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AFSWC-TDR-63-11

SPINNING UNGUIDED ROCKET TRAJECTORY
DIGITAL COMPUTER PROGRAM (SPURT)

by

Allen D. Dayton
Lt USAF

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Air Force Systems Command
Kirtland Air Force Base
New Mexico

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FOREWORD

The author wishes to acknowledge the assistance of Mr. Carl S. Christensen, who did much of the original logic and programing of SPURT. Mr. Christensen, now with the Aerospace Corporation, Los Angeles, California, was formerly a lieutenant at the Air Force Special Weapons Center.
ABSTRACT

SPURT is a five-degree-of-freedom trajectory digital computer program for spinning unguided space probe vehicles. The program was written for the Control Data Corporation, 1604 digital computer.

SPURT will compute trajectories for a vehicle up to a maximum of ten stages and has provision for computing the trajectories of the separated stages.

This generalized program computes the trajectory over an oblate spheroidal, rotating Earth with atmosphere, in a geocentric rectangular coordinate system. All input and output data are in geodetic coordinates.

Coasting flight trajectories are computed in two subroutines. The first is a Keplerian solution, which also computes orbital elements and "look angles" for various tracking stations. The second uses three-degree-of-freedom point mass equations solved by numerical integration.

The program will prepare two special output tapes. One is used in plotting output data and the other is used to prepare a special tape for the Atlantic Missile Range.

PUBLICATION REVIEW

This report has been reviewed and is approved.
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</table>
1. INTRODUCTION.

The Spinning Unguided Rocket Trajectory (SPURT) digital computer program is designed to provide a generalized computer program for calculating trajectories of spinning unguided space probe vehicles such as the SLV-1B. Many trajectory programs are available\(^1\)–\(^5\) but none meet the demands required by the Space Vehicle Branch (SWTTS) of AFSWC. The program is written in a mixture of FORTