAMMA = -8.3987153834020E+01  DEGREES
    PHI =  9.6702299739651E-01  DEGREES    THETA = -8.5007019764791E+01  DEGREES        OMEGA = -4.1812564383969E-01  DEGREES/SEC
     VX = -1.1294559770390E+01   KM/SE       VZ = -1.3516435333584E-04 KM/SEC        THTQ = -1.8886890485703E+01DEGREES/SEC
 PRES2 =  9.7202202984772E+01MILLIBARS


     STATE DERIVATIVES

           H DOT = -1.2260042559429E-01              V DOT = -2.1261890766770E-03          GAMMA DOT = -4.1800467850392E-01
         PHI DOT =  1.2096533576649E-04          THETA DOT = -4.1812564383969E-01            OMEGA DOT =  1.2487073840844E-02
             DVX = -1.0761568515514E-02                DVZ =  0.                                 DTHT = -7.2976691720237E-03
          DPRES2 =  2.2011146062925E+05

     RELATIVE VELOCITY    =    1.2326672888599E-01  KM/SEC             PRESSURE     =   9.9430720504457E+01  MILLIBARS
     WIND VELOCITY        =    0.                   KM/SEC             DENSITY      =   2.0676336264243E+08  KG/KM**3
     DYNAMIC PRESSURE     =    1.5708522323757E+01  MILLIBARS          ALPHA        =   0.                   DEGREES
     MOLECULAR WEIGHT     =    4.3199395814762E+01  KG-MOL             CA           =   9.7992219328574E-01  UNIT FREE
     TEMPERATURE          =    2.4986069126253E+02  DEGREES K          CN           =   0.                   UNIT FREE
     MACH NUMBER          =    4.7507081751083E-01  UNIT FREE          CMQ          =  -8.0000000000000E-02  UNIT FREE
     AXIAL FORCE          =   -2.4321144845062E-01  KG-KM/SEC**2       MOMENT       =   2.3646549942168E-10  KG-KM/SEC**2
     NORMAL FORCE         =    0.                   KG-KM/SEC**2       GRAVITY      =   8.6831457590882E-03  KM/SEC**2
     CENTER OF PRESSURE   =   -1.5026909901210E-04  KM                 AXIAL ACCEL=    -1.0761568515514E-02  KM/SEC**2
     MOMENT ACCELERATION =    1.0463075195650E-11 KM/SEC**2            NORMAL ACCEL=     0.                    KM/SEC**2
        EPSILON              =    -5.2842933374700E-02


     MEASUREMENT VALUES

          ACCELEROMETERS =         -1.0761569E-02                      RATE GYRO    =          -7.2976692E-03
                                    0.                                 ALTIMETER    =           6.6592872E+01
          PRESSURE       =          1.1720614E+07                      TEMPERATURE =            2.5852763E+02


     DSN TRAKING FOR        STATION 1       STATION 2       STATION 3
     RANGE =           7.07698546E+07  7.07725669E+07  7.07642699E+07       KM
     RANGE RATE =      1.32420263E+01  1.26673137E+01  1.29327290E+01       KM/SEC

     REFRACTIVITY VALUES
     DELTA RANGE =     0.              0.              0.                   KM
     DELTA R-RATE =    0.              0.              0.                  KM/SEC


          COMMUNICATION ANGLE IS       2.65385025E+01


          ANGLE BETWEEN ENTRY PLANE AND SKY IS  1.14499053E+02


     REFERENCE PLANE   LATITUDE        LONGITUDE

  PLANETO-EQUATORIAL  1.54183495E+01 -3.09428140E+01
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      DATA GENERATOR PROBLEM    PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-3M


ACTUAL STATE VECTOR AT    228.00 SECONDS     INTEGRATION STEP SIZE =      .50    PHASE=  1

      H  =  5.3522303564525E+01  KM              V =  4.7023292744981E-02  KM/SEC         GAMMA = -8.9862858296025E+01  DEGREES
     PHI =  9.6853319667307E-01  DEGREES     THETA = -9.0970202614706E+01  DEGREES        OMEGA =  3.7616165277171E-04  DEGREES/SEC
     VX = -1.3003037235514E+01   KM/SE         VZ = -1.3450778280913E-04 KM/SEC        THTQ = -2.4794411083124E+01DEGREES/SEC
 PRES2 =  8.5874000421342E+02MILLIBARS


     STATE DERIVATIVES

          H DOT = -4.7023158042172E-02              V DOT =  0.                          GAMMA DOT =  3.7721823092692E-04
        PHI DOT =  1.0565781552084E-06          THETA DOT =  3.7616165277171E-04          OMEGA DOT = -2.7825980244181E-05
            DVX = -8.7429270305256E-03                DVZ =  0.                               DTHT =  6.5652593606100E-06
         DPRES2 =  5.7234623785090E+05

     RELATIVE VELOCITY    =   4.7084124738637E-02  KM/SEC            PRESSURE    =   8.7495146000807E+02  MILLIBARS
     WIND VELOCITY        =   0.                   KM/SEC            DENSITY     =   1.3957636110178E+09  KG/KM**3
     DYNAMIC PRESSURE     =   1.5471445049608E+01  MILLIBARS         ALPHA       =   0.                   DEGREES
     MOLECULAR WEIGHT     =   4.3232588835757E+01  KG-MOL            CA          =   8.0830883685563E-01  UNIT FREE
     TEMPERATURE          =   3.2595421062523E+02  DEGREES K         CN          =   0.                   UNIT FREE
     MACH NUMBER          =   1.5893679074447E-01  UNIT FREE         CMQ         =  -8.0000000000000E-02  UNIT FREE
     AXIAL FORCE          =  -1.9759015088988E-01  KG-KM/SEC**2      MOMENT      =  -5.2693564554860E-13  KG-KM/SEC**2
     NORMAL FORCE         =   0.                   KG-KM/SEC**2      GRAVITY     =   8.7203751396574E-03  KM/SEC**2
     CENTER OF PRESSURE   =  -1.3941094897277E-04  KM                AXIAL ACCEL=  -8.7429270305257E-03  KM/SEC**2
     MOMENT ACCELERATION =  -2.3315736528699E-14  KM/SEC**2          NORMAL ACCEL=   0.                    KM/SEC**2
        EPSILON            =  -1.3881112200865E-01


     MEASUREMENT VALUES

          ACCELEROMETERS =          -8.7429270E-03                       RATE GYRO    =          6.5652594E-06
                                     0.                                  ALTIMETER    =          5.3522304E+01
          PRESSURE       =           8.9942607E+07                       TEMPERATURE =          3.2432498E+02


     DSN TRAKING FOR          STATION 1         STATION 2         STATION 3
     RANGE =             7.07723354E+07  7.07749395E+07  7.07666932E+07        KM
     RANGE RATE =        1.31755778E+01  1.25981750E+01  1.28725575E+01        KM/SEC

     REFRACTIVITY VALUES
     DELTA RANGE =      0.               0.               0.                   KM
     DELTA R-RATE =     0.               0.               0.                  KM/SEC


          COMMUNICATION ANGLE IS        2.65369363E+01


          ANGLE BETWEEN ENTRY PLANE AND SKY IS  1.14497780E+02


     REFERENCE PLANE   LATITUDE        LONGITUDE

  PLANETO-EQUATORIAL  1.54168425E+01 -3.09429153E+01
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Case B-2: LTR Mode B Reconstruction Program Sample Case

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   TEMPERATURE MEASUREMENT                                              AT TRAJECTORY TIME   40.00SEC
       PROBLEM     PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-3M


     TRAJECTORY
                           ORIGINAL NOMINAL                   MOST RECENT NOMINAL            ACTUAL               UNITS
       H                 6.5650898180481E+01               6.5650898180481E+01       6.6592872491646E+01      KM
       V                 1.2659477407515E-01               1.2659477407515E-01       1.2327865119756E-01      KM/SEC
       GAMMA            -8.3650001600529E+01              -8.3650001600529E+01      -8.3987153834020E+01      DEGREES
       PHI               4.8437244337613E-01               4.8437244337613E-01       9.6702299739651E-01      DEGREES


   SMOOTH GYRO DATA
                              ACTUAL                        RECONSTRUCTED            UNITS

 SMOOTH THETA      -8.5007019764791E+01            0.                            DEGREES
 SMOOTH OMEGA      -4.1812564383969E-01            0.                            DEGREES/SEC


     ENTRY PARAMETERS BASED ON MOST RECENT NOMINAL
       WIND VELOCITY       =    0.                   KM/SEC             DYNAMIC PRESSURE    =    1.6559191150278E+01MILLIBARS
       RELATIVE VELOCITY   =    1.2658218348745E-01KM/SEC             MACH NUMBER         =    4.8522446962874E-01 UNIT FREE
       EPSILON             =   -5.1418159731060E-02 DEGREES            CA                  =    9.4974284655508E-01 UNIT FREE
       ALPH                =    0.                   DEGREES            GRAVITY             =    8.6858208398923E-03KM/SEC**2


  DEVIATIONS FROM MOST RECENT NOMINAL
     TRAJECTORY
                     ESTIMATED                        ACTUAL                   (ERROR EST-ACT)           UNITS
       H         1.0384352704990E-01            9.4197431116481E-01       -8.3813078411491E-01      KM
       V         1.2605552265850E-03           -3.3161228775906E-03        4.5766781041756E-03      KM/SEC
       GAMMA     2.8455291020724E-02           -3.3715223349145E-01        3.6560752451217E-01      DEGREES
       PHI       7.1750476365649E-02            4.8265055402038E-01       -4.1090007765473E-01      DEGREES

      SOLVE FOR PARAMETERS
                -4.5375564512887E-03            5.0000000000000E+00       -5.0045375564513E+00
                -3.3011947905498E-03           -4.0000000000000E+00        3.9966988052094E+00
                 7.1375020134447E-05            2.0000000000000E+00       -1.9999286249799E+00
                -1.3252864935987E-06           -7.0000000000000E+00        6.9999986747135E+00

      ESTIMATED DEVIATIONS FROM ORIGINAL NOMINAL OF SOLVE FORPARAMETERS
              0.
              0.
              0.
              0.


     ENTRY PARAMETERS BASED ON MOST RECENT NOMINAL


       RELATIVE VELOCITY    =    1.2658218348745E-01   KM/SEC             PRESSURE    =    1.0047446246634E+02   MILLIBARS
       WIND VELOCITY        =    0.                    KM/SEC             DENSITY     =    2.0669213416153E+08   KG/KM**3
       DYNAMIC PRESSURE     =    1.6559191150278E+01   MILLIBARS          ALPHA       =    0.                    DEGREES
       MOLECULAR WEIGHT     =    4.2888539999999E+01   KG-MOL             CA          =    9.4974284655508E-01   UNIT FREE
       TEMPERATURE          =    2.5075307570466E+02   DEGREES K          CN          =    0.                    UNIT FREE
       MACH NUMBER          =    4.8522446962874E-01   UNIT FREE          CMQ         =    0.                    UNIT FREE
       AXIAL FORCE          =   -2.4848617876750E-01   KG-KM/SEC**2       MOMENT      =    0.                    KG-KM/SEC**2
       NORMAL FORCE         =    0.                    KG-KM/SEC**2       GRAVITY     =    8.6858208398923E-03   KM/SEC**2
       CENTER OF PRESSURE   =   -1.5061784311685E-04   KM                 EPSILON     =   -5.1418159731060E-02   DEGREES
```

```
 STATE TRANSITION MATRIX PARTITIONS
         PHI       MATRIX
  9.9913567E-01  -8.9993435E-01   1.7898026E-02   0.
  1.6835441E-03   8.1850107E-01  -1.0318177E-03   0.
  4.1405765E-05   5.2729421E-02   9.3489874E-01   0.
  1.5969620E-08   1.7551806E-05   1.9999049E-05   1.0000000E+00


SOLVE FOR PARAMETERS =     3    5    7    9
         PSI       MATRIX
  2.4732436E-05   4.8384831E-05  -1.3491545E-06   0.
 -4.8000347E-05  -9.3748332E-05   2.6157182E-06   0.
 -1.1222942E-06  -2.1969336E-06   6.1207046E-08   0.
 -4.6746358E-10  -9.1454587E-10   2.5500852E-11   0.


DYNAMIC CONSIDER PARAMETERS =   20  140
         THU       MATRIX
  5.7327025E-03  -5.9841157E-04
 -1.1127897E-02   8.9685259E-05
 -2.6009058E-04  -7.6937024E-02
 -1.0835255E-07  -8.0476345E-07


DYNAMIC-MEASUREMENT CONSIDER PARAMETERS =    4    6    8  152  153  156  161    1
         THW       MATRIX
  4.0295751E-04  -2.1513697E-06   0.              0.              0.             -2.1932150E-02  -8.8658207E-03   4.7022307E-13
 -7.8024432E-04   4.1711011E-06   0.              0.              0.              4.2628625E-02   1.7198305E-02  -9.1293164E-13
 -1.8351185E-05   9.7598840E-08   0.              0.              0.              9.9198829E-04   4.0200109E-04  -2.1323968E-14
 -7.6163998E-09   4.0663801E-11   0.              0.              0.              4.1453396E-07   1.6757467E-07  -8.8875820E-18


DIAGONAL OF DYNAMIC NOISE MATRIX
  0.              0.              0.              0.


          STATE
          PP       MATRIX
  1.3296010E+00   6.0187900E-01   1.5395687E-02   5.6336014E-03
  6.0187900E-01   3.6023469E-03  -3.6487380E-01  -2.2510976E-02
  1.5395687E-02  -3.6487380E-01   6.0082312E+00   5.3968616E-02
  5.6336014E-03  -2.2510976E-02   5.3968616E-02   9.4392196E-01
         CXQ CORR  MATRIX
  1.0861254E-01   2.0504901E-01   2.0426552E-03   2.6685563E-08
  8.8644783E-03   2.7898822E-01   1.4712681E-02   1.3862195E-07
  1.9455169E-03   9.1584908E-03   3.7247115E-04  -1.9385650E-07
  8.5438219E-04   6.6530170E-04  -8.9901213E-05   6.0121456E-07
         CXU CORR  MATRIX
 -3.0846086E-02   3.3724555E-03
 -4.9426851E-01   3.6800143E-01
 -2.7564848E-02  -9.9336847E-01
 -8.8138199E-03   3.7319474E-03
         CXV CORR  MATRIX
  1.9335041E-05   3.9340344E-09  -2.0126856E-09  -8.4497718E-10   0.               6.2681937E-02   0.
 -2.1507017E-05  -4.3759587E-09   2.2387779E-09   9.3989653E-10   0.               2.7378387E-01   0.
  1.8690959E-04   3.8029851E-08  -1.9456397E-08  -8.1682958E-09   0.               1.5922693E-02   0.
 -8.3510449E-04  -1.6991584E-07   8.6930395E-08   3.6495616E-08   0.               5.2769429E-03   0.
         CXW CORR  MATRIX
```

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  7.9352823E-01  7.5141653E-03 -5.2911701E-08 -1.4924414E-09  2.6862521E-10 -5.3354374E-01 -1.1237689E-01  1.8447093E-05
  3.8252887E-01  5.4743386E-02 -2.9689747E-07 -6.8538411E-08 -2.9288174E-09 -2.5013563E-01 -1.3741712E-01  9.3301064E-07
  2.1134343E-02  1.4814325E-03  2.3353304E-07  1.3279938E-07  8.1013105E-09 -9.9338839E-03 -4.3095706E-03  2.3661756E-07
  6.7737945E-03 -3.3199808E-04 -6.5350823E-07 -5.1599843E-07 -3.3319569E-08 -2.1391639E-03 -2.1961845E-04  1.3867632E-07


          SOLVE FOR
          QQ      MATRIX
  4.9997045E+00 -1.3593046E-04  7.6087902E-06  2.0691636E-09
 -1.3593046E-04  3.1620305E+00  8.7506739E-06  2.3774067E-09
  7.6087902E-06  8.7506739E-06  1.2247446E+00 -1.3459242E-10
  2.0691636E-09  2.3774067E-09 -1.3459242E-10  6.3245553E+00
        CQU CORR  MATRIX
  8.2938499E-04 -1.4824875E-03
  9.5385450E-04 -1.7049718E-03
 -5.3392590E-05  9.5436796E-05
 -1.4524905E-08  2.5962432E-08
        CQV CORR  MATRIX
  3.0851376E-06  6.2772233E-10 -3.2114811E-10 -1.3482624E-10  0.             -5.1237974E-04  0.
  3.5510759E-06  7.2252519E-10 -3.6965006E-10 -1.5518860E-10  0.             -5.8927485E-04  0.
 -1.9682535E-07 -4.0047377E-11  2.0488581E-11  8.6016330E-12  0.              3.2985021E-05  0.
  2.6625306E-09  5.4173593E-13 -2.7715674E-13 -1.1635753E-13  0.              8.9729319E-09  0.
        CQW CORR  MATRIX
 -9.1378968E-04  2.8036140E-05 -4.8989989E-09  4.5784397E-10  6.9110183E-11  3.9050372E-04  6.0944115E-05 -1.9481968E-08
 -1.0509262E-03  3.2243646E-05 -5.6316241E-09  5.2842748E-10  7.9601221E-11  4.4910837E-04  7.0090276E-05 -2.2405714E-08
  5.8826232E-05 -1.8048593E-06  3.1695080E-10 -2.8337079E-11 -4.3765700E-12 -2.5139112E-05 -3.9233429E-06  1.2541735E-09
  1.5995718E-08 -4.9302722E-10  2.4801281E-12  1.7236981E-12  1.0916056E-13 -6.8337629E-09 -1.0628444E-09  3.4106139E-13

       ACTUAL DYNAMIC NOISE
          R       MATRIX
  1.0000000E+00


       UNMODELED DYNAMIC NOISE COVARIANCE MATRIX
       0.             0.             0.             0.

GAIN MATRICES
         K1       MATRIX
  7.9383341E-02
  2.4932652E-04
 -1.0950281E-03
 -5.2515406E-06
         K2       MATRIX
 -6.2684259E-02
  4.3774940E-01
  8.6556582E-03
  3.0426702E-08


         RESIDUAL UNCERTAINITY MATRIX
                  MATRIX
  1.8613001E+01
```

```
     TEMPERATURE MEASUREMENT                                                  =    2.62560676E+02


        OBSERVATION MATRIX PARTITIONS
           H          MATRIX
 -1.6363648E+00    1.8788746E+02   -2.1123239E-02    0.


        SOLVE FOR PARAMETERS
           M          MATRIX
  0.               8.9725640E-01    1.0274360E-01    0.


        DYNAMIC-MEASUREMENT CONSIDER PARAMETERS
           G          MATRIX
  1.4954273E+00    1.6391125E-01    0.               0.               0.               5.4877302E+00    6.6288937E+00    0.


        MEASUREMENT CONSIDER PARAMETERS
           L          MATRIX
  0.               0.               0.               0.               0.               0.               2.6256068E+02

MEASUREMENTS
                                ESTIMATED                      ACTUAL                    RESIDUALS
                          2.6262462778547E+02           2.5923383039205E+02          3.3907973934238E+00


    DEVIATIONS FROM MOST RECENT NOMINAL
       TRAJECTORY
                     ESTIMATED                       ACTUAL                   (ERROR EST-ACT)            UNITS
         H        -1.6532929786635E-01         9.4197431116481E-01      -1.1073036090312E+00      KM
         V         4.1513952775784E-04        -3.3161228775906E-03       3.7312624053485E-03      KM/SEC
         GAMMA     2.4119558543084E-01        -3.3715223349145E-01       5.7834781892229E-01      DEGREES
         PHI       7.2770737172407E-02         4.8265055402038E-01      -4.0987981684797E-01      DEGREES

        SOLVE FOR PARAMETERS
                   2.0801206685134E-01         5.0000000000000E+00      -4.7919879331486E+00
                  -1.4876207319814E+00        -4.0000000000000E+00       2.5123792680186E+00
                  -2.9278208207038E-02         2.0000000000000E+00      -2.0292782082070E+00
                  -1.4284572758164E-06        -7.0000000000000E+00       6.9999985715427E+00


          STATE
          PP          MATRIX
  1.2847354E+00    5.6926864E-01    2.7971470E-02    6.1969552E-03
  5.6926864E-01    3.4380009E-03   -3.6859455E-01   -2.3156804E-02
  2.7971470E-02   -3.6859455E-01    6.0021308E+00    5.3961499E-02
  6.1969552E-03   -2.3156804E-02    5.3961499E-02    9.4392106E-01
         CXQ CORR  MATRIX
  1.2701083E-01    6.6071195E-02   -6.0168640E-03    2.2084526E-08
  2.6250266E-02    1.3148311E-01    5.8790496E-03    1.3875459E-07
 -4.9257072E-04    4.5013636E-02    1.7486967E-03   -1.9311751E-07
  7.8113833E-04    1.8536314E-03   -4.7991700E-05    6.0124367E-07
         CXU CORR  MATRIX
 -1.5569685E-02   -1.1284551E-02
 -4.9870215E-01    3.6825217E-01
 -3.0359426E-02   -9.9187863E-01
 -8.8981951E-03    3.8081727E-03
         CXV CORR  MATRIX
  2.2913635E-05    4.6621584E-09   -2.3852001E-09   -1.0013683E-09    0.               6.1952845E-02   -1.6223530E-01
```

```
-1.9127504E-05  -3.8918073E-09   1.9910819E-09   8.3590739E-10   0.               2.8344664E-01  -1.9041106E-01
 1.8660839E-04   3.7968567E-08  -1.9425044E-08  -8.1551328E-09   0.               1.6432531E-02   2.7445563E-02
-8.3512026E-04  -1.6991905E-07   8.6932037E-08   3.6496305E-08   0.               5.2920020E-03   8.3695743E-04
        CXW CORR  MATRIX
 3.2730389E-01  -2.2154490E-02  -4.8439307E-08   1.0469356E-09   4.2379475E-10  -6.2182862E-01  -1.2977071E-01   2.1536195E-05
 2.9056477E-01   2.2231015E-02  -3.0367218E-07  -6.8773171E-08  -2.8977150E-09  -3.4384192E-01  -1.5979468E-01   3.8471126E-06
 3.7047100E-02   6.5464165E-03   2.3270120E-07   1.3249595E-07   8.0648812E-09   1.8392130E-03  -2.0353175E-03  -1.7674756E-07
 7.2584883E-03  -1.7758670E-04  -6.5354146E-07  -5.1601228E-07  -3.3320353E-08  -1.7798353E-03  -1.5013132E-04   1.2606347E-07


         SOLVE FOR
         QQ         MATRIX
 4.9923851E+00   4.0169585E-02   1.6600546E-03   3.1965218E-09
 4.0169585E-02   2.5360854E+00  -2.2705229E-02  -1.2492021E-08
 1.6600546E-03  -2.2705229E-02   1.2241751E+00  -7.6779222E-10
 3.1965218E-09  -1.2492021E-08  -7.6779222E-10   6.3245553E+00
        CQU CORR  MATRIX
-2.4925371E-03   1.5176504E-03
 4.6872810E-02  -4.3398876E-02
 1.8179304E-03  -1.5952005E-03
-1.3251628E-08   2.4812081E-08
        CQV CORR  MATRIX
 2.4996803E-06   5.0860135E-10  -2.6020480E-10  -1.0924067E-10   0.               7.9836892E-05   3.2967051E-02
 1.2538060E-05   2.5510759E-09  -1.3051523E-09  -5.4793648E-10   0.              -8.6863085E-03  -4.5320153E-01
 1.3531684E-07   2.7532453E-11  -1.4085838E-11  -5.9135971E-12   0.              -3.0091566E-04  -1.8564627E-02
 2.6627566E-09   5.4178193E-13  -2.7718027E-13  -1.1636740E-13   0.               8.7457333E-09  -1.2631490E-08
        CQW CORR  MATRIX
 1.8173148E-02   6.1102242E-03  -6.1904747E-09  -6.8090182E-11   3.9586511E-11   1.4544808E-02   2.7980813E-03  -5.1632517E-07
-2.6371987E-01  -8.3571715E-02   1.0633720E-08   7.8981516E-09   5.0650597E-10  -1.9401289E-01  -3.7539096E-02   6.8018275E-06
-1.0690265E-02  -3.4268251E-03   1.0403181E-09   2.6819530E-10   1.2304020E-11  -7.9954952E-03  -1.5452299E-03   2.8102434E-07
 8.6819499E-09  -2.8234321E-09   2.4886202E-12   1.7238999E-12   1.0917191E-13  -1.2256836E-08  -2.1115579E-09   5.3141838E-13

       ACTUAL DYNAMIC NOISE
         R          MATRIX
 1.0000000E+00


       UNMODELED DYNAMIC NOISE COVARIANCE MATRIX
       0.              0.              0.              0.

GAIN MATRICES
         K1         MATRIX
 7.9383341E-02
 2.4932652E-04
-1.0950281E-03
-5.2515406E-06
         K2         MATRIX
-6.2684259E-02
 4.3774940E-01
 8.6556582E-03
 3.0426702E-08


         RESIDUAL UNCERTAINITY MATRIX
                    MATRIX
 1.8613001E+01

       ACTUAL MEASUREMENT NOISE
     7.0620339999994E-01

       MEASUREMENT COVARIANCE MATRIX
     5.0000000000000E-01
```

```
 QUASI   EVENT                                            AT TRAJECTORY TIME  200.00SEC
     PROBLEM     PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-3M


   TRAJECTORY
                       ORIGINAL NOMINAL               MOST RECENT NOMINAL           ACTUAL          UNITS
     H                5.385103217 2930E+01          5.4126948939188E+01      5.4889639538585E+01    KM
     V                5.0583322350468E-02           5.1388456988696E-02      5.0753583405048E-02    KM/SEC
     GAMMA           -8.9872095158927E+01          -8.9729075346098E+01     -8.9872450118514E+01    DEGREES
     PHI              4.8598056383263E-01           5.1586776724075E-01      9.6850361440395E-01    DEGREES


DEVIATIONS FROM MOST RECENT NOMINAL
   TRAJECTORY
                 ESTIMATED                       ACTUAL               (ERROR EST-ACT)         UNITS
     H        0.                          7.6269059939750E-01    -7.6269059939750E-01    KM
     V        0.                         -6.3487358364878E-04     6.3487358364878E-04    KM/SEC
     GAMMA   -4.5474735088646E-13        -1.4337477241634E-01     1.4337477241588E-01    DEGREES
     PHI      0.                          4.5263584716320E-01    -4.5263584716320E-01    DEGREES

    SOLVE-FOR    NOMINAL VALUE
          3       4.1833522903870E-01
          5      -1.8664337626212E+00
          7      -4.6156637725942E-02
          9      -1.6733425731222E-06

    SOLVE FOR PARAMETERS
              0.                          4.5816647709613E+00    -4.5816647709613E+00
              0.                         -2.1335662373787E+00     2.1335662373787E+00
              0.                          2.0461566377259E+00    -2.0461566377259E+00
              0.                         -6.9999983266574E+00     6.9999983266574E+00

    ESTIMATED DEVIATIONS FROM ORIGINAL NOMINAL OF SOLVE FORPARAMETERS
          -4.1833522903870E-01
           1.8664337626212E+00
           4.6156637725942E-02
           1.6733425731222E-06
```

```
      PRESSUREMEASUREMENT                                          AT TRAJECTORY TIME  230.00SEC
          PROBLEM     PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-3M
 QUASI-STATIC MODEL


        TRAJECTORY
                            ORIGINAL NOMINAL                MOST RECENT NOMINAL          ACTUAL             UNITS
          H                5.2394782182760E+01             5.2648796450763E+01     5.3428497604172E+01    KM
          V                4.6614638116347E-02             4.7276238912708E-02     4.6781281413375E-02    KM/SEC
          GAMMA           -8.9861588096744E+01            -8.9862868142229E+01    -8.9862128891986E+01    DEGREES
          PHI              4.8601227158746E-01             5.1590639850163E-01     9.6853531004188E-01    DEGREES


      SMOOTH GYRO DATA
                               ACTUAL                   RECONSTRUCTED           UNITS

    SMOOTH THETA      -9.0970192557385E+01         0.                          DEGREES
    SMOOTH OMEGA       3.7571856446973E-04         0.                          DEGREES/SEC


        ENTRY PARAMETERS BASED ON MOST RECENT NOMINAL
          WIND VELOCITY      =    0.                       KM/SEC          DYNAMIC PRESSURE    =    1.5998963651897E+01MILLIBARS
          RELATIVE VELOCITY  =   4.7276103513401E-02KM/SEC                 MACH NUMBER         =    1.6118339613134E-01 UNIT FREE
          EPSILON            =  -1.3822765148786E-01 DEGREES               CA                  =    7.7962128296895E-01 UNIT FREE
          ALPH               =    0.                       DEGREES         GRAVITY             =    8.7228717129088E-03KM/SEC**2


     DEVIATIONS FROM MOST RECENT NOMINAL
        TRAJECTORY
                     ESTIMATED                          ACTUAL               (ERROR EST-ACT)           UNITS
          H        0.                           7.7970115340827E-01     -7.7970115340827E-01      KM
          V        0.                          -4.9495749933293E-04      4.9495749933293E-04      KM/SEC
          GAMMA    0.                           7.3925024253185E-04     -7.3925024253185E-04      DEGREES
          PHI      0.                           4.5262891154025E-01     -4.5262891154025E-01      DEGREES

         SOLVE FOR PARAMETERS
                   0.                           4.5816647709613E+00     -4.5816647709613E+00
                   0.                          -2.1335662373787E+00      2.1335662373787E+00
                   0.                           2.0461566377259E+00     -2.0461566377259E+00
                   0.                          -6.9999983266574E+00      6.9999983266574E+00

         ESTIMATED DEVIATIONS FROM ORIGINAL NOMINAL OF SOLVE FORPARAMETERS
              -4.1833522903870E-01
               1.8664337626212E+00
               4.6156637725942E-02
               1.6733425731222E-06


        ENTRY PARAMETERS BASED ON MOST RECENT NOMINAL


          RELATIVE VELOCITY   =   4.7276103513401E-02   KM/SEC              PRESSURE   =   8.7973770811783E+02   MILLIBARS
          WIND VELOCITY       =   0.                    KM/SEC              DENSITY    =   1.4316554063095E+09   KG/KM**3
          DYNAMIC PRESSURE    =   1.5998963651897E+01   MILLIBARS           ALPHA      =   0.                    DEGREES
          MOLECULAR WEIGHT    =   4.2888539999999E+01   KG-MOL              CA         =   7.7962128296895E-01   UNIT FREE
          TEMPERATURE         =   3.1697808454498E+02   DEGREES K           CN         =   0.                    UNIT FREE
          MACH NUMBER         =   1.6118339613134E-01   UNIT FREE           CMQ        =   0.                    UNIT FREE
          AXIAL FORCE         =  -1.9707549456176E-01   KG-KM/SEC**2        MOMENT     =   0.                    KG-KM/SEC**2
          NORMAL FORCE        =   0.                    KG-KM/SEC**2        GRAVITY    =   8.7228717129088E-03   KM/SEC**2
          CENTER OF PRESSURE  =  -1.3948811237912E-04   KM                  EPSILON    =  -1.3822765148786E-01   DEGREES
```

```
 STATE TRANSITION MATRIX PARTITIONS
         PHI         MATRIX
  9.9730743E-01  -9.0169484E-01   8.5422106E-04   0.
  0.              1.0000000E+00   0.              0.
 -2.4494386E-05   1.6988356E-02   8.3172245E-01   0.
  9.3426519E-10   4.1536571E-07   7.0834819E-06   1.0000000E+00


SOLVE FOR PARAMETERS =     3   5    7    9
         PSI         MATRIX
  9.2647650E-05   6.3978079E-05   0.              0.
  0.              0.              0.              0.
  8.9537641E-07   6.1329513E-07   0.              0.
 -3.2100993E-11  -2.2179182E-11   0.              0.


DYNAMIC CONSIDER PARAMETERS =   20  140
         THU         MATRIX
  2.5288088E-02   4.4230524E-04
  0.              0.
  2.4431996E-04  -1.6351681E-01
 -8.7624918E-09  -6.5259512E-07


DYNAMIC-MEASUREMENT CONSIDER PARAMETERS =    4    6    8  152  153  156  161    1
         THW         MATRIX
  4.9508438E-04   0.              0.              0.              0.             -7.0924211E-02  -1.7308367E-02   2.0440343E-12
  0.              0.              0.              0.              0.              0.              0.              0.
  4.8348397E-06   0.              0.              0.              0.             -6.5367176E-04  -1.6481471E-04   1.9568016E-14
 -1.7138087E-10   0.              0.              0.              0.              2.4664371E-08   6.0035842E-09  -7.0878113E-19


DIAGONAL OF DYNAMIC NOISE MATRIX
  0.              0.              0.              0.


          STATE
          PP         MATRIX
  8.2744387E-01   2.1011491E-01   1.3216089E-01  -9.6466669E-02
  2.1011491E-01   7.4465541E-04   5.2761690E-01  -1.2389246E-01
  1.3216089E-01   5.2761690E-01   2.7835248E+00   9.0928365E-02
 -9.6466669E-02  -1.2389246E-01   9.0928365E-02   9.3319703E-01
         CXQ CORR  MATRIX
  1.9974101E-01   8.3373301E-02   1.8766235E-03  -7.2027546E-08
 -9.2152917E-03   4.0366289E-02  -2.2955273E-03  -7.3298085E-08
 -2.4288006E-02   5.9804023E-02  -3.7949632E-04   4.8359249E-08
  4.1167191E-03  -3.0477655E-03   9.9751997E-04   5.8802681E-07
         CXU CORR  MATRIX
  1.0422991E-01  -1.3204176E-01
 -2.9155121E-01  -5.2684189E-01
 -3.9854678E-04  -9.9999957E-01
  6.7620075E-02  -9.1067104E-02
         CXV CORR  MATRIX
 -1.4610396E-01  -2.9626268E-05   1.5116182E-05   6.9334783E-06   0.              5.3006558E-02  -5.4599948E-02
 -5.6992846E-01  -1.1559243E-04   5.8978652E-05   2.6947627E-05   0.              1.8484716E-01  -1.2435163E-01
 -5.3287327E-04  -1.0800308E-07   5.5106246E-08   2.5488575E-08   0.              2.5939312E-04  -1.2405979E-04
 -3.9914475E-02  -8.1229459E-06   4.1448364E-06   1.7767715E-06   0.             -3.6338198E-02   6.1130666E-02
```

```
          CXW CORR  MATRIX
   4.5371310E-01  -4.1798117E-03   2.8461625E-08   2.0920956E-08   1.3369915E-09  -8.1569003E-01  -8.8703579E-02   4.3755923E-05
  -1.9167173E-01   1.2843444E-03   9.6799629E-08   8.2306952E-08   5.3680492E-09  -1.2375571E-01  -2.3938529E-02   1.0932359E-05
  -1.6372822E-04   1.2470859E-06   6.6623892E-11   5.8565417E-11   3.8357578E-12  -8.4927924E-05  -1.2791774E-05   1.7033356E-08
  -5.9767574E-02   5.8307885E-03  -6.2341214E-07  -5.0769895E-07  -3.2923859E-08   5.8148126E-02   2.8159005E-02  -8.3327448E-09


           SOLVE FOR
           QQ       MATRIX
   4.9684828E+00   1.7175284E-02   8.9853774E-04   2.5324868E-09
   1.7175284E-02   2.3828783E+00  -2.9012570E-02  -3.1337431E-08
   8.9853774E-04  -2.9012570E-02   1.2239861E+00  -2.7444515E-10
   2.5324868E-09  -3.1337431E-08  -2.7444515E-10   6.3245553E+00
          CQU CORR  MATRIX
  -4.3212707E-02   2.4301106E-02
   4.1868191E-02  -5.9796152E-02
   8.6277163E-04   3.7756202E-04
   4.7565376E-08  -4.8438765E-08
          CQV CORR  MATRIX
  -1.4627893E-03  -2.7794742E-07   1.4179132E-07   1.4328014E-07   0.              2.2319276E-02   3.4241990E-02
   1.8328576E-02   3.7240728E-06  -1.9001483E-06  -8.4149919E-07   0.             -2.2908800E-02  -3.6715894E-01
   3.6186138E-03   7.3420521E-07  -3.7461367E-07  -1.7002759E-07   0.             -1.0107860E-03  -1.5028904E-02
  -2.9605274E-08  -6.0233966E-12   3.0725920E-12   1.3271169E-12   0.             -2.4887853E-08   4.3873903E-08
          CQW CORR  MATRIX
   4.3304361E-02   7.3741592E-03  -3.9102993E-09  -3.3682128E-09  -2.1976343E-10   3.1781108E-02   6.6502089E-03  -3.7847792E-07
  -3.7048815E-02  -8.0198044E-02   6.4844249E-08   1.1362169E-08   3.7356787E-10  -5.2784497E-03   7.8426687E-03   3.7883604E-07
   8.6981462E-03  -3.4530132E-03   1.7895014E-09  -4.8440190E-11  -1.6377065E-11   1.0180349E-04  -6.0050524E-04  -1.9761125E-07
  -4.0072333E-08   3.2356938E-09   2.5165534E-12   1.7357495E-12   1.0978727E-13   4.8470278E-08   2.4921007E-08   2.3115018E-13

         ACTUAL DYNAMIC NOISE
            R       MATRIX
   1.3000000E+10


         UNMODELED DYNAMIC NOISE COVARIANCE MATRIX
         0.              0.              0.              0.

 GAIN MATRICES
           K1       MATRIX
   1.8407496E-08
  -9.5201358E-11
  -3.3119239E-09
  -8.1961091E-12
           K2       MATRIX
   1.8924330E-08
   1.2398394E-08
   1.0313545E-09
  -1.5735700E-14


          RESIDUAL UNCERTAINITY MATRIX
                    MATRIX
   1.9433886E+13
```

```
     PRESSUREMEASUREMENT                                                =   8.95840856E+07


        OBSERVATION MATRIX PARTITIONS
           H       MATRIX
 -1.2573654E+07   6.8842557E+07  -7.8192698E+03   0.


        SOLVE FOR PARAMETERS
           M       MATRIX
  4.0658261E+05   5.1192561E+05   0.              0.


        DYNAMIC-MEASUREMENT CONSIDER PARAMETERS
           G       MATRIX
  4.0611272E+06   0.              0.              0.              0.             -3.2483136E+08  -1.0995444E+08   8.1145005E-03


        MEASUREMENT CONSIDER PARAMETERS
           L       MATRIX
  0.              0.              0.              0.              0.              8.9584086E+07   0.

MEASUREMENTS
                                ESTIMATED                      ACTUAL                     RESIDUALS
                          8.9584085553111E+07         9.1131178069595E+07        -1.5470925164847E+06


    DEVIATIONS FROM MOST RECENT NOMINAL
       TRAJECTORY
                     ESTIMATED                      ACTUAL                   (ERROR EST-ACT)             UNITS
         H        2.8478099957196E-02         7.7970115340827E-01        -7.5122305345107E-01        KM
         V       -1.4728529611394E-04        -4.9495749933293E-04         3.4767220321898E-04        KM/SEC
         GAMMA   -2.9357513181557E-01         7.3925024253185E-04        -2.9431438205810E-01        DEGREES
         PHI     -7.2651845172863E-04         4.5262891154025E-01        -4.5335542999198E-01        DEGREES

        SOLVE FOR PARAMETERS
                  2.9277689147708E-02         4.5816647709613E+00        -4.5523870818135E+00
                  1.9181463333361E-02        -2.1335662373787E+00         2.1527477007121E+00
                  1.5956007602780E-03         2.0461566377259E+00        -2.0445610369656E+00
                 -2.4344584322059E-08        -6.9999983266574E+00         6.9999983023128E+00


          STATE
          PP       MATRIX
  8.2345519E-01   3.2282781E-01   1.7028882E-01  -9.6715564E-02
  3.2282781E-01   6.1512324E-04   4.5469693E-01  -1.5149556E-01
  1.7028882E-01   4.5469693E-01   2.6548491E+00   9.4636726E-02
 -9.6715564E-02  -1.5149556E-01   9.4636726E-02   9.3319474E-01
         CXO CORR  MATRIX
  1.9908191E-01   8.1538237E-02   1.5196694E-03  -7.1295572E-08
  3.0031614E-04   6.4533205E-02  -2.4453737E-04  -9.6216500E-08
 -2.0177268E-02   6.9948490E-02   7.7256924E-04   4.7247093E-08
  4.1545639E-03  -2.9976777E-03   1.0057698E-03   5.8800393E-07
         CXU CORR  MATRIX
  1.3011937E-01  -1.6226194E-01
 -5.2869625E-01  -4.3298236E-01
 -8.1584683E-02  -9.5388425E-01
  6.7048798E-02  -9.0401426E-02
         CXV CORR  MATRIX
 -1.8057178E-01  -3.6616507E-05   1.8682807E-05   8.5651818E-06   0.              4.4970467E-02  -5.8954611E-02
```

```
-4.5620510E-01  -9.2530373E-05   4.7211715E-05   2.1557647E-05   0.              2.8118772E-01  -1.2221903E-01
 1.0738873E-01   2.1779088E-05  -1.1112328E-05  -5.0832360E-06   0.              2.6788210E-02   1.2948247E-02
-3.9154585E-02  -7.9688360E-06   4.0662050E-06   1.7407999E-06   0.             -3.6151603E-02   6.1222892E-02
        CXW CORR  MATRIX
 3.7914087E-01  -3.3197361E-03   3.3516262E-08   2.5635841E-08   1.6479983E-09  -8.3263188E-01  -8.5670630E-02   4.6026375E-05
 2.9948347E-01  -4.5401148E-03   8.3142299E-08   6.7697149E-08   4.3900285E-09  -5.9874259E-02  -5.2952920E-02  -1.0175979E-06
 2.4529898E-01  -2.8135075E-03  -1.5651452E-08  -1.4690342E-08  -9.6971012E-10   4.1448793E-02  -1.1085064E-02  -6.5641816E-06
-5.8039519E-02   5.8109855E-03  -6.2352436E-07  -5.0780406E-07  -3.2930796E-08   5.8440711E-02   2.8081126E-02  -5.4672708E-08


         SOLVE FOR
         QQ  '      MATRIX
 4.9677824E+00   1.6796930E-02   8.3628967E-04   2.7170372E-09
 1.6796930E-02   2.3822513E+00  -2.9105631E-02  -3.1094029E-08
 8.3628967E-04  -2.9105631E-02   1.2239777E+00  -2.3370431E-10
 2.7170372E-09  -3.1094029E-08  -2.3370431E-10   6.3245553E+00
        CQU CORR  MATRIX
-3.8892932E-02   1.9263609E-02
 4.7789288E-02  -6.6698887E-02
 1.8196407E-03  -7.3746549E-04
 4.4740031E-08  -4.5146398E-08
        CQV CORR  MATRIX
-7.2161645E-03  -1.4447605E-06   7.3713350E-07   4.1564089E-07   0.              2.0909213E-02   3.3549796E-02
 1.0473318E-02   2.1309857E-06  -1.0873086E-06  -4.6964415E-07   0.             -2.4845582E-02  -3.6820785E-01
 2.3460630E-03   4.7612501E-07  -2.4293360E-07  -1.0978823E-07   0.             -1.3233889E-03  -1.5183186E-02
-2.5847720E-08  -5.2613442E-12   2.6837706E-12   1.1492437E-12   0.             -2.3964846E-08   4.4329148E-08
        CQW CORR  MATRIX
 3.0227858E-02   7.5252174E-03  -3.0729676E-09  -2.5824783E-09  -1.6789839E-10   2.9571788E-02   7.2412216E-03  -2.7734694E-08
-5.4932258E-02  -8.0014191E-02   6.6006044E-08   1.2439292E-08   4.4456746E-10  -8.3043737E-03   8.6509036E-03   8.5820026E-07
 5.8043906E-03  -3.4198536E-03   1.9748498E-09   1.2546554E-10  -4.8980034E-12  -3.8787898E-04  -4.6998738E-04  -1.2001795E-07
-3.1527718E-08   3.1377118E-09   2.5160062E-12   1.7352360E-12   1.0975337E-13   4.9916173E-08   2.4535612E-08   2.0351951E-15

       ACTUAL DYNAMIC NOISE
          R         MATRIX
 1.3000000E+10


       UNMODELED DYNAMIC NOISE COVARIANCE MATRIX
       0.              0.              0.              0.

GAIN MATRICES
         K1         MATRIX
 1.8407496E-08
-9.5201350E-11
-3.3119239E-09
-5.1961091E-12
         K2         MATRIX
 1.8924330E-08
 1.2398394E-08
 1.0313545E-09
-1.5735700E-14


         RESIDUAL UNCERTAINITY MATRIX
                    MATRIX
 1.9433886E+13

       ACTUAL MEASUREMENT NOISE
     8.5621099999883E+03

       MEASUREMENT COVARIANCE MATRIX
     1.0000000000000E+05
```

PART III

LTR PROGRAMMERS' MANUAL

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I. INTRODUCTION

This *Lander Trajectory Reconstruction Programmers' Manual* is intended to supply the reader with sufficient information about the lander trajectory reconstruction (LTR) program to enable him to modify it for his own uses. Both the overall structure of the program and the computational flow of individual subroutines are presented in this manual.

Chapters II and III describe the overall flow and operation of the program and present the graphical structure of the various segments.

Chapter IV of this volume contains the definitions of common variables. The variables are defined in the order of appearance within the common block, and the common blocks are presented alphabetically.

Chapter V documents each of the subroutines in detail. The purpose of the subroutine is given, and subroutines required by the subroutine are listed. Arguments to the subroutine and local variables of interest are defined, and usage of common variables is noted. The mathematical analysis and a flow chart are provided whenever necessary for a thorough understanding of the subroutine.

II. SUMMARY OF LTR OPERATION

The LTR program is segmented by an overlay structure to conserve core storage. There are five overlay sections, which are discussed in the following sections.

A. MAIN

The executive subroutine MAIN controls overall program execution and calls the remaining sections according to values from input data. The rest of the subroutines in this overlay section are called from several of the remaining overlay sections and appear in the main overlay to conserve core.

B. DATGEN

The data generator overlay section generates the actual trajectory, the actual measurements, the quantized ARU-VRU data, and the actual atmosphere experienced by the vehicle as it descends. Several input/output files are written for use by subsequent overlay sections in reconstructing the atmosphere and trajectory.

C. PRPRØS

The preprocessor overlay section operates on the quantized ARU-VRU data generated by DATGEN and filters them using a least-squares curve-fitting technique. File 16 is written with the smoothed data for use by the reconstructor.

D. LTRCØN

The reconstructor overlay section utilizes the I/Ø files written by DATGEN and PRPRØS to reconstruct the atmosphere and descent trajectory. It is presumed that files 10 and 16 have been previously written on magnetic tape or are generated immediately prior to the start of reconstruction. Derived measurements are used to drive the dynamic equations, and a Kalman-Schmidt filter is employed to refine the estimated errors between "actual" and "assumed" parameters. Up to 15 data files may be written for plotting purposes, according to data supplied from NAMELIST input.

E. SUMMRY

The summary overlay section prints the summary tables from I/Ø files written by LTRCØN and calls the user-written plot package according to information supplied by LTRCØN. A sample plot package is described in Appendix A.

III. LTR Program Structure

A. LTR SUBROUTINE CLASSIFICATION

The subroutines that make up the LTR program are listed according to category in Table III-1. Table III-2 lists the subroutines again with a brief summary of their purposes. The individual subroutines are documented in detail in alphabetical order in Chapter V.

B. LTR SUBROUTINE HIERARCHY

As described in Chapter II, the LTR program is composed of three distinct parts. Each part is governed by an executive routine that is called from the main routine according to the value of RUNN0. The calling hierarchy of the LTR program is given in Figure III-1. Each of the three parts is broken down separately in Figures III-2 thru III-4. Subroutines in parentheses are called by the preceding subroutine. An asterisk indicates an expansion elsewhere in the hierarchy charts. BL0CK DATA in Figure III-1 is adjoined to LTR by dotted lines, indicating that data initialized there are available to all subroutines.

Table III-1 LTR Subroutines

I. Executive Subroutines

1. LTRTWØ
2. DATGEN
3. LTRCØN
4. SUMMRY

II. Integrator Subroutines

1. ATMSET
2. DERIV1
3. RKUTDG
4. ATMØSP
5. DERIV3
6. DERIVE
7. NTM
8. NTM2
9. RKUT3
10. RKUTL3

III. Matrix Manipulation Subroutines

1. ADD
2. CØPY
3. CØRMAT
4. CØRR
5. CØRRD
6. DMULTT
7. DTAB
8. INVPD2
9. INVPSD
10. MULT
11. MULTD
12. MULTT
13. SUB
14. SYMTRZ
15. TMULT
16. TMULTT
17. TAB
18. MATRIX

IV. Measurement Subroutines

1. ØBSM1
2. SENSØR
3. ATTACK
4. MEAZUR
5. ØBSM

V. Range/Doppler Measurement Subroutines

1. AECEQ
2. ECLIP
3. ELCAR
4. EPHEM
5. EQUATR
6. GEØG
7. GHA
8. PLANE
9. SUBSØL
10. TIME

Table III-1 (Cont)

VI. Filter Subroutines

1. DYNØIZ
2. FILTER
3. HMM
4. JACØBN
5. NØRMNZ
6. RNUM
7. STM

VII. Input/Output Subroutines

1. MATØUT
2. TIMEX
3. PRINT1
4. SETUP1
5. PRPRØS
6. SMØØT2
7. CØNVRT
8. NEXTAA
9. NEXTIM
10. ØUTPHI
11. ØUTPP
12. PRINT
13. PSTØRE
14. READAC
15. RSTART
16. SCHED
17. SETICN
18. SETPLT
19. SETUP
20. PLØTS

VIII. Data Initialization Subroutines

1. BLKDAT
2. BEGIN

Table III-2 Purpose of Subroutines

SUBROUTINE	PURPOSE
AECEQ	Computes transformation from ecliptic to geocentric equatorial
ATMSET (ATMDAT)	Initializes and computes atmospheric parameters
ADD	Adds matrix X and matrix Y
ATTACK	Computes angle of attack measurement
ATM0SP	Calculates atmospheric parameters in mode A
BLKDAT	Initializes common variables
BEGIN	Resets common variables for reconstructor
C0PY	Copies matrix/vector X into matrix/vector Y
C0RMAT	Converts covariance matrix into correlation matrix
C0RR	Computes correlations for off-diagonal block of partitioned covariance matrix
C0RRD	Computes correlations for diagonal block of partitioned covariance matrix
[illegible]VRT	Converts state vectors to output units
DMULTT	Multiplies a diagonal matrix X times the transpose of matrix Y
DTAB	Performs table lookup with two independent variables

Table III-2 (Cont)

SUBROUTINE	PURPOSE
DATGEN	Drives data generator to provide input to reconstructor
DERIV1	Computes derivatives for integration by the data generator
DERIV3	Computes derivatives for integration by the mode B reconstructor
DERIVE	Computes derivatives for integration by the mode A reconstructor
DYNØIZ	Computes dynamic noise covariance matrix
ECLIP	Computes planetocentric ecliptic state of spacecraft for DSN tracking
EPHEM	Computes heliocentric ecliptic coordinates of the planets
EQUATR	Computes transformation from geoequatorial to planetoequatorial
FILTER	Computes estimates and covariance matrices
GEØG	Computes transformation from planetoequatorial to planetogeographical
GHA	Computes Greenwich hour angle of the vernal equinox
HMM	Computes observation matrix H for Kalman filter equations
INVPD2	Inverts positive definite matrix X (NxN)
INVPSD	Inverts positive definite 2x2 matrix X

Table III-2 (Cont)

SUBROUTINE	PURPOSE
JAC0BN	Computes sensitivity matrices by numerical differencing
LTRTW0	Controls overall program for data generation and trajectory reconstruction
LTRC0N	Drives reconstructor portion of LTR
MAT0UT	Prints matrix X
MULT	Multiplies matrix X times matrix Y
MULTD	Multiplies matrix X times diagonal matrix Y
MULTT	Multiplies matrix X times matrix Y transposed
MATRIX	Performs matrix alegbra through use of multiple entry points
MEAZUR	Processes measurements
NEXTAA	Takes accelerometer data from preprocessor tape
NEXTIM	Selects measurement or other event
N0RMNZ	Computes normally distributed noise
NTM	Propagates most recent nominal trajectory
NTM2	Propagates original nominal trajectory
0BSM1	Contains measurement equations for the data generator

Table III-2 (Cont)

SUBROUTINE	PURPOSE
0BSM	Contains measurement equations for the reconstructor
0UTPHI	Prints intermediate variables and phi matrix
0UTPP	Prints correlation, gain, and dynamic noise matrices
PLANE	Computes entry plane orientation to reference plane
PRINT1	Prints trajectory and measurements from the data generator
PRPR0S (SM00T2)	Preprocesses accelerometer and gyro measurements for the reconstructor
PRINT	Prints trajectory and measurements from the reconstructor
PST0RE	Stores data for plot package
PL0TS	Drives system plot package
RKUTDG	Integrator for data generator
READAC	Reads "actual" measurements created by data generator
RSTART	Punches restart cards for reconstructor
RKUT3	Integrator for mode A reconstructor
RKUTL3	Integrator for mode B reconstructor
RNUM	Generates measurement noise on "actual" measurements
SUBS0L	Computes transformation from planetocentric ecliptic to subsolar orbital plane

Table III-2 (Concl)

SUBROUTINE	PURPOSE
SENS0R	Quantizes accelerometer and gyro measurements
SETUP1	Reads input data for data generator
SCHED	Reads and sequences measurements and events
SETICN	Sets iteration counters for printout
SETPLT	Reads plot control variables
SETUP	Reads input data for reconstructor
STM	Calculates state transition matrices
SUMMRY	Controls summary print and plotting
TMULT	Multiplies matrix X transposed times matrix Y
TMULTT	Multiplies matrix X transposed times matrix Y transposed
TAB	Performs table lookup with one independent variable
TIMEX	Calculates central processor time
TIME	Converts Julian date to/from calendar date, epoch 1900

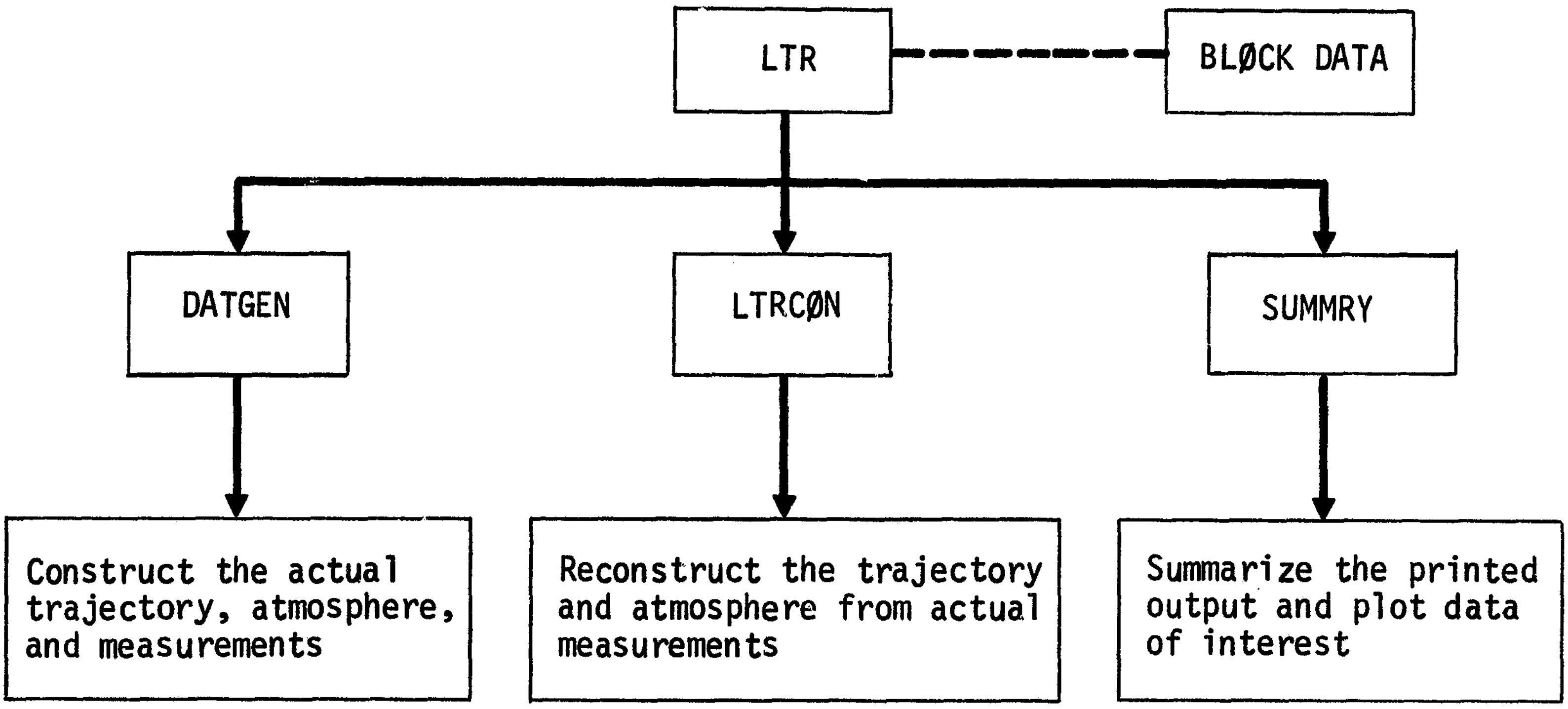

Figure III-1 LTR Executive Flow Diagram

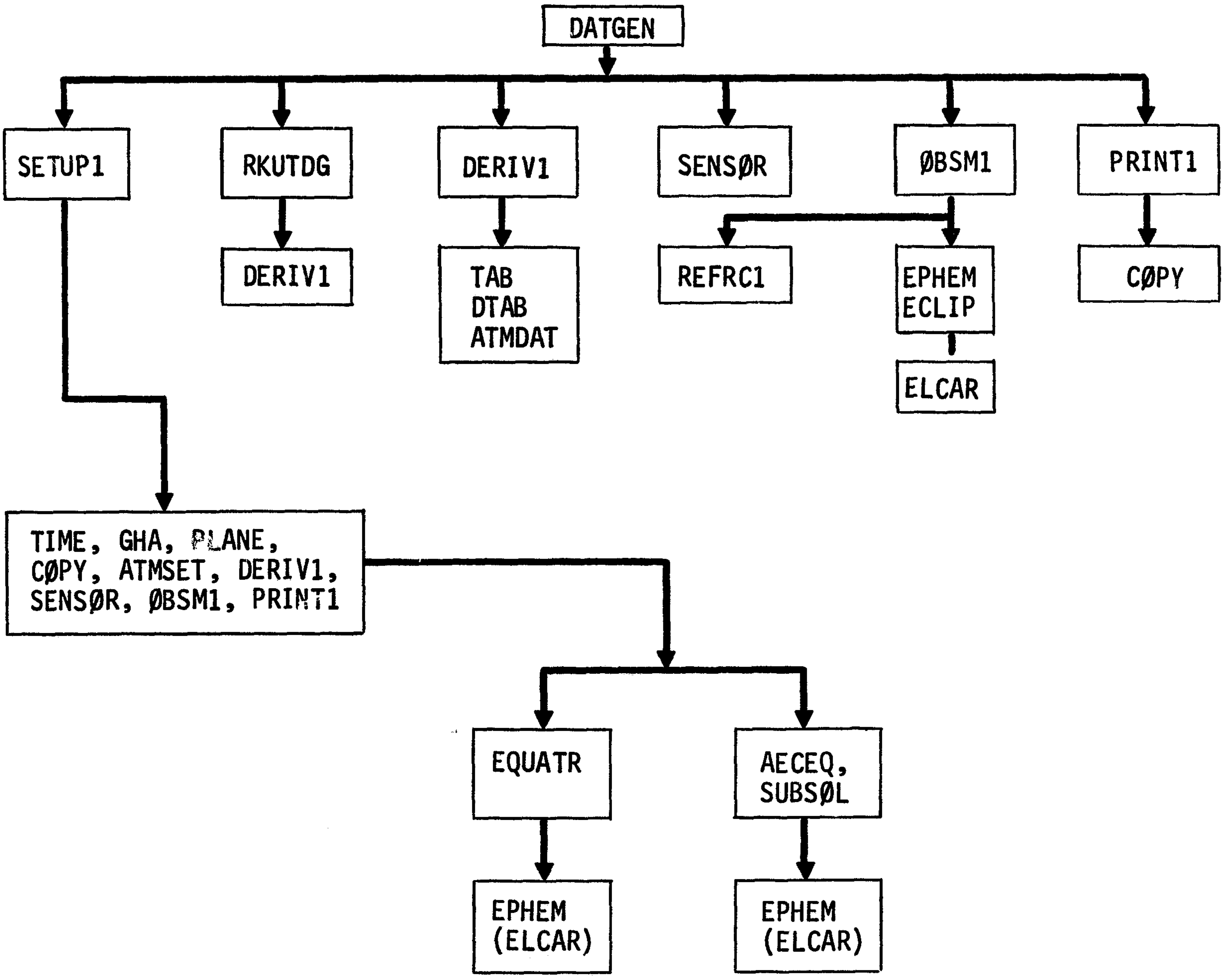

Figure III-2 DATGEN Executive Flow Diagram

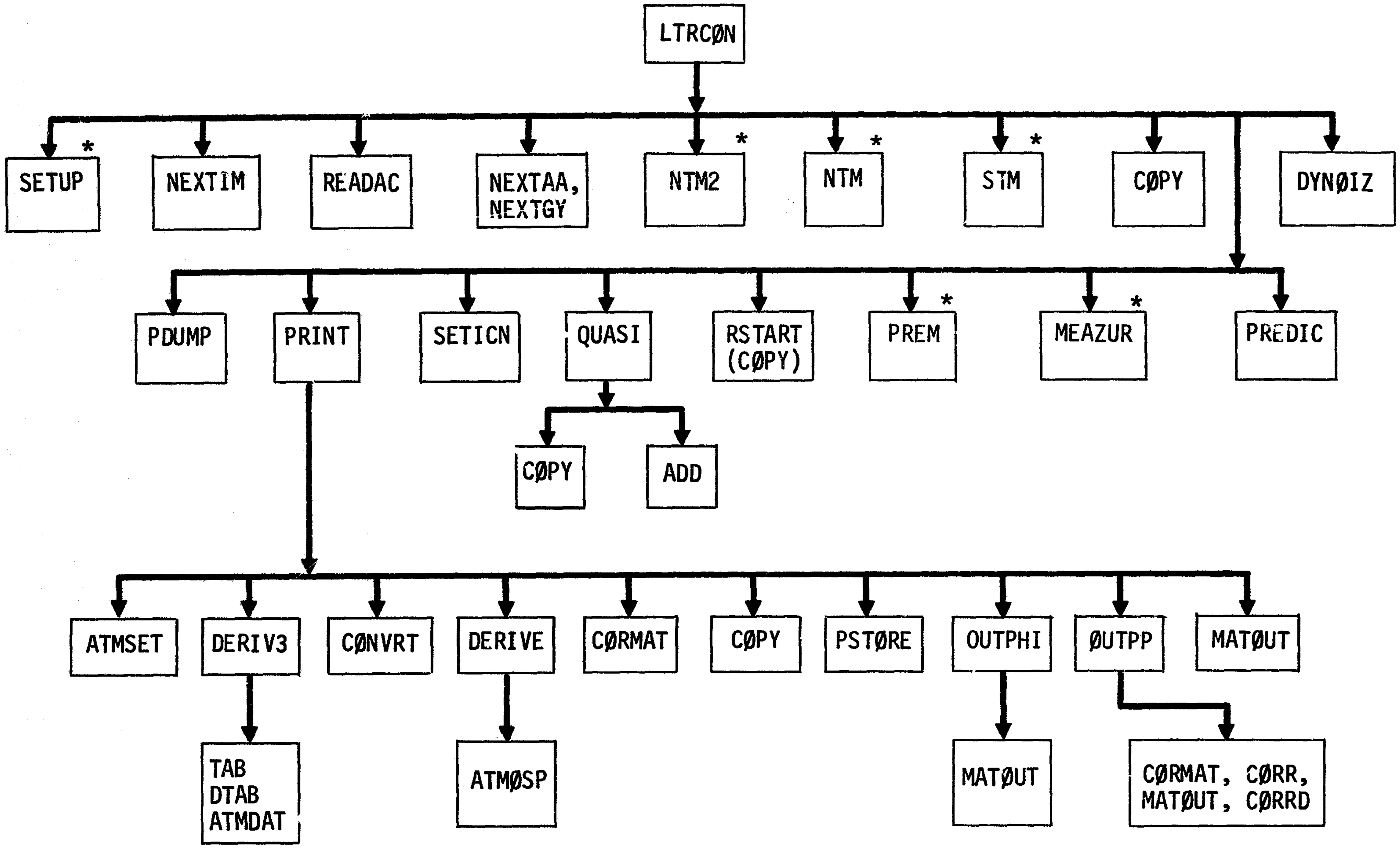

Figure III-3 LTRCØN Executive Flow Diagram

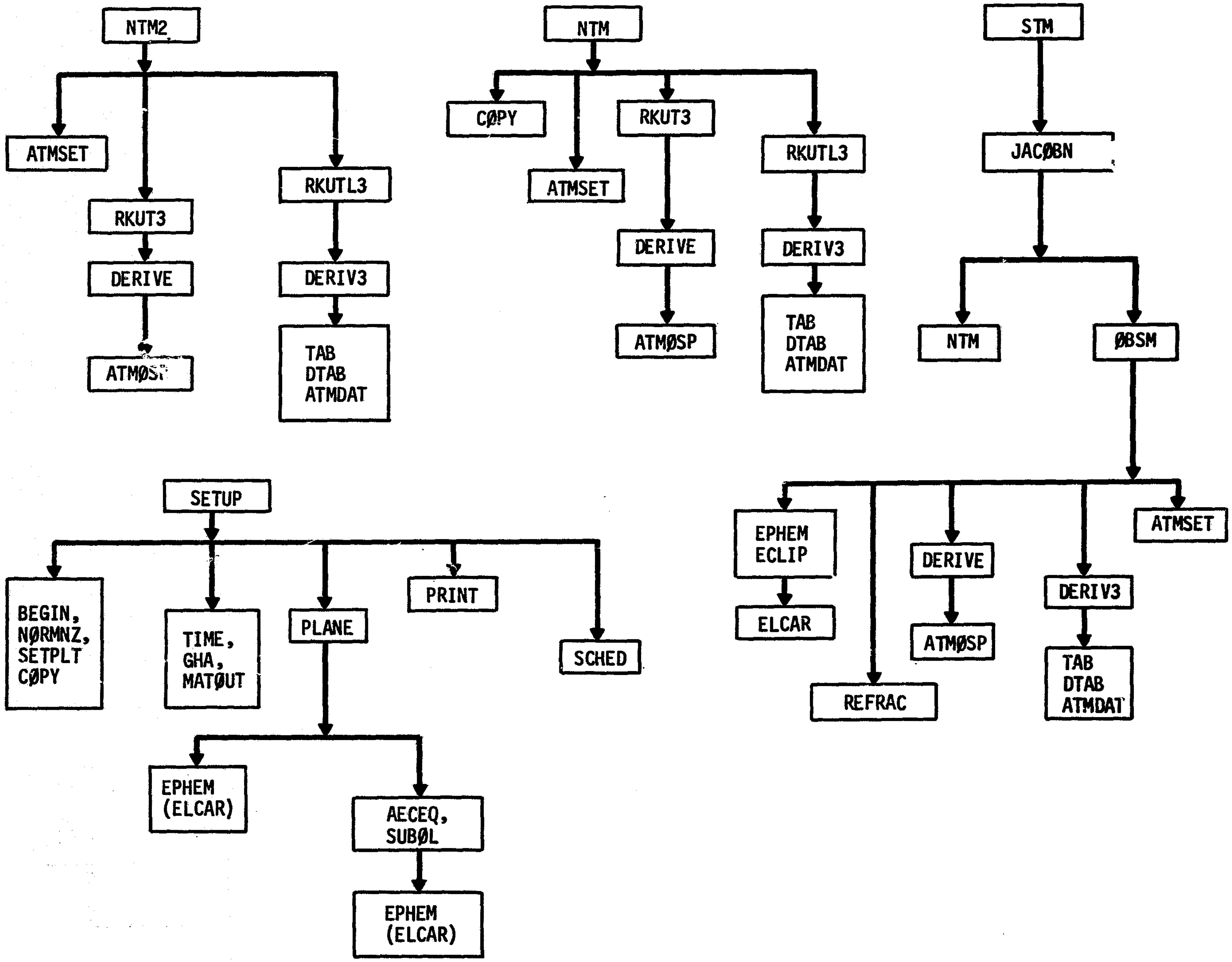

Figure III-3 (cont)

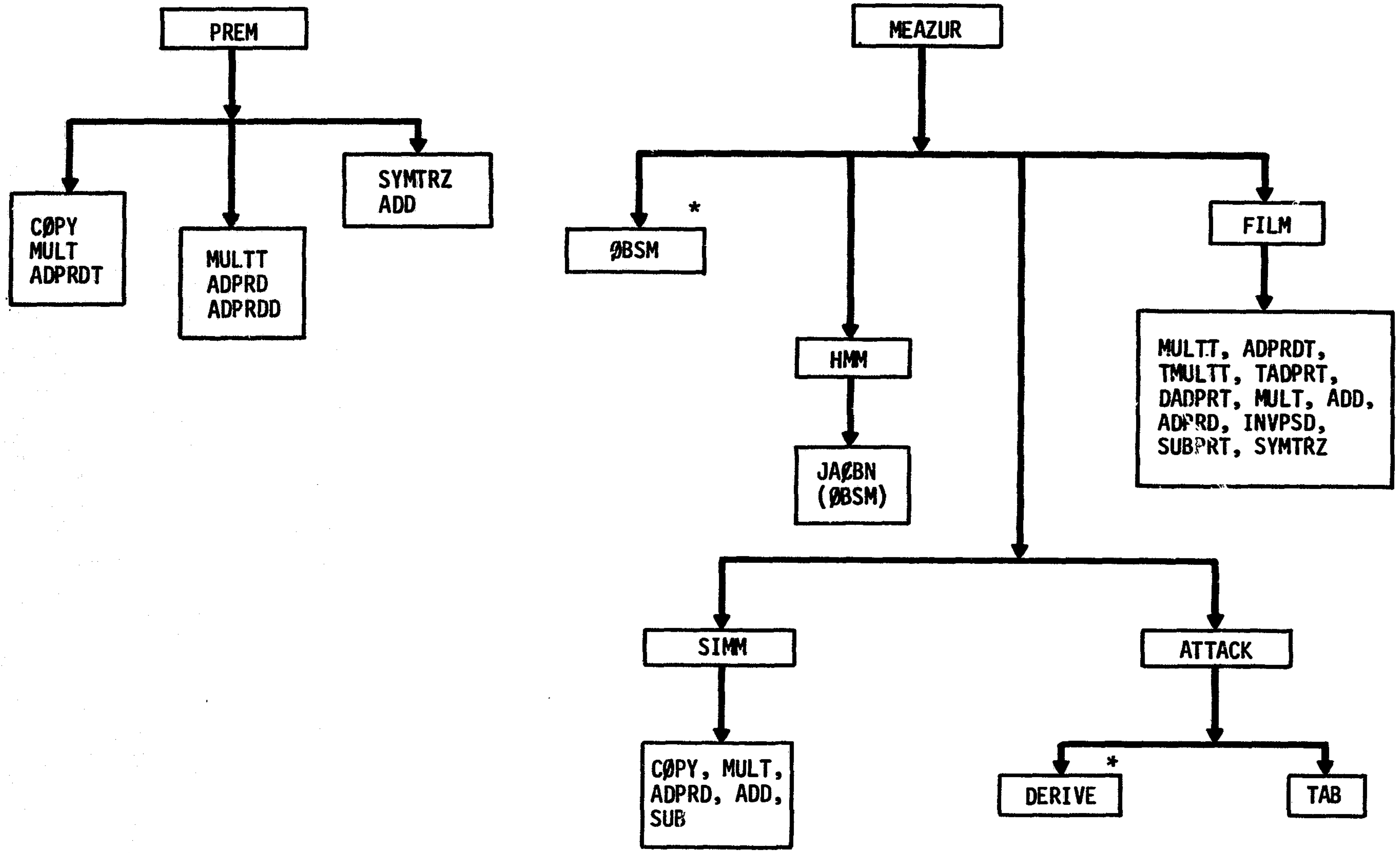

Figure III-3 (Concl)

IV. COMMON VARIABLE DEFINITIONS

A. COMMON VARIABLES BY BLOCKS

In this section common blocks are listed in alphabetical order. Variables within these blocks are defined in the order they appear within the block.

/ACCEL/

ACCLX	Actual acceleration along the X-axis (written in DATGEN)
ACCLZ	Actual acceleration along the Z-axis (written in DATGEN)

/ACT/

RH0A	Actual density (read in READAC)
TEMPA	Actual stagnation temperature (read in READAC)
ACCLXC	Actual acceleration along the X-axis (read in READAC)
ACCLZC	Actual acceleration along the Z-axis (read in READAC)
MWTA	Actual molecular weight (read in READAC)

/ALREDY/

GENDAT	Flag to determine if data generator has been run before reconstructor (set .TRUE. in SETUP1)
RESTRT	Flag to determine if data generator and reconstructor are being restarted (read in SETUP1, SETUP)

/AM/

MWTM	Nominal molecular weight (input in SETUP)
THETI	Initial attitude angle (input in SETUP)

/ATMS/

BKTBL(20)	Breakpoints of ratios of lift to drag versus Mach number used to calculate angle of attack measurement
GAMTBL(20)	Breakpoints of ratios of specific heats versus molecular weight used to calculate Mach number and speed of sound

/AX/

AXC	Reconstructed acceleration along X-axis as experienced by VRU
AZC	Reconstructed acceleration along Z-axis as experienced by VRU
THTC	Change in inertial pitch attitude since TZER0
0MGC	Reconstructed angular velocity as experienced by ARU
ALPHA	Reconstructed angle of attack

/BM/

EDNBM(30)	Estimated deviations from most recent nominal trajectory before a measurement
QEDNBM(30)	Estimated deviations in solve-for parameters from most recent nominal before a measurement

/CØVARP/

P(36)	State covariance matrix
Q(100)	Solve-for parameter covariance matrix
DU(20)	Dynamic-consider parameter covariance matrix
DV(20)	Measurement-consider parameter covariance matrix
DW(10)	Dynamic/measurement-consider parameter covariance matrix
CXQ(60)	Covariance matrix relating state parameters to solve-for parameters
CXU(120)	Covariance matrix relating state parameters to dynamic-consider parameters
CXV(120)	Covariance matrix relating state parameters to measurement-consider parameters
CXW(60)	Covariance matrix relating state parameters to dynamic/measurement-consider parameters
CQU(200)	Covariance matrix relating solve-for parameters to dynamic-consider parameters
CQV(200)	Covariance matrix relating solve-for parameters to measurement-consider parameters
CQW(100)	Covariance matrix relating solve-for parameters to dynamic/measurement-consider parameters
SP(36)	P matrix saved before a new measurement, event, etc
SQ(100)	Q matrix saved before a new measurement, event, etc
SDU(20)	DU matrix saved before a new measurement, event, etc
SDV(20)	DV matrix saved before a new measurement, event, etc

SDW(10)	DW matrix saved before a new measurement, event, etc
SCXQ(60)	CXQ matrix saved before a new measurement, event, etc
SCXU(120)	CXU matrix saved before a new measurement, event, etc
SCXV(120)	CXV matrix saved before a new measurement, event, etc
SCXW(60)	CXW matrix saved before a new measurement, event, etc
SCQU(200)	CQU matrix saved before a new measurement, event, etc
SCQV(200)	CQV matrix saved before a new measurement, event, etc
SCQW(100)	CQW matrix saved before a new measurement, event, etc
CXQC(60)	Correlation matrix of CXQ matrix
CXUC(120)	Correlation matrix of CXU matrix
CXVC(120)	Correlation matrix of CXV matrix
CXWC(60)	Correlation matrix of CXW matrix
CQUC(200)	Correlation matrix of CQU matrix
CQVC(200)	Correlation matrix of CQV matrix
CQWC(100)	Correlation matrix of CQW matrix
PHI(36)	State transition matrix
PSI(60)	Sensitivity matrix relating state parameters to solve-for parameters
THU(120)	Sensitivity matrix relating state parameters to dynamic-consider parameters
THW(60)	Sensitivity matrix relating state parameters to dynamic/measurement-consider parameters

HM(24)	Partition of observation matrix relating observables to state
MM(40)	Partition of observation matrix relating observables to solve-for parameters
LM(80)	Partition of observation matrix relating observables to measurement-consider parameters
GM(40)	Partition of observation matrix relating observables to dynamic/measurement-consider parameters
JM(16)	Kalman filter J matrix
W1(24) W2(40) W3(80) W4(80) W5(40)	Working matrices for filter equations
K1(24)	Kalman gain matrix for state parameters
K2(40)	Kalman gain matrix for solve-for parameters
WØRK(400) W(120)	Working matrices for filter equations
R(16)	Measurement noise matrix
DYN(36)	Dynamic noise matrix
PP(36)	Correlation matrix of P matrix
QQ(100)	Correlation matrix of Q matrix
JIN(16)	J inverse of Kalman filter equations
SQDU(20)	Standard deviations of dynamic-consider parameters

SQDV(20)	Standard deviations of measurement-consider parameters
SQDW	Standard deviations of dynamic/measurement-consider parameters
PPC(36)	PP matrix converted to output units
QEDN(10)	Estimated deviations of solve-for parameters from nominal values
QEDNBC(10)	QEDN matrix before a quasi-event

/DET/

CDELT1 CDELT2 CDELT3	Cosines of calibrated misalignments of the VRU and ARU after biasing
SDELT1 SDELT2 SDELT3	Sines of calibrated misalignments of the VRU and ARU after biasing
SUBDL1	Intermediate term used to calculate axial and normal acceleration

/DOPLER/

TZERO	Trajectory time TC at start of data generator and reconstructor
DATEJ	Julian date, epoch 1900, corresponding to TZERO (calculated in SETUP1, SETUP)
SALT(3)	Station location altitudes for DSN tracking in kilometers
SLAT(3)	Station location latitudes for DSN tracking in radians
SLON(3)	Station location longitudes for DSN tracking in radians

RANGE(3)	Actual range measurement (km)
RANGER(3)	Actual range-rate measurements (km/s)
0MEGAE	Angular velocity of earth (rad/s)
0BLIC	Obliquity of the ecliptic (radians)
REARTH	Radius of the earth (kilometers)
GHAT0	Greenwich hour angle of the vernal equinox at TZER0
SCPEC(6)	Spacecraft planetocentric ecliptic coordinates based on ECL0NG(1), ECLINC(1), PHIR(1)
PHIR(3)	Reference angle phi for ecliptic, planetoequatorial, and subsolar orbital planes, respectively
ECL0NG(3)	Reference longitude for ecliptic, planetoequatorial, and subsolar orbital planes, respectively
ECLINC(3)	Reference inclination for ecliptic, planetoequatorial, and subsolar orbital planes, respectively
DELRR(3)	Range perturbations due to refractivity
DELRRR(3)	Range-rate perturbations due to refractivity
R0TN0	The target planet angular velocity component normal to the entry plane
NTP	Integer number of the target planet (see EPHEM for range of values)

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/DERIV/

- -

VA	Velocity of atmosphere at vehicle position
SGAM	Sine of vehicle flightpath angle
CGAM	Cosine of vehicle flightpath angle
V	Velocity of vehicle

GAM	Vehicle flightpath angle
FE	Vehicle range angle

/GYRACC/

NACCEL	Flag used to delete accelerometer data from dynamic equations
NGYRØ	Flag used to delete gyro data from dynamic equations

/INTCØM/

GEND	Integer to indicate number of gyro elements
IAA	Indicates which accelerometer data partition to use to calculate state derivatives
ICNTR	Indicates number of increments between print points
IEND	Indicates end of accelerometer data partitions for a given interval
IGYRØ	Indicates which gyro data partition to use to calculate state derivatives
INDEP(15)	Indicators of independent variables for plot package
IPRINT	Print increment counter used with ICNTR to control print points
IX	Not used
LASTIM	Not used
LICNTR(15)	Array of values for ICNTR
LISTSM	Not used
LISTS(6)	List of state parameters

LISTQ(10)	List of solve-for parameters
LISTU(20)	List of dynamic-consider parameters
LISTV(20)	List of measurement-consider parameters
LISTW(10)	List of dynamic/measurement-consider parameters
M	Parameter used to quantize VRU and ARU data
MCNTR	Indicates which measurement or event is currently being processed
MC0DE(250)	Array of values of MCNTR
M0DE	Not used
N	Parameter used to quantize VRU and ARU data
NE	Number of state parameters in LISTS
NICNTR	Indicates LICNTR value of interest
NM	Number of observables in a measurement
NMEAS	Not used
NMPTS	Number of breakpoints of altitude versus molecular weight
NPRED	Not used
NQS	Set to NQ and used to set up plot package
NQUASI	Not used
NTPTS	Number of breakpoints of altitude versus ambient temperature
NVAR(15)	Array of number of dependent variables for plot package
NS	Number of state parameters in LISTS
NQ	Number of solve-for parameters in LISTQ

NU	Number of dynamic-consider parameters in LISTU
NV	Number of measurement-consider parameters in LISTV
NW	Number of dynamic/measurement-consider parameters in LISTW
PR0B(40)	Array of Hollerith data for problem identification
RUNN0	Indicates which part of LTR is being executed (data generator, reconstructor, etc)
SUM	Not used
SUMFAR	Not used
SIZEP	Not used
TYPE	Current value of MC0DE used to process event or measurement

/L0GC0M/

CDEL	Logical to reduce time needed to compute state derivatives when C(55), C(56), C(63) are not perturbed
HITGND	Logical set to .TRUE. when vehicle impacts the planet
LASTYM	Logical used to quantize VRU and ARU data
LINEAR(15)	Array of logicals to set linear scales for plot package
L0G(15)	Array of logicals to set log scales for plot package
LTR1	Logical to control mode B logic
LTR2	Logical to control mode A logic
MACHN0	Logical to control updating of Mach number for LTR2 mode of reconstructor

PARACH	Not used
PL0TL(15)	Array of logicals used to control storage of plot data (subroutine PST0RE)
REDRR1	Not used
REDRR2	Logical to control calculation of measurement noise for altimeter
SUMTB(15)	Array of logicals to control print of summary tables (subroutine SUMMRY)
TERHT	Logical used to control terrain height modeling
UPDATE	Not used

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/0BSERV/

- -

ACC(3,3)	Not used
ACCDT	Not used
ACCT	Not used
AQUANT	Not used
BF(16,4)	Bias factors used to perturb actual measurements read in READAC
BTBL(50)	Not used
DELT(18)	Misalignment angles for gyro and accelerometer measurements
EPSM(50)	Table of shock wave density ratios versus velocity to calculate stagnation pressure measurement
ETA	Altimeter beam angle used in altimeter measurements

GQUANT	Not used
GYRØDT	Not used
RR(16,4,3)	Array of measurement noise, dimensioned on measurement type, measurement component, and noise option
SD(16,4)	Array of measurement noise standard deviations, dimensioned by measurement type and measurement component
SF(16,4)	Scale factors used to perturb actual measurements read in READAC

/PRE/

PRSDAT	Actual dynamic pressure stored on unit 10 for reconstructor printout
SDMWT	Standard deviation of molecular weight used to calculate standard deviation of temperature

/PLØT2/

XMAT(1000,19)	Storage of plot variables for use by plot package

/PRED/

PREDIC	Not used
PREDND(50)	Not used
STC	Not used
XNPM(30)	Not used
XNPMS(30)	Not used

/PRINTS/

AEEDEN	Actual error in estimated deviation from most recent nominal value of density
AEESLV(10)	Actual error in estimated deviations from most recent nominal solve-for values after a measurement
AEESTT(6)	Actual errors in estimated deviations from most recent nominal trajectory state
AEETMP	Actual error in estimated deviation from most recent nominal value of ambient temperature
ALPHAA	Actual angle of attack in degrees
DENS	Estimated deviation from most recent nominal value of density
EDNC(6)	Estimated deviations from most recent nominal trajectory state
0MGCC	Reconstructed angular velocity converted to degrees
PPD(6)	Diagonal elements of PP matrix after a measurement
PPDBM(6)	Diagonal elements of PP matrix before a measurement
PPXD	Actual dynamic pressure in millibars
QQD(10)	Diagonal elements of QQ matrix after a measurement
QQDBM(10)	Diagonal elements of QQ matrix before a measurement
RESI(4)	Measurement residuals
SDDENS	Standard deviation in density after a measurement
SDMWT2	Not used
SDTEMP	Standard deviation in ambient temperature after a measurement

THETRC	Reconstructed angle THETA
XNAC(6)	Actual state in output units
XNC(6)	Most recent nominal state in output units
SDENBM	Standard deviation in density before a measurement
STEMBM	Standard deviation in ambient temperature before a measurement
TEMEDN	Estimated deviation in ambient temperature after a measurement
DENSBM	Estimated deviation in density before a measurement
TEMDBM	Estimated deviation in ambient temperature before a measurement

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/PRNT3/

EDNBQC(30)	Converted estimated deviations from most recent nominal trajectory before a quasi-event
EDNBMC(30)	EDNBM converted to output units before a quasi-event
XNBQC(30)	Most recent nominal trajectory (converted) before a quasi-event

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/STATE/

CARC0R(6)	Cartesian coordinates of heliocentric ecliptic position and velocity of a specified planet
C0NEL(7)	Conic elements of heliocentric ecliptic orbit of a specified planet and gravitational constant of the planet

/SIZE/

XSTEP	Quantizing factor for axial acceleration
ZSTEP	Quantizing factor for normal acceleration
TSTEP	Quantizing factor for rate gyro attitude

/SMØ/

VXQA(9)	Axial acceleration values before smoothing
VZQA(9)	Normal acceleration values before smoothing
THTQA(9)	Rate gyro values before smoothing
CAN(3,3)	B transposed times B
D(3,3)	Inverse of CAN matrix
E(3,9)	Pseudoinverse of B
B(9,3)	Least-squares filter matrix used to smooth accelerometer and gyro data
A1(3)	Quadratic coefficients used by reconstructor for smoothed axial acceleration values
A2(3)	Quadratic coefficients used by reconstructor for smoothed normal acceleration values
A3(3)	Quadratic coefficients used by reconstructor for smoothed gyro values
AA(3,3,50)	Values of A1, A2, A3 stored by SMØØT2 and read by NEXTAA for each integration interval
VXQ	Latest axial acceleration stored in VXQA array for curve fitting by least-squares filter
VZQ	Latest normal acceleration stored in VZQA array for curve fitting by least-squares filter
THTQ	Latest rate gyro value stored in THTQA array for curve fitting by least-squares filter

/SUMRY/

TIMEF	Final trajectory time reached by the reconstructor

/TRAJ/

ARØTBL(316,4)	Table of vehicle aerodynamic coefficients for integrators divided into four parts: A. CA table of ALPHA versus Mach number B. CN table of ALPHA versus Mach number C. CMQ table of ALPHA versus Mach number D. CP table of ALPHA versus Mach number
AF	Axial force calculated from surface area and dynamic pressure
AGAM	Ratio of specific heats used to calculate Mach number and speed of sound
ALPH	Computed angle of attack assuming an atmosphere stationary with respect to the rotating planet
AM	Moment acceleration computed by data generator
AR	Universal gas constant
ATMØSS(33,5)	Five tables of breakpoints of molecular weights and temperatures versus altitude
ATMØS(33)	ATMØSS table chosen according to NATMØS
AX	Axial aerodynamic acceleration
AY	Normal aerodynamic acceleration
C(200)	Biases and scale factors used to calculate "real world" model in the data generator and to calculate sensitivity matrices and state deviations in the reconstructor (for a breakdown of the elements of the C array, see input description of the *Users' Manual)*

CA	Axial force coefficient computed from AR0TBL tables
CACT(200)	Data generator values of the C array used by the reconstructor to compute actual deviations from most recent nominal values of solve-for parameters
CBQ(30)	Scale factors and biases before a quasi-event used to compute estimated deviations from most recent nominal values of solve-for parameters
CDTBL(50)	Parachute drag coefficient table
CMQ	Moment coefficient computed from AR0TBL tables
CN	Normal force coefficient computed from AR0TBL tables
C0(200)	Original reconstructor C array values used to calculate estimated deviations from original nominal values of solve-for parameters
DIA	Vehicle base diameter
DP	Dynamic pressure
DT	Integration step size (seconds) for data generator and reconstructor
DXN(30)	First derivatives of state parameters, actual VRU-ARU data, and ambient pressure deivative
EDN(30)	Estimated deviations from most recent nominal trajectory after a measurement
EDNBQ(30)	EDN array before a quasi-event
EPS	Epsilon, the angle between the inertial velocity and relative velocity vectors
FD	Parachute drag force
GA	Local gravitational acceleration
G0	Gravitational acceleration at zero altitude
MACH	Mach number

MASS	Mass of the vehicle
MASSA	Perturbed vehicle mass
MEAS(4)	Reconstructed measurements calculated in 0BSM to drive the filter equations
MEZACT(4)	Measurements calculated by the data generator and perturbed by noise, scale, and bias factors
MEZEST(10)	Estimated measurements calculated from MEAS array for filter equations
MEZN0Z(16,4)	Measurement noise components used to calculate MEZACT array
MU	Gravitational constant of the target planet
MWT	Actual molecular weight used to calculate Mach number
0MEG	Rotational rate of the target planet
PRES	Ambient pressure state variable
RAD	Conversion factor from radians to degrees
RH0	Atmospheric density
RI	Rotational inertia of the vehicle
RM	Radius of the target planet
SA	Reference surface area of the vehicle
SDP	Parachute reference area
SS	Speed of sound
TAPETM	Trajectory time stored on unit 10 for processing groups of events and measurements
TC	Current trajectory time (seconds)
TDIFF	Difference between current trajectory time and time of next measurement or event

TEMP	Ambient temperature
TEND	Trajectory time of the next event or measurement
TF	Final trajectory time
TMN(250)	Array of measurement and event times
VR	Relative velocity of the vehicle
VW	Actual wind velocity for data generator
WDTBL(50)	Table of breakpoints of wind velocity versus altitude
XD	Location of parachute bridle apex relative to origin of vehicle body axes
XG	Axial distance to center of gravity
XM	Axial distance to accelerometer location
XN(30)	Most recent nominal trajectory state
XNA(30)	Actual trajectory state (read in READAC)
XNAS(30)	Not used
XNBQ(30)	Most recent nominal trajectory state before a quasi-event
XNS(30)	Not used
X0(30)	Original nominal trajectory state
X0S(30)	Not used
XP	Axial location of center of pressure
YG	Not used
YM	Not used
ZM	Moment force calculated from surface area, dynamic pressure, and relative velocity

ZN	Normal force calculated from surface area and dynamic pressure
ZG	Normal distance to center of gravity
ZMM	Normal distance to accelerometer location

- -

/XMACH/

- -

RMACHB	Mach number at the beginning of an integration interval for calculation of sensitivity matrices

/LØMØD/

FRSTMR	Logical to indicate first call to integrator with current step size
QSMCHG	Logical to indicate a change to the quasi-static dynamic model and integration step size
CØND	Logical to control computation of computed angle of attack (ALPH) and vehicle attitude angle (THETA)

/PHASE/

IPHAS	Indicator for parachute deployment = 1, parachute has not deployed = 2, parachute has deployed = 3, parachute has been released

/QMPTI/

QSALT	Altitude at which to change to quasi-static model
QSDT	Integration step size used by DATGEN after change to quasi-static model
SDT	Step size used in data generator before change to quasi-static model
QST	Value of TC at which change to quasi-static model occurred
XMT(16)	Altitude breakpoints and molecular weights of molecular weight profile
XMFH(5)	Altitude breakpoints for all mole fraction profiles

XMFW(5,5)	Mole fractions of component gases
CGMW(5)	Molecular weights of component gases
VMASS(3)	Vehicle mass before parachute deployment, after deployment, and after release
VSA(3)	Vehicle reference surface area before parachute deployment, after deployment, and after release
VDIA(3)	Vehicle base diameter before parachute deployment, after deployment, and after release
VRI(3)	Vehicle rotational inertia before parachute deployment, after deployment, and after release
HD	Altitude at which to deploy parachute
HR	Altitude at which to release parachute
TD	Value of TC at which parachute was deployed
TR	Value of TC at which parachute was released
TH(7)	Terrain height model for altimeter measurements
ØDB	Bound on dynamic pressure to control calculation of vehicle attitude and angle of attack
CAC	Coefficient of axial force (CA) perturbed by bias and scale factors
CDC	Parachute drag coefficient (CD) perturbed by bias and scale factors

V. INDIVIDUAL SUBROUTINE DOCUMENTATION

SUBROUTINE ADD

PURPOSE : TO ADD TWO RECTANGULAR MATRICES AND STORE IN A THIRD MATRIX

ENTRY PARAMETERS

NCX	NUMBER OF COLUMNS OF X, Y, AND Z MATRICES
NRX	NUMBER OF ROWS OF X, Y, AND Z MATRICES
X	INPUT MATRIX
Y	INPUT MATRIX
Z	OUTPUT MATRIX (SUM OF X AND Y)

LOCAL SYMBOLS

I	INDEX
N	NUMBER OF ELEMENTS OF X, Y, AND Z MATRICES

SUBROUTINE AECEQ

PURPOSE: COMPUTE THE CO-ORDINATE TRANSFORMATION FROM GEOCENTRIC ECLIPTIC PLANE TO GEOCENTRIC EQUATORIAL PLANE

ENTRY PARAMETERS:

A	CO-ORDINATE TRANSFORMATION FROM GEOCENTRIC ECLIPTIC PLANE TO GEOCENTRIC EQUATORIAL PLANE
DJ	JULIAN DATE, EPOCH JANUARY 0, 1900

LOCAL SYMBOLS:

D	JULIAN DATE DIVIDED BY 10000.
OB	OBLIQUITY OF THE ECLIPTIC IN DEGREES
RAD	CONVERSION FACTOR FROM DEGREES TO RADIANS
COSOB	COSINE OF THE OBLIQUITY
SINOB	SINE OF THE OBLIQUITY

AECEQ Analysis

Subroutine AECEQ computes the coordinate transformation from geocentric ecliptic to geocentric equatorial coordinates. If A denotes the coordinate transformation matrix, then

$$\vec{x}_{\text{equatorial}} = A\,\vec{x}_{\text{ecliptic}}$$

and

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varepsilon & -\sin\varepsilon \\ 0 & \sin\varepsilon & \cos\varepsilon \end{bmatrix}$$

where obliquity of the ecliptic is given (in degrees) by

$$\varepsilon = 23^\circ.452294 - 0^\circ.0035626\ D - 0^\circ.000000123\ D^2 + 0.0000000103\ D^3$$

and

$$D = \text{Julian date (epoch 1900)} * 10^{-4} \quad .$$

```
SUBROUTINE ATMOSP

PURPOSE :      COMPUTE ATMOSPHERE QUANTITIES FOR MODE  A  RECONSTRUCTOR


SUBROUTINES CALLED: DTAB

COMMONS : TRAJ      AX        ATMS      PRE       DOPLER    QMPTI
          PHASE

LOCAL SYMBOLS
        AERO        AERODYNAMIC FORCE COEFFICIENTS

        ALFA        ABSOLUTE VALUE OF ANGLE OF ATTACK

        CAC         PERTURBED COEFFICIENT OF AXIAL FORCE


USED/COMMN---  AGAM      ALPH      AR        AXC       C         CA
    CAC        DP        IPHAS     GAMTBL    MACHNO    MASS      MASSA
    MWT        RHO       SA        TC        TZERO     VR        XN

SET/COMMON---  AGAM      CA        DP        MACH      MACHNO    MASSA
               RHO       .EMP      CAC

FCT CALLED---  TAB
```

ATMØSP Analysis

Subroutine ATMØSP computes Mach number and atmospheric density and temperature for the mode A reconstruction process. The required equations are derived in Chapter IV.

Dynamic pressure q can be related to the calibrated axial accelerometer measurement a_{x_c} according to

$$q = - \frac{(m + C_{30})\ a_{x_c}}{(C_{20} \cdot C_A + C_{16}) + (C_{96} \cdot C_D + C_{97})} \qquad (1)$$

so that density can be immediately obtained from

$$\rho = \frac{2q}{V_r^2} \quad . \qquad (2)$$

These equations correspond to equations (IV-17) and (IV-18), respectively, but with relevant scale factors and biases incorporated. These scale factors and biases are defined as follows:

C_{16} = axial aerodynamic coefficient C_A bias

C_{20} = C_A scale factor

C_{30} = mass m bias

C_{96} = parachute drag coefficient C_D scale factor

C_{97} = C_D bias.

Mach number M is computed from the equation

$$M = \left[\frac{2q}{\gamma p}\right]^{\frac{1}{2}} \qquad (3)$$

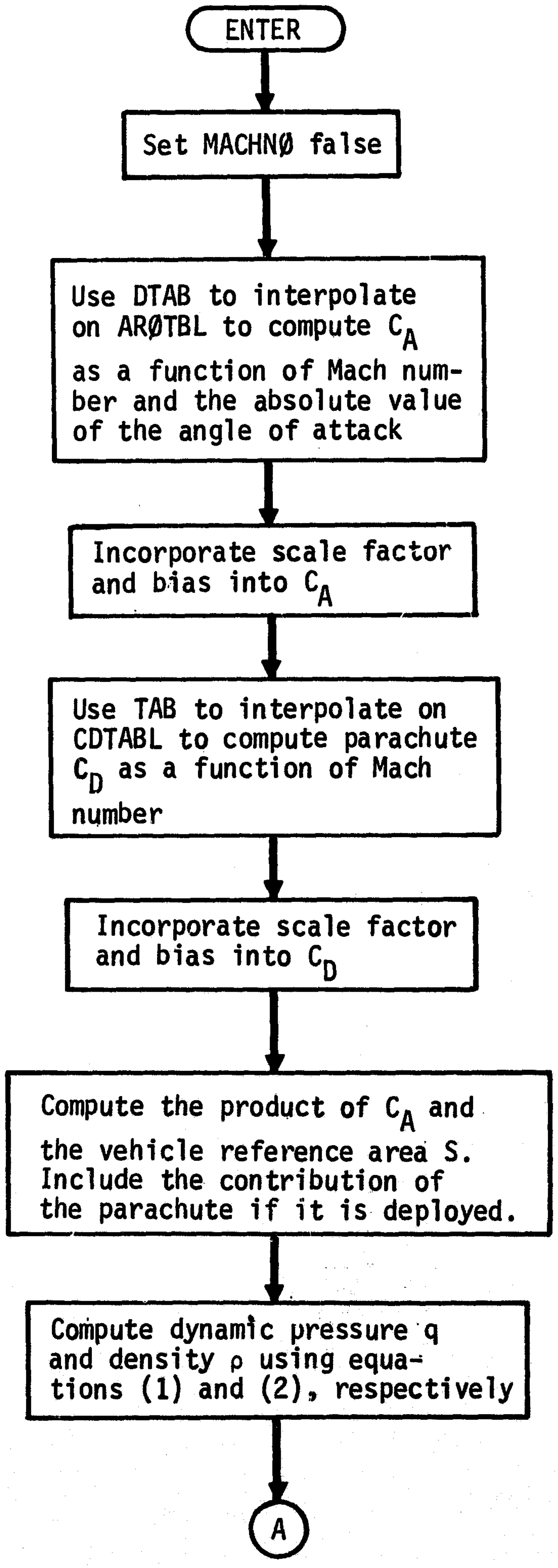
where γ is the ratio of specific heats and p is the ambient pressure, which has been obtained by integrating the hydrostatic equation in subroutine DERIVE.

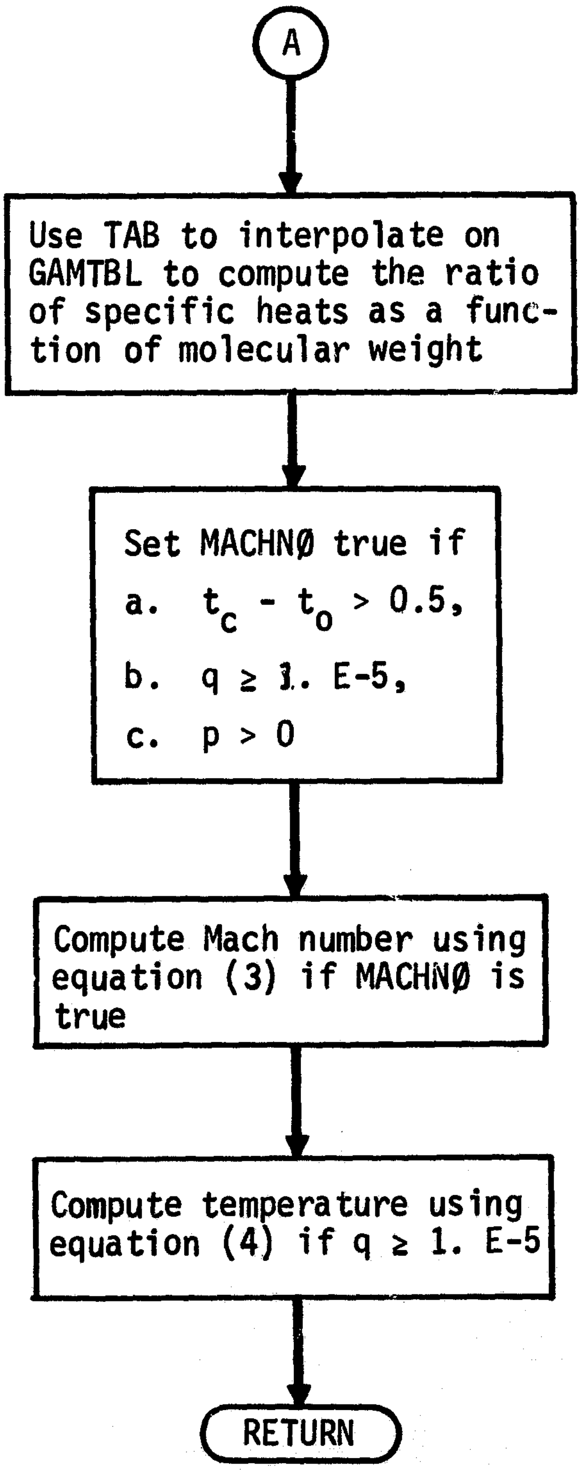
Temperature is obtained from the equation of state

$$T = \frac{pM}{\rho R} \tag{4}$$

where M denotes molecular weight and R denotes the universal gas constant.

ATM0SP Flow Chart




A
Use TAB to interpolate on GAMTBL to compute the ratio of specific heats as a function of molecular weight
Set MACHN0 true if
a. $t_c - t_o > 0.5$,
b. $q \geq 1.$ E-5,
c. $p > 0$
Compute Mach number using equation (3) if MACHN0 is true
Compute temperature using equation (4) if $q \geq 1.$ E-5
RETURN

SUBROUTINE ATMSET

PURPOSE :   COMPUTE ATMOSPHERIC TEMPERATURE, MOLECULAR WEIGHT,
PRESSURE, DENSITY, AND SPEED OF SOUND AT HEIGHT H

ENTRY PARAMETERS

H	VEHICLE HEIGHT ABOVE MEAN PLANET SURFACE

COMMONS : TRAJ   QMPTI   INTCOM

LOCAL SYMBOLS

CUMPRD	RATIO OF PRESSURE AT ATMOSPHERE BREAKPOINTS TO SURFACE PRESSURE
E	ATMOSPHERE BREAKPOINT HEIGHTS IN ASCENDING SEQUENCE
MB	ZERO HEIGHT INTERCEPTS FOR LINEAR SEGMENTS OF MOLECULAR WEIGHT VERSUS HEIGHT FUNCTIONS
MNOS	MOLECULAR WEIGHT BREAKPOINT INDICES ASSOCIATED WITH ATMOSPHERE BREAKPOINTS
MS	SLOPES OF LINEAR SEGMENTS OF MOLECULAR WEIGHT VERSUS HEIGHT FUNCTIONS
N	ONE LESS THAN THE NUMBER OF BREAKPOINTS
NBPTS	NUMBER OF ATMOSPHERE BREAKPOINTS (TEMPERATURE PLUS MOLECULAR WEIGHT)
NBPTS1	NBPTS - 1
ST	INTEGRAL OF RATIO OF MOLECULAR WEIGHT TO TEMPERATURE
TB	ZERO HEIGHT INTERCEPTS FOR LINEAR SEGMENTS OF TEMPERATURE VERSUS HEIGHT FUNCTIONS
TNOS	TEMPERATURE BREAKPOINT INDICES ASSOCIATED WITH ATMOSPHERE BREAKPOINTS
TS	SLOPES OF LINEAR SEGMENTS OF TEMPERATURE VERSUS HEIGHT FUNCTIONS
XX	RATIO OF DENSITY TO PRESSURE AT HEIGHT H
ZS	ABSOLUTE MAGNITUDE OF TS
ZZZ	NEGATIVE OF EXPONENT IN PRESSURE VERSUS HEIGHT FUNCTION

```
USED/COMMN--- AGAM      APO       AR        GO        MOL       MPT
              MWT       NMPTS     NTPTS     PRES      TEMP      TMP
              TPT       CGMW      XMFH      XMFW

SET/COMMON--- MPT       MWT       PRES      RHO       SS        TEMP
              MOL

FCT CALLED--- F1        F2

FCT DFND  --- F1        F2

ENTRY PNT --- ATMDAT    ATMSET
```

ATMSET Analysis

ATMSET determines the temperature, molecular weight, pressure, density, and speed of sound of the atmosphere as a function of height above the mean surface, h. The atmosphere is modeled by assuming piece-wise linear representation for the temperature and molecular weight versus height. The remaining atmospheric parameters are then found from the hydrostatic equations and the perfect gas law.

The temperature T at height h between the j and j+1 temperature breakpoints is given by

$$T(h) = Ts_j \, h + Tb_j \quad . \tag{1}$$

The molecular weight M at height h between the i and i+1 molecular weight breakpoints is given by

$$M(h) = Ms_i \, h + Mb_i \quad . \tag{2}$$

The hydrostatic equation

$$\frac{dP}{dh} = - \rho g \tag{3}$$

where g = acceleration due to gravity, and the perfect gas law,

$$\rho(h) = \frac{P(h)}{R} \cdot \frac{M(h)}{T(h)} \tag{4}$$

where R = gas constant, may be integrated from the atmosphere breakpoint (temperature or molecular weight) immediately below the height h to give the pressure P(h)

$$P(h) = P(h_k) \; \mathrm{EXP} \left[- \frac{g}{R} \int_{h_k}^{h} \frac{M(\zeta)}{T(\zeta)} \, d\zeta \right] \cdot \tag{5}$$

$$\int_{h_k}^{h} \frac{M(\zeta)}{T(\zeta)}\, d\zeta = \begin{cases} \dfrac{1}{Tb_j}(h - h_k) \left\} Mb_i + \dfrac{1}{2} Ms_i \; (h - h_k) \right\{ , & Ts_j = 0 \\ \dfrac{Ms_i}{Ts_j}(h - h_k) + \dfrac{Mb_i \cdot Ts_j - Tb_j \cdot Ms_i}{Ts_j} \, \ell n \, \dfrac{Tb_j + Ts_j\, h}{Tb_j + Ts_j\, h_k}, & Ts_j \neq 0 \end{cases} \qquad (6)$$

where

i = the index of the molecular weight breakpoint immediately below h,

j = the index of the temperature breakpoint immediately below h.

For a given surface pressure P(ho), the pressure P(h) may be found by repeated application of the above expression

$$P(h) = P(ho) \left\{ \frac{P(h_k)}{P(ho)} \right\} \mathrm{EXP} \left[- \frac{g}{R} \int_{h_k}^{h} \frac{M(\zeta)}{T(\zeta)}\, d\zeta \right] . \qquad (7)$$

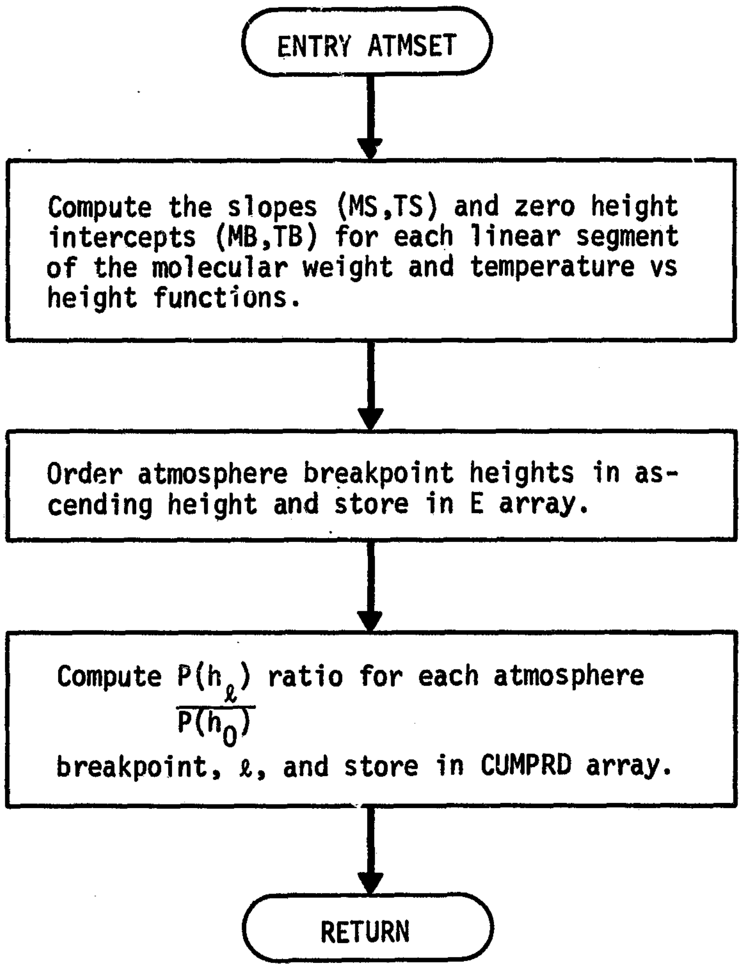
The density is then found from equation (4) and the speed of sound at height h is given by

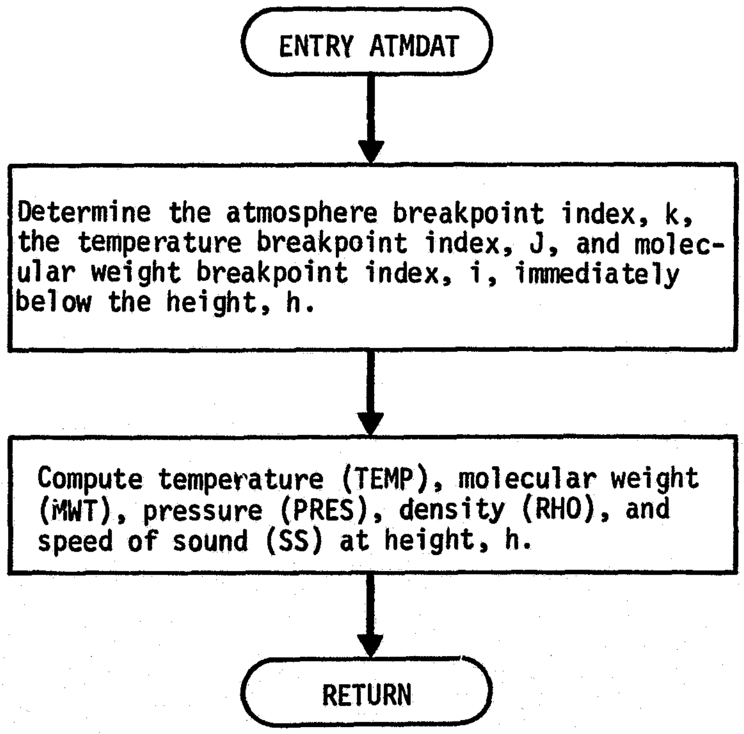
$$ss(h) = \gamma_s \left[\frac{RT(h)}{M(h)} \right]^{\frac{1}{2}} \qquad (8)$$

where γ_s = ratio of specific heats.

The subroutine has two entry points -- ATMST and ATMDAT. Entry ATMSET computes and stores the ratios $P(h_\ell)/P(ho)$ for each atmosphere breakpoint . Entry ATMDAT computes the temperature, molemolecular weight, pressure, density, and speed of sound at height h.

The flow of the ATMSET subroutine is illustrated.


ENTRY ATMSET
Compute the slopes (MS,TS) and zero height intercepts (MB,TB) for each linear segment of the molecular weight and temperature vs height functions.
Order atmosphere breakpoint heights in ascending height and store in E array.
Compute $\frac{P(h_\ell)}{P(h_0)}$ ratio for each atmosphere breakpoint, ℓ, and store in CUMPRD array.
RETURN


ENTRY ATMDAT
Determine the atmosphere breakpoint index, k, the temperature breakpoint index, J, and molecular weight breakpoint index, i, immediately below the height, h.
Compute temperature (TEMP), molecular weight (MWT), pressure (PRES), density (RHO), and speed of sound (SS) at height, h.
RETURN

```
SUBROUTINE ATTACK

PURPOSE :      COMPUTE VEHICLE ANGLE OF ATTACK


SUBROUTINES CALLED: DERIVE

COMMONS : AX         ATMS      TRAJ      GYRACC

LOCAL SYMBOLS
        BK          INTERPOLATED VALUE OF LIFT OVER DRAG
                    VERSUS MACH NUMBER

        DALPHA      INTERMEDIATE VARIABLE FOR ITERATIVE SOLUTION

        FALPHA      INTERMEDIATE VARIABLE FOR ITERATIVE SOLUTION

        I           INDEX

        ZETA        RATIO OF MEASURED ACCELERATIONS

USED/COMMN--- ALPHA     AXC       AZC       BKTBL     MACH      NACCEL

SET/COMMON--- ALPHA

FCT CALLED--- TAB

LOADED    --- MACHNO
```

ATTACK Analysis

Subroutine ATTACK computes the actual angle of attack measurement, which is currently defined only for the mode A reconstruction process. The ratio of calibrated accelerations a_{z_c}/a_{x_c} is used to define the angle of attack measurement $\tilde{\alpha}$. The vehicle lift/drag ratio can be related to a_{x_c}, a_{z_c}, and $\tilde{\alpha}$ as follows:

$$\frac{L}{D} = \frac{a_{z_c} \cos \tilde{\alpha} - a_{x_c} \sin \tilde{\alpha}}{a_{x_c} \cos \tilde{\alpha} + a_{z_c} \sin \tilde{\alpha}} \qquad (1)$$

Furthermore, $\frac{L}{D}$ has the form

$$\frac{L}{D} = k\,\tilde{\alpha} \qquad (2)$$

where k is a tabulated function of Mach number. Eliminating $\frac{L}{D}$ from equations (1) and (2) yields

$$\tan \tilde{\alpha} = \frac{\zeta - k\,\tilde{\alpha}}{1 + \zeta\, k\,\tilde{\alpha}} \qquad (3)$$

where

$$\zeta = a_{z_c}/a_{x_c} .$$

Equation (3) is solved iteratively for $\tilde{\alpha}$ using a standard Newton iteration technique. Rewriting equation (3) as

$$F = (1 + \zeta\, k\,\tilde{\alpha}) \tan \tilde{\alpha} + k\,\tilde{\alpha} - \zeta = 0 \qquad (4)$$

the iteration process is defined by

$$\tilde{\alpha}_{i+1} = \tilde{\alpha}_i - \left(\frac{F}{\partial F/\partial \tilde{\alpha}}\right)_i \qquad (5)$$

where

$$\frac{\partial F}{\partial \tilde{\alpha}} = k + 1 + \tilde{\alpha} \left[-2\,\zeta\, k + \tilde{\alpha} \left(1 - \frac{4}{3} k\,\zeta\,\tilde{\alpha}\right)\right] \qquad (6)$$

$$\tilde{\alpha}_o = \frac{\zeta}{k + 1} \qquad (7)$$

which is an approximate solution of equation (3) for small $\tilde{\alpha}$ and ζ.

SUBROUTINE AUXIL

PURPOSE: PRINT AUXILIARY INFORMATION FROM THE DATA GENERATOR

SUBROUTINES CALLED: AECEQ ECLIP EPHEM EQUATR GEOG SUBSOL

COMMONS: DOPLER STATE TRAJ

LOCAL SYMBOLS

DJ	JULIAN DATE, EPOCH JANUARY 0, 1900
ECLGEQ	TRANSFORMATION FROM ECLIPTIC TO GEOCENTRIC EQUATORIAL
EN	ECLIPTIC UNIT VECTOR NORMAL TO ENTRY PLANE
EPSC	SPACECRAFT GEOCENTRIC ECLIPTIC STATE
GEQPEQ	TRANSFORMATION FROM GEOCENTRIC EQUATORIAL TO PLANETOCENTRIC EQUATORIAL
HPE	HELIOCENTRIC ECLIPTIC STATE OF THE EARTH
HPP	HELIOCENTRIC ECLIPTIC STATE OF THE TARGET PLANET
PECSSO	TRANSFORMATION FROM PLANETOCENTRIC ECLIPTIC TO SUB-SOLAR ORBITAL
PLEQGF	TRANSFORMATION FROM PLANETOCENTRIC EQUATORIAL TO PLANETOCENTRIC GEOGRAPHICAL
PLSC	SPACECRAFT PLANETOCENTRIC ECLIPTIC STATE
PPE	PLANETOCENTRIC ECLIPTIC STATE OF THE EARTH
PSI	COMMUNICATION ANGLE
RLONG	LONGITUDE GROUND TRACE RELATIVE TO REFERENCE PLANE
RPLEQ	PLANETOCENTRIC EQUATORIAL SPACECRAFT STATE
RSS	SPACECRAFT STATE RELATIVE TO SUB-SOLAR ORBITAL OR PLANETOCENTRIC GEOGRAPHICAL PLANES
THETA	LATITUDE GROUND TRACE RELATIVE TO REFERENCE PLANE
XNU	ANGLE BETWEEN THE ENTRY PLANE AND PLANE OF THE SKY

USED/COMMN--- CARCOR DATEJ ECLINC ECLONG NTP RAD TC TZERO XN

WRITTEN --- PSI RLONG THETA XNU

AUXIL Analysis

Subroutine AUXIL computes the following auxiliary information:

1. Latitude and longitude ground trace relative to three coordinate systems:
    a. Planetocentric equatorial,
    b. Subsolar orbital-plane,
    c. Planetocentric geographical;
2. Communication angle;
3. Angle between the entry plane and the plane of the sky.

Given the spacecraft position components (x,y,z) relative to an arbitrary orthogonal coordinate system, the latitude and longitude are given by the following equations:

a. Latitude (relative to xy-plane)

$$\theta = \tan^{-1}\left(\frac{z}{\sqrt{x^2 + y^2}}\right)$$

b. longitude (relative to x-axis)

$$\lambda = \tan^{-1}(y/x)$$

The communication angle ψ is defined as the angle between the spacecraft and earth position vectors relative to the center of the target planet. Thus

$$\psi = \cos^{-1}\left[\frac{\vec{r} \cdot \left(\vec{r}_e - \vec{r}_p\right)}{|\vec{r}| \cdot |\vec{r}_e - \vec{r}_p|}\right] \quad , \qquad 0 \leq \psi \leq \pi$$

where $\vec{r}$ is the spacecraft position relative to the target planet, and $\vec{r}_e$ and $\vec{r}_p$ are the position vectors of the earth and the target planet, respectively, relative to the sun.

The angle η between the entry plane and the plane of the sky is defined as the angle between the normals of each plane. The unit vector $\vec{e}_n$ normal to the entry plane is given by

$$\vec{e}_n = \begin{bmatrix} \sin i_\varepsilon \ \sin \Omega_\varepsilon \\ -\sin i_\varepsilon \ \cos \Omega_\varepsilon \\ \cos i_\varepsilon \end{bmatrix}$$

relative to the planetocentric ecliptic system, where inclination i_ε and longitude of the ascending node Ω_ε define the orientation of the entry plane relative to the same system (see subroutine ECLIP). The plane of the sky is defined as the plane perpendicular to the range vector $\vec{\rho}$ from the earth to the spacecraft. The unit vector normal to this plane is

$$\vec{e}_\rho = \frac{\vec{\rho}}{\rho}$$

Then

$$\eta = \cos^{-1} \left(\vec{e}_\rho \cdot \vec{e}_n \right)$$

$$0 \le \eta \le \pi$$

```
SUBROUTINE BEGIN

PURPOSE:     RESETS COMMON VARIABLES FOR USE BY LTRCON

LOCAL SYMBOLS:        NONE

SET/COMMN---ACCT      C         CDTBL     DELT      HITGND    ICNTR
            LTR1      LTR2      MACH      MASS      MODE      PARACH
            REDRR1    REDRR2    RHO       RR        TC        TEMP
            TEND      TERHT     TSTEP     XS        XM        XN
            XSTEP     ZG        ZMM       ZSTEP
```

BEGIN Analysis

BEGIN resets common variables prior to trajectory reconstruction, which may have been changed by the data generator. BEGIN is called by subroutine SETUP prior to reading input data for the reconstructor.

```
SUBROUTINE BLK DATA

PURPOSE :     INITIALIZES COMMON VARIALES FOR LATER USE BY DATGEN


COMMONS : OBSERV    TRAJ      ATMS      GY          ATTT      TER
          SIZE

LOCAL SYMBOLS:      NONE


LOADED     ---  ACCT      AGAM      AQUANT    AR        AROTBL    ATMCSS
                BKTBL     BTBL      C         CDTBL     CGMW      DELT
    DIA         DT        EPSM      ETA       GAMTBL    GO        GQUANT
    HITGND      ICNTR     LTR1      LTR2      MACH      MASS      MODE
    MU          NACCEL    NGYRO     NMPTS     NTPTS     OMEG      PARACH
    QSALT       QSDT      QSMCHG    QST       RAD       REDRR1    REDRR2
    RHO         RI        RM        RR        SA        SALT      SLAT
    SLON        SDP       TC        TDIFF     TEMP      TEND      TERHT
    TF          TH        TSTEP     THTQA     TD        TR        VXQA
    VZQA        VMASS     VSA       VDIA      VRI       WDTBL     XD
    XG          XM        XMFH      XMFW      XN        XSTEP     ZG
    ZMM         ZSTEP
```

BLØCK DATA Analysis

Common variables are preset by data statements for use in the data generator (DATGEN). The variables are reinitialized in subroutine BEGIN for use in the reconstructor (LTRCØN). For a general description of storage in ARØTBL, see subroutine DTAB.

```
SUBROUTINE CONVRT

PURPOSE :    CONVERTS A VECTOR OF INTERNAL VALUES AND STORES
             INTO AN OUTPUT VECTOR


ENTRY PARAMETERS
          A       VECTOR OF INTERNAL PROGRAM VALUES

          B       OUTPUT VECTOR OF CONVERTED VALUES

          N       LOGIC VARIABLE TO CONTROL CONVERSION


COMMONS : TRAJ

LOCAL SYMBOLS          NONE

USED/COMMN--- RAD
```

SUBROUTINE COPY

PURPOSE : SET ONE MATRIX EQUAL TO ANOTHER

ENTRY PARAMETERS

NCZ	NUMBER OF COLUMNS IN Z MATRIX
NRZ	NUMBER OF ROWS IN Z MATRIX
W	MATRIX TO BE COPIED
Z	MATRIX WHICH IS SET EQUAL TO W MATRIX

LOCAL SYMBOLS

I	INDEX
N	PRODUCT OF NRZ AND NCZ

SUBROUTINE CORMAT

PURPOSE : COMPUTE A MATRIX OF CORRELATION COEFFICIENTS FROM A COVARIANCE MATRIX

ENTRY PARAMETERS

A	COVARIANCE MATRIX (N X N)
B	MATRIX WHOSE DIAGONAL ELEMENTS ARE THE SQUARE ROOTS OF THE CORRESPONDING ELEMENTS OF A AND WHOSE OFF-DIAGONAL ELEMENTS ARE THE CORRELATION COEFFICIENTS OF THE CORRESPONDING ELEMENTS OF A
N	DIMENSION OF A AND B (N X N)

LOCAL SYMBOLS

I	INDEX
II	INDEX OF DIAGONAL ELEMENT OF I-TH ROW
J	INDEX
JJ	INDEX OF DIAGONAL ELEMENT OF J-TH COLUMN
K	INDEX OF THE IJ-TH ELEMENT

SUBROUTINE CORR

PURPOSE : COMPUTE CORRELATION COEFFICIENTS FOR OFF-DIAGONAL BLOCK OF A PARTITIONED COVARIANCE MATRIX

ENTRY PARAMETERS

A	DIAGONAL BLOCK OF COVARIANCE MATRIX WHERE ROWS CORRESPOND TO THE ROWS OF C
B	DIAGONAL BLOCK OF COVARIANCE MATRIX WHOSE COLUMNS CORRESPOND TO THE COLUMNS OF C
C	OFF-DIAGONAL BLOCK OF COVARIANCE MATRIX
D	MATRIX WHOSE ELEMENTS ARE THE CORRELATION COEFFICIENTS OF THE CORRESPONDING ELEMENTS OF C
N1	NUMBER OF ROWS OF C
N2	NUMBER OF COLUMNS OF C

SUBROUTINES CALLED: COPY

LOCAL SYMBOLS

I	INDEX
J	INDEX
N	NUMBER OF ELEMENTS IN C
X	SQUARE ROOT OF DIAGONAL ELEMENT OF COVARIANCE MATRIX

CORR Analysis

CORR computes the correlation coefficient corresponding to elements of an off-diagonal block of a partitioned covariance matrix.

Let the covariance matrix be partitioned as

$$P = \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & A & \cdot & C & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & B & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$$

where A and B are diagonal blocks and C is an off-diagonal block having rows and columns in common with A and B respectively. The matrix whose elements are the correlation coefficient of the corresponding elements of C is given by

$$D_{ij} = \frac{C_{ij}}{\sqrt{A_{ii} B_{jj}}} \quad .$$

SUBROUTINE CORRD

PURPOSE : COMPUTE THE CORRELATION COEFFICIENTS FOR THE OFF-DIAGONAL BLOCK OF A PARTITIONED COVARIANCE MATRIX

ENTRY PARAMETERS

A	DIAGONAL BLOCK OF COVARIANCE MATRIX WHOSE ROWS CORRESPOND TO THE ROWS OF C
B	ELEMENTS OF DIAGONAL BLOCK OF COVARIANCE MATRIX WHOSE COLUMNS CORRESPOND TO THE COLUMNS OF C
C	OFF-DIAGONAL BLOCK OF COVARIANCE MATRIX
D	MATRIX WHOSE ELEMENTS ARE THE CORRELATION COEFFICIENTS OF THE CORRESPONDING ELEMENTS OF C
N1	NUMBER OF ROWS OF C
N2	NUMBER OF COLUMNS OF C

SUBROUTINES CALLED: COPY

LOCAL SYMBOLS

I	INDEX
J	INDEX
N	NUMBER OF ELEMENTS OF C
X	SQUARE ROOT OF DIAGONAL ELEMENT OF COVARIANCE MATRIX

CORRD Analysis

CORRD computes the correlation coefficients corresponding to elements of an off-diagonal block of a partitioned covariance matrix when the diagonal block having columns corresponding to the off-diagonal block is diagonal.

Let the covariance matrix be partitioned as

$$P = \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & A & \cdot & C & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & B & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix} , \; B = \text{diag } (b_{ij} \cdots b_{n_2})$$

where A and B are diagonal blocks and C is an off-diagonal block having rows and columns in common with A and B respectively. The matrix where elements are the correlation coefficients of the corresponding elements of C is given by

$$D_{ij} = \frac{C_{ij}}{\sqrt{A_{ii} \, b_j}} \quad .$$

```
SUBROUTINE DATGEN

PURPOSE :      EXECUTIVE CONTROL FOR DATA GENERATOR


SUBROUTINES CALLED: ALTFILE    DERIV1     OBSM1      PRINT1     RKUTDG
           SENSOR     SETUP1

COMMONS : ACCEL      INTCOM     TRAJ       QMPTI      LOGMOD     PHASE

LOCAL SYMBOLS
        NALT         DUMMY CALL ARGUMENT

        NC           ITERATIVE COUNTER FOR PRINTOUT

        UPDAIT       DUMMY CALL ARGUMENT


USED/COMMN--- DT         HITGND     ICNTR      IPHAS      QSALT      QSDT
              TC         TF

WRITTEN   --- ACCLX      ACCLZ      MEASS      MWT        PRES       RHO
              TC         TEMP       XN

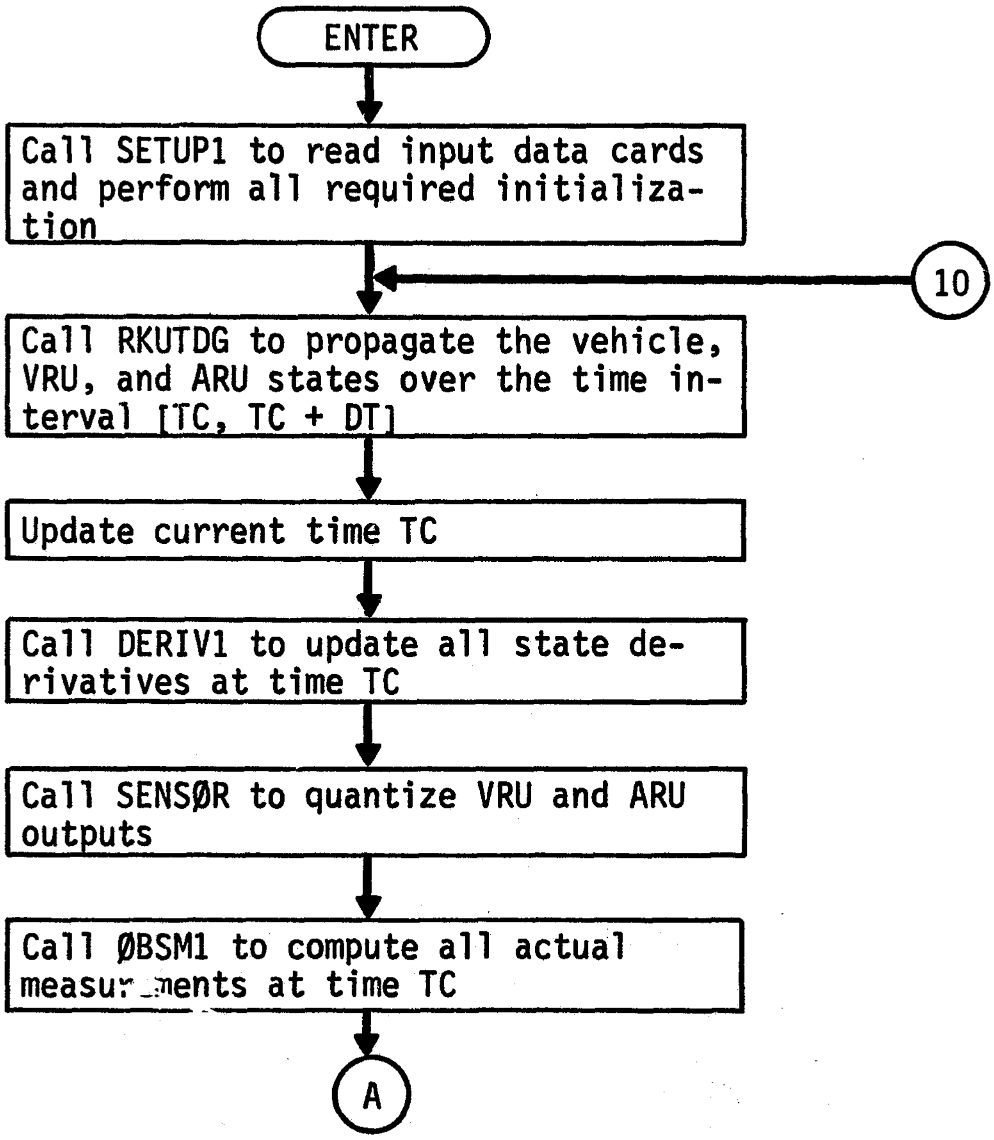
SET/COMMON--- TC         TD         TR         QSMCHG     QST        DT

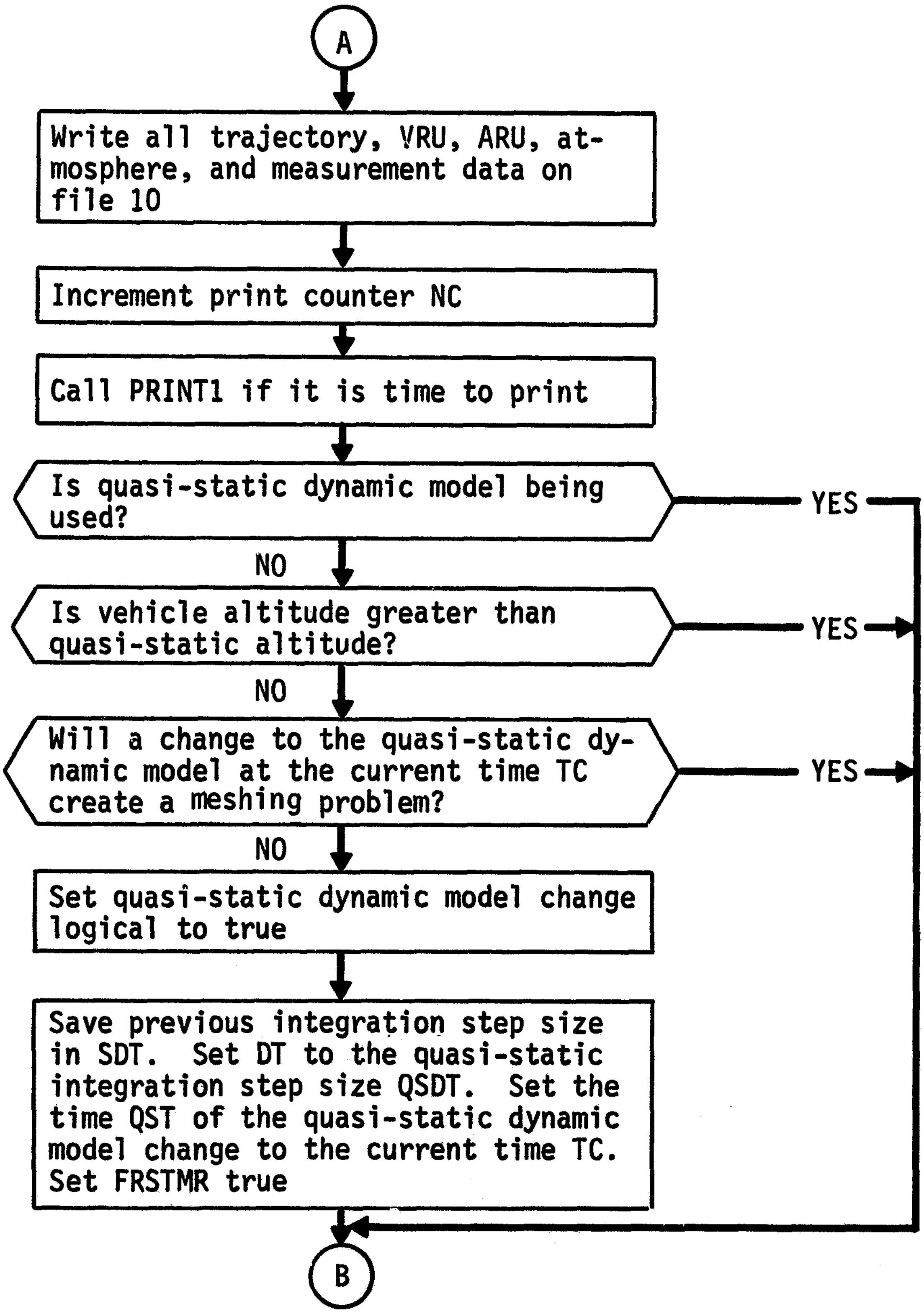
LOADED    --- NC
```

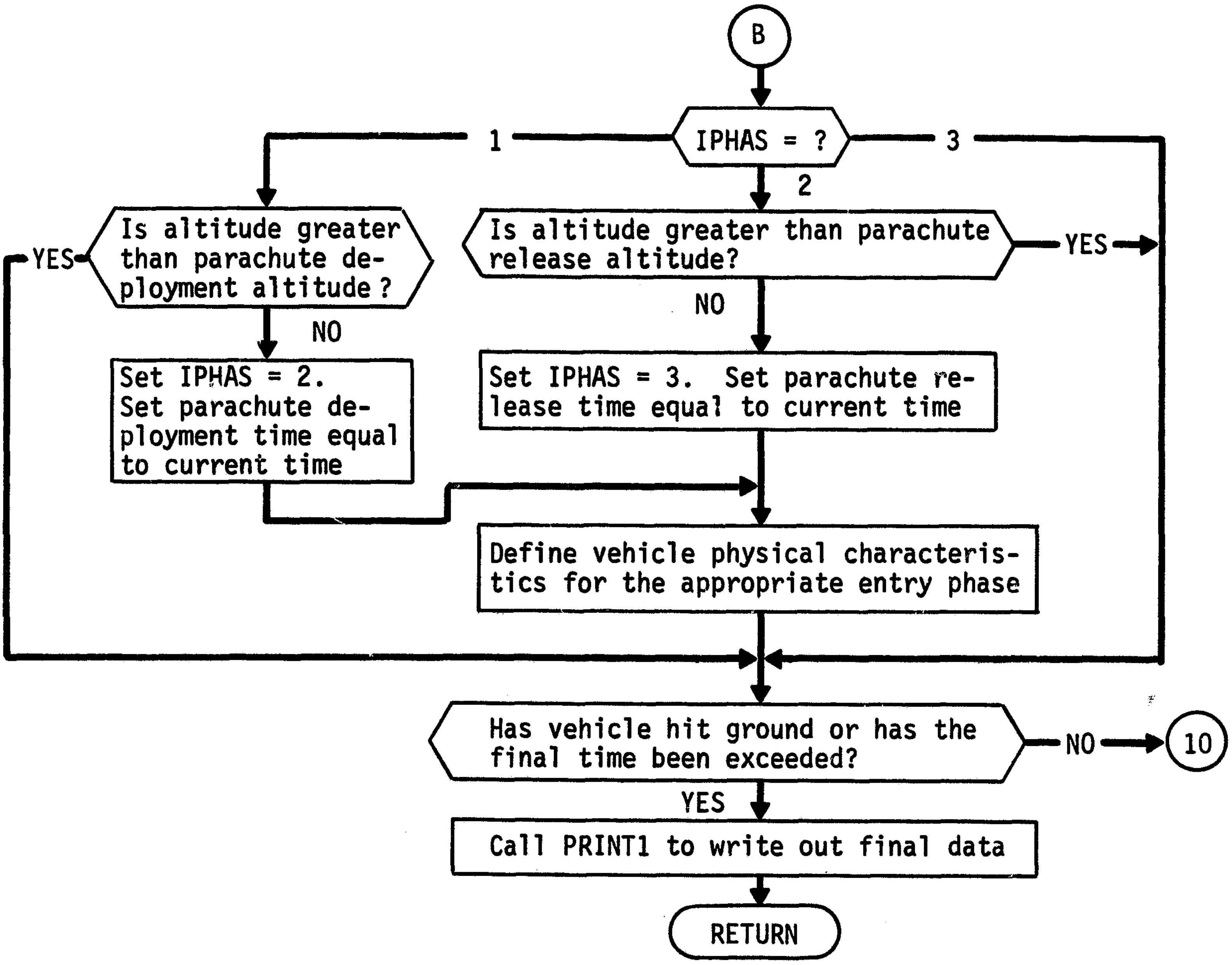
DATGEN Analysis

Subroutine DATGEN is the executive subroutine for the LTR data generator and controls the entire computational flow for actual trajectory propagation, actual atmosphere parameter computation, actual measurement computation, and printout.

DATGEN Flow Chart




A
Write all trajectory, VRU, ARU, atmosphere, and measurement data on file 10
Increment print counter NC
Call PRINT1 if it is time to print
Is quasi-static dynamic model being used?
YES
NO
Is vehicle altitude greater than quasi-static altitude?
YES
NO
Will a change to the quasi-static dynamic model at the current time TC create a meshing problem?
YES
NO
Set quasi-static dynamic model change logical to true
Save previous integration step size in SDT. Set DT to the quasi-static integration step size QSDT. Set the time QST of the quasi-static dynamic model change to the current time TC. Set FRSTMR true
B


B
IPHAS = ?
1
2
3
Is altitude greater than parachute deployment altitude ?
YES
NO
Set IPHAS = 2. Set parachute deployment time equal to current time
Is altitude greater than parachute release altitude?
YES
NO
Set IPHAS = 3. Set parachute release time equal to current time
Define vehicle physical characteristics for the appropriate entry phase
Has vehicle hit ground or has the final time been exceeded?
NO
10
YES
Call PRINT1 to write out final data
RETURN

SUBROUTINE DERIV1

PURPOSE : COMPUTE STATE DERIVATIVES FOR DATA GENERATOR

ENTRY PARAMETERS

T	TRAJECTORY TIME AT WHICH DERIVATIVES ARE DESIRED
UPDAIT	NOT CURRENTLY USED
XNEW	VEHICLE STATE VECTOR AT TIME T

SUBROUTINES CALLED: ATMDAT DTAB

COMMONS : ACCEL TRAJ DET DOPLER QMPTI PHASE

LOCAL SYMBOLS

AERO	AERODYNAMIC FORCE COEFFICIENTS
ALF	ABSOLUTE VALUE OF ANGLE OF ATTACK
CAE	COSINE OF ALPH PLUS EPS
CGAM	COSINE OF GAM
FE	PERTURBED VALUE OF VEHICLE DOWN RANGE ANGLE
GAM	PERTURBED VALUE OF VEHICLE FLIGHT PATH ANGLE
H	PERTURBED VALUE OF VEHICLE ALTITUDE
OMG	PERTURBED VALUE OF VEHICLE ANGULAR VELOCITY
RADIUS	DISTANCE FROM CENTER OF PLANET TO VEHICLE
SADP	VEHICLE REFERENCE AREA TIMES DYNAMIC PRESSURE
SAE	SINE OF ALPH PLUS EPS
SGAM	SINE OF GAM
THT	PERTURBED VALUE OF VEHICLE ATTITUDE ANGLE
V	PERTURBED VALUE OF VEHICLE VELOCITY
VA	ATMOSPHERE VELOCITY
X	COMPUTED VRU OFFSET FROM CENTER OF GRAVITY ALONG X-AXIS
Z	COMPUTED VRU OFFSET FROM CENTER OF GRAVITY ALONG Z-AXIS
ZP	LOCATION OF CENTER OF PRESSURE ALONG Z-AXIS

```
USED/COMMN--- ACCLX     ACCLZ     AF        ALPH      AX        AY
              C         CA        CDELT1    CDELT2    CDELT3    CMQ
              CN        DIA       DP        DXN       EPS       GA
              MASS      MU        RHO       RI        RM        ROTNO
              SA        SDELT1    SDELT2    SS        VR        VW
              WDTBL     XG        XM        XP        ZG        ZM
              ZMM       ZN

SET/COMMON--- ACCLX     ACCLZ     AF        ALPH      AM        AX
              AY        CA        CMQ       CN        DP        DXN
              EPS       GA        MACH      VR        VW        WDTBL
              XP        ZM        ZN

FCT CALLED--- TAB       WINDV

FCT DFND  --- F
```

DERIV1 Analysis

Subroutine DERIV1 is the dynamic model subroutine used in the generation of the actual trajectory, actual VRU and ARU outputs, and actual atmospheric parameters. Subroutine DERIV1 computes derivatives of the variables h, v, γ, ϕ, θ, ω, v_x, v_z, A_θ, and p for use in the integration subroutine RKUTDG.

Certain preliminary calculations are required before the required derivatives can be evaluated. First, the local acceleration of gravity is computed from

$$g = \frac{\mu}{r^2} \tag{1}$$

where μ is the planet gravitational constant and r is the radial distance from the planet center. Atmosphere velocity v_a, vehicle relative velocity v_r, and the angle ε between the inertial velocity v and the relative velocity are computed from the following relations:

$$v_a = r\,\omega_n + v_w \tag{2}$$

$$v_r = \frac{v - v_a \cos\gamma}{\cos\varepsilon} \tag{3}$$

$$\varepsilon = \tan^{-1}\left[\frac{v_a \sin\gamma}{v - v_a \cos\gamma}\right] \tag{4}$$

where ω_n denotes the component of the planet rotational velocity in the entry plane. Angle of attack is given by

$$\alpha = \theta + \phi - \gamma - \varepsilon \tag{5}$$

Axial, normal, and parachute drag forces are given, respectively, by

$$A = -C_A\,q\,S \tag{6}$$

$$N = -C_N\,q\,S \tag{7}$$

$$F_d = C_D\,q\,S_D \tag{8}$$

The aerodynamic damping moment is computed from

$$M = C_{M_q} \omega d^2 q \, S/v_r \tag{9}$$

The equations of motion which constitute the dynamic model used to compute the actual entry trajectory are summarized below:

$$\dot{h} = v \sin \gamma \tag{10}$$

$$\dot{v} = -g \sin \gamma + \frac{A}{m} \cos (\alpha + \varepsilon) + \frac{N}{m} \sin (\alpha + \varepsilon) - \frac{F_d}{m} \cos \varepsilon \tag{11}$$

$$\dot{\gamma} = \left(\frac{v}{r} - \frac{g}{v}\right) \cos \gamma + \frac{1}{v} \left[\frac{A}{m} \sin (\alpha + \varepsilon) - \frac{N}{m} \cos (\alpha + \varepsilon) - \frac{F_d}{m} \cos \varepsilon\right] \tag{12}$$

$$\dot{\phi} = \frac{v}{r} \cos \gamma \tag{13}$$

$$\dot{\theta} = \omega \tag{14}$$

$$\dot{\omega} = \frac{1}{I} \Big[\left(z_p - z_g\right) A - \left(x_p - x_g\right) N + M + z_g F_d \cos \alpha - \left(x_g - x_d\right) F_d \sin \alpha \Big] \tag{15}$$

The parachute terms, of course, appear only when the parachute is deployed (IPHAS = 2).

The actual nongravitational acceleration experienced by the VRU is given by

$$\dot{v}_x = a_x \cos \delta_1 - a_z \sin \delta_1 \tag{16}$$

$$\dot{v}_z = a_x \sin \delta_2 + a_z \cos \delta_2 \tag{17}$$

The actual angular velocity experienced by the ARU is given by

$$\dot{A}_\theta = \omega \cos \delta_3 \tag{18}$$

The rate of change of ambient pressure is computed from

$$\dot{p} = -\rho g \dot{h} \tag{19}$$

which is just the time-differential form of the hydrostatic equation.

If the quasi-static dynamic model is to be used, equation (11) is replaced with

$$\dot{v} = 0 \tag{20}$$

and v is computed from the terminal velocity solution

$$v = \left[\frac{2m\ g\ |\sin\ \gamma|}{\rho\ \left(C_A\ S + C_D\ S_D\right)} \right] \tag{21}$$

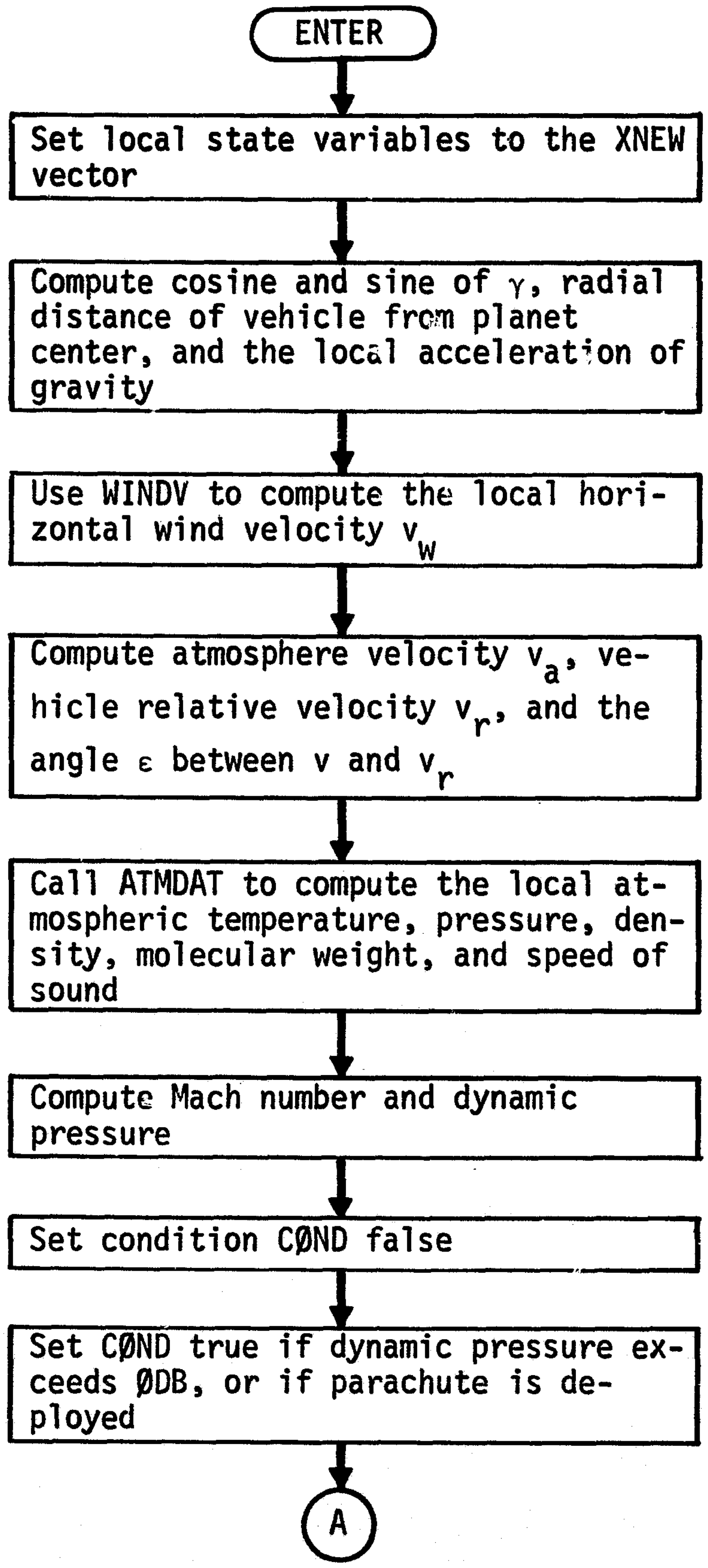
The logical variable CØND is set to true if either dynamic pressure exceeds ØDB or if the parachute is deployed. Whenever CØND is true, the angle of attack and the rotational state are computed as follows:

$$\alpha = 0 \tag{22}$$

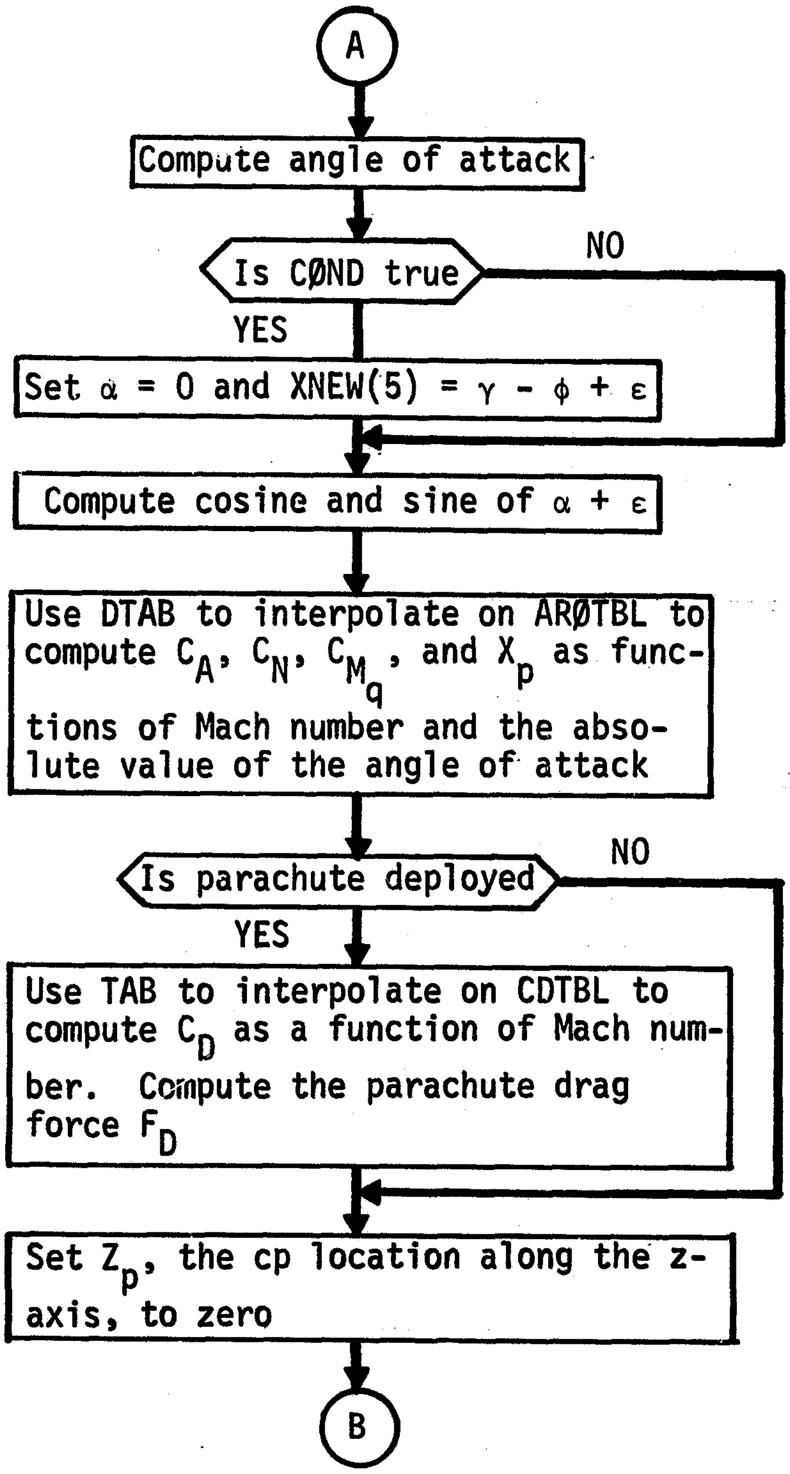
$$\theta = \gamma - \phi + \varepsilon \tag{23}$$

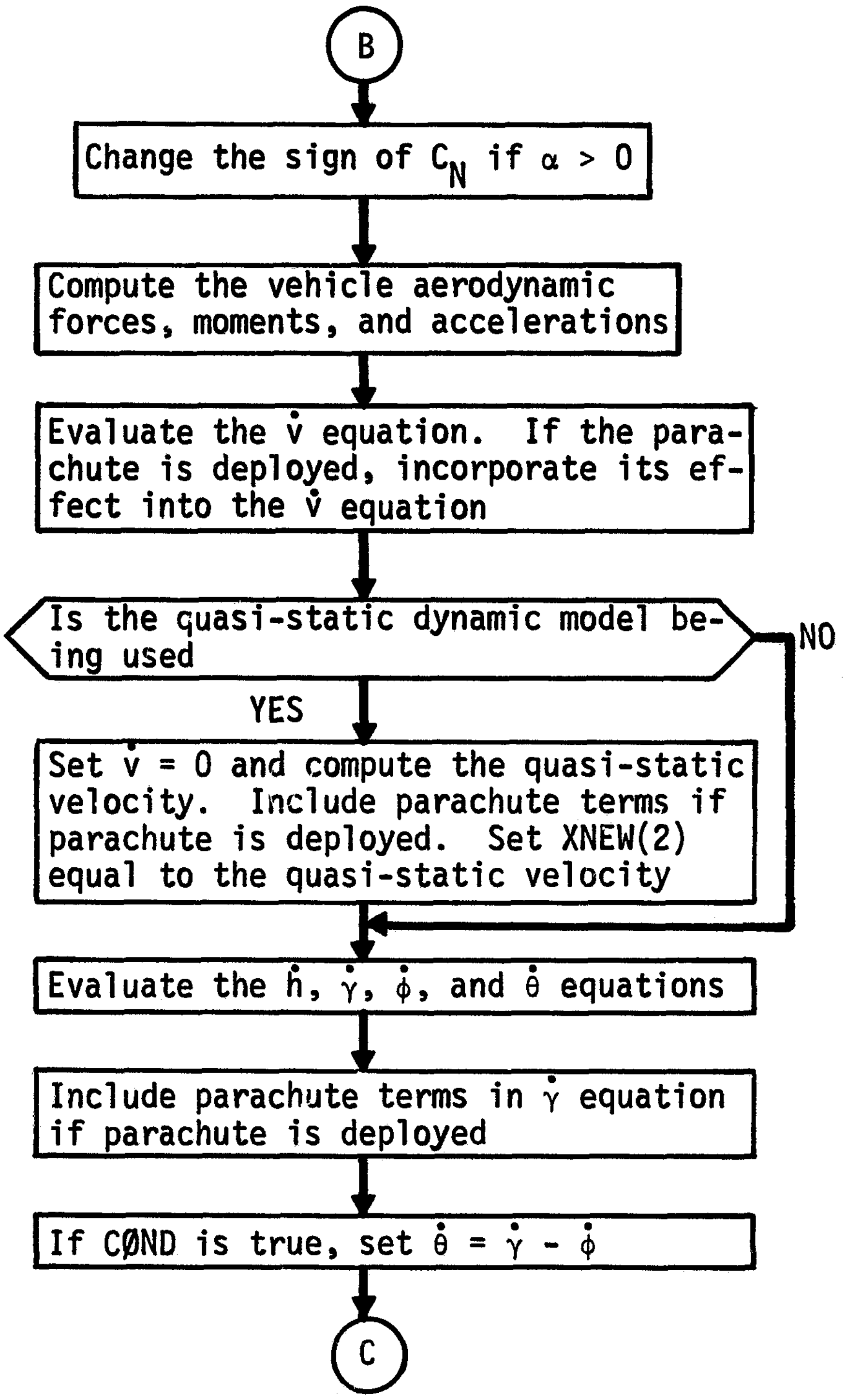
$$\omega = \dot{\gamma} - \dot{\phi} \tag{24}$$

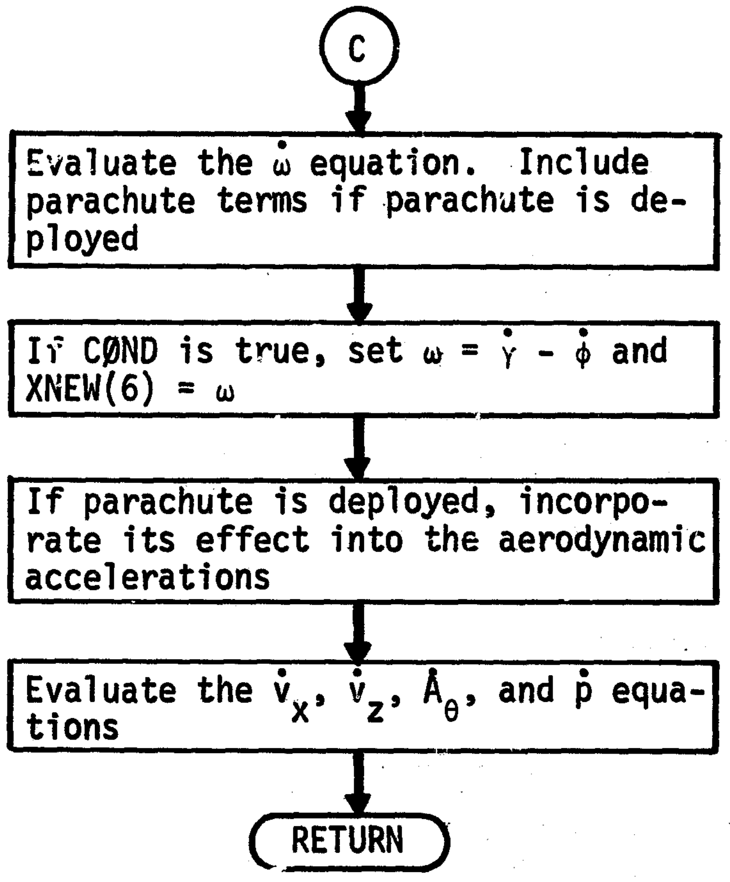
DERIV1 Flow Chart



DERIV1-5


A
Compute angle of attack
Is CØND true
NO
YES
Set α = 0 and XNEW(5) = $\gamma - \phi + \varepsilon$
Compute cosine and sine of $\alpha + \varepsilon$
Use DTAB to interpolate on ARØTBL to compute C_A, C_N, C_{M_q}, and X_p as functions of Mach number and the absolute value of the angle of attack
Is parachute deployed
NO
YES
Use TAB to interpolate on CDTBL to compute C_D as a function of Mach number. Compute the parachute drag force F_D
Set Z_p, the cp location along the z-axis, to zero
B


B
Change the sign of C_N if $\alpha > 0$
Compute the vehicle aerodynamic forces, moments, and accelerations
Evaluate the $\dot{v}$ equation. If the parachute is deployed, incorporate its effect into the $\dot{v}$ equation
Is the quasi-static dynamic model being used
NO
YES
Set $\dot{v} = 0$ and compute the quasi-static velocity. Include parachute terms if parachute is deployed. Set XNEW(2) equal to the quasi-static velocity
Evaluate the $\dot{h}$, $\dot{\gamma}$, $\dot{\phi}$, and $\dot{\theta}$ equations
Include parachute terms in $\dot{\gamma}$ equation if parachute is deployed
If CØND is true, set $\dot{\theta} = \dot{\gamma} - \dot{\phi}$
C


C
Evaluate the $\dot{\omega}$ equation. Include parachute terms if parachute is deployed
If CØND is true, set $\omega = \dot{\gamma} - \dot{\phi}$ and XNEW(6) = ω
If parachute is deployed, incorporate its effect into the aerodynamic accelerations
Evaluate the $\dot{v}_x$, $\dot{v}_z$, $\dot{A}_\theta$, and $\dot{p}$ equations
RETURN

SUBROUTINE DERIV3

PURPOSE : COMPUTE MODE 8 VEHICLE STATE DERIVATIVES

ENTRY PARAMETERS

T	TRAJECTORY TIME (NOT CURRENTLY USED)
UPDAIT	LOGICAL TO CONTROL UPDATING OF VEHICLE STATE VECTOR
XNEW	VEHICLE STATE VECTOR AT TIME T

SUBROUTINES CALLED: ATMDAT DTAB

COMMONS : TRAJ GY INTCOM DOPLER LOGMOD PHASE

LOCAL SYMBOLS

AERO	AERODYNAMIC FORCE COEFFICIENTS
ALF	ABSOLUTE VALUE OF ANGLE OF ATTACK
CAE	COSINE OF ALPH PLUS EPS
CASA	CA TIMES SA
CGAM	COSINE OF GAM
DEPS	INTERMEDIATE VARIABLE TO COMPUTE ALPH
FE	PERTURBED VALUE OF VEHICLE DOWN RANGE ANGLE
GAM	PERTURBED VALUE OF VEHICLE FLIGHT PATH ANGLE
H	PERTURBED VALUE OF VEHICLE ALTITUDE
PARDE	INTERMEDIATE VARIABLE TO COMPUTE ALPH
RADIUS	DISTANCE FROM CENTER OF PLANET TO VEHICLE
SADP	VEHICLE REFERENCE AREA TIMES DYNAMIC PRESSURE
SAE	SINE OF ALPH PLUS EPS
SGAM	SINE OF GAM
V	PERTURBED VALUE OF VEHICLE VELOCITY
VA	ATMOSPHERE VELOCITY

```
USED/COMMN--- AF        AGY       ALPH      AX        AY        BGY
              C         CA        CMQ       CN        DIA       DP
              DT        DXN       EPS       GA        GB        GD
              GS        GYRO      IGYRO     MASS      MASSA     MU
              RHO       RI        RM        ROTNO     SA        SS
              TC        VR        VW        WDTBL     XG        XP
              ZG        ZM        ZN        IPHAS     QSMCHG

SET/COMMON--- AF        ALPH      AM        AX        AY        CA
              CMQ       CN        DP        DXN       EPS       GA
              IGYRO     MACH      MASSA     VR        VW        WDTBL
              XP        ZM        ZN

FCT CALLED--- TAP       WINDV

FCT DFND  --- F
```

DERIV3 Analysis

Surbourine DERIV3 is the filter dynamic model subroutine employed in the mode B reconstruction process. The primary purpose of DERIV3 is to evaluate the derivatives of the state variables h, v, γ, and ϕ for use in the integration subroutine RKUTL3 in the computation of both the nominal trajectory and the state transition matrix partitions. State transition matrices are computed by perturbing the relevant C_j's that appear in the DERIV3 equations.

Certain preliminary calculations are required before the derivatives of the state variables can be evaluated. The local acceleration of gravity is computed from

$$g = \frac{\mu}{r^2} \tag{1}$$

where μ is the planet gravitational constant and r is the radial distance from the planet center. Atmosphere velocity v_a, vehicle relative velocity v_r, and the angle ε between the inertial velocity v and the relative velocity are computed from the following relations:

$$v_a = r\ \omega_n + v_w \tag{2}$$

$$v_r = \frac{v - v_a \cos \gamma}{\cos \varepsilon} \tag{3}$$

$$\varepsilon = \tan^{-1}\left[\frac{v_a \sin \gamma}{v - v_a \cos \gamma}\right] \tag{4}$$

where ω_n denotes the component of the planet rotational velocity in the entry plane.

Angle of attack α is given by

$$\alpha = \theta + \phi - \gamma - \varepsilon \tag{5}$$

However, attitude angle θ is not available in the mode B reconstruction process since gyro measurements are not permitted in this mode. Thus, in mode B α is nominally set to zero. It is still necessary, however, to compute the perturbations in α resulting from perturbations in the state variables and other parameters in order to compute valid state transition matrix partitions. The perturbation $\delta\alpha$ is given by

$$\delta\alpha = \delta\theta + \delta\phi - \delta\gamma - \delta\varepsilon \tag{6}$$

where $\delta\theta = C_{140}$, $\delta\phi = C_{104}$, $\delta\gamma = C_{103}$, and

$$\delta\varepsilon = \frac{\sin^2 \varepsilon}{v_a^2 \sin^2 \gamma} [-v\ \omega_n \sin \gamma \cdot \delta h + (v \cos \gamma - v_a)\ v_a\ \delta\gamma - v_a \sin \gamma \cdot \delta v] \tag{7}$$

In this latter equation, which was derived by differentiating equation (4), $\delta h = C_{101}$ and $\delta v = C_{102}$.

Axial, normal, and parachute drag aerodynamic forces are given, respectively, by

$$A = - C_A\ q\ S \tag{8}$$

$$N = - C_N\ q\ S \tag{9}$$

$$F_d = C_D\ q\ S_D \quad . \tag{10}$$

The equations of motion that constitute the mode B filter dynamic model are summarized as

$$\dot{h} = v \sin \gamma \tag{11}$$

$$\dot{v} = -g \sin \gamma + \frac{A}{m} \cos (\alpha + \varepsilon) + \frac{N}{m} \sin (\alpha + \varepsilon) - \frac{F_d}{m} \cos \varepsilon \tag{12}$$

$$\dot{\gamma} = \left(\frac{v}{r} - \frac{g}{v}\right) \cos \gamma + \frac{1}{v} \left[\frac{A}{m} \sin (\alpha + \varepsilon) - \frac{N}{m} \cos (\alpha + \varepsilon) - \frac{F_d}{m} \sin \varepsilon\right] \tag{13}$$

$$\dot{\phi} = \frac{v}{r} \cos \quad . \tag{14}$$

The parachute terms, of course, appear only when the parachute is deployed (IPHAS = 2).

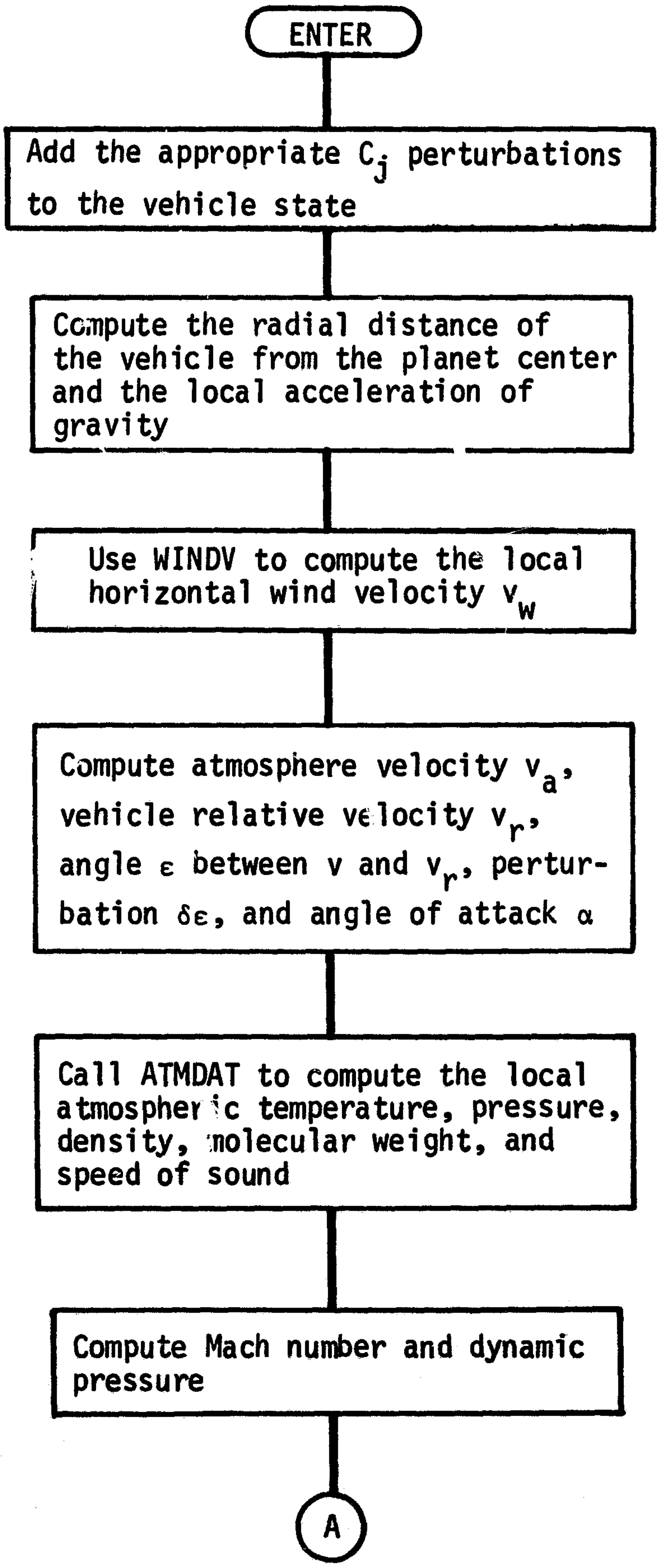
If the quasistatic dynamic model is to be used, equation (12) is replaced with

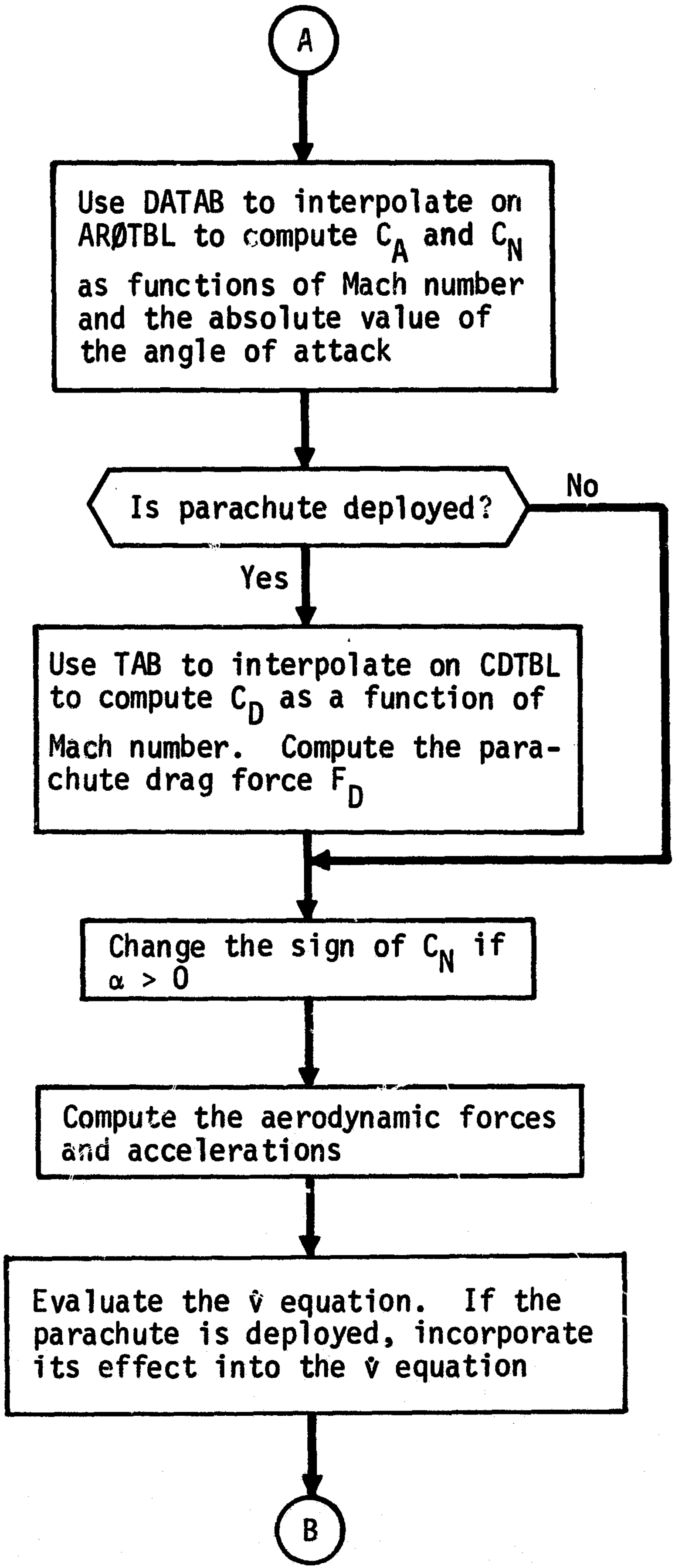
$$\dot{v} = 0 \qquad (15)$$

and v is computed from the terminal velocity solution

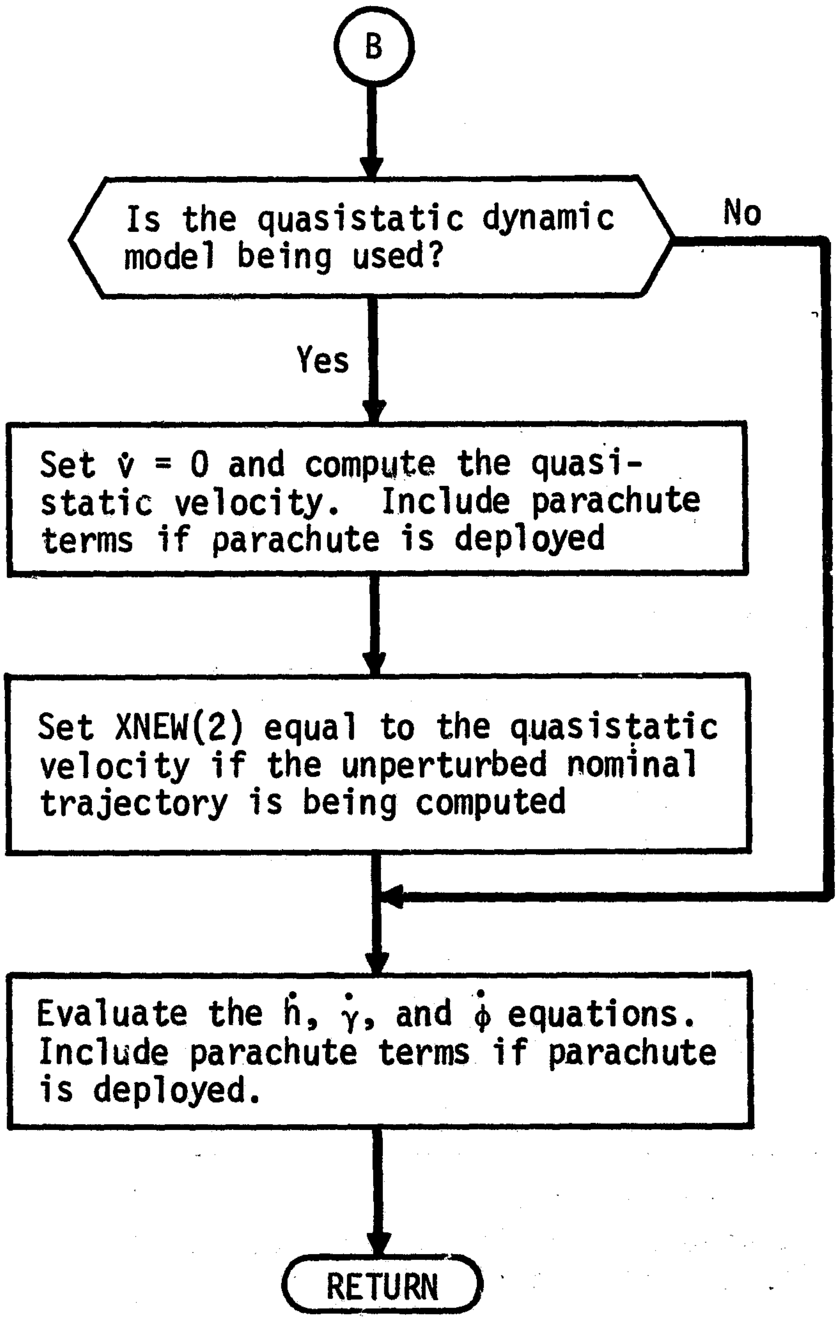
$$v = \left[\frac{2\ (m + C_{30})\ g\ |\sin \gamma|}{\rho\ (C_A\ S + C_D\ S_D)}\right]^{1/2} + C_{102} \qquad (16)$$

DERIV3 Flow Chart




A
Use DATAB to interpolate on ARØTBL to compute C_A and C_N as functions of Mach number and the absolute value of the angle of attack
Is parachute deployed?
No
Yes
Use TAB to interpolate on CDTBL to compute C_D as a function of Mach number. Compute the parachute drag force F_D
Change the sign of C_N if $\alpha > 0$
Compute the aerodynamic forces and accelerations
Evaluate the $\dot{v}$ equation. If the parachute is deployed, incorporate its effect into the $\dot{v}$ equation
B

DERIV3-6


B
Is the quasistatic dynamic model being used?
No
Yes
Set $\dot{v}$ = 0 and compute the quasistatic velocity. Include parachute terms if parachute is deployed
Set XNEW(2) equal to the quasistatic velocity if the unperturbed nominal trajectory is being computed
Evaluate the $\dot{h}$, $\dot{\gamma}$, and $\dot{\phi}$ equations. Include parachute terms if parachute is deployed.
RETURN

SUBROUTINE DERIVE

PURPOSE : COMPUTE MODE A VEHICLE STATE DERIVATIVES

ENTRY PARAMETERS

T	TRAJECTORY TIME AT WHICH DERIVATIVES ARE DESIRED
UPDAIT	LOGICAL TO CONTROL UPDATING OF VEHICLE STATE VECTOR
XNEW	VEHICLE STATE VECTOR AT TIME T

SUBROUTINES CALLED: ATMOSP

COMMONS : SMO TRAJ AX LOGCOM DET DERIV
OBSERV INTCOM AM GYRACC DOPLER LOGMOD
PHASE

LOCAL SYMBOLS

AXM	MEASURED AXIAL ACCELERATION
AZM	MEASURED NORMAL ACCELERATION
CAE	COSINE OF ALPH PLUS EPS
DOMGC	CALIBRATED ANGULAR ACCELERATION
DOMGM	MEASURED ANGULAR ACCELERATION
H	PERTURBED VALUE OF VEHICLE ALTITUDE
IALPHA	INDICATOR TO CONTROL ALPH COMPUTATION
OMGM	MEASURED ANGULAR VELOCITY
RADIUS	DISTANCE FROM CENTER OF PLANET TO VEHICLE
SAE	SINE OF ALPH PLUS EPS
THTM	MEASURED ALTITUDE ANGLE
X	COMPUTED VRU LOCATION ALONG X-AXIS
Z	COMPUTED VRU LOCATION ALONG Z-AXIS

```
USED/COMMN--- AA        ALPH      AXC       AZC       C         CDEL
              CDELT1    CDELT2    CGAM      DELT      DT        DXN
              EPS       FE        GA        GAM       IAA       MU
              MWTM      NACCEL    NGYRO     OMGC      PSIN      RHO
              RM        ROTNO     SDELT1    SDELT2    SGAM      SUBDL1
              TC        THETI     THTC      V         VA        XG
              XM        ZG        ZMM       IPHAS     QSMCHG

SET/COMMON--- ALPH      AXC       AZC       C         CDELT1    CDELT2
              CDELT3    CGAM      DXN       EPS       FE        GA
              GAM       IAA       MWT       OMGC      PRES      SDELT1
              SDELT2    SDELT3    SGAM      SUBDL1    THTC      V
              VA        VR

FCT CALLED--- WINDV

FCT DFND  --- F
```

DERIVE Analysis

Subroutine DERIVE is the filter dynamic model subroutine employed in the mode A reconstruction process. The primary purpose of DERIVE is to evaluate the derivatives of the state variables h, v, γ, ϕ, and p for use in the integration subroutine RKUT3 in computation of the nominal trajectory and ambient pressure and the state transition matrix partitions. State transition matrices are computed by perturbing the relevant C_j's that appear in the DERIVE equations.

Certain preliminary calculations are required before the derivatives of the state variables can be evaluated. The first computation concerns the calibration of cg and VRU offsets and VRU and ARU misalignments using the following equations:

$$\bar{x}_c = (x_m + C_{28}) - (x_g + C_{26}) \tag{1}$$

$$\bar{z}_c = (z_m + C_{29}) - (z_g + C_{27}) \tag{2}$$

$$\delta_{1_c} = \delta_1 - C_{55} \tag{3}$$

$$\delta_{2_c} = \delta_2 - C_{56} \tag{4}$$

$$\delta_{3_c} = \delta_3 - C_{63} \tag{5}$$

where x_m and z_m define the nominal VRU location; x_g and z_g, the nominal cg location; δ_1 and δ_2, the nominal VRU misalignment angles; δ_3, the nominal ARU misalignment; and C_{26}, C_{27}, C_{28}, C_{29}, C_{55}, C_{56}, and C_{63}, biases in all these quantities.

The measured VRU and ARU data are obtained from the AA(I, J, K) array, which contains the coefficients a_{ij} generated by the preprocessor smoothing process. Index I specifies the sensor type:

I = 1 : axial VRU;

I = 2 : normal VRU;

I = 3 : ARU.

Index J refers to the coefficient in the quadratic function that is fitted in a least-squares sense to five quantized data points (see Section II.D). Index K is the time index in the AA(I, J, K) array. The measured axial and normal VRU data are obtained from

$$a_{x_m} = a_{12} \tag{6}$$

$$a_{z_m} = a_{22} \tag{7}$$

The measured ARU data are obtained from

$$\theta_m = a_{31} \tag{8}$$

$$\omega_m = a_{32} \tag{9}$$

$$\dot{\omega}_m = 2\ a_{33} \quad . \tag{10}$$

If normal VRU data are not available, a_{z_m} and misalignment δ_2 are set to zero. In this situation it is no longer meaningful to treat the normal VRU scale factor C_{53} as a solve-for or consider parameters. For this reason C_{53} has a fixed value of 1. and cannot be perturbed. However, the normal VRU bias C_{54} can still be treated as a consider parameter representing the anticipated, but not measured, normal accelerations. Since these normal accelerations are not constant, C_{54} cannot be treated as a solve-for parameter when normal VRU data are not available. If ARU data are absent, ω_m, $\dot{\omega}_m$, and misalignment δ_3 are set to zero and the nominal angle of attack α is assumed to be zero.

The measured VRU and ARU data are calibrated for scale factor, bias, and misalignment errors using the following equations:

$$a_{x_c} = \frac{1}{\cos\left(\delta_{1_c} - \delta_{2_c}\right)} \left[\frac{a_{x_m} - C_{52}}{C_{51}} \cos \delta_{2_c} + \frac{a_{z_m} - C_{54}}{C_{53}} \sin \delta_{1_c}\right]$$

$$+ \omega_c^2 \bar{x}_c - \dot{\omega}_c \bar{z}_c \qquad (11)$$

$$a_{z_c} = \frac{1}{\cos\left(\delta_{1_c} - \delta_{2_c}\right)} \left[- \frac{a_{x_m} - C_{52}}{C_{51}} \sin \delta_{2_c} + \frac{a_{z_m} - C_{54}}{C_{53}} \cos \delta_{1_c}\right]$$

$$+ \omega_c^2 \bar{z}_c + \dot{\omega}_c \bar{x}_c \qquad (12)$$

$$\theta_c = \frac{1}{C_{124}} \left[\theta_m - C_{125} \left(t - t_o\right)\right] \qquad (13)$$

$$\omega_c = \frac{1}{C_{124}} \left(\omega_m - C_{125}\right) \qquad (14)$$

$$\dot{\omega}_c = \frac{\dot{\omega}_m}{C_{124}} \quad . \qquad (15)$$

The local acceleration of gravity is computed from

$$g = \frac{\mu}{r} \qquad (16)$$

where μ is the planet gravitational constant and r is the radial distance from the planet center. Atmosphere velocity v_a, vehicle relative velocity v_r, and the angle ε between the inertial velocity v and the relative velocity are computed from the following relations:

$$v_a = r\, \omega_n + v_w \qquad (17)$$

$$v_r = \frac{v - v_a \cos \gamma}{\cos \varepsilon} \tag{18}$$

$$\varepsilon = \tan^{-1} \left[\frac{v_a \sin \gamma}{v - v_a \cos \gamma} \right] \tag{19}$$

where ω_n denotes the component of the planet rotational velocity in the entry plane.

Angle of attack α is given by

$$\alpha = \theta_c + \theta_o + \phi - \gamma - \varepsilon + C_{140} \tag{20}$$

where θ_o is the initial attitude angle and the calibrated attitude measurement θ_c represents the change in attitude since initial time t_o. Parameter C_{140} represents the initial attitude error. When nominal α is chosen to be zero, as it is when ARU data are not available or when the parachute is deployed, perturbations in α resulting from perturbations in the state variables and other parameters are computed from

$$\delta\alpha = \delta(\theta_c + \theta_o) + \delta\phi - \delta\gamma - \delta\varepsilon \tag{21}$$

where $\delta(\theta_c + \theta_o) = C_{140}$, $\delta\phi = C_{104}$, $\delta\gamma = C_{103}$, and

$$\delta\varepsilon = \frac{\sin^2 \varepsilon}{v_a^2 \sin^2 \gamma} [- v \omega_n \sin \gamma \cdot \delta h + (v \cos \gamma - v_a) v_a \delta\gamma - v_a \sin \gamma \cdot \delta v] \quad . \tag{22}$$

In this latter equation, which was derived by differentiating equation (19), $\delta h = C_{101}$ and $\delta v = C_{102}$.

Subroutine ATMØSP is not called until significant axial aerodynamic deceleration has developed. Currently, ATMØSP is called when

$$a_{x_c} \leq - 0.5 \times 10^{-3} \text{ km/s}^2$$

in order to compute Mach number and atmospheric density and temperature.

The equations of motion that constitute the mode A filter dynamic model are summarized as

$$\dot{h} = v \sin \gamma \qquad (23)$$

$$\dot{v} = -g \sin \gamma + a_{x_c} \cos (\quad + \varepsilon) + a_{z_c} \sin (\alpha + \varepsilon) \qquad (24)$$

$$\dot{\gamma} = \left(\frac{v}{r} - \frac{g}{v}\right) \cos \gamma + \frac{1}{v} \left[a_{x_c} \sin (\alpha + \varepsilon) - a_{z_c} \cos (\alpha + \varepsilon)\right] \qquad (25)$$

$$\dot{\phi} = \frac{v}{r} \cos \gamma \qquad (26)$$

$$\dot{p} = - g \rho \dot{h} \quad . \qquad (27)$$

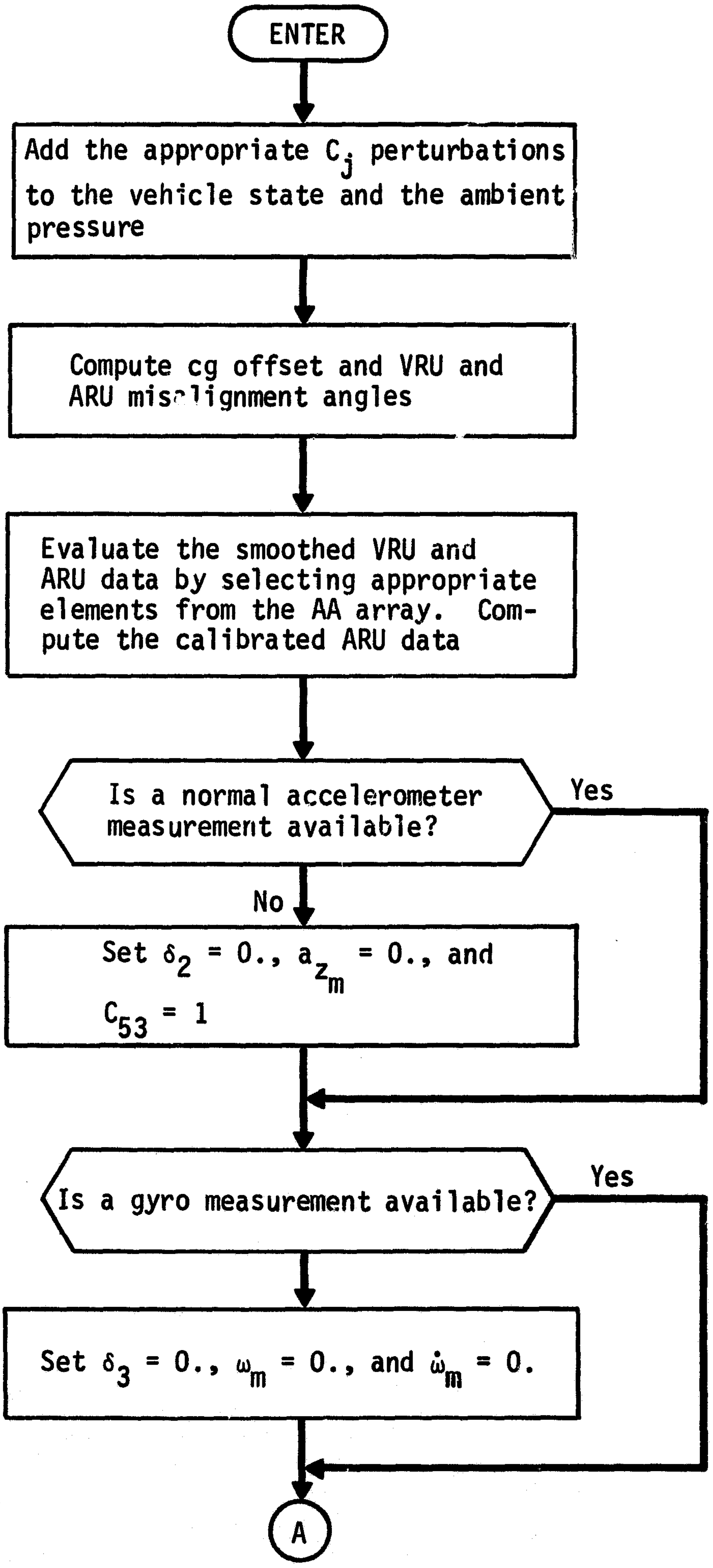
If the quasistatic dynamic model is to be used, equation (24) is replaced with

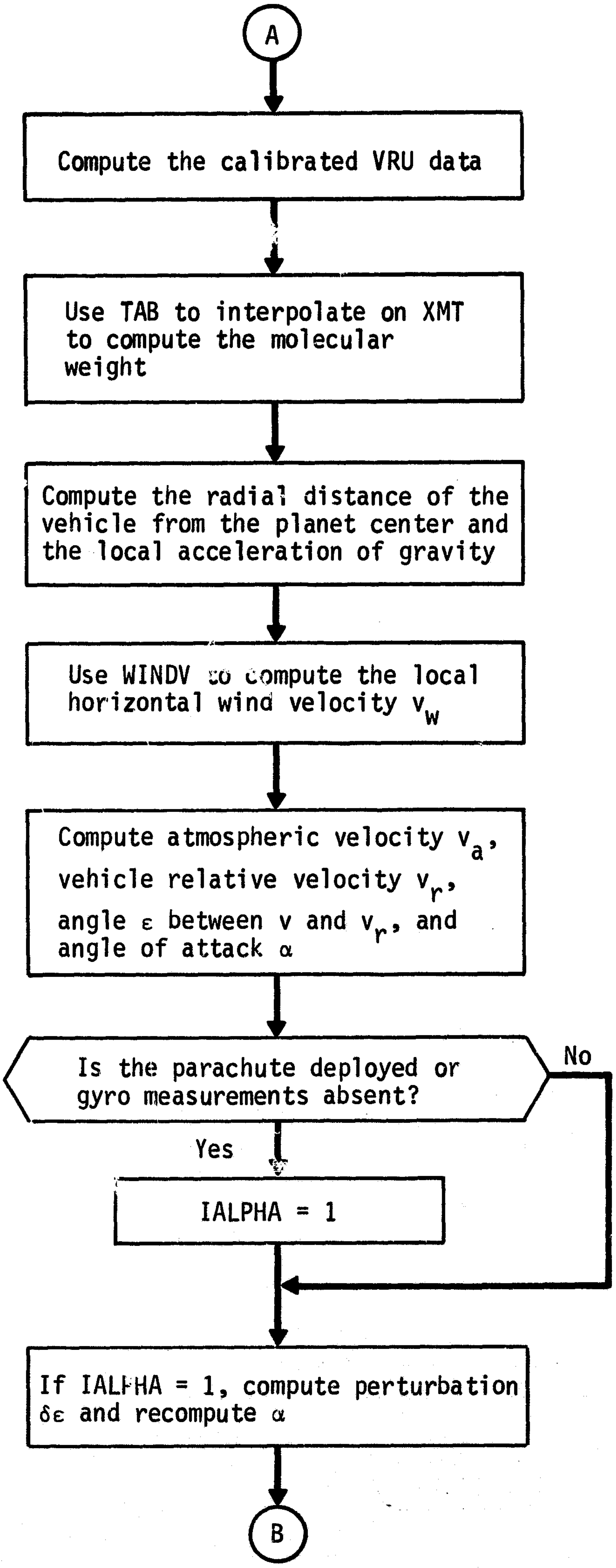
$$\dot{v} = 0 \qquad (28)$$

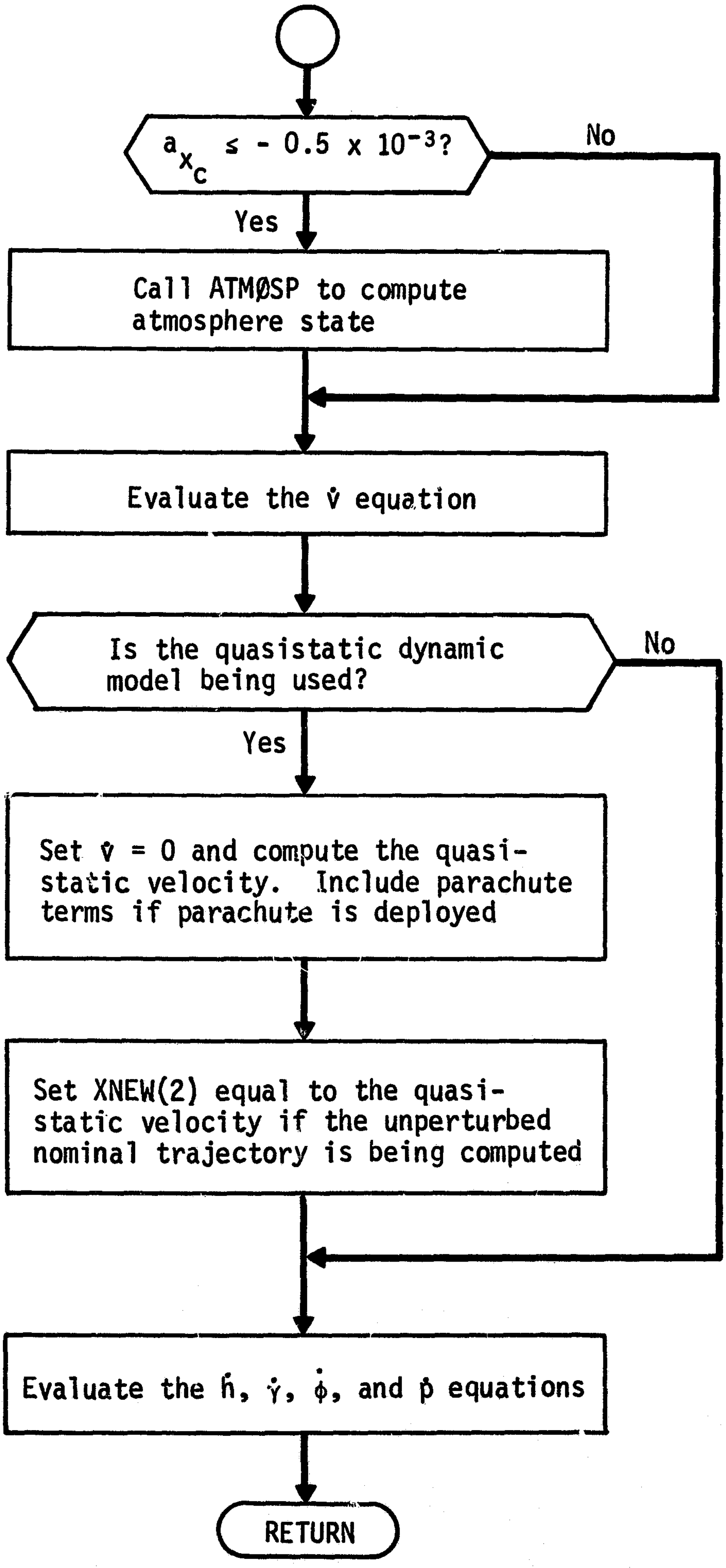
and v is computed from the terminal velocity solution

$$v = \left[\frac{2 (m + C_{30}) g |\sin \gamma|}{\rho (C_A S + C_D S_D)}\right]^{1/2} + C_{102} \quad . \qquad (29)$$

DERIVE Flow Chart




A
Compute the calibrated VRU data
Use TAB to interpolate on XMT to compute the molecular weight
Compute the radial distance of the vehicle from the planet center and the local acceleration of gravity
Use WINDV to compute the local horizontal wind velocity v_w
Compute atmospheric velocity v_a, vehicle relative velocity v_r, angle ε between v and v_r, and angle of attack α
Is the parachute deployed or gyro measurements absent?
No
Yes
IALPHA = 1
If IALPHA = 1, compute perturbation $\delta\varepsilon$ and recompute α
B


$a_{x_c} \leq -0.5 \times 10^{-3}$?
No
Yes
Call ATMØSP to compute atmosphere state
Evaluate the $\dot{V}$ equation
Is the quasistatic dynamic model being used?
No
Yes
Set $\dot{V}$ = 0 and compute the quasi-static velocity. Include parachute terms if parachute is deployed
Set XNEW(2) equal to the quasi-static velocity if the unperturbed nominal trajectory is being computed
Evaluate the $\dot{h}$, $\dot{\gamma}$, $\dot{\phi}$, and $\dot{p}$ equations
RETURN

SUBROUTINE DMULTT

PURPOSE : TO MULTIPLY A DIAGONAL MATRIX BY THE TRANSPOSE OF A RECTANGULAR MATRIX AND STORE INTO A RECTANGULAR MATRIX

ENTRY PARAMETERS

NCY	NUMBER OF COLUMNS OF Y MATRIX
ND	NUMBER OF DIAGONAL ELEMENTS OF X MATRIX
NRY	NUMBER OF ROWS OF Y MATRIX AND NUMBER OF COLUMNS OF Z MATRIX
X	DIAGONAL INPUT MATRIX
Y	RECTANGULAR INPUT MATRIX
Z	RECTANGULAR OUTPUT MATRIX (X TIMES Y TRANSPOSED)

LOCAL SYMBOLS

I	INDEX
J	INDEX
P	I-TH DIAGONAL ELEMENT OF X MATRIX

SUBROUTINE DTAB

PURPOSE : PERFORMS LINEARLY INTERPOLATED DOUBLE TABLE LOOKUP

ENTRY PARAMETERS

A	OUTPUT VECTOR OF INTERPOLATED VALUES (DEPENDENT VARIABLES)
LT	LENGTH OF EACH PARTITION OF TABLE WHENEVER NT.GT.1
NT	NUMBER OF ELEMENTS OF A TO BE CALCULATED
TABLE	INPUT TABLE OF BREAK POINTS AND COEFFICIENTS
X	FIRST INDEPENDENT VARIABLE
Y	SECOND INDEPENDENT VARIABLE

LOCAL SYMBOLS

COORD	POINTERS TO BREAKPOINTS NEAREST TO X AND Y, USED TO FIND N
FRAC	PER CENT DIFFERENCES BASED ON X AND Y, RESPECTIVELY. FRAC(1) IS USED TO FIND W1,W2 AND FRAC(2) TO FIND A(I)
I	INDEX
J	DO LOOP INITIALIZER
K	DO LOOP TERMINATOR
L	INDEX
N	INDEX TO FIND W1 AND W2
N1	INTEGER VALUE OF TABLE (1)
POINT	LOCAL VALUES OF X AND Y
W1	LOWER BOUND OF A(I)
W2	UPPER BOUND OF A(I)

DTAB Analysis

TABLE is a partitioned matrix, each submatrix containing:

1) N1 - The number of values in the X table;
2) N2 - The number of values in the Y table;
3) The N1 values of the X table;
4) The N2 values of the Y table;
5) The first N1 values of X versus Y;
6) The second N1 values of X versus Y;

•
•
•

7) The last (= N2) N1 values of X versus Y.

Thus, each partition contains N1 x N2 + N1 + N2 + 2 elements. If X1, X2 from 3) above are the bounds of X so X1.LE.X.LE.X2 and Y., Y2 from 4) above are the bounds of Y so Y1.LE.Y.LE.Y2, then W1 represents A(I) only if Y = Y1 and W2 represents A(I) only if Y = Y2. That is, W1 and W2 are lower and upper bounds of A(I), which are computed according to standard single table lookup schemes. A(I) is then computed by

$$A(I) = FRAC(2) * (W2 - W1) + W1$$

as in the standard formulae.

SUBROUTINE DYNOIZ

PURPOSE :   CURRENTLY SETS DYNAMIC NOISE MATRIX TO ZERO

COMMONS : COVARP   INTCOM

LOCAL SYMBOLS

I	INDEX
NN	NUMBER OF STATE VARIABLES SQUARED

USED/COMMN--- NS

SET/COMMON--- DYN

SUBROUTINE ECLIP

PURPOSE: TRANSFORM SPACECRAFT ALTITUDE, VELOCITY, FLIGHT PATH ANGLE, DOWNRANGE ANGLE, ETC. TO PLANETOCENTRIC ECLIPTIC POSITION AND VELOCITY COMPONENTS

ENTRY PARAMETERS

XPEC	SPACECRAFT PLANETOCENTRIC ECLIPTIC STATE COMPONENTS
XV	SPACECRAFT ALTITUDE, VELOCITY, FLIGHT PATH ANGLE, AND DOWNRANGE ANGLE

COMMONS: DOPLER TRAJ

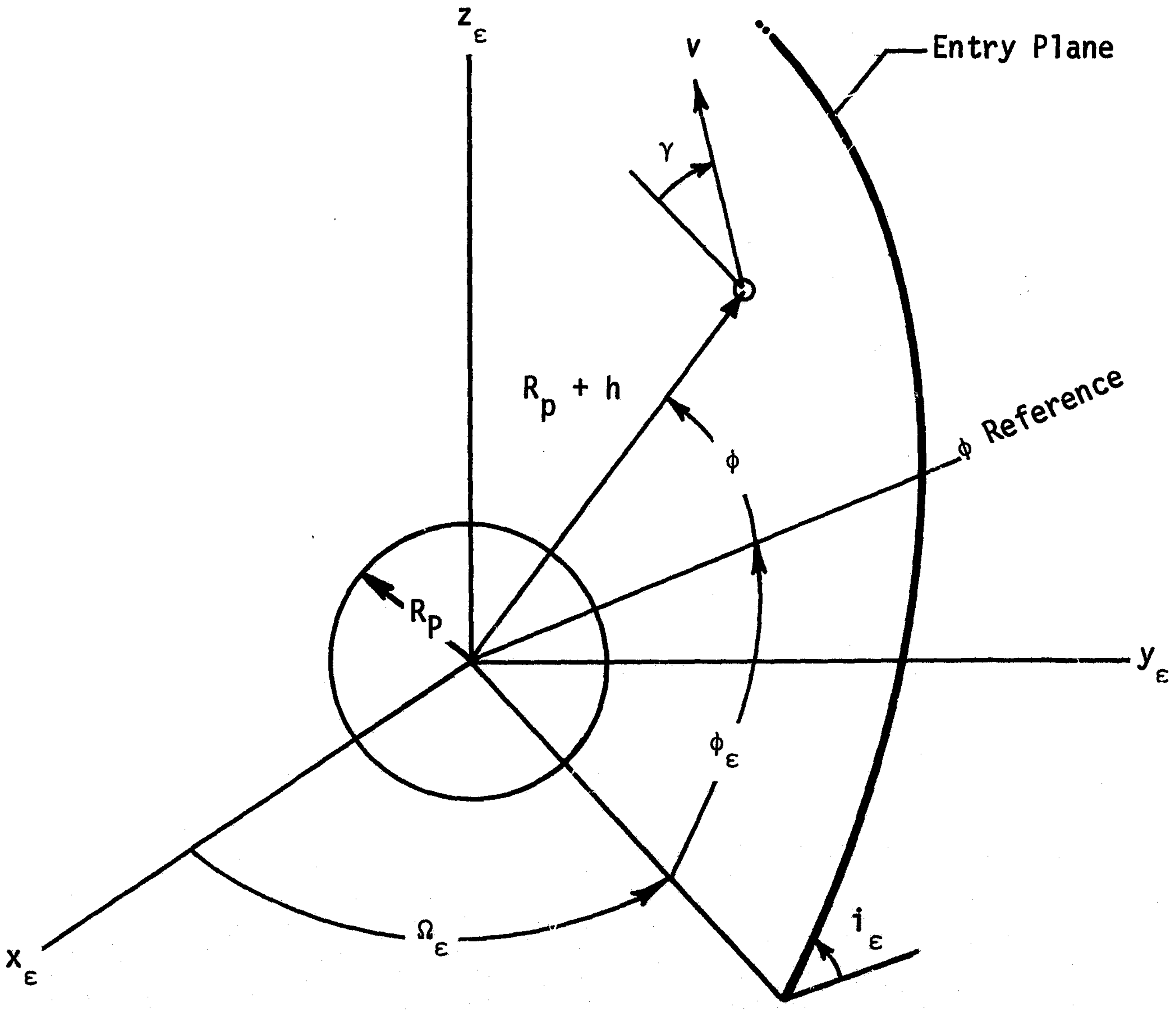
LOCAL SYMBOLS

COSEI	COSINE OF ENTRY PLANE INCLINATION
COSEL	COSINE OF ENTRY PLANE LONGITUDE OF ASCENDING NODE
COSG	COSINE OF GAMMA
GAMMA	AUXILIARY ANGLE
RMAG	SPACECRAFT PLANETOCENTRIC POSITION MAGNITUDE
SINEI	SINE OF ENTRY PLANE INCLINATION
SINEL	SINE OF ENTRY PLANE LONGITUDE OF ASCENDING NODE
SINT	SINE OF THETA
THETA	AUXILIARY ANGLE

USED/COMMN--- ECLINC ECLONG PHIR RM

ECLIP Analysis

Subroutine ECLIP transforms the standard LTR spacecraft state variables h, v, γ, $\phi + \phi_\varepsilon$, Ω_ε, and i_ε to planetocentric ecliptic Cartesian components r_x, r_y, r_z, v_x, v_y, and v_z. In the figure below x_ε y_ε z_ε denotes the planetocentric ecliptic coordinate system and R_p denotes the planet radius.



The transformation equations are summarized as:

$$r_x = r\,(\cos\theta \cos\Omega_\varepsilon - \sin\theta \cos i_\varepsilon \sin\Omega_\varepsilon)$$

$$r_y = r\,(\cos\theta \sin\Omega_\varepsilon + \sin\theta \cos i_\varepsilon \cos\Omega_\varepsilon)$$

$$r_z = r \sin\theta \sin i_\varepsilon$$

$$v_x = v\,(\cos\psi \cos\Omega_\varepsilon - \sin\psi \cos i_\varepsilon \sin\Omega_\varepsilon)$$

$$v_y = v\,(\cos\psi \sin\Omega_\varepsilon + \sin\psi \cos i_\varepsilon \cos\Omega_\varepsilon)$$

$$v_z = v \sin\theta \sin i_\varepsilon$$

where

$$r = R_p + h,$$

$$\theta = \phi + \phi_\varepsilon,$$

$$\psi = \phi + \phi_\varepsilon - \gamma + \frac{\pi}{2} \;.$$

SUBROUTINE ELCAR

PURPOSE: TRANSFORMATION OF CONIC ELEMENTS TO CARTESIAN COORDINATES

ENTRY PARAMETERS

A	SEMIMAJOR AXIS
E	ECCENTRICITY
GM	GRAVITATIONAL CONSTANT OF CENTRAL BODY
R	POSITION VECTOR IN REFERENCE SYSTEM
RM	POSITION MAGNITUDE
TA	TRUE ANOMALY
TFP	TIME FROM PERIAPSIS
V	VELOCITY VECTOR IN REFERENCE SYSTEM
VM	VELOCITY MAGNITUDE
W	ARGUMENT OF PERIAPSIS
XI	INCLINATION IN REFERENCE SYSTEM
XN	LONGITUDE OF ASCENDING NODE

LOCAL SYMBOLS

AUXF	ECCENTRIC ANOMALY (HYPERBOLIC CASE)
AVA	MEAN ANOMALY (ELLIPTIC CASE)
CI	COSINE OF INCLINATION
CK	VELOCITY FACTOR USED TO CALCULATE FINAL VELOCITY VECTOR
CN	COSINE OF LONGITUDE OF ASCENDING NODE
COSEA	COSINE OF ECCENTRIC ANOMALY (ELLIPTIC CASE)
CT	COSINE OF TRUE ANOMALY
CW	COSINE OF SUM OF ARGUMENT OF PERIAPSIS AND TRUE ANOMALY, ALSO COSINE OF ARGUMENT OF PERIAPSIS
DIV	INTERMEDIATE VARIABLE USED TO CALCULATE TFP
EA	ECCENTRIC ANOMALY (ELLIPTIC CASE)
P	SEMI-LATUS RECTUM

RAD	CONVERSION FACTOR FROM DEGREES TO RADIANS
SI	SINE OF INCLINATION
SINEA	SINE OF ECCENTRIC ANOMALY
SINHF	HYPERBOLIC SINE OF AUXF
SN	SINE OF LONGITUDE OF ASCENDING NODE
ST	SINE OF TRUE ANOMALY
SW	SINE OF THE SUM OF ARGUMENT OF PERIAPSIS AND TRUE ANOMALY, ALSO SINE OF ARGUMENT OF PERIAPSIS
TANG	INTERMEDIATE VARIABLE USED TO CALCULATE SINHF

ELCAR Analysis

ELCAR transforms the standard conic elements of a massless point referenced to a gravitational body to Cartesian position and velocity components with respect to that body.

Let the gravitational constant of the body be denoted μ and the given conic elements $(a, e, i, \omega, \Omega, f)$. The semilatus rectum p is

$$p = a\,(1 - e^2) \quad . \tag{1}$$

Then the magnitude of the radius vector is given by

$$r = \frac{p}{1 + e \cos f} \quad . \tag{2}$$

The unit vector in the direction of the position vector is

$$u_x = \cos(\omega + f) \cos \Omega - \cos i \sin(\omega + f) \sin \Omega$$

$$u_y = \cos(\omega + f) \sin \Omega + \cos i \sin(\omega + f) \cos \Omega \tag{3}$$

$$u_z = \sin(\omega + f) \sin i \quad . \tag{3}$$

The position vector $\vec{r}$ is therefore

$$\vec{r} = r\hat{u} \quad . \tag{4}$$

The velocity vector $\vec{v}$ is given by

$$v_x = \sqrt{\mu/p}\ [(e + \cos f)(-\sin \omega \cos \Omega - \cos i \sin \Omega \cos \omega)$$
$$- \sin f\,(\cos \omega \cos \Omega - \cos i \sin \Omega \sin \omega)]$$

$$v_y = \sqrt{\mu/p}\ [(e + \cos f)(-\sin \omega \sin \Omega + \cos i \cos \Omega \cos \omega)$$
$$- \sin f\,(\cos \omega \sin \Omega + \cos i \cos \Omega \sin \omega)]$$

$$v_z = \sqrt{\mu/p}\ [(e + \cos f) \sin i \cos \omega - \sin f \sin i \sin \omega] \quad . \tag{5}$$

The conic time from periapsis t_p is computed from different formulae, depending on the sign of the semimajor axis. For $a > 0$

(elliptical motion)

$$t_p = \sqrt{a^3/\mu}\ (E - e \sin E)$$

$$\cos E = \frac{e + \cos f}{1 + e \cos f} \qquad \sin E = \frac{\sqrt{1 - e^2} \sin f}{1 + e \cos f} . \tag{6}$$

For $a < 0$ (hyperbolic motion), the time from periapsis is

$$t_p = \sqrt{a^3/\mu}\ (e \sinh H - H)$$

$$\tanh \frac{H}{2} = \sqrt{\frac{e - 1}{e + 1}}\ \tan \frac{f}{2} . \tag{7}$$

SUBROUTINE EPHEM

PURPOSE: COMPUTE HELIOCENTRIC ECLIPTIC POSITION AND VELOCITY COMPONENTS OF AN ARBITRARY PLANET

ENTRY PARAMETERS

DJ	JULIAN DATE, EPOCH 1900, JANUARY 0.
NP	PLANET CODE NUMBER

SUBROUTINES CALLED: ELCAR

COMMONS: STATE

LOCAL SYMBOLS

AU	CONVERSION FACTOR FROM A. U. TO KILOMETERS
CAPOM	LONGITUDE OF THE ASCENDING NODE
CD	JULIAN DATE IN UNITS OF 10,000 EPHEMERIS DAYS
CDC	CD CUBED
CDS	CD SQUARED
COSTA	COSINE OF TRUE ANOMALY
EA	ECCENTRIC ANOMALY
ECAM	INTERMEDIATE VARIABLE USED IN ITERATIVE SOLUTION OF KEPLER EQUATION
ECC	ECCENTRICITY
I	INDEX
IJ	INDEX
IJKL	INDEX
ITEMP	MEAN ANOMALY DIVIDED BY 360 DEGREES
OMEGA	ARGUMENT OF PERIAPSIS
OMEGAT	LONGITUDE OF PERIAPSIS
PI	CONSTANT = 3.141592653589793
PMU	ARRAY OF GRAVITATIONAL CONSTANTS
RAD	CONVERSION FACTOR FROM RADIANS TO DEGREES
RM	PLANET HELIOCENTRIC POSTITION MAGNITUDE

```
        SINTA       SINE OF TRUE ANOMALY

        SMA         SEMI-MAJOR AXIS

        T           JULIAN DATE IN CENTURIES

        TA          TRUE ANOMALY

        TC          CUBE OF  T

        TFP         TIME FROM PERIAPSIS PASSAGE

        TM          CONVERSION FACTOR FROM DAYS TO SECONDS

        TS          SQUARE OF  T

        VM          PLANET HELIOCENTRIC VELOCITY MAGNITUDE

        XI          INCLINATION

        XMNA        MEAN ANOMALY

        XMU         PLANET GRAVITATIONAL CONSTANT

SET/COMMON--- CARCOR     CONEL

LOADED    --- AU         PI          PMU         RAD         TM
```

EPHEM Analysis

Subroutine EPHEM computes the heliocentric ecliptic position and velocity components of an arbitrary planet at a given Julian date. The elements are referred to the mean equinox and ecliptic of date except for Pluto. The time interval from the epoch is denoted by T when measured in Julian centuries of 36,525 ephemeris days, by D = 3.6525 T when measured in units of 10,000 ephemeris days. Times are measured with respect to the epoch 1900 January 0.5 E.T. = J.D. 2415020.0. Angular relations are expressed in radians.

The first step in this process consists of computing the six mean orbital elements of the planet using standard ephemeris polynomials. The six orbital elements are semimajor axis a, eccentricity e, inclination i, longitude of the ascending node Ω, argument of periapsis ω, and mean anomaly M. Kepler's equation

$$M = E - e \sin E$$

is then solved iteratively to determine the eccentric anomaly E. Subsequent computations are basic conic manipulations:

$$p = a\,(1 - e^2)$$

$$r = a\,(1 - e \cos E)$$

$$v = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)}$$

$$\cos f = \frac{p - r}{er} \qquad \sin f = \sqrt{1 - \cos^2 f} \;\cdot\; \operatorname{sgn}(\sin E)$$

$$\cos \gamma = \frac{\sqrt{\mu p}}{rv} \qquad \sin \gamma = \sqrt{1 - \cos^2 \gamma} \;\cdot\; \operatorname{sgn}(\sin E)$$

$$\omega = \tilde{\omega} - \Omega \ .$$

The heliocentric ecliptic position and velocity components of the planet are then

$$\vec{r} = r_x\,\hat{i} + r_y\,\hat{j} + r_z\,\hat{k}$$

$$r_x = r \cos(\omega + f) \cos \Omega - r \sin(\omega + f) \sin \Omega \cos i$$

$$r_y = r \cos(\omega + f) \sin \Omega + r \sin(\omega + f) \cos \Omega \cos i$$

$$r_z = r \sin(\omega + f) \sin i$$

$$\vec{v} = \frac{v}{r}\left[(\hat{w} \times \vec{r}) \cos \gamma + \vec{r} \sin \gamma\right]$$

where $\hat{w} = (\sin i \sin \Omega)\,\hat{i} - (\sin i \cos \Omega)\,j + (\cos i)\,\hat{k}$.

Planetary Ephemerides*

Mean Elements of Mercury

$i = 0.1222233228 + 3.24776685 \times 10^{-5}\ T - 3.19770295 \times 10^{-7}\ T^2$

$\Omega = 0.8228518595 + 2.068578774 \times 10^{-2}\ T + 3.034933644 \times 10^{-6}\ T^2$

$\tilde{\omega} = 1.3246996178 + 2.714840259 \times 10^{-2}\ T + 5.143873156 \times 10^{-6}\ T^2$

$e = 0.20561421 + 0.00002046\ T - 0.000000030\ T^2$

$M = 1.785111955 + 7.142471000 \times 10^{-2}\ d + 8.72664626 \times 10^{-9}\ D^2$

$a = 0.3870986$ A.U. = 57,909,370 km.

Mean Elements of Venus

$i = 0.0592300268 + 1.755510339 \times 10^{-5}\ T - 1.696847884 \times 10^{-8}\ T^2$

$\Omega = 1.3226043500 + 1.570534527 \times 10^{-2}\ T + 7.155849933 \times 10^{-6}\ T^2$

$\tilde{\omega} = 2.2717874591 + 2.457486613 \times 10^{-2}\ T + 1.704120089 \times 10^{-5}\ T^2$

$e = 0.00682069 - 0.00004774\ T + 0.000000091\ T^2$

$M = 3.710626172 + 2.796244623 \times 10^{-2}\ d + 1.682497399 \times 10^{-6}\ D^2$

$a = 0.7233316$ A.U. = 108,209,322 km.

Mean Elements of Earth (Barycenter)

$i = 0$

$\Omega = 0$

$$\tilde{\omega} = 1.7666368138 + 3.000526417 \times 10^{-2}\ T + 7.902463002 \times 10^{-6}\ T^2 + 5.817764173 \times 10^{-8}\ T^3$$

$e = 0.01675104 - 0.00004180\ T - 0.000000126\ T^2$

$$M = 6.256583781 + 1.720196977 \times 10^{-2}\ d - 1.954768762 \times 10^{-7}\ D^2 - 1.22173048 \times 10^{-9}\ D^3$$

$a = 1.0000003$ A.U. = 149,598,530 km.

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*Space Research Conic Program, Phase III, JPL, May 1969 (Planetary Constants).

Mean Elements of Mars

$$i = 0.0322944089 - 1.178097245 \times 10^{-5}\ T + 2.201054112 \times 10^{-7}\ T^2$$

$$\Omega = 0.8514840375 + 1.345634309 \times 10^{-2}\ T - 2.424068406 \times 10^{-8}\ T^2$$
$$- 9.308422677 \times 10^{-8}\ T^3$$

$$\tilde{\omega} = 5.8332085089 + 3.212729365 \times 10^{-2}\ T + 2.266503959 \times 10^{-6}\ T^2$$
$$- 2.084698829 \times 10^{-8}\ T^3$$

$$e = 0.09331290 + 0.000092064\ T - 0.000000077\ T^2$$

$$M = 5.576840523 + 9.145887726 \times 10^{-3}\ d + 2.365444735 \times 10^{-7}\ D^2$$
$$+ 4.363323130 \times 10^{-10}\ D^3$$

$$a = 1.5236915\ \text{A.U.} = 227{,}941{,}963\ \text{km.}$$

Mean Elements of Jupiter

$$i = 0.0228410270 - 9.696273622 \times 10^{-5}\ T$$

$$\Omega = 1.7355180770 + 1.764479392 \times 10^{-2}\ T$$

$$\tilde{\omega} = 0.2218561704 + 2.812302353 \times 10^{-2}\ T$$

$$e = 0.0483376 + 0.00016302\ T$$

$$M = 3.93135411 + 1.450191928 \times 10^{-3}\ d$$

$$a = 5.202803\ \text{A.U.} = 778{,}331{,}525\ \text{km.}$$

Means Elements of Saturn

$$i = 0.0435037861 - 7.757018898 \times 10^{-8}\ T$$

$$\Omega = 1.9684445802 + 1.523977870 \times 10^{-2}\ T$$

$$\tilde{\omega} = 1.5897996653 + 3.419861162 \times 10^{-2}\ T$$

$$e = 0.0558900 - 0.00034705\ T$$

$$M = 3.0426210430 + 5.837120844 \times 10^{-4}\ d$$

$$a = 9.538843\ \text{A.U.} = 1{,}426{,}996{,}160\ \text{km.}$$

Mean Elements of Uranus

$i = 0.0134865470 + 0.9696273622 \times 10^{-5}\ T$

$\Omega = 1.2826407705 + 8.912087493 \times 10^{-3}\ T$

$\tilde{\omega} = 2.9502426085 + 2.834608631 \times 10^{-2}\ T$

$e = 0.0470463 + 0.00027204\ T$

$M = 1.2843599198 + 2.046548840 \times 10^{-4}\ d$

$a = (19.182281 - 0.00057008\ T)\ \text{A.U.} = (2{,}869{,}640{,}310 - 85271\ T)\ \text{km.}$

Mean Elements of Neptune

$i = 0.0310537707 - 1.599885148 \times 10^{-4}\ T$

$\Omega = 2.2810642235 + 1.923032859 \times 10^{-2}\ T$

$\tilde{\omega} = 0.7638202701 + 1.532704516 \times 10^{-2}\ T$

$e = 0.00852849 + 0.00007701\ T$

$M = 0.7204851506 + 1.033089473 \times 10^{-4}\ d$

$a = (30.057053 + 0.001210166\ T)\ \text{A.U.} = (4{,}496{,}490{,}000 + 181039\ T)\ \text{km.}$

Mean Elements of Pluto

$i = 0.2996706970859694$

$\Omega = 1.1914337550102258$

$\tilde{\omega} = 3.909919302791948$

$e = 0.2488033053623924$

$M = 3.993890007 + 0.6962635708298997 \times 10^{-4}\ d$

$a = 39.37364135300176\ \text{A.U.} = 5{,}890{,}213{,}786.146\ 730\ \text{km.}$

SUBROUTINE EQUATR

PURPOSE: COMPUTE COORDINATE TRANSFORMATION MATRIX FROM GEOCENTRIC EQUATORIAL TO PLANETOCENTRIC EQUATORIAL

ENTRY PARAMETERS

AGCAC	COORDINATE TRANSFORMATION FROM GEOCENTRIC EQUATORIAL TO PLANETOCENTRIC EQUATORIAL
D	JULIAN DATE, EPOCH 1900
NP	TARGET PLANET CODE

SUBROUTINES CALLED: EPHEM EXIT

COMMONS : STATE

LOCAL SYMBOLS

AHCGC	COORDINATE TRANSFORMATION FROM GEOCENTRIC EQUATORIAL TO GEOCENTRIC ECLIPTIC
CSDECL	COSINE OF DECL
CSEOBL	COSINE OF EOBL
CSINM	COSINE OF INM
CSNDM	COSINE OF NODEM
CSRASC	COSINE OF RASC
DECL	DECLINATION OF TARGET PLANET POLE
DGTR	CONVERSION FACTOR FROM DEGREES TO RADIANS
ECEQ	COORDINATE TRANSFORMATION FROM GEOCENTRIC ECLIPTIC TO PLANETOCENTRIC EQUATORIAL
ED	JULIAN DATE, EPOCH 4713 B.C.
EOBL	OBLIQUITY OF THE ECLIPTIC
I	INDEX
J	INDEX
K	INDEX
NORM	UNIT VECTOR NORMAL TO TARGET PLANET ORBITAL PLANE
PBAR	CROSS PRODUCT OF POLE AND NORM
PMAG	MAGNITUDE OF PBAR

POLE	UNIT VECTOR ALIGNED WITH TARGET PLANET POLAR AXIS
POLMAG	MAGNITUDE OF POLE
QBARP	CROSS PRODUCT OF POLE AND PBAR
QMAG	MAGNITUDE OF QBARP
RASC	RIGHT ASCENSION OF TARGET PLANET POLE
SNDECL	SINE OF DECL
SNEOBL	SINE OF EOBL
SNINM	SINE OF INCLINATION INM
SNNDM	SINE OF NODE NDM
SNRASC	SINE OF RASC
T	JULIAN DATE, EPOCH 1900, DIVIDED BY 36525
TPRIM	BESSELIAN DATE

USED/COMMN--- INM NODEM

EQUATR Analysis

Subroutine EQUATR computes the coordinate transformation matrix A from geocentric equatorial to planetocentric equatorial coordinates. Matrix A is computed from

$$A = A_1 A_2 \tag{1}$$

where A_2 is the coordinate transformation matrix from geocentric equatorial to geocentric ecliptic coordinates and is given by

$$A_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varepsilon & \sin\varepsilon \\ 0 & -\sin\varepsilon & \cos\varepsilon \end{bmatrix} \tag{2}$$

where ε is the obliquity of the ecliptic. Matrix A_1 is the coordinate transformation matrix from geocentric ecliptic to planetocentric equatorial coordinates. The derivation of A_1 is summarized below.

The coordinate transformation A_1 is defined by

$$A_1 = [\hat{X} \mid \hat{Y} \mid \hat{Z}]^T \tag{3}$$

where $\hat{X}$, $\hat{Y}$, and $\hat{Z}$ are unit vectors aligned with the planetocentric equatorial coordinate axes and referenced to the geocentric ecliptic coordinate system. Unit vector $\hat{Z}$ is aligned with the planet pole. Unit vector $\hat{X}$ lies along the intersection of the planet equatorial and orbital planes and points at the planet vernal equinox. Unit vector $\hat{Y}$ completes the orthogonal triad and is given by

$$\hat{Y} = \hat{Z} \times \hat{X}. \tag{4}$$

It remains to obtain expressions for $\hat{X}$ and $\hat{Z}$. Let $\hat{N}$ denote the unit vector normal to the planet orbital plane, and let $\hat{P}$ denote the unit vector aligned with the planet polar axis. Then

$$\hat{Z} = \hat{P} \tag{5}$$

and

$$\hat{X} = \frac{\hat{P} \times \hat{N}}{|\hat{P} \times \hat{N}|} \tag{6}$$

The unit vector $\hat{N}$, referred to the ecliptic coordinate system, is given by

$$\hat{N} = \begin{bmatrix} \sin i \sin \Omega \\ -\sin i \cos \Omega \\ \cos i \end{bmatrix} \tag{7}$$

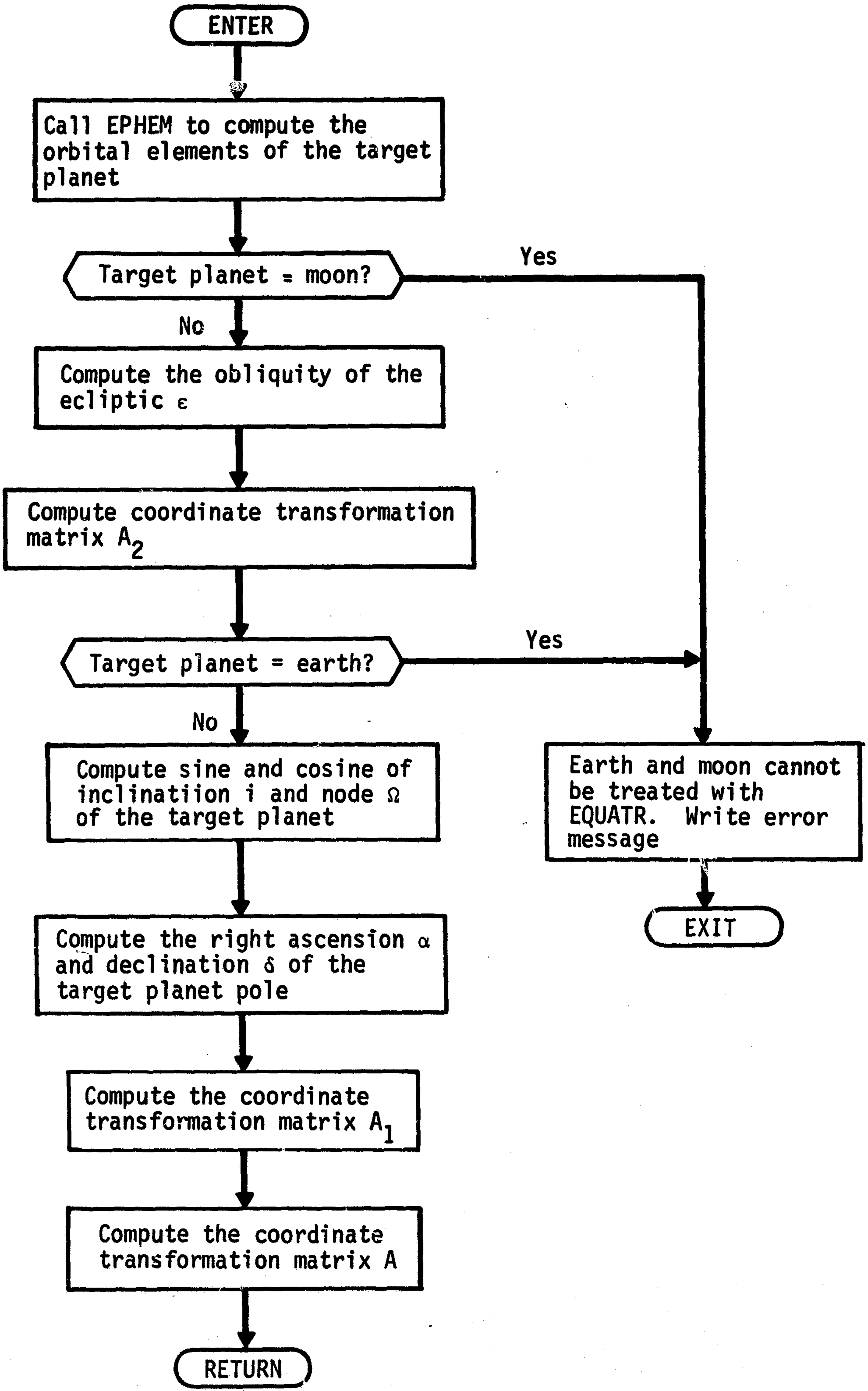
where i and Ω are the inclination and longitude of the ascending node, respectively, of the planet orbital plane. The unit vector $\hat{P}$, referred to the ecliptic system, is given by

$$\hat{P} = \begin{bmatrix} \cos \alpha \cos \delta \\ \cos \varepsilon \sin \alpha \cos \delta + \sin \varepsilon \sin \delta \\ -\sin \varepsilon \sin \alpha \cos \delta + \cos \varepsilon \sin \delta \end{bmatrix} \tag{8}$$

where α and δ are the right ascension and declination, respectively, of the planet polar axis relative to the geocentric equatorial coordinate system, and ε is the obliquity of the ecliptic. Expressions for α and δ for each planet were obtained from JPL TR 32-1306, *Constants and Related Information for Astrodynamic Calculations*, 1968, by Melbourne, *et al.*

The use of subroutine EQUATR is restricted to planets other than the earth and moon.

EQUATR Flow Chart



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SUBROUTINE FILTER

PURPOSE :    PERFORMS COVARIANCE PROPAGATION AND KALMAN GAIN MATRIX
             CALCULATIONS PRIOR TO MEASUREMENTS AND OTHER EVENTS


SUBROUTINES CALLED: ADD       ADPRD     ADPROD    ADPRDT    COPY
          DADPRT    INVPSD    MULT      MULTT     SUB       SUBPRT
          SYMTRZ    TADPRT    TMULTT

COMMONS : TRAJ      COVARP    BM        INTCOM

LOCAL SYMBOLS
        I        INDEX

        J        INDEX

        WQ2      ESTIMATED DEVIATION FROM NOMINAL MEASUREMENT


USED/COMMN---   ELEMENTS FROM COMMON/COVARP/
                              COMMON/INTCOM/

SET/COMMON---   ELEMENTS FROM COMMON/COVARP/

ENTRY PNT --- FILM      FILTER    PREM      QUASI     SIMM
```

FILTER Analysis

The augmented state deviation vector is defined as

$$x^A = \begin{bmatrix} x \\ q \\ u \\ v \\ w \end{bmatrix} \qquad (1)$$

where

x = basic state vector,

q = vector of solve-for parameters,

u = vector of dynamic consider parameters,

v = vector of measurement consider parameters,

w = vector of dynamic/measurement consider parameters.

The dynamic model for the linearized equations has the form

$$x^A_{k+1} = \Phi^A_{k+1,k}\, x^A_{k+1} + Q^A_{N_{k+1,k}} \qquad (2)$$

where the augmented state transition matrix, $\Phi^A_{k+1,k}$, may be partitioned as

$$\Phi^A = \begin{bmatrix} \phi & \psi & \theta_u & \theta_v & \theta_w \\ 0 & I & 0 & 0 & 0 \\ 0 & 0 & I & 0 & 0 \\ 0 & 0 & 0 & I & 0 \\ 0 & 0 & 0 & 0 & I \end{bmatrix} . \qquad (3)$$

Henceforth the state transition matrix partitions will be written without stating the associated time interval, which will always be assumed to be $[t_k, t_{k+1}]$. The augmented dynamic noise vector $Q^A_{N_{k+1,k}}$ may be partitioned

$$Q^A_{N_{k+1,h}} = \begin{bmatrix} Q_N \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (4)$$

where the associated time interval is again understood to be $[t_k, t_{k+1}]$.

The measurement deviation vector is related to the augmented state deviations through the relation

$$y_k = H^A_k x^A_k + \eta_k$$

where the augmented measurement matrix may be partitioned as

$$H^A_k = [H \; M \; 0 \; L \; G] \qquad (5)$$

and η_k is the measurement noise.

The augmented state covariance matrix may be written in partitioned form as

$$P^A = \begin{bmatrix} P & C_{xq} & C_{xu} & C_{xv} & C_{xw} \\ C^T_{xq} & Q & C_{qu} & C_{qv} & C_{qw} \\ C^T_{xu} & C^T_{qu} & D_u & 0 & 0 \\ C^T_{xv} & C^T_{qv} & 0 & D_v & 0 \\ C^T_{xw} & C^T_{qw} & 0 & 0 & D_w \end{bmatrix} . \qquad (6)$$

Prediction and filtering equations for the partitions appearing in the previous equations will be written below. Equations need not be written for the consider parameter covariances D_u, D_v, and D_w since they remain constant. A minus superscript on a covariance partition indicates its value immediately prior to processing a measurement; a plus superscript indicates its value immediately after processing a measurement. To improve numerical accuracy and to avoid nonpositive definite covariance matrices, P and Q are symmetrized after the computations.

At entry point FILM, the following computations are made. First, the measurement residual covariance matrix

$$
\begin{aligned}
J_{k+1} &= H^{A}_{k+1} P^{A-}_{k+1} H^{AT}_{k+1} + R_{k+1} \\
&= H_{k+1} \left\{ P^{-}_{k+1} H^{T}_{k+1} + C^{-}_{xq_{k+1}} M^{T}_{k+1} + C^{-}_{xv_{k+1}} L^{T}_{k+1} + C^{-}_{xw_{k+1}} G^{T}_{k+1} \right\} \\
&\quad + M_{k+1} \left\{ C^{-T}_{xq_{k+1}} H^{T}_{k+1} + Q^{-}_{k+1} M^{T}_{k+1} + C^{-}_{qv_{k+1}} L^{T}_{k+1} + C^{-}_{qw_{k+1}} G^{T}_{k+1} \right\} \\
&\quad + L_{k+1} \left\{ C^{-T}_{xv_{k+1}} H^{T}_{k+1} + C^{-T}_{qv_{k+1}} M^{T}_{k+1} + D_{v} L^{T}_{k+1} \right\} \\
&\quad + G_{k+1} \left\{ C^{-T}_{xw} H^{T}_{k+1} + C^{-T}_{qw_{k+1}} M^{T}_{k+1} + D_{w} G^{T}_{k+1} \right\} + R_{k+1} \quad . \qquad (7)
\end{aligned}
$$

The Kalman gain matrix

$$
K^{A}_{k+1} = P^{A-}_{k+1} H^{AT}_{k+1} (J_{k+1})^{-1} = \begin{bmatrix} K1_{k+1} \\ K2_{k+1} \\ K3_{k+1} \\ K4_{k+1} \\ K5_{k+1} \end{bmatrix} \qquad (8)
$$

$$
K^{AM}_{k+1} = \begin{bmatrix} K1_{k+1} \\ K2_{k+1} \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (8A)
$$

Only the $K1_{k+1}$ and $K2_{k+1}$ partitions are used,

$$K1_{k+1} = \left\{P^-_{k+1} H^T_{k+1} + C^-_{xq_{k+1}} M^T_{k+1} + C^-_{xv_{k+1}} L^T_{k+1} + C^-_{xw_{k+1}} G^T_{k+1}\right\}\left(J_{k+1}\right)^{-1} \tag{9}$$

$$K2_{k+1} = \left\{C^{-T}_{xq_{k+1}} H^T_{k+1} + Q^-_{k+1} M^T_{k+1} + C^-_{qv_{k+1}} L^T_{k+1} + C^-_{qw_{k+1}} G^T_{k+1}\right\}\left(J_{k+1}\right)^{-1} \tag{10}$$

The partitions of the covariance update equation

$$P^{A+}_{k+1} = P^{A-}_{k+1} - K^A_{k+1} H^A_{k+1} P^{A-}_{k+1} \tag{11}$$

are given by

$$P^+_{k+1} = P^-_{k+1} - K1_{k+1} \left\{H_{k+1} P^-_{k+1} + M_{k+1} C^{-T}_{xq_{k+1}} + L_{k+1} C^{-T}_{xv_{k+1}} + G_{k+1} C^{-T}_{xw_{k+1}}\right\} \tag{12}$$

$$C^+_{xq_{k+1}} = C^-_{xq_{k+1}} - K1_{k+1} \Delta_{k+1} \tag{13}$$

$$C^+_{xu_{k+1}} = C^-_{xu_{k+1}} - K1_{k+1} \Gamma_{k+1} \tag{14}$$

$$C^+_{xv_{k+1}} = C^-_{xv_{k+1}} - K1_{k+1} \Omega_{k+1} \tag{15}$$

$$C^+_{xw_{k+1}} = C^-_{xw_{k+1}} - K1_{k+1} \Lambda_{k+1} \tag{16}$$

$$Q^+_{k+1} = Q^-_{k+1} - K2_{k+1} \Delta_{k+1} \tag{17}$$

$$C^+_{qu_{k+1}} = C^-_{qu_{k+1}} - K2_{k+1} \Gamma_{k+1} \tag{18}$$

$$C^+_{qv_{k+1}} = C^-_{qv_{k+1}} - K2_{k+1} \Omega_{k+1} \tag{19}$$

$$C^+_{qw_{k+1}} = C^-_{qw_{k+1}} - K2_{k+1} \Lambda_{k+1} \tag{20}$$

where

$$\Delta_{k+1} = H_{k+1}\, C^{-}_{xq_{k+1}} + M_{k+1}\, Q^{-}_{k+1} + L_{k+1}\, C^{-T}_{qv_{k+1}} + G_{k+1}\, C^{-T}_{qw_{k+1}} \tag{21}$$

$$\Gamma_{k+1} = H_{k+1}\, C^{-}_{xu_{k+1}} + M_{k+1}\, C^{-}_{qu_{k+1}} \tag{22}$$

$$\Omega_{k+1} = H_{k+1}\, C^{-}_{xv_{k+1}} + M_{k+1}\, C^{-}_{qv_{k+1}} + L_{k+1}\, D_v \tag{23}$$

$$\Lambda_{k+1} = H_{k+1}\, C^{-}_{xw_{k+1}} + M_{k+1}\, C^{-}_{qw_{k+1}} + G_{k+1}\, D_w \quad . \tag{24}$$

The remaining partitions, D_u, D_v, D_w, are not updated since they are associated with consider parameters.

At entry point PREM, the following computations are made. First the partitions of the covariance prediction equation

$$P^{A-}_{k+1} = \Phi^{A}_{k+1,h}\, P^{A+}_{k}\, \Phi^{AT}_{k+1,h} \tag{25}$$

are given by

$$\begin{aligned} P^{-}_{k+1} = {} & \left\{ \phi P^{+}_{k} + \psi C^{+T}_{xq_k} + \theta_u\, C^{+T}_{xu_k} + \theta_w\, C^{+T}_{xw_k} \right\} \phi^{T} \\ & + C^{-}_{xq_{k+1}}\, \psi^{T} + C^{-}_{xu_{k+1}}\, \theta_u^{T} + C^{-}_{xw_{k+1}}\, \theta_w^{T} \end{aligned} \tag{26}$$

$$C^{-}_{xq_{k+1}} = \phi C^{+}_{xq_k} + \psi Q^{+}_{k} + \theta_u\, C^{+T}_{qu_k} + \theta_w\, C^{+T}_{qw_k} \tag{27}$$

$$C^{-}_{xu_{k+1}} = \phi C^{+}_{xu_k} + \psi C^{+}_{qu_k} + \theta_u\, D_u \tag{28}$$

$$C^{-}_{xv_{k+1}} = \phi C^{+}_{xv_k} + \psi C^{+}_{qv_k} \tag{29}$$

$$C^{-}_{xw_{k+1}} = \phi C^{+}_{xw_k} + \psi C^{+}_{qw_k} + \theta_w\, D_w \quad . \tag{30}$$

Since all solve-for and consider parameter deviations are assumed to be constant between measurements, the following relations are used

$$Q_{k+1}^{-} = Q_{k}^{+} \tag{31}$$

$$C_{qu_{k+1}}^{-} = C_{qu_k}^{+} \tag{32}$$

$$C_{qv_{k+1}}^{-} = C_{qv_k}^{+} \tag{33}$$

$$C_{qw_{k+1}}^{-} = C_{qw_k}^{+} \tag{34}$$

Again since the solve-for and consider parameter deviations are constant between measurements, only the basic state partition of the estimated state prediction or propagation equation is required

$$\hat{x}_{k+1}^{-} = \phi \hat{x}_{k}^{+} + \psi \hat{q}_{k}^{+} \tag{35}$$

At entry point SIMM, the following computations are made. First the measurement residual is computed as

$$\varepsilon_{k+1} = y_{k+1}^{a} - \left\{ \tilde{y}_{k+1} + H_{k+1} \hat{x}_{k+1}^{-} + M_{k+1} \hat{q}_{k+1}^{-} \right\} .$$

Then the partition of the estimated state update equation

$$\hat{x}_{k+1}^{A+} = \hat{x}_{k+1}^{A-} + K_{k+1}^{Am} \varepsilon_{k+1}$$

where

$$K_{k+1}^{Am} = \begin{bmatrix} K1 \\ K2 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

is given by

$$\hat{x}^{+}_{k+1} = \hat{x}^{-}_{k+1} + K1_{k+1}\,\varepsilon_{k+1}$$

$$\hat{q}^{+}_{k+1} = \hat{q}^{-}_{k+1} + K2_{k+1}\,\varepsilon_{k+1} \quad .$$

At entry point QUASI, the computations associated with a quasi-linear filtering event are made

$$\tilde{x}^{+} = \tilde{x}^{-} + \hat{x}^{-}$$

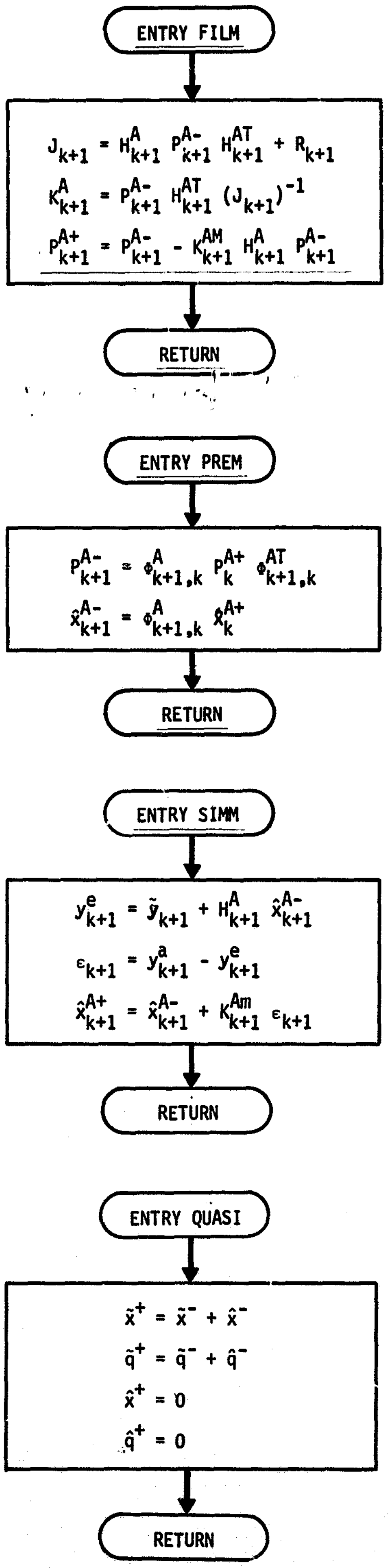
$$\tilde{q}^{+} = \tilde{q}^{-} + \hat{q}^{-}$$

$$\hat{x}^{+} = 0$$

$$\hat{q}^{+} = 0$$

where the superscript ~ indicates the nominal value of the state or solve-for parameter. The + superscript indicates the value after the quasi-linear filtering event, whereas the - superscript indicates the value before.

The flow of the FILTER subroutine is illustrated.



FILTER Flow Chart

SUBROUTINE GEOG

PURPOSE: COMPUTE THE CO-ORDINATE TRANSFORMATION FROM PLANETOCENTRIC EQUATORIAL PLANE TO PLANETOCENTRIC GEOGRAPHICAL PLANE

ENTRY PARAMETERS:

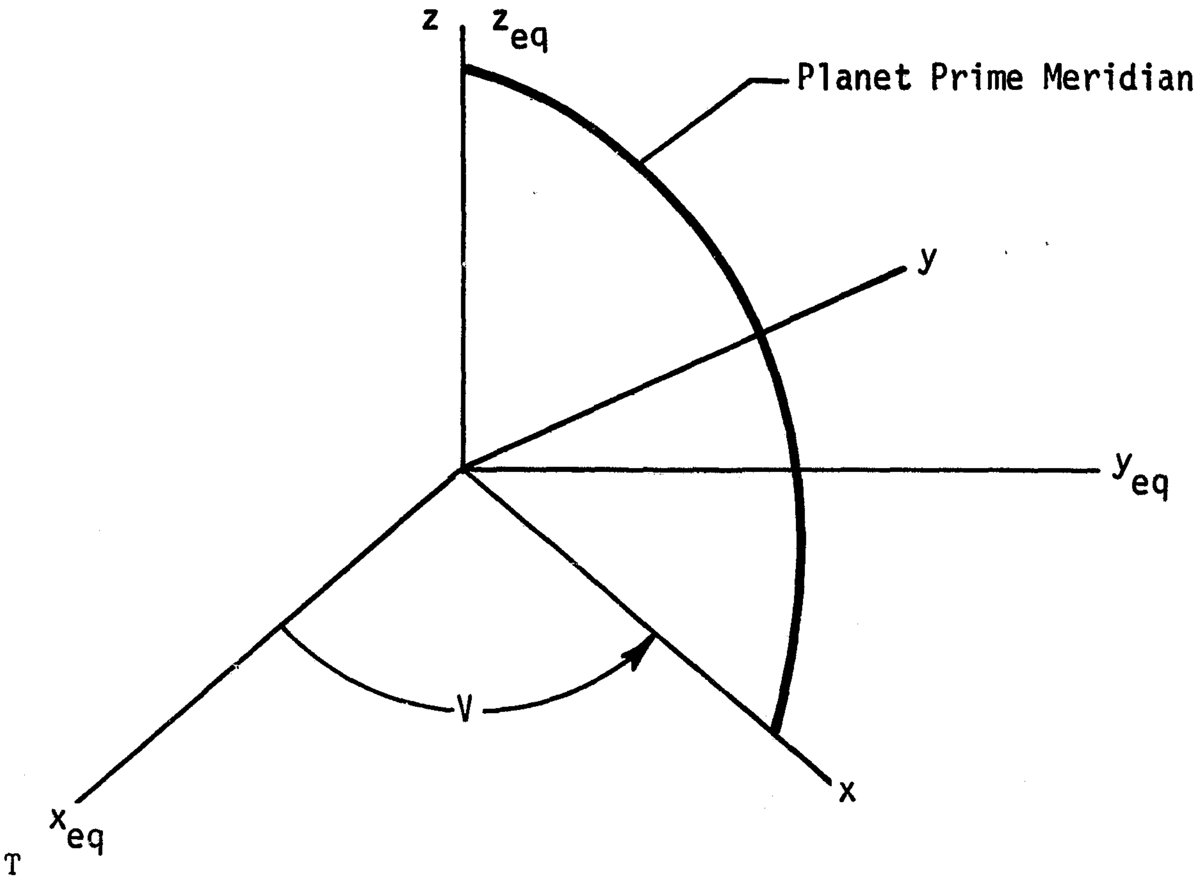
NP	TARGET PLANET CODE
D	JULIAN DATE, EPOCH JANUARY 0, 1900
EQGF	CO-ORDINATE TRANSFORMATION FROM PLANETOCENTRIC EQUATORIAL TO PLANETOCENTRIC GEOGRAPHICAL

LOCAL SYMBOLS:

ED	JULIAN DATE, EPOCH 4713 B. C.
DGTR	CONVERTS DEGREES TO RADIANS
VEHA	HOUR ANGLE OF THE VERNAL EQUINOX

GE0G Analysis

Subroutine GE0G computes the coordinate transformation from planetocentric equatorial to planetocentric geographical coordinate for an arbitrary planet. The geographical coordinate system is defined so the z-axis is aligned with the planet spin vector and the x-axis lies in the plane of the planet prime meridian. The prime meridian is oriented relative to the planet vernal equinox T by the hour angle of the vernal equinox V. In the figure shown below the xyz axes define the planetocentric geographical system, the x_{eq} y_{eq} z_{eq} axes define the planetocentric equatorial system.



The expressions used to evaluate V for each planet were obtained from JPL TR32-1306, *Constants and Related Information for Astrodynamic Calculations*, 1968, by Melbourne *et al.*

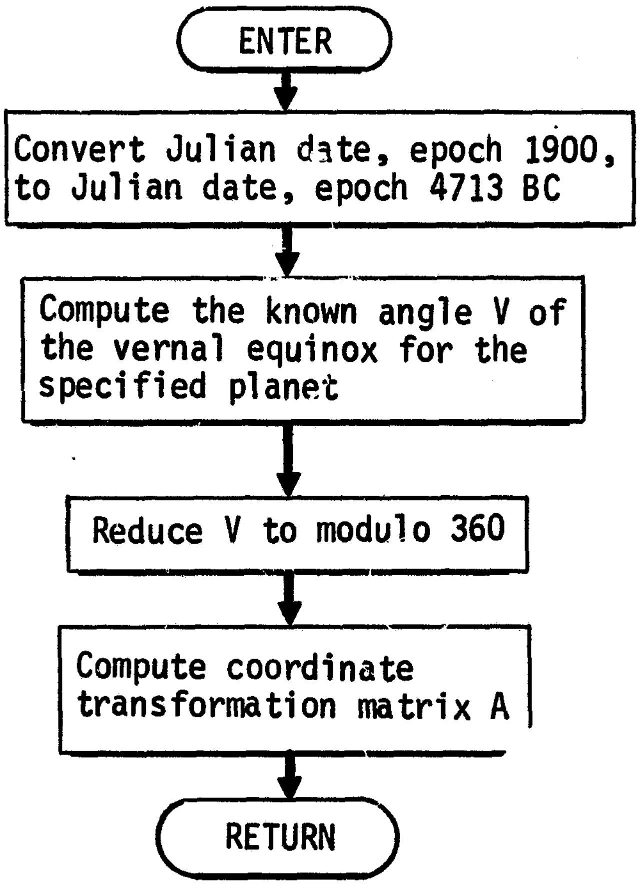
The coordinate transformation matrix is given by

$$A = \begin{bmatrix} \cos V & \sin V & 0 \\ -\sin V & \cos V & 0 \\ 0 & 0 & 1 \end{bmatrix} .$$

Thus

$$\vec{x}_{\text{geographical}} = A\, \vec{x}_{\text{equatorial}} .$$

GEOG Flow Chart



SUBROUTINE GHA

PURPOSE: COMPUTES GREENWICH HOUR ANGLE OF THE VERNAL EQUINOX

ENTRY PARAMETERS:

DATEJ	JULIAN DATE, EPOCH AT JANUARY 0, 1900
GH	GREENWICH HOUR ANGLE OF THE VERNAL EQUINOX IN RADIANS

LOCAL SYMBOLS:

EOMEG	EARTH ROTATION RATE IN DEGREES/DAY
REFJD	JULIAN DATE OF 1950 JANUARY 1, EPOCH AT 4713 B.C.
TSTAR	JULIAN DATE, EPOCH AT 1950 JANUARY 1
ID	INTEGER PART OF TSTAR
D	ID CONVERTED TO REAL
TFRAC	FRACTIONAL PART OF TSTAR

GHA Analysis

Subroutine GHA computes the Greewich hour angle GHA of the vernal equinox at a given Julian date (JD), epoch 1900 January $0^d\ 12^h$, using

$$GHA = 100.0755426 + 0.985647346\ d + 2.9015 \times 10^{-13}\ d^2 + \omega t$$

where

ω = Earth's rotation rate (deg/day)

d = integer part of T^*

t = fractional part of T^*

and

T^* = Julian date, epoch 1950 January $1^d\ 0^h$.

The Julian dates relative to epochs 1900 and 1950 are related as follows:

$$T^* = JD + 2415020.0 - 2433282.5$$

where

2415020.0 = 1900 January $0^d\ 12^h$ referenced to 4713 BC January $0^d\ 12^h$

and

2433282.5 = 1950 January $1^d\ o^h$ referenced to 4713 BC January $0^d\ 12^h$

```
SUBROUTINE HMM

PURPOSE :     CONTROLS COMPUTATION OF OBSERVATION MATRIX PARTITIONS


SUBROUTINES CALLED: JACOBN

COMMONS : TRAJ      COVARP    INTCOM

LOCAL SYMBOLS
        OBSM        EXTERNAL VARIABLE NAME USED BY JACOBN FOR
                    COMPUTATION OF MEASUREMENT VALUES

USED/COMMN--- C         DU        DV        DW        GM        HM
              LISTQ     LISTS     LISTV     LISTW     LM        MM
              NM        NQ        NS        NV        NW        P
              Q
```

HMM Analysis

Subroutine HMM is an executive routine that controls the computation of the partitions of the observation matrix. The matrix partitions are all computed by numerical differencing, which is carried out by calling JACOBN. The indices of the variables to be perturbed to compute columns of the observation matrix are stored in LISTS, LISTQ, LISTV, and LISTW for the H, M, L, and G partitions, respectively. The size of the perturbations are governed by the variance of the parameters that are stored in arrays P, Q, DV and DW. The unperturbed measurement values are stored in the MEAS array.

The linearized measurement equation in partitioned form is given by

$$y = \left[H \,\vdots\, M \,\vdots\, O \,\vdots\, L \,\vdots\, G \right] \begin{bmatrix} x \\ q \\ u \\ v \\ w \end{bmatrix} .$$

SUBROUTINE INVPD2

PURPOSE : INVERTS A POSITIVE DEFINITE SYMMETRIC MATRIX

ENTRY PARAMETERS

A	A WORKING MATRIX (N X N)
D	VECTOR OF DIAGONAL ELEMENTS OF AN N X N MATRIX
L	LOWER TRIANGULAR MATRIX WITH ONES ON THE DIAGONAL
N	DIMENSION OF S
S	POSITIVE DEFINITE SYMMETRIC MATRIX TO BE INVERTED
SI	INVERSE OF S

SUBROUTINES CALLED: EXIT MATOUT

LOCAL SYMBOLS

I	INDEX
I1	I - 1
J	INDEX
J1	J - 1
J11	J + 1
K	INDEX
SUM	INTERMEDIATE SUM

INVPD2 Analysis

This subroutine inverts a positive definite symmetric matrix by a modified Cholesky method. Let S be the positive definite matrix to be inverted. The method proceeds by determining matrices L and D so L is lower triangular with 1s on the diagonal, D is diagonal, and

$$S = LD\,L^T$$

L and D may be found recursively from the relations

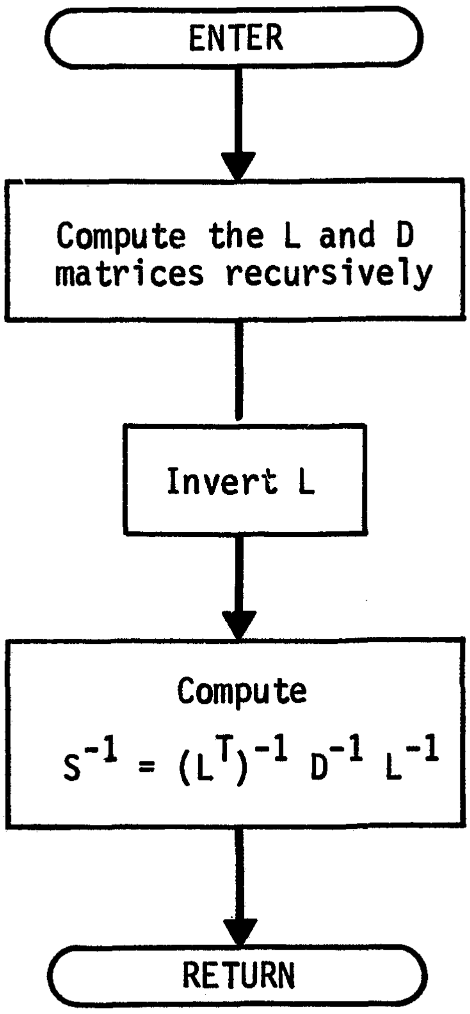
$$d_j = s_{jj} - \sum_{k=1}^{j-1} d_k\, \ell_{jk}^2$$

$$\ell_{ij} = \frac{\left\{ s_{ij} = \sum_{k=1}^{j-1} d_k\, \ell_{ik}\, \ell_{jk} \right\}}{d_j}\,, \quad i > j$$

The inverse of S is then given by

$$S^{-1} = (L^T)^{-1}\, D^{-1}\, L^{-1}$$

INVPD2 Flow Chart



```
SUBROUTINE INVPSD

PURPOSE :    TO INVERT A  1X1  OR  2X2  MATRIX


ENTRY PARAMETERS
        N        SIZE OF  X  AND  Y  MATRICES

        X        MATRIX TO BE INVERTED

        Y        INVERSE MATRIX (OUTPUT)


LOCAL SYMBOLS
        I        INDEX

        RECDET   RECIPROCAL OF THE DETERMINANT OF  X
```

SUBROUTINE JACOBN

PURPOSE : COMPUTE THE JACOBIAN MATRIX OF A VECTOR FUNCTION WITH RESPECT TO A SPECIFIC SUBSET OF PARAMETERS BY NUMERICAL DIFFERENCING

ENTRY PARAMETERS

C	VECTOR OF PARAMETERS
COVAR	COVARIANCE MATRIX CONTAINING THE VARIANCE OF THE PARAMETERS
FCT	EXTERNAL FUNCTION USED TO COMPUTE VALUES OF THE VECTOR FUNCTION
ZACOBN	THE JACOBIAN MATRIX
LIST	LIST OF INDICATORS OF THE SUBSET OF PARAMETERS TO BE USED
M	DIMENSION OF COVAR
N	NUMBER OF PARAMETERS IN THE SUBSET
NZ	DIMENSION OF THE VECTOR FUNCTION
ZADD	NOMINAL VALUE OF THE VECTOR FUNCTION

SUBROUTINES CALLED: FCT (EXTERNAL SUPPLIED AS ENTRY PARAMETER)

LOCAL SYMBOLS

CSAVE	TEMPORARY STORAGE FOR UNPERTURBED VALUE OF PARAMETER
DIFF	PERTURBATION APPLIED TO PARAMETER
E	CONSTANT USED IN COMPUTING THE SIZE OF THE PERTURBATION INDEX
II	INDEX OF THE I-TH DIAGONAL ELEMENT OF COVAR
L	INDEX OF THE PARAMETER BEING PERTURBED
ZADDP	PERTURBED VALUE OF THE VECTOR FUNCTION
ZP	DUMMY PARAMETER

LOADED --- E

JAC0BN Analysis

JAC0BN computes the Jacobian matrix of an NZ dimension vector with respect to the subset of parameters in the C Array whose indicates are in LIST. The computation is carried out by numerical differencing. The vector function is evaluated by calling FCT. The unperturbed values of the function are stored in ZADD. The parameters are perturbed by an amount depending on this variance. The variances are stored in the array C0VAR.

```
SUBROUTINE LTRCON

PURPOSE :     EXECUTIVE CONTROL FOR RECONSTRUCTOR


SUBROUTINES CALLED: COPY      DYNOIZ    MEASUR    NEXTAA    NEXTIM
          NTM       NTM2      PDUMP     PREDIC    PREM      PRINT
          QUASI     READAC    RESTRT    SETICN    SETUP     STM


COMMONS : SMO       GY        TRAJ      SUMRY

LOCAL SYMBOLS
        I           INDEX

        J           INDEX

        Z           MOST RECENT NOMINAL STATE AT START AND END
                    OF CURRENT INTEGRATION INTERVAL

        ZADD        CHANGE IN  Z  VECTOR OVER THE INTERVAL

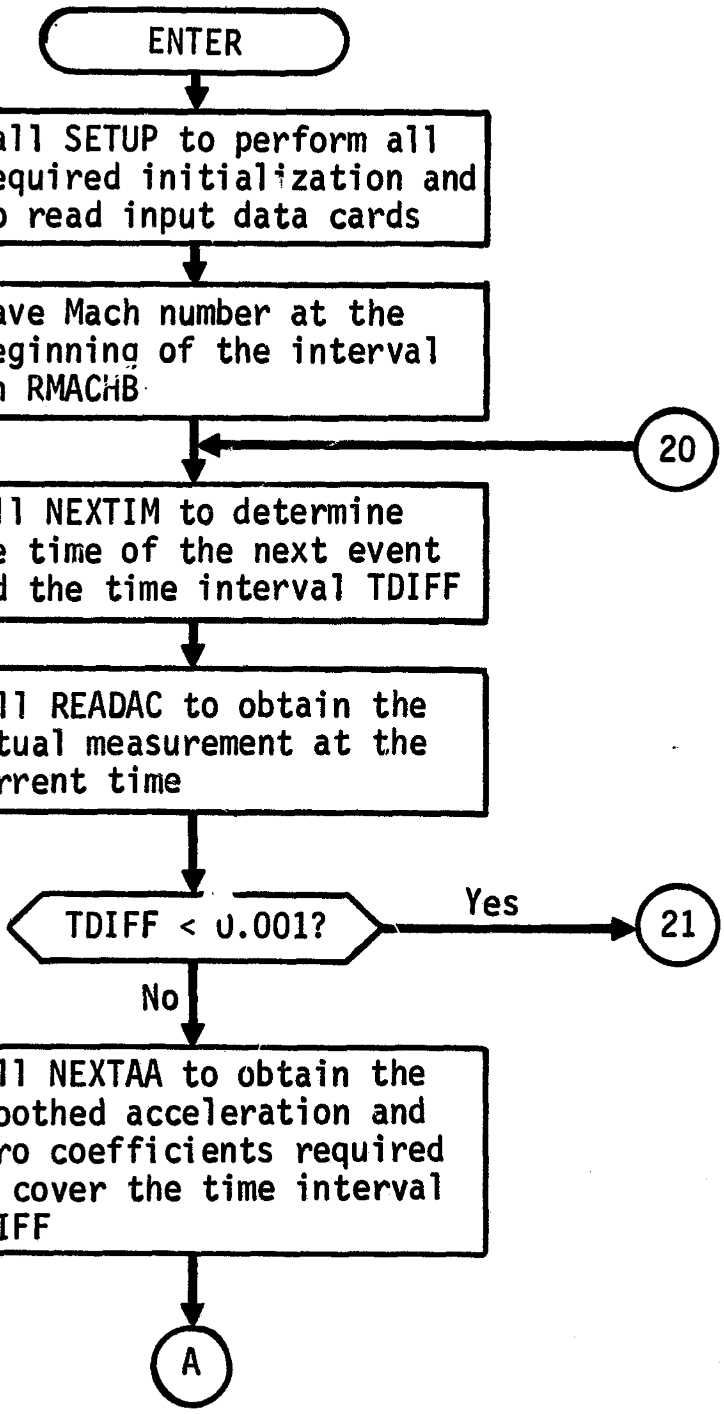

USED/COMMN--- AA        IEND      LTR1      LTR2      TC        TDIFF
              TEND      TYPE

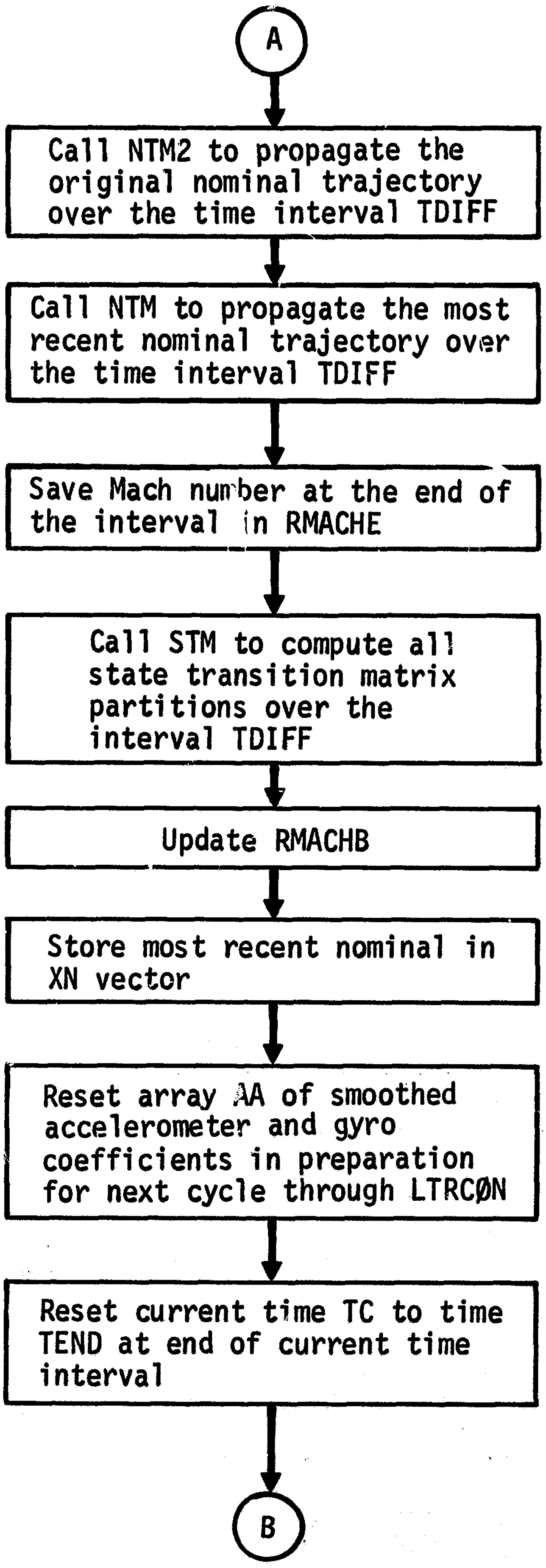
SET/COMMON--- AA        TC        TIMEF
```

LTRC0N Analysis

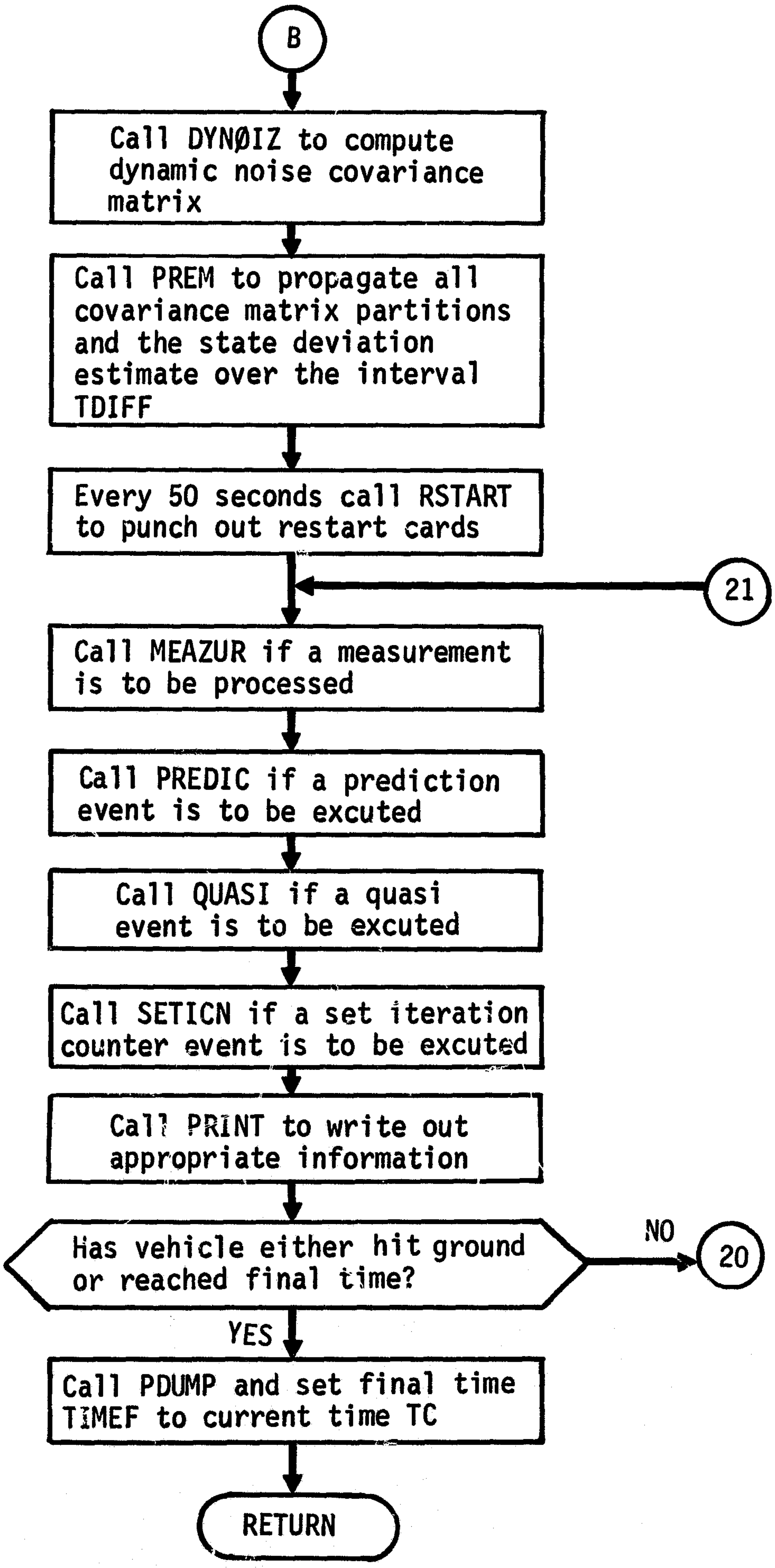
Subroutine LTRC0N is the executive subroutine for the LTR reconstruction program and controls the entire computational flow for trajectory propagation, state transition matrix computation, measurement processing, event execution, and printout.

LTRC0N Flow Chart




A
Call NTM2 to propagate the original nominal trajectory over the time interval TDIFF
Call NTM to propagate the most recent nominal trajectory over the time interval TDIFF
Save Mach number at the end of the interval in RMACHE
Call STM to compute all state transition matrix partitions over the interval TDIFF
Update RMACHB
Store most recent nominal in XN vector
Reset array AA of smoothed accelerometer and gyro coefficients in preparation for next cycle through LTRCON
Reset current time TC to time TEND at end of current time interval
B

LTRC0N-3


B
Call DYN0IZ to compute dynamic noise covariance matrix
Call PREM to propagate all covariance matrix partitions and the state deviation estimate over the interval TDIFF
Every 50 seconds call RSTART to punch out restart cards
21
Call MEAZUR if a measurement is to be processed
Call PREDIC if a prediction event is to be excuted
Call QUASI if a quasi event is to be excuted
Call SETICN if a set iteration counter event is to be excuted
Call PRINT to write out appropriate information
Has vehicle either hit ground or reached final time?
NO
20
YES
Call PDUMP and set final time TIMEF to current time TC
RETURN

```
SUBROUTINE MAIN

PURPOSE :     CONTROLS OVERALL PROGRAM FLOW FOR DATA GENERATION,
              PREPROCESSING, TRAJECTORY RECONSTRUCTON, AND
              SUMMARY OUTPUT


SUBROUTINES CALLED: EXIT      TIMEX

COMMONS : ALREDY    DOPLER    INTCOM    LOGCOM

USED/COMMN--- LTR1      LTR2      RUNNO

SET/COMMON---GENDAT    NTP       OMEGAE    REARTH    RESTRT

READ       --- RUNNO
```

MAIN Analysis

RUNN0 controls program flow. If RUNN0 = 1, the data generator and preprocessor are executed and control goes to statement 10, where another value of RUNN0 is read. If RUNN0 = 2, the main LTR program is called to reconstruct the lander trajectory and print the summary output, which may include a plotting package. Control then passes to statement 10. If RUNN0 = 3, the program exits to the system.

SUBROUTINE MATOUT

PURPOSE : MATRIX PRINTOUT WITH HOLLERITH NAME

ENTRY PARAMETERS

NAME	HOLLERITH NAME OF X MATRIX
NC	NUMBER OF COLUMNS OF X MATRIX
NR	NUMBER OF ROWS OF X MATRIX
X	MATRIX TO BE PRINTED OUT

LOCAL SYMBOLS

I	INDEX
N	TOTAL NUMBER OF ELEMENTS OF X
NEND	LOCATION IN X OF THE END OF THE I-TH ROW
NSTART	LOCATION IN X OF THE START OF THE I-TH ROW

WRITTEN --- NAME X

MAT0UT Analysis

The matrix X is written out by rows with up to 8 values per line and can be a column vector or a rectangular matrix. Each row of X starts a new line, and a return is generated when NEND ≥ N.

SUBROUTINE MATRIX

PURPOSE : TO MULTIPLY TWO RECTANGULAR MATRICES AND/OR THEIR TRANSPOSES AND ADD TO OR SUBTRACT FROM A THIRD RECTANGULAR MATRIX, STORING INTO THE THIRD MATRIX

ENTRY PARAMETERS

L	NUMBER OF ROWS IN X MATRIX AND Z MATRIX
M	NUMBER OF COLUMNS IN X MATRIX AND/OR NUMBER OF ROWS IN Y MATRIX
N	NUMBER OF COLUMNS IN Y MATRIX AND Z MATRIX
X	INPUT MATRIX OF DIMENSION L X M, L, OR M X L
Y	INPUT MATRIX OF DIMENSION M X N, N, OR N X M
Z	OUTPUT MATRIX OF DIMENSION L X N

SUBROUTINES CALLED: ADD DMULTT MULT MULTD MULTT SUB TMULTT

COMMONS : COVARP

LOCAL SYMBOLS : NONE

ENTRY PNT --- ADPRD ADPRDD ADPRDT DADPRT MATRIX SUBPRT TADPRT

USED/COMMN--- WORK

```
SUBROUTINE MEAZUR
PURPOSE :     PROCESSES MEASUREMENTS THROUGHT THE FILTER EQUATIONS

SUBROUTINES CALLED: ATTACK    FILM      HMM       OBSM      SIMM

COMMONS : AX        INTCOM    TRAJ      SMO

LOCAL SYMBOLS
        TMLAST      TRAJECTORY TIME OF LAST MEASUREMENT

        XX          DUMMY CALL ARGUMENT

USED/COMMN--- ALPHA     IPRINT    MCNTR     MEZACT    NMEAS
              TMN       TYPE      AA

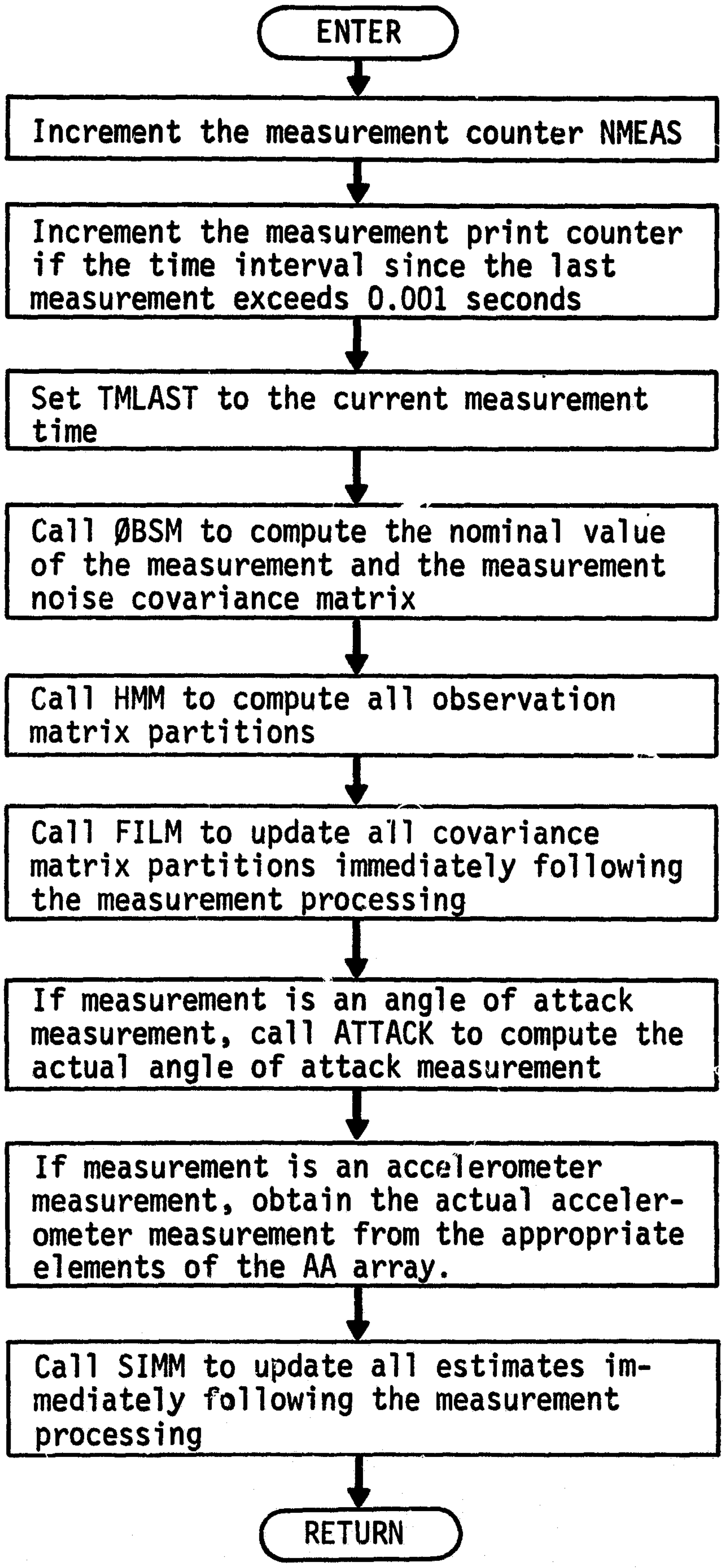
SET/COMMON--- IPRINT    MEZACT    NMEAS

LOADED    --- TMLAST
```

MEAZUR Analysis

Subroutine MEAZUR is the executive measurement processing subroutine. It controls the computation of all quantities required to generate a new estimate of the state and the associated error covariance matrix partitions. Subroutine MEAZUR also computes the actual angle of attack measurement for mode A and the actual accelerometer measurements for mode B. Unlike other measurement types available in the LTR program, the actual values of these two measurement types cannot be computed in the data generator since they are computed from information generated in the preprocessor, which is always run after the data generator has been run.

MEAZUR Flow Chart



Increment the measurement counter NMEAS

Increment the measurement print counter if the time interval since the last measurement exceeds 0.001 seconds

Set TMLAST to the current measurement time

Call ØBSM to compute the nominal value of the measurement and the measurement noise covariance matrix

Call HMM to compute all observation matrix partitions

Call FILM to update all covariance matrix partitions immediately following the measurement processing

If measurement is an angle of attack measurement, call ATTACK to compute the actual angle of attack measurement

If measurement is an accelerometer measurement, obtain the actual accelerometer measurement from the appropriate elements of the AA array.

Call SIMM to update all estimates immediately following the measurement processing

SUBROUTINE MULT

PURPOSE : TO MULTIPLY ONE RECTANGULAR MATRIX BY ANOTHER AND STORE INTO A THIRD RECTANGULAR MATRIX

ENTRY PARAMETERS

NCX	NUMBER OF COLUMNS OF X MATRIX AND NUMBER OF ROWS OF Y MATRIX
NCY	NUMBER OF COLUMNS OF Y MATRIX AND Z MATRIX
NRX	NUMBER OF ROWS OF X MATRIX AND Z MATRIX
X	INPUT MATRIX
Y	INPUT MATRIX
Z	PRODUCT OF X AND Y MATRICES (OUTPUT)

LOCAL SYMBOLS

I	INDEX
J	INDEX
K	INDEX
SUM	DOT PRODUCT OF I-TH ROW OF X AND J-TH COLUMN OF Y

SUBROUTINE MULTD

PURPOSE : TO MULTIPLY A RECTANGULAR MATRIX TIMES A DIAGONAL MATRIX

ENTRY PARAMETERS

NCX	NUMBER OF COLUMNS OF X AND NUMBER OF COLUMNS OF Z
ND	NUMBER OF DIAGONAL ELEMENTS OF Y
NRX	NUMBER OF ROWS OF X AND NUMBER OF ROWS OF Z
X	RECTANGULAR INPUT MATRIX
Y	DIAGONAL INPUT MATRIX
Z	RECTANGULAR OUTPUT MATRIX

LOCAL SYMBOLS

I	INDEX
J	INDEX
P	J-TH DIAGONAL ELEMENT OF Y

SUBROUTINE MULTT

PURPOSE : TO MULTIPLY ONE RECTANGULAR MATRIX BY THE TRANSPOSE OF ANOTHER MATRIX AND STORE INTO A THIRD MATRIX

ENTRY PARAMETERS

NCX	NUMBER OF COLUMNS OF X AND Y MATRICES
NRX	NUMBER OF ROWS OF X AND Z MATRICES
NRY	NUMBER OF ROWS OF Y AND NUMBER OF COLUMNS OF Z
X	RECTANGULAR INPUT MATRIX
Y	RECTANGULAR INPUT MATRIX (TO BE TRANSPOSED)
Z	OUTPUT MATRIX (X TIMES Y TRANSPOSED)

LOCAL SYMBOLS

I	INDEX
J	INDEX
K	INDEX
SUM	DOT PRODUCT OF I-TH COLUMN OF X AND J-TH COLUMN OF Y

SUBROUTINE NEXTAA

PURPOSE : READS SMOOTHED GYRO AND ACCELEROMETER DATA FOR INTEGRATION TO NEXT EVENT

SUBROUTINES CALLED: ALTFILE

COMMONS : SMO TRAJ

LOCAL SYMBOLS

I	INDEX
J	INDEX
NALT	DUMMY CALL ARGUMENT
NG	CALCULATED NUMBER OF RECORDS TO BE READ
TIME	TIME CORRESPONDING TO EACH RECORD

```
USED/COMMN--- DT        IEND      TC        TDIFF

READ      --- AA        TIME

SET/COMMON--- IAA       IEND      TEND
```

NEXTAA Analysis

Subroutine NEXTAA reads from file 16 the smoothed accelerometer and gyro coefficients (as determined by subroutine PREPRØS) required to cover the time interval to the next event.

The first time NEXTAA is called, IEND is zero, which causes the coefficients for time zero to be read. Thereafter, the coefficients for the beginning of the interval are obtained from the last point of the previous interval.

Subroutine NEXTAA also determines the number NG of records to be read to cover the interval from TC through TEND. However, if an end-of-file is encountered while these coefficients are being read, then the number IEND of coefficient records read is adjusted and TEND is reset to correspond to the last record read.

```
SUBROUTINE NEXTIM

PURPOSE :     READS EVENT DATA AND INITIALIZES CONTROL PARAMETERS
              FOR A MEASUREMENT OR OTHER EVENT


SUBROUTINES CALLED: ALTFILE   EXIT      PDUMP

COMMONS : TRAJ      INTCOM    QMPTI     LOGMOD    PHASE

LOCAL SYMBOLS
        NALT       DUMMY ARGUMENT USED TO CALL ALTFILE


USED/COMMN--- MCNTR     MCODE     TC        TDIFF     TEND      TMN
              IPHAS     QSDT      QST       TD        TR        VDIA
              VMASS     VRI       VSA


READ      --- MCODE     TMN

SET/COMMON--- MCNTR     TC        TDIFF     TEND      TYPE
              DT        DIA       IPHAS     MASS      RI
              SA        QSMCHG
```

NEXTIM Analysis

Subroutine NEXTIM computes the next event time and the time difference between the current time and the next event time. The logic proceeds as follows:

a. If the event schedule buffer has been used up, as determined by MCNTR = 250, then another 250 elements of the schedule is read from file 20 and MCNTR is set to zero.

b. Current time TC is updated, schedule index MCNTR is incremented, and the time TEND and type TYPE of the next event are taken from the schedule.

c. If the current time TC is equal to the time QST to change to the quasi-static dynamic model, then QSMCHG is set to true and the integration step size is changed to the quasi-static integration step size.

d. The entry phase IPHAS is determined by comparing current time TC to the time of parachute deployment TD and the time of parachute deployment TD and the time of parachute release TR. The vehicle parameters MASS, RI, SA, and DIA are then selected for this phase.

SUBROUTINE NORMNZ

PURPOSE : COMPUTES RANDOM VARIABLES FROM A DISTRIBUTION WITH ZERO MEAN AND STANDARD DEVIATION ONE

ENTRY PARAMETERS

SIGMA	OUTPUT RANDOM VARIABLE

LOCAL SYMBOLS

A	SUM OF THE VALUES OF RR
N	INTEGER PORTION OF SS MULTIPLIED BY 1.E-7
NX	CONTROLS START OF RANDOM SELECTION
RR	DIFFERENCE OF SS AND N
SS	INTERMEDIATE SUM OF SS, WW, YY, AND ZZ
WW	SEED VALUE FOR BUILDING SS
YY	SEED VALUE FOR BUILDING SS
ZZ	SEED VALUE FOR BUILDING SS

LOADED --- NX

NØRMNZ Analysis

NØRMNZ builds a random number from a distribution with a mean of zero and standard deviation of one. From preset seed values (NX = 0) or from values stored in a previous call (NX = 1), the variables WW, YY, ZZ are always positive and, when summed with SS, yield a number X such that X is in the open interval between 1.E + 7 and 1.E + 8, with occasional (i.e., greater than 3 sigma) values outside this interval. RR is then found as

RR = X modulo (integer portion of X)

so that RR is normally distributed over (0,1). Finally,

$$\text{SIGMA} = \left(\sum_{i=1}^{12} \text{RR} \right) - 6.$$

```
SUBROUTINE NTM

PURPOSE :    CONTROLS INTEGRATION OF MOST RECENT NOMINAL STATE
             VECTOR FROM TIME TC TO TIME TEND

ENTRY PARAMETERS
        UPDAIT      LOGICAL TO CONTROL UPDATING OF A NOMINAL STATE
                    (TRUE) OR A PERTURBED STATE (FALSE)

        XADD        DIFFERENCE IN STATE VECTOR OVER THE INTERVAL

        XNEW        RESULTING STATE VECTOR AT TIME TEND


SUBROUTINES CALLED: ATMSET    COPY      RKUTL3    RKUT3
                    DERIVE    DERIV3

COMMONS : LOGCOM    TRAJ      INTCOM    XMACH     LOGMOD

LOCAL SYMBOLS
        XXX         DUMMY CALL ARGUMENT

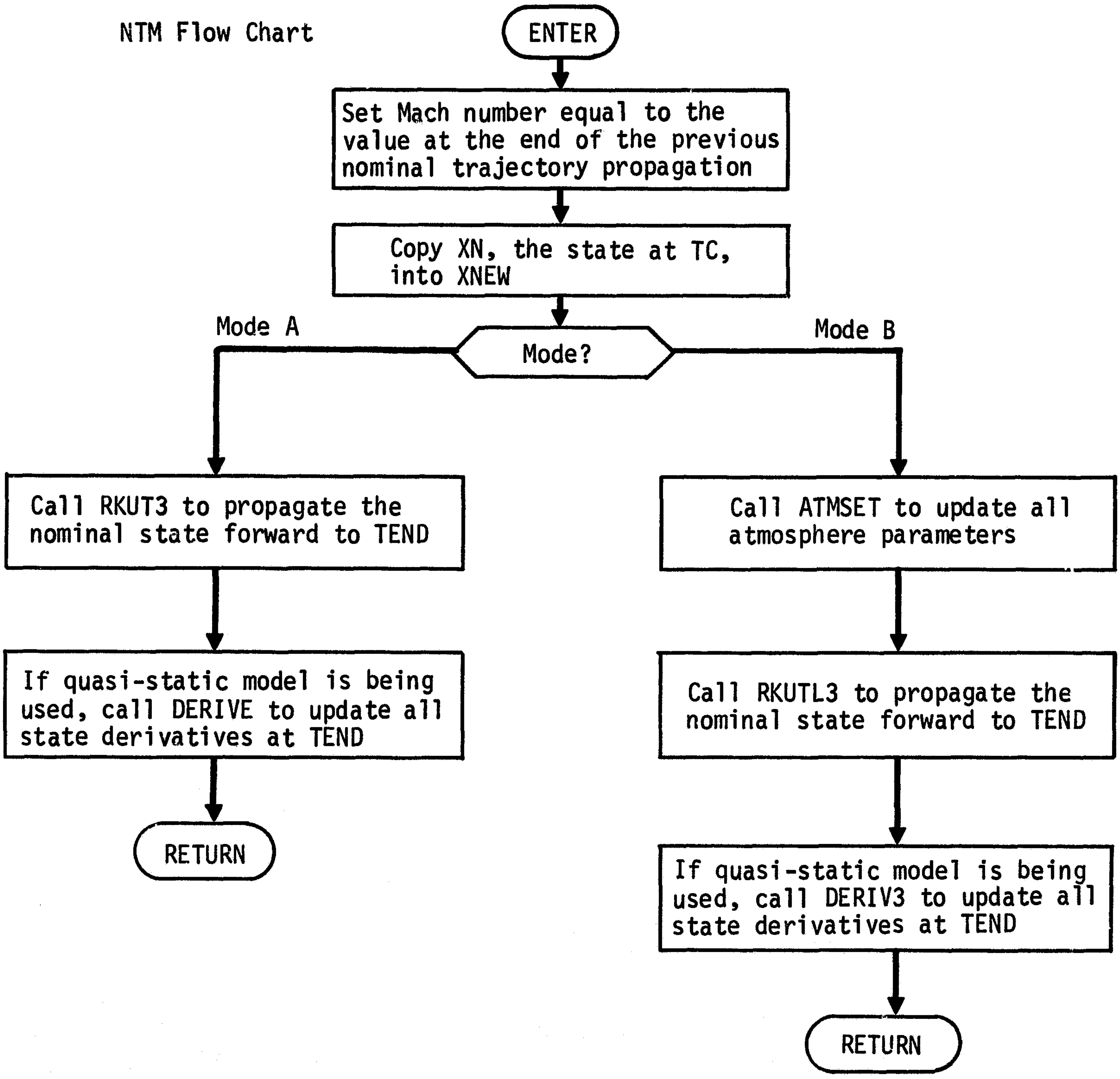

USED/COMMN--- LTR1      QSMCHG    RMACHB    TC        XN

SET/COMMON--- MACH
```

NTM Analysis

Subroutine NTM controls the propagation of the most recent nominal state vector over the time interval [TC, TEND] for both mode A and mode B.

NTM Flow Chart



```
SUBROUTINE NTM2

PURPOSE :    CONTROLS INTEGRATION OF ORIGINAL NOMINAL STATE VECTOR
             FROM TIME TC TO TIME TEND

ENTRY PARAMETERS
        X           ORIGINAL NOMINAL STATE AT TIME TEND


SUBROUTINES CALLED: ATMSET    RKUTL3    RKUT3     DERIVE    DERIV3

COMMONS : LOGCOM    TRAJ      LOGMOD

LOCAL SYMBOLS
        XADD        DIFFERENCE IN STATE VECTOR OVER THE INTERVAL

        XXX         DUMMY CALL ARGUMENT


USED/COMMN--- LTR1      QSMCHG    TC
```

NTM2 Analysis

Subroutine NTM2 controls the propagation of the original nominal state vector over the time interval [TC, TEND] for both mode A and mode B. A flow chart for NTM2 is not presented since it would be quite similar to the NTM flow chart. See NTM Analysis for more details.

SUBROUTINE OBSM

PURPOSE : COMPUTES MEASUREMENTS FOR RECONSTRUCTOR

ENTRY PARAMETERS

MEASUR	LOGICAL FOR CALCULATION OF MEASUREMENT NOISE MATRICES
OUTARG	MEASUREMENT COMPONENTS CALCULATED ACCORDING TO ICODE
XXX	DUMMY CALL ARGUMENT

SUBROUTINES CALLED: ATMSET DERIVE DERIV3 ECLIP EPHEM

COMMONS : OBSERV TRAJ STATE DOPLER LOGCOM INTCOM
COVARP XMACH

LOCAL SYMBOLS

ACRAME	ACTUAL RANGE AND RANGE-RATE VECTORS
AL	DISTANCE FROM EARTH CENTER TO DSN STATION
ALAT	LATITUDE OF DSN STATION
ALON	LONGITUDE OF DSN STATION
ALT	COMPUTED ALTITUDE USED TO FIND MEASUREMENT NOISE
ANG	DOWNRANGE ANGLE AT BEGINNING OF DIRECT SEARCH MINIMIZATION PROCESS
ARG1	AXIAL NON-GRAVITATIONAL ACCELERATION AT VEHICLE CENTER OF GRAVITY
ARG2	NORMAL NON-GRAVITATIONAL ACCELERATION AT VEHICLE CENTER OF GRAVITY
COSG	COSINE OF GANG
COSLAT	COSINE OF ALAT
COSOB	COSINE OF OBLIC
DELTA	HALF THE ANGLAR DISTANCE(RELATIVE TO PLANET CENTER)
DEL1	PERTURBED MISALIGNMENT ANGLE
DEL2	PERTURBED MISALIGNMENT ANGLE
DEL3	PERTURBED MISALIGNMENT ANGLE
DJUL	JULIAN DATE AT TIME TC
GANG	LONGITUDE OF DSN STATION AT TIME TC
HESE	HELIOCENTRIC ECLIPTIC STATE OF EARTH

HESP	HELIOCENTRIC ECLIPTIC STATE OF TARGET PLANET
HEST	GEOCENTRIC ECLIPTIC STATE OF DSN STATION
HIGHPT	DOWNRANGE ANGLE AT END OF DIRECT SEARCH MINIMIZATION PROCESS
ICODE	CURRENT MEASUREMENT TYPE BEING PROCESSED
IJ	INDEX OF RANGE,RANGE-RATE MEASUREMENT
ITEST	INTERMEDIATE INTEGER TO FIND DSN STATION NUMBER
MINALT	MINIMUM DISTANCE BETWEEN VEHICLE AND PLANET TERRAIN
SING	SINE OF GANG
SINLAT	SINE OF ALAT
SINOB	SINE OF OBLIC
STEP	ANGULAR STEPSIZE EMPLOYED IN DIRECT SEARCH MINIMIZATION PROCESS
TM	NUMBER OF SECONDS PER DAY
UPDAIT	DUMMY CALL ARGUMENT
WM	DISTANCE FROM PLANET CENTER TO PLANET TERRAIN
XGA	PERTURBED AXIAL DISTANCE TO CENTER OF GRAVITY
XMA	PERTURBED AXIAL DISTANCE TO ACCELEROMETER LOCATION
Z	FUNCTION ACTUALLY MINIMIZED IN RADAR ALTIMETER DIRECT SEARCH MINIMIZATION PROCESS
ZGA	PERTURBED NORMAL DISTANCE TO CENTER OF GRAVITY
ZMA	PERTURBED NORMAL DISTANCE TO ACCELEROMETER LOCATION

```
USED/COMMN--- ACC       ACCDT     ACCT      AF        AGAM      ALPH
              AQUANT    BTBL      C         CARCOR    DATEJ     DELT
              DP        DXN       EPSM      ETA       GHATO     GQUANT
              GYRODT    LTR1      LTR2      MACH      MASS      MASSA
              MCNTR     MCODE     OBLIC     OMEGAE    PRES      RANGE
              RANGER    REARTH    REDRR1    REDRR2    RHO       RI
              RM        RMACHB    ROTNO     RR        SA        SALT
              SCPEC     SLAT      SLON      TC        TEMP      TERHT
              TZERO     VR        XG        XM        XN        XP
              ZG        ZMM       ZN

SET/COMMON--- ACC       ACCT      MACH      MASSA     NM        R
              RANGE     RANGER

FCT CALLED--- FF        TAB
FCT DFND  --- FF
```

ØBSM Analysis

Subroutine ØBSM has three functions:

a. Compute nominal measurement for each measurement type.

b. Compute perturbed measurement for use in the numerical differencing computation of observation matrix partitions.

c. Compute measurement noise covariance matrix for each measurement type.

The computation of nominal measurements in ØBSM is very similar to the computation of actual measurements in ØBSM1. The equations used to compute nominal radar altimeter, stagnation pressure, stagnation temperature, range, and range-rate measurements have the same form as those used to compute the corresponding actual measurements in ØBSM1 and will not be discussed further (see subroutine ØBSM1 for details).

The C_j in subroutine ØBSM1 represent actual errors. In ØBSM, however, the C_j represent both nominal and perturbed values of the errors. The C_j are perturbed only when ØBSM is being used in the numerical differencing computation of observation matrix partitions.

If a measurement is being processed, ØBSM also computes the measurement noise covariance matrix. The equations used to compute the measurement noise covariance matrix for each measurement type are summarized in section 3.2 of the Analytic Manual.

Accelerometer and angle of attack measurements require further discussion since their treatment in ØBSM differs from their treatment in ØBSM1. Accelerometer measurements are used in the filter observation model only for the mode B reconstruction process. In mode A accelerometer measurements are treated as part of the dynamic model and all computations relating to mode A accelerometer measurements are performed in subroutine DERIVE; none are performed in ØBSM. The following equations are used in ØBSM to compute the accelerometer measurements for mode B:

$$a_x = \left[\frac{A}{\left(m + C_{30}\right)} \cos\left(\delta_1 + C_{55}\right) - \frac{N}{\left(m + C_{30}\right)} \sin\left(\delta_1 + C_{55}\right)\right] C_{51} + C_{52} \tag{1}$$

$$a_z = \left[\frac{A}{\left(m + C_{30}\right)} \sin\left(\delta_2 + C_{56}\right) + \frac{N}{\left(m + C_{30}\right)} \cos\left(\delta_2 + C_{56}\right)\right] C_{53} + C_{54} \tag{2}$$

where A and N are the axial and normal aerodynamic forces (including effect of parachute), δ_1 and δ_2 are misalignment angles, and m is vehicle mass. Bias terms C_{30}, C_{52}, C_{54}, C_{55}, and C_{56} are readily identifiable, as are scale factors C_{51} and C_{53}.

The angle of attack measurement, which is currently defined only for mode A, is defined as the angle of attack α computed in subroutine DERIVE.

Prior to computing any measurement, ØBSM calls the relevant dynamic model subroutines (DERIVE, if mode A; DERIV3 and ATMSET, if mode B) to ensure that all dynamic quantities have the proper values at the time of the measurement, since many of these quantities are required in the computation of measurements.

SUBROUTINE OBSM1

PURPOSE : COMPUTE MEASUREMENTS FOR DATA GENERATOR

COMMONS : TRAJ STATE DOPLER OBSERV LOGCOM

LOCAL SYMBOLS

ACRAME	ACTUAL RANGE AND RANGE-RATE VECTORS
AL	DISTANCE FROM EARTH CENTER TO DSN STATION
ALAT	LATITUDE OF DSN STATION
ALON	LONGITUDE OF DSN STATION
ANG	DOWNRANGE ANGLE AT BEGINNING OF DIRECT SEARCH MINIMIZATION PROCESS
ARG1	AXIAL NON-GRAVITATIONAL ACCELERATION AT VEHICLE CENTER OF GRAVITY
ARG2	NORMAL NON-GRAVITATIONAL ACCELERATION AT VEHICLE CENTER OF GRAVITY
COSG	COSINE OF GANG
COSLAT	COSINE OF ALAT
COSOB	COSINE OF OBLIC
DELTA	HALF THE ANGULAR DISTANCE (RELATIVE TO PLANET CENTER) COVERED IN THE DIRECT SEARCH MINIMIZATION PROCESS
DJUL	JULIAN DATE AT TIME TC
GANG	LONGITUDE OF DSN STATION AT TIME TC
HESE	HELIOCENTRIC ECLIPTIC STATE OF EARTH
HESP	HELIOCENTRIC ECLIPTIC STATE OF TARGET PLANET
HEST	GEOCENTRIC ECLIPTIC STATE OF DSN STATION
HIGHPT	DOWNRANGE ANGLE AT END OF DIRECT SEARCH MINIMIZATION PROCESS
I	INDEX
IJ	INDEX OF RANGE, RANGE-RATE MEASUREMENT
MINALT	MINIMUM DISTANCE BETWEEN VEHICLE AND PLANET TERRAIN
SING	SINE OF GANG

SINLAT	SINE OF ALAT
SINOB	SINE OF OBLIC
STEP	ANGULAR STEPSIZE EMPLOYED IN DIRECT SEARCH MINIMIZATION PROCESS
TM	NUMBER OF SECONDS PER DAY
W	DISTANCE FROM PLANET CENTER TO PLANET TERRAIN
Z	FUNCTION ACTUALLY MINIMIZED IN RADAR ALTITUDE DIRECT SEARCH MINIMIZATION PROCESS

```
USED/COMMN--- AGAM      AX        AY        C         CARCOR    CDELT1
              CDELT2    CDELT3    DATEJ     DP        DXN       EPSM
              ETA       GHATO     MACH      OBLIC     OMEGAE    PRES
              RANGE     RANGER    REARTH    RHO       RM        ROTNO
              SALT      SCPEC     SDELT1    SDELT2    SLAT      SLON
              TC        TEMP      TERHT     TZERO     VR        XG
              XM        XN        ZG        ZMN

SET/COMMON--- MEASS     RANGE     RANGER

FCT CALLED--- F         TAB

FCT DFND  --- F
```

ØBSM1 Analysis

Subroutine ØBSM1 computes the actual measurements for most measurement types available in the LTR program and incorporates the effects of all error sources except noise into these measurements. Those measurements not computed in ØBSM1 are the quantized VRU and ARU measurements, which are computed in subroutine SENSØR. The equations used to compute the actual measurements in ØBSM1 are summarized below.

If the terrain height model is not used, the radar altimeter measurement is given by

$$\tilde{h} = C_{71} h + C_{72} \qquad (1)$$

where h is the vehicle altitude, C_{71} is the altimeter scale factor, and C_{72} is the altimeter bias. If the terrain height model is used, the radar altimeter measurement is defined as the shortest distance between the vehicle and the planet terrain within the altimeter sweep angle 2η. The altimeter measurement is computed from

$$\tilde{h} = C_{71} \left[\left(h + R_p^2\right) + \tilde{f}\right]^{1/2} + C_{72} \qquad (2)$$

where $\tilde{f}$ is the minimum value of

$$f = W^2 - 2W\left(h + R_p\right) \cos\left(\tilde{\phi} - \phi\right) \qquad (3)$$

with respect to $\tilde{\phi}$, and is found using a direct search technique. For more details see section 2.4 of the Analytic Manual.

Unquantized accelerometer (VRU) and rate gyro (ARU) measurements, which are currently not used in the LTR reconstruction program, are given by

$$\dot{v}_x = a_x \cos \delta_1 - a_z \sin \delta_1 \qquad (4)$$

$$\dot{v}_z = a_x \sin \delta_2 + a_z \cos \delta_2 \qquad (5)$$

and

$$\dot{A} = \omega \cos \delta_3 \qquad (6)$$

where δ_1, δ_2, and δ_3 are the axial accelerometer, normal accelerometer, and rate gyro misalignment angles, respectively, ω is the vehicle angular velocity, and a_x and a_z are the axial and normal nongravitational accelerations at the VRU location. These latter accelerations are computed from

$$a_x = a_{xg} - \omega^2 \bar{x} + \dot{\omega} \bar{z} \tag{7}$$

$$a_z = a_{zg} - \omega^2 \bar{z} - \dot{\omega} \bar{x} \tag{8}$$

where a_{xg} and a_{zg} are the axial and normal nongravitational acceleration at the vehicle cg location, and $\bar{x}$ and $\bar{z}$ denote the offset of the VRU relative to the cg. Scale factor and bias errors for these unquantized measurements are currently undefined.

The stagnation pressure measurement p_o is a function of Mach number regime. If Mach number $M \geq 3$, then

$$p_o = C_{81} \left[\tfrac{1}{2} C_p \, \rho \, v_r^2 + p \right] + C_{82} \tag{9}$$

where ρ is the density, p is the ambient pressure, and the coefficient of pressure C_p is given by

$$C_p = 2 - \varepsilon \tag{10}$$

where ε is the ratio of densities in front of an behind the shock wave. Scale factor C_{81} and bias C_{82} are the error terms used in the supersonic regimes. If $1 \leq M < 3$, then p_o is again given by equation (9), but C_p is now given by

$$C_p = \frac{p}{8} \left[\left(\frac{\gamma + 1}{2} M^2 \right)^{\frac{\gamma}{\gamma - 1}} \cdot \left(\frac{\gamma + 1}{2\gamma M^2 - \gamma + 1} \right)^{\frac{1}{\gamma - 1}} - 1 \right] \tag{11}$$

where γ is the ratio of specific heats. If $M < 1$, then

$$p_o = C_{83} \left[p \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{\gamma}{\gamma - 1}} \right] + C_{84} \tag{12}$$

where C_{83} and C_{84} are the subsonic scale factor and bias errors, respectively.

The stagnation temperature measurement is computed from

$$T_o = C_{91}\left[T\left(1 + \frac{\gamma - 1}{2} M^2\right)\right] + C_{92} \tag{13}$$

where T is the ambient temperature and C_{91} and C_{92} are the scale factor and bias errors, respectively.

Range and range-rate measurements are given by

$$\rho = \left|\,\vec{\rho}\,\right| \tag{14}$$

and

$$\dot{\rho} = \frac{\dot{\vec{\rho}} \cdot \vec{\rho}}{\rho}, \tag{15}$$

respectively, where

$$\vec{\rho} = \vec{r} + \vec{r}_p - \vec{r}_\ell - \vec{r}_s \tag{16}$$

$$\dot{\vec{\rho}} = \dot{\vec{r}} + \dot{\vec{r}}_p - \dot{\vec{r}}_\ell - \dot{\vec{r}}_s \tag{17}$$

$(\vec{r}, \dot{\vec{r}})$ = vehicle state relative to target planet

$\left(\vec{r}_p, \dot{\vec{r}}_p\right)$ = target planet state relative to Sun

$\left(\vec{r}_\ell, \dot{\vec{r}}_\ell\right)$ = Earth state relative to Sun

$\left(\vec{r}_s, \dot{\vec{r}}_s\right)$ = tracking station state relative to Earth.

All vectors are assumed to be referred to an ecliptic coordinate system. The geocentric ecliptic coordinates of the i-th tracking station state are given by

$$x_s = \left(R_o + h_i'\right) \cos\theta_i' \cos G_i' \tag{18}$$

$$y_s = \left(R_o + h_i'\right) \left[\cos\theta_i' \cos\varepsilon \sin G_i' + \sin\theta_i' \sin\varepsilon\right] \tag{19}$$

$$z_s = \left(R_o + h_i'\right) \left[-\cos\theta_i' \sin\varepsilon \sin G_i' + \sin\theta_i' \cos\varepsilon\right] \tag{20}$$

$$\dot{x}_s = -\omega_\ell \left(R_o + h_i'\right) \cos\theta_i' \sin G_i' \tag{21}$$

$$\dot{y}_s = \omega_\ell \left(R_o + h_i' \right) \cos \theta_i' \cos \varepsilon \cos G_i' \tag{22}$$

$$z_s = -\omega_\ell \left(R_o + h_i' \right) \cos \theta_i' \sin \varepsilon \cos G_i' \tag{23}$$

where

$$h_i' = h_i + C_{108+3i} \tag{24}$$

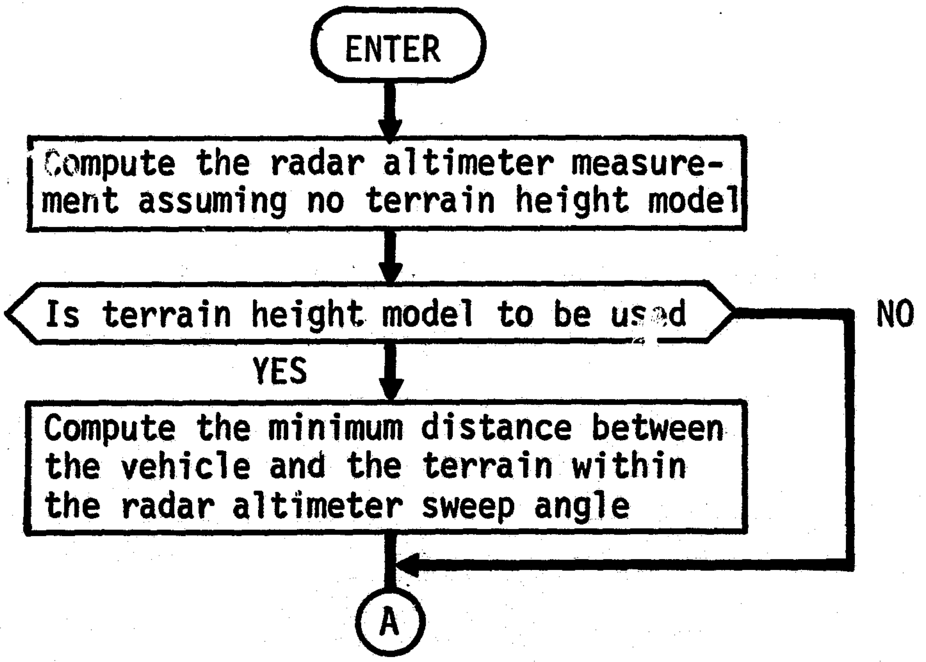
$$\theta_i' = \theta_i + C_{109+3i} \tag{25}$$

$$G_i' = \lambda_i' + \omega_\ell \left(t - t_o \right) + \text{GHA} \left(t_o \right) \tag{26}$$

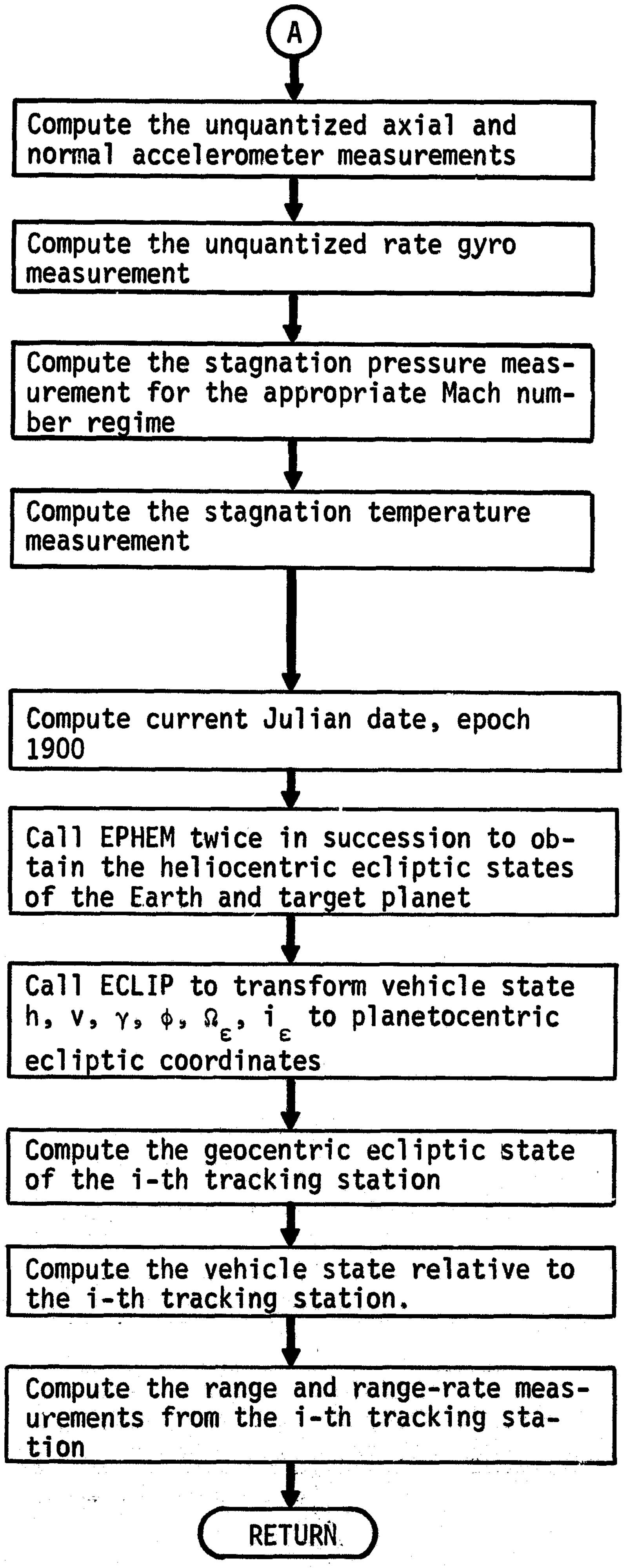
$$\lambda_i' = \lambda_i + C_{110+3i} \tag{27}$$

In these equations R_o denotes the Earth radius; h_i, the altitude of the i-th station; θ_i, the latitude; λ_i, the longitude; ω_ℓ, the Earth's angular velocity; t, the current time; t_o, the initial time; GHA $\left(t_o\right)$, the initial Greenwich hour angle of the vernal equinax; ε, the obliquity of the ecliptic; and C_{108+3i}, C_{109+3i}, and C_{110+3i}, station location errors. A range bias C_{63+i} is added to the range computed using equation (14), and a range-rate bias C_{66+i} is added to the range-rate computed using equation (15).

0BSM1 Flow Chart



0BSM1-5



A

Compute the unquantized axial and normal accelerometer measurements

Compute the unquantized rate gyro measurement

Compute the stagnation pressure measurement for the appropriate Mach number regime

Compute the stagnation temperature measurement

Compute current Julian date, epoch 1900

Call EPHEM twice in succession to obtain the heliocentric ecliptic states of the Earth and target planet

Call ECLIP to transform vehicle state $h, v, \gamma, \phi, \Omega_\varepsilon, i_\varepsilon$ to planetocentric ecliptic coordinates

Compute the geocentric ecliptic state of the i-th tracking station

Compute the vehicle state relative to the i-th tracking station.

Compute the range and range-rate measurements from the i-th tracking station

RETURN

```
SUBROUTINE OUTPHI

PURPOSE :     PRINT ENTRY PARAMETERS AND COVARIANCE MATRIX PARTITIONS


SUBROUTINES CALLED: MATOUT

COMMONS : TRAJ      COVARP

LOCAL SYMBOLS
        ALPHO       ALPH  IN DEGREES

        DPP         DP  IN MILLIBARS

        I           INDEX

        NS1         SQUARE OF NUMBER OF STATE VARIABLES NS

        NS2         NUMBER OF STATE VARIABLES PLUS 1

        PPX         PRES  IN MILLIBARS


USED/COMMN--- ALPH      DP        DYN       LISTQ     LISTU     LISTW
              NQ        NS        NU        NW        PRES      RAD
              TYPE

WRITTEN    --- AF       ALPHO     CA        CNQ       CN        DPP
              EPS       F         GA        LF        MACH      MWT
              PPX       RHO       TEMP      VR        VW        XP
              ZM        ZN
```

OUTPHI Analysis

The following entry parameters are printed, based on the most recent nominal trajectory:

1) Relative velocity (km/s);
2) Stagnation (atmospheric) pressure (millibars);
3) Wind velocity (km/s);
4) Atmospheric density (kg/km**3);
5) Dynamic pressure (millibars);
6) Angle of attack (degrees);
7) Molecular weight (kg-mol);
8) Coefficient of axial force (unit free);
9) Atmospheric temperature (degrees K);
10) Coefficient of normal force (unit free);
11) MACH number (unit free);
12) Coefficient of dynamic moment (unit free);
13) Axial force (kg-km/s**2);
14) Moment (kg-km/s**2);
15) Normal force (kg-km/s**2);
16) Gravitational acceleration (km/s**2);
17) Center of pressure (km);
18) Angle between inertial velocity and relative velocity (degrees).

If time is other than T_o, the following matrix partitions are printed:

1) State transition matrix Φ;

2) Solve-for parameter matrix Ψ;

3) Dynamic-consider parameter matrix;

4) Dynamic/measurement-consider parameter matrix;

5) Diagonal of the dynamic noise matrix.

```
SUBROUTINE OUTPP

PURPOSE :     OUTPUT CORRELATION MATRICES AND STANDARD DEVIATIONS
              OF AUGMENTED STATE COVARIANCE PARTITIONS

SUBROUTINES CALLED: CORMAT    CORR      CORRD     MATOUT

COMMONS : COVAPP    INTCOM    LOGCOM    TRAJ      PRINTS

LOCAL SYMBOLS
        I           INDEX

        J           INDEX

        NS1         NUMBER OF STATE VARIABLES SQUARED

        NS2         NUMBER OF STATE VARIABLES PLUS 1


USED/COMMN--- DU         DV        DW        DYN                 LTR2
              NQ         NS        NU        NV        NW        PP
              QQ         RAD       SQDU      SQDV      SQDW

WRITTEN   --- DYN

SET/COMMON--- PP         PPD       QQD
```

SUBROUTINE PLANE

PURPOSE: COMPUTE THE ORIENTATION OF THE ENTRY PLANE RELATIVE TO SPECIFIED REFERENCE PLANES

ENTRY PARAMETERS

D	JULIAN DATE, EPOCH JANUARY 0, 1900
ICOOR	INDICATES THE INPUT REFERENCE PLANE

SUBROUTINES CALLED: AECEQ EQUATR SUBSOL

COMMONS: DOPLER TRAJ

LOCAL SYMBOLS

COSG	COSINE OF REFERENCE LONGITUDE OF ASCENDING NODE
COSI	COSINE OF REFERENCE INCLINATION
COSP	COSINE OF REFERENCE PLANE LATITUDE
COSPHI	COSINE OF CALCULATED REFERENCE PLANE LATITUDE
ECLGEQ	TRANSFORMATION MATRIX FROM ECLIPTIC TO GEOCENTRIC EQUATORIAL
ENEC	ECLIPTIC UNIT VECTOR NORMAL TO ENTRY PLANE
ENMAG	MAGNITUDE OF ENEC, ENPL, OR ENSS VECTORS
ENPL	PLANETO-EQUATORIAL UNIT VECTOR NORMAL TO ENTRY PLANE
ENSS	SUB-SOLAR UNIT VECTOR NORMAL TO ENTRY PLANE
EREC	ECLIPTIC UNIT VECTOR ALIGNED WITH PHIR(1)
ERPL	PLANETO-EQUATORIAL UNIT VECTOR ALIGNED WITH PHIR(2)
ERSS	SUB-SOLAR UNIT VECTOR ALIGNED WITH PHIR(3)
GEQPEQ	TRANSFORMATION FROM GEOCENTRIC-EQUATORIAL TO PLANETOCENTRIC-EQUATORIAL
I	INDEX
J	INDEX
K	INDEX
PECSSO	TRANSFORMATION FROM PLANETOCENTRIC-ECLIPTIC TO SUB-SOLAR ORBITAL
SING	SINE OF REFERENCE LONGITUDE OF ASCENDING NODE

SINI	SINE OF REFERENCE INCLINATION
SINP	SINE OF REFERENCE PLANE LATITUDE
SINPHI	SINE OF CALCULATED REFERENCE PLANE LATITUDE
SUMEN	INTERMEDIATE SUM
SUMER	INTERMEDIATE SUM
TEMPOR	TEMPORARY TRANSFORMATION MATRIX

```
USED/COMMN--- ECLINC       ECLONG      OMEG        PHIR
SET/COMMON--- ECLINC       ECLONG      PHIR        ROTNO
```

PLANE Analysis

Given the orientation of the entry plane and the ϕ reference line relative to 1 of 3 coordinate systems, subroutine PLANE computes the orientation of the entry plane and the ϕ reference line relative to the remaining two coordinate systems. The orientation of the entry plane is defined by the inclination i and the longitude of the ascending node Ω, and the location of the ϕ reference line in the entry plane is defined by ϕ_{ref} (see subroutine ECLIP). These quantities are computed relative to the following three coordinate systems: (1) planetocentric ecliptic, (2) planetocentric equatorial, and (3) subsolar orbital plane.

Given i, Ω, and ϕ_{ref} relative to one of the three coordinate systems, the unit vector $\vec{e}_n$ normal to the entry plane and the unit vector $\vec{e}_r$ aligned with the ϕ reference line can be computed from

$$\vec{e}_n = \begin{bmatrix} \sin i \sin \Omega \\ -\sin i \cos \Omega \\ \cos i \end{bmatrix}$$

$$\vec{e}_r = \begin{bmatrix} \cos \phi_{ref} \cos \Omega - \sin \phi_{ref} \cos i \cos \Omega \\ \cos \phi_{ref} \sin \Omega + \sin \phi_{ref} \cos i \cos \Omega \\ \sin \phi_{ref} \sin i \end{bmatrix}$$

The coordinate transformations from the given coordinate system to the remaining two coordinate systems are then computed, and $\vec{e}_n$ and $\vec{e}_r$ are transformed to these systems.

Denoting the components of the transformed $\vec{e}_n$ and $\vec{e}_r$ as

$$\vec{e}_n = \left(e_{n_x}, e_{n_y}, e_{n_z}\right)$$

$$\vec{e}_r = \left(e_{r_x}, e_{r_y}, e_{r_z}\right) ,$$

the angles i', Ω', and ϕ'_{ref} defining the entry plane and ϕ reference line relative to the new coordinate system can be computed as follows:

$$\Omega' = \tan^{-1}\left(\frac{e_{n_x}}{-e_{n_y}}\right)$$

$$i' = \cos^{-1}\left(e_{n_z}\right)$$

$$\phi'_{ref} = \tan^{-1}\left(\frac{\sin \phi'_{ref}}{\cos \phi'_{ref}}\right)$$

where

$$\sin \phi'_{ref} = \frac{e_{r_z}}{\sin i'}$$

$$\cos \phi'_{ref} = \left[\frac{\vec{e}_z \times \vec{e}_n}{|\vec{e}_z \times \vec{e}_n|}\right] \cdot e_r$$

and $\vec{e}_z$ is a unit vector aligned with the z-axis of the new coordinate system.

Subroutine PLANE also computes the component of the planet inertial angular velocity normal to the entry plane. Letting ω_p denote the inertial angular velocity of the planet and ω_n, the component normal to the entry plane, we can compute ω_n as follows:

$$\omega_n = \omega_p \, \vec{e}_\omega \cdot \vec{e}_n$$

where $\vec{e}_\omega = (0,0,1)$ is a unit vector aligned with the planet spin axis and $\vec{e}_n$ is a unit vector normal to the entry plane. Both unit vectors are referred to the planetocentric equatorial coordinate system.

SUBROUTINE PLOTS

PURPOSE : PLOT N FRAMES OF GRAPHIC INFORMATION ON THE DD280 PLOTTER FROM DATA STORED DURING THE TRAJECTORY.

ENTRY PARAMETERS

JJ	NUMBER OF ELEMENTS USED IN EACH COLUMN OF XMAT
LABEL	LIST OF HOLLERITH NAMES OF INDEPENDENT AND DEPENDENT VARIABLES
LINEAR	LOGICAL VARIABLE - IF TRUE, PLOT A LINEAR GRID WITH SCALE NUMBERS
LOG	LOGICAL VARIABLE - IF TRUE, PLOT A SEMI-LOG GRID WITH X-AXIS LINEAR
N	NUMBER OF FRAMES TO BE PLOTTED FOR EACH INDEPENDENT VARIABLE
NI	NUMBER OF INDEPENDENT VARIABLES (1 OR 2)
TITLE	LIST OF HOLLERITH TITLES FOR PLOT IDENTIFICATION

SUBROUTINES CALLED: ABSBEAM CHAROPT FRAME LINEOPT LINES
MAPG MAPGSL SYMBOL

COMMONS : INTCOM PLOT2

LOCAL SYMBOLS

DEVAR	LIST OF COLUMN POSITIONS OF DEPENDENT VARIABLES
J	INDEX, SET TO 1 AND 2
K	INDEX, SET TO I-TH VALUE OF DEVAR
XLABEL	VALUE OF LABEL(1) OR LABEL(2), HOLLERITH NAME OF AN INDEPENDENT VARIABLE
XMAX	MAXIMUM VALUE OF J-TH COLUMN ELEMENTS OF XMAT, J=1,2
XMIN	MINIMUM VALUE OF J-TH COLUMN ELEMENTS OF XMAT, J=1,2
YLABEL	VALUE OF LABEL(K), HOLLERITH NAME OF A DEPENDENT VARIABLE
YMAX	MAXIMUM VALUE OF K-TH COLUMN ELEMENTS OF XMAT, K=1,N
YMIN	MINIMUM VALUE OF K-TH COLUMN ELEMENTS OF XMAT, K=1,N

USED/COMMN--- XMAT

LOADED --- DEVAR XLABEL YLABEL

PLØTS Analysis

Subroutine PLØTS functions as an executive program to plot data of interest. For a complete description of the DD280 plotter, see Appendix B.

SUBROUTINE PREDIC

PURPOSE : NOT CURRENTLY USED AS PREDICTION EVENT

LOCAL SYMBOLS--- NONE

SUBROUTINE PRINT

PURPOSE : PRINT OUTPUT FROM THE RECONSTRUCTOR

SUBROUTINES CALLED: ATMSET CONVRT COPY CORMAT DERIVE DERIV3 MATOUT OUTPHI OUTPP PSTORE

COMMONS : ACT PRINTS TRAJ AX BM PRNT3 COVARP GY PRE SUMRY OBSERV AM GYRACC LOGMOD LOGCOM INTCOM

LOCAL SYMBOLS

AEEQUA	ERRORS BETWEEN ESTIMATED AND ACTUAL DEVIATIONS FROM MOST RECENT NOMINAL TRAJECTORY AFTER A MEASUREMENT
AEEQUC	ERRORS BETWEEN ESTIMATED AND ACTUAL DEVIATIONS FROM MOST RECENT SOLVE-FOR PARAMETERS AFTER A MEASUREMENT
AESOLB	ERRORS BETWEEN ESTIMATED AND ACTUAL DEVIATIONS FROM MOST RECENT SOLVE-FOR VALUES BEFORE A MEASUREMENT
ALPHO	ALPH IN DEGREES
BESTAT	ERRORS BETWEEN ESTIMATED AND ACTUAL DEVIATIONS FROM MOST RECENT NOMINAL TRAJECTORY BEFORE A MEASUREMENT
CACTUL	ACTUAL DEVIATIONS FROM MOST RECENT NOMINAL VALUES OF SOLVE-FORS BEFORE AND AFTER A MEASUREMENT
CORGIN	ESTIMATED DEVIATIONS FROM ORGINAL NOMINAL OF SOLVE-FOR PARAMETERS
CQ	NOMINAL VALUES OF SOLVE-FOR PARAMETERS
DENSA	ACTUAL DENSITY
DEV	ESTIMATED DEVIATIONS FROM MOST RECENT NOMINAL TRAJECTORY AFTER A QUASI EVENT
DEVQ	ESTIMATED DEVIATIONS FROM MOST RECENT SOLVE-FOR PARAMETER VALUES AFTER A QUASI EVENT
DPP	DYNAMIC PRESSURE CONVERTED TO MILLIBARS
ICODE	CURRENT VALUE OF MCODE USED FOR LABEL IDENTIFICATION
LABEL	HOLLERITH ARRAY OF MEASUREMENT TYPES
LCON	CALLING PARAMETER FOR SUBROUTINE CONVRT
L1	HOLLERITH ARRAY OF STATE PARAMETERS
L2	HOLLERITH ARRAY (NOT USED)

L3	HOLLERITH ARRAY OF ATMOSPHERE PARAMETERS
L4	HOLLERITH ARRAY OF OUTPUT UNITS
L5	HOLLERITH ARRAY OF OUTPUT UNITS
QXACT	ACTUAL DEVIATIONS FROM MOST RECENT NOMINAL TRAJECTORY AFTER A QUASI EVENT
TMPACT	ACTUAL DEVIATION IN TEMPERATURE FROM MOST RECENT VALUE
ULABEL	HOLLERITH ARRAY OF OUTPUT UNITS
XOC	ORIGINAL NOMINAL TRAJECTORY VALUES
XRECEN	ACTUAL DEVIATIONS FROM MOST RECENT NOMINAL TRAJECTORY BEFORE OR AFTER A MEASUREMENT
XXX	DUMMY ARGUMENT

```
USED/COMMN--- ACCLXC    ACCLZC    AEEDEN    AEESTT    AEETMP    ALPH
              ALPHA     AXC       AZC       C         CACT      CBQ
              CD        DENS      DENSBM    DP        EDNBMC    EDNBQC
              EDNC      NGYRO     ICNTR     IPRINT    QSMCHG    LISTQ
              LTR1      LTR2      MACHNO    MCNTR     MCODE     MEZACT
              MEZEST    MWT       MWTA      NM        NQ        NS
              NV        NW        OMGC      OMGCC     PARACH    PP
              PPD       PPDBM     PPXD      PRSDAT    QEDN      QEDNBC
              QEDNBM    QQ        RAD       RHO       RHOA      SDMWT
              TEMDBM    TEMEDN    TEMP      TEMPA     THETI     THETRC
              THTC      TYPE      VR        XNAC      XNBQC     XNC

WRITTEN   --- AEEQUA    AEEQUC    AEESLV    AESOLB    AEESTT    ALPHO
              BESTAT    CA        CACTUL    CORGIN    CQ        DEV
              DEVQ      DPP       EDNBMC    EDNC      EPS       QEDN
              GA        LABEL     LISTQ     L1        L3        L5
              MACH      MEAS      MEZACT    MEZEST    MEZNOZ    PROB
              QEDNBM    QXACT     RESI      SD        SDDENS    SDENBM
              SDTEMP    STEMBM    TC        ULABEL    VR        VW
              XNAC      XNC       XOC       XRECEN

SET/COMMON--- AEEDEN    AEESLV    AEESTT    AEETMP    ALPHAA    DENS
              DENSBM    OMGCC     PPD       PPDBM     PPXD      QQD
              QQDBM     RESI      SDDENS    SDENBM    SDMWT2    SDTEMP
              STEMBM    TEMDBM    TEMEDN    THETRC

LOADED    --- LABEL     L1        L2        L3        L4        L5
              ULABEL
```

```
SUBROUTINE PRINT1

PURPOSE :      PRINT OUTPUT FROM THE DATA GENERATOR


SUBROUTINES CALLED: COPY

COMMONS : TRAJ       SUMRY      DOPLER    PHASE

LOCAL  SYMBOLS
        ALPHO       ALPH IN DEGREES

        DPP         DYNAMIC PRESSURE IN MILLIBARS

        DXNA        STATE DERIVATIVES IN OUTPUT UNITS

        I           INDEX

        PPX         STAGNATION PRESSURE IN MILLIBARS

        XNEW        ACTUAL STATE VECTOR IN OUTPUT UNITS


USED/COMMN--- ALPH       DP        DXN       MEASS     NE        PARACH
              PRES       RAD       XN

WRITTEN   --- AF         ALPHO     AM        AX        AY        CA
              CMQ        CN        DELRR     DELRRR    DPP       DXNA
    DT        EPSC       GA        IPHAS     MACH      MEASS     MWT
    PPX       PROB       RHO       TC        TEMP      VR        VW
    XNEW      XP         ZM        ZN
```

PRINT1 Analysis

The problem identification is printed. If the parachute has been deployed, a message is printed. The current time, actual state vectors, and state derivatives are printed in appropriate output units. The following atmospheric and acceleration terms are printed:

1) Relative velocity (km/s);
2) Stagnation pressure (millibars);
3) Wind velocity (km/s);
4) Atmospheric density (kg/km^3)
5) Dynamic pressure (millibars)
6) Angle of attack (degrees);
7) Molecular weight (kg-mol);
8) Coefficient of axial force (unit free);
9) Stagnation temperature (degrees K);
10) Coefficient of normal force (unit free);
11) Mach number (unit free);
12) Coefficient of moment (unit free);
13) Axial force (kg-km/s^2);
14) Moment (kg/km/s^2);
15) Normal force (kg-km/s^2);
16) Gravitational acceleration (km/s^2);
17) Center of pressure (km);
18) Axial acceleration (km/s^2);
19) Moment acceleration (km/s^2);
20) Normal acceleration (km/s^2);
21) Angle between V and V_R (degrees).

Measurement values that do not affect the dynamic equations are also printed.

