LANDING TRAJECTORY RECONSTRUCTION COMPUTER PROGRAM

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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.

### Key Words
- Planetary Entry Probe
- Planetary Lander
- Trajectory Reconstruction
- Planetary Atmosphere Reconstruction
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.
**CONTENTS**

<table>
<thead>
<tr>
<th>Part I. LTR Analytical Manual</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>II. Modeling of Actual Trajectory, Atmosphere, and Measurements</td>
<td>3</td>
</tr>
<tr>
<td>A. Entry Geometry and Equations of Motion</td>
<td>5</td>
</tr>
<tr>
<td>B. Planetary Atmosphere Model</td>
<td>11</td>
</tr>
<tr>
<td>C. Accelerometer and Gyro Models</td>
<td>13</td>
</tr>
<tr>
<td>D. Preprocessing of Gyro and Accelerometer Measurements</td>
<td>15</td>
</tr>
<tr>
<td>E. Other Onboard Measurement Models</td>
<td>18</td>
</tr>
<tr>
<td>F. Earth-Based Range and Doppler Measurement Models</td>
<td>22 thru 24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>III. Recursive State Estimation</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Recursive Estimation Algorithm</td>
<td>25</td>
</tr>
<tr>
<td>B. Measurement Noise Models</td>
<td>29</td>
</tr>
<tr>
<td>C. Computation of State Transition and Observation Matrices</td>
<td>30</td>
</tr>
<tr>
<td>D. Quasi-Linear Filtering Event</td>
<td>34</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IV. Mode A State Estimation and Atmosphere Reconstruction</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Mode A Dynamic Model</td>
<td>35</td>
</tr>
<tr>
<td>B. Mode A Recursive Trajectory and Atmosphere Reconstruction</td>
<td>39 thru 42</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>V. Mode B State Estimation and Atmosphere Reconstruction</td>
<td>43</td>
</tr>
<tr>
<td>A. Mode B Dynamic Model</td>
<td>43</td>
</tr>
<tr>
<td>B. Mode B Recursive Trajectory and Atmosphere Reconstruction</td>
<td>45</td>
</tr>
<tr>
<td>VI. Individual Subroutine Analyses</td>
<td>46</td>
</tr>
<tr>
<td>VII. References</td>
<td>47</td>
</tr>
<tr>
<td>Part II. LTR Users' Manual</td>
<td>49</td>
</tr>
<tr>
<td>I. Introduction</td>
<td>51</td>
</tr>
<tr>
<td>II. Input Description</td>
<td>52</td>
</tr>
<tr>
<td>A. Data Deck and Tape Structure</td>
<td>52</td>
</tr>
<tr>
<td>B. Data Generator Input Variable Definitions</td>
<td>67</td>
</tr>
<tr>
<td>C. Reconstruction Program Input Variable Definitions</td>
<td></td>
</tr>
<tr>
<td>III. Output Description</td>
<td>81</td>
</tr>
<tr>
<td>A. Data Generator Output Description</td>
<td>81</td>
</tr>
<tr>
<td>B. Reconstruction Program Output Description</td>
<td>83</td>
</tr>
<tr>
<td>IV. Sample Cases</td>
<td>89</td>
</tr>
<tr>
<td>A. LTR Mode A Sample Case</td>
<td>89</td>
</tr>
<tr>
<td>B. LTR Mode B Sample Case</td>
<td>94</td>
</tr>
<tr>
<td>C. Quasi-Static Dynamic Model Sample Case</td>
<td>98</td>
</tr>
<tr>
<td>D. Selected Pages from LTR Sample Cases</td>
<td>100</td>
</tr>
<tr>
<td>Part III. LTR Programmers' Manual</td>
<td>133</td>
</tr>
<tr>
<td>I. Introduction</td>
<td>135</td>
</tr>
<tr>
<td>II. Summary of LTR Operation</td>
<td>136</td>
</tr>
<tr>
<td>III. LTR Program Structure</td>
<td>138</td>
</tr>
<tr>
<td>A. LTR Subroutine Classification</td>
<td>138</td>
</tr>
<tr>
<td>B. LTR Subroutine Hierarchy</td>
<td>138</td>
</tr>
</tbody>
</table>
IV. Common Variable Definitions ............... 151
   A. Common Variables by Blocks ............... 151
V. Individual Subroutine Documentation ......... 173

Appendix A. CDC 280 Software Package ........... A-1

Figures
Part I
II-1 Entry Geometry ............................ 6
II-2 Entry Vehicle Geometry ........................ 8
II-3 Smoothing of Quantized Data .................. 17
II-4 Altimeter and Terrain Height Geometry ......... 20
II-5 Earth-Based Tracking Geometry ............... 23

Part III
III-1 LTR Executive Flow Diagram ............... 146
III-2 DATGEN Executive Flow Diagram ............. 147
III-3 LTRCON Executive Flow Diagram ............. 148

Tables
Part II
II-1 C(j) Variables ............................ 60

Part III
III-1 LTR Subroutines ........................... 139
III-2 Purpose of Subroutines ....................... 141
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 $x_e, y_e, z_e$ by the longitude of the ascending node $\Omega_e$ and the inclination $i_e$. The reference line from which the downrange angle $\phi$ is measured, is defined in the entry plane by the angle $\phi_e$. 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 $\gamma$, downrange angle $\phi$, attitude $\theta$, and angular velocity $\omega$. Flightpath angle $\gamma$ 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 $\theta$ is measured from the local horizontal (corresponding to $\phi = 0$) to the $x$ body axis. The vehicle angle of attack $\alpha$ 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

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

where $\epsilon$ is the angle between $v$ and $v_r$. The angle $\epsilon$ is given by

$$\epsilon = \tan^{-1} \left[ \frac{v_a \sin \gamma}{v - v_a \cos \gamma} \right] \tag{II-3}$$
Figure II-1 Entry Geometry
If \( \omega_p \) denotes the angular velocity vector of the planet, and if \( \hat{e}_n \) denotes a unit vector normal to the entry plane, then the atmosphere velocity in the entry plane can be written as

\[
v_a = (\omega_p \cdot \hat{e}_n) r + v_w \tag{II-4}
\]

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

\[
\alpha = \theta + \phi - \gamma - \epsilon \tag{II-5}
\]

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

\[
A = -C_A q S \tag{II-6}
\]

\[
N = -C_N q S \tag{II-7}
\]

\[
M = C_M \omega d^2 q S/v_r \tag{II-8}
\]

The parachute force is given by

\[
F_d = C_D q S_D \tag{II-9}
\]

In these equations \( C_A, C_N, \) and \( C_M \) are the axial force, normal force, and damping moment coefficients, respectively, and are tabulated functions of angle of attack \( \alpha \) 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

\[
q = \frac{1}{2} \rho \frac{v^2}{r}
\]

where \( \rho \) 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

\[
\begin{align*}
\dot{h} &= v \sin \gamma \\
\dot{v} &= -g \sin \gamma + \frac{A}{m} \cos (\alpha + \varepsilon) + \frac{N}{m} \sin (\alpha + \varepsilon) - \frac{F_d}{m} \cos \varepsilon \\
\dot{\gamma} &= \left( \frac{v}{r} \right) \cos \gamma + \frac{1}{v} \left[ \frac{A}{m} \sin (\alpha + \varepsilon) - \frac{N}{m} \cos (\alpha + \varepsilon) \\
&\quad - \frac{F_d}{m} \sin \varepsilon \right] \\
\dot{\phi} &= \frac{v}{r} \cos \gamma \\
\dot{\theta} &= \omega \\
\dot{\omega} &= \frac{1}{I} \left[ (z_p - z_g) A - (x_p - x_g) N + M + z_g F_d \cos \alpha \\
&\quad - (x_g - x_d) F_d \sin \alpha \right]
\end{align*}
\]

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

\[
g = \frac{\mu}{r^2}
\]

where \( \mu \) 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 \( |\dot{\psi}| \ll 1 \), an unstable \( \dot{\psi} \) 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 \( \dot{\psi} \) with the approximate equation \( \dot{\psi} = 0 \), and replacing \( \psi \) in the remaining equations with the terminal velocity \( v_T \), which is computed from

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

This equation was obtained by setting \( \dot{\psi} \), \( \alpha \), and \( \epsilon \) to zero and \( v_T \) 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 \( \alpha \) to zero during max q without significantly disturbing the accuracy of the computed translational motion. Setting \( \alpha = 0 \) in equation (II-5) yields

\[
\theta = \gamma - \phi + \epsilon \tag{II-19}
\]

Differentiating this equation, and assuming \( \epsilon \) 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; \( \rho \), density; \( M \), molecular weight; \( T \), ambient temperature; and \( R \), the universal gas constant.
Combining equations (II-21) and (II-22) yields

\[
\frac{dp}{dh} = - \frac{p g v M}{RT} \quad .
\]

(II-23)

Assuming constant \( g \), the integral of this equation has the form

\[
p(h) = p(h_k) \exp \left[ -\frac{g}{R} \int_{h_k}^{h} \frac{M(C)}{T(C)} \, dc \right] .
\]

(II-24)

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

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

\[
h_j \leq h \leq h_{j+1}
\]

(II-25)

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

\[
h_i \leq h \leq h_{i+1}
\]

(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 \( a_{ji} \) denote the mole fraction of the \( j \)th gas at altitude \( h_i \), the molecular weight at \( h_i \) is given by

\[
M(h_i) = \sum_j a_{ji} m_j
\]

(II-27)

where \( m_j \) is the molecular weight of the \( j \)th 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

\[
w(h) = w(h_n) + \frac{w(h_{n+1}) - w(h_n)}{h_{n+1} - h_n} (h - h_n)
\]

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 accelerometer 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

\[
a_x = a_{xg} - \omega^2 \bar{x} + \omega \bar{z}
\]

\[
a_z = a_{zg} - \omega^2 \bar{z} - \omega \bar{x}
\]

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

\[
\bar{x} = x_m - x_g
\]

\[
\bar{z} = z_m - z_g
\]
and where \( a_x \) and \( a_z \) denote the x and z components of the actual nongravitational acceleration at the vehicle cg.

Because of accelerometer misalignment errors \( \delta_1 \) and \( \delta_2 \), the actual nongravitational acceleration experience by the VRU is given by

\[
\begin{align*}
\dot{v}_x &= a_x \cos \delta_1 - a_z \sin \delta_1 \\
\dot{v}_z &= a_x \sin \delta_2 + a_z \cos \delta_2.
\end{align*}
\]

The actual output of the VRU 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

\[
\begin{align*}
v_{xq}(t_k) &= Q \left( C_{sx} \int_0^{t_k} \dot{v}_x \, dt + C_{bx} \right) \\
v_{zq}(t_k) &= Q \left( C_{sz} \int_0^{t_k} \dot{v}_z \, dt + C_{bz} \right)
\end{align*}
\]

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 \( \Delta q \), the quantum level, then

\[
Q(\ ) = I \left\{ \frac{1}{\Delta q} \right\} \times \Delta q
\]

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 $\omega$. Because of the gyro misalignment error $\delta_3$, the actual angular velocity experience by the ARU is given by

$$\dot{\theta} = \omega \cos \delta_3.$$  \hspace{1cm} (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

$$A_{\theta q}(t_k) = Q \left\{ C_{s\theta} \int_0^{t_k} \dot{\theta} dt + C_{b\theta} t_k \right\}.$$ \hspace{1cm} (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 $\mathbf{\theta}_m$, angular velocity $\mathbf{\omega}_m$, and angular acceleration $\mathbf{\dot{\omega}}_m$ 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 $\mathbf{\theta}_m(t)$ can be expressed as a quadratic function over this interval, so that

$$\mathbf{\theta}_m(t) = C_1 + C_2 (t - t_k) + C_3 (t - t_k)^2 \quad \text{(II-40)}$$

The coefficients $C_1$, $C_2$, and $C_3$ are chosen to obtain a least-squares fit to the data points $A_{6q}(t_{k-2})$ through $A_{6q}(t_{k+2})$. The solution to this problem is given by the following equations:

$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} = (B^T B)^{-1} B \begin{bmatrix} A_{6q}(t_{k-2}) \\ \vdots \\ A_{6q}(t_{k+2}) \end{bmatrix} \quad \text{(II-41)}$$

where

$$B = \begin{bmatrix} 1 & -2\Delta & 4\Delta^2 \\ 1 & -\Delta & 2\Delta^2 \\ 1 & 0 & 0 \\ 1 & \Delta & 2\Delta^2 \\ 1 & 2\Delta & 4\Delta^2 \end{bmatrix} \quad \text{(II-42)}$$

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:

$$\mathbf{\theta}_m(t_k) = C_1 \quad \text{(II-43)}$$

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

$$\mathbf{\omega}_m(t_k) = C_2 \quad \text{(II-44)}$$

$$\mathbf{\dot{\omega}}_m(t_k) = 2 C_3 \quad \text{(II-45)}$$
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 PRPR6S and SMOOTH2 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

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

where $T$ is ambient temperature; $\gamma$, 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:

$M \geq 3$:

$$p_o = \frac{1}{2} C_p \rho \frac{\nu^2}{r} + p$$ \hspace{1cm} (II-47)

$$C_p = 2 - c;$$ \hspace{1cm} (II-48)

$1 \leq M < 3$:

$$p_o = \frac{1}{2} C_p \rho \frac{\nu^2}{r} + p$$ \hspace{1cm} (II-49)
\[
\frac{p}{\rho} = \frac{\rho}{8} \left[ \left( \frac{\gamma + 1}{2} \right)^{\gamma-1} \times \left( \frac{\gamma + 1}{2 \gamma M^2 - \gamma + 1} \right)^{1/\gamma-1} - 1 \right]; \quad (II-50)
\]

\[M < 1:
\]
\[p_o = p \left( 1 + \frac{\gamma - 1}{2} \right)^{\gamma-1} \quad (II-51)\]

where \(p_o\) is stagnation pressure; \(p\), ambient pressure; \(C_p\), coefficient of pressure; \(M\), Mach number; \(\gamma\), ratio of specific heats; and \(\varepsilon\), ratio of densities in front of and behind the shock wave. The ratio \(\varepsilon\) is a tabulated function of \(\nu\). 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 \(2\pi\). Terrain height \(\tau\) above the mean surface is assumed to have the form

\[
\tau = C_1 + C_2 \sin (C_3 \phi' + C_4) + C_5 \cos (C_6 \phi' + C_7) \quad (II-52)
\]

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

\[
\phi' = \phi - \hat{\omega}_p \cdot \hat{e}_n (t - t_o) \quad . \quad (II-53)
\]

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

\[
\delta = \left[ (h + R_p)^2 + w^2 - 2w (h + R_p) \cos (\phi - \phi) \right]^{1/2} \quad (II-54)
\]
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 \( h \) is equivalent to minimization of the function

\[
f = w^2 - 2w (h + R_p) \cos (\phi - \phi)
\]

The function \( f \) is minimized using a direct search over the interval \([\phi-\delta, \phi+\delta]\) with respect to \( \phi \). The angle \( \delta \) is given by

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

The actual radar altimeter measurement is computed by multiplying the minimum \( h \) 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 \( a_x / a_z \) can be used to define an angle of attack measurement \( \bar{\alpha} \). The ratio of vehicle lift \( L \) and drag \( D \) can be related to \( a_x, a_z, \) and \( \bar{\alpha} \) according to the equation

\[
\frac{L}{D} = \frac{a_z \cos \bar{\alpha} - a_x \sin \bar{\alpha}}{a_x \cos \bar{\alpha} + a_z \sin \bar{\alpha}}
\]

Solving for \( \bar{\alpha} \), we obtain

\[
\tan \bar{\alpha} = \frac{a_x - \frac{L}{D}}{a_x \left( \frac{a_z}{a_x} \right) + \frac{L}{D}}
\]

The ratio \( L/D \) has the form

\[
\frac{L}{D} = k \bar{\alpha}
\]
where \( k \) is a tabulated function of Mach number. To compute the angle of attack measurement \( \delta \), equation II-58 is solved iteratively using

\[
\frac{a_x}{z} = \frac{a_x}{k+1} \quad \text{(II-60)}
\]

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 \( x_0y_0z_0 \) by the latitude \( \delta \), longitude \( \lambda \), Greenwich hour angle GHA of the vernal equinox, earth radius \( R_0 \), and altitude \( h \) above the mean earth sphere. The spacecraft has position \( \mathbf{r} \) and velocity \( \mathbf{v} \) relative to the target planet. These vectors are normally expressed relative to the planetocentric ecliptic coordinate system \( x_\mathbf{e}y_\mathbf{e}z_\mathbf{e} \).

The range \( \rho \) between the spacecraft and the tracking station is given by

\[
\rho = |\mathbf{r} + \mathbf{v} - \mathbf{r}_e - \mathbf{r}_s| \quad \text{(II-61)}
\]

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

\[
x_s = (R_0 + h) \cos \delta \cos \gamma \quad \text{(II-62)}
\]

\[
y_s = (R_0 + h) [\cos \delta \cos \epsilon \sin \gamma + \sin \delta \sin \epsilon] \quad \text{(II-63)}
\]

\[
z_s = (R_0 + h) [-\cos \delta \sin \epsilon \sin \gamma + \sin \delta \cos \epsilon] \quad \text{(II-64)}
\]
Figure II-5 Earth-Based Tracking Geometry
where ε is the obliquity of the ecliptic, and

\[ G = \lambda + \omega_e (t - t_0) + \text{GHA} (t_0) \] \quad (II-65)

In this last equation, \( \omega_e \) represents the inertial angular velocity of the earth; \( t - t_0 \), the time interval since epoch \( t_0 \); and \( \text{GHA} (t_0) \), the Greenwich hour angle at epoch.

The range rate \( \dot{\rho} \) between the spacecraft and the tracking station is given by

\[ \dot{\rho} = \frac{\dot{\rho} \cdot e}{\rho} = \frac{\dot{\rho} \cdot \rho}{\rho} \] \quad (II-66)

where \( \dot{\rho} \) is a unit vector directed along the range vector \( \rho \), and \( \dot{\rho} \) is given by

\[ \dot{\rho} = \frac{1}{\rho} \left( \frac{1}{r_p} - \frac{1}{r_e} - \frac{1}{r_s} \right) \] \quad (II-67)

where \( \frac{1}{r_p} \) and \( \frac{1}{r_s} \) denote the velocity of the target planet and the earth, respectively, relative to the sun, and \( \frac{1}{r_s} \) denotes the velocity of the tracking station relative to the center of the earth.

The heliocentric ecliptic components of \( \frac{1}{r_s} \) are given by

\[ \dot{x}_s = -\omega_e (R_o + h) \cos \theta \sin \varpi \] \quad (II-68)
\[ \dot{y}_s = \omega_e (R_o + h) \cos \theta \cos \epsilon \cos \varpi \] \quad (II-69)
\[ \dot{z}_s = -\omega_e (R_o + h) \cos \theta \sin \epsilon \cos \varpi \] \quad (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 incorporate 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

\[
x^A = \begin{bmatrix} x \\ q \\ u \\ v \\ w \end{bmatrix}
\]  

(III-1)
where

\[ x = \text{basic state vector}, \]
\[ q = \text{vector of solve-for parameters}, \]
\[ u = \text{vector of dynamic-consider parameters}, \]
\[ v = \text{vector of measurement-consider parameters}, \]
\[ w = \text{vector of dynamic/measurement-consider parameters}. \]

The linearized dynamic model is assumed to have the form

\[ x_{k+1}^A = \phi_{k+1,k}^A x_k^A + q_{k+1,k}^N \quad \text{(III-2)} \]

where \( \phi_{k+1,k}^A \) is the augmented state transition matrix over the interval \([t_k, t_{k+1}]\) and \( q_{k+1,k}^N \) represents the effects of dynamic noise over the interval. Since the dynamic noise affects the basic state only,

\[ q_{k+1,k}^N = \begin{bmatrix}
q_{N_{k+1,k}}^N \\
0 \\
0 \\
0
\end{bmatrix} \quad \text{(III-3)} \]

The linearized measurement model is assumed to have the form

\[ y_k^A = H_k^A x_k^A + \eta_k \quad \text{(III-4)} \]

where \( y_k \) represents the deviation of the observation from the nominal observation at \( t_k \), \( H_k^A \) relates changes in \( x_k^A \) to changes in the measurement \( y_k \), and \( \eta_k \) represents the measurement noise.

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

$$P_{A} = E \left[ (\hat{x}_{k} - x_{k}^{A}) (\hat{x}_{k} - x_{k}^{A})^{T} \right]$$

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 \( t_{k} \), \( P_{k+1}^{+} \), to the covariance prior to processing the next measurement at \( t_{k+1} \), \( P_{k+1}^{-} \), is given by

$$P_{k+1}^{-} = P_{k+1,k}^{A} + \hat{x}_{k+1,k}^{A} + Q_{k+1,k}^{A}$$

(III-5)

Before presenting the filtering equations, the measurement residual at \( t_{k} \) must be defined. The measurement residual, \( \varepsilon_{k} \), 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, \( y_{k}^{r} \), based on the actual state deviation, \( x_{k}^{A} \) plus a random noise component \( v_{k}^{r} \) and a bias component \( b \)

$$y_{k}^{a} = y_{k}^{r} + v_{k}^{r} + b$$

(III-6)
If a modified gain matrix is defined by

\[ \mathbf{K}_{k+1} \]

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

\[ y^e_k = \hat{y}_k + H_k \hat{x}_k^A \quad \text{(III-7)} \]

The measurement residual is then simply

\[ \epsilon_k = y^a_k - y^e_k \quad \text{(III-8)} \]

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

\[ J_{k+1} = H_{k+1} P_{k+1} H_{k+1}^T + R_{k+1} \quad \text{(III-9)} \]

\[ K_{k+1}^A = P_{k+1}^A H_{k+1}^T (J_{k+1})^{-1} \quad \text{(III-10)} \]

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:

\[ K_{k+1}^A = \begin{bmatrix} K_{1,k+1} \\ K_{2,k+1} \\ K_{3,k+1} \\ K_{4,k+1} \\ K_{5,k+1} \end{bmatrix} \quad \text{(III-11)} \]

If a modified gain matrix is defined by
then the estimated state update equation may be written

$\hat{x}^+_{k+1} = \hat{x}^-_{k+1} + K_{k+1}^A \epsilon_{k+1}$

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

$P^+_{k+1} = P^-_{k+1} - K_{k+1}^A H_{k+1} P^-_{k+1} H_{k+1}^T$.

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:

$R = \begin{cases} C_1, & p_o \geq 20 \text{ millibars} \\ C_2, & p_o < 20 \text{ millibars} \end{cases}$

(III-15)
The measurement noise covariance for a radar altimeter measurement $\dot{h}$ can be either set to a constant or computed as a function of the measurement itself. Currently, with the latter option

$$R = \text{maximum} \begin{cases} [0.005 \, \dot{h}, \, 0.05] & , \, \dot{h} \geq 6 \\ [0.015 \, \dot{h}, \, 0.005] & , \, \dot{h} < 6 \end{cases}$$ (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

$$\sigma_{\dot{h}}^2 = \sigma_{\dot{h}}^2 \left( \frac{1}{T_s} \right)$$ (III-17)

where $\sigma_{\dot{h}}^2$ 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

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

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

$$\dot{X} = \frac{\partial f}{\partial X} X$$ (III-19)
where $x^A$ represents small deviations from the nominal augmented state $\mathbf{x}^A$. 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

$$x^A_{k+1} = \phi(t_{k+1}, t_k) x^A_k$$  \hspace{1cm} (III-20)

If the augmented state vector is partitioned into the basic state vector, $\mathbf{x}$; solve-for parameter vector, $\mathbf{q}$; dynamic-consider parameter vector, $\mathbf{u}$; measurement parameter vector, $\mathbf{v}$; and dynamic/measurement parameter vector, $\mathbf{w}$; it is possible to make a corresponding partition of the state transition matrix $\phi$. Before writing $\phi$ 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 $\phi$ will be either zero matrices or identity matrices except for those associated with the basic state vector. Thus the partitioned form of $\phi$ is

$$\phi = \begin{bmatrix}
\phi & \psi & \theta & 0 & 0 \\
0 & I & 0 & 0 & 0 \\
0 & 0 & I & 0 & 0 \\
0 & 0 & 0 & I & 0 \\
0 & 0 & 0 & 0 & I
\end{bmatrix}$$  \hspace{1cm} (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 $j$th column of $\phi$ be designated by $\phi_j$. Now consider the special case of equation (III-20) in which $x^A_k$ is a vector whose only nonzero element is the $j$th element:
\[ x_k^A = [0, \cdots, 0, \delta_j, 0, \cdots, 0]^T = d_j \quad (III-22) \]

Equation (III-20) becomes
\[ x^A(t_{k+1}; d_j, t_k) = \phi_i \delta_j \quad (III-23) \]

from which we obtain the \( j \)th column of \( \phi \) as
\[ \phi_i = \frac{x^A(t_{k+1}; d_j, t_k)}{\delta_j} \quad (III-24) \]

The numeration of this expression is evaluated by integrating the state equations over the interval \([t_k, t_{k+1}]\) as follows. Let
\[ I_j = \int_{t_k}^{t_{k+1}} f \left( x^A(\tau) + d_j, \tau \right) d\tau = x^A(t_{k+1}; x_k^A + d_j, t_k) - (x_k^A + d_j) \quad (III-25) \]

and
\[ I = \int_{t_k}^{t_{k+1}} f \left( x^A(\tau), \tau \right) d\tau = x^A(t_{k+1}; x_k^A, t_k) - x_k^A \quad (III-26) \]

then
\[ x^A(t_{k+1}; d_j, t_k) = I_j - I + d_j \quad (III-27) \]

Thus the state transition matrix is computed by evaluating the integral \( I \) once and the integral \( I_j \) once for each column of \( \phi \).

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

\[ Y = Y (X^A, t) \]  

(III-28)

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

\[ y = \frac{\partial Y}{\partial X^A} x^A = H^A x^A \]  

(III-29)

where \( y \) and \( x^A \) represent deviations from the nominal values of \( Y \) and \( x^A \).

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

\[
\begin{bmatrix}
x \\
qu \\
v \\
w
\end{bmatrix}
= [H : M : 0 : L : G]
\begin{bmatrix}
u \\
v \\
w
\end{bmatrix}
\]

(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

\[ y = Y (x^A + d_j, t) - Y (x^A, t) = H^A_j \delta_j \]  

(III-31)
Thus

$$H^A_{.j} = \frac{Y(X^A + d_j, t) - Y(X^A, t)}{j}.$$ (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 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:

$$\tilde{x}_j^+ = \tilde{x}_j^- + \tilde{x}_j^-$

$$\tilde{q}_j^+ = \tilde{q}_j^- + \tilde{q}_j^-$$

$$\tilde{x}_j = 0$$

$$\tilde{q}_j = 0$$

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

\[ x = (h, v, \gamma, \phi, p)^T \]  (IV-1)

where

- \( h \) = vehicle altitude
- \( v \) = vehicle velocity
- \( \gamma \) = vehicle flightpath angle
- \( \phi \) = 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

\[ \dot{x} = g(x) + f(x) \]  (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

\[
f(a_x, a_z, \theta_m)
\]

where \( a_x \) and \( a_z \) represent (smoothed) axial and normal accelerometer (VRU) data, respectively, and \( \theta_m \) 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 \( a_x \), 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

\[
\dot{h} = v \sin \gamma \quad \text{(IV-3)}
\]

\[
\dot{v} = -g \sin \gamma + a_x \cos (\alpha + \epsilon) + a_z \sin (\alpha + \epsilon) \quad \text{(IV-4)}
\]

\[
\dot{\gamma} = \left(\frac{v}{r} - \frac{g}{v}\right) \cos \gamma + \frac{1}{v} \left[ a_x \sin (\alpha + \epsilon) - a_z \cos (\alpha + \epsilon) \right] \quad \text{(IV-5)}
\]

\[
\dot{\phi} = \frac{v}{r} \cos \gamma \quad \text{(IV-6)}
\]

\[
\dot{\rho} = -g \rho \dot{h} \quad \text{(IV-7)}
\]

where \( a_x \) and \( a_z \) represent corrected axial and normal accelerometer data, respectively, and \( \alpha + \epsilon \) can be obtained from equation (II-5)

\[
\alpha + \epsilon = \theta_c + \theta_o + \phi - \gamma \quad \text{(IV-8)}
\]

where attitude \( \theta \) has been represented as the sum of the initial attitude \( \theta_o \) and the change in (corrected) attitude \( \theta_o \) since \( t_o \).

This permits the mode A filter to treat \( \theta_o \) as a solve-for or consider parameter. The angle \( \epsilon \) 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 \( \rho \) represents atmospheric density.
Accelerations \( a_x \) and \( a_z \) and attitude \( \theta \) are referred to as corrected quantities since the measured accelerations \( a_{xm} \) and \( a_{zm} \) and the measured attitude \( \theta_m \) have been corrected or calibrated for scale factor, bias, and misalignment errors. The equations relating corrected quantities to measured quantities are summarized as

\[
a_x = \frac{1}{\cos(\delta_1 - \delta_2)} \left\{ \frac{a_{xm} - c_{sx}}{c_{bx}} \cos \delta_2 - \frac{a_{zm} - c_{sz}}{c_{bz}} \sin \delta_1 \right\} + \omega_c^2 x - \omega_c z \tag{IV-9}
\]

\[
a_z = \frac{1}{\cos(\delta_1 - \delta_2)} \left\{ -\frac{a_{xm} - c_{sx}}{c_{bx}} \sin \delta_2 - \frac{a_{zm} - c_{sz}}{c_{bz}} \cos \delta_1 \right\} + \omega_c^2 z + \omega_c x \tag{IV-10}
\]

\[
\theta_c = \frac{1}{c_{s\theta}} \left\{ \theta_m - c_{d\theta} t \right\} \tag{IV-11}
\]

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 \( \omega_c \) and angular acceleration \( \ddot{\omega}_c \) are given by

\[
\omega_c = \frac{1}{c_{s\theta}} \left\{ \omega_m - c_{d\theta} \right\} \tag{IV-12}
\]

\[
\ddot{\omega}_c = \frac{\ddot{\omega}_m}{c_{s\theta}} \tag{IV-13}
\]
where $\omega_m$ and $\dot{\omega}_m$ are measured angular velocity and angular acceleration, respectively. Misalignment angles $\delta_1$ and $\delta_2$ are calibrated using

$$\delta_1 = 61 - \delta_1$$  \hspace{1cm} (IV-14)

$$\delta_2 = 62 - \delta_2$$  \hspace{1cm} (IV-15)

where $61$ and $62$ are the nominal misalignment angles, and $\delta_1$ and $\delta_2$ are misalignment biases.

Returning to equation (IV-7), it is apparent that a method for obtaining density $\rho$ must be available before this final state equation can be integrated. Unlike mode B, an atmospheric model cannot be used for generating $\rho$. Instead, in mode A an approximate relationship between $\rho$ and $a_x$ 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

$$q = -\frac{m}{C_A S} a_x$$  \hspace{1cm} (IV-16)

The parachute effect can be incorporated approximately by writing

$$q = -\frac{m}{(C_A S + C_D S_D)} a_x$$  \hspace{1cm} (IV-17)

Having related dynamic pressure $q$ to $a_x$, it is a simple matter to relate $\rho$ to $a_x$ since

$$\rho = \frac{2q}{v_r^2}$$  \hspace{1cm} (IV-18)

where $v_r$ is the relative velocity given by equation (II-2). With density $\rho$ 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

38
of state

\[ T = \frac{\rho M}{R} \quad (IV-19) \]

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:

\[
\begin{align*}
a_c &= 0 \\
\delta_c &= 0
\end{align*}
\quad (IV-20)
\]

If a gyro is not available, we assume

\[
\begin{align*}
\omega_c &= 0 \\
\phi_c &= 0
\end{align*}
\quad (IV-21)
\]

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 VII. 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

\[ \rho = \frac{2m_a x_c}{\sqrt{r} (C_A S + C_D S_D)} . \]  (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 \( \rho \) depends through equation (IV-22). Denoting all such parameters as \( \omega \), we would obtain a first variation of equation (IV-22) having the form

\[ \delta \rho = \Gamma_1 (\delta x, \delta \omega)^T \]  (IV-23)

where \( \Gamma_1 \) is the Jacobian matrix

\[ \Gamma_1 = \left[ -\frac{\partial \rho}{\partial (x, \omega)} \right] . \]  (IV-24)

Then the derived estimated deviation of density would be given by

\[ \delta \beta = \Gamma_1 (\delta \hat{x}, \delta \hat{\omega})^T \]  (IV-25)
where estimates $\delta \hat{x}$ and $\delta \hat{\phi}$ 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 $\delta \hat{\phi}$ can be found from

$$
\sigma^2_{\hat{\phi}} = \Gamma_1 \begin{bmatrix}
P & C_{xw} \\
C_{xw}^T & W
\end{bmatrix} \Gamma_1^T
$$

(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

$$
\delta \hat{T} = \Gamma_2 (\delta \hat{x}, \delta \hat{\phi})^T
$$

(IV-27)

where

$$
\Gamma_2 = \left[ \begin{array}{c}
\frac{\partial S}{\partial x} \\
\frac{\partial S}{\partial w}
\end{array} \right]
$$

(IV-28)

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

$$
\sigma^2_T = \Gamma_2 \begin{bmatrix}
P & C_{xw} \\
C_{xw}^T & W
\end{bmatrix} \Gamma_2^T
$$

(IV-29)

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

$$
\delta \hat{\phi} = \frac{2\rho}{v_r} \delta \phi
$$

(IV-30)
and

\[
\sigma_p^2 = \frac{4\varphi^2}{v_r} \sigma_v^2 \tag{IV-31}
\]

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

\[
\delta \hat{T} = T \left( \frac{\delta \varphi}{p} + 2 \frac{\delta \varphi}{v_r} + \frac{\delta M}{M} \right) \tag{IV-32}
\]

and

\[
\sigma_T^2 = \frac{T^2}{p^2} \sigma_p^2 + \frac{4T^2}{v_r^2} \sigma_v^2 + \frac{T^2}{M^2} \sigma_M^2 \tag{IV-33}
\]

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 \( \delta \beta \) and \( \delta \hat{T} \) and more realistic variances of \( \rho \) and \( \sigma_T^2 \).

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

\[ x = (h, v, \gamma, \phi)^T \]  

where

- \( h \) = altitude
- \( v \) = velocity
- \( \gamma \) = flightpath angle
- \( \phi \) = 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:

\[ \dot{h} = v \sin \gamma \]  

\[ \dot{v} = -g \sin \gamma + \frac{A}{m} \cos (\alpha + \epsilon) + \frac{N}{m} \sin (\alpha + \epsilon) - \frac{F_d}{m} \cos \epsilon \]  

\[ \dot{\gamma} = \left( \frac{v}{r} - \frac{b}{v} \right) \cos \gamma + \frac{1}{v} \left[ \frac{A}{m} \sin (\alpha + \epsilon) - \frac{N}{m} \cos (\alpha + \epsilon) - \frac{F_d}{m} \sin \epsilon \right] \]  

\[ \dot{\phi} = \frac{F_d}{m} \sin \epsilon \]
\[ \dot{\phi} = \frac{V}{r} \cos \gamma \quad (V-5) \]

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

\[ A = -C_A q S \quad (V-6) \]
\[ N = -C_N q S \quad (V-7) \]
\[ F_d = C_D q S_D \quad (V-8) \]

where dynamic pressure \( q = \frac{1}{2} \rho \frac{V^2}{r} \). 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 \( \alpha \) is zero.

Before the aerodynamic forces given by equations (V-6) through (V-8) can be evaluated, it is necessary to obtain density \( \rho \). Unlike mode A that extracts density from the axial accelerometer measurement \( x_c \), 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:

\[ a_x = \left( \frac{A}{m} \cos \delta_1 - \frac{N}{m} \sin \delta_1 \right) C_{sx} + C_{bx} \]  
\[ a_z = \left( \frac{A}{m} \sin \delta_2 + \frac{N}{m} \cos \delta_2 \right) C_{sz} + C_{bz} \]

where aerodynamic forces A and N are given by equations (V-6) and (V-7), \( \delta_1 \) and \( \delta_2 \) 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


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**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>XN(1)</td>
<td>Initial nominal vehicle altitude $h$</td>
<td>km</td>
</tr>
<tr>
<td>XN(2)</td>
<td>Initial nominal vehicle velocity $v$</td>
<td>km/s</td>
</tr>
<tr>
<td>XN(3)</td>
<td>Initial nominal vehicle flight path angle $\gamma$</td>
<td>deg</td>
</tr>
<tr>
<td>XN(4)</td>
<td>Initial nominal vehicle downrange angle $\phi$</td>
<td>deg</td>
</tr>
<tr>
<td>XN(5)</td>
<td>Initial nominal vehicle attitude angle $\theta$</td>
<td>deg</td>
</tr>
<tr>
<td>XN(6)</td>
<td>Initial nominal vehicle angular velocity $\omega$</td>
<td>deg/s</td>
</tr>
<tr>
<td>XN(7)</td>
<td>Initial value of integral of axial VRU output</td>
<td>km/s</td>
</tr>
<tr>
<td>XN(8)</td>
<td>Initial value of integral of normal VRU output</td>
<td>km/s</td>
</tr>
<tr>
<td>XN(9)</td>
<td>Initial value of integral of ARU output</td>
<td>rad</td>
</tr>
</tbody>
</table>

**ICOOR**
- Code that defines coordinate system relative to which the entry plane is oriented using the variables ECLINC, ECLONG, and PHIR (3)
  - 1: planetocentric ecliptic
  - 2: planetocentric equatorial
  - 3: subsolar orbital plane

**ECLINC**
- Inclination of the entry plane relative to xy-plane of ICOOR coordinate system | deg |

**ECLONG**
- Longitude of the ascending node of the entry plane relative to ICOOR coordinate system | deg |

**PHIR**
- Angle between the line of nodes and the $\phi$ reference line. Sum of argument of periapsis and initial true anomaly of vehicle | deg |
TC Initial trajectory time (0.) s
TF Final trajectory time s
IYR Initial calendar date corresponding thru to initial trajectory time TC.
SECSI IYR = year (integer)
IMO = 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
ØDB Maximum dynamic pressure permitted for integration of the complete set of equations of motion. Whenever dynamic pressure exceeds ØDB, 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 (1. x 10^5) kg/km•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 (?)
= 2, Mercury
3, Venus
5, Mars
6, Jupiter
7, Saturn
8, Uranus
9, Neptune
10, Pluto
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM</td>
<td>Planet radius (6050.)</td>
<td>km</td>
</tr>
<tr>
<td>MU</td>
<td>Planet gravitational constant ((3.2486 \times 10^5))</td>
<td>(\text{km}^3/\text{s}^2)</td>
</tr>
<tr>
<td>GØ</td>
<td>Acceleration of gravity at planet surface ((8.867 \times 10^{-3}))</td>
<td>(\text{km/s}^2)</td>
</tr>
<tr>
<td>ØMEG</td>
<td>Planet angular velocity ((2.997 \times 10^{-7}))</td>
<td>rad/s</td>
</tr>
<tr>
<td>ATMØS(1)</td>
<td>Surface pressure</td>
<td>(\text{kg/km-s}^2)</td>
</tr>
<tr>
<td>ATMØS(18) thru ATMØS(33)</td>
<td>Nominal atmosphere temperature profile. ATMØS(18) through ATMØS(25) define the altitude breakpoints in ascending order. ATMØS(26) through ATMØS(33) define the corresponding temperatures at each of the altitude breakpoints</td>
<td>km, °K</td>
</tr>
<tr>
<td>NTPTS</td>
<td>Number of altitude breakpoints used to define the temperature profile. NTPTS must not exceed 7 (6)</td>
<td>--</td>
</tr>
<tr>
<td>XMFH</td>
<td>Altitude breakpoints (in ascending order) for all mole fraction profiles. XMFH(1) must be set equal to ATMØS(18) ((0., 120., 370., 1000., 0.))</td>
<td>km</td>
</tr>
<tr>
<td>XMFW</td>
<td>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</td>
<td>--</td>
</tr>
<tr>
<td>NMPTS</td>
<td>Number of altitude breakpoints used to define the mole fraction profile in XMFH. NMPTS must not exceed 5 (4)</td>
<td>--</td>
</tr>
<tr>
<td>CGMW</td>
<td>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.))</td>
<td>--</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>AR</td>
<td>Universal gas constant ( (8.31432 \times 10^{-3}) )</td>
<td></td>
</tr>
<tr>
<td>AGAM</td>
<td>Ratio of specific heats (1.4)</td>
<td></td>
</tr>
<tr>
<td>WDTBL</td>
<td>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., 0.))</td>
<td>km, km/s</td>
</tr>
<tr>
<td>TH</td>
<td>Nominal terrain height profile coefficients ( C_1, C_2, \ldots, 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</td>
<td></td>
</tr>
<tr>
<td>TERHT</td>
<td>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</td>
<td></td>
</tr>
</tbody>
</table>

**c. Entry Vehicle Variables**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPHAS</td>
<td>Code defining entry phase (1)</td>
<td></td>
</tr>
<tr>
<td>= 1, phase prior to parachute deployment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2, parachute phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3, phase following parachute release</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VMASS</td>
<td>Vehicle mass as a function of IPHAS</td>
<td>kg</td>
</tr>
<tr>
<td>(174., 122., 100.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>VSA</td>
<td>Vehicle reference area as a function of IPHAS</td>
<td>km²</td>
</tr>
<tr>
<td>VDIA</td>
<td>Vehicle reference diameter as a function of IPHAS</td>
<td>km</td>
</tr>
<tr>
<td>VRI</td>
<td>Vehicle rotational inertia as a function of IPHAS</td>
<td>kg-km²</td>
</tr>
<tr>
<td>XG</td>
<td>Vehicle cg offset along x-axis</td>
<td>km</td>
</tr>
<tr>
<td>ZG</td>
<td>Vehicle cg offset along z-axis</td>
<td>km</td>
</tr>
<tr>
<td>XD</td>
<td>Parachute bridle apex location along x-axis</td>
<td>km</td>
</tr>
<tr>
<td>SDP</td>
<td>Parachute reference area</td>
<td>km²</td>
</tr>
<tr>
<td>CDTBL</td>
<td>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)</td>
<td></td>
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### Measurement Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>XM</td>
<td>Velocity reference unit (VRU) location along x-axis</td>
<td>km</td>
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<tr>
<td>ZMM</td>
<td>VRU location along z-axis</td>
<td>km</td>
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<td>XSTEP</td>
<td>Quantum level for x-axis VRU (1.5 x 10⁻⁵)</td>
<td>km/s</td>
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<td>Variable</td>
<td>Description</td>
<td>Unit</td>
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<td>----------</td>
<td>------------------------------------------------------------------------------</td>
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<tr>
<td>ZSTEP</td>
<td>Quantum level for z-axis VRU</td>
<td>km/s</td>
</tr>
<tr>
<td></td>
<td>(1.5 x 10^{-5})</td>
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<tr>
<td>TSTEP</td>
<td>Quantum level for attitude reference unit</td>
<td>rad</td>
</tr>
<tr>
<td>DELT</td>
<td>Nominal axial accelerometer, normal accelerometer, and gyro misalignment</td>
<td>rad</td>
</tr>
<tr>
<td></td>
<td>angles (0., 0., 0.)</td>
<td></td>
</tr>
<tr>
<td>VXQA</td>
<td>Initial axial accelerometer quantized data for five time points centered</td>
<td>km/s</td>
</tr>
<tr>
<td></td>
<td>about initial time (5 * 0.)</td>
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<tr>
<td>VZQA</td>
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<td>km/s</td>
</tr>
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<td></td>
<td>about initial time (5 * 0.)</td>
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<td>THTQA</td>
<td>Initial gyro quantized data for five time points centered about initial</td>
<td>rad</td>
</tr>
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<td></td>
<td>time (5 * 0.)</td>
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<tr>
<td>ETA</td>
<td>Radar altimeter sweep half-angle</td>
<td>rad</td>
</tr>
<tr>
<td></td>
<td>(0.7854)</td>
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<tr>
<td>SALT</td>
<td>Array of altitudes above mean earth surface for three tracking stations</td>
<td>km</td>
</tr>
<tr>
<td>SLAT</td>
<td>Array of latitudes in degrees north for three tracking stations</td>
<td>deg</td>
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<tr>
<td>SLON</td>
<td>Array of longitudes in degrees east for three tracking stations</td>
<td>deg</td>
</tr>
<tr>
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<td>The following tracking station locations are preset:</td>
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<td><strong>SALT  SLAT  SLON</strong></td>
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<td>1.</td>
<td>Goldstone 1.031 35.384 -116.833</td>
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</tr>
<tr>
<td>2.</td>
<td>Madrid .05 40.417 -3.667</td>
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<td>3.</td>
<td>Canberra .05 -35.311 149.136</td>
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<td>NOFRAC</td>
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<td>= false, refractivity model will be used</td>
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</tr>
<tr>
<td></td>
<td>true, refractivity model will not be used</td>
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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>
<thead>
<tr>
<th>J</th>
<th>C(j)</th>
<th>Units</th>
<th>Data Generator</th>
<th>Mode A</th>
<th>Mode B</th>
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<td>✓</td>
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<td>VRU offset in z-direction, $Z_m$</td>
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* $C(2)$ may appear in the data generator namelist only if $C(151)$ also appears and is identical to $C(2)$.  
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<td>Gyro (ARU) misalignment $\delta_3$ bias</td>
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<td>Range bias (station 1)</td>
<td>km</td>
<td>✓</td>
<td>✓</td>
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<td>Range bias (station 2)</td>
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<td>Range bias (station 3)</td>
<td>km</td>
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<td>69</td>
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*Accelerometer bias has units of km/s in data generator and units of km/s² in modes A and B.
<table>
<thead>
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<th>j</th>
<th>C(j)</th>
<th>Units</th>
<th>Data Generator</th>
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* C(105) is used as an internal variable for computing sensitivity matrices associated with the 5th state variable in mode A.
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* \(C(140)\) may only appear in data generator namelist; index 140, however, may appear in any parameter augmentation list in modes A and B.
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Table II-1 (Concl)

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</table>
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 BLOCK DATA subroutine. One could, of course, remove the existing aerodynamic tables from BLOCK 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 BLOCK 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 $0.03$, then one would insert

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

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 $ODB$. 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 $ODB$ 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 ODB, 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) $|\dot{v}| \ll 1$, and (2) $\gamma \approx -90^\circ$. 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**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>XN(I) thru XN(4)</td>
<td>See Section B.1</td>
</tr>
<tr>
<td>XN(5)</td>
<td>Initial nominal ambient pressure; required only for mode A (0.)</td>
</tr>
<tr>
<td>THETI</td>
<td>Initial nominal vehicle attitude angle θ; required only for mode A (0.)</td>
</tr>
<tr>
<td>XO(I) thru XO(5)</td>
<td>Initial original nominal vehicle state. XO(I) corresponds to XN(I) above for I = 1, 2, ..., 5</td>
</tr>
<tr>
<td>ICPOR</td>
<td>See Section B.1</td>
</tr>
<tr>
<td>ECLINC</td>
<td>See Section B.1</td>
</tr>
<tr>
<td>ECLONG</td>
<td>See Section B.1</td>
</tr>
<tr>
<td>PHIR</td>
<td>See Section B.1</td>
</tr>
<tr>
<td>TC</td>
<td>See Section B.1</td>
</tr>
<tr>
<td>TF</td>
<td>See Section B.1</td>
</tr>
<tr>
<td>IYR</td>
<td>See Section B.1</td>
</tr>
<tr>
<td>SECSI</td>
<td>See Section B.1</td>
</tr>
<tr>
<td>EDN(1)</td>
<td>Initial vehicle altitude estimate δh (0.)</td>
</tr>
<tr>
<td>EDN(2)</td>
<td>Initial vehicle velocity estimate δv (0.)</td>
</tr>
<tr>
<td>EDN(3)</td>
<td>Initial vehicle flightpath angle estimate δφ (0.)</td>
</tr>
<tr>
<td>EDN(4)</td>
<td>Initial vehicle downrange angle estimate δρ (0.)</td>
</tr>
<tr>
<td>EDN(5)</td>
<td>Initial ambient pressure estimate δp required only for mode A (0.)</td>
</tr>
</tbody>
</table>

---

68
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>QEDN</td>
<td>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.).</td>
</tr>
<tr>
<td>DT</td>
<td>Nonfunctional</td>
</tr>
<tr>
<td>QSDT</td>
<td>Integration step size used after time QST; input only if data generator is not run</td>
</tr>
<tr>
<td>SDT</td>
<td>Integration step size used in the data generator; should be input only if data generator is not run</td>
</tr>
<tr>
<td>QST</td>
<td>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</td>
</tr>
<tr>
<td>TD</td>
<td>Time of parachute deployment as determined by the data generator. Should be input only if data generator is not run</td>
</tr>
<tr>
<td>TR</td>
<td>Time of parachute release as determined by data generator. Should be input only if data generator is not run</td>
</tr>
<tr>
<td>TEND</td>
<td>Time of next event. Should be input only if data generator is not run</td>
</tr>
</tbody>
</table>

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 NOFRAC. 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
NGYRØ 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

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

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 MCODE 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. Non-functional currently
2. Use of \( C(j) \) Table in Reconstruction Program

Just as the \( C(j) \) variables defined in Table II-1 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 BL\( \text{OCK DATA} \), the same \( C(j) \) variables must be used in the reconstruction program to change the existing aerodynamic tables in BL\( \text{OCK DATA} \) 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 \( C_A \) 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:

\[
\begin{align*}
\text{LISTQ} &= 20, & \text{NQ} &= 1 \\
\text{LISTU} &= 21, 30, & \text{NU} &= 2 \\
\text{LISTV} &= 67, 68, 69, & \text{NV} &= 3 \\
\text{LISTW} &= 51, & \text{NW} &= 1 .
\end{align*}
\]

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 \( \text{NACCEL} \) 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 \( \text{NGYRO} \) 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:

\[
\begin{array}{cccc}
\text{F10.3} & \text{F10.3} & \text{F10.3} & \text{I10} \\
\text{START} & \text{TIMEND} & \text{TIMDIF} & \text{CODE} \\
\end{array}
\]

where

- \text{START} is the time (in seconds) to start a measurement or event,
- \text{TIMEND} is the time (in seconds) to end a measurement or event,
- \text{TIMDIF} is the time (in seconds) between measurements or events,
- \text{CODE} 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·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);
j) 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 ≠ 0);
7) Number and list of dynamic-consider parameters (appear only if NU ≠ 0);
8) Number and list of measurement-consider parameters (appear only if NV ≠ 0);
9) Number and list of dynamic/measurement-consider parameters (appear only if NW ≠ 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 ≠ 0);

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

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

14) Vector of dynamic/measurement-consider parameter variances (appears only if NW ≠ 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 MACHNO is true. MACHNO 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 MACHNO 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:

   \[
   \begin{align*}
   &XN=248.9, 11.08, -38.8, 0., -38.8, 0., \\
   &DT=.19, TF=500., \\
   &IYR=1977, I=5, IDAY=16, IHR=23, IMIN=54, \\
   &SECS=41., \\
   &ICOOR=3, PHIR=0., ECLINC=140.61, ECLLONG=68.2, \\
   &OEB=15.6E+5, \\
   &G0=8.867E-3, RN=6050., \theta=3.2486E5, \\
   &ATMOS(1)=1.104E10, \\
   &ATMOS(18)=0.1, 1.15, 1.25, 1.37, 1.75, 2*0., \\
   &ATMOS(26)=73.8, 30., 170., 2*210., 710., \\
   &NTPTS=6, NMPTS=4, \\
   &WDBL=2., 0., 10., 0., 0., \\
   &TERH=.FALSE., AGAM=1.4, \\
   &VMASS=174., 122., 100., \\
   &VSA=1.474E-6, .292E-6, .292E-6, \\
   &VDIA=1.37E-3, .61E-3, .61E-3, \\
   &VRI=1.37E-5, .5E-5, .5E-5, \\
   &XG=0., XM=0., ZG=0., ZM=0., \\
   &XSTEP=1.5E-5, ZSTEP=1.5E-5, TSTEP=.004, \\
   &IGNTR=20, \\
   &RESTR=.FALSE.,
   \end{align*}
   \]


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 (USA), 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

\[
C(21) = 2 \times 1.05 = 2.1
\]

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 \( m \times q \). Since dynamic pressure obviously exceeds \( ODB \), 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:

\[
\begin{align*}
XN & = 248.0, 11.08, -38.8, 0.0, 5.4E-9, \\
X0 & = 248.0, 11.08, -38.8, 0.0, 5.4E-9, \\
\text{THET}I & = -38.8, \text{TP} = 500.0, \\
\text{IYR} & = 1977, \text{IM} & = 5, \text{IDAY} & = 16, \text{IH}R & = 23, \text{IMIN} & = 54, \text{SECSI} & = 41, \text{LOR} & = -3, \text{PHIR} & = 0.0, \text{ECLINC} & = 140.61, \text{ECLONG} & = 68.2, \\
\text{G0} & = 8.867E-3, \text{RM} & = 6050.0, \text{MEG} & = 2.997E-7, \text{MU} & = 3.2486E-5, \\
\text{WDTBL} & = 2.0, 0.0, 10.0, 0.0, \text{TERHT} & = \text{FALSE}, \text{VMASS} & = 174.0, 122.0, 100.0, \\
\text{VSA} & = 1.474E-6, 0.292E-6, 0.292E-6, \text{VDIA} & = 1.37E-3, 0.61E-3, 0.61E-3, \\
\end{align*}
\]
VRI=1.76E-5, .5E-5, .5E-5,
XG=0., XM=0., ZG=0., ZMM=0.,
ICNTR=1, RESTRT=.FALSE.,
NGYRØ=.TRUE., LTR2=.TRUE.,
C(16)=-.13, 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 NGYRØ and LTR2. Setting NGYRØ 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.

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Time (sec)</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800.</td>
<td>2000.</td>
<td>20.</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>60.</td>
<td>2000.</td>
<td>50.</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>80.</td>
<td>2000.</td>
<td>100.</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>2000.</td>
<td>30.</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>100.</td>
<td>30.</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>150.</td>
<td>2000.</td>
<td>200.</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>200.</td>
<td>200.</td>
<td>10.</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>350.</td>
<td>350.</td>
<td>10.</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>700.</td>
<td>700.</td>
<td>10.</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>1200.</td>
<td>1200.</td>
<td>10.</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>1400.</td>
<td>1400.</td>
<td>10.</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>100000.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 -0.943 to -0.515° and downrange angle errors from -.38 to .090°. The velocity error increases slightly. Reconstructed ARU data are zero, and will remain zero since NGYTR 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 re-
main 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 pre-
sented first.

1. Data Generator

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

\[ \begin{align*}
XN &= 248., 11.06, -74., 0., -65., 0., \\
DT &= 1, QSALT=55., TP=500., \\
YR &= 1977, IMO=5, IDAY=16, IHR=23, IMIN=54, SECSI=41., \\
ICOOR &= 3, PHIR=14.624, ECLONG=137.82, \\
ECGLIN &= 89.36, \\
OB &= 15. E+5, \\
\phi &= 8.867 E-3, RM=6050., \Omega=2.997 E-7, MU=3.2486 E+5, \\
\text{ATMOS}(1) &= 1.104 E+10, \\
\text{ATMOS}(18) &= 50., 60., 115., 125., 127., 2*0., \\
\text{ATMOS}(26) &= 738., 260., 170., 2*210., 710., \\
\text{NTPTS} &= 6, \text{NMPTS} = 4, \\
\text{AGAM} &= 14, \\
\text{WDYF} &= 2., 0., 10., 0., 0., \\
\text{ETHER} &= \text{.FALSE.}, \\
\text{VMASS} &= 22.6, \text{VDIA} = 448 E-3, \text{VSA} = 158 E-6, \\
\text{VRI} &= 1.085 E-6, \\
\text{XG} &= 0., \text{XM} = 0., \text{ZG} = 0., \text{ZM} = 0., \\
\text{XSTEP} &= 1.5 E-5, \text{ZSTEP} = 1.5 E-5, \text{TSTEP} = 0.004, \\
\text{ICNTR} &= 20, \\
\text{RESTRT} &= \text{.FALSE.},
\end{align*} \]

94
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 ODB. 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.

\[
\begin{align*}
XN & = 248.0, 11.06, -74.0, 0.0, \\
XØ & = 248.0, 11.06, -74.0, 0.0,
\end{align*}
\]
IYR=1977, IM=5, IDAY=16, IHR=23, IMIN=54, SEC=41.,
IC=3, PI=14.624, ECLONG=137.82, ECLINC=89.36,
TF=500.,

GR=8.867E-3, RM=6050., ØMEG=2.997E-7,
MU=3.2486E+5,
ATMOS(1)=1.104E+10,
ATMOS(18)=0., 60., 115., 125., 137., 175., 2*0.0,
ATMOS(26)=738., 260., 170., 2*210., 710.,
NTPTS=6, NMPTS=4,
AGAM=1.4,
TERH=FALSE.,
WDTB=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.,
IGNTR=1,
REST=.FALSE.,
NACCEL=.TRUE., NYG=TRUE.,
LRT=.TRUE.,

C(16)=1., C(21)=2., 4., .23,
P=200., 0., 0., 0.,
 2.5E-4, 0., 0.,
 0., 0., 1.22E-3, 0.,
 0., 0., 3.234E-4,

NQ=4, LISTQ=3, 5, 7, 9,
Q=25., 0., 0., 0.,
 10., 0., 0.,
 0., 0., 1.5, 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, LIST=t4, 6, 8, 152, 153, 156, 161, 1,

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 ATMOS variables must
appear in the above namelist.

Both NACCEL and NGYRO 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 corres-
ponding 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 considered parameters
by the filter. Certain of the component mole fraction profile pa-
rameters are also considered by the filter.

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

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Event Time</th>
<th>Value</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.</td>
<td>2000.</td>
<td>100.</td>
<td>4</td>
</tr>
<tr>
<td>40.</td>
<td>2000.</td>
<td>150.</td>
<td>5</td>
</tr>
<tr>
<td>10.</td>
<td>2000.</td>
<td>60.</td>
<td>21</td>
</tr>
<tr>
<td>60.</td>
<td>60.</td>
<td>10.</td>
<td>12</td>
</tr>
<tr>
<td>200.</td>
<td>200.</td>
<td>10.</td>
<td>12</td>
</tr>
<tr>
<td>600.</td>
<td>600.</td>
<td>10.</td>
<td>12</td>
</tr>
<tr>
<td>1500.</td>
<td>1500.</td>
<td>10.</td>
<td>12</td>
</tr>
<tr>
<td>100000.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 ±3σ range predicted by the filter. For example, compare the altitude error of -0.751 kilometer with the predicted 1-σ standard deviation of 0.823 kilometer, and the surface temperature error of -4.55°K with the predicted 1-σ 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 Venusian 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 ($\gamma = -90^\circ$) was assumed for this study. The initial vehicle velocity was 863 m/s at an 85-kilometer altitude. A ballistic coefficient of $30.01 \times 10^6$ kg/km$^2$ was assumed until the parachute was deployed at the 50-kilometer altitude, after which the ballistic coefficient was changed to $25.539 \times 10^6$ 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.

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Temperature (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.</td>
<td>738.</td>
</tr>
<tr>
<td>13.5</td>
<td>640.</td>
</tr>
<tr>
<td>42.</td>
<td>387.</td>
</tr>
<tr>
<td>60.</td>
<td>256.</td>
</tr>
<tr>
<td>115.</td>
<td>170.</td>
</tr>
</tbody>
</table>

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

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

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
<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STATE OF QIVATIVES</strong></td>
<td></td>
</tr>
<tr>
<td>$H$</td>
<td>-6.8534570405358E+00</td>
</tr>
<tr>
<td>$H'$</td>
<td>8.1064099383858E-02</td>
</tr>
<tr>
<td>$OVX$</td>
<td>-1.83354088475E-07</td>
</tr>
<tr>
<td>$L$</td>
<td>1.31021532261265E-02</td>
</tr>
<tr>
<td>$KM$</td>
<td></td>
</tr>
<tr>
<td>$KM/SEC$</td>
<td></td>
</tr>
<tr>
<td><strong>RATE GYRO</strong></td>
<td>8.6245925E-06</td>
</tr>
<tr>
<td><strong>ALTIMETER</strong></td>
<td>3.223641503164E-07</td>
</tr>
<tr>
<td><strong>TEMPERATURE</strong></td>
<td>4.817054175G191E-04</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>9.641501226725E-03</td>
</tr>
<tr>
<td>$V$</td>
<td>5.16340479111E-03</td>
</tr>
<tr>
<td>$V'$</td>
<td>1.31021532261265E-02</td>
</tr>
<tr>
<td><strong>GAMMA</strong></td>
<td>3.7301718471E-02</td>
</tr>
<tr>
<td><strong>OMEGA</strong></td>
<td>-8.6245925E-06</td>
</tr>
<tr>
<td><strong>THETA</strong></td>
<td>2.27665548845E-09</td>
</tr>
<tr>
<td><strong>OMEGA'</strong></td>
<td>-3.7301718471E-02</td>
</tr>
<tr>
<td><strong>THETA'</strong></td>
<td>7.9373196E+04</td>
</tr>
<tr>
<td><strong>ALPHA</strong></td>
<td>2.7665548845E-09</td>
</tr>
<tr>
<td><strong>K</strong></td>
<td>1.6938586E+02</td>
</tr>
<tr>
<td><strong>M</strong></td>
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<tr>
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<tr>
<td>$DELTA RANGE**'$</td>
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<td>$RANGE'$</td>
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<tr>
<td>$DELTA RANGE'$</td>
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<tr>
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<tr>
<td><strong>ANGLE BETWEEN ENTRY PLANE AND SKY IS</strong></td>
<td>5.56679225E+01</td>
</tr>
</tbody>
</table>
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 = 7.905510396786E+01 KM
PHI = 2.97394586974E+00 DEGREES
VX = -6.616086812675E+03 KM/SE
PRESS = 6.49319849495E+00 MILLIBARS

V = 4.61269433334E+00 KM/SEC
THETA = -3.976343195315E+01 DEGREES
V7 = 2.459399287369E-06 KM/SEC

ACTUAL STATE VECTOR AT 24.00 SECONDS
H = 7.905510396786E+01 KM
PHI = 2.3873543655747E+00 DEGREES
VX = -6.616086812675E+03 KM/SE
PRESS = 6.49319849495E+00 MILLIBARS

H DOT = -2.80076656959E+00 KM/SEC
PHI DOT = 3.4261833305652E+00 DEGREES

GAMMA = -3.7386323563832E+01 DEGREES
OMEGA = -9.0499521023880E-02 DEGREES/SEC
THETA DOT = -3.294245991386E+00 DEGREES/SEC

RELATIVE VELOCITY = 4.617701719657E+00 KM/SEC
WIND VELOCITY = 9. KM/SEC
DYNAMIC PRESSURE = 1.341358372066E+03 MILLIBARS
MOLECULAR WEIGHT = 4.146776647707E+01 KG/MOL
TEMPERATURE = 2.798182543449E+02 DEGREES K
MACH NUMBER = 1.4574363918225E+01 UNIT FREE
AXIAL FORCE = -4.262858644173E+02 KG/KM/SEC**2
NORMAL FORCE = 9. KG/KM/SEC**2
MOMENT ACCELERATION = 4.363541001409E-10 KM/SEC**2
EPSILON = 1.82692690915E-02

MEASUREMENT VALUES
ACCELEROMETERS = -2.3133423473662E+00 KM/SEC
PRESSURE = 3.4262949E+08 MILLIBARS
RATE GYRO = -1.5795146133445E-03 UNIT FREE
ALTImETER = 7.9134566E+01 MILLIBARS
TEMPERATURE = 1.5857416E+04 DEGREES K

COMMUNICATION ANGLE IS 4.70728715E+01
ANGLE BETWEEN ENTRY PLANE AND SKY IS 6.55879825E+01

REFERENCE PLANE LATITUDE = 3.16044666E+00 3.46407315E+01
SUB-SOLAR ORBITAL = 6.55879825E+01
### Data Generator Problem

#### Preliminary Main Probe-Mode A-Venus

**Actual State Vector** at 00.00 Seconds

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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>$V$</td>
<td>9.965956165505E-02 KM/SEC</td>
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<tr>
<td>$Vx$</td>
<td>-1.11973662625E+01 KM/SEC</td>
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<tr>
<td>$Vz$</td>
<td>-6.00874902466885E-06 KM/SEC</td>
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<tr>
<td>$H$</td>
<td>5.4465670986454E-01 DEGREES</td>
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<tr>
<td>$THETA$</td>
<td>9000 RAD</td>
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<td>$INTEGRATION$ $STEP$ $SIZE$</td>
<td>$0.10$</td>
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**State Derivatives**

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<tr>
<td>$V$ DOT</td>
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<tr>
<td>$THETA$ DOT</td>
<td>-1.237721211298E-01</td>
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<td>$VX$</td>
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**Measurement Values**

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<tr>
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<td>1.42033936E+01</td>
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**Angular Values**

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<tr>
<td>$COMMUNICATION$ $ANGLE$</td>
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<tr>
<td>$ANGLE$ BETWEEN$ENTRY$ $PLANE$ AND $SKY$</td>
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**Reference Plane**

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>Planets-Favorable</td>
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<tr>
<td>PLANETO-EQUATORIAL</td>
<td>7.95541564E+01</td>
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</table>
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

<table>
<thead>
<tr>
<th>H = 6.15735362867E+01 KM</th>
<th>V = 7.85694640941E-02 KM/SEC</th>
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</thead>
<tbody>
<tr>
<td>PH = 2.49406978391E+00 DEGREES</td>
<td>THETA = -9.2459134958E+01 DEGREES</td>
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<tr>
<td>VX = -1.19370499613E+02 KM/SEC</td>
<td>VZ = -6.98251157067E+00 KM/SEC</td>
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<td>PRES2 = 1.93325979221E+02 MILLIBARS</td>
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STATE DERIVATIVES

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<thead>
<tr>
<th>H DOT = -7.8554717665486E-02</th>
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<tbody>
<tr>
<td>PH DOT = 2.49406978391E+00 DEGREES</td>
<td>THETA DOT = -7.33197977691E+00 DEGREES</td>
</tr>
<tr>
<td>VDX = -9.210862715521E-07</td>
<td>OMEGA DOT = 7.28052487395E+00 DEGREES</td>
</tr>
<tr>
<td>OPRFS2 = 2.7236933157538E+00</td>
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RELATIVE VELOCITY

<table>
<thead>
<tr>
<th>WIND VELOCITY = 0.0 KM/SEC</th>
<th>DYNAMIC PRESSURE = 1.23011001586E+01 MILLIBARS</th>
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</thead>
<tbody>
<tr>
<td>MOLECULAR WEIGHT = 4.32121111509E+01 KG-MOL</td>
<td>PRESSURE = 2.1211949E+07</td>
</tr>
<tr>
<td>TEMPERATURE = 2.97406163528E+02 DEGREES K</td>
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</tr>
<tr>
<td>MACH NUMBER = 2.98325350119E+01 UNIT FREE</td>
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<tr>
<td>AXIAL FORCE = -1.46269266500E+00 KG-KM/SEC**2</td>
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<tr>
<td>CENTER OF PRESSURE = -4.4695956895368E+00 KM</td>
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<tr>
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<tr>
<td>EPSILON = 1.3911347690023E+01</td>
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</table>

MEASUREMENT VALUES

| ACCELEROMETERS = -9.2108637E-03 |
| PRESSURE = -1.2796715E+00 |

DSN TRACKING FOR STATION 1 STATION 2 STATION 3

| RANGE = 7.87722363E+07 |
| RANGE RATE = 1.319774097E+01 |
| REFRACTIVITY VALUES |
| DELTA RANGE = 0.0 |
| DELTA R-RATE = 0.0 |
| COMMUNICATION ANGLE IS 4.71657221E+01 |

REFERENCE PLANE LATITUDE LONGITUDE

PLANET-EQUATORIAL -3.7930936E+08 3.95639611E+01
DATA GENERATOR PROBLEM  PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-M

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

H = 5.656256723176E+01  KM
PHI = 2.49217999645E+00  DEGREES
VX = -1.36366795762E+01  KM/SEC
PRES2 = 4.99893152697E+02  MILLIMARS

STATE DERIVATIVES
H DOT = -9.4723256658343E-02
PHI DOT = -1.2636690947E-05

RELATIVE VELOCITY = 5.1473256565959E-02  KM/SEC
WIND VELOCITY = 0.  KM/SEC
DYNAMIC PRESSURE = 1.2567626920246E+01  MILLIMARS
MOLECULAR WEIGHT = 4.3224986708641E+02  KG/MOL
TEMPERATURE = 2.167459642067E+02  DEGREES K
MACH NUMBER = 1.9664961997167E-01  UNIT FREE
AXIAL FORCE = -1.3154894375071E+00  KG-KM/SEC**2
NORMAL FORCE = -3.9767416313181E-08  KG-KM/SEC**2
CENTER OF PRESSURE = -6.1028000910216E+04  K4
MOMENT ACCELERATION = -1.277715887784E-14  KM/SEC**2
EPSILON = 1.4599416979134E+00

MEASUREMENT VALUES
ACCELEROMETERS = -8.8999674E-03
PRESSURE = 4.5974276E+02

COMMUNICATION ANGLE IS 4.71654254E+01
ANGLE BETWEEN ENTRY PLANE AND SKY IS 6.55970446E+01

REFERENCE PLANE LATITUDE  LONGITUDE
PLANETO-EQUATORIAL -3.37932791E+00  3.98532256E+01
Case A-2: LTR Mode A Reconstruction Program Sample Case
## RANGE MEASUREMENT FROM STATION 1

### AT TRAJECTORY TIME 10.000 SEC

#### PROBLEM PRELIMINARY MAIN PROBE-MOJOE A-VENUS-P AS IN 2-3M

### TRAJECTORY

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original Nominal</th>
<th>Most Recent Nominal</th>
<th>Actual</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1.7875831986536E+02</td>
<td>1.7875831986536E+02</td>
<td>1.694166914170E+02</td>
<td>KM</td>
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<tr>
<td>V</td>
<td>7.943119326361E-01</td>
<td>7.943119326361E-01</td>
<td>1.391781973869E+00</td>
<td>DEGREES</td>
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<tr>
<td>GAMMA</td>
<td>-3.83397203641E+01</td>
<td>-3.83397203641E+01</td>
<td>-3.793441212626E+01</td>
<td>DEGREES</td>
</tr>
<tr>
<td>PHI</td>
<td>3.982960876251E+01</td>
<td>3.982960876251E+01</td>
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<td>DEGREES</td>
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### ATMOSPHERE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original Nominal</th>
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<th>Actual</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
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<td>6.274026892695E-08</td>
<td>6.274026892695E-08</td>
<td>3.223660536362E-07</td>
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<td>DENSITY</td>
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<td>1.173307485930E-02</td>
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<tr>
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<td>3.699020080080E-02</td>
<td>6.339014668135E+02</td>
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<td>MOL WT</td>
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<td>3.567296946951E+01</td>
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### VRU-APU DATA

<table>
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<td>THETA</td>
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<tr>
<td>OMEGA</td>
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<td>AXC</td>
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<tr>
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### ENTRY PARAMETERS BASED ON MOST RECENT NOMINAL

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<tbody>
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<td>WIND VELOCITY</td>
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</tr>
<tr>
<td>RELATIVE VELOCITY</td>
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<td>KM/SEC</td>
</tr>
<tr>
<td>EPSILON</td>
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<td>DEGREES</td>
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<tr>
<td>ALPH</td>
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</table>

### DEVIATIONS FROM MOST RECENT NOMINAL

#### TRAJECTORY

<table>
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<tr>
<th>Parameter</th>
<th>Estimated</th>
<th>Actual</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
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<td>V</td>
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<td>-3.802311485321E-01</td>
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### ATMOSPHERE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimated</th>
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<th>Units</th>
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</thead>
<tbody>
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<td>DEGREE K</td>
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#### SOLVE FOR PARAMETERS

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### ESTIMATED DEVIATIONS FROM ORIGINAL NOMINAL OF SOLVE FOR PARAMETERS

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<tr>
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<tr>
<td>Normal Force</td>
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**State Transition Matrix Partitions**

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**Dynamic-Measurement Consider Parameters**

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**Diagonal of Dynamic Noise Matrix**

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<tbody>
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**CW Core Matrix**

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**State Transition Matrix**

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**Actual Dynamic Noise Matrix**

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**Matrix Partitions**

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

GAIN MATRICES
K1
-1.7893895E-02
-2.6524013E-04
2.699712E-04
1.719563E-06

RESIDUAL UNCERTAINTY MATRIX
MATRIX
2.998587E+03
### Range Measurement

\[ \text{Range Measurement} = 7.07705978E+07 \text{ km} \]

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### Deviations from Most Recent Nominal Trajectory

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<th>V</th>
<th>Gamma</th>
<th>PHI</th>
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<tr>
<td>[ -1.3710431154544E+00 ]</td>
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### Static PP Matrix

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<tr>
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### Cxy Corr Matrix

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### ACTUAL DYNAMIC NOISE
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<th>Gain Matrices</th>
<th>Gain Matrix</th>
<th>Residual Uncertainty Matrix</th>
<th>Actual Measurement Noise</th>
<th>Measurement Covariance Matrix</th>
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**Doppler Measurement from Station 1**

**Preliminary Main Probe Mode A-Venus-P as in 2-3H**

### Trajectory

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<th>Units</th>
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<td><strong>GAMMA</strong></td>
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<td><strong>DEGREES</strong></td>
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<td><strong>PHI</strong></td>
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### Atmosphere

<table>
<thead>
<tr>
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<th>Units</th>
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<tbody>
<tr>
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<td><strong>TEMP</strong></td>
<td>1.35779797018E+02</td>
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<td><strong>MCL HT</strong></td>
<td>4.3019703504E+01</td>
<td>4.3019703504E+01</td>
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### V/ArU Data

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<td><strong>OMEGA</strong></td>
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<td>0.00</td>
<td><strong>DEGREES/SEC</strong></td>
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<td><strong>NU</strong></td>
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### Entry Parameters Based on Most Recent Nominal

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<tbody>
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<td><strong>RELATIVE VELOCITY</strong></td>
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### Deviations from Most Recent Nominal

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<td><strong>V</strong></td>
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### Atmosphere

<table>
<thead>
<tr>
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### Solve for Parameters

|                      | 0.00 | 0.00 |

### Estimated Deviations from Original Nominal of Solve for Parameters

|                      | 0.00 | 0.00 |

### Entry Parameters Based on Most Recent Nominal

<p>| <strong>RELATIVE VELOCITY</strong> | 4.99435265156E-02 | <strong>METERS SEC</strong> |
| <strong>PRESSURE</strong>          | 2.663204316221E+02 | <strong>MILLIBARS</strong> |</p>
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<table>
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<th>DIAGONAL OF DYNAMIC NOISE MATRIX</th>
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<td>STATE_MATRICES</td>
</tr>
<tr>
<td>8.4029630E+00  -5.465617E-01  1.437795E-01  9.926634E+01  3.77897E+01</td>
</tr>
<tr>
<td>-5.465617E-01  1.032692E-03  6.227767E-01  9.556325E+01  1.200227E+01</td>
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<tr>
<td>1.032692E-03  1.452629E-01  1.452629E-01  8.756518E+01  3.77897E+01</td>
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<td>1.452629E-01  1.452629E-01  1.452629E-01  8.756518E+01  3.77897E+01</td>
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<table>
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</thead>
<tbody>
<tr>
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<td>-2.011597E-01  1.508092E+02  0.  0.  0.</td>
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<tr>
<td>2.453557E-04  -1.104227E-02  1.122519E-05  1.357387E-05  -3.363734E-05</td>
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<td>-1.104227E-02  1.122519E-05  1.357387E-05  -3.363734E-05  1.508092E+02</td>
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<tr>
<td>1.093448E-06  6.216534E-06  5.624460E-06  5.624460E-06  5.624460E-06</td>
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<tr>
<td>6.709558E-05  3.363555E+03  1.355379E-05  6.337487E-06  7.774318E+06</td>
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| CXX\_CORR\_MATRICES                                    |
| -1.597689E+02  9.395535E-02  3.363555E+03  1.355379E-05  6.337487E-06 |
| 9.395535E-02  9.395535E-02  3.363555E+03  1.355379E-05  6.337487E-06 |
| 1.508092E+02  1.597689E+02  9.395535E-02  3.363555E+03  1.355379E-05 |
| 9.395535E-02  9.395535E-02  3.363555E+03  1.355379E-05  6.337487E-06 |

<table>
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<tr>
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<tr>
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<td>9.395535E-02  9.395535E-02  3.363555E+03  1.355379E-05  6.337487E-06</td>
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<tr>
<td>1.508092E+02  1.597689E+02  9.395535E-02  3.363555E+03  1.355379E-05</td>
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<table>
<thead>
<tr>
<th>ACTUAL DYNAMIC NOISE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CXX_CORR_MATRICES</td>
</tr>
<tr>
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</tr>
<tr>
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<tr>
<td>9.395535E-02  9.395535E-02  3.363555E+03  1.355379E-05  6.337487E-06</td>
</tr>
</tbody>
</table>
UNMODELED DYNAMIC NOISE COVARIANCE MATRIX

\[
\begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{pmatrix}
\]

GAIN MATRICES

\[
K_1
\]

\[
\begin{pmatrix}
1.264936\times10^2 \\
-8.279777\times10^2 \\
3.691767\times10^1 \\
2.962764\times10^2 \\
-4.150461\times10^1
\end{pmatrix}
\]

RESIDUAL UNCERTAINTY MATRIX

\[
4.693570\times10^{-5}
\]

STANDARD DEVIATIONS ON DENSITY AND TEMPERATURE

\[
\begin{pmatrix}
\text{DENSITY} & 4.329495840480E+07 \\
\text{TEMPERATURE} & 1.076471073417E+01
\end{pmatrix}
\]
RANGE-RATE MEASUREMENT = \(1.31681900 \times 10^1\) KM/SEC

**OBSERVATION MATRIX PARTITIONS**

<table>
<thead>
<tr>
<th>H MATRIX</th>
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<th>N MATRIX</th>
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<tr>
<td>8.441323E-08</td>
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**DYNAMIC-MEASUREMENT CONSIDER PARAMETERS**

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<th>N MATRIX</th>
</tr>
</thead>
<tbody>
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</table>

**MEASUREMENT CONSIDER PARAMETERS**

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**MEASUREMENTS**

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<th>RESIDUALS</th>
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<tr>
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**DEVATIONS FROM MOST RECENT NOMINAL TRAJECTORY**

<table>
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<tr>
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<th>ERROR EST-ACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: -4.72264150579E+00</td>
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<td>5.615939130256E+00</td>
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<tr>
<td>V: 3.13633419629E+00</td>
<td>2.39236971522E-02</td>
<td>2.49236971522E-02</td>
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<tr>
<td>GAMMA: -5.17064122941E+00</td>
<td>6.34248070319E-01</td>
<td>2.38458504264E+00</td>
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<tr>
<td>PHI: 6.03690049596E-01</td>
<td>5.27170652433E-01</td>
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**ATMOSPHERE**

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<th>ERROR EST-ACT</th>
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<tbody>
<tr>
<td>PRESSURE: -9.07822130648E+01</td>
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<td>1.91297290203E+01</td>
</tr>
<tr>
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<td>-6.53459529047E+00</td>
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<td>TEMP: 1.25164619919E+00</td>
<td>1.25164619919E+00</td>
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**solve for parameters**

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<tr>
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<th>CXY CORR MATRIX</th>
<th>CYY CORR MATRIX</th>
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<tr>
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<td>6.384401E-01</td>
<td>-9.877404E-01</td>
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<tr>
<td>-5.8569172E+00</td>
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<tr>
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<td>-3.4755565E-03</td>
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**pressures**

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<tr>
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</tr>
<tr>
<td></td>
<td>Actual Dynamic Noise</td>
<td>$\mathbf{R}$ Matrix</td>
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<tr>
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<td>----------------------</td>
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<table>
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<tr>
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</tr>
<tr>
<td>$9.6123998E-03$</td>
<td>$-5.1042560E-01$</td>
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</tbody>
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$\text{ACTUAL DYNAMIC NOISE}$

$\text{R MATRIX}$

$1.0000000E-12$

$\text{UNMODELED DYNAMIC NOISE COVARIANCE MATRIX}$

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>$0.$</td>
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<td>$0.$</td>
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$\text{GAIN MATRICES}$

$\text{K1 MATRIX}$

<p>| | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$1.3541434E+02$</td>
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<td>$3.6947676E+01$</td>
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<td>$-2.9527896E-02$</td>
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<tr>
<td>$-6.1657697E+01$</td>
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</table>

$\text{RESIDUAL UNCERTAINTY MATRIX}$

$\text{R MATRIX}$

$4.680576E-05$

$\text{STANDARD DEVIATIONS ON DENSITY AND TEMPERATURE}$

$\text{DENSITY}$ $3.0011948449657E+07$

$\text{TEMPERATURE}$ $1.0327883539926E+01$

$\text{ACTUAL MEASUREMENT NOISE}$

$+5.996609020016E-08$

$\text{MEASUREMENT COVARIANCE MATRIX}$

$1.099499999908E-07$
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**

- \( H = 6.6592872936464E+01 \) \( \text{KM} \)
- \( PH = 9.672029973082E+01 \) \( \text{DEGREES} \)
- \( VX = -1.129459770390E+01 \) \( \text{KM/SEC} \)
- \( PRESS = 9.7202298772E+01 \) \( \text{MILLIBARS} \)

**INTEGRATION STEP SIZE = .10 PHASE= 1**

- \( V = 1.232785159756E+01 \) \( \text{KM/SEC} \)
- \( THETA = -5.3514335304E+01 \) \( \text{DEGREES} \)
- \( VZ = -1.3514335304E+01 \) \( \text{KM/SEC} \)

**STATE DERIVATIVES**

- \( H DOT = -1.226042559429E-01 \) \( \text{KM/SEC} \)
- \( PH DOT = 1.299633539084E-04 \) \( \text{DEGREES} \)
- \( OVX = -1.076156851914E\pm 02 \) \( \text{DEGREES} \)
- \( DPRES = 2.29111448629E\pm 05 \) \( \text{MILLIBARS} \)

**RELATIVE VELOCITY = 1.232785159756E+01 \( \text{KM/SEC} \)\)**

**WIND VELOCITY = 0. \( \text{KM/SEC} \)\)**

**DYNAMIC PRESSURE = 9.943072804457E+01 \( \text{MILLIBARS} \)\)**

**MOLECULAR WEIGHT = 2.067636264243E+03 \( \text{KG/MOL} \)\)**

**TEMPERATURE = 8.000690890968E-02 \( \text{UNIT FREE} \)\)**

**AXIAL FORCE = -2.43211445056ZE-01 \( \text{KG-KM/SEC**2} \)\)**

**NORM FORCE = 0. \( \text{KG-KM/SEC**2} \)\)**

**CENTER OF PRESSURE = 1.260298981219E-04 \( \text{KM} \)\)**

**MOMENT ACCELERATION = 1.046307595950E+01 \( \text{KN/SEC**2} \)\)**

**MEASUREMENT VALUES**

- **ACCELEROMETERS = -1.0761569E+02 \( \text{MILLIBARS} \)\)**
- **PRESSURE = 9.943072804457E+01 \( \text{MILLIBARS} \)\)**
- **DENSITY = 2.067636264243E+03 \( \text{KG/KM**3} \)\)**
- **ALPHA = 0. \( \text{DEGREES} \)\)**
- **CA = 9.7992219328574E-01 \( \text{UNIT FREE} \)\)**
- **CN = 0. \( \text{UNIT FREE} \)\)**
- **CMO = -8.000690890968E-02 \( \text{UNIT FREE} \)\)**
- **MOMENT = 2.43211445056ZE-01 \( \text{KG-KM/SEC**2} \)\)**
- **NORMAL ACCEL = 0. \( \text{KM/SEC**2} \)\)**

**DSN TRACKING FOR RANGE**

- \( 7.0769546E+07 \) \( \text{KM} \)
- \( 7.07725669E+07 \) \( \text{KM} \)
- \( 7.0764289E+07 \) \( \text{KM} \)

**RANGE RATE = 1.32622026E+01 \( \text{KM/SEC} \)\)**

**REFRACTIVITY VALUES**

- \( DELTA RANGE = 0. \) \( \text{KM} \)
- \( DELTA R-RATE = 0. \) \( \text{KM/SEC} \)

**COMMUNICATION ANGLE IS 2.65385029E+01**

**ANGLE BETWEEN ENTRY PLANE AND SKY IS 1.1449053E+02**

**REFERENCE PLANE LATITUDE LONGITUDE**

- \( PLANETO-EQUATORIAL 1.54183495E+01 -3.09428140E+01 \)
## DATA GENERATOR PROBLEM

PRELIMINARY MAIN PROBE-MODE A-VENUS-P AS IN 2-3M

### ACTUAL STATE VECTOR AT 228.00 SECONDS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
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<tr>
<td><strong>PHI</strong></td>
<td>9,6863321667330E-01 DEGREES</td>
</tr>
<tr>
<td><strong>VX</strong></td>
<td>-1,345647789251E+01 KM/SEC</td>
</tr>
<tr>
<td><strong>PRES2</strong></td>
<td>8,99740042342E+02 MILLIBARS</td>
</tr>
<tr>
<td><strong>V =</strong></td>
<td>4,57032974408E+01 KM/SEC</td>
</tr>
<tr>
<td><strong>THETA</strong></td>
<td>-9,0070264706E+01 DEGREES</td>
</tr>
<tr>
<td><strong>VZ</strong></td>
<td>-1,345647789251E+01 KM/SEC</td>
</tr>
<tr>
<td><strong>PHASE</strong></td>
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</tr>
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</table>

### INTEGRATION STEP SIZE = .50

### PHASE = 1

### STATE DERIVATIVES

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
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<td><strong>PHI DOT</strong></td>
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<tr>
<td><strong>V DOT</strong></td>
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<tr>
<td><strong>V DOT</strong></td>
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</tr>
<tr>
<td><strong>VZ DOT</strong></td>
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</tr>
<tr>
<td><strong>PRES2 DOT</strong></td>
<td>5,7234662578580E+05</td>
</tr>
</tbody>
</table>

### RELATIVE VELOCITY = 4,7004124736537E-02 KM/SEC

### WIND VELOCITY = 0.

### DYNAMIC PRESSURE = 1,5471445046080E+01 MILLIBARS

### MOLECULAR WEIGHT = 1,3232568035760E+01 KG-MOL

### TEMPERATURE = 1,2495421065230E+02 DEGREES K

### RACH NUMBER = 1,5583679074470E+01 UNIT FREE

### AXIAL FORCE = -1,970256150899E-01 KG-KM/SEC**2

### CENTER OF PRESSURE = -1,3941094897277E-04 KM

### MOMENT ACCELERATION = -2,3315736528690E+04 KM/SEC**2

### EPSILON = -1,3881112028069E+01

### MEASUREMENT VALUES

<table>
<thead>
<tr>
<th>Accelerometers</th>
<th>Rate Gyro</th>
<th>Altimeter</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
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<td>6.565294E-06</td>
<td>-8.9942467E+07</td>
<td>3.2432448E+02</td>
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### ONS TRACKING FOR STATION 1 STATION 2 STATION 3

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<th>7.077233054E+07</th>
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<td>1.351795775E+01</td>
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### REFRACTIVITY VALUES

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<tr>
<td>Normal Range</td>
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### COMMUNICATION ANGLE IS 2.65369386E+01

### ANGLE BETWEEN ENTRY PLANE AND SKY IS 1.14497780E+02

### REFERENCE PLANE LATITUDE LONGITUDE

| Planet-Equalitarian | 1.54168429E+01 | -3.09429193E+01 |

### PLANET-EQUATORIAL
Case B-2: LTR Mode B Reconstruction Program Sample Case
### Temperature Measurement

**Problem**: Preliminary main probe-mode A-Venus-P as in 2-3

**At Trajectory Time**: 40.000000 sec

#### Trajectory

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<thead>
<tr>
<th>Units</th>
<th>Actual</th>
<th>RECONSTRUCTED</th>
<th>Error EST-Actual</th>
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<td>1.23279015295E+01</td>
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<tr>
<td>Gamma</td>
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<td>-8.39719383402E+01</td>
<td>2.6648E+00</td>
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<tr>
<td>Phi</td>
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#### Smooth Gyro Data

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<tr>
<td>-4.1812564383E-01</td>
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#### Smooth Theta

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<th>Smooth Omega</th>
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</tr>
<tr>
<td>-4.1812564383E-01</td>
<td>0.0</td>
</tr>
</tbody>
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##### Entry Parameters Based on Most Recent Nominal

- **WIND VELOCITY**: 0.000 KM/SEC
- **RELATIVE VELOCITY**: 1.265821348766E-01 KM/SEC
- **EPSILON**: 0.00 DEGREES
- **ALPH**: 0.00 DEGREES

##### Deviations from Most Recent Nominal Trajectory

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<th>Error EST-Actual</th>
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<td>V</td>
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<tr>
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<td>-4.16900776473E-01</td>
</tr>
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#### Solve for Parameters

- 5.000000000000E+00
- 3.998998674713E+00
- 6.999998674713E+00

##### Estimated Deviations from Original Nominal of Solve Parameters

- 0.000000000000E+00
- 0.000000000000E+00
- 0.000000000000E+00

##### Entry Parameters Based on Most Recent Nominal

- **RELATIVE VELOCITY**: 1.265821348766E-01 KM/SEC
- **WIND VELOCITY**: 0.000 KM/SEC
- **DYNAMIC PRESSURE**: 4.285059999996E-01 MILLIBARS
- **MOLECULAR WEIGHT**: 4.843724433761E-01 KG-MOL
- **TEMPERATURE**: 2.507530757046E+02 DEGREES K
- **ALPHA**: 0.00 DEGREES
- **CENTER OF PRESSURE**: -1.506178431168E-04 KM

##### Other Parameters

- **PRESSURE**: 1.004744624663E+02 MILLIBARS
- **DENSITY**: 2.066921341615E+08 KG/KM**2**
- **ALPHA**: 0.00 DEGREES
- **CN**: 0.00 UNIT FREE
- **MOMENT**: 0.00 UNIT FREE
- **GRAVITY**: 8.655820839692E-03 KM/SEC**2**
### State Transition Matrix Partitions

**P**

| PHI MATRIX | 9.9913567E-01 | -8.9993419E-01 | 1.7998926E-02 |
| 1.6879441E-03 | 6.1895107E-01 | -1.0316177E-03 |
| 4.1459765E-05 | 5.2729212E-02 | 9.3499174E-01 |
| 1.3999628E-08 | 1.7951866E-09 | 1.9999049E-05 |

**SOtE FOR PARAMETERS = 3 5 7 9**

**PSI MATRIX**

| 2.0732416E-05 | 4.3464116E-05 |
| -1.3491545E-06 | 0.00 |
| -4.8003475E-05 | -3.746332E-05 |
| 2.6157182E-06 | 0.00 |
| -1.122792E-06 | -2.1693386E-06 |
| 6.1207946E-08 | 0.00 |
| -4.6746599E-05 | -1.1565878E-06 |
| 2.9580925E-11 | 0.00 |

**Dynamic Consider Parameters = 20 140**

**THU MATRIX**

| 5.7327685E-09 | -9.084157E-04 |
| -1.127897E-02 | 8.0565294E-09 |
| -2.625966E-04 | -7.697824E-04 |
| -1.035255E-07 | -8.476345E-07 |

**Dynamic-Measurement Consider Parameters = 4 6 8 152 153 156 161 1**

**THW MATRIX**

| 4.029751E-04 | -2.1573697E-06 |
| -7.827437E-04 | 4.770111E-06 |
| -1.251180E-06 | 6.589540E-08 |
| -7.616399E-09 | 4.666381E-11 |

**Diagonal of Dynamic Noise Matrix**

| 0.00 | 0.00 | 0.00 |

**State PP Matrix**

| 1.3296010E+00 | 6.6187908E-01 | -1.539567E-02 |
| 6.8187998E-01 | 3.023469E-03 | -3.649380E-01 |
| 1.6435656E-02 | 6.503412E-00 | 5.3958161E-02 |
| 9.683654E-04 | -1.251197E-06 |
| 2.6621976E-02 | 5.396481E-02 |

**CXX CORR MATRIX**

| 1.0565125E-01 | 2.9504921E-01 |
| 8.6864783E-03 | 2.7898322E-01 |
| 1.065716E-03 | 9.156490E-03 |
| 8.5438212E-04 | 6.653170E-04 |

**CXX CORR MATRIX**

| 1.3296010E+00 | 6.8187908E-01 |
| 5.3968616E-02 |
| 9.683654E-04 | 2.6621976E-02 |

**CXX CORR MATRIX**

| -1.932915E-04 | -2.1573697E-06 |
| -7.827437E-04 | 4.770111E-06 |
| -1.251180E-06 | 6.589540E-08 |
| -7.616399E-09 | 4.666381E-11 |

**State PP Matrix**

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| 5.3968616E-02 | 9.683654E-04 | 2.6621976E-02 |

**CXX CORR MATRIX**

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| 1.065716E-03 | 9.156490E-03 |
| 8.5438212E-04 | 6.653170E-04 |

**CXX CORR MATRIX**

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| -7.827437E-04 | 4.770111E-06 |
| -1.251180E-06 | 6.589540E-08 |
| -7.616399E-09 | 4.666381E-11 |

**State PP Matrix**

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| 1.065716E-03 | 9.156490E-03 |
| 8.5438212E-04 | 6.653170E-04 |

**CXX CORR MATRIX**

| -1.932915E-04 | -2.1573697E-06 |
| -7.827437E-04 | 4.770111E-06 |
| -1.251180E-06 | 6.589540E-08 |
| -7.616399E-09 | 4.666381E-11 |
SOLVE FOR
DO MATRIX
3.9977894E+00 -1.3522689E-04 7.6937802E-06 2.9069163E-09
9.3592094E-09 3.1520305E+00 8.9750673E-06 2.9377406E-09
7.6087925E-06 8.7505732E-06 1.2374666E+00 -1.359742E-10
2.8691636E-09 2.3774657E-09 -1.349242E-10 6.396553E+00

COV CORR MATRIX
1.4931649E-06 -1.6249475E-03
9.5289594E-04 1.7497187E-03
5.3395269E-05 2.983624E-04
2.99852E-04 2.8924475E-03

COV CORR MATRIX
3.8581376E-04 4.2772333E-10 -3.214441E-10 -1.345622E-04
9.5167595E-06 7.2655199E-10 -3.691604E-06 -1.582445E-09
3.9628597E-07 -4.8467377E-11 2.0136339E-12 3.2985021E-05
2.6683216E-09 5.4373959E-13 -2.7716517E-13 6.9769309E-09

COV CORR MATRIX
9.1378296E-04 2.8036140E-05 -4.9098999E-09 4.9756397E-10
1.2952262E-03 3.2243646E-05 -5.611624E-09 5.2982749E-10
3.5902722E-05 -1.8048593E-06 3.1699605E-10 -2.838767E-12
9.6929571E-08 -4.9382722E-10 2.4801291E-12 1.7236981E-12

ACTUAL DYNAMIC NOISE MATRIX

UNMODELED DYNAMIC NOISE COVARIANCE MATRIX

GAIN MATRICES

RESIDUAL UNCERTAINTY MATRIX
TEMPERATURE MEASUREMENT

OBSERVATION MATRIX PARTITIONS

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<thead>
<tr>
<th>MEASUREMENTS</th>
<th>ESTIMATED</th>
<th>ACTUAL</th>
<th>RESIDUALS</th>
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<tr>
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<td>6.6288937E+00</td>
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DEVIATIONS FROM MOST RECENT NOMINAL TRAJECTORY

<table>
<thead>
<tr>
<th>ESTIMATED</th>
<th>ACTUAL</th>
<th>(ERROR EST-ACT)</th>
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<td>H -1.6532929E+02</td>
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<td>W 4.813927779E-04</td>
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SOLVE FOR PARAMETERS

| MEASUREMENT CONSIDER PARAMETERS | | | |
| L MATRIX | 0. | 0. | 0. | 2.6256068E+02 |
| H MATRIX | 0. | 1.0274360E-01 | 0. | |
| G MATRIX | 1.4494273E+00 | 1.6391129E-01 | 0. | |
| | | 5.4677302E+00 | 6.6288937E+00 | 0. |

STATE PP MATRIX

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DEVIATIONS FROM MOST RECENT NOMINAL TRAJECTORY

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<th>ESTIMATED</th>
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SOLVE FOR PARAMETERS

| MEASUREMENT CONSIDER PARAMETERS | | | |
| L MATRIX | 0. | 0. | 0. | 2.6256068E+02 |
| H MATRIX | 0. | 1.0274360E-01 | 0. | |
| G MATRIX | 1.4494273E+00 | 1.6391129E-01 | 0. | |
| | | 5.4677302E+00 | 6.6288937E+00 | 0. | |

STATE PP MATRIX

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QUASI EVENT AT TRAJECTORY TIME 200.00SEC

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

TRAJECTORY

<table>
<thead>
<tr>
<th></th>
<th>ORIGINAL NOMINAL</th>
<th>MOST RECENT NOMINAL</th>
<th>ACTUAL</th>
<th>UNITS</th>
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<td>KM</td>
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<td>DEGREES</td>
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<tr>
<td>PHI</td>
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<td>5.158676724075E+01</td>
<td>4.685836144399E+01</td>
<td>DEGREES</td>
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DEVIATIONS FROM MOST RECENT NOMINAL

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<tbody>
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<td>V</td>
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SOLVE-FOR NOMINAL VALUE

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<th>5</th>
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SOLVE FOR PARAMETERS

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ESTIMATED DEVIATIONS FROM ORIGINAL NOMINAL OF SOLVE-FOR PARAMETERS

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<th>1.86643376262E+00</th>
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<tbody>
<tr>
<td>H</td>
<td>-1.67334273122E+00</td>
<td>-1.67334273122E+00</td>
<td>4.615663722956E-02</td>
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<td>0.00</td>
<td>4.615663722956E-02</td>
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<td>GAMMA</td>
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<td>4.615663722956E-02</td>
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<tr>
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<td>2.13566237374E+00</td>
<td>2.13566237374E+00</td>
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<table>
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<tr>
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<th>V</th>
<th>GAMMA</th>
<th>PHI</th>
</tr>
</thead>
<tbody>
<tr>
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PRESSURE MEASUREMENT AT TRAJECTORY TIME 230.00 SEC
PROBLEM PRELIMINARY MAIN PROBE-Node A-VENUS-P AS IN 2-3 H
QUASI-STATIC MODEL

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**Phi Matrix**

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**Dynamic Consider Parameters = 23 140**

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**Diagonal of Dynamic Noise Matrix**

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**Cxo Corr Matrix**

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### UNMODELED DYNAMIC NOISE COVARIANCE MATRIX

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### WISSUAL UNCERTAINTY MATRIX

| 1.943356E+13 |


MMEASUREMENT

OBSERVATION MATRIX PARTITIONS

\[
\begin{array}{l}
\text{M MATRIX} \\
\begin{pmatrix}
1.2573654E+07 & 6.8842957E+07 & -7.8192698E+03 \\
0 & 0 & 0
\end{pmatrix}
\end{array}
\]

SOLVE FOR PARAMETERS

\[
\begin{array}{l}
\text{M MATRIX} \\
\begin{pmatrix}
4.069261E+05 & 5.192616E+05 & 0. \\
0 & 0 & 0
\end{pmatrix}
\end{array}
\]

DYNAMIC-MEASUREMENT CONSIDER PARAMETERS

\[
\begin{array}{l}
\text{G MATRIX} \\
\begin{pmatrix}
4.0611272E+06 & 0. \\
0 & 0
\end{pmatrix}
\end{array}
\]

MEASUREMENT CONSIDER PARAMETERS

\[
\begin{array}{l}
\text{L MATRIX} \\
\begin{pmatrix}
0. & 0. & 0.
\end{pmatrix}
\end{array}
\]

MEASUREMENTS

\[
\begin{array}{l}
\text{ESTIMATED} & \text{ACTUAL} & \text{RESIDUALS}
\end{array}
\]

DEVIATIONS FROM MOST RECENT NOMINAL TRAJECTORY

\[
\begin{array}{l}
\text{ESTIMATED} & \text{ACTUAL} & \text{ERROR EST-ACT} & \text{UNITS}
\end{array}
\]

STATE

\[
\begin{array}{l}
\text{PP MATRIX} \\
\begin{pmatrix}
8.2345519E-01 & 3.2282781E-01 & 1.7028882E-01 \\
3.2282781E-01 & 6.1512324E-04 & 2.6548411E+01 \\
1.7028882E-01 & 2.6548411E+01 & 9.4367266E-02 \\
-9.6715664E-02 & -1.5149556E-01 & 9.4367266E-02
\end{pmatrix}
\end{array}
\]

\[
\begin{array}{l}
\text{CXO CORR MATRIX} \\
\begin{pmatrix}
-1.9908191E-01 & -8.1538237E-02 & 4.0154639E-06
\end{pmatrix}
\end{array}
\]

\[
\begin{array}{l}
\text{CXV CORR MATRIX} \\
\begin{pmatrix}
1.8057178E-01 & -3.6616597E-09
\end{pmatrix}
\end{array}
\]

\[
\begin{array}{l}
= 8.9584056E+07
\end{array}
\]
| -4.5628510E+01 | -2.5383733E-05 | 4.7217156E-05 | 2.1557667E-05 | 0. | 2.8118772E-01 | -1.2221903E-01 |
| 1.0738673E-01 | 2.1779688E-05 | -1.1112328E-06 | -5.0332360E-06 | 0. | 2.6788219E-02 | 1.2948247E-02 |
| -4.9195508E-02 | -7.6883680E-06 | 4.9862050E-06 | 1.7407999E-06 | 0. | 6.5190383E-02 | 6.1229929E-02 |
| 3.7191876E-01 | -3.3197316E-03 | 3.3516262E-08 | 2.5638641E-08 | 1.6479938E-09 | -3.5263188E-01 | -9.5678038E-02 | 4.6026375E-05 |
| 2.3129899E-01 | -2.6154073E-03 | -1.6501482E-08 | -1.4692347E-08 | -2.6974121E-10 | 4.1448749E-02 | -1.1868364E-02 | -4.4941418E-06 |
| -6.8939919E-03 | 5.8108959E-03 | -6.2395463E-07 | -5.9786666E-07 | -5.7986122E-08 | 5.8446711E-02 | 2.4881229E-02 | -5.4672788E-08 |

**SOLVE FOR**

| 4.9677824E+00 | 1.6796930E-02 | 8.3628967E-04 | 2.7170372E-09 |
| 1.6796930E-02 | 2.3822510E+00 | -2.9105631E-02 | -3.1944209E-08 |
| 8.3628967E-04 | -2.9105631E-02 | 1.2397774E+00 | -2.3370431E-10 |
| 2.7170372E-09 | -3.1944209E-08 | -2.3370431E-10 | 6.3245553E+00 |

**COV CORR MATRIX**

| -3.8292932E-02 | 1.2953650E-02 | -4.6698887E-02 | 1.8196407E-03 |
| 4.7799286E-02 | -2.9105631E-02 | 1.2239774E+00 | -2.3370431E-10 |
| 4.7799286E-02 | 1.2953650E-02 | 1.2397774E+00 | -2.3370431E-10 |
| -4.4740333E-06 | -2.3370431E-10 | 4.4.3214448E-06 | 6.3245553E+00 |

**COV CORR MATRIX**

| -7.1026446E-03 | -1.4476585E-06 | 7.3713358E-07 | 4.1564890E-07 |
| 1.8073471E-06 | -1.0873866E-06 | 6.5554535E-06 | 1.8945592E-06 |
| 2.4360030E-03 | -2.4293608E-07 | -1.0798823E-07 | -1.3238389E-03 |
| -2.9867727E-08 | -2.5653442E-12 | 2.6377966E-12 | 1.0924378E-12 |

**COV CORR MATRIX**

| 3.2275585E-02 | 7.5252174E-03 | -3.5729676E-09 | 2.5842783E-09 |
| 1.8089870E-06 | -1.0873866E-06 | 6.5554535E-06 | 1.8945592E-06 |
| 5.8657083E-03 | -3.4195853E-03 | 1.9784898E-09 | -1.2769850E-09 |
| -3.1527718E-08 | 3.1377119E-09 | 2.9160066E-12 | 1.7392360E-12 |

**ACTUAL DYNAMIC NOISE**

| 1.3088580E+10 |

**UNMODELED DYNAMIC NOISE COVARIANCE MATRIX**

| 0. | 0. | 0. | 0. |

**GAIN MATRICES**

<table>
<thead>
<tr>
<th>K1</th>
<th>K2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9457490E-08</td>
<td>1.2052439E-09</td>
</tr>
<tr>
<td>-5.9730150E-11</td>
<td>-3.3197230E-09</td>
</tr>
<tr>
<td>8.7601925E-12</td>
<td>1.0975789E-14</td>
</tr>
</tbody>
</table>

**RESIDUAL UNCERTAINTY MATRIX**

| 1.9433896E+13 |

**ACTUAL MEASUREMENT NOISE**

| 1.5621099999998E+05 |

**MEASUREMENT COVARIANCE MATRIX**

| 1.0000000000000E+05 |
PART III

LTR PROGRAMMERS' MANUAL
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. PRPRΦS

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. LTRCON

The reconstructor overlay section utilizes the I/O files written by DATGEN and PRPROS 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/O files written by LTRCON and calls the user-written plot package according to information supplied by LTRCON. 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 RUNNO. 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. BLOCK 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. COPPY
3. CØRMAT
4. CØRR
5. CØRRD
6. DMULTT
7. DTAB
8. INVPSD
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. GØEØ
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. CONVRT
8. NEXTAA
9. NEXTIM
10. ØUØPHI
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>
<thead>
<tr>
<th>SUBROUTINE</th>
<th>PURPOSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>AECEQ</td>
<td>Computes transformation from ecliptic to geocentric equatorial</td>
</tr>
<tr>
<td>ATMSET</td>
<td>Initializes and computes atmospheric parameters</td>
</tr>
<tr>
<td>(ATMDAT)</td>
<td></td>
</tr>
<tr>
<td>ADD</td>
<td>Adds matrix X and matrix Y</td>
</tr>
<tr>
<td>ATTACK</td>
<td>Computes angle of attack measurement</td>
</tr>
<tr>
<td>ATMOSP</td>
<td>Calculates atmospheric parameters in mode A</td>
</tr>
<tr>
<td>BLKDAT</td>
<td>Initializes common variables</td>
</tr>
<tr>
<td>BEGIN</td>
<td>Resets common variables for reconstructor</td>
</tr>
<tr>
<td>COPY</td>
<td>Copies matrix/vector X into matrix/vector Y</td>
</tr>
<tr>
<td>CORMAT</td>
<td>Converts covariance matrix into correlation matrix</td>
</tr>
<tr>
<td>CORR</td>
<td>Computes correlations for off-diagonal block of partitioned covariance matrix</td>
</tr>
<tr>
<td>CORRDRD</td>
<td>Computes correlations for diagonal block of partitioned covariance matrix</td>
</tr>
<tr>
<td>CVRT</td>
<td>Converts state vectors to output units</td>
</tr>
<tr>
<td>DMULTT</td>
<td>Multiplies a diagonal matrix X times the transpose of matrix Y</td>
</tr>
<tr>
<td>DTAB</td>
<td>Performs table lookup with two independent variables</td>
</tr>
</tbody>
</table>
### Table III-2 (Cont)

<table>
<thead>
<tr>
<th>SUBROUTINE</th>
<th>PURPOSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATGEN</td>
<td>Drives data generator to provide input to reconstructor</td>
</tr>
<tr>
<td>DERIV1</td>
<td>Computes derivatives for integration by the data generator</td>
</tr>
<tr>
<td>DERIV3</td>
<td>Computes derivatives for integration by the mode B reconstructor</td>
</tr>
<tr>
<td>DERIVE</td>
<td>Computes derivatives for integration by the mode A reconstructor</td>
</tr>
<tr>
<td>DYNØIZ</td>
<td>Computes dynamic noise covariance matrix</td>
</tr>
<tr>
<td>ECLIP</td>
<td>Computes planetocentric ecliptic state of spacecraft for DSN tracking</td>
</tr>
<tr>
<td>EPHEM</td>
<td>Computes heliocentric ecliptic coordinates of the planets</td>
</tr>
<tr>
<td>EQUATR</td>
<td>Computes transformation from geoequatorial to planetoequatorial</td>
</tr>
<tr>
<td>FILTER</td>
<td>Computes estimates and covariance matrices</td>
</tr>
<tr>
<td>GEØG</td>
<td>Computes transformation from planetoequatorial to planetogeographical</td>
</tr>
<tr>
<td>GHA</td>
<td>Computes Greenwich hour angle of the vernal equinox</td>
</tr>
<tr>
<td>HMM</td>
<td>Computes observation matrix H for Kalman filter equations</td>
</tr>
<tr>
<td>INVPD2</td>
<td>Inverts positive definite matrix $X$ ($NxN$)</td>
</tr>
<tr>
<td>INVPSD</td>
<td>Inverts positive definite 2x2 matrix $X$</td>
</tr>
<tr>
<td>SUBROUTINE</td>
<td>PURPOSE</td>
</tr>
<tr>
<td>------------</td>
<td>---------</td>
</tr>
<tr>
<td>JACOBN</td>
<td>Computes sensitivity matrices by numerical differencing</td>
</tr>
<tr>
<td>LTRTWØ</td>
<td>Controls overall program for data generation and trajectory reconstruction</td>
</tr>
<tr>
<td>LTRCØN</td>
<td>Drives reconstructor portion of LTR</td>
</tr>
<tr>
<td>MATØUT</td>
<td>Prints matrix X</td>
</tr>
<tr>
<td>MULT</td>
<td>Multiplies matrix X times matrix Y</td>
</tr>
<tr>
<td>MULTD</td>
<td>Multiplies matrix X times diagonal matrix Y</td>
</tr>
<tr>
<td>MULTT</td>
<td>Multiplies matrix X times matrix Y transposed</td>
</tr>
<tr>
<td>MATRIX</td>
<td>Performs matrix algebra through use of multiple entry points</td>
</tr>
<tr>
<td>MEAZUR</td>
<td>Processes measurements</td>
</tr>
<tr>
<td>NEXTAA</td>
<td>Takes accelerometer data from preprocessor tape</td>
</tr>
<tr>
<td>NEYTIM</td>
<td>Selects measurement or other event</td>
</tr>
<tr>
<td>NØRMNZ</td>
<td>Computes normally distributed noise</td>
</tr>
<tr>
<td>NTM</td>
<td>Propagates most recent nominal trajectory</td>
</tr>
<tr>
<td>NTM2</td>
<td>Propagates original nominal trajectory</td>
</tr>
<tr>
<td>ØBSM1</td>
<td>Contains measurement equations for the data generator</td>
</tr>
</tbody>
</table>
Table III-2 (Cont)

<table>
<thead>
<tr>
<th>SUBROUTINE</th>
<th>PURPOSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBSM</td>
<td>Contains measurement equations for the reconstructor</td>
</tr>
<tr>
<td>OUYVIH1</td>
<td>Prints intermediate variables and phi matrix</td>
</tr>
<tr>
<td>OUTPP</td>
<td>Prints correlation, gain, and dynamic noise matrices</td>
</tr>
<tr>
<td>PLANE</td>
<td>Computes entry plane orientation to reference plane</td>
</tr>
<tr>
<td>PRINT1</td>
<td>Prints trajectory and measurements from the data generator</td>
</tr>
<tr>
<td>PRPRRØS</td>
<td>Preprocesses accelerometer and gyro measurements for the reconstructor</td>
</tr>
<tr>
<td>(SMØOT2)</td>
<td></td>
</tr>
<tr>
<td>PRINT</td>
<td>Prints trajectory and measurements from the reconstructor</td>
</tr>
<tr>
<td>PSTORE</td>
<td>Stores data for plot package</td>
</tr>
<tr>
<td>PLOTS</td>
<td>Drives system plot package</td>
</tr>
<tr>
<td>RKUTDG</td>
<td>Integrator for data generator</td>
</tr>
<tr>
<td>READAC</td>
<td>Reads &quot;actual&quot; measurements created by data generator</td>
</tr>
<tr>
<td>RSTART</td>
<td>Punches restart cards for reconstructor</td>
</tr>
<tr>
<td>RKUT3</td>
<td>Integrator for mode A reconstructor</td>
</tr>
<tr>
<td>RKUTL3</td>
<td>Integrator for mode B reconstructor</td>
</tr>
<tr>
<td>RNUM</td>
<td>Generates measurement noise on &quot;actual&quot; measurements</td>
</tr>
<tr>
<td>SUBSØL</td>
<td>Computes transformation from planeto-centric ecliptic to subsolar orbital plane</td>
</tr>
</tbody>
</table>
### Table III-2 (Concl)

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

Reconstruct the trajectory and atmosphere from actual measurements

Summarize the printed output and plot data of interest

Figure III-1 LTR Executive Flow Diagram
Figure III-2 DATGEN Executive Flow Diagram
Figure III-3  LTRCON 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/

RHΩA  Actual density (read in READAC)

TΩMPA  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)

NWTA  Actual molecular weight (read in READAC)

/ALREADY/

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)
MWTM  Nominal molecular weight (input in SETUP)

THETI  Initial attitude angle (input in SETUP)

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

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 TZERO

ØMGC  Reconstructed angular velocity as experienced by ARU

ALPHA  Reconstructed angle of attack

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
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(36)</td>
<td>State covariance matrix</td>
</tr>
<tr>
<td>Q(100)</td>
<td>Solve-for parameter covariance matrix</td>
</tr>
<tr>
<td>DU(20)</td>
<td>Dynamic-consider parameter covariance matrix</td>
</tr>
<tr>
<td>DV(20)</td>
<td>Measurement-consider parameter covariance matrix</td>
</tr>
<tr>
<td>DW(10)</td>
<td>Dynamic/measurement-consider parameter covariance matrix</td>
</tr>
<tr>
<td>CXQ(60)</td>
<td>Covariance matrix relating state parameters to solve-for parameters</td>
</tr>
<tr>
<td>CXU(120)</td>
<td>Covariance matrix relating state parameters to dynamic-consider parameters</td>
</tr>
<tr>
<td>CXV(120)</td>
<td>Covariance matrix relating state parameters to measurement-consider parameters</td>
</tr>
<tr>
<td>CXW(60)</td>
<td>Covariance matrix relating state parameters to dynamic/measurement-consider parameters</td>
</tr>
<tr>
<td>CQU(200)</td>
<td>Covariance matrix relating solve-for parameters to dynamic-consider parameters</td>
</tr>
<tr>
<td>CQV(200)</td>
<td>Covariance matrix relating solve-for parameters to measurement-consider parameters</td>
</tr>
<tr>
<td>CQW(100)</td>
<td>Covariance matrix relating solve-for parameters to dynamic/measurement-consider parameters</td>
</tr>
<tr>
<td>SP(36)</td>
<td>P matrix saved before a new measurement, event, etc</td>
</tr>
<tr>
<td>SQ(100)</td>
<td>Q matrix saved before a new measurement, event, etc</td>
</tr>
<tr>
<td>SDU(20)</td>
<td>DU matrix saved before a new measurement, event, etc</td>
</tr>
<tr>
<td>SDV(20)</td>
<td>DV matrix saved before a new measurement, event, etc</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>SCXQ(60)</td>
<td>CXQ matrix saved before a new measurement, event, etc</td>
</tr>
<tr>
<td>SCXU(120)</td>
<td>CXU matrix saved before a new measurement, event, etc</td>
</tr>
<tr>
<td>SCXV(120)</td>
<td>CXV matrix saved before a new measurement, event, etc</td>
</tr>
<tr>
<td>SCXW(60)</td>
<td>CXW matrix saved before a new measurement, event, etc</td>
</tr>
<tr>
<td>SCQU(200)</td>
<td>CQU matrix saved before a new measurement, event, etc</td>
</tr>
<tr>
<td>SCQV(200)</td>
<td>CQV matrix saved before a new measurement, event, etc</td>
</tr>
<tr>
<td>SCQW(100)</td>
<td>CQW matrix saved before a new measurement, event, etc</td>
</tr>
<tr>
<td>CXQC(60)</td>
<td>Correlation matrix of CXQ matrix</td>
</tr>
<tr>
<td>CXUC(120)</td>
<td>Correlation matrix of CXU matrix</td>
</tr>
<tr>
<td>CXVC(120)</td>
<td>Correlation matrix of CXV matrix</td>
</tr>
<tr>
<td>CXWC(60)</td>
<td>Correlation matrix of CXW matrix</td>
</tr>
<tr>
<td>CQUC(200)</td>
<td>Correlation matrix of CQU matrix</td>
</tr>
<tr>
<td>CQVC(200)</td>
<td>Correlation matrix of CQV matrix</td>
</tr>
<tr>
<td>CQWC(100)</td>
<td>Correlation matrix of CQW matrix</td>
</tr>
<tr>
<td>PHI(36)</td>
<td>State transition matrix</td>
</tr>
<tr>
<td>PSI(60)</td>
<td>Sensitivity matrix relating state parameters to solve-for parameters</td>
</tr>
<tr>
<td>THU(120)</td>
<td>Sensitivity matrix relating state parameters to dynamic-consider parameters</td>
</tr>
<tr>
<td>THW(60)</td>
<td>Sensitivity matrix relating state parameters to dynamic/measurement-consider parameters</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>HM(24)</td>
<td>Partition of observation matrix relating observables to state</td>
</tr>
<tr>
<td>MM(40)</td>
<td>Partition of observation matrix relating observables to solve-for parameters</td>
</tr>
<tr>
<td>LM(80)</td>
<td>Partition of observation matrix relating observables to measurement-consider parameters</td>
</tr>
<tr>
<td>GM(40)</td>
<td>Partition of observation matrix relating observables to dynamic/measurement-consider parameters</td>
</tr>
<tr>
<td>JM(16)</td>
<td>Kalman filter J matrix</td>
</tr>
<tr>
<td>W1(24)</td>
<td>Working matrices for filter equations</td>
</tr>
<tr>
<td>W2(40)</td>
<td>Working matrices for filter equations</td>
</tr>
<tr>
<td>W3(80)</td>
<td>Working matrices for filter equations</td>
</tr>
<tr>
<td>W4(80)</td>
<td>Working matrices for filter equations</td>
</tr>
<tr>
<td>W5(40)</td>
<td>Working matrices for filter equations</td>
</tr>
<tr>
<td>K1(24)</td>
<td>Kalman gain matrix for state parameters</td>
</tr>
<tr>
<td>K2(40)</td>
<td>Kalman gain matrix for solve-for parameters</td>
</tr>
<tr>
<td>WORK(400)</td>
<td>Working matrices for filter equations</td>
</tr>
<tr>
<td>W(120)</td>
<td>Working matrices for filter equations</td>
</tr>
<tr>
<td>R(16)</td>
<td>Measurement noise matrix</td>
</tr>
<tr>
<td>DYN(36)</td>
<td>Dynamic noise matrix</td>
</tr>
<tr>
<td>PP(36)</td>
<td>Correlation matrix of P matrix</td>
</tr>
<tr>
<td>QQ(100)</td>
<td>Correlation matrix of Q matrix</td>
</tr>
<tr>
<td>JIN(16)</td>
<td>J inverse of Kalman filter equations</td>
</tr>
<tr>
<td>SQDU(20)</td>
<td>Standard deviations of dynamic-consider parameters</td>
</tr>
</tbody>
</table>
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  Co-sines of calibrated misalignments of the VRU and ARU after biasing
CDELT2
CDELT3

SDELT1  Sines of calibrated misalignments of the VRU and ARU after biasing
SDELT2
SDELT3

SUBDL1  Intermediate term used to calculate axial and normal acceleration

/DOPPLER/

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)
ΩMEGAE Angular velocity of earth (rad/s)
ΩBLIC  Obliquity of the ecliptic (radians)
REARTH  Radius of the earth (kilometers)
GHATØ  Greenwich hour angle of the vernal equinox at TZERO
SCPEC(6)  Spacecraft planetocentric ecliptic coordinates based on ECLØNG(1), ECLINC(1), PHIR(1)
PHIR(3)  Reference angle phi for ecliptic, planetoequatorial, and subsolar orbital planes, respectively
ECLØNG(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
RØTNØ  The target planet angular velocity component normal to the entry plane
NTP  Integer number of the target planet (see EPHEM for range of values)

/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

/INTCOM/

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
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LISTQ(10)</td>
<td>List of solve-for parameters</td>
</tr>
<tr>
<td>LISTU(20)</td>
<td>List of dynamic-consider parameters</td>
</tr>
<tr>
<td>LISTV(20)</td>
<td>List of measurement-consider parameters</td>
</tr>
<tr>
<td>LISTW(10)</td>
<td>List of dynamic/measurement-consider parameters</td>
</tr>
<tr>
<td>M</td>
<td>Parameter used to quantize VRU and ARU data</td>
</tr>
<tr>
<td>MCNTR</td>
<td>Indicates which measurement or event is currently being processed</td>
</tr>
<tr>
<td>MCODE(250)</td>
<td>Array of values of MCNTR</td>
</tr>
<tr>
<td>NØDE</td>
<td>Not used</td>
</tr>
<tr>
<td>N</td>
<td>Parameter used to quantize VRU and ARU data</td>
</tr>
<tr>
<td>NE</td>
<td>Number of state parameters in LISTS</td>
</tr>
<tr>
<td>NICNTR</td>
<td>Indicates LICNTR value of interest</td>
</tr>
<tr>
<td>NM</td>
<td>Number of observables in a measurement</td>
</tr>
<tr>
<td>NMEAS</td>
<td>Not used</td>
</tr>
<tr>
<td>NMPTS</td>
<td>Number of breakpoints of altitude versus molecular weight</td>
</tr>
<tr>
<td>NPRED</td>
<td>Not used</td>
</tr>
<tr>
<td>NQS</td>
<td>Set to NQ and used to set up plot package</td>
</tr>
<tr>
<td>NQUASI</td>
<td>Not used</td>
</tr>
<tr>
<td>NTPTS</td>
<td>Number of breakpoints of altitude versus ambient temperature</td>
</tr>
<tr>
<td>NVAR(15)</td>
<td>Array of number of dependent variables for plot package</td>
</tr>
<tr>
<td>NS</td>
<td>Number of state parameters in LISTS</td>
</tr>
<tr>
<td>NQ</td>
<td>Number of solve-for parameters in LISTQ</td>
</tr>
</tbody>
</table>
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
PROB(40) Array of Hollerith data for problem identification
RUNNO 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 MODE used to process event or measurement

/LOGCOM/

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
LOG(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
MACHNØ Logical to control updating of Mach number for LTR2 mode of reconstructor
PARACH  Not used

PLØTL(15)  Array of logicals used to control storage of plot data (subroutine PSTØRE)

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

/OBSERV/

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

/PRSDAT/

Actual dynamic pressure stored on unit 10 for reconstructor printout

SDMWT  Standard deviation of molecular weight used to calculate standard deviation of temperature

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

/PRSDAT/

PREDIC  Not used
PREDND(50)  Not used
STC  Not used
XNPM(30)  Not used
XNPMS(30)  Not used
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEEDEN</td>
<td>Actual error in estimated deviation from most recent nominal value of density</td>
</tr>
<tr>
<td>AEESLV(10)</td>
<td>Actual error in estimated deviations from most recent nominal solve-for values after a measurement</td>
</tr>
<tr>
<td>AEESTT(6)</td>
<td>Actual errors in estimated deviations from most recent nominal trajectory state</td>
</tr>
<tr>
<td>AEETMP</td>
<td>Actual error in estimated deviation from most recent nominal value of ambient temperature</td>
</tr>
<tr>
<td>ALPHAA</td>
<td>Actual angle of attack in degrees</td>
</tr>
<tr>
<td>DENS</td>
<td>Estimated deviation from most recent nominal value of density</td>
</tr>
<tr>
<td>EDNC(6)</td>
<td>Estimated deviations from most recent nominal trajectory state</td>
</tr>
<tr>
<td>ØMGCC</td>
<td>Reconstructed angular velocity converted to degrees</td>
</tr>
<tr>
<td>PPD(6)</td>
<td>Diagonal elements of PP matrix after a measurement</td>
</tr>
<tr>
<td>PPDBM(6)</td>
<td>Diagonal elements of PP matrix before a measurement</td>
</tr>
<tr>
<td>PPXD</td>
<td>Actual dynamic pressure in millibars</td>
</tr>
<tr>
<td>QQD(10)</td>
<td>Diagonal elements of QQ matrix after a measurement</td>
</tr>
<tr>
<td>QQDBM(10)</td>
<td>Diagonal elements of QQ matrix before a measurement</td>
</tr>
<tr>
<td>RESI(4)</td>
<td>Measurement residuals</td>
</tr>
<tr>
<td>SDDENS</td>
<td>Standard deviation in density after a measurement</td>
</tr>
<tr>
<td>SDMWT2</td>
<td>Not used</td>
</tr>
<tr>
<td>SDTEMP</td>
<td>Standard deviation in ambient temperature after a measurement</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>THETRC</td>
<td>Reconstructed angle THETA</td>
</tr>
<tr>
<td>XNAC(6)</td>
<td>Actual state in output units</td>
</tr>
<tr>
<td>XNC(6)</td>
<td>Most recent nominal state in output units</td>
</tr>
<tr>
<td>SDENBM</td>
<td>Standard deviation in density before a measurement</td>
</tr>
<tr>
<td>STEMBM</td>
<td>Standard deviation in ambient temperature before a measurement</td>
</tr>
<tr>
<td>TEMEDN</td>
<td>Estimated deviation in ambient temperature after a measurement</td>
</tr>
<tr>
<td>DENSBM</td>
<td>Estimated deviation in density before a measurement</td>
</tr>
<tr>
<td>TEMDBM</td>
<td>Estimated deviation in ambient temperature before a measurement</td>
</tr>
<tr>
<td></td>
<td>/PRNT3/</td>
</tr>
<tr>
<td>EDNBQC(30)</td>
<td>Converted estimated deviations from most recent nominal trajectory before a quasi-event</td>
</tr>
<tr>
<td>EDNBM(30)</td>
<td>EDNBM converted to output units before a quasi-event</td>
</tr>
<tr>
<td>XNBQC(30)</td>
<td>Most recent nominal trajectory (converted) before a quasi-event</td>
</tr>
<tr>
<td></td>
<td>/STATE/</td>
</tr>
<tr>
<td>CARCOR(6)</td>
<td>Cartesian coordinates of heliocentric ecliptic position and velocity of a specified planet</td>
</tr>
<tr>
<td>CONEL(7)</td>
<td>Conic elements of heliocentric ecliptic orbit of a specified planet and gravitational constant of the planet</td>
</tr>
</tbody>
</table>
XSTEP  Quantizing factor for axial acceleration
ZSTEP  Quantizing factor for normal acceleration
TSTEP  Quantizing factor for rate gyro attitude

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 SMOOTH2 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

165
TIMEF

Final trajectory time reached by the reconstructor

AROTBL(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

ATMÖS(33,5)

Five tables of breakpoints of molecular weights and temperatures versus altitude

ATMÖS(33)

ATMÖS table chosen according to NATMÖS

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)
<table>
<thead>
<tr>
<th><strong>CA</strong></th>
<th>Axial force coefficient computed from AROTBL tables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CACT(200)</strong></td>
<td>Data generator values of the C array used by the reconstructor to compute actual deviations from most recent nominal values of solve-for parameters</td>
</tr>
<tr>
<td><strong>CBQ(30)</strong></td>
<td>Scale factors and biases before a quasi-event used to compute estimated deviations from most recent nominal values of solve-for parameters</td>
</tr>
<tr>
<td><strong>CDTBL(50)</strong></td>
<td>Parachute drag coefficient table</td>
</tr>
<tr>
<td><strong>CMQ</strong></td>
<td>Moment coefficient computed from AROTBL tables</td>
</tr>
<tr>
<td><strong>CN</strong></td>
<td>Normal force coefficient computed from AROTBL tables</td>
</tr>
<tr>
<td><strong>CØ(200)</strong></td>
<td>Original reconstructor C array values used to calculate estimated deviations from original nominal values of solve-for parameters</td>
</tr>
<tr>
<td><strong>DIA</strong></td>
<td>Vehicle base diameter</td>
</tr>
<tr>
<td><strong>DP</strong></td>
<td>Dynamic pressure</td>
</tr>
<tr>
<td><strong>DT</strong></td>
<td>Integration step size (seconds) for data generator and reconstructor</td>
</tr>
<tr>
<td><strong>DXN(30)</strong></td>
<td>First derivatives of state parameters, actual VRU-ARU data, and ambient pressure derivative</td>
</tr>
<tr>
<td><strong>EDN(30)</strong></td>
<td>Estimated deviations from most recent nominal trajectory after a measurement</td>
</tr>
<tr>
<td><strong>EDNBQ(30)</strong></td>
<td>EDN array before a quasi-event</td>
</tr>
<tr>
<td><strong>EPS</strong></td>
<td>Epsilon, the angle between the inertial velocity and relative velocity vectors</td>
</tr>
<tr>
<td><strong>FD</strong></td>
<td>Parachute drag force</td>
</tr>
<tr>
<td><strong>GA</strong></td>
<td>Local gravitational acceleration</td>
</tr>
<tr>
<td><strong>GØ</strong></td>
<td>Gravitational acceleration at zero altitude</td>
</tr>
<tr>
<td><strong>MACH</strong></td>
<td>Mach number</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
</tr>
<tr>
<td>------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>MASS</td>
<td>Mass of the vehicle</td>
</tr>
<tr>
<td>MASSA</td>
<td>Perturbed vehicle mass</td>
</tr>
<tr>
<td>MEAS(4)</td>
<td>Reconstructed measurements calculated in OBSM to drive the filter equations</td>
</tr>
<tr>
<td>MEZACT(4)</td>
<td>Measurements calculated by the data generator and perturbed by noise, scale, and bias factors</td>
</tr>
<tr>
<td>MEZEST(10)</td>
<td>Estimated measurements calculated from MEAS array for filter equations</td>
</tr>
<tr>
<td>MEZNOZ(16,4)</td>
<td>Measurement noise components used to calculate MEZACT array</td>
</tr>
<tr>
<td>MU</td>
<td>Gravitational constant of the target planet</td>
</tr>
<tr>
<td>MNT</td>
<td>Actual molecular weight used to calculate Mach number</td>
</tr>
<tr>
<td>ØMEG</td>
<td>Rotational rate of the target planet</td>
</tr>
<tr>
<td>PRES</td>
<td>Ambient pressure state variable</td>
</tr>
<tr>
<td>RAD</td>
<td>Conversion factor from radians to degrees</td>
</tr>
<tr>
<td>RHØ</td>
<td>Atmospheric density</td>
</tr>
<tr>
<td>RI</td>
<td>Rotational inertia of the vehicle</td>
</tr>
<tr>
<td>RM</td>
<td>Radius of the target planet</td>
</tr>
<tr>
<td>SA</td>
<td>Reference surface area of the vehicle</td>
</tr>
<tr>
<td>SDP</td>
<td>Parachute reference area</td>
</tr>
<tr>
<td>SS</td>
<td>Speed of sound</td>
</tr>
<tr>
<td>TAPETM</td>
<td>Trajectory time stored on unit 10 for processing groups of events and measurements</td>
</tr>
<tr>
<td>TC</td>
<td>Current trajectory time (seconds)</td>
</tr>
<tr>
<td>TDIFF</td>
<td>Difference between current trajectory time and time of next measurement or event</td>
</tr>
</tbody>
</table>
TEMP  Ambient temperature
TEND  Trajectory time of the next event or measurement
TF    Final trajectory time
T.2N(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

/MACH/

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

COND    Logical to control computation of computed angle of attack (ALPH) and vehicle attitude angle (THETA)

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

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

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

ENTRY PARAMETERS

NGX   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 SYMBOL:
J
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

$$\hat{x}_{\text{equatorial}} = A \hat{x}_{\text{ ecliptic}}$$

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

$$\varepsilon = 23^\circ.452294 - 0^\circ.0035626 \ D - 0^\circ.000000173 \ D^2 + 0.0000000103 \ D^3$$

and

$$D = \text{Julian date (epoch 1900)} \times 10^{-4}$$
SUBROUTINE ATMOSP

PURPOSE: COMPUTE ATMOSPHERE QUANTITIES FOR MODE A RECONSTRUCTOR

SUBROUTINES CALLED: OTAR

COMMONS: TRAJ, AX, ATMS, PRE, DOPLER, QMPTI

LOCAL SYMBOLS
  AERO: AERODYNAMIC FORCE COEFFICIENTS
  ALFA: ABSOLUTE VALUE OF ANGLE OF ATTACK
  CAC: PERTURBED COEFFICIENT OF AXIAL FORCE

USED/COMMON: AGAM, ALPH, AR, AXC, C, CA, GAM, GATOL, MACHNO, MASS, MASA
  MWT, RHO, SA, TC, TZERO, VR, XN

SET/COMMON: AGAM, CA, DP, GMACH, MACHNO, MASSA
  RHO, LEP, CAC

FCT CALLED: TA
ATMOSP Analysis

Subroutine ATMOSP 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 \( a_x \) according to

\[
q = \frac{(m + C_{30}) a_x}{(C_{20} \cdot C_A + C_{16}) + (C_{96} \cdot C_D + C_{97})}
\]

so that density can be immediately obtained from

\[
\rho = \frac{2q}{\gamma^2 r}
\]

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

\[
M = \left[ \frac{2q}{\gamma p} \right]^\frac{1}{2}
\]

where \( \gamma \) 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

\[ T = \frac{pM}{\rho R} \]  

(4)

where \( M \) denotes molecular weight and \( R \) denotes the universal gas constant.
Set MACHNØ false

Use DTAB to interpolate on ARØTBL to compute $C_A$ as a function of Mach number and the absolute value of the angle of attack.

Incorporate scale factor and bias into $C_A$.

Use TAB to interpolate on CDTABL to compute parachute $C_D$ as a function of Mach number.

Incorporate scale factor and bias into $C_D$.

Compute the product of $C_A$ and the vehicle reference area $S$. Include the contribution of the parachute if it is deployed.

Compute dynamic pressure $q$ and density $p$ using equations (1) and (2), respectively.
Use TAB to interpolate on GAMTBL to compute the ratio of specific heats as a function of molecular weight.

Set MACHNO true if:
- \( t_c - t_0 > 0.5 \),
- \( q \geq 1 \times 10^{-5} \),
- \( p > 0 \).

Compute Mach number using equation (3) if MACHNO is true.

Compute temperature using equation (4) if \( q \geq 1 \times 10^{-5} \).

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
QMPTI INTCOM

LOCAL SYMBOLS
CUMPRO RATIO OF PRESSURE AT ATMOSPHERE BREAKPOINTS TO SURFACE PRESSURE
F ATMOSPHERE BREAKPOINT HEIGHTS IN ASCENDING SEQUENCE
MB ZERO HEIGHT INTERCEPTS FOR LINEAR SEGMENTS OF MOLECULAR WEIGHT VERSUS HEIGHT FUNCTIONS
MNO5 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
NRPTS NUMBER OF ATMOSPHERE BREAKPOINT TEMPERATURE PLUS MOLECULAR WEIGHT
NRPTSl NRPTS - 1
ST INTEGRAL OF RATIO OF MOLECULAR WEIGHT TO TEMPERATURE
TB ZERO HEIGHT INTERCEPTS FOR LINEAR SEGMENTS OF TEMPERATURE VERSUS HEIGHT FUNCTIONS
TN0S 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
Z5 ABSOLUTE MAGNITUDE OF TS
777 NEGATIVE OF EXPONENT IN PRESSURE VERSUS HEIGHT FUNCTION
<table>
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<tr>
<th>USF3/COMMN---</th>
<th>AGAM</th>
<th>APO</th>
<th>AR</th>
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<td>ENTRY PNT ---</td>
<td>ATMOAT</td>
<td>ATMSET</td>
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</table>

- FCT CALLED--- F1
- FLT DFND --- F1
- ENTRY PNT --- ATMOAT
- ATMSET

---

ATMSET-8
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

$$T(h) = T_{b_j} h + T_{b_{j+1}}$$  \hspace{1cm} (1)

The molecular weight M at height h between the i and i+1 molecular weight breakpoints is given by

$$M(h) = M_{b_i} h + M_{b_{i+1}}$$  \hspace{1cm} (2)

The hydrostatic equation

$$\frac{dP}{dh} = - \rho g$$  \hspace{1cm} (3)

where g = acceleration due to gravity, and the perfect gas law,

$$\rho(h) = \frac{P(h)}{R} \cdot \frac{M(h)}{T(h)}$$  \hspace{1cm} (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)

$$P(h) = P(h_k) \exp \left[ - \frac{g}{R} \int_{h_k}^{h} \frac{M(\zeta)}{T(\zeta)} d\zeta \right]$$  \hspace{1cm} (5)
\[
\int_{h_k}^{h} \frac{M(z)}{T(z)} \, dz = \begin{cases} 
\frac{1}{T_b} (h - h_k) \left\{ M_{i+1} + \frac{1}{2} M_i (h - h_k) \right\}, & T_s_j = 0 \\
\frac{M_i}{T_s_j} (h - h_k) + \frac{M_{i+1} - T_s - T_b \cdot M_i}{T_s_j \ln \frac{T_b + T_s h}{T_b + T_s h_k}}, & T_s_j \neq 0
\end{cases}
\]

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 \(P(h_0)\), the pressure \(P(h)\) may be found by repeated application of the above expression

\[
P(h) = P(h_0) \left\{ \frac{P(h_k)}{P(h_0)} \right\} \exp \left[ - \frac{\mathcal{E}}{R} \int_{h_k}^{h} \frac{M(z)}{T(z)} \, dz \right].
\]

The density is then found from equation (4) and the speed of sound at height \(h\) is given by

\[
\sigma(h) = \gamma_s \left[ \frac{RT(h)}{M(h)} \right]^{1/2}
\]

where \(\gamma_s\) = ratio of specific heats.

The subroutine has two entry points -- ATMST and ATMDAT. Entry ATMSET computes and stores the ratios \(P(h_k)/P(h_0)\) for each atmosphere breakpoint. Entry ATMDAT computes the temperature, molecular weight, pressure, density, and speed of sound at height \(h\).

The flow of the ATMSET subroutine is illustrated.
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 (MW), pressure (PRESS), density (RHO), and speed of sound (SS) at height, h.

RETURN

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 \( P(h_s/h_0) \) ratio for each atmosphere breakpoint, \( s \), and store in CUMPRD array.

RETURN
ATTACK-A

SUBROUTINE ATTACK
PURPOSE: COMPUTE VEHICLE ANGLE OF ATTACK

SUBROUTINES CALLED: DERIVE

COMMONS: AX, ATMS, TRAJ, GYRACC

LOCAL SYMBOLS:
- SK: INTERPOLATED VALUE OF LIFT OVER DRAG VERSUS MACH NUMBER
- JALPHA: INTERMEDIATE VARIABLE FOR ITERATIVE SOLUTION
- FALPHA: INTERMEDIATE VARIABLE FOR ITERATIVE SOLUTION
- I: INDEX
- ZETA: RATIO OF MEASURED ACCELERATIONS

USED/COMMON: ALPHA, AXC, AZC, BKTBL, MACH, NACCEL
SET/COMMON: ALPHA

FCT CALLED: TAR

LOADED: MACHNO
ATRACK Analysis

Subroutine ATTRACK 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 $\hat{a}$. The vehicle lift/drag ratio can be related to $a_{x_c}$, $a_{z_c}$, and $\hat{a}$ as follows:

$$\frac{L}{D} = \frac{a_{x_c} \cos \hat{a} - a_{z_c} \sin \hat{a}}{a_{x_c} \cos \hat{a} + a_{z_c} \sin \hat{a}} \quad (1)$$

Furthermore, $\frac{L}{D}$ has the form

$$\frac{L}{D} = k \hat{a} \quad (2)$$

where $k$ is a tabulated function of Mach number. Eliminating $\frac{L}{D}$ from equations (1) and (2) yields

$$\tan \hat{a} = \frac{\frac{L}{D} - k \hat{a}}{1 + \zeta k \hat{a}} \quad (3)$$

where

$$\zeta = \frac{a_{z_c}}{a_{x_c}} \hat{a}.$$

Equation (3) is solved iteratively for $\hat{a}$ using a standard Newton iteration technique. Rewriting equation (3) as

$$F = (1 + \zeta k \hat{a}) \tan \hat{a} + k \hat{a} - \zeta = 0 \quad (4)$$

the iteration process is defined by

$$\hat{a}_{i+1} = \hat{a}_i - \left( \frac{F}{\frac{\partial F}{\partial \hat{a}}} \right)_i \quad (5)$$

where

$$\frac{\partial F}{\partial \hat{a}} = k + 1 + \hat{a} \left[ -2 \zeta k + \hat{a} \left( 1 - \frac{4}{3} \zeta k \hat{a} \right) \right] \quad (6)$$

$$\hat{a}_0 = \frac{\zeta}{k + 1} \quad (7)$$

which is an approximate solution of equation (3) for small $\hat{a}$ and $\zeta$.
SUBROUTINE AUXIL

PURPOSE: PRINT AUXILIARY INFORMATION FROM THE DATA GENERATOR

SUBROUTINES CALLED: AECEQ ECLIP EPHM EQUATR GEOG SUBSOL

COMMONS DOPLER STATE TRAJ

LOCAL SYMBOLS

JJ JULIAN DATE, EPOCH JANUARY 0, 1900
ECLGEQ TRANSFORMATION FROM ECLIPTIC TO GEOCENTRIC EQUATORIAL
FN 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
RPSEQ 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/COMMON --- CARCOR DATEJ ECLINC ECLONG NTP
RA0 TC TPERO 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)
   
   \[
   \lambda = \tan^{-1}\left(\frac{y}{x}\right)
   \]

The communication angle \(\psi\) is defined as the angle between the spacecraft and earth position vectors relative to the center of the target planet. Thus

\[
\psi = \cos^{-1}\left[\frac{\hat{r} \cdot (\hat{r}_e - \hat{r}_p)}{|\hat{r}| \cdot |\hat{r}_e - \hat{r}_p|}\right], \quad 0 \leq \psi \leq \pi
\]

where \(\hat{r}\) is the spacecraft position relative to the target planet, and \(\hat{r}_e\) and \(\hat{r}_p\) are the position vectors of the earth and the target planet, respectively, relative to the sun.
The angle $\eta$ between the entry plane and the plane of the sky is defined as the angle between the normals of each plane. The unit vector $\mathbf{e}_n$ normal to the entry plane is given by

$$
\mathbf{e}_n = \begin{bmatrix}
\sin \iota \cos \Omega \\
-\sin \iota \sin \Omega \\
\cos \iota
\end{bmatrix}
$$

relative to the planetocentric ecliptic system, where inclination $\iota$ and longitude of the ascending node $\Omega$ 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 $\mathbf{p}$ from the earth to the spacecraft. The unit vector normal to this plane is

$$
\mathbf{e}_\rho = \frac{\mathbf{p}}{\rho}
$$

Then

$$
\eta = \cos^{-1} \left( \mathbf{e}_\rho \cdot \mathbf{e}_n \right)
$$

$$
0 \leq \eta \leq \pi
$$
SUBROUTINE BEGIN

PURPOSE: RESETS COMMON VARIABLES FOR USE BY LTRCON

LOCAL SYMBOLS

SET/COMM---ACCT
LTR1  LTR2  MACH  MASS  MODE  PARACH
REDR1  REDR2  RHO  RR  TC  TEMP
TEN3  TERHT  TSTEP  XS  XM  XN
XSTEP  ZG  ZHM  ZSTEP
BEGIN

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 ALK DATA

PURPOSE: Initializes common variables for later use by DATGEN

COMMONS: OBSERV TRAJ ATMS GY ATT T

LOCAL SYMBOLS: NONE

LOADED: ACT AGAM AQUANT AR AROTBL ATMSS

DIA DT EPSM ETA GATBL GO GQUANT

HITGND ICNTR LTR1 LTR2 MACH MASS MODE

MU NACCEL NGYRD NPTPS NPTPS OMEG PARACH

QSMQTS QSMCHG QST RAD REDRR1 REDRR2

RHO RQ RM RR SA SALT SLAT

SLON SDP TC TDIFF TEMP TENJ TERTHT

TF TH TSTEP TTIME TD TR VQA

VZQA VMASS VSA VOA VRI WDTBL XQ

XG XM XMFX XMFW XN XSTEP XG

ZMM ZSTEP ZG
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 (LTRCON). For a general description of storage in AROTBL, see subroutine DFAB.
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
USE#COMM--- RAJ
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

\[
P = \begin{bmatrix}
  \cdot & \cdot & \cdot \\
  \cdot & A & C \\
  \cdot & \cdot & \cdot \\
  \cdot & \cdot & B \\
\end{bmatrix}
\]

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

\[
D_{ij} = \frac{C_{ij}}{\sqrt{A_{ii} B_{jj}}}
\]
SUBROUTINE CORRO

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

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

$$P = \begin{bmatrix}
\cdot & \cdot & \cdot & \cdot & \cdot \\
\cdot & A & C & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot \\
\cdot & B & \cdot & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot \\
\end{bmatrix}, \quad B = \text{diag} \left( b_{i1} \ldots b_{n2} \right)$$

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

$$D_{ij} = \frac{C_{ij}}{\sqrt{A_{ii}b_{jj}}}.$$
SUBROUTINE DATGEN

PURPOSE: EXECUTIVE CONTROL FOR DATA GENERATOR

SURROUNDTES CALLED: ALTFILE, DERIV1, OBSM1, PRINT1, RKUTDG, SENSOR, SETUP

COMMONS: ACCEL, INTCON, TRAJ, QMPTI, LOGNOJ, PHASE

LOCAL SYMBOLS:
- NALT: DUMMY CALL ARGUMENT
- NC: ITERATIVE COUNTER FOR PRINTOUT
- UPDAIT: DUMMY CALL ARGUMENT

USES/COMMONS:
- TC, TF, HTGNBD, ICNTR, IPHAS, QSMCHG
- ACCLX, ACCLZ, MEASS, MWT, PRES, RHO
- QSMCHG, QST, QSMCHG, QSMCHG

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?

NO

Is vehicle altitude greater than quasi-static altitude?

NO

Will a change to the quasi-static dynamic model at the current time TC create a meshing problem?

NO

Set quasi-static dynamic model change logical to true

YES

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
Define vehicle physical characteristics for the appropriate entry phase

Has vehicle hit ground or has the final time been exceeded?

YES

Call PRINT1 to write out final data

RETURN

NO

Is altitude greater than parachute deployment altitude?

YES

Set IPHAS = 2. Set parachute deployment time equal to current time

NO

Is altitude greater than parachute release altitude?

YES

Set IPHAS = 3. Set parachute release time equal to current time

NO

Define vehicle physical characteristics for the appropriate entry phase
SUBROUTINE DERIV1

PURPOSE: COMPUTE STATE DERIVATIVES FOR DATA GENERATOR

ENTRY PARAMETERS:
- T: Trajectory time at which derivatives are desired
- UPJAIT: Not currently used
- XNEW: Vehicle state vector at time T

SUBROUTINES CALLED: ATMDAT, OTAR

COMMONS:
- ACEL: TRAJ, OET, DOLPER, OMPTI, 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
- RAJUS: 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
DERIV1-8

USEB/COMMN--- ACCLX ACCLZ AF ALPH AX AY
   C CA C3ELT1 C3ELT2 C3ELT3 CMQ
   CN OIA DP DXN EPS GA
   MASS NU RHO RI RM ROTNO
   SA SDELT1 SDFLT2 SS VR VW
   WDFBL XG XH XP ZG ZM

SET/COMMON--- ACCLX ACCLZ AF ALPH AM AX
   AY GA CMO GN JP DXN
   EPS GA MACH VR VN WDFBL
   XP ZM ZN

FCT CALLED--- TAR MINDV

FCT DFNO --- 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, \( \gamma \), \( \phi \), \( \theta \), \( \omega \), vₓ, vᵧ, Aᵧ, 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

\[
g = \frac{\mu}{r^2}
\]

where \( \mu \) 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 \( \varepsilon \) between the inertial velocity \( v \) and the relative velocity are computed from the following relations:

\[
v_a = r \omega_n + v_w
\]

\[
v_r = \frac{v - v_a \cos \gamma}{\cos \varepsilon}
\]

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

where \( \omega_n \) denotes the component of the planet rotational velocity in the entry plane. Angle of attack is given by

\[
\alpha = \theta + \phi - \gamma - \varepsilon
\]

Axial, normal, and parachute drag forces are given, respectively, by

\[
A = -C_A q S
\]

\[
N = -C_N q S
\]

\[
F_d = C_D q S_D
\]
The aerodynamic damping moment is computed from

$$M = C_m q v^2 q S/\nu_r$$  \hspace{1cm} (9)

The equations of motion which constitute the dynamic model used to compute the actual entry trajectory are summarized below:

$$\dot{h} = v \sin \gamma$$  \hspace{1cm} (10)

$$\dot{v} = -g \sin \gamma + \frac{A}{m} \cos (\alpha + \epsilon) + \frac{N}{m} \sin (\alpha + \epsilon) - \frac{F_d}{m} \cos \epsilon$$  \hspace{1cm} (11)

$$\dot{\gamma} = \left(\frac{v}{r} - \frac{\nu}{v}\right) \cos \gamma + \frac{1}{v} \left[\frac{A}{m} \sin (\alpha + \epsilon) - \frac{N}{m} \cos (\alpha + \epsilon) - \frac{F_d}{m} \cos \epsilon\right]$$  \hspace{1cm} (12)

$$\dot{\phi} = \frac{v}{r} \cos \gamma$$  \hspace{1cm} (13)

$$\dot{\theta} = \omega$$  \hspace{1cm} (14)

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

$$\dot{v}_x = a_x \cos \delta_1 - a_z \sin \delta_1$$  \hspace{1cm} (16)

$$\dot{v}_z = a_x \sin \delta_2 + a_z \cos \delta_2$$  \hspace{1cm} (17)

The actual angular velocity experienced by the ARU is given by

$$\dot{A}_\theta = \omega \cos \delta_3$$  \hspace{1cm} (18)

The rate of change of ambient pressure is computed from

$$\dot{p} = -p_g \dot{h}$$  \hspace{1cm} (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

\[ \dot{v} = 0 \quad (20) \]

and \( v \) is computed from the terminal velocity solution

\[ v = \frac{2m g |\sin \gamma|}{\rho \left( C_A S + C_D S_D \right)} \quad (21) \]

The logical variable \( \text{COND} \) is set to true if either dynamic pressure exceeds \( ODB \) or if the parachute is deployed. Whenever \( \text{COND} \) is true, the angle of attack and the rotational state are computed as follows:

\[ \alpha = 0 \quad (22) \]
\[ \theta = \gamma - \phi + \varepsilon \quad (23) \]
\[ \omega = \gamma - \dot{\phi} \quad (24) \]
DERIV1 Flow Chart

1. Enter
2. Set local state variables to the XNEW vector
3. Compute cosine and sine of \( \gamma \), radial distance of vehicle from planet center, and the local acceleration of gravity
4. Use WINDV to compute the local horizontal wind velocity \( v_w \)
5. Compute atmosphere velocity \( v_a \), vehicle relative velocity \( v_r \), and the angle \( \epsilon \) between \( v \) and \( v_r \)
6. Call ATMDAT to compute the local atmospheric temperature, pressure, density, molecular weight, and speed of sound
7. Compute Mach number and dynamic pressure
8. Set condition COND false
9. Set COND true if dynamic pressure exceeds \( \Delta P \), or if parachute is deployed
Compute angle of attack

Is COND true?

NO

YES

Set $\alpha = 0$ and $X_{NEW(5)} = \gamma - \phi + \varepsilon$

Compute cosine and sine of $\alpha + \varepsilon$

Use DTAB to interpolate on AROTBL 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

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 COND is true, set $\dot{\theta} = \dot{\gamma} - \dot{\phi}$

C
Evaluate the $\dot{\omega}$ equation. Include parachute terms if parachute is deployed.

If COND is true, set $\omega = \dot{\gamma} - \dot{\phi}$ and $\text{XNEW}(6) = \omega$.

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 OERIV

PURPOSE: COMPUTE NOJE & VEHICLE STATE DERIVATIVES

ENTRY PARAMETERS

- \( T \): TRAJECTORY TIME (NOT CURRENTLY USED)
- \( UPD\): LOGICAL TO CONTROL UPDATING OF VEHICLE STATE VECTOR
- \( XNE\): VEHICLE STATE VECTOR AT TIME \( T \)

SUBROUTINES CALLED: ATM DAT DT AB

COMMONS: TRAJ GY INT COM DOPLER LOG MOD 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
- PAROE: 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
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DERIV3 Analysis

Subborne 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 0 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'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

\[ g = \frac{\mu}{r^2} \]  

(1)

where \( \mu \) 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 \( \epsilon \) between the inertial velocity \( v \) and the relative velocity are computed from the following relations:

\[ v_a = r \omega_n + v_w \]  

(2)

\[ v_r = \frac{v - v_a \cos \gamma}{\cos \epsilon} \]  

(3)

\[ \epsilon = \tan^{-1} \left[ \frac{v_a \sin \gamma}{v - v_a \cos \gamma} \right] \]  

(4)

where \( \omega_n \) denotes the component of the planet rotational velocity in the entry plane.

Angle of attack \( \alpha \) is given by

\[ \alpha = \theta + \phi - \gamma - \epsilon \]  

(5)

However, attitude angle \( \theta \) is not available in the mode B reconstruction process since gyro measurements are not permitted in this mode. Thus, in mode B \( \alpha \) is nominally set to zero. It is
still necessary, however, to compute the perturbations in a result-
ing 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

$$\delta \alpha = \delta \theta + \delta \phi - \delta \gamma - \delta \varepsilon$$  \hspace{1cm} (6)

where $\delta \theta = C_{140}$, $\delta \phi = C_{104}$, $\delta \gamma = C_{103}$, and

$$\delta \varepsilon = \frac{\sin^2 \varepsilon}{v_a^2 \sin^2 \gamma} [-v_n \sin \gamma \cdot \delta h + (v \cos \gamma - v_a) v_a \delta \gamma$$

$$- v_a \sin \gamma \cdot \delta \nu]$$  \hspace{1cm} (7)

In this latter equation, which was derived by differentiating equa-
tion (4), $\delta h = C_{101}$ and $\delta \nu = C_{102}$.

Axial, normal, and parachute drag aerodynamic forces are given,
respectively, by

$$A = - C_A q S$$  \hspace{1cm} (8)

$$N = - C_N q S$$  \hspace{1cm} (9)

$$F_d = C_D q S_D$$  \hspace{1cm} (10)

The equations of motion that constitute the mode B filter dynamic
model are summarized as

$$\dot{h} = v \sin \gamma$$  \hspace{1cm} (11)

$$\dot{v} = -g \sin \gamma + \frac{A}{m} \cos (\alpha + \varepsilon) + \frac{N}{m} \sin (\alpha + \varepsilon) - \frac{F_d}{m} \cos \varepsilon$$  \hspace{1cm} (12)

$$\dot{\gamma} = \frac{(v - F_d)}{r} \cos \gamma + \frac{1}{v} \left[ \frac{A}{m} \sin (\alpha + \varepsilon) - \frac{N}{m} \cos (\alpha + \varepsilon) \right.$$ \hspace{1cm} (13)

$$- \frac{F_d}{m} \sin \varepsilon \right]$$

$$\dot{\phi} = \frac{v}{r} \cos$$  \hspace{1cm} (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

\[ \dot{v} = 0 \]  

and \( v \) is computed from the terminal velocity solution

\[ v = \left[ \frac{2 (m + C_{30}) g \sin \gamma}{\rho (C_A S + C_D S_D)} \right]^{\frac{1}{2}} + C_{102} \]
Add the appropriate $C_j$ perturbations to the vehicle state.

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 atmosphere velocity $v_a$, vehicle relative velocity $v_r$, angle $\epsilon$ between $v$ and $v_r$, perturbation $\delta \epsilon$, and angle of attack $\alpha$.

Call ATMDAT to compute the local atmospheric temperature, pressure, density, molecular weight, and speed of sound.

Compute Mach number and dynamic pressure.

A
Use DATAB to interpolate on ARΘTBL to compute $C_A$ and $C_N$ as functions of Mach number and the absolute value of the angle of attack.

Is parachute deployed? 

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.
Is the quasistatic dynamic model being used?

Yes:
Set \( \dot{y} = 0 \) and compute the quasistatic velocity. Include parachute terms if parachute is deployed.

Set \( X_{\text{NEW}}(2) \) equal to the quasistatic velocity if the unperturbed nominal trajectory is being computed.

Evaluate the \( \dot{h}, \dot{y}, \) and \( \dot{\phi} \) equations. Include parachute terms if parachute is deployed.

RETURN

No:
SUBROUTINE DERIV

PURPOSE: COMPUTE MoE 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 CALLED: TRAJ, AX, LOGCOM, DET, DERIV

LOCAL SYMBOLS:
AXM  MEASURED AXIAL ACCELERATION
AZN  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
RAJUS  DISTANCE FROM CENTER OF PLANET TO VEHICLE
SAE  SINE OF ALPH PLUS EPS
THIM  MEASURED ALTITUDE ANGLE
X  COMPUTED VRU LOCATION ALONG X-AXIS
Z  COMPUTED VRU LOCATION ALONG Z-AXIS
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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 \( h, v, \gamma, \phi, \) 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:

\[
\begin{align*}
\bar{x}_c &= (x_m + C_{28}) - (x_g + C_{26}) \\
\bar{z}_c &= (z_m + C_{29}) - (z_g + C_{27}) \\
\delta_1 &= \delta_1 - C_{55} \\
\delta_2 &= \delta_2 - C_{56} \\
\delta_3 &= \delta_3 - C_{63}
\end{align*}
\]

where \( x_m \) and \( z_m \) define the nominal VRU location; \( x_g \) and \( z_g \), the nominal cg location; \( \delta_1 \) and \( \delta_2 \), the nominal VRU misalignment angles; \( \delta_3 \), 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:

\[
\begin{align*}
I = 1 & : \text{axial VRU}; \\
I = 2 & : \text{normal VRU}; \\
I = 3 & : \text{ARU}.
\end{align*}
\]
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:

\[ a_{xm} = a_{12} \]  \hspace{2cm} (6)

\[ a_{zm} = a_{22} \]  \hspace{2cm} (7)

The measured ARU data are obtained from:

\[ \theta_m = a_{31} \]  \hspace{2cm} (8)

\[ \omega_m = a_{32} \]  \hspace{2cm} (9)

\[ \dot{\omega}_m = 2 a_{33} \]  \hspace{2cm} (10)

If normal VRU data are not available, \( a_{zm} \) and misalignment \( \delta_2 \) 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, \( \omega_m \), \( \dot{\omega}_m \), and misalignment \( \delta_3 \) are set to zero and the nominal angle of attack \( a \) is assumed to be zero.

The measured VRU and ARU data are calibrated for scale factor, bias, and misalignment errors using the following equations:
\[ a_x = \frac{1}{c_52} \left( \frac{a_{x_m} - c_52}{c_51} \cos \delta_2 + \frac{a_{z_m} - c_54}{c_53} \sin \delta_1 \right) \]
\[ + \omega_c^2 x_c - \dot{\omega}_c \dot{z}_c \]  
\[ a_z = \frac{1}{c_52} \left( -\frac{a_{x_m} - c_52}{c_51} \sin \delta_2 + \frac{a_{z_m} - c_54}{c_53} \cos \delta_1 \right) \]
\[ + \omega_c^2 z_c + \dot{\omega}_c \dot{x}_c \]  
\[ \theta_c = \frac{1}{c_{124}} \left[ \theta_m - c_{125} (t - t_0) \right] \]
\[ \omega_c = \frac{1}{c_{124}} (\omega_m - c_{125}) \]
\[ \dot{\omega}_c = \frac{\dot{\omega}_m}{c_{124}} \]  

The local acceleration of gravity is computed from
\[ g = \frac{\mu}{r} \]  

where \( \mu \) 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 \( \epsilon \) between the inertial velocity \( v \) and the relative velocity are computed from the following relations:
\[ v_a = r \omega_n + v_w \]
where \( \omega_n \) denotes the component of the planet rotational velocity in the entry plane.

Angle of attack \( \alpha \) is given by

\[
\alpha = \theta_c + \theta_o + \phi - \gamma - \varepsilon + C_{140}
\]  

(20)

where \( \theta_o \) is the initial attitude angle and the calibrated attitude measurement \( \theta_c \) represents the change in attitude since initial time \( t_0 \). Parameter \( C_{140} \) represents the initial attitude error.

When nominal \( \alpha \) is chosen to be zero, as it is when ARU data are not available or when the parachute is deployed, perturbations in \( \alpha \) resulting from perturbations in the state variables and other parameters are computed from

\[
\delta \alpha = \delta(\theta_c + \theta_o) + \delta \phi - \delta \gamma - \delta \varepsilon
\]  

(21)

where \( \delta(\theta_c + \theta_o) = C_{140} \), \( \delta \phi = C_{104} \), \( \delta \gamma = C_{103} \), and

\[
\delta \varepsilon = \frac{\sin^2 \gamma}{v_a^2 \sin^2 \gamma} \left[ - \omega_n \sin \gamma \cdot \delta h + (v \cos \gamma - v_a) v_a \delta \gamma \right. \\
- v_a \sin \gamma \cdot \delta v \right]
\]  

(22)

In this latter equation, which was derived by differentiating equation (19), \( \delta h = C_{101} \) and \( \delta v = C_{102} \).
Subroutine ATMOSP is not called until significant axial aerodynamic deceleration has developed. Currently, ATMOSP is called when

\[ a_x \leq -0.5 \times 10^{-3} \text{ km/s}^2 \]

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

\[ \dot{\gamma} = v \sin \gamma \quad (23) \]

\[ \dot{v} = -g \sin \gamma + a_{x_c} \cos (\alpha + \epsilon) + a_{z_c} \sin (\alpha + \epsilon) \quad (24) \]

\[ \dot{\gamma} = \left( \frac{v}{r} - \frac{g}{v} \right) \cos \gamma + \frac{1}{v} \left[ a_{x_c} \sin (\alpha + \epsilon) - a_{z_c} \cos (\alpha + \epsilon) \right] \quad (25) \]

\[ \dot{\phi} = \frac{v}{r} \cos \gamma \quad (26) \]

\[ \dot{\rho} = -g \rho \dot{h} \quad (27) \]

If the quasistatic dynamic model is to be used, equation (24) is replaced with

\[ \dot{v} = 0 \quad (28) \]

and \( v \) is computed from the terminal velocity solution

\[ v = \left[ \frac{2 \left( m + C_{30} \right) g \left| \sin \gamma \right|}{\rho \left( C_A S + C_D S_D \right)} \right]^{\frac{1}{2}} + C_{102} \quad (29) \]

\[ \text{DERIVE-5} \]
Add the appropriate $C_j$ perturbations to the vehicle state and the ambient pressure

Compute $cg$ offset and VRU and ARU misalignment angles

Evaluate the smoothed VRU and ARU data by selecting appropriate elements from the AA array. Compute the calibrated ARU data

Is a normal accelerometer measurement available?

Yes

No

Set $\delta_2 = 0.0$, $a_z = 0.0$, and $C_{53} = 1$

Is a gyro measurement available?

Yes

Set $\delta_3 = 0.0$, $\omega_m = 0.0$, and $\dot{\omega}_m = 0$. 

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 $\epsilon$ between $v$ and $v_r$, and angle of attack $\alpha$

Is the parachute deployed or gyro measurements absent?  

No

$\text{IALPHA} = 1$

Yes

If $\text{IALPHA} = 1$, compute perturbation $\Delta \epsilon$ and recompute $\alpha$
\[ a_{x_c} \leq 0.5 \times 10^{-3} ? \]

**No**

Call ATMOSP to compute atmosphere state

**Yes**

Evaluate the \( \dot{\phi} \) equation

Is the quasistatic dynamic model being used?

**No**

**Yes**

Set \( \psi = 0 \) and compute the quasi-static velocity. Include parachute terms if parachute is deployed

Set \( X_{NEW(2)} \) equal to the quasi-static velocity if the unperturbed nominal trajectory is being computed

Evaluate the \( \dot{h}, \dot{\gamma}, \dot{\phi}, \text{ and } \rho \) 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
ND
NRY
X
Y
Z

NUMBER OF COLUMNS OF Y MATRIX
NUMBER OF DIAGONAL ELEMENTS OF X MATRIX
NUMBER OF ROWS OF Y MATRIX AND NUMBER OF COLUMNS OF Z MATRIX
DIAGONAL INPUT MATRIX
RECTANGULAR INPUT MATRIX
RECTANGULAR OUTPUT MATRIX (X TIMES Y TRANSPOSED)

LOCAL SYMBOLS

I
J
P

INDEX
INDEX
I-TH DIAGONAL ELEMENT OF X MATRIX
SUBROUTINE OTAB

PURPOSE: PERFORMS LINEARLY INTERPOLATED DOUBLE TABLE LOOKUP

ENTRY PARAMETERS

A   OUTPUT VECTOR OF INTERPOLATED VALUES
(LYPENJENT 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 (I)
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 Y1, 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

\[ A(I) = \text{FRAC}(2) \times (W2 - W1) + W1 \]

as in the standard formulae.
SUBROUTINE DYNOIZ

PURPOSE: CURRENTLY SETS DYNAMIC NOISE MATRIX TO ZERO

COMMONS: COVARP INTCOM

LOCAL SYMBOLS
  I INJEX
  NN NUMBER OF STATE VARIABLES SQUARED

USED/COMMON--- 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: JOPLER TRAJ 

LOCAL SYMBOLS 
COSEI COSINE OF ENTRY PLANE INCLINATION 
COSEL COSINE OF ENTRY PLANE LONGITUDE OF ASCENDING NOE 
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 NOE 
SINT SINE OF THETA 
THETA AUXILIARY ANGLE 

USE3/COMMON--- ECLINC ECLONG PHIR PM
ECLIP Analysis

Subroutine ECLIP transforms the standard LTR spacecraft state variables \( h, v, \gamma, \phi + \phi_e, \Omega_e, \) and \( i_e \) to planetocentric ecliptic Cartesian components \( r_x, r_y, r_z, v_x, v_y, \) and \( v_z \). In the figure below \( x_e, y_e, z_e \) denotes the planetocentric ecliptic coordinate system and \( R_p \) denotes the planet radius.
The transformation equations are summarized as:

\[
\begin{align*}
    r_x &= r (\cos \theta \cos \Omega - \sin \theta \cos i \sin \Omega) \\
    r_y &= r (\cos \theta \sin \Omega + \sin \theta \cos i \cos \Omega) \\
    r_z &= r \sin \theta \sin i \\
    v_x &= v (\cos \psi \cos \Omega - \sin \psi \sin i \sin \Omega) \\
    v_y &= v (\cos \psi \sin \Omega + \sin \psi \cos i \cos \Omega) \\
    v_z &= v \sin \theta \sin i
\end{align*}
\]

where

\[
\begin{align*}
    r &= R_p + h, \\
    \theta &= \phi + \phi_e, \\
    \psi &= \phi + \phi_e - \gamma + \frac{\pi}{2}
\end{align*}
\]
**SURROUTINE ELCAR**

**PURPOSE:** Transformation of conic elements to Cartesian coordinates

**ENTRY PARAMETERS**
- \( A \): Semimajor axis
- \( E \): Eccentricity
- \( G_M \): Gravitational constant of central body
- \( R \): Position vector in reference system
- \( R_M \): Position magnitude
- \( \Theta_A \): True anomaly
- \( T_F P \): Time from periapsis
- \( V \): Velocity vector in reference system
- \( V_M \): Velocity magnitude
- \( \Omega \): Argument of periapsis
- \( \Xi \): Inclination in reference system
- \( \Xi_N \): Longitude of ascending node

**LOCAL SYMBOLS**
- \( A_U X_F \): Eccentric anomaly (Hyperbolic case)
- \( A_V A \): Mean anomaly (Elliptic case)
- \( C_I \): Cosine of inclination
- \( C_K \): Velocity factor used to calculate final velocity vector
- \( C_N \): Cosine of longitude of ascending node
- \( C_O S_E_A \): Cosine of eccentric anomaly (Elliptic case)
- \( C_T \): Cosine of true anomaly
- \( C_W \): Cosine of sum of argument of periapsis and true anomaly, also cosine of argument of periapsis
- \( J_I V \): Intermediate variable used to calculate \( T_F P \)
- \( E_A \): Eccentric anomaly (Elliptic case)
- \( P \): Semilatus rectum
ELCAR-B

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

\[
p = a (1 - e^2) .
\]

Then the magnitude of the radius vector is given by

\[
r = \frac{p}{1 + e \cos f} .
\]

The unit vector in the direction of the position vector is

\[
\begin{align*}
\hat{u}_x &= \cos (\omega + f) \cos \Omega - \cos i \sin (\omega + f) \sin \Omega \\
\hat{u}_y &= \cos (\omega + f) \sin \Omega + \cos i \sin (\omega + f) \cos \Omega \\
\hat{u}_z &= \sin (\omega + f) \sin i .
\end{align*}
\]

The position vector \(\hat{r}\) is therefore

\[
\hat{r} = r \hat{u} .
\]

The velocity vector \(\hat{v}\) is given by

\[
\begin{align*}
\hat{v}_x &= \sqrt{\frac{\mu}{p}} \left[ (e + \cos f)(-\sin \omega \cos \Omega - \cos i \sin \Omega \cos \omega) \\
&\quad - \sin f (\cos \omega \cos \Omega - \cos i \sin \Omega \sin \omega) \right] \\
\hat{v}_y &= \sqrt{\frac{\mu}{p}} \left[ (e + \cos f)(-\sin \omega \sin \Omega + \cos i \cos \Omega \cos \omega) \\
&\quad - \sin f (\cos \omega \sin \Omega + \cos i \cos \Omega \sin \omega) \right] \\
\hat{v}_z &= \sqrt{\frac{\mu}{p}} \left[ (e + \cos f) \sin i \cos \omega - \sin f \sin i \sin \omega \right].
\end{align*}
\]

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)

\[ t_p = \sqrt{\frac{a^3}{\mu}} (E - e \sin E) \]

\[
\cos E = \frac{e + \cos f}{1 + e \cos f} \quad \sin E = \frac{\sqrt{1 - e^2} \sin f}{1 + e \cos f}. \tag{6}
\]

For \( a < 0 \) (hyperbolic motion), the time from periapsis is

\[ t_p = \sqrt{\frac{a^3}{\mu}} (e \sinh H - H) \]

\[
\tanh \frac{H}{2} = \sqrt{\frac{e - 1}{e + 1}} \tan \frac{f}{2}. \tag{7}
\]
SUBROUTINE EPHEN

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
  CAPOK  LONGITUDE OF THE ASCENDING NODE
  CD  JULIAN DATE IN UNITS OF 10,000 EPHemeris Days
  CCE  CD CUBED
  CJS  CJ 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
  OMESEAT  LONGITUDE OF OMESEARS
  PI  CONSTANT = 3.141592653589793
  PMU  ARRAY OF GRAVITATIONAL CONSTANTS
  RAJ  CONVERSION FACTOR FROM RADIANS TO DEGREES
  RM  PLANET HELIOCENTRIC POSITION MAGNITUDE
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINTA</td>
<td>Sine of True Anomaly</td>
</tr>
<tr>
<td>SMA</td>
<td>Semi-Major Axis</td>
</tr>
<tr>
<td>T</td>
<td>Julian Date in Centuries</td>
</tr>
<tr>
<td>TA</td>
<td>True Anomaly</td>
</tr>
<tr>
<td>TC</td>
<td>Cube of T</td>
</tr>
<tr>
<td>TFP</td>
<td>Time from Periapsis Passage</td>
</tr>
<tr>
<td>TM</td>
<td>Conversion Factor from Days to Seconds</td>
</tr>
<tr>
<td>TS</td>
<td>Square of T</td>
</tr>
<tr>
<td>VM</td>
<td>Planet Heliocentric Velocity Magnitude</td>
</tr>
<tr>
<td>XI</td>
<td>Inclination</td>
</tr>
<tr>
<td>XMNA</td>
<td>Mean Anomaly</td>
</tr>
<tr>
<td>XMU</td>
<td>Planet Gravitational Constant</td>
</tr>
</tbody>
</table>

**Units:**
- **SET/COMMON:**
  - **CARCOR**
  - **CONEL**
- **LOADED:**
  - **AU**
  - **PI**
  - **PMU**
  - **RAD**
  - **TM**
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:

\[ p = a (1 - e^2) \]
\[ r = a (1 - e \cos E) \]
\[ v = \sqrt{\frac{2}{T} - \frac{1}{a}} \]
\[ \cos f = \frac{p - r}{er} \]
\[ \sin f = \sqrt{1 - \cos^2 f} \cdot \text{sgn} (\sin E) \]
\[ \cos \gamma = \frac{\sqrt{up}}{rv} \]
\[ \sin \gamma = \sqrt{1 - \cos^2 \gamma} \cdot \text{sgn} (\sin E) \]
\[ \omega = \tilde{\omega} - \Omega \, . \]

The heliocentric ecliptic position and velocity components of the planet are then

\[ \vec{r} = r_x \hat{i} + r_y \hat{j} + r_z \hat{k} \]
\[ r_x = r \cos (\omega + f) \cos \Omega - r \sin (\omega + f) \sin \Omega \cos i \]
\[ r_y = r \cos (\omega + f) \sin \Omega + r \sin (\omega + f) \cos \Omega \cos i \]
\[ r_z = r \sin (\omega + f) \sin i \]
\[ \dot{\vec{r}} = \frac{\vec{v}}{r} [\hat{\omega} \times \vec{r}] \cos \gamma + \vec{r} \sin \gamma \]

where \( \hat{\omega} = (\sin i \sin \Omega) \hat{i} - (\sin i \cos \Omega) \hat{j} + (\cos i) \hat{k} \, . \]
Planetary Ephemerides*

Mean Elements of Mercury

\[ i = 0.122233228 + 3.24776685 \times 10^{-5} T - 3.19770295 \times 10^{-7} T^2 \]
\[ \Omega = 0.8228518595 + 2.068578774 \times 10^{-2} T + 3.034933644 \times 10^{-6} T^2 \]
\[ \omega = 1.3246996178 + 2.714840259 \times 10^{-2} T + 5.143873156 \times 10^{-6} T^2 \]
\[ e = 0.20561421 + 0.00002046 T - 0.000000030 T^2 \]
\[ M = 1.785111955 + 7.142471000 \times 10^{-2} d + 8.72664626 \times 10^{-9} D^2 \]
\[ a = 0.3870986 \text{ A.U.} = 57,909,370 \text{ km}. \]

Mean Elements of Venus

\[ i = 0.0592300268 + 1.755510339 \times 10^{-5} T - 1.696847884 \times 10^{-8} T^2 \]
\[ \Omega = 1.3226043500 + 1.570534527 \times 10^{-2} T + 7.155849933 \times 10^{-6} T^2 \]
\[ \omega = 2.2717874591 + 2.457486613 \times 10^{-2} T + 1.704120089 \times 10^{-5} T^2 \]
\[ e = 0.00682069 - 0.00004774 T + 0.000000091 T^2 \]
\[ M = 3.710626172 + 2.796244623 \times 10^{-2} d + 1.682497399 \times 10^{-6} D^2 \]
\[ a = 0.7233316 \text{ A.U.} = 108,209,322 \text{ km}. \]

Mean Elements of Earth (Barycenter)

\[ i = 0 \]
\[ \Omega = 0 \]
\[ \omega = 1.7666368138 + 3.000526417 \times 10^{-2} T + 7.902463002 \times 10^{-6} T^2 \]
\[ + 5.817764173 \times 10^{-8} T^3 \]
\[ e = 0.01675104 - 0.00004180 T - 0.000000126 T^2 \]
\[ M = 6.256583781 + 1.720196977 \times 10^{-2} d - 1.954768762 \times 10^{-7} D^2 \]
\[ - 1.22173048 \times 10^{-9} D^3 \]
\[ a = 1.0000003 \text{ A.U.} = 149,598,530 \text{ km}. \]

Mean Elements of Mars

\[ i = 0.0322944089 - 1.178097245 \times 10^{-5} T + 2.201054112 \times 10^{-7} T^2 \]
\[ \Omega = 0.8514840375 + 1.345634309 \times 10^{-2} T - 2.424068406 \times 10^{-8} T^2 \]
\[ \omega = 5.8332085089 + 3.212729365 \times 10^{-2} T + 2.266503959 \times 10^{-6} T^2 \]
\[ e = 0.09331290 + 0.000092064 T - 0.000000077 T^2 \]
\[ M = 5.576840523 + 9.145887726 \times 10^{-3} d + 2.365444735 \times 10^{-7} D^2 \]
\[ a = 1.5236915 \text{ A.U.} = 227,941,963 \text{ km.} \]

Mean Elements of Jupiter

\[ i = 0.0228410270 - 9.696273622 \times 10^{-5} T \]
\[ \Omega = 1.7355180770 + 1.764479392 \times 10^{-2} T \]
\[ \omega = 0.2218561704 + 2.812302353 \times 10^{-2} T \]
\[ e = 0.0483376 + 0.00016302 T \]
\[ M = 3.93135411 + 1.450191928 \times 10^{-3} d \]
\[ a = 5.202803 \text{ A.U.} = 778,331,525 \text{ km.} \]

Means Elements of Saturn

\[ i = 0.0435037861 - 7.757018898 \times 10^{-8} T \]
\[ \Omega = 1.9684445802 + 1.523977870 \times 10^{-2} T \]
\[ \omega = 1.5897996653 + 3.419861162 \times 10^{-2} T \]
\[ e = 0.0558900 - 0.00034705 T \]
\[ M = 3.0426210430 + 5.837120844 \times 10^{-4} d \]
\[ a = 9.538843 \text{ A.U.} = 1,426,996,160 \text{ km.} \]
Mean Elements of Uranus

\[ i = 0.0134865470 + 0.9696273622 \times 10^{-5} \text{ T} \]
\[ \Omega = 1.2826407705 + 8.912087493 \times 10^{-3} \text{ T} \]
\[ \omega = 2.9502426085 + 2.834608631 \times 10^{-2} \text{ T} \]
\[ e = 0.0470463 + 0.00027204 \text{ T} \]
\[ M = 1.2843599198 + 2.046548840 \times 10^{-4} \text{ d} \]
\[ a = (19.182281 - 0.00057008 \text{ T}) \text{ A.U.} = (2,869,640,310 - 85271 \text{ T}) \text{ km.} \]

Mean Elements of Neptune

\[ i = 0.0310537707 - 1.599885148 \times 10^{-4} \text{ T} \]
\[ \Omega = 2.2810642235 + 1.923032859 \times 10^{-2} \text{ T} \]
\[ \omega = 0.7638202701 + 1.532704516 \times 10^{-2} \text{ T} \]
\[ e = 0.00852849 + 0.00007701 \text{ T} \]
\[ M = 0.7204851506 + 1.033089473 \times 10^{-4} \text{ d} \]
\[ a = (30.057053 + 0.001210166 \text{ T}) \text{ A.U.} = (4,496,490,000 + 181039 \text{ T}) \text{ km.} \]

Mean Elements of Pluto

\[ i = 0.2996706970859694 \]
\[ \Omega = 1.1914337550102258 \]
\[ \omega = 3.909919302791948 \]
\[ e = 0.2488033053623924 \]
\[ M = 3.993890007 + 0.6962635708298997 \times 10^{-4} \text{ d} \]
\[ a = 39.37364135300176 \text{ A.U.} = 5,890,213,786.146 730 \text{ km.} \]
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: EPHM EXIT

COMMONS 1 STATE

LOCAL SYMBOLS
AHCGC COORDINATE TRANSFORMATION FROM GEOCENTRIC EQUATORIAL TO GEOCENTRIC ECLIPTIC
CSDECL COSINE OF DECL
CSEQDL COSINE OF EORL
CSINM COSINE OF INM
CSNOM COSINE OF NOOEM
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
EOB 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
PMAS MAGNITUDE OF PBAR
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLE</td>
<td>Unit vector aligned with target planet polar axis</td>
</tr>
<tr>
<td>POLMAG</td>
<td>Magnitude of pole</td>
</tr>
<tr>
<td>QBARP</td>
<td>Cross product of pole and prar</td>
</tr>
<tr>
<td>QMAG</td>
<td>Magnitude of QBARP</td>
</tr>
<tr>
<td>PASC</td>
<td>Right ascension of target planet pole</td>
</tr>
<tr>
<td>SNJECL</td>
<td>Sine of decl</td>
</tr>
<tr>
<td>SNEOBL</td>
<td>Sine of eol</td>
</tr>
<tr>
<td>SNINM</td>
<td>Sine of inclination inm</td>
</tr>
<tr>
<td>SNNOM</td>
<td>Sine of noje nom</td>
</tr>
<tr>
<td>SNRASC</td>
<td>Sine of rasc</td>
</tr>
<tr>
<td>T</td>
<td>Julian date, epoch 1980, divided by 365.25</td>
</tr>
<tr>
<td>TPRIM</td>
<td>Besselian date</td>
</tr>
</tbody>
</table>

USED/COMM=--- INV NODEM
EQUATR Analysis

Subroutine EQUATR computes the coordinate transformation matrix A from geocentric equatorial to planetocentric equatorial coordinates. Matrix A is computed from

\[ A = A_1 A_2 \]  

(1)

where \( A_2 \) is the coordinate transformation matrix from geocentric equatorial to geocentric ecliptic coordinates and is given by

\[ A_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \end{bmatrix} \]  

(2)

where \( \theta \) 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

\[ A_1 = \begin{bmatrix} \hat{X} & \hat{Y} & \hat{Z} \end{bmatrix}^T \]  

(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

\[ \hat{Y} = \hat{Z} \times \hat{X}. \]  

(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

\[ \hat{Z} = \hat{P} \]  

(5)

and

\[ \hat{X} = \frac{\hat{P} \times \hat{N}}{|\hat{P} \times \hat{N}|} \]  

(6)
The unit vector \( \hat{N} \), referred to the ecliptic coordinate system, is given by

\[
\hat{N} = \begin{bmatrix}
\sin i \sin \Omega \\
-\sin i \cos \Omega \\
\cos i
\end{bmatrix}
\]  

(7)

where \( i \) and \( \Omega \) 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

\[
\hat{P} = \begin{bmatrix}
\cos \alpha \cos \delta \\
\cos \epsilon \sin \alpha \cos \delta + \sin \epsilon \sin \delta \\
-\sin \epsilon \sin \alpha \cos \delta + \cos \epsilon \sin \delta
\end{bmatrix}
\]  

(8)

where \( \alpha \) and \( \delta \) are the right ascension and declination, respectively, of the planet polar axis relative to the geocentric equatorial coordinate system, and \( \epsilon \) is the obliquity of the ecliptic. Expressions for \( \alpha \) and \( \delta \) for each planet were obtained from JPL TR 32-1306, Constants and Related Information for Astrodynamie Calculations, 1968, by Melbourne, et al.

The use of subroutine EQUATR is restricted to planets other than the earth and moon.
Compute the coordinate transformation matrix $A$

**Flow Chart**

1. **ENTER**
2. Call EPHEM to compute the orbital elements of the target planet
3. **Target planet = moon?**
   - **Yes**
   - **No**
4. Compute the obliquity of the ecliptic $\varepsilon$
5. Compute coordinate transformation matrix $A_2$
6. **Target planet = earth?**
   - **Yes**
   - **No**
7. Compute sine and cosine of inclination $i$ and node $\Omega$ of the target planet
8. Compute the right ascension $\alpha$ and declination $\delta$ of the target planet pole
9. Compute the coordinate transformation matrix $A_1$
10. Compute the coordinate transformation matrix $A$
11. **RETURN**
12. Earth and moon cannot be treated with EQUATR. Write error message
13. **EXIT**

**EQUATR-3**
SUBROUTINE FILTER

PURPOSE

PERFORMS COVARIANCE PROPAGATION AND KALMAN GAIN MATRIX CALCULATIONS PRIOR TO MEASUREMENTS AND OTHER EVENTS

SUBROUTINES CALLED: ADD ADPRO AOP200 ADPRDT COPY
                     JADPRT INVPSJ MULT MJLTT SUB SUBPRT
                     SYMTRZ TADPRT TNULT

COMMONS: TRAJ COVARP BM INTCOM

LOCAL SYMBOLS

I INDEX
J INDEX
WQ2 ESTIMATED DEVIATION FROM NOMINAL MEASUREMENT

USEB/COMMN: --- ELEMENTS FROM COMMON/COVARP/
             COMMON/INTCOM/

SET/COMMN: --- ELEMENTS FROM COMMON/COVARP/

ENTRY PNT: --- FILM FILTER PREM QUASI SIMM
FILTER Analysis

The augmented state deviation vector is defined as

\[ x^A = \begin{bmatrix} x \\ q \\ u \\ v \\ w \end{bmatrix} \]  \hspace{1cm} (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

\[ x^A_{k+1} = \Phi^A_{k+1,k} x^A_k + Q^A_{N_{k+1,k}} \]  \hspace{1cm} (2)

where the augmented state transition matrix, \( \Phi^A_{k+1,k} \), may be partitioned as

\[ \Phi^A = \begin{bmatrix} \phi & \psi & \theta & u & v & w \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \]  \hspace{1cm} (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...
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

$$y_k = H_{k}^{A} x_{k}^{A} + n_k$$

where the augmented measurement matrix may be partitioned as

$$H_{k}^{A} = [H M 0 L G]$$

and $n_k$ is the measurement noise.

The augmented state covariance matrix may be written in partitioned form as

$$P^A = \begin{bmatrix} P & C_{xq} & C_{xu} & C_{xv} & C_{xw} \\
T & Q & C_{qu} & C_{qv} & C_{qw} \\
T & C_{xq} & T_{qu} & D_u & 0 & 0 \\
T & C_{xv} & T_{qv} & 0 & D_v & 0 \\
T & C_{xw} & T_{qw} & 0 & 0 & D_w \end{bmatrix}$$

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

$$J_{k+1} = H^A_{k+1} P^A_{k+1} H^AT_{k+1} + R_{k+1}$$

$$= H_{k+1} \left\{ P_{k+1}^T H_{k+1}^T + C_{xq_{k+1}}^T M_{k+1}^T + C_{xv_{k+1}}^T L_{k+1}^T + C_{xw_{k+1}}^T G_{k+1}^T \right\}$$

$$+ M_{k+1} \left\{ C_{xq_{k+1}}^T H_{k+1}^T + Q_{k+1} L_{k+1}^T + C_{xv_{k+1}} Q_{k+1} L_{k+1}^T + C_{xw_{k+1}} G_{k+1} L_{k+1}^T \right\}$$

$$+ L_{k+1} \left\{ C_{xq_{k+1}}^T H_{k+1}^T + C_{xv_{k+1}} L_{k+1}^T + D_{L_{k+1}} L_{k+1}^T \right\}$$

$$+ G_{k+1} \left\{ C_{xq_{k+1}}^T H_{k+1}^T + C_{xv_{k+1}} H_{k+1}^T + D_{G_{k+1}} G_{k+1} L_{k+1}^T \right\} + R_{k+1} \right\} \quad (7)$$

The Kalman gain matrix

$$K^A_{k+1} = P^A_{k+1} H^AT_{k+1} (J_{k+1})^{-1} = \begin{bmatrix} K_{1{k+1}} \\ K_{2{k+1}} \\ K_{3{k+1}} \\ K_{4{k+1}} \\ K_{5{k+1}} \end{bmatrix}$$

$$K^A_{k+1} = \begin{bmatrix} K_{1{k+1}} \\ K_{2{k+1}} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

(8A)
Only the $K_{1k+1}$ and $K_{2k+1}$ partitions are used,

$$K_{1k+1} = \left\{ P_{k+1}^{-} H_{k+1}^{T} + C_{xq_{k+1}}^{-} M_{k+1}^{T} + C_{xv_{k+1}}^{-} L_{k+1}^{T} + C_{w_{k+1}}^{-} G_{k+1}^{T} \right\}^{-1} \left( J_{k+1} \right)$$ (9)

$$K_{2k+1} = \left\{ C_{xq_{k+1}}^{-T} H_{k+1}^{T} + Q_{k+1}^{-} M_{k+1}^{T} + C_{q_{k+1}}^{-} L_{k+1}^{T} + C_{qw_{k+1}}^{-} G_{k+1}^{T} \right\}^{-1} \left( J_{k+1} \right)$$ (10)

The partitions of the covariance update equation

$$P_{k+1}^{+} = P_{k+1}^{-} - K_{k+1}^{A} H_{k+1}^{A} P_{k+1}^{-}$$ (11)

are given by

$$P_{k+1}^{+} = P_{k+1}^{-} - K_{1k+1} \left\{ H_{k+1}^{+} P_{k+1}^{-} + M_{k+1}^{+} C_{xq_{k+1}}^{-T} + L_{k+1}^{+} C_{xv_{k+1}}^{-T} + C_{w_{k+1}}^{+} C_{xw_{k+1}}^{-T} \right\}$$ (12)

$$C_{xq_{k+1}}^{+} = C_{xq_{k+1}}^{-} - K_{1k+1} \Delta_{k+1}$$ (13)

$$C_{xu_{k+1}}^{+} = C_{xu_{k+1}}^{-} - K_{1k+1} \Gamma_{k+1}$$ (14)

$$C_{xv_{k+1}}^{+} = C_{xv_{k+1}}^{-} - K_{1k+1} \Omega_{k+1}$$ (15)

$$C_{wx_{k+1}}^{+} = C_{wx_{k+1}}^{-} - K_{1k+1} \Lambda_{k+1}$$ (16)

$$Q_{k+1}^{+} = Q_{k+1}^{-} - K_{2k+1} \Delta_{k+1}$$ (17)

$$C_{qu_{k+1}}^{+} = C_{qu_{k+1}}^{-} - K_{2k+1} \Gamma_{k+1}$$ (18)

$$C_{qv_{k+1}}^{+} = C_{qv_{k+1}}^{-} - K_{2k+1} \Omega_{k+1}$$ (19)

$$C_{qw_{k+1}}^{+} = C_{qw_{k+1}}^{-} - K_{2k+1} \Lambda_{k+1}$$ (20)
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

$$p^{A-}_{k+1} = p^A_{k+1, h} p^A_{k, h}$$

are given by

$$p^{A-}_{k+1} = \left\{ \phi \phi^T + \psi \psi^T + \theta_u \psi \psi^T + \theta_w \phi \phi^T \right\} + \psi \psi^T + \theta_u \theta_u^T + \theta_w \theta_w^T$$

$$c^{xq}_{k+1} = \phi \phi^T + \psi \psi^T + \theta_u \psi \psi^T + \theta_w \phi \phi^T$$

$$c^{xu}_{k+1} = \phi \phi^T + \psi \psi^T + \theta_u \psi \psi^T + \theta_w \phi \phi^T$$

$$c^{xv}_{k+1} = \phi \phi^T + \psi \psi^T + \theta_u \psi \psi^T + \theta_w \phi \phi^T$$

$$c^{xw}_{k+1} = \phi \phi^T + \psi \psi^T + \theta_u \psi \psi^T + \theta_w \phi \phi^T$$
Since all solve-for and consider parameter deviations are assumed to be constant between measurements, the following relations are used

\[ Q_{k+1}^- = Q_k^+ \quad (31) \]

\[ C_{qu_k+1}^- = C_{qu_k}^+ \quad (32) \]

\[ C_{qv_k+1}^- = C_{qv_k}^+ \quad (33) \]

\[ C_{qw_k+1}^- = C_{qw_k}^+ \quad (34) \]

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

\[ \hat{x}_{k+1}^- = \hat{x}_{k}^+ + \psi_q^+ \quad (35) \]

At entry point SIMM, the following computations are made. First the measurement residual is computed as

\[ \varepsilon_{k+1} = y_{k+1}^a \quad \left\{ y_{k+1} - H_{k+1} \hat{x}_{k+1}^- + M_{k+1} q_{k+1}^- \right\} \]

Then the partition of the estimated state update equation

\[ \hat{x}_{k+1}^{A+} = \hat{x}_{k+1}^{A-} + K_{k+1} \varepsilon_{k+1} \]

where

\[ K_{k+1} = \begin{bmatrix} K1 \\ K2 \\ 0 \\ 0 \end{bmatrix} \]

\[ K_{Am} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \]
FILTER-7

is given by

\begin{align*}
\hat{x}^+_{k+1} &= \hat{x}^-_{k+1} + K_1 e_{k+1} \\
\hat{q}^+_{k+1} &= \hat{q}^-_{k+1} + K_2 e_{k+1}
\end{align*}

At entry point QUASI, the computations associated with a quasi-linear filtering event are made

\begin{align*}
\hat{x}^+ &= \hat{x}^- + \hat{x}^- \\
\hat{q}^+ &= \hat{q}^- + \hat{q}^- \\
\hat{x}^+ &= 0 \\
\hat{q}^+ &= 0
\end{align*}

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

ENTRY FILM

\[ j_{k+1}^a = H_{k+1} j_k^a + A_{k+1} - n_{k+1} \]
\[ p_{k+1}^a = P_k^a H_k (j_k^a)^{-1} \]
\[ p_{k+1}^a = P_k^a - H_{k+1} j_{k+1}^a + A_{k+1} \]

RETURN

ENTRY PREM

\[ p_{k+1}^a = p_{k+1}^a \]
\[ p_{k+1}^a = p_{k+1}^a \]

RETURN

ENTRY SIMM

\[ x_{k+1}^a = x_{k+1}^a + H_{k+1} j_{k+1}^a \]
\[ x_{k+1}^a = x_{k+1}^a - x_{k+1}^a \]
\[ x_{k+1}^a = x_{k+1}^a + x_{k+1}^a \]

RETURN

ENTRY QUASI

\[ \delta^a = \delta^a + \delta^a \]
\[ \delta^a = \delta^a + \delta^a \]
\[ \delta^a = 0 \]
\[ \delta^a = 0 \]

RETURN

FILTER-8
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
Subroutine GEØG 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 Astrodynamics 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

\[
\vec{x}_{\text{geographical}} = A \vec{x}_{\text{equatorial}}.
\]

GEØG Flow Chart

1. ENTER
2. Convert Julian date, epoch 1900, to Julian date, epoch 4713 BC
3. Compute the known angle V of the vernal equinox for the specified planet
4. Reduce V to modulo 360
5. Compute coordinate transformation matrix A
6. RETURN
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

\[ \omega = \text{Earth's rotation rate (deg/day)} \]
\[ d = \text{integer part of } T^* \]
\[ t = \text{fractional part of } T^* \]

and

\[ T^* = \text{Julian date, epoch 1950 January 1}^d 0^h. \]

The Julian dates relative to epochs 1900 and 1950 are related as follows:

\[ T^* = JD + 2415020.0 - 2433282.5 \]

where

\[ 2415020.0 = 1900 \text{ January 0}^d 12^h \text{ referenced to 4713 BC January 0}^d 12^h \]

and

\[ 2433282.5 = 1950 \text{ January 1}^d 0^h \text{ referenced to 4713 BC January 0}^d 12^h \]
SUBROUTINE HMM

PURPOSE: CONTROLS COMPUTATION OF OBSERVATION MATRIX PARTITIONS

SUBROUTINES CALLED: JACORN

COMMONS: TRAJ, COVARP, INTCOM

LOCAL SYMBOLS: ORSM

EXTERNAL VARIABLE NAME USED BY JACORN FOR COMPUTATION OF MEASUREMENT VALUES

USED/COMMON--- C

LISTQ

LISTS

LISTV

LISTW

LM

HN

LO

DU

DV

DW

GM

HM

LIST

LISTS

LISTV

LISTW

LM

HN

LO

C

0

N

S

V

W

P
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 JACORN. 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

\[
y = \begin{bmatrix} H & M & O & L & G \end{bmatrix} \begin{bmatrix} x \\ q \\ u \\ v \\ w \end{bmatrix}.
\]
SUBROUTINE INVPO?

PURPOSE: INVERTS A POSITIVE DEFINITE SYMMETRIC MATRIX

ENTRY PARAMETERS:
- A: A WORKING MATRIX (N X N)
- J: 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 $1$s on the diagonal, $D$ is diagonal, and

$$S = LD L^T$$

$L$ and $D$ may be found recursively from the relations

$$d_j = s_{jj} - \sum_{k=1}^{j-1} d_k k_{jk}^2$$

$$k_{ij} = \frac{\sum_{k=1}^{j-1} d_k k_{ik} k_{jk}}{d_j}, \quad i > j$$

The inverse of $S$ is then given by

$$S^{-1} = (L^T)^{-1} D^{-1} L^{-1}$$
Compute the $L$ and $D$ matrices recursively

Invert $L$

Compute

\[ S^{-1} = (L^T)^{-1} P^{-1} L^{-1} \]

RETURN
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
RECET RECIPROCAL OF THE DETERMINANT OF X
SUBROUTINE JACOB

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
JACOB Analysis

JACOB 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 COVAR.
SUBROUTINE LTRCON

PURPOSE: EXECUTIVE CONTROL FOR RECONSTRUCTOR

SUBROUTINES CALLED: COPY, DYNOIZ, MEASUR, NEXTAA, NEXTIM
                   NTM, NTM2, PDUMP, PREDIC, PREM, PRINT
                   QUASI, READAC, RESTRT, SETION, 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
ZA00 CHANGE IN Z VECTOR OVER THE INTERVAL

USED/COMMON: AA IEND LTR1 LTR2 TC TDIFF
              TENV3 TYPE
              SET/COMMON: AA TC TIMEF
LTCRN Analysis

Subroutine LTCRN 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.

LTCRN Flow Chart

1. ENTER
2. Call SETUP to perform all required initialization and to read input data cards
3. Save Mach number at the beginning of the interval in RMACHB
4. Call NEXTIM to determine the time of the next event and the time interval TDIFF
5. Call READAC to obtain the actual measurement at the current time
6. If TDIFF < 0.001, go to block 21. Otherwise, go to block 20.
7. Call NEXTAA to obtain the smoothed acceleration and gyro coefficients required to cover the time interval TDIFF

20

21

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 JA of smoothed accelerometer and gyro coefficients in preparation for next cycle through LTRCØN

Reset current time TC to time TEND at end of current time interval
Call DYNØIZ 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

Call MEAZUR if a measurement is to be processed

Call PREDIC if a prediction event is to be executed

Call QUASI if a quasi event is to be executed

Call SETICN if a set iteration counter event is to be executed

Call PRINT to write out appropriate information

Has vehicle either hit ground or reached final time?

Call PDUMP and set final time TIMEF to current time TC

RETURN
SUBROUTINE MAIN

PURPOSE: CONTROLS OVERALL PROGRAM FLOW FOR DATA GENERATION, PREPROCESSING, TRAJECTORY RECONSTRUCTION, AND SUMMARY OUTPUT

SUBROUTINES CALLED: EXIT, TIMEX
COMMINS: A'REDY, Dopler, INTCOM, LOGCOM
USED/COMM: LTR1, LTR2, RUNNO
SET/COMMON: GENDAT, NTP, OMEGAE, REARTH, RESTRT
READ: RUNNO
RUNN\$ controls program flow. If RUNN\$ = 1, the data generator and preprocessor are executed and control goes to statement 10, where another value of RUNN\$ is read. If RUNN\$ = 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 RUNN\$ = 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
MATOUT 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 $\text{NEND} \geq \text{N}$. 
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 N X N, N, OR N X M
Z - OUTPUT MATRIX OF DIMENSION L X N

SUBROUTINES CALLED: ADD DMULT MULTI MULTO MULTT
SUB TMULT

COMMONS: COVARP

LOCAL SYMBOLS: NONE

ENTRY PHT --- ADPRO ADPROD ADPRT DADPRT MATRIX SUBPRT TADPRT

USED/COMM: --- WORK
SUBROUTINE MEAZUR

PURPOSE: PROCESSES MEASUREMENTS THROUGH THE FILTER EQUATIONS

SUBROUTINES CALLED: ATTACK, FILM, HMM, ORSN, SIMM

COMMONS: IA, INTCOM, TRAJ, SMD

LOCAL SYMBOLS: TMLAST, TRAJECTORY TIME OF LAST MEASUREMENT
XX, DUMMY CALL ARGUMENT

USED/COMMON--- ALPHA, IPRINT, MCNTR, MEZACT, NMEAS
THN, TYPE, AA

SET/COMMON--- IPRINT, MEZACT, NMEAS

LOADED --- TMLAST

288
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

ENTER

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

RETURN
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 MULTO

PURPOSE I 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 MULT

PURPOSE: TO MULTIPLY ONE RECTANGULAR MATRIX BY THE TRANSPOSE OF ANOTHER MATRIX AND STORE INTO A THIRD MATRIX

ENTRY PARAMETERS

NGX  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: NO MO 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

USEB/COMMON--- DT  IEND  TC  TDIFF
READ  --- AA  TIME
SET/COMMON--- IAA  IEND  TENO
NEXTAA Analysis

Subroutine NEXTAA reads from file la the smoothed accelerometer and gyro coefficients (as determined by subroutine PREPR0S) 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:
- HALT: Dummy argument used to call ALTFILE
- MCTRL, MCODE, TC, TDIFF, TEND, TMN
- IPHAS, QSDT, QST, TD, TR, VOIA
- VMASS, VR1, VSA

READ --- MCODE, TMN

SET/COMMON--- MCTRL, TC, TDIFF, TEND, TYPE
- DI, QIA, 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 NORMZ

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
NORMNZ Analysis

NORMNZ 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

\[ RR = X \text{ modulo (integer portion of } X) \]

so that RR is normally distributed over (0,1). Finally,

\[ SIGMA = \left( \sum_{i=1}^{12} RR \right) - 6. \]
SUBROUTINE NTM

PURPOSE: CONTROLS INTEGRATION OF MOST RECENT NOMINAL STATE VECTOR FROM TIME TC TO TIME TEND

ENTRY PARAMETERS
  UPDAT — 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  LOGM03

LOCAL SYMBOLS:
  XXX — DUMMY CALL ARGUMENT

USED/COMMON:
  LTR1  QSMCHG  RMACH9  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

```
ENTER

Set Mach number equal to the value at the end of the previous nominal trajectory propagation

Copy XN, the state at TC, into XNEW

Mode A

Call RKUT3 to propagate the nominal state forward to TEND

If quasi-static model is being used, call DERIVE to update all state derivatives at TEND

RETURN

Mode B

Call ATMSET to update all atmosphere parameters

Call RKUTL3 to propagate the nominal state forward to TEND

If quasi-static model is being used, call DERIV3 to update all state derivatives at TEND

RETURN
```
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:
   XADO: DIFFERENCE IN STATE VECTOR OVER THE INTERVAL
   XXX: DUMMY CALL ARGUMENT

USED/COMMON:
   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 EPHEN

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
COSOBI COSINE OF OBLIC
DELTA HALF THE ANGLAR DISTANCE(RELATIVE TO PLANET CENTER)
DEL1 PERTURBED MISALIGNMENT ANGLE
DEL2 PERTURRED MISALIGNMENT ANGLE
DEL3 PERTURRED MISALIGNMENT ANGLE
DJUL JULIAN DATE AT TIME TC
GANP LONGITUDE OF DSN STATION AT TIME TC
HESE HELIOCENTRIC ECLIPTIC STATE OF EARTH
OBSM—B

HELIiocentric elliptic 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
SINC SINE OF GAN
SINA SINE OF ALON
SINOB SINE OF OBLIC
STEP ANGULAR STEPSIZE EMPLOYED IN DIRECT SEARCH MINIMIZATION PROCESS
TM NUMBER OF SECONDS PER DAY
UPDAIT DUMMY CALL ARGUMENT
WW 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/COMMON--- ACC ACCOT ACCT AF AGAM ALPH
AQUANT BTLB C CACOR DATEJ DELT
DP DXN EPSM ETA GHATO GQUANT
GYROD LTR1 LTR2 MACH MASS MASSA
MCNTR MCODE OBLIC OMEGAE PRES RANGE
RANGER REARTH REJJRR REJRR2 RHO RI
RM RMACHB ROTNO RR SA SALT
SGPEC SLAT SLOH TC TEMP TERMT
TZERO VR XG XM XN XP
ZG ZMM ZN

SET/COMMON--- ACC ACCT MACH MASSA NM R
RANGE RANGER

FCT CALLED--- FF TAR
FCT DFND --- FF
Subroutine OBSM 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 OBSM is very similar to the computation of actual measurements in OBSM1. 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 OBSM1 and will not be discussed further (see subroutine OBSM1 for details).

The C_j in subroutine OBSM1 represent actual errors. In OBSM, however, the C_j represent both nominal and perturbed values of the errors. The C_j are perturbed only when OBSM is being used in the numerical differencing computation of observation matrix partitions.

If a measurement is being processed, OBSM 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 OBSM differs from their treatment in OBSM1. 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 OBSM. The following equations are used in OBSM to compute the accelerometer measurements for mode B:
\[ a_x = \left( \frac{A}{m + C_{30}} \right) \cos (\delta_1 + C_{55}) - \left( \frac{N}{m + C_{30}} \right) \sin (\delta_1 + C_{55}) \right] C_{51} + C_{52} \]

\[ a_z = \left( \frac{A}{m + C_{30}} \right) \sin (\delta_2 + C_{56}) + \left( \frac{N}{m + C_{30}} \right) \cos (\delta_2 + C_{56}) \right] C_{53} + C_{54} \]

where \( A \) and \( N \) are the axial and normal aerodynamic forces (including effect of parachute), \( \delta_1 \) and \( \delta_2 \) 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 \( \alpha \) 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 ORSMI**

**PURPOSE**: Compute measurements for data generator

**COMMONS**

- **T**, **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**: Index of range, range-rate measurement
- **MINALT**: Minimum distance between vehicle and planet terrain
- **SING**: Sine of gang
SINLAT  SINE OF ALAT
SINDB  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/COMMON--- AGAM AX AY C CARCOR CJELT1
       CJELT2 CJELT3 DATEJ DP DXN EPSM
       ETA GHAT0 MACH OBLIC OMEGAE PRES
       RANGE RANGER REARTH RH0 RM ROTNO
       SALT SCPEC SDELT1 SDELT2 SLAT SLON
       TC TEPH TEPHT TZERO VR XG
       XM XN XG ZG ZHN

SET/COMMON--- MEASS RANGE RANGER

FCT CALLED--- F TAB
FCT DFND --- F
OBSM1 Analysis

Subroutine OBSM1 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 OBSM1 are the quantized VRU and ARU measurements, which are computed in subroutine SENSÖR. The equations used to compute the actual measurements in OBSM1 are summarized below.

If the terrain height model is not used, the radar altimeter measurement is given by

\[ h = C_{71} h + C_{72} \] (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 \( 2\pi \). The altimeter measurement is computed from

\[ \tilde{h} = C_{71} \left[ \left( h + R_{p}^{2} \right) + \tilde{f} \right]^{\frac{1}{2}} + C_{72} \] (2)

where \( \tilde{f} \) is the minimum value of

\[ f = W^{2} - 2W \left( h + R_{p} \right) \cos (\tilde{\phi} - \phi) \] (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

\[ \dot{v}_{x} = a_{x} \cos \delta_{1} - a_{z} \sin \delta_{1} \] (4)

\[ \dot{v}_{z} = a_{x} \sin \delta_{2} + a_{z} \cos \delta_{2} \] (5)

and

\[ \dot{\omega} = \omega \cos \delta_{3} \] (6)

310
where \( \delta_1, \delta_2, \) and \( \delta_3 \) are the axial accelerometer, normal accelerometer, and rate gyro misalignment angles, respectively, \( \omega \) 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

\[
a_x = a_xg - \omega^2 \bar{x} + \dot{\omega} \bar{z} \\
a_z = a_zg - \omega^2 \bar{z} + \dot{\omega} \bar{x}
\]  

(7) \hspace{1cm} (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

\[
p_o = C_{81} \left[ \frac{1}{2} C_p \frac{\rho}{\rho_r} \frac{v^2}{r} + p \right] + C_{82}
\]  

(9)

where \( \rho \) is the density, \( p \) is the ambient pressure, and the coefficient of pressure \( C_p \) is given by

\[
C_p = 2 - \varepsilon
\]  

(10)

where \( \varepsilon \) 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

\[
C_p = \frac{p}{8} \left[ \frac{\gamma + 1}{2} M^2 \right]^{\frac{\gamma}{\gamma - 1}} \left( \frac{\gamma + 1}{2 \gamma M^2 - \gamma + 1} \right)^{\frac{1}{\gamma - 1}} - 1
\]  

(11)

where \( \gamma \) is the ratio of specific heats. If \( M < 1 \), then

\[
p_o = C_{83} \left[ p \left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{\gamma}{\gamma - 1}} \right] + C_{84}
\]  

(12)

where \( C_{83} \) and \( C_{84} \) are the subsonic scale factor and bias errors, respectively.
The stagnation temperature measurement is computed from

\[
T_o = C_{g1} \left[ T \left( 1 + \frac{\gamma - 1}{2} \frac{M^2}{T} \right) \right] + C_{g2}
\]

(13)

where \( T \) is the ambient temperature and \( C_{g1} \) and \( C_{g2} \) are the scale factor and bias errors, respectively.

Range and range-rate measurements are given by

\[
\rho = \| \dot{\rho} \| \quad \text{and} \quad \rho = \frac{\rho \cdot \dot{\rho}}{\| \rho \|}
\]

(14)

(15)

respectively, where

\[
\dot{\rho} = \dot{r} + \dot{r}_p - \dot{r}_p - \dot{r}_s
\]

(16)

\[
\rho = r + r_p - r_p - r_s
\]

(17)

\((\dot{r}, \ddot{r})\) = vehicle state relative to target planet

\((\dot{r}_p, \ddot{r}_p)\) = target planet state relative to Sun

\((\dot{r}_e, \ddot{r}_e)\) = Earth state relative to Sun

\((\dot{r}_s, \ddot{r}_s)\) = 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

\[
x_s = (R_o + h_i) \cos \theta_i \cos G_i
\]

(18)

\[
y_s = (R_o + h_i) \left[ \cos \theta_i \cos \epsilon \sin G_i + \sin \theta_i \sin \epsilon \right]
\]

(19)

\[
z_s = (R_o + h_i) \left[ -\cos \theta_i \sin \epsilon \sin G_i + \sin \theta_i \cos \epsilon \right]
\]

(20)

\[
\dot{x}_s = -\omega_e (R_o + h_i) \cos \theta_i \sin G_i
\]

(21)
\[
\begin{align*}
\dot{y}_s &= \omega_z \left( R_o + h_i \right) \cos \theta_i \cos \epsilon \cos G_i^r \\
\dot{z}_s &= -\omega_z \left( R_o + h_i \right) \cos \theta_i \sin \epsilon \cos G_i^r
\end{align*}
\]

where
\[
\begin{align*}
h_i^r &= h_i + C_{108+3i} \\
\theta_i^r &= \theta_i + C_{109+3i} \\
G_i^r &= \lambda_i^r + \omega_z \left( t - t_o \right) + \text{GHA} \left( t_o \right) \\
\lambda_i^r &= \lambda_i + C_{110+3i}
\end{align*}
\]

In these equations \( R_o \) denotes the Earth radius; \( h_i \), the altitude of the \( i \)-th station; \( \theta_i \), the latitude; \( \lambda_i \), the longitude; \( \omega_z \), the Earth's angular velocity; \( t \), the current time; \( t_o \), the initial time; \( \text{GHA} \left( t_o \right) \), the initial Greenwich hour angle of the vernal equinox; \( \epsilon \), the obliquity of the ecliptic; and \( C_{108+3i} \), \( C_{109+3i} \), \( C_{110+3i} \), station location errors. A range bias \( C_{63+1} \) is added to the range computed using equation (14), and a range-rate bias \( C_{66+1} \) is added to the range-rate computed using equation (15).

**OBSM1 Flow Chart**

1. **Enter**
2. Compute the radar altimeter measurement assuming no terrain height model
3. Is terrain height model to be used?
   - **Yes**
     - Compute the minimum distance between the vehicle and the terrain within the radar altimeter sweep angle
   - **No**
313
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 \( h, v, \gamma, \phi, \Omega_\epsilon, \epsilon \) 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

OPP 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/COMMON--- ALPH NQ TYPE

OPP NS

DYN NU

LISTQ NW

LISTU PRES

LISTW RAD

WRITTEN --- AF ALPHO EPS EPS

GA GA F

CMQ LF CN MACH

CN OP NP DPP

MWT NWT XP

ZN ZN RHO TEMP VV

VR VN 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 $T_0$, the following matrix partitions are printed:

1) State transition matrix $\Phi$;
2) Solve-for parameter matrix $\Psi$;
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, CORRJ, MATOUT

COMMONS: COVARP, INTCOM, LOGCOM, TRAJ, PRINTS

LOCAL SYMBOLS:
- I: INDEX
- J: INDEX
- NS1: NUMBER OF STATE VARIABLES SQUARED
- NS2: NUMBER OF STATE VARIABLES PLUS 1

USED/COMMON:
- DU, NV, DW, DYN, LTR2
- NO, NS, NU, NV, NW, PP
- QQ, RAD, SQDU, SQDV, SQDW

WRITTEN:
- JVN

SET/COMMON:
- PP, PPD, QD
SUBROUTINE PLANE

PURPOSE:
COMPUTE THE ORIENTATION OF THE ENTRY PLANE RELATIVE TO SPECIFIED REFERENCE PLANES

ENTRY PARAMETERS:
- 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)
- FRSS: SUB-SOLAR UNIT VECTOR ALIGNED WITH PHIR(3)
- GEQPEQ: TRANSFORMATION FROM GEOCENTRIC-EQUATORIAL TO PLANETO-CENTRIC-EQUATORIAL
- I: INDEX
- J: INDEX
- K: INDEX
- PECSSO: TRANSFORMATION FROM PLANETO-CENTRIC-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 INTERMEJIATE SUM
TEMPOR TEMPORARY TRANSFORMATION MATRIX

USED/COMM-- ECLINC ECOLONG OMEG PHIR
SET/COMMON-- ECLINC ECOLONG PHIR ROTNO
PLANE Analysis

Given the orientation of the entry plane and the $\phi$ reference line relative to one of three coordinate systems, subroutine PLANE computes the orientation of the entry plane and the $\phi$ 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 $\Omega$, and the location of the $\phi$ reference line in the entry plane is defined by $\phi_{\text{ref}}$ (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 $i$, $\Omega$, and $\phi_{\text{ref}}$ relative to one of the three coordinate systems, the unit vector $\mathbf{e}_n$ normal to the entry plane and the unit vector $\mathbf{e}_r$ aligned with the $\phi$ reference line can be computed from

$$
\mathbf{e}_n = \begin{bmatrix}
\sin i \sin \Omega \\
-\sin i \cos \Omega \\
\cos i
\end{bmatrix}
$$

$$
\mathbf{e}_r = \begin{bmatrix}
\cos \phi_{\text{ref}} \cos \Omega - \sin \phi_{\text{ref}} \cos i \cos \Omega \\
\cos \phi_{\text{ref}} \sin \Omega + \sin \phi_{\text{ref}} \cos i \cos \Omega \\
\sin \phi_{\text{ref}} \sin i
\end{bmatrix}
$$

The coordinate transformations from the given coordinate system to the remaining two coordinate systems are then computed, and $\mathbf{e}_n$ and $\mathbf{e}_r$ are transformed to these systems.

Denoting the components of the transformed $\mathbf{e}_n$ and $\mathbf{e}_r$ as

$$
\mathbf{e}_n = (e_{n_x}, e_{n_y}, e_{n_z})
$$

$$
\mathbf{e}_r = (e_{r_x}, e_{r_y}, e_{r_z})
$$
the angles \(i', \Omega', \) and \(\phi'_{\text{ref}}\) defining the entry plane and \(\phi\) reference line relative to the new coordinate system can be computed as follows:

\[
\Omega' = \tan^{-1}\left(\frac{e_{nx}}{-e_{ny}}\right)
\]

\[
i' = \cos^{-1}\left(e_{nz}\right)
\]

\[
\phi'_{\text{ref}} = \tan^{-1}\left(\frac{\sin \phi'_{\text{ref}}}{\cos \phi'_{\text{ref}}}\right)
\]

where

\[
\sin \phi'_{\text{ref}} = \frac{e_{rz}}{\sin i'}
\]

\[
\cos \phi'_{\text{ref}} = \left[\frac{\hat{e}_z \times \hat{e}_n}{|\hat{e}_z \times \hat{e}_n|}\right] \cdot \hat{e}_r
\]

and \(\hat{e}_z\) 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 \(\omega_p\) denote the inertial angular velocity of the planet and \(\omega_n\), the component normal to the entry plane, we can compute \(\omega_n\) as follows:

\[
\omega_n = \omega_p \cdot \hat{e}_o \cdot \hat{e}_n
\]

where \(\hat{e}_o = (0,0,1)\) is a unit vector aligned with the planet spin axis and \(\hat{e}_n\) 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/COMMON--- 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 JERIVE
                      DERIV3 MATOUT OUTPHI OUTPP PSTORE

COMMONS I ACT
            PRINTS TRAJ AX BY PRNT3
            COVARP GY PRE SJMRY OBSERV AM
            GYRACC LOGMOD LOGCON INTCON

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
AESDLB 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 ORIGINAL 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
JPP 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)
| Print-B |

**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

**IMPACT**
- 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

**USE/EQUAL---**

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**LOADED ---**

| LABEL | L1 | L2 | L3 | L4 | L5 |

327
SURROUTINE PRINT1

PURPOSE: PRINT OUTPUT FROM THE DATA GENERATOR

SURROUTINES CALLED: COPY

COMMONS: TRAJ, SUMP, DOPLER, PHASE

LOCAL SYMBOLS:

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328
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/km³);
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/s²);
14) Moment (kg/km/s²);
15) Normal force (kg-km/s²);
16) Gravitational acceleration (km/s²);
17) Center of pressure (km);
18) Axial acceleration (km/s²);
19) Moment acceleration (km/s²);
20) Normal acceleration (km/s²);
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, INVPO2, MJLIT, SMOOT2, TMULT

COMMONS: SMO, TRAJ, LOGCOM, INTCOM, LOGM03, 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

USEB/COMMON: B JT N QSDT QSMCHG OST
READ --- THTQ TYME VXQ VZQ
SET/COMMON: B DT LASTYM QSMCHG TC
PRPROS Analysis

Subroutine PRPROS is the executive preprocessor subroutine and controls computation of the coefficients used to smooth quantized VRU and ARU data. The operation of PRPROS is more easily described by including a description of the operation of SMOOT2.

As quantized VRU and ARU data are input into PRPROS, the quantized data arrays are shifted up and the new data are inserted in the bottom of each array (in SMOOT2) 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:

\[
\begin{bmatrix}
C_1 \\
C_2 \\
C_3
\end{bmatrix}
= E \cdot \begin{bmatrix}
q_{k-2} \\
\vdots \\
q_{k+2}
\end{bmatrix}
\]

where

\[
E = (B^T B)^{-1} B
\]

\[
B = \begin{bmatrix}
1 & -2\Delta & 4\Delta^2 \\
1 & -\Delta & 2\Delta^2 \\
1 & 0 & 0 \\
1 & \Delta & 2\Delta^2 \\
1 & 2\Delta & 4\Delta^2
\end{bmatrix}
\]

\[\Delta = t_k - t_{k-1}\]

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 PRPRØS 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 SMOOTH2 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 SMOOT2

Read quantized VRU and ARU data

EOF?

Yes

No

Call SMOOT2 to compute coefficients of smoothing quadratic

Set LASTYM true. Call SMOOT2 twice in succession to obtain final set of smoothing quadratic coefficients

Time to change to quasi-static model?

Yes

Set step size to quasi-static step size. Set QSMCHG true

No

RETURN
SUBROUTINE PSTORE

PURPOSE: STORES TRAJECTORY PLOTTING INFORMATION ON LOGICAL DISK FILES

SUBROUTINES CALLED: ALTFILE (MARTIN-CDC SYSTEMS ROUTINE FOR BUFFERS)

COMMONS: ACT, SUMRY, PRINTS, AX, TRAJ, PRNT3, COVARP, 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
- MRNEJ: 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
- QMRNEO: 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/COMM: AEDEN, AEESLV, AESTT, AEETMP, C, DENS
- DENS5M: EDNC, JM, LISTQ
- ME5: HMT, MMTA, NN, NQ, NS
- PLOT: PP0, PPX3, QE3N, QQ3, RAO
- RNO: SODENS, SOTEMP, TEMOBM, TEMOBN, TEMEDN
- TEM: TEMPA, TYPE, XN, XNAC, XNC

WRITTEN: ACDLXG, ACCLXG, ACDEN, AEEDEN, AEESLV, AESTT, AEETHP
- ALFMES: ALPHAA, AXC, AZC, EDNBMC, EDNC
- H: QMPNEO, QMGCC, PP0, PPDBM
- QC: QEDBNM, QMRNEO, RATIOA, RATIOQ, RATIOS
- RESI: SODENS, SDEN4H, S3TEMP, STEM4, TC
- TN2TRC: XNAC, XNC

334
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 MEASUREMENTS FROM UNIT 10 AND PERTURBS WITH RANDOM NOISE, SCALE, AND BIAS FACTORS

SUBROUTINES CALLED: EXIT, POUMP, RNUM

COMMONS: ACT, OBSERV, TRAJ, PRE

LOCAL SYMBOLS:
  I  INDEX
  ICODE  TYPE OF MEASUREMENT BEING PROCESSED
  J  INDEX
  N  NUMBER OF MEASUREMENT NOISE COMPONENTS

USE/COMMON--- BF  MCNTM  MCODE  MEZNOZ  SF  TAPETH
  TEND  MEASS

READ--- ACCLZC  ACCLZC  MEASS  MNTA  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 MEZNØZ.
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 I 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
   UPDAIL LOGICAL (NOT CURRENTLY USED)
   W      INTERMEDIATE WORKING ARRAY
   XC     INTERMEDIATE WORKING ARRAY

USED COMMONS C DT DXN NE OMEG ROTNO

SET COMMONS HITGND

FCT CALLED: F

FCT DFDN: F

LOADED: FRSTIM

338
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:

\[
\begin{align*}
    k_1 &= h f(x_k, t_k) \\
    k_2 &= h f(x_k + \frac{h}{2} k_1, t_k + \frac{h}{2}) \\
    k_3 &= h f(x_k + \frac{h}{2} k_2, t_k + \frac{h}{2}) \\
    k_4 &= h f(x_k + k_3, t_k + h) \\
    x_{k+1}^* &= x_k + \frac{1}{6} (k_1 + 2k_2 + 2k_3 + k_4)
\end{align*}
\]

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:

\[
\begin{align*}
    x_1^* &= k_1 \\
    k_1 &= h f(x_{k+1}^*, t_{k+1}) \\
    k_2 &= 3.6 k_1 - 4.2 (x_{k+1}^* - x_k) + 1.6 x_1^* \\
    k_3 &= h f(x_{k+1}^* + \frac{h}{2} k_1 + \frac{h}{2} k_2, t_{k+1} + \frac{h}{2})
\end{align*}
\]
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.

SUBROUTINE RKUTL3

PURPOSE: INTEGRATOR FOR MODE 8 RECONSTRUCTOR

ENTRY PARAMETERS
TEND: FINAL TIME OF INTEGRATION
TSTART: STARTING TIME OF INTEGRATION
UPDATAIT: 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: 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/COMMON--- 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
UPDATT 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: JERIVE

COMMONS: TRAJ LOGCOM INTCOM

LOCAL SYMBOLS

N 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/COMMONS: 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

\[ XADD = x_{k+1} - x_k \]

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/COMMON--- SJ
SET/COMMON--- HZNOZ
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
NOU 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--- CQJ CQV CQW CKJ CXU CXV
CXW CW DS DV DW EP EQ EQDN
NU NV NW P Q QEDN

WRITTEN --- E3V TO XNAC XNC XOC P
O CXO CXU CXV CXW CQO
CQV COV DU DV DW QEDN

346
SUBROUTINE SCHEO

PURPOSE: SEQUENTIAL SCHEDULING OF MEASUREMENTS AND EVENTS FOR THE RECONSTRUCTOR

SUBROUTINES CALLED: ALTFILE EXIT

COMMONS I 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
NPRED - 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
<table>
<thead>
<tr>
<th>USEB/COMMN</th>
<th>DT</th>
<th>MCODE</th>
<th>TC</th>
<th>TR</th>
<th>QST</th>
<th>TF</th>
<th>TMN</th>
</tr>
</thead>
<tbody>
<tr>
<td>READ</td>
<td>COJE</td>
<td>TIMEND</td>
<td>MCODE</td>
<td>START</td>
<td>TIMDIF</td>
<td>TMN</td>
<td></td>
</tr>
<tr>
<td>WRITTEN</td>
<td>COJE</td>
<td>TIMEND</td>
<td>MCODE</td>
<td>NEVENT</td>
<td>START</td>
<td>TIMDIF</td>
<td></td>
</tr>
<tr>
<td>SET/COMMON</td>
<td>LICNTR</td>
<td>MCODE</td>
<td>NPREO</td>
<td>PREDND</td>
<td>TMN</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SCHED Analysis

SCHED reads and sequences measurements and other events for use by the reconstructor. START, TIMEND, TIMDIF, and CODE(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 CODE(N) and written with identifiers. Groups of 250 measurements and events are then ordered on time, with TNN and MODE used as storage. TMN and MODE 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.
If \( I_{START} \) (low) > \( I_{END} \) (low), set \( I_{START} \) (low) = 1.0E+10

When \( K = 250 \), write \( TMN \), \( MCODE \) arrays. Set \( LASTT = TMN(K) \) and go to 60

When \( K = 250 \), write \( TMN \), \( MCODE \) arrays. Set \( LASTT = TMN(K) \) and go to 60

Set \( I_{START} \) (low) = 1.0E+10

Select lowest time in \( IST^T \) array and set \( TMN(K) \) and \( MCODE(K) \)

Set type 17 events for parachute and QUASI-STATIC models

Write measurement and event schedules

Read and write measurement and event cards

Set \( TMN(K) \) - \( LASTT < 1.0 + DT \)

Select lowest time in \( IST^T \) array and set \( TMN(K) \) and \( MCODE(K) \)

When \( K = 250 \), write \( TMN \), \( MCODE \) arrays. Set \( LASTT = TMN(K) \) and go to 60

If \( IST^T \) (low) > \( I_{END} \) (low), set \( IST^T \) (low) = 1.0E+10

Increment \( TMN \) and \( NEVENT(J) \) and \( MCODE \) values

Check for type 13 EVENTS, increment \( IST^T \) (low)

Write final array of \( TMN \) and \( MCODE \) values

RETURN
SUBROUTINE SENSOR

PURPOSE: COMPUTES THE QUANTIZED OUTPUT OF ACCELEROMETER AND GYRO SENSORS

SUBROUTINES CALLED: ALTFILE

COMMONS: TRAJ, SNQ, SIZE, DOPPLER

LOCAL SYMBOLS: NALT, DUMMY ARGUMENT

USED/COLMN: C, XSTEP, TC, TSTEP, TZERO, XN

WRITTEN: TC, THTQ, VXQ, VZQ

SET/COLMN: THTQ, VXQ, VZQ
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, \( \Delta \). 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, \( \lfloor \cdot \rfloor \).

The quantized accelerometer outputs are given by

\[
V_{xq} = \left\lfloor \frac{C_s x V_x + C_b x}{\Delta x} \right\rfloor \Delta x
\]

\[
V_{zq} = \left\lfloor \frac{C_s z V_z + C_b z}{\Delta z} \right\rfloor \Delta z
\]

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,

\[
A_{\theta q} = \left\lfloor \frac{C_{s \theta} A_\theta + C_{b \theta} t}{\Delta \theta} \right\rfloor \Delta \theta
\]

where \( A_\theta \) 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--- NO:

READ: --- INDEP LINEAR LOG NVAR PLOTL PLTVAR
SUMTB

SET/COMMN--- INDEP LINEAR LOG NVAR PLOTL SUMTB
SUBROUTINE SETIC

PURPOSE: INITIALIZES PRINT INCREMENT COUNTERS AT AN ITERATION COUNTER SET EVENT

COMMONS: INTCOM
LOCAL SYMBOLS: NONE

USFD/COMM--- 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 LTRCON. TYPE is set in subroutine NEXTIM. IPRINT, the counter for groups of measurements, is updated in subroutine MEASUR.
### SETUP-A

**SUBROUTINE SETUP**

**PURPOSE**
Read and initialize data for the reconstructor

**SUBROUTINES CALLED**
<table>
<thead>
<tr>
<th>MINUT</th>
<th>NORMN2</th>
<th>BEGIN</th>
<th>COPY</th>
<th>EXIT</th>
<th>GHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>HATOUT</td>
<td>PLANE</td>
<td>PRINT</td>
<td>SCHED</td>
<td>SETPLT</td>
<td></td>
</tr>
</tbody>
</table>

**COMMONS**

- SMO
- OBSERV
- ACT
- AX
- TRAJ
- LOGCOM

**JET**
- COVARP
- JOPLER
- ALREDY
- INTCOM
- AM

**GYRACC**
- PRE
- GMITI
- PHASE

**LOCAL SYMBOLS**

- JJAY: 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
SETUP-B

USED/COMM--- AP0 AROTBL C DATEJ DENT ECLINC
ECLONG GENDAT LISTU LISTW LTR1 LTR2
MODE NACCFL NE NRYO NO NS
NU NV NW PHIR RAD RESTRT
RR SLAT SLON TC THETI XN
XMAS X0

READ --- AA ACCDT ACCLXC ACLZC AGAM AQUANT
AR ATM0SS BKBL BTBL BCTBL CACT
CDEL COTBL CQV CQX DIA DT
CXJ CXV CXW ECLINC ECLONG
EJN ERAN ETA GAMTBL GO GQANT
GVROOT ICNTR ICDOOR IDAY IMH III
IMEN IMQ IYR LISTQ LISTS LISTU
LISTV L1STW LTR1 LTR2 Mass Montr
MODE MSATS MU MXTA MMTH NACCL
MATMOS NE NRYO NMEA NMPS NQ
NS NTP NTPT3 NU NV NW
OMG P PHIR PLOT PRP PRSRT PRSDAT
Q REJN REJRN REJRR2 RESTRT RDQ
RI RM RR SA SALT SD
SDMWT SDP SECSI SLAT SLOI SLD
TAPSTM TPSAV TC TEMPA TEND TERTI
TF THETI 4ME TIME WTBL X3 XG
XM XN XNA XO YG YN
ZG ZHM

WRITTEN --- C DIA I J LISTQ LISTU
LLISTV LISTW L1 L2 Mass MNAME
LUABLE XG XN XQ YG YN

SET/COMMON--- ACC ALPHA AROTBL AXC AZC BF
CDEL1 CDEL2 CDEL3 CQV CQW CQX CQX
CQUX CQV CQX CQX CQX CQX CQX
DVI DW ECLINC ECLONG EDN
GM HM ICHR IEND IPRINT IX
IENO IEND IX LASTIM LTR2
K5 LISTO LISTS LISTS M Mass MNAME
LISTW LM LTR2 MCNTR MM NACCL
NE NRYO NICNTR NMEA NQQA
NS NSLIC OMGC P PHI PHIR
0P PPC PSY Q QEJN QENBC
QX QU RESTRT SQQV SQQV SQQV
SCFX SFX SFX SFX SFX SFX SFX
SDET2 SDIET3 SDU SDV SQ SQ
SIZEP SLAT SLOI SP SQ SQQ
TDQV SQDV SQDV SQDV SQDV SQDV
THU TWH TYPR TZERO N WORK
W1 W2 W3 W4 W5 XN
XNAS X0

LOADED --- ICOMN L1 L2 MNAME ULAB ULABEL
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 NORMNZ 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 AROTBL 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 PR̂B 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 TZERO, the earth's obliquity is computed, and GHA is called to find the Greenwich hour angle at TZERO. 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 XOS arrays, and the actual atmosphere variables at TZERO 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 X̂. 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 TZERO, and subroutine SCHED is called to read and sequence measurement and event information. Control then returns to LTROCN.
SUBROUTINE SETUP

PURPOSE: INITIALIZE AND READ DATA FOR THE DATA GENERATOR

SUBROUTINES CALLED: ALTFILE, ATMSET, COPY, DATE, DERIV

COMMONS: ACCEL, TRAJ, JET, OBSERV, GY, NATMOS

LOCAL SYMBOLS

APP, SURFACE PRESSURE IN MILLIBARS
FRAN, 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/COMMON--- AP, AROTBL, C, DATEJ, DDEL, ECLONG
ECLINC, GHATO, IPOOR, IPHAS, M00S, MOL, MPT
NE, NMPTS, PHIR, RAD, RESTR, SLAT
SLUN, TCT, TDEL, THERM, TF
WSTP, XG, XM, XN, ZG

WRITE--- A00LX, ACCLZ, APP, C, DIA, MBL
MEAS, MOL, MPT, MU, MNT, OMEG
PRES, RAO, RAO, RIO, RI, RM
SA, TC, TEMP, TF, TMP, TPT
XR, XM, XN, ZG, ZMM

SET/COMMON--- AP, AROTBL, C, CJELT1, CJELT2, CJELT3
DEL, DIA, IPHAS, M00S, MOL, MPT, NE
RI, SA, SDLT1, SDLT2, SDLT3, TMP, TPT
TZERO, WSTP, XG, XM, XN, ZG, ZMM
SETUP1 is called from DATGEN to initialize and read data via NAME-LIST for the data generator. Elements of the AROTBL array are converted to radians and the variable GENDAT is set .TRUE. so that the reconstructor (see subroutine SETUP) will not convert AROTBL 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 TZERO. Subroutine GHA is called to compute the Greenwich hour angle at TZERO. Since one set has been read into the first elements of PHIR, ECLANG, and ECLINC regardless of the value of ICOR, 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 NATMOS. 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, SENSOR, and OBSM1 are called to initialize the trajectory integration at TZERO and PRINT1 is called to print the data generator output at TZERO. Control then returns to DATGEN for the data generator execution.
SUPROUTINE SMOOT2

PURPOSE: COMPUTE QUADRATIC TO APPROXIMATE QUANTIZED ARU-VRU SENSOR DATA AND OUTPUT ON UNIT 16

SUPROUTINES CALLED: MULT

COMMONS: SMO, TPAJ, LOGCOM, INTCOM, ALREADY

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/COMMON: DT, THTO, LASTIM, M, N, RESTRT, TC
- THTOA, VXO, VXQA, VZO, VZOA

WRITTEN: A1, A2, A3, TC

SET/COMMON: TC, THTOA, VXQA, VZOA

LOADED: IS
SMOOT2 Analysis

Subroutine SMOOT2 computes the smoothing quadratic coefficients used to smooth quantized VRU and ARU sensor data. See subroutine PRPRB5 for more details.
SMOOTH2 Flow Chart

ENTER

No

First time in SMOOTH2.

Yes

Initialize IS and IT

Yes

Restart?

No

Initialize quantized data arrays VXQA, VZQA, and THTQA

Set IT equal to zero

Update IT counter and time TC. Shift elements of quantized data arrays

LASTYM true?

Yes

No

Insert quantized data into bottom of quantized data arrays

RRETURN

Yes

IT ≤ 2?

No

Compute coefficients of smoothing quadratic and write them on file 16

RETURN
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/COMMON— NS: PHI
SET/COMMON— PHI

--- 364 ---
STM Analysis

STM is an executive routine that controls the calculation of the partitions of the augmented state transition matrix.

The augmented state vector, \( \bar{X} \), may be partitioned into the basic state vector, \( \bar{x} \); solve-for parameter, \( \bar{q} \); dynamic consider parameter, \( \bar{u} \); measurement consider parameters, \( \bar{v} \); and dynamic/measurement consider parameters, \( \bar{w} \). When the state transition matrix is partitioned to correspond with the augmented state vector partitions, the state equation may be written

\[
\dot{X}(t_f) = \begin{bmatrix}
\psi_{t_F,t_o} & \psi_{t_F,t_o} & \vartheta_{t_F,t_o} & 0 & \vartheta_{t_F,t_o} \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
X(t_o) \\
q(t_o) \\
u(t_o) \\
v(t_o) \\
w(t_o)
\end{bmatrix}
\]

The partitions \( \psi, \vartheta_u, \) and \( \vartheta_w \) are computed by numerical differencing, i.e., the value of the j-th element of \( \bar{X}(t_o) \) is perturbed by an amount \( \delta_j \), and the resulting change in \( \bar{X}(t_f) \) is found by integrating the equations of motion. The j-th column of \( \phi \) is then given by \( \Delta \bar{X}(t_f)/\delta_j \).

The actual computation of the partitions of \( \phi \) are obtained by calling JACOBN once for each partition. The elements of \( \bar{X}(t_o) \) to be perturbed are indicated by indices stored in the arrays LISTS, LISTQ, LISTU, and LISTW. The magnitude of the perturbation \( \delta_j \) is determined from the variance of the parameter, \( \sigma_j^2 \). 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
- EQS: Co-ordinate transformation 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 aligned with Z-axis of sub-solar planet-orbital plane
- C1: Magnitude of EZS
- C2: Magnitude of planet position vector
- EXS: Unit vector aligned with X-axis of sub-solar planet-orbital plane
- EYS: Unit vector aligned with Y-axis of sub-solar planet-orbital plane
- XP: Planet position and velocity vectors

USED/COMMONS: CARCOR
Subroutine SUBSOL 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 $\hat{e}_x$, $\hat{e}_y$, and $\hat{e}_z$ are aligned with the axes of the subsolar planet orbital plane system.

These unit vectors are defined as

$$
\hat{e}_x = -\frac{\vec{r}}{r} \\
\hat{e}_y = \hat{e}_z \times \hat{e}_x \\
\hat{e}_z = \frac{\vec{r} \times \vec{v}}{|\vec{r} \times \vec{v}|}
$$
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

$$
A = \begin{bmatrix}
\dot{e}_x^S \\
\dot{e}_y^S \\
\dot{e}_z^S
\end{bmatrix}
$$

Thus

$$\mathbf{x}_{\text{subsolar}} = A \mathbf{x}_{\text{ecliptic}}$$

SUBSØL Flow Chart

1. ENTER
2. Call EPHEM to compute the ecliptic position/velocity state of the planet at the current Julian date (epoch 1900)
3. Compute the ecliptic components of the unit vectors $\dot{e}_x^S$, $\dot{e}_y^S$, and $\dot{e}_z^S$
4. Compute coordinate transformation matrix $A$
5. RETURN
SUBROUTINE SUMMARY

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/COMM--- NVAR PLOTL SUMT9
READ --- ITAPE XMAT
WRITTEN --- LABEL PROB TIMEF TITLE XMAT
SET/COMMON--- PROB
LOADED --- LABEL TITLE TARONE TARTWO
SUMMARY 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 PLATS is called to plot using the system plot package.
SUBROUTINE SYMTRZ

PURPOSE I 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>
<thead>
<tr>
<th>TABLE</th>
<th>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</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>VALUE OF THE INDEPENDENT VARIABLE</td>
</tr>
</tbody>
</table>

LOCAL SYMBOLS:

<table>
<thead>
<tr>
<th>K</th>
<th>INDEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>INDEX</td>
</tr>
</tbody>
</table>
TAB Analysis

The index \( K \) is set to \( \text{TABLE}(1)+1 \), and \( X \) is tested against \( \text{TABLE}(L) \), \( L = 3, K \). If \( X \leq \text{TABLE}(L) \),

\[ M = K + L - 1 \]

and

\[ \text{TAB} = \frac{(X - \text{TABLE}(L-1))}{(\text{TABLE}(L) - \text{TABLE}(L-1))} \ast (\text{TABLE}(M) - \text{TABLE}(M-1) + \text{TABLE}(M-1)) \]

where \( \text{TABLE} \) 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

JAY JULIAN DATE, EPOCH 1900
IVR CALENDAR YEAR
MO CALENDAR MONTH
IDAY CALENDAR DAY
IMR 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
PJULIAN 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
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 TMULT

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 PRODUCT 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 W3TBL ARRAY
WDTBC PERTURBED WIND BREAKPOINTS

USED/COMMON--- C WDTAL
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:

<table>
<thead>
<tr>
<th>TYPE KEY</th>
<th>ACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Return to RUN mode</td>
</tr>
<tr>
<td>S</td>
<td>Change to STEP mode</td>
</tr>
<tr>
<td>G</td>
<td>Go to next page if in STEP mode</td>
</tr>
</tbody>
</table>

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 use of IDENTIFY)

Run.

EOR

PROGRAM TEST (FILMPR, FILMPL, TAPE5 = FILMPR, TAPE6 = FILMPR)

\[ \text{Establish Film print file} \]
\[ \text{Send Establish tape file 5 put to file} \]
\[ \text{Establish tape 6 plot film} \]
\[ \text{Print file} \]

DIMENSION XLABEL(3), YLABEL(3), TITLE(3)

DATA ((XLABEL(I), I = 1,3) = 10H XA,10HXIS -- LIN,10HEAR)

DATA ((YLABEL(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.

New Method
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) where
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

CALL SPLT (XO, XS, XN, TITLE, O, T, YMIN1, YMAX1, YMIN1, YMAX1, ... , YMIN1, YMAX1, YN, ... )

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, 10^4XS = total range of the independent variable over one frame. If the value of the independent variable exceeds the value of 10^4XS, 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=0) 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 Y1 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 $Y_{MIN1}$, $Y_{MAX1}$, $Y_{N1}$. The scale of each dependent variable is computed as

$$\frac{Y_{MAX_i} - Y_{MIN_i}}{10}$$ per major grid division;

however if more than three dependent variables are requested, all $N$ variables will be plotted at the

$$\frac{Y_{MAX_i} - Y_{MIN_i}}{10}$$ scale but the BCD name of the first variable is the only one that will appear as part of the frame identification.

If $Y_{MAX_i} = Y_{MIN_i}$, 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.
CALL MAP (0., 1., 0., 1., 0., 1., 0., 1.) sets up a linear-linear mapping,

CALL MAPGLL (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

\[ X_{MIN} = Y_{MIN} = X_{MI} = Y_{MI} = 0. \text{ and } X_{MAX} = Y_{MAX} = 1. \]

The scale numbers will overplot the grid lines if \( X_{MI} \) or \( Y_{MI} \) 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

\[ X_{MIN} \leq X_{MAX}, Y_{MIN} \leq Y_{MAX}, X_{MI} \leq X_{MA}, Y_{MI} \geq Y_{MA} \]

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 ≤ I ≤ 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:

<table>
<thead>
<tr>
<th>Symbols/</th>
<th>Lines/</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Line</td>
</tr>
<tr>
<td>Miniature</td>
<td>128</td>
</tr>
<tr>
<td>Small</td>
<td>86</td>
</tr>
<tr>
<td>Medium</td>
<td>64</td>
</tr>
<tr>
<td>Large</td>
<td>43</td>
</tr>
</tbody>
</table>

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
bbbl.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.

<table>
<thead>
<tr>
<th>FUNCTION</th>
<th>RELATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTRF</td>
<td>greater than</td>
</tr>
<tr>
<td>GEQF</td>
<td>greater than or equal to</td>
</tr>
<tr>
<td>EQLF</td>
<td>equal to</td>
</tr>
<tr>
<td>SEQF</td>
<td>less than or equal to</td>
</tr>
<tr>
<td>SMLF</td>
<td>less than</td>
</tr>
<tr>
<td>UNQF</td>
<td>not equal to</td>
</tr>
</tbody>
</table>

These functions call -ZGTRF- to establish the value.

-TEST- is called by the mapping routines to establish legal arguments.

-ADJUST- 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 Sp.
1 = 01 (BCD) Eject
+ = 60 (BCD) Suppress Sp.

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 programmed 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 programming 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:

<table>
<thead>
<tr>
<th>Col 1</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FORMSFASH6A3</td>
</tr>
<tr>
<td></td>
<td>FORMSFASH6A4</td>
</tr>
</tbody>
</table>

For a secret file.
For a confidential file.
Example to initialize FILMPR with secret forms flash:

Job Card
CHARGE.
REQUEST TAPE1, HY.
COPYCR (INPUT, FILMPR, 1)
RUN(S)
LOG
...
...
7_8_9
FORMSFLASH6A3
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, 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*I

   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 ('FIGURE 3.$')
    CALL FRAME
```
FIGURE 1.
FIGURE 2.