```
SUBROUTINE PRPROS

PURPOSE :       CONTROLS SMOOT2 FOR PRODUCTION OF QUADRATIC WHICH
                APPROXIMATES ARU-VRU SENSOR DATA

SUBROUTINES CALLED: ALTFILE   INVPD2    MJLTT     SMOOT2    TMULT


COMMONS : SMO        TRAJ      LOGCOM    INTCOM    LOGMOD    QMPTI

LOCAL SYMBOLS
        A            WORKING MATRIX

        DE           WORKING MATRIX

        I            INDEX

        L            WORKING MATRIX

        NALT         DUMMY CALL ARGUMENT

        TYME         TIME ASSOCIATED WITH CURRENT VXQ, VZQ, THTQ


USED/COMMN--- B          DT        N         QSDT      QSMCHG    QST

READ      --- THTQ       TYME      VXQ       VZQ

SET/COMMON--- B          DT        LASTYM    QSMCHG    TC
```

PRPRØS Analysis

Subroutine PRPRØS is the executive preprocessor subroutine and controls computation of the coefficients used to smooth quantized VRU and ARU data. The operation of PRPRØS is more easily described by including a description of the operation of SMØØT2.

As quantized VRU and ARU data are input into PRPRØS, the quantized data arrays are shifted up and the new data are inserted in the bottom of each array (in SMØØT2) so the arrays hold exactly the five most recent data points. The coefficients of the smoothing quadratic for each data array are determined as follows:

$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} = E \cdot \begin{bmatrix} q_{k-2} \\ \vdots \\ q_{k+2} \end{bmatrix} \qquad (1)$$

where

$$E = (B^T B)^{-1} B \qquad (2)$$

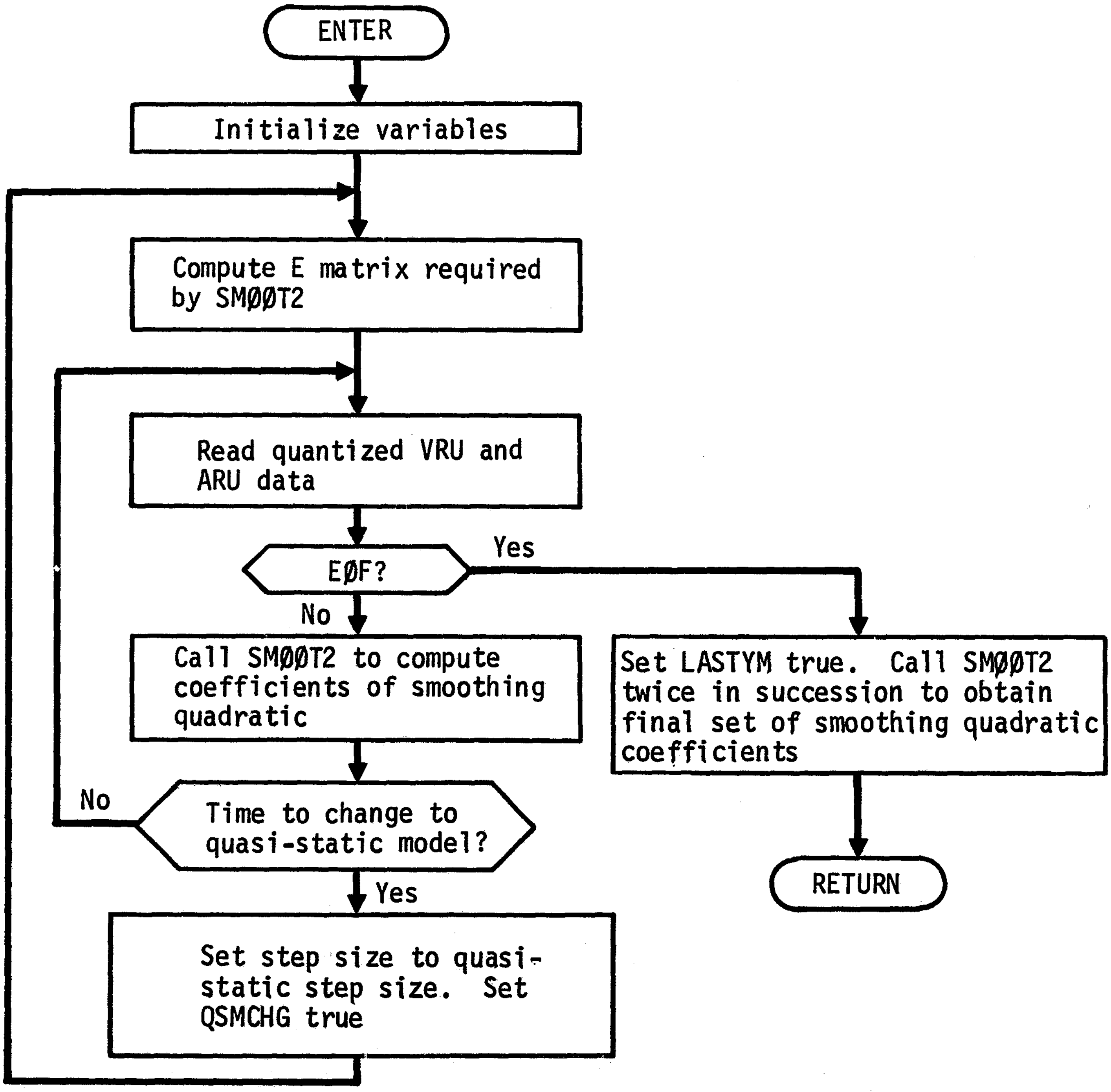
$$B = \begin{bmatrix} 1 & -2\Delta & 4\Delta^2 \\ 1 & -\Delta & 2\Delta^2 \\ 1 & 0 & 0 \\ 1 & \Delta & 2\Delta^2 \\ 1 & 2\Delta & 4\Delta^2 \end{bmatrix} \qquad (3)$$

$$\Delta = t_k - t_{k-1} \qquad (4)$$

and the C_j are the desired coefficients and $q_{k-2}, \ldots, q_{k+2}$ represent a set of five evenly spaced quantized data points over the time interval $[t_{k-2}, t_{k+2}]$. The matrix E is computed only twice-at the initial time, and when the dynamic model is changed to the quasistatic dynamic model.

An exception to this scheme occurs when PRPR0S is first called. In this case the coefficients are not determined until three data points are available. The two preceding data points are assumed to be zero by the five-point smoother.

Another exception occurs at the end of the process. After all quantized data have been input, the coefficients for the last two time points must still be computed. This is accomplished by calling SM00T2 twice in succession without reading any more quantized data. This is equivalent to assuming that the final two quantized data points are equal to the last quantized data point actually read.


ENTER
Initialize variables
Compute E matrix required by SMØØT2
Read quantized VRU and ARU data
EØF?
Yes
No
Call SMØØT2 to compute coefficients of smoothing quadratic
Set LASTYM true. Call SMØØT2 twice in succession to obtain final set of smoothing quadratic coefficients
RETURN
Time to change to quasi-static model?
No
Yes
Set step size to quasi-static step size. Set QSMCHG true

SUBROUTINE PSTORE

PURPOSE : STORES TRAJECTORY PLOTTING INFORMATION ON LOGICAL DISK FILES

SUBROUTINES CALLED: ALTFILE (MARTIN-CDC SYSTEMS ROUTINE FOR BUFFERS)

COMMONS :					
ACT	PRINTS	AX	TRAJ	PRNT3	COVARP
SUMRY	BM	INTCOM			

LOCAL SYMBOLS

ALFMES	MEAS(1) IN DEGREES WHEN TYPE = 6
H	VALUE OF VEHICLE ALTITUDE
I	INDEX
J	I-TH VALUE OF LISTQ, USED TO ISOLATE ELEMENTS OF C ARRAY
MRNED	MOST RECENT NOMINAL STATE PLUS ESTIMATED DEVIATIONS
MRNEDA	MOST RECENT NOMINAL ATMOSPHERE PLUS ESTIMATED DEVIATIONS
NALT	DUMMY CALL ARGUMENT
QC	QC(I) CONTAINS THE J-TH ELEMENT OF C
QMRNED	MOST RECENT NOMINAL VALUES OF SOLVE-FORS PLUS ESTIMATED DEVIATIONS
RATIOA	RATIOS OF ACTUAL ERRORS IN ESTIMATIONS TO STANDARD DEVIATIONS
RATIOQ	RATIOS OF ACTUAL ERRORS IN SOLVE-FORS TO STANDARD DEVIATIONS
RATIOS	RATIOS OF ACTUAL ERRORS IN STATE TO STANDARD DEVIATIONS

USED/COMMN---	AEEDEN	AEESLV	AEESTT	AEETMP	C	DENS
	DENSBM	EDNC	JM	LISTQ		
	MEAS	MWT	MWTA	NM	NQ	NS
	PLOTL	PPD	PPXD	QEDN	QQD	RAD
	RHO	RHOA	SDDENS	SDTEMP	TEMDBM	TEMEDN
	TEMP	TEMPA	TYPE	XN	XNAC	XNC
WRITTEN ---	ACCLXC	ACCLZC	AEEDEN	AEESLV	AEESTT	AEETMP
	ALFMES	ALPHAA	AXC	AZC	EDNBMC	EDNC
	H	MRNED	OMGCC	PPD	PPDBM	
	QC	QEDNBM	QMRNED	RATIOA	RATIOQ	RATIOS
	RESI	SDDENS	SDENBM	SDTEMP	STEMBM	TC
	THETRC	XNAC	XNC			

PSTØRE Analysis

PSTØRE stores trajectory parameters, estimates, and deviations from nominal values. If NQ = 0, information relating to solve-for parameters is not calculated or stored. Information is stored if the appropriate value of PLØTL is .TRUE.

```
SUBROUTINE READAC

PURPOSE :      READS ACTUAL MEASUEMENTS FROM UNIT 10 AND PERTURBS
               WITH RANDOM NOISE, SCALE, AND BIAS FACTORS


SUBROUTINES CALLED: EXIT      PDUMP     RNUM

COMMONS : ACT       OBSERV    TRAJ      PRE

LOCAL SYMBOLS
        I           INDEX

        ICODE       TYPE OF MEASUREMENT BEING PROCESSED

        J           INDEX

        N           NUMBER OF MEASUREMENT NOISE COMPONENTS


USED/COMMN--- BF        MCNTR     MCODE     MEZNOZ    SF        TAPETM
              TEND      MEASS

READ      --- ACCLXC    ACCLZC    MEASS     MWTA      PRSDAT    RHOA
              TAPETM    TEMPA     XNA

SET/COMMON--- HITGND    MEZACT    TEND      TYPE
```

READAC Analysis

READAC perturbs the actual measurement data with noise, scale, and bias factors and passes the perturbed measurements to the reconstructor for processing. If several measurements are taken at the same time, unit 10 is not reinterrogated. PARACH and HITGND are set to .TRUE. whenever actual altitude reaches the appropriate values. Subroutine RNUM is called to calculate the random noise MEZN0Z.

```
SUBROUTINE RKUTDG

PURPOSE :    INTEGRATE VECTOR X FROM TIME TSTART TO TIME TEND


ENTRY PARAMETERS
        TEND         FINAL TIME OF INTEGRATION

        TSTART       STARTING TIME OF INTEGRATION

        X            STATE VECTOR (OF SIZE NE) TO BE INTEGRATED


SUBROUTINES CALLED: DERIV1

COMMONS : TRAJ       DOPLER    LOGCOM

LOCAL SYMBOLS
        FRSTIM       LOGICAL VARIABLE TO CONTROL FIRST CALL TO RKUTDG

        H            INTEGRATION STEPSIZE

        I            INDEX

        KK           INTERMEDIATE WORKING ARRAY

        K1           INTERMEDIATE WORKING ARRAY

        K2           INTERMEDIATE WORKING ARRAY

        K3           INTERMEDIATE WORKING ARRAY

        K4           INTERMEDIATE WORKING ARRAY

        L1           INTERMEDIATE WORKING ARRAY

        T            CURRENT TIME OF INTEGRATION

        UPDAIT       LOGICAL (NOT CURRENTLY USED)

        W            INTERMEDIATE WORKING ARRAY

        XC           INTERMEDIATE WORKING ARRAY


USED/COMMN--- C          DT         DXN        NE         OMEG       ROTNO
              TERHT      TZERO

SET/COMMON--- HITGND

FCT CALLED--- F

FCT DFND  --- F

LOADED    --- FRSTIM
```

RKUTDG Analysis

Subroutine RKUTDG is the integration subroutine employed in the LTR data generator program. The algorithm employed is a modified Runge-Kutta method, although the classical fourth-order Runge-Kutta is used to start the integration process.

The system of equations to be integrated has the form

$$\dot{x} = f(x, t)$$

where x is the n-dimensional state vector and t is the time. The classical fourth-order Runge-Kutta algorithm is summarized as:

$$k_1 = h\ f\left(x_k, t_k\right)$$

$$k_2 = h\ f\left(x_k + \tfrac{1}{2} k_1, t_k + \frac{h}{2}\right)$$

$$k_3 = h\ f\left(x_k + \tfrac{1}{2} h_2, t_k + \frac{h}{2}\right)$$

$$k_4 = h\ f\left(x_k + k_3, t_k + h\right)$$

$$x_k^* = x_k$$

$$x_{k+1} = x_k + \frac{1}{6}\left(k_1 + 2k_2 + 2k_3 + k_4\right)$$

where h is the step size, x_k is the state at the beginning of the interval, and x_{k+1} is the state at the end of the interval. The state x_k^* is required by the modified Runge-Kutta algorithm, which is summarized as:

$$\ell_1 = k_1$$

$$k_1 = h\ f\left(x_{k+1}, t_{k+1}\right)$$

$$k_2 = 3.6\ k_1 - 4.2\left(x_{k+1} - x_k^*\right) + 1.6\ \ell_1$$

$$k_3 = h\ f\left(x_{k+1} + \tfrac{1}{4} k_1 + \tfrac{1}{4} k_2, t_{k+1} + \frac{h}{2}\right)$$

$$k_4 = h\ f\left(x_{k+1} - k_2 + 2k_3,\ t_{k+1} + h\right)$$

$$x^*_{k+1} = x_{k+1}$$

$$x_{k+2} = x_{k+1} + \frac{1}{6}\left(k_1 + 4k_3 + k_4\right).$$

The advantage of using the modified Runge-Kutta algorithm lies in the fact that the state derivatives need be evaluated only three times, and not four times as is required in the classical Runge-Kutta algorithm.

Another function of RKUTDG is to determine when the vehicle hits the planet surface. The first component of the state x, which is the vehicle altitude, is compared with the terrain height. If the two are equal, RKUTDG sets the logical variable HITGND to true, sets TEND to the current time, and returns.

Reference A. S. Chai: *A Modified Runge-Kutta Method, Simulation*, May 1968.

SUBROUTINE RKUTL3

PURPOSE : INTEGRATOR FOR MODE B RECONSTRUCTOR

ENTRY PARAMETERS

TEND	FINAL TIME OF INTEGRATION
TSTART	STARTING TIME OF INTEGRATION
UPDAIT	LOGICAL VARIABLE TO CONTROL UPDATING OF STATE VECTOR WHEN STATE DERIVATIVES ARE COMPUTED
X	STATE VECTOR BEING INTEGRATED
XADD	CHANGE IN STATE VECTOR OVER THE INTERVAL

SUBROUTINES CALLED: DERIV3

COMMONS : TRA. LOGCOM INTCOM

LOCAL SYMBOLS

H	INTEGRATION STEPSIZE
KK	INTERMEDIATE WORKING ARRAY
K1	INTERMEDIATE WORKING ARRAY
K2	INTERMEDIATE WORKING ARRAY
K3	INTERMEDIATE WORKING ARRAY
K4	INTERMEDIATE WORKING ARRAY
L	INDEX ON NUMBER OF INTEGRATION STEPS REQUIRED TO INTEGRATE THROUGH THE TIME INTERVAL
L1	INTERMEDIATE WORKING ARRAY
M	NUMBER OF INTEGRATION STEPS REQUIRED TO INTEGRATE OVER THE ENTIRE INTERVAL
ST	TOTAL INTEGRATION INTERVAL
T	CURRENT TIME OF INTEGRATION
W	INTERMEDIATE WORKING ARRAY
WI	INTERMEDIATE VARIABLE
XC	INTERMEDIATE WORKING ARRAY

USED/COMMN--- DT DXN NE

RKUTL3 Analysis

Subroutine RKUTL3 is the integration subroutine employed in the mode B reconstruction program, and employs the same Runge-Kutta algorithm that is used in subroutine RKUT3. The derivatives required by RKUTL3 are computed in subroutine DERIV3 (see subroutine RKUT3 for more details).

SUBROUTINE RKUT3

PURPOSE : INTEGRATOR FOR MODE A RECONSTRUCTOR

ENTRY PARAMETERS

TEND	FINAL TIME OF INTEGRATION
TSTART	STARTING TIME OF INTEGRATION
UPDAIT	LOGICAL TO CONTROL UPDATING OF STATE VECTOR WHEN STATE DERIVATIVES ARE COMPUTED
X	STATE VECTOR (OF SIZE NE) BEING INTEGRATED
XADD	CHANGE IN STATE VECTOR OVER THE INTERVAL

SUBROUTINES CALLED: DERIVE

COMMONS : TRAJ LOGCOM INTCOM

LOCAL SYMBOLS

H	INTEGRATION STEPSIZE
KK	INTERMEDIATE WORKING ARRAY
K1	INTERMEDIATE WORKING ARRAY
K2	INTERMEDIATE WORKING ARRAY
K3	INTERMEDIATE WORKING ARRAY
K4	INTERMEDIATE WORKING ARRAY
L	INDEX ON NUMBER OF STEPS REQUIRED TO INTEGRATE THROUGH THE TIME INTERVAL
L1	INTERMEDIATE WORKING ARRAY
M	NUMBER OF INTEGRATION STEPS REQUIRED TO INTEGRATE OVER THE ENTIRE INTERVAL
ST	TOTAL INTEGRATION INTERVAL
T	CURRENT TIME OF INTEGRATION
W	INTERMEDIATE WORKING ARRAY
WI	INTERMEDIATE VARIABLE
XC	INTERMEDIATE WORKING ARRAY

USED/COMMN--- DT DXN NE

RKUT3 Analysis

Subroutine RKUT3 is the integration subroutine employed in the mode A reconstruction program. The Runge-Kutta algorithm is the same as that employed in subroutine RKUTDG, except that the classical Runge-Kutta algorithm is used initially whenever RKUT3 is called. This procedure is required since RKUT3 is used to integrate more than one trajectory (original nominal, most recent nominal, and perturbed trajectories) and the local variables that contain information from the last integration may not correspond to the desired trajectory. Because the total interval TEND-TSTART may not be an exact multiple of the step size DT, DT is always adjusted so an exact multiple is attained.

Subroutine RKUT3 also computes the variable XADD, which is used in the computation of the state transition matrix and is defined as

$$\text{XADD} = x_{k+1} - x_k$$

where x_k and x_{k+1} are the states at the beginning and end, respectively, of the integration interval.

Subroutine RKUT3 does not have the hit-ground test appearing in RKUTDG since impact occurs when the actual trajectory, not the nominal trajectory, impacts the planet surface.

SUBROUTINE RNUM

PURPOSE : CALCULATES RANDOMLY SAMPLED MEASUREMENT NOISE FOR A GIVEN MEASUREMENT TYPE

ENTRY PARAMETERS

ICODE	MEASUREMENT TYPE
NCOMP	NUMBER OF COMPONENTS TO BE STORED

SUBROUTINES CALLED: NORMNZ

COMMONS : TRAJ OBSERV

LOCAL SYMBOLS

J	INDEX
NOISE	NORMALLY DISTRIBUTED NUMBER OF MEAN ZERO AND STANDARD DEVIATION UNITY

USED/COMMN--- SD

SET/COMMON--- MEZNOZ

SUBROUTINE RSTART

PURPOSE : PROVIDE RESTART CAPABILITY BY PUNCHING MATRICES OF INTEREST

SUBROUTINES CALLED: COPY

COMMONS : COVARP TRAJ INTCOM

LOCAL SYMBOLS

I	INDEX
NQQ	NQ SQUARED
NQU	NQ TIMES NU
NQV	NQ TIMES NV
NQW	NQ TIMES NW
NSS	NS SQUARED
NXQ	NS TIMES NQ
NXU	NS TIMES NU
NXV	NS TIMES NV
NXW	NS TIMES NW
XNAC	COPY OF XNA, ACTUAL STATE VECTOR
XNC	COPY OF XN, MOST RECENT NOMINAL STATE VECTOR
XOC	COPY OF XO, ORIGINAL NOMINAL STATE VECTOR

```
USED/COMMN--- CQU        CQV        CQW        CXQ        CXU        CXV
              CXW        DU         DV         DW         NQ         NS
              NU         NV         NW         P          Q          QEDN
              RAD

WRITTEN   --- EDN        TC         XNAC       XNC        XOC        P
              Q          CXQ        CXU        CXV        CXW        CQU
              CQV        CQW        DU         DV         DW         QEDN
```

SUBROUTINE SCHED

PURPOSE : SEQUENTIAL SCHEDULING OF MEASUREMENTS AND EVENTS FOR THE RECONSTRUCTOR

SUBROUTINES CALLED: ALTFILE EXIT

COMMONS : TRAJ PRED QMPTI

LOCAL SYMBOLS

CODE	ARRAY OF EVENT AND MEASUREMENT CODES
I	INDEX
IEND	INTEGER NUMBERS OF STEPSIZES DT IN TIMEND
ISTART	INTEGER NUMBERS OF STEPSIZES DT IN START
ITMDIF	INTEGER NUMBERS OF STEPSIZES DT IN TIMDIF
J	VALUE OF CODE WHOSE ISTART TIME IS LOWEST
K	CURRENT EVENT OR MEASUREMENT BEING SEQUENCED
L	INDEX FOR SET ITERATION COUNTER EVENT
LASTT	LAST TIME STORED IN TMN ARRAY
LOW	INDEX OF LOWEST ISTART VALUES
N	COUNTS NUMBER OF EVENT CARDS
NALT	DUMMY ARGUMENT
NENT	ACTUAL NUMBER OF EVENT CARDS
NEVENT	ARRAY CONTAINING TOTAL NUMBERS OF EACH TYPE OF EVENT
NPRD	SEQUENCES PREDICTION EVENTS (NOT USED)
START	TIME TO START N-TH EVENT
TIMDIF	TIME BETWEEN OCCURANCES OF N-TH EVENT
TIMEND	TIME TO END N-TH EVENT
TOTAL	TOTAL NUMBER OF EVENTS

```
USED/COMMN--- DT          MCODE       TC          TF          TMN
              TD          TR          QST

READ      --- CODE        TIMEND      MCODE       START       TIMDIF      TMN

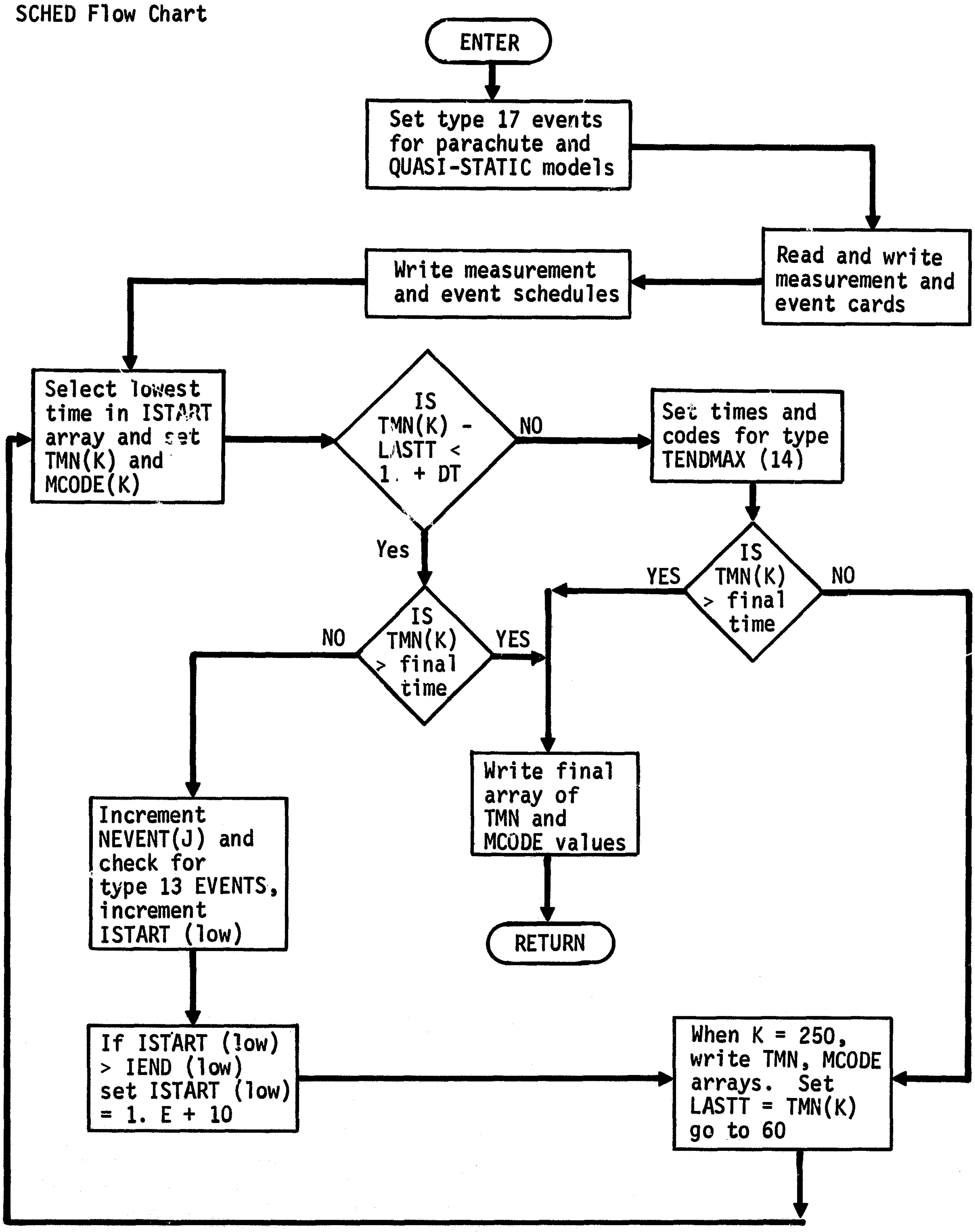

WRITTEN   --- CODE        TIMEND      MCODE       NEVENT      START       TIMDIF
              TMN         TOTAL

SET/COMMON--- LICNTR      MCODE       NPRED       PREDND      TMN
```

SCHED Analysis

SCHED reads and sequences measurements and other events for use by the reconstructor. START, TIMEND, TIMDIF, and CØDE(N) are read and written for identification purposes. START, TIMEND, and TIMDIF are converted to integer numbers of integration steps DT and stored. The process is repeated until a START value of 100000. or some other hard-wired value is read. All values read are then separated into groups according to CØDE(N) and written with identifiers. Groups of 250 measurements and events are then ordered on time, with TMN and MCØDE used as storage. TMN and MCØDE are written on unit 20 for processing by subroutine NEXTIM. The process continues until the final measurement time exceed TF. Whenever a start time exceeds an end time for an event type (start times are incremented), the start time is set to 1.E + 10. The last group of times and codes is then written, unit 20 is rewound, and the total number of events and total number of each type of event are printed with identifiers.

SCHED Flow Chart



```
SUBROUTINE SENSOR

PURPOSE:      COMPUTES THE QUANTIZED OUTPUT OF ACCELEROMETER AND
              GYRO SENSORS

SUBROUTINES CALLED:    ALTFILE

COMMONS:    TRAJ        SMO         SIZE        DOPLER

LOCAL SYMBOLS
        NALT      DUMMY ARGUMENT


USED/COMMN--- C             TC           TSTEP        TZERO        XN
              XSTEP         ZSTEP


WRITTEN   --- TC            THTQ         VXQ         VZQ

SET/COMMON--- THTQ          VXQ          VZQ
```

SENSOR Analysis

Subroutine SENSOR computes the quantized output of an accelerometer or gyro sensor. The quantized output of a sensor is found by first modifying the integral of the actual sensor input by appropriate scale factor, C_s, and bias, C_b, terms. This is then divided by the quantization step size, Δ. The greatest integer contained in this number is the sensor output count. The quantized output is then the output count times the quantization step size.

Let the operation of finding the largest integer contained in a number be designated by enclosing the number in brackets, { }. The quantized accelerometer outputs are given by

$$V_{xq} = \left\{ \frac{C_{sx} V_x + C_{bx}}{\Delta_x} \right\} \Delta_x$$

$$V_{zq} = \left\{ \frac{C_{sz} V_z + C_{bz}}{\Delta_z} \right\} \Delta_z$$

where V_x and V_z are the integrals of the actual accelerations experienced by the x and z accelerometers, respectively.

The quantized output of the gyro is found similarly except that the bias term is also integrated,

$$A_{\theta q} = \left\{ \frac{C_{s\theta} A_\theta + C_{b\theta} t}{\Delta_\theta} \right\} \Delta_\theta$$

where A_θ is the integral of the actual angular rate experience by the gyro and t is the time since the instrument was last initialized.

```
SUBROUTINE SETPLT

PURPOSE :      INITIALIZES PLOT VARIABLES AND READS PLOTTING NAMELIST


SUBROUTINES CALLED: ALTFILE   INIT280

COMMONS : INTCOM    LOGCOM

LOCAL SYMBOLS
        I           INDEX

        J           INDEX AND LOGICAL DISK FILE NUMBER

        NALT        DUMMY CALL ARGUMENT

        PLTVAR      PLOTTING NAMELIST SECTION NAME


USED/COMMN--- NQS

READ      --- INDEP     LINEAR    LOG       NVAR      PLOTL     PLOTVAR
              SUMTB

SET/COMMON--- INDEP     LINEAR    LOG       NVAR      PLOTL     SUMTB
```

SETICN-A

```
SUBROUTINE SETICN

PURPOSE :    INITIALIZES PRINT INCREMENT COUNTERS AT AN ITERATION
             COUNTER SET EVENT

COMMONS : INTCOM

LOCAL SYMBOLS :    NONE

USED/COMMN--- LICNTR    NICNTR

SET/COMMON--- ICNTR     IPRINT    NICNTR
```

SETICN Analysis

IPRINT is reset to 0 for later incrementing and usage. NICNTR is the counter for the N-th iteration counter set event, incremented by 1. ICNTR is the N-th value of LICNTR, a vector of print increments that allows the user to change print increments for denser print at critical trajectory intervals. SETICN is called whenever TYPE = 13 in LTRCØN. TYPE is set in subroutine NEXTIM. IPRINT, the counter for *groups* of measurements, is updated in subroutine MEASUR.

SUBROUTINE SETUP

PURPOSE : READ AND INITIALIZE DATA FOR THE RECONSTRUCTOR

SUBROUTINES CALLED: ALTFILE BEGIN COPY EXIT GHA
MATOUT NORMNZ PLANE PRINT SCHED SETPLT
TIME

COMMONS : SMO OBSERV ACT AX TRAJ LOGCOM
DET COVARP DOPLER ALREDY INTCOM AM
GYRACC PRE OMPTI PHASE

LOCAL SYMBOLS

DDAY	INTERMEDIATE JULIAN DATE
ERAN	NAME OF NAMELIST SECTION
ICOMM	ALLOWS USER TO INPUT COMMENTS PRIOR TO NAMELIST INPUT
ICOOR	INDICATES REFERENCE PLANE INPUTS
IDAY	CALENDAR DAY AT TZERO
IHR	HOUR OF DAY AT TZERO
III	TESTED AGAINST ICOMM TO IDENTIFY COMMENT CARDS
IMIN	MINUTE OF HOUR AT TZERO
IMO	CALENDAR MONTH AT TZERO
IYR	CALENDAR YEAR AT TZERO
LL	DECREMENT FOR AROTBL CONVERSION
L1	ARRAY OF HOLLERITH LABELS
L2	ARRAY OF HOLLERITH LABELS
MNAME	ARRAY OF HOLLERITH LABELS
NALT	DUMMY CALL ARGUMENT
NATMOS	INDICATES CHOICE OF ATMOSPHERES
NOISE	DUMMY CALL ARGUMENT TO SEED RANDOM NOISE GENERATOR
SECSI	FRACTIONAL SECONDS AT TZERO
ULAB	ARRAY OF HOLLERITH LABELS
ULABEL	ARRAY OF HOLLERITH LABELS

```
USED/COMMN--- APD       AROTBL    C         DATEJ     DELT      ECLINC
              ECLONG    GENDAT    LISTU     LISTW     LTR1      LTR2
              MODE      NACCEL    NE        NGYRO     NQ        NS
              NU        NV        NW        PHIR      RAD       RESTRT
              RR        SLAT      SLON      TC        THETI     XN
              XNAS      XO
READ      --- AA        ACCDT     ACCLXC    ACCLZC    AGAM      AQUANT
              AR        ATMOSS    BKTBL     BTBL      C         CACT
              CDEL      CDTBL     CQU       CQV       CQW       CXQ
              CXU       CXV       CXW       DELT      DIA       DT
              DU        DV        DW        DYN       ECLINC    ECLONG
              EDN       ERAN      ETA       GAMTBL    GO        GQUANT
              GYRODT    ICNTR     ICOOR     IDAY      IHR       III
              IMIN      IMO       IYR       LISTQ     LISTS     LISTU
              LISTV     LISTW     LTR1      LTR2      MASS      MCNTR
              MODE      MSATS     MU        MWTA      MWTM      NACCEL
              NATMOS    NE        NGYRO     NMEAS     NMPTS     NQ
              NS        NTP       NTPTS     NU        NV        NW
              OMEG      P         PHIR      PLOT      PROB      PRSDAT
              Q         QEDN      REDRR1    REDRR2    RESTRT    RHOA
              RI        RM        RR        SA        SALT      SD
              SDMWT     SDP       SECSI     SLAT      SLON
              TAPETM    TAPSAV    TC        TEMPA     TEND      TERHT
              TF        THETI     TIME      WDTBL     XD        XG
              XM        XN        XNA       XO        YG        YM
              ZG        ZMM
WRITTEN   --- C         DIA       I         J         LISTQ     LISTU
              LLISTV    LISTW     L1        L2        MASS      MNAME
              MU        NQ        NU
              NV        NW        OMEG      PROB      RAD       RI
              RM        RR        SA        TC        TF        ULAB
              ULABEL    XG        XM        XN        ZG        ZMM
SET/COMMON--- ACC       ALPHA     AROTBL    AXC       AZC       BF
              CDELT1    CDELT2    CDELT3    CQU       CQUC      CQV
              CQVC      CQW       CQWC      CXQ       CXQC      CXU
              CXUC      CXV       CXVC      CXW       CXWC      DU
              DV        DW        DYN       ECLINC    ECLONG    EDN
              GM        HM        ICNTR     IEND      IPRINT    IX
              IEND      IPRINT    IX        LASTIM              LTR2
              K5        LISTQ     LISTS     LISTSM    LISTU     LISTV
              LISTW     LM        LTR2      MCNTR     MM        NACCEL
              NE        NGYRO     NICNTR    NMEAS     NQS       NQUASI
              NS        OBLIC     OMGC      P         PHI       PHIR
              PP        PPC       PSI       Q         QEDN      QEDNBC
              QQ        R         RESTRT    SCQU      SCQV      SCQW
              SCXQ      SCXU      SCXV      SCXW      SD        SDELT1
              SDELT2    SDELT3    SDU       SDV       SDW       SF
              SIZEP     SLAT      SLON      SP        SQ        SQDU
              SQDV      SQDW      SURDL1    SUMFAR    THETI     THTC
              THU       THW       TYPE      TZERO     W         WORK
              W1        W2        W3        W4        W5        XN
              XNAS      XO
LOADED    --- ICOMM     L1        L2        MNAME     ULAB      ULABEL
```

SETUP Analysis

Subroutine SETUP reads and initializes the data necessary for the reconstruction program. Subroutine BEGIN is called to reset data changed by the data generator. Print counters, logic variables, and dynamic equation parameters are initialized. Scale factors are set to one and standard deviations and bias factors are set to zero. Subroutine N0RMNZ is called to seed the random noise generator. If logic variable GENDAT is .FALSE., the data generator was not run (i.e., the actual trajectory resides on previously generated data tapes), and the AR0TBL array must be converted. A series of data cards containing Hollerith information is read and printed. If the first character was a C, the card is presumed to be a comment card. Successive cards are read until the array PR0B contains the problem identification.

The matrices associated with the Kalman filter equations are set to zero, and the namelist section ERAN is read and written. The basic integration step size DT is set to twice the step used in the computation of the actual trajectory in the data generator, and the vehicle physical properties are chosen according to IPHAS. The number of state parameters NS is set according to mode A or mode B, the LISTS array is initialized, and subroutine SETPLT is called to read the plot package variables. SETUP then checks the deletion of accelerometer or gyro data for the mode A dynamic equations. If such data are deleted, C(54) or C(140) must appear as a consider parameter if either appears at all.

Subroutine TIME is called to calculate the Julian date at TZER0, the earth's obliquity is computed, and GHA is called to find the Greenwich hour angle at TZER0. Subroutine PLANE is called to calculate the orientation of the entry plane to the three reference coordinate systems. If GENDAT is .FALSE., the DSN station locations are converted to radians.

The initial trajectory conditions, vehicle characteristics, planetary values, and problem identification are printed. The lists of augmentation parameters and associated covariance matrices are printed. The nominal values of the C array are printed, the trajectory state is stored in the XNS and X0S arrays, and the actual atmosphere variables at TZER0 are read from unit 10. If the trajectory is not being restarted, the most recent nominal trajectory is also the original nominal trajectory and XN is stored in X0. Covariance and correlation matrices are stored in saving matrices, and initial accelerometer values are read from unit 16. Subroutine PRINT is called to print the trajectory and atmosphere values at TZER0, and subroutine SCHED is called to read and sequence measurement and event information. Control then returns to LTRC0N.

```
SUBROUTINE SETUP1

PURPOSE :     INITIALIZE AND READ DATA FOR THE DATA GENERATOR


SUBROUTINES CALLED: ALTFILE     ATMSET      COPY        DATE        DERIV1
            GHA     OBSM1       PRINT1      SENSOR      PLANE       TIME

COMMONS : ACCEL     TRAJ        DET         OBSERV      GY          ALREDY
          SUMRY     TER         SIZE        DOPLER      QMPTI       INTCOM

LOCAL SYMBOLS
          APP           SURFACE PRESSURE IN MILLIBARS

          ERAN          NAMELIST SECTION NAME

          I             INDEX

          J             INDEX

          LL            INDEX TO CONVERT AROTBL ARRAY

          NALT          DUMMY ARGUMENT TO CALL ALTFILE

          NATMOS        INDICATES WHICH ATMOSPHERE TO USE

          XXX           DUMMY ARGUMENT TO CALL ATMSET

USED/COMMN--- APO       AROTBL      C           DATEJ       DELT        ECLONG
    ECLINC    GHATO     ICOOR       IPHAS       MASS        MOL         MPT
    NE        NMPTS     NTPTS       PHIR        RAD         RESTRT      SLAT
    SLON      TMP       TPT         WDTBL       XG          XM          XN
    ZG        ZMM

READ      --- AR        C           DELT        DT          ERAN        ETA
              GO        ICNTR       LTR1        LTR2        NATMOS      PROB
              RESTRT    TC          TDIF        TEND        TERHT       TF
              TSTEP     XG          XM          XN          XSTEP       ZG
              ZMM       ZSTEP

WRITTEN   --- ACCLX     ACCLZ       APP         C           DIA         MASS
              MEASS     MOL         MPT         MU          MWT         OMEG
              PRES      PROB        RAD         RHO         RI          RM
              SA        TC          TEMP        TF          TMP         TPT
              XG        XM          XN          ZG          ZMM

SET/COMMON--- APO       AROTBL      C           CDELT1      CDELT2      CDELT3
    DELT      DIA       IPHAS       MASS        MOL         MPT         NE
    RI        SA        SDELT1      SDELT2      SDELT3      TMP         TPT
    TZERO     WDTBL     XG          XM          XN          ZG          ZMM
```

SETUP1 Analysis

SETUP1 is called from DATGEN to initialize and read data via NAMELIST for the data generator. Elements of the ARØTBL array are converted to radians and the variable GENDAT is set .TRUE. so that the reconstructor (see subroutine SETUP) will not convert ARØTBL elements. Problem identification and namelist ERAN are read and subroutine TIME is called to calculate the Julian date, epoch 1900, from the input calendar date. The obliquity of the ecliptic is calculated and trajectory time TC is stored as TZERØ. Subroutine GHA is called to compute the Greenwich hour angle at TZERØ. Since one set has been read into the first elements of PHIR, ECLØNG, and ECLINC regardless of the value of ICØØR, subroutine PLANE computes the orientation of the remaining reference planes. DSN tracking station latitudes and longitudes are converted to radians, and the desired target planet atmosphere is stored according to NATMØS. ARU-VRU misalignment errors are added to nominal location values. If RESTRT is false, state parameter values are perturbed with nominal errors read from input. Input data are converted to internal units and the atmosphere and vehicle characteristics are written, together with the perturbed state parameters and problem identification. Subroutines ATMSET, DERIV1, SENSØR, and ØBSM1 are called to initialize the trajectory integration at TZERØ and PRINT1 is called to print the data generator output at TZERØ. Control then returns to DATGEN for the data generator execution.

```
SUBROUTINE SMOOT2

PURPOSE :      COMPUTE QUADRATIC TO APPROXIMATE QUANTIZED
               ARU-VRU SENSOR DATA AND OUTPUT ON UNIT 16

SUBROUTINES CALLED: MULT

COMMONS : SMO        TRAJ      LOGCOM    INTCOM    ALREDY

LOCAL SYMBOLS
        I          INDEX

        IS         FLAG TO INDICATE IF FIRST CALL TO SMOOT2

        IT         COUNTS NUMBER OF TIMES SMOOT2 HAS BEEN CALLED
                   TO CONTROL PRODUCTION OF SENSOR COEFFICIENTS

        J          INDEX

USED/COMMN--- DT        LASTIM    M         N         RESTRT    TC
              THTQ      THTQA     VXQ       VXQA      VZQ       VZQA

WRITTEN   --- A1        A2        A3        TC

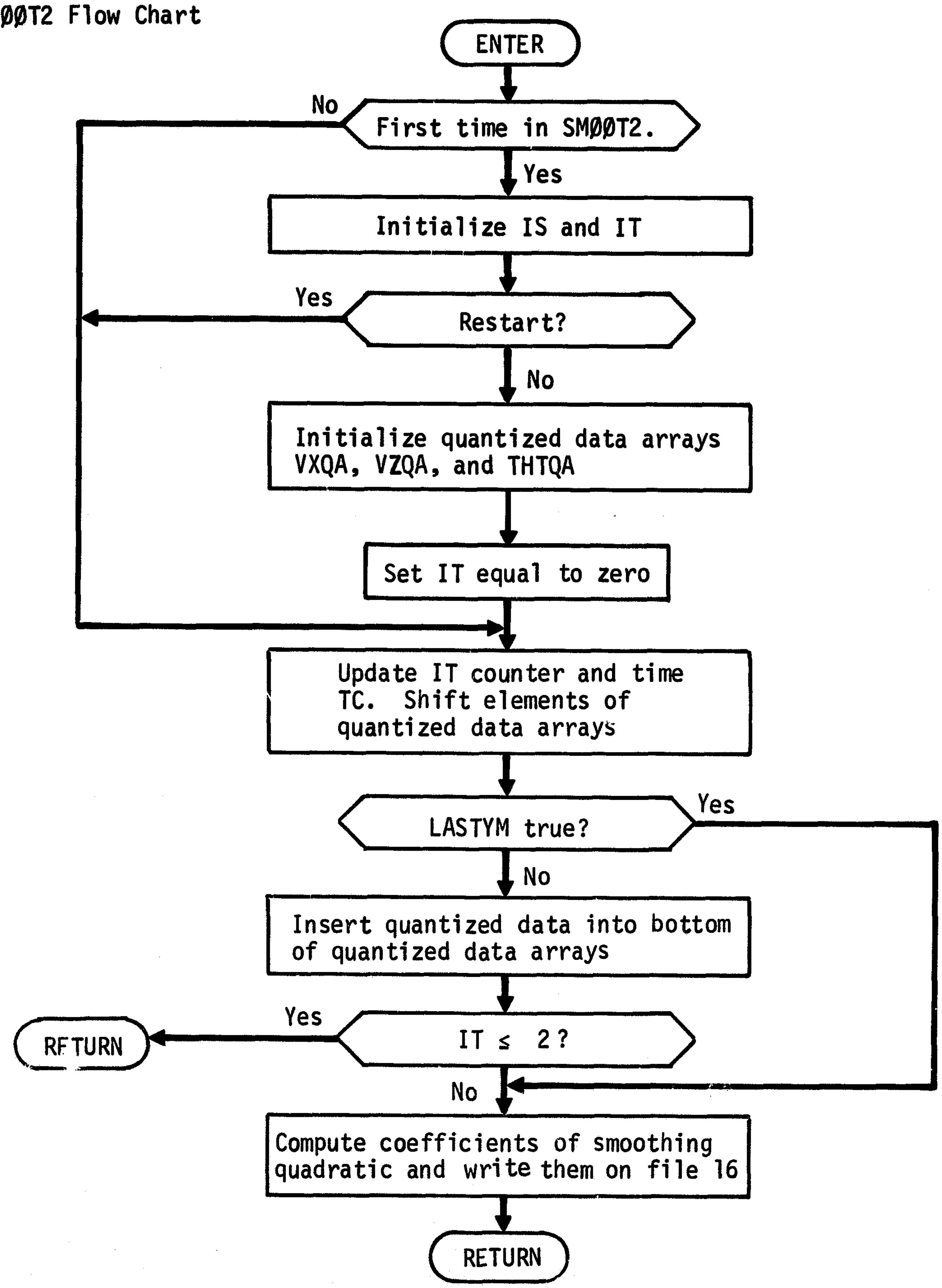
SET/COMMON--- TC        THTQA     VXQA      VZQA

LOADED    --- IS
```

SM00T2 Analysis

Subroutine SM00T2 computes the smoothing quadratic coefficients used to smooth quantized VRU and ARU sensor data. See subroutine PRPR0S for more details.

SM00T2 Flow Chart



```
SUBROUTINE STM

PURPOSE :     CONTROLS THE CALCULATION OF THE AUGMENTED STATE
              TRANSITION MATRIX PARTITIONS


ENTRY PARAMETERS
        ZADD        NOMINAL CHANGE IN THE STATE VECTOR OVER THE
                    INTERVAL OF INTEREST

SUBROUTINES CALLED: JACOBN

COMMONS : TRAJ      COVARP    INTCOM

LOCAL SYMBOLS
        I           INDEX

        NTM         EXTERNAL VARIABLE FOR INTEGRATION OF STATE EQUATION

        N1          NUMBER OF BASIC STATE VARIABLES SQUARED

        N2          NUMBER OF BASIC STATE VARIABLES PLUS 1

USED/COMMN--- NS        PHI

SET/COMMON--- PHI
```

STM Analysis

STM is an executive routine that controls the calculation of the partitions of the augmented state transition matrix.

The augmented state vector, $\overline{X}$, may be partitioned into the basic state vector, $\overline{x}$; solve-for parameter, $\overline{q}$; dynamic consider parameter, $\overline{u}$; measurement consider parameters, $\overline{v}$; and dynamic/measurement consider parameters, $\overline{w}$. When the state transition matrix is partitioned to correspond with the augmented state vector partitions, the state equation may be written

$$\overline{X}(t_F) = \Phi_{t_F,t_o} \overline{X}(t_o) = \begin{bmatrix} \phi_{t_F,t_o} & \psi_{t_F,t_o} & \theta_{u_{t_F,t_o}} & 0 & \theta_{w_{t_F,t}} \\ 0 & I & 0 & 0 & 0 \\ 0 & 0 & I & 0 & 0 \\ 0 & 0 & 0 & I & 0 \\ 0 & 0 & 0 & 0 & I \end{bmatrix} \begin{bmatrix} \overline{x}(t_o) \\ \overline{q}(t_o) \\ \overline{u}(t_o) \\ \overline{v}(t_o) \\ \overline{w}(t_o) \end{bmatrix}$$

The partitions ϕ, ψ, θ_u, and θ_w are computed by numerical differencing, i.e., the value of the j-th element of $\overline{X}(t_o)$ is perturbed by an amount δj, and the resulting change in $\overline{X}(t_F)$ is found by integrating the equations of motion. The j-th column of Φ is then given by $\Delta\overline{X}(t_F)/\delta j$.

The actual computation of the partitions of Φ are obtained by calling JACOBN once for each partition. The elements of $\overline{X}(t_o)$ to be perturbed are indicated by indices stored in the arrays LISTS, LISTQ, LISTU, and LISTW. The magnitude of the perturbation δj is determined from the variance of the parameter, $\sigma^2_{x_j}$. These variances are stored in the covariance matrices P, Q, D_u and D_w.

SUBROUTINE SUB

PURPOSE : TO SUBTRACT ONE RECTANGULAR MATRIX FROM ANOTHER AND STORE INTO A THIRD RECTANGULAR MATRIX

ENTRY PARAMETERS

NCX	NUMBER OF COLUMNS OF X, Y, AND Z MATRICES
NRX	NUMBER OF ROWS OF X, Y, AND Z MATRICES
X	MATRIX TO SUBTRACT FROM Y
Y	MATRIX TO BE SUBTRACTED FROM
Z	OUTPUT MATRIX (Y - X)

LOCAL SYMBOLS

I	INDEX
N	TOTAL NUMBER OF ELEMENTS OF X, Y, AND Z MATRICES

SUBROUTINE SUBSOL

PURPOSE: COMPUTES THE CO-ORDINATE TRANSFORMATION FROM PLANETOCENTRIC ECLIPTIC PLANE TO SUB-SOLAR PLANET-ORBITAL PLANE

SUBROUTINES CALLED: EPHEM

ENTRY PARAMETERS:

NP	TARGET PLANET CODE
D	JULIAN DATE, EPOCH JANUARY 0, 1900
EQSS	CO-ORDINATE TRANSOFRMATION FROM PLANETOCENTRIC ECLIPTIC PLANE TO SUB-SOLAR PLANET-ORBITAL PLANE

COMMONS: STATE

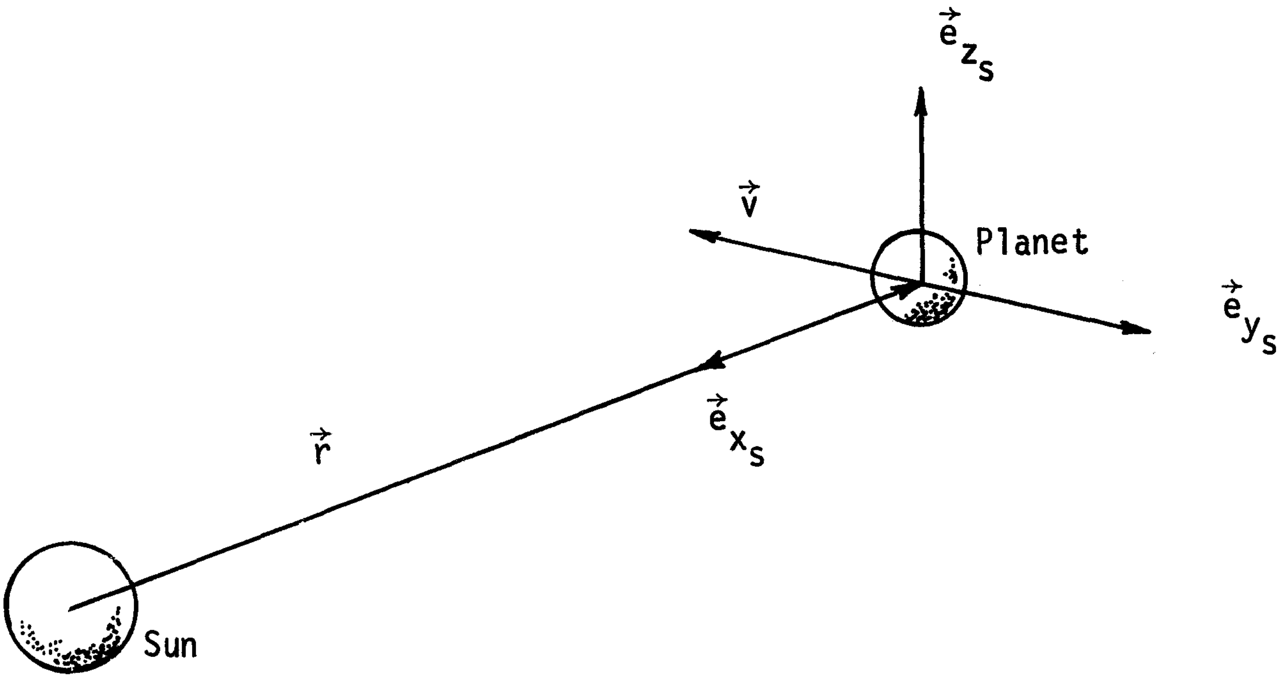
LOCAL SYMBOLS:

EZS	CROSS PRODUCT OF PLANET POSITION AND VELOCITY VECTORS, OR UNIT VECTOR ALLIGNED WITH Z-AXIS OF SUB-SOLAR PLANET-ORBITAL PLANE
C1	MAGNITUDE OF EZS
C2	MAGNITUDE OF PLANET POSITION VECTOR
EXS	UNIT VECTOR ALLIGNED WITH X-AXIS OF SUB-SOLAR PLANET-ORBITAL PLANE
EYS	UNIT VECTOR ALLIGNED WITH Y-AXIS OF SUB-SOLAR PLANET-ORBITAL PLANE
XP	PLANET POSITION AND VELOCITY VECTORS

USED/COMMON: CARCOR

SUBS0L Analysis

Subroutine SUBS0L computes the transformation from planetocentric ecliptic coordinates to subsolar planet orbital plane coordinates for an arbitrary planet. The subsolar planet orbital plane coordinate system is defined as the planetocentric system whose x-axis points directly at the sun, whose z-axis is normal to the planet's orbital plane, and whose y-axis is normal to the xz-plane and lies in the planet's orbital plane. In the figure below $\vec{r}$ and $\vec{v}$ denote the position and velocity vectors, respectively, of the planet relative to the sun. Unit vectors $\vec{e}_x$, $\vec{e}_y$, and $\vec{e}_z$ are aligned with the axes of the subsolar planet orbital plane system.



These unit vectors are defined as

$$\vec{e}_{x_s} = -\frac{\vec{r}}{r}$$

$$\vec{e}_{y_s} = \vec{e}_{z_s} \times \vec{e}_{x_s}$$

$$\vec{e}_{z_s} = \frac{\vec{r} \times \vec{v}}{|\vec{r} \times \vec{v}|}$$

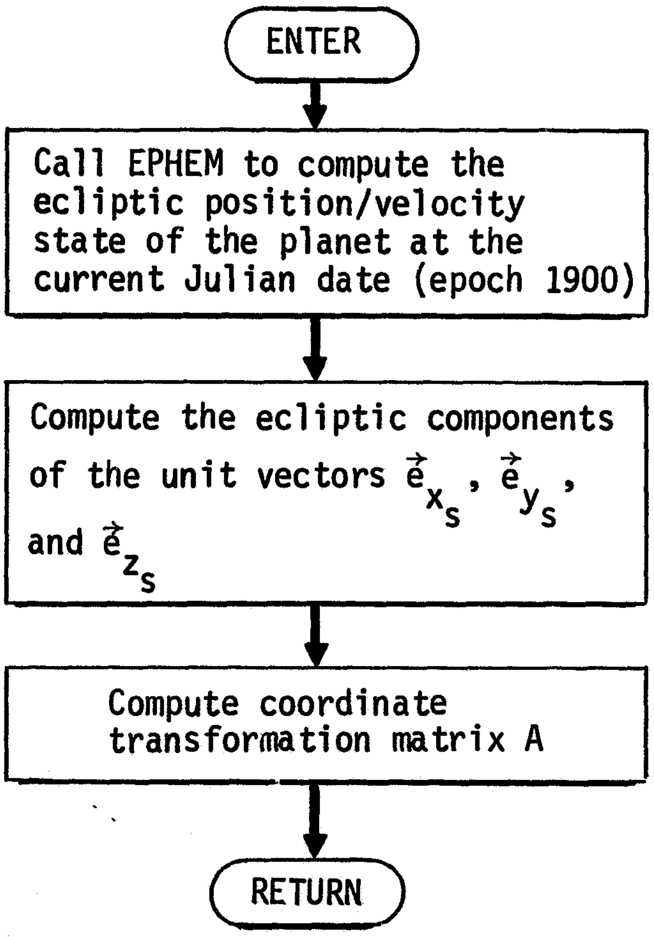
If these unit vectors are referred to the ecliptic coordinate system, the coordinate transformation A from planetocentric ecliptic to subsolar planet orbital plane coordinates is given by

$$A = \begin{bmatrix} \vec{e}_{x_s}^{\,T} \\ \hline \vec{e}_{y_s}^{\,T} \\ \hline \vec{e}_{z_s}^{\,T} \end{bmatrix}$$

Thus

$$\vec{x}_{subsolar} = A\,\vec{x}_{ecliptic}$$

SUBSOL Flow Chart



```
SUBROUTINE SUMMRY

PURPOSE :    WRITES SUMMARY PRINT AND CALLS PLOT PACKAGE


SUBROUTINES CALLED: ALTFILE   PLOTS

COMMONS : SUMRY     PLOT2     INTCOM    LOGCOM

LOCAL SYMBOLS
        I           INDEX

        ITAPE       LOGICAL DISK FILE NUMBER

        J           INDEX

        K           INDEX

        LABEL       HOLLERITH LIST OF PLOT VARIABLES

        NALT        DUMMY CALL ARGUMENT

        NPLOTS      NUMBER OF PLOTS IN I-TH SECTION

        NV          NUMBER OF VARIABLES IN I-TH SECTION

        TITLE       HOLLERITH LIST OF SECTION TITLES


USED/COMMN--- NVAR      PLOTL     SUMTB

READ      --- ITAPE     XMAT

WRITTEN   --- LABEL     PROB      TIMEF     TITLE     XMAT

SET/COMMON--- PROB

LOADED    --- LABEL     TITLE     TABONE    TABTWO
```

SUMMRY Analysis

If SUMTB(I) is .TRUE., the I-th summary table is written (containing problems identification, title, and label information) and plot values are stored on unit 10. Subroutine PLØTS is called to plot using the system plot package.

SUBROUTINE SYMTRZ

PURPOSE : TO DETERMINE THE SYMMETRIC COMPONENTS OF A SQUARE MATRIX BY TAKING ONE HALF THE SUM OF THE MATRIX AND ITS TRANSPOSE

ENTRY PARAMETERS

N	DIMENSION OF X
X	SQUARE MATRIX WHICH IS REPLACED BY ITS SYMMETRIC COMPONENT

LOCAL SYMBOLS

I	INDEX
J	INDEX

```
FUNCTION   TAB

PURPOSE :    TO PERFORM A LINEARLY INTERPOLATED TABLE LOOKUP


ENTRY PARAMETERS
        TABLE      SINGLY DIMENSIONED ARRAY WHOSE FIRST ENTRY INDICATES
                   THE NUMBER  N  OF BREAK POINTS.  THE  N  BREAK POINTS
                   OF THE INDEPENDENT VARIABLE ARE NEXT AND THE REMAINING
                   N  VALUES ARE THE BREAK POINTS OF THE DEPENDENT VARIABLE

        X          VALUE OF THE INDEPENDENT VARIABLE

LOCAL SYMBOLS
        K       INDEX

        L       INDEX
```

TAB Analysis

The index K is set to TABLE(1)+1, and X is tested against TABLE(L), L = 3, K. If X ≤ TABLE(L),

$$M = K + L - 1$$

and

$$TAB = \frac{(X - TABLE(L-1))}{(TABLE(L) - TABLE(L-1))} * (TABLE(M) - TABLE(M-1) + TABLE(M-1))$$

where TABLE is a singly dimensioned array whose first entry indicates the number N of break points. The N break points of the independent variable are next, and the remaining N values are the break points of the dependent variable.

SUBROUTINE TIME

PURPOSE: TRANSFORM CALENDAR DATE TO/FROM JULIAN DATE, EPOCH 1900

ENTRY PARAMETERS

DAY	JULIAN DATE, EPOCH 1900
IYR	CALENDAR YEAR
MO	CALENDAR MONTH
IDAY	CALENDAR DAY
IHR	HOUR OF THE DAY
MIN	MINUTE OF THE HOUR
SEC	FRACTIONAL SECONDS
ICODE	OPERATIONAL MODE =1, JULIAN DATE IS INPUT, CALENDAR DATE IS OUTPUT =0, CALENDAR DATE IS INPUT, JULIAN DATE IS OUTPUT

LOCAL SYMBOLS

IA	NUMBER OF CENTURIES
IB	YEARS IN PRESENT CENTURY
IP	NUMBER OF MONTH (BASED ON MARCH AS NUMBER ZERO)
IQ	NUMBER OF YEARS
IR	NUMBER OF CENTURIES DIVIDED BY 4
IS	NUMBER OF YEARS SINCE LAST 400 YEAR SECTION BEGAN
IT	NUMBER OF LEAP YEARS IN PRESENT CENTURY
IU	NUMBER OF YEARS SINCE LAST LEAP YEAR
IV	NUMBER OF DAYS IN LAST YEAR
IX	INTERMEDIATE VARIABLE
J	INTERMEDIATE VARIABLE
JD	NUMBER OF DAYS IN JULIAN DATE
P	JULIAN DATE
R	FRACTIONAL PORTION OF DAY IN JULIAN DATE

```
SUBROUTINE TIMEX

PURPOSE :   TO PRINT TIME ELAPSED SINCE LAST CALL


ENTRY PARAMETERS
        NAME     A HOLLERITH NAME OF A SUBROUTINE


SUBROUTINES CALLED: CPWMS     XRCL

LOCAL SYMBOLS
        N       LOGIC VARIABLE SET TO +1 OR -1

        T       ELAPSED TIME IN SECONDS (T2-T1)

        T1      PREVIOUS TIME IN SECONDS

        T2      CURRENT TIME IN SECONDS


WRITTEN   --- NAME      T

LOADED    --- N
```

TIMEX Analysis

XRCL and CPWMS are Martin Marietta/CDC system routines that, together, return real clock time in seconds. If N < 0, elapsed time and a Hollerith subroutine name are printed. T1 is set to T2 and N to -N prior to return.

SUBROUTINE TMULT

PURPOSE : TO MULTIPLY THE TRANSPOSE OF A RECTANGULAR MATRIX BY ANOTHER RECTANGULAR MATRIX AND STORE IN A THIRD MATRIX

ENTRY PARAMETERS

NCX	NUMBER OF COLUMNS OF X AND NUMBER OF ROWS OF Z
NCY	NUMBER OF COLUMNS OF Y AND Z MATRICES
NRX	NUMBER OF ROWS OF X AND Y MATRICES
X	INPUT RECTANGULAR MATRIX (TO BE TRANSPOSED)
Y	INPUT RECTANGULAR MATRIX
Z	OUTPUT MATRIX (X TRANSPOSED TIMES Y)

LOCAL SYMBOLS

I	INDEX
J	INDEX
K	INDEX
SUM	PRODUCT OF I-TH COLUMN OF X AND J-TH COLUMN OF Y

SUBROUTINE TMULTT

PURPOSE : TO MULTIPLY THE TRANSPOSES OF TWO RECTANGULAR MATRICES AND STORE INTO A THIRD RECTANGULAR MATRIX

ENTRY PARAMETERS

NCX	NUMBER OF COLUMNS OF X AND NUMBER OF ROWS OF Z
NRX	NUMBER OF ROWS OF X AND NUMBER OF COLUMNS OF Y
NRY	NUMBER OF ROWS OF Y AND NUMBER OF COLUMNS OF Z
X	INPUT MATRIX (TO BE TRANSPOSED)
Y	INPUT MATRIX (TO BE TRANSPOSED)
Z	PRODUCT OF X TRANSPOSED AND Y TRANSPOSED (OUTPUT)

LOCAL SYMBOLS

I	INDEX
J	INDEX
K	INDEX
SUM	DOT PROUCT OF I-TH COLUMN OF X AND J-TH ROW OF Y

FUNCTION WINDV

PURPOSE: COMPUTE PERTURBED WIND PROFILES

ENTRY PARAMETERS

X	CURRENT ALTITUDE OF VEHICLE

SUBROUTINES CALLED: TAB

COMMONS : TRAJ

LOCAL SYMBOLS

I	INDEX
J	INDEX
N	NUMBER OF ELEMENTS IN WDTBL ARRAY
WDTBC	PERTURBED WIND BREAKPOINTS

USED/COMMN--- C WDTBL

APPENDIX A

CDC 280 SOFTWARE PACKAGE

1. INTRODUCTION

This document has been written to provide the user with software information that he might require in using the CDC 280 for producing microfilm or hardcopy.

These routines are a part of the CDC 6000 MACE Operating System and utilize the CDC 280 as an on-line peripheral device.

2. THE CDC 6000 OPERATION SYSTEM INTERFACE

2.1 Interfacing the 280 Display and Recorder with the MACE Operation System requires the addition of two special file names, Film Plot (FILMPL) and Film Print (FILMPR). Film Plot files (FILMPL) and other I/O files, such as OUTPUT, that are used by the program must be declared on the program name card for the particular job. The Film Print file (FILMPR) can be declared in the same manner, or it can be established via a control card. Data sent to either of these files during job execution is written on the system disk in the same manner as print data.

Each file being filmed can be controlled by Output control point commands. The commands are: END, REPEAT, and SUPPRESS.

280 CONSOLE OPERATION

When the RUN mode is selected on the console, output data directed to the 280 is transferred to both the console CRT and the recorder CRT. (The RUN mode should not be confused with the RUN control card. By use of the 280 console keyboard, the operator has the options to stop the 280 and monitor each page of output. The operator accomplishes this by selecting the STEP mode on the console and stepping through successive pages of output display until he desires to return to the normal RUN mode. The operator can change modes by pressing keys in the following manner:

TYPE KEY	ACTION
R	Return to RUN mode
S	Change to STEP mode
G	Go to next page if in STEP mode

Jobs can automatically be put in the STEP mode by keying in (1. ON SW1.) at the 6000 console. This STEP mode of operation can then be removed by keying in (1. OFF SW1.).

2.2 Examples of Job Generation Film Print and Film Plot Files

D205,3,500,50000.

```
Charge.

    IDENTIFY (FILMPL,3)   (See 2.3 for an explanation on
    IDENTIFY (FILMPR,3)   use of IDENTIFY)

Run.

EOR

    PROGRAM TEST (FILMPR, FILMPL,TAPE5 = FILMPR,TAPE6 = FILMPL)
                     ↑                       ↑      ↑       ↑
                 Establish                 Send   Estab-  Estab-
                 Film print                tape   lish    lish
                 file                      5 out- tape 6  film
                                           put to file    plot
                                           film           file
                                           print
                                           file

    DIMENSION XLABEL(3), YLABEL(3), TITLE(3)

    DATA ((XLABEL(I),I = 1,3) = 10H  XA,10HXIS -- LIN,10HEAR)

    DATA ((XLABEL(I),I = 1,3) = 10H  YA,10HXIS -- LIN,10HEAR)

    DATA ((TITLE(I),I = 1.3) = 10HLINEAR TES,10HT PLOT,10H DEJ)

C   Initialize Linear Graph Plot (straight line)

    CALL BPLT

    CALL SPLT  (     )

    X = 0.

    DO 1 I = 1,11

    Y = X

C   Plot a Point in the Linear Graph

    CALL FPLT(X,Y)

1 X = X+100000.0
```

C Close Out or Terminate Graph

```
CALL EPLT
.
.
.
ETC.
```

2.3 The IDENTIFY card is the method by which the device and type of microfilm and/or hardcopy is specified for non-standard options.

Standard: FILMPR(BCD) TO MICROFILM = (no IDENTIFY card required)
FILMPL(BINARY) TO HARDCOPY = (no IDENTIFY card required)

Nonstandard: IDENTIFY (FILE1,FORM)

FILE1 = FILMPL(BINARY FILE)
= FILMPR(BCD FILE)

FORM = 1 (HARDCOPY)
= 2 (MICROFILM)
= 3 (BOTH)

Example: Binary and BCD files to both hardcopy and microfilm.

<u>New Method</u>

```
IDENTIFY(FILMPL,3)
IDENTIFY(FILMPR,3)
```

3. PLOTTING

3.1 DD202

These FORTRAN subroutines have been rewritten to produce a file (FILMPL) for plotting on the CDC 280. The only change required in a user's program is to identify the file FILMPL in the PROGRAM statement in place of TAPE44.

DD202 has five entries: BPLT, SPLT, FPLT, EPLT, REVPL.

3.1.1 BPLT

The function of BPLT is to provide initialization and need be called only at the start of the job.

```
CALL BPLT(A,B)

CALL BPLT (2HNB, 2HLC) wnere
2HNB indicates no background grid lines.
2HLC indicates a larger character size.
```

3.1.2 SPLT

The function of SPLT is to provide frame identification for the data that are to be plotted This frame identification is repeated for as many frames as are necessary to plot the data. The frame identification consists of a title, symbolic names of the dependent and independent variables, the scales of the dependent variables, and the scale of the independent variable properly incremented on all frames produced. Thus, SPLT should be called only whenever it is desired to change any of the frame identification variables. The frame identification information is supplied by a

CALL SPLT (XO,XS,XN,TITLE,O.,T,YMIN1,YMAX1,
YNL,..........YMIN_i,YMAX_i,YN_i)

where

XO is the value of the independent variable at which plotting is to begin.

XS is the scale of the independent variable. Since each frame of a plot is divided into 10 major divisions, 10*XS = total range of the independent variable over one frame. If the value of the independent variable exceeds the value of 10*XS, plotting is continued onto a new frame with the frame identification repeated as already noted.

In this case, plotting may not be resumed on a previous frame, i.e., subsequent values of the independent variable may not be less than that value which caused a new frame to be produced. If the user attempts to do this or if the user inadvertently supplies an XS of 0.0, an error message is printed. The job is not terminated, but no more plotting will be done.

XN is the name of the independent variable in Hollerith and many consist of one to six alphanumeric characters.

TITLE is a 60 contiguous character Hollerith array which will be printed below each frame generated.

O. is self evident, and at present is a dummy argument.

T is a flag specifying whether point plots (T=O) or vector plots (T=1 or T=1.) are desired. If the plots are Secret or Confidential, the Secret or Confidential label is generated by setting the last four characters of the sixty-character TITLE parameter of SPLT to either "SECR" or "CONF".

YMIN1 is the minimum grid value for the first dependent variable.

YMAX1 is the maximum grid value of the first dependent variable.

> (If the dependent variable goes out of the interval (YMIN-YMAX) no plotting is done off the grid, but is resumed normally at the point where Y_i reenters the interval)

YN1 is the name of the first dependent variable in Hollerith and may consist of one to six alphanumeric characters.

The number of remaining arguments for SPLT depends on the number of dependent variables to be plotted. A maximum of i=10 dependent variables is allowed and three arguments are required for each additional variable in the same order as YMIN1, YMAX1, YN1. The scale of each dependent variable is computed as

$$\frac{YMAX_i - YMIN_i}{10}$$ per major grid division;

however if more than three dependent variables are requested, all N variables will be plotted at the

$$\frac{YMAX_i = YMIN_i}{10}$$ scale but the BCD name of the first variable is the only one that will appear as part of the frame identification.

If $YMAX_i = YMIN_i$, the action taken is identical to that described under the XS argument discussion.

3.1.3 FPLT

The third entry to be called is FPLT. FPLT must be called once for each point (or set of points) to be plotted.

FPLT is used by a:

CALL FPLT (X,Y1......Y_i)

where:

X is the value of the independent variable.

Y1 is the value of the first dependent variable at point X. Again, there may be a maximum of i = 10 dependent variable values. The number of dependent variable values specified in FPLT must agree with the number specified by the SPLT arguments. The FPLT arguments must have floating point values.

3.1.4 EPLT

The function of EPLT is to terminate the plot information. Thus, it must be called before the user program terminates to insure that all plotting information is put on the file. It must also be called before a new SPLT is called to insure that all of the previous frame identifications is processed before the new frame identification specs are input through SPLT. EPLT is called by

```
CALL EPLT (0)
```

3.1.5 REVPL

The function of REVPL is to provide an option for switching from vector to print plotting or vice versa. Each time the REVPL entry is called, the mode of plotting is reversed. The applications for this option might be in plotting discrete functions to eliminate a vector between points of discontinuity.

```
CALL REVPL
```

3.1.6 FRAMECT

The function of FRAMECT is to place on the dayfile the number of frames that have been advanced. FRAMECT is automatically called by EPLT.

```
CALL FRAMECT (N,I)
```

where:

N is the number of frames

I = 0 - no dayfile message

1 - a dayfile message.

3.2 LRL-KAFB Package

3.2.1 Most of this report was taken from "CRT Plotting Routines in Use at LRL-Livermore" written by Judith D. Ford and Marilyn J. Welsh (UCRL-14427-T), and modified by Lt. Peter R. Keller of KAFB.

This report describes a system of plotting routines. These FORTRAN routines provide a flexible package for point, line, and character plotting via a CDC 280 display device.

This report gives detailed descriptions of the 280 routines, including purpose, operation, usage, and examples. The routines are separated into the following classes:

1. Mapping routines.

   These routines set up scale factors for converting the user's coordinates to the 280 raster point coordinates (raster point defined later). These routines may also draw scales with grid lines or short marks along the axes.

2. Arrow, line, and point plotting routines.

   These routines provide the facility for plotting various types of curves.

3. Character plotting routines.

   These routines provide the facility for plotting alphanumeric information.

4. Absolute plotting routines.

   These routines position the beam independent of the scaling defined by the mapping routines.

5. Utility routines.

   These routines give the facilities for framing and initializing the plot package.

6. Internal routines.

Internal routines perform various functions necessary to the operation of the system, and the user is normally not aware of their existence.

The CDC 280 plane is defined to be a (1024 by 1024) square of addressable points on the face of a cathode ray tube (CRT). These points are called raster points. Information is displayed by unblanking the CRT beam. The beam may be moved to a new position without unblanking (i.e., without plotting a line). Points may only be positioned at a raster point. Lines may only be drawn between two raster points (i.e., the beam unblanked between these two raster points may or may not intersect other raster points).

In the following description of the 280 routines, it is assumed that all arguments are given in the same mode as the dummy arguments, using the standard FORTRAN conventions for the names of integer and floating point variables. The dummy arguments spelled -DUM- are not used by the routine. These arguments are reserved in some cases for future options.

For the purposes of these routines this 280 plane is regarded as having the usual X, Y cartesian coordinates, both of which range from 0. to 1. with the origin at the lower left corner. If no mapping routine is called all coordinates for the plotting routines are assumed to be between 0. and 1.

3.2.2 This group of routines makes it unnecessary for the user to scale his own numbers for plotting on the 280. This is accomplished by establishing a mapping from the user's coordinate plane onto some portion of the 280 plane. This, by the way, allows more than one graph to be plotted on a frame.

CALL MAP (XMIN,XMAX,YMIN,YMAX,XMI,XMA,YMI,YMA)

XMIN, XMAX, YMIN, YMAX are the user's maximum and minimum cartesian coordinates.

XMI, XMA, YMI, YMA are the maximum and minimum coordinates of the 280 plane desired to be used.

This description encompasses a group of twelve routines, each of which establishes a mapping from the rectangle in the user's plane with corners (XMIN, YMIN), (XMAX, YMAX) onto the rectangle in the 280 plane with corners (XMI, YMI), (XMA, YMA). Unless reset, this mapping applies to all subsequent plotting, except the absolute plotting routines.

Linear mappings are established by -MAP-, -MAPG-, and -MAPS-.

MAP establishes a mapping only.

MAPG plots a grid with scale numbers.

MAPS plots a rectangle with scale numbers and short marks along the axes.

The suffixes -LL-, -SL-, and -LS- may be used with any of -MAP-, -MAPG-, or -MAPS- to modify the mapping as follows:

LL establishes a log-log mapping.

SL establishes a semi-log mapping with the X-axis linear.

LS establishes a semi-log mapping with the Y-axis linear.

The cycles are determined automatically.

Examples:

CALL MAP (0., 1., 0., 1., 0., 1., 0., 1.) sets up a linear-linear mapping,

CALL MAPSLL (1., 10., 1., 100000., .1, .999, .1, .999) sets up a 1 cycle by 5 cycle scale, and

CALL MAPGSL (-100., 10., 1., 100., .1, .5, .1, .999) sets up a linear by 2 cycle grid.

The mapping function is initially set

XMIN - YMIN = XMI = YMI = 0. and XMAX = YMAX = YMA = 1.

The scale numbers will overplot the grid lines if XMI or YMI is less than .078125 for linear scaling or .043 for logarithmic scaling.

Plotting routines specifying point(s) out of the defined user domain are handled in two ways.

1. If the scaled coordinate is within the 280 range then the routine is executed at the scaled coordinate.

2. If the scaled coordinate is outside of the 280 range then this coordinate is projected on the nearest extreme edge and the routine executes there.

An error message is printed whenever a mapping routine is called with

XMIN $\geq$ XMAX, YMIN $\geq$ YMAX, XMI $\geq$ XMA, YMI $\geq$ YMA

or a log mapping is called with a nonpositive argument.

CALL MAPP (RMAX, XMI, XMA, YMI)

RMAX is the maximum radius for the user's polar coordinates.

XMI, XMA, YMI are the same as in -MAP- above.

-MAPP- establishes a mapping from the circle of radius RMAX in the user's polar coordinate plane into the square in the 280 plane with corners (XMI, YMI), (XMA, YMA) where YMA = YMI + (XMA - XMI).

Vertical and horizontal reference axes will be plotted, with scale numbers along the zero-degree axis, and with the origin at the center of the square. All (X,Y) pairs given in later plotting routines will be interpreted as polar coordinates (R, θ) until another mapping routine is called.

CALL MAPX (XMIN, XMAX, YMIN, YMAX, XMI, XMA, YMI, YMA, I)

I is an integer $1 \leq I \leq 13$.

The remaining arguments are the same as in -MAP- above.

-MAPX- allows the mapping to be specified at execution time, according to the value of I. A call to -MAPX- is equivalent to a call to one of the above mapping routines, with the integers 1-13 corresponding to these routines in the following order:

MAP, MAPSL, MAPLS, MAPLL, MAPG, MAPGSL, MAPGLS, MAPGLL, MAPS, MAPSSL, MAPSLS, MAPSLL, MAPP.

When I = 13 the arguments in MAPX correspond to MAPP as follows

CALL MAPX (DUM, RMAX, DUM, DUM, XMI, XMA, YMI, DUM, 13).

ARROW, LINE AND POINT PLOTTING ROUTINES

These routines may be used to display and/or photograph data in graphic form. The user's (X,Y) coordinates in these plotting routines are scaled by the scale factors set up by a mapping routine. If no mapping routine has been called, these coordinates are assumed to be in the range 0. to 1.

CALL ARROW (X1, Y1, X2, Y2, Z)

(X1, Y1) and X2, Y2) are coordinates of two points.

Z is a floating point number 1.

-ARROW- sweeps a line from (X1, Y1) to (X2, Y2) and draws an arrowhead at (X2, Y2). The arrowhead measures Z raster points in length. Z = 10 is a normal size arrowhead. The intensity is set by -LINEOPT-. The final beam position is (X2, Y2).

CALL LINE (X1, Y1, X2, Y2)

(X1, Y1) and (X2, Y2) are the coordinates of two points. -LINE- will sweep a line from (X1, Y1) to (X2, Y2) with intensity set by -LINEOPT-.

CALL LINEOPT (DUM, INTEN)

DUM is a dummy argument.

INTEN is the intensity at which all arrows, lines, points, and vectors will be plotted.

0 low intensity (fine line).

1 high intensity (heavy line).

-LINEOPT- is initially set to low intensity.

The mapping routines reset -LINEOPT- from within.

CALL LINEP (X1, Y1, X2, Y2, K)

(X1, Y1) and (X2, Y2) are the coordinates of two points.

K is an integer.

-LINEP- plots a line consisting of every Kth raster point between (X1, Y1) and (X2, Y2). Intensity is set by -LINEOPT-.

CALL LINES (X,Y,N)

X and Y are the names (first word addresses) of arrays of the X and Y coordinates of points.

N is the number of points.

-LINES- connects the N points given by the arrays X and Y with line segments. The final beam position is (X(N), Y(N)). The lines are swept with intensity as set by -LINEOPT-.

CALL POINT (X,Y)

X and Y are the coordinates of a point.

-POINT- will plot a point at (X, Y) with intensity set by -LINEOPT-.

CALL POINTS (X, Y, N)

X and Y are the names (first word addresses) of arrays of the X and Y coordinates of points.

N is the number of points.

-POINTS- plots the N points given by the arrays X and Y. The intensity is set by -LINEOPT-.

CALL SETBEAM (X, Y)

X is the abscissa at which the beam is to be positioned.

Y is the ordinate at which the beam is to be positioned.

-SETBEAM- causes the beam to be positioned at (X, Y) without unblanking.

CALL VECTOR (X2, Y2)

(X2, Y2) is the coordinate of a point.

-VECTOR- sweeps a line from the current beam position to (X2, Y2) with intensity set by -LINEOPT-.

3.2.3 Character Plotting Routines

This group of routines allows the plotting of alphanumeric information, either to label the various curves, lines, etc., produced by the point and line plotting routines, or as a more versatile alternative to an off-line printer (this is distinct from the -FILMPR- option. -FILMPR- merely simulates the printer). This versatility derives from:

1) The capability of positioning a line of alphanumeric information anywhere on the current frame (vs the top-to-bottom progression of a page printer).

2) The two orientations, two intensities and four character sizes that are available, and

3) The expanded character set, which includes many non-key punchable characters (not immediately available).

CALL CHAROPT (DUM, DUM, ISIZE, IOR, DUM)

ISIZE = 0 miniature
        1 small
        2 medium
        3 large

IOR   = 0 horizontal (0°)
        1 vertical (90°)

-CHAROPT- specifies the size (ISIZE) and orientation (IOR) of all characters to be plotted. The option is changed by a second call to -CHAROPT-.

The maximum string length and line limits for the various sizes are:

	Symbols/ Line	Lines/ Frame
Miniature	128	64
Small	86	43
Medium	64	32
Large	43	22

In the character plotting routines, the 280 plane is considered to be a grid of rectangles, each containing one character of the chosen size. The number and dimensions of these rectangles depend on the character size and orientation. Characters are drawn within the rectangle. The rectangle is positioned such that the current beam position is in the center of the rectangle. After the character has been drawn the beam is positioned in the center of the next rectangle.

CALL NUMBER (X, F)

X is a variable (fixed or floating).

F is any allowable FORTRAN format 10 characters.

-NUMBER- converts the variable X under the given format, determines the field width and plots the resulting characters as -SYMBOL- would.

Example:

```
   .
   .
   .
   X = 1.E5
   CALL NUMBER (X, 5HE10.2)
   .
   .
   .
would plot
   bbb1.00E05
   and
   .
   .
   .
   I = 42
   CALL NUMBER (I, 9H4HIN = , I3)
   .
   .
   .
would plot
   INb = b42
```

CALL SYMBOL (A)

or

CALL SYMBOL (MH...$.)

A is the first word of BCD data. The end of string is designated by $.

MH...$. is a Hollerith text of M characters. The last two characters must be $., which designates the end of string.

-SYMBOL- encodes BCD data into the 280 character set and plots it starting at the current beam position with options as given by -CHAROPT-.

If $. does not appear at the end of string -SYMBOL- attempts to plot words up to the field length.

3.2.4 Absolute Plotting Routines

These routines position the beam independently of the defined mapping function. The arguments range from 0. to 1. Out of range points are projected on the nearest extreme edge of the plotting area.

CALL ABSBEAM (X, Y)

X, Y are coordinates of a point.

-ABSBEAM- causes the beam to be positioned at (X, Y) without unblanking.

CALL ABSLINE (X1, Y1, X2, Y2)

(X1, Y1), (X2, Y2) are coordinates of two points.

-ABSLINE- draws a line from (X1, Y1) to (X2, Y2).

CALL ABSPT (X, Y)

X, Y are coordinates of a point.

-ABSPT- plots a point at (X, Y).

CALL ABSVECT (X, Y)

X, Y are coordinates of a point.

-ABSVECT- draws a vector from the last beam position to (X, Y).

3.2.5 Utility Routines

CALL INIT280

-INIT280- initializes the 280 routines and must be called before any of the plotting routines.

CALL FRAME

-FRAME- advances the microfilm to the next blank frame after emptying the buffer.

-FRAME- should be the last routine called in order to empty the buffer.

3.2.6 Internal Routines

These routines are essential to the plotting routines, but are not called directly by the user, only by other routines in the system.

-GRID80- is called by the mapping routines which draw scale marks or grid lines and label them with scale number.

-GTRF-, -GEQF-, -EQLF-, -SEQF-, -SMLF-, -UNQF-, and -ZGTRF- are functions which are used in -GRID80-. Each has two arguments and returns a value of 1 if the first argument stands in the indicated relation to the second, a value of 0 otherwise.

FUNCTION	RELATION
GTRF	greater than
GEQF	greater than or equal to
EQLF	equal to
SEQF	less than or equal to
SMLF	less than
UNQF	not equal to

These functions call -ZGTRF- to establish the value.

-TEST- is called by the mapping routines to establish legal arguments.

-ADJOST- is called by some of the plotting routines to convert nonlinear arguments to linear before scaling.

-LENGTH- is called by number to count the number of characters to be plotted.

-STREND- is called by symbol to test for end of string symbol.

-PSCALE- is called by the mapping routines to establish the scaling.

-PLOTQ- is called by the plotting routines and forms the 280 instructions.

3.3 SC4020 Conversion

3.3.1 SC4020 Binary PLOT Files may be converted to a CDC 280 FIIMPL File by calling the FORTRAN Subroutine SCDD. The calling sequence is:

CALL SCDD (I,J,K)

where I = Number of files to be converted.

J = Tape number of SC4020 FILE

K = 0, debug printout is inhibited

1, debug printout is not inhibited

3.3.2 Example:

```
PROGRAM TEST (OUTPUT, TAPE45, FILMPL)

.
.
.
CALL ENDPLOT
ENDFILE 45
REWIND 45
CALL SCDD(1, 45, 0)
.
.
.
```

3.3.3 SC4020 Binary Plot Tapes produced on the IBM 360 or 7094 must be processed by program DD219. This program will read tapes written in 36-bit increments.

4. PRINTING

4.1 CDC 6000 Print Files

4.1.1 Print files may be recorded by the CDC 280 with the following format:

Up to 128 characters per line are accepted.

The first character of each line is interpreted as the vertical spacing control and is replaced with a space code. The control characters are:

0 = 12 (BCD) Double Space
1 = 01 (BCD) Eject
+ = 60 (BCD) Suppress Space

Any other character causes single spacing.

Vertical spacing control is accomplished before the line is filmed (preprint spacing).

A maximum of 64 lines per frame is admissible. More than 64 lines force an automatic frame advance.

*40 FR will produce 40 blank frames of microfilm for spacing purposes.

4.2 Non-CDC 6000 Print Files

4.2.1 Print Files may be created on other computers for recording on the CDC 280.

Tapes must be written in the following manner:

Unlabeled 7 track tape (BCD)

Single blocked records of 130 characters (Last 2 characters blank).

Blocked records:

Maximum size is 1820 characters.

An END OF FILE terminates processing.

4.3 Forms Flash

A Forms Flash may be programed for use as an outline for each frame of CDC 280 recording of Print Data.

Those desiring the use of a Forms Flash should design a Forms Flash on a grid layout with the following specifications.

Grid size allows 128 characters per line and 64 lines per page for data.

Symbol sizes may be:

128 characters per line
86 characters per line
64 characters per line
43 characters per line

Symbols may be oriented horizontally (left to right) or oriented 90° counter clockwise.

The Grid Layout should be submitted to Dept. 6643 for programing and implementation.

4.4 Special Capabilities

Jobs requiring Secret or Confidential output on microfilm or hardcopy may be obtained as follows:

FILMPR - If this file is utilized to generate secret or confidential output, a forms flash must be used to label the microfilm or hardcopy as secret or confidential. This forms flash is generated by initializing FILMPR with one of the following BCD records:

Col 1	
FORMSFLASH6A3	For a secret file.
FORMSFLASH6A4	For a confidential file.

Example to initialize FILMPR with secret forms flash:

```
Job Card
CHARGE.
REQUEST TAPE1,HY.
COPYCR (INPUT, FILMPR, 1)
RUN(S)
LGØ
...
...
7
 8
  9
FØRMSFLASH6A3
7
 8
  9
...
...
```

5. ILLUSTRATIONS

Figure A-1 was generated by the following sequence of instructions:

```
CALL INIT280
CALL MAPG(-1000., 1000., 50., 100., .1, 1., .1, 1.)
CALL ABSLINE (0., 0., 0., 1.)
CALL ABSVECT (1., 1.)
CALL ABSVECT (1., 0.)
CALL ABSVECT (0., 0.)
CALL ABSBEAM (.4, .05)
CALL CHAROPT (0, 0, 0, 0, 0)
CALL SYMBOL (8HX-AXIS$.)
CALL ABSBEAM (.05,.4)
CALL CHAROPT (0, 0, 0, 1, 0)
CALL SYMBOL (8HY-AXIS$.)
CALL CHAROPT (0, 0, 0, 0, 0)
CALL ABSBEAM (.45, .02)
CALL SYMBOL (11HFIGURE 1.$.)
CALL FRAME
```

Figure A-2 was generated by the following sequence of instructions:

```
CALL MAPGSL (-1., 1., 1., 100000., .1, .5, .1, 1.)
CALL MAPGLL (1., 10., 100., 1000., .6, 1., .1, .5)
CALL MAPS (-10., 10, 6., 7., .6, 1., .6, 1.)
CALL CHAROPT (0, 0, 0, 0, 0)
CALL ABSBEAM (.45, .001)
CALL SYMBOL (11HFIGURE 2.$.)
CALL FRAME
```

Figure A-3 was generated by the following sequence of instructions:

```
     DIMENSION X(100), Y(100)
     DO 1 I=1, 100
     X(I)=I

   1 Y(I)=7.2*1

     CALL MAPP (100., 0., .5, 0.)
     DO 2 I=1, 100
   2 CALL POINT (X(I), Y(I))
     CALL MAPP (100., .5, 1., .5)
     DO 3 I=1, 98, 4
   3 CALL ARROW (X(I), Y(I), X(I+2), Y(I+2), 8.)
     CALL CHAROPT (0, 0, 0, 0, 0)
     CALL ABSBEAM (.45, .001)
     CALL SYMBOL (11HFIGURE 3.$.)
     CALL FRAME
```

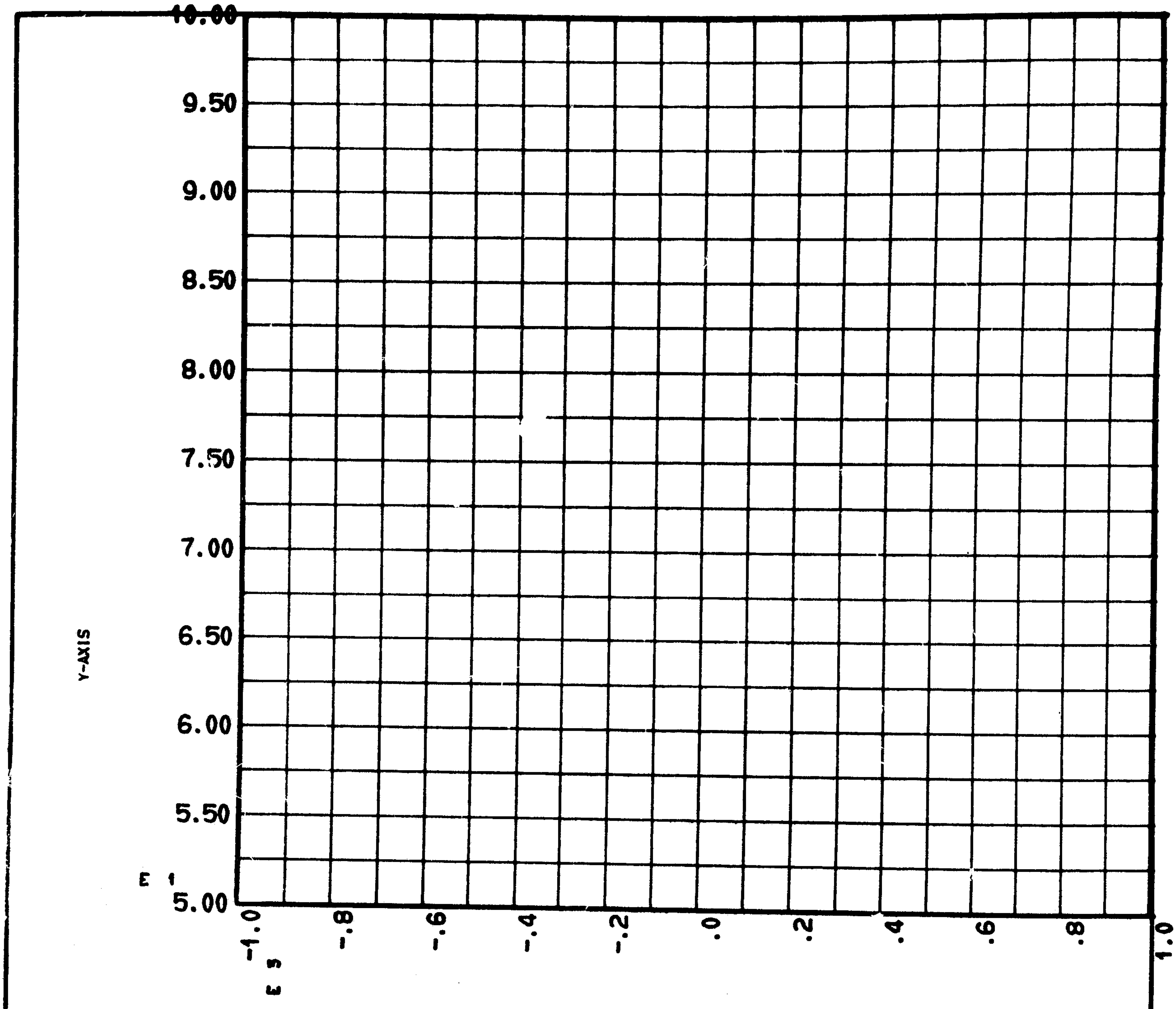

10.00
9.50
9.00
8.50
8.00
7.50
7.00
6.50
6.00
5.50
E 1
5.00
Y-AXIS
-1.0
-.8
-.6
-.4
-.2
.0
.2
.4
.6
.8
1.0
E 5
X-AXIS

FIGURE 1.

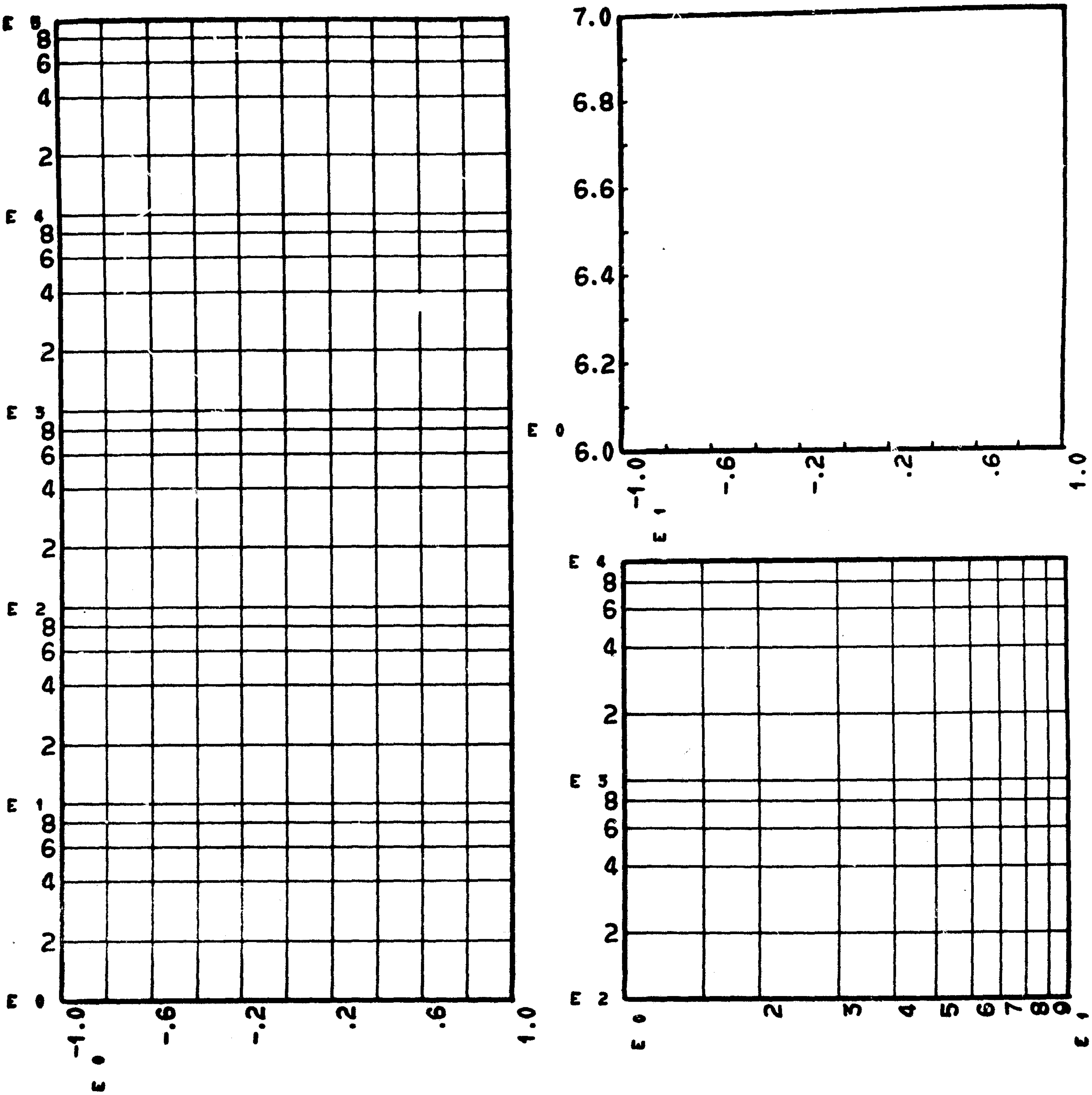

E 5
8
6
4
2
E 4
8
6
4
2
E 3
8
6
4
2
E 2
8
6
4
2
E 1
8
6
4
2
E 0
-1.0
-.6
-.2
.2
.6
1.0
E 0
7.0
6.8
6.6
6.4
6.2
6.0
E 0
-1.0
-.6
-.2
.2
.6
1.0
E 1
E 4
8
6
4
2
E 3
8
6
4
2
E 2
E 0
2
3
4
5
6
7
8
9
E 1

FIGURE 2.

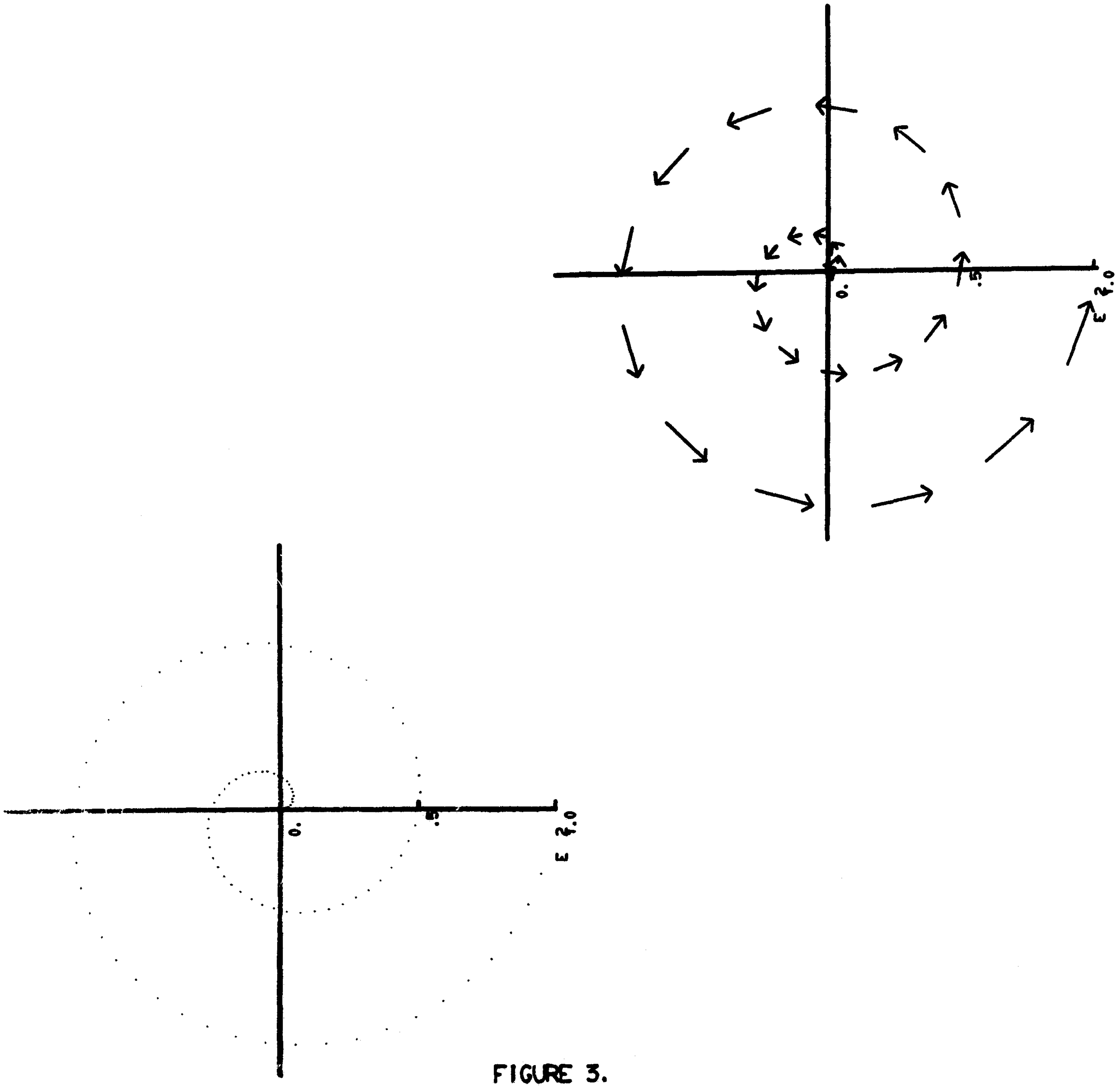


FIGURE 3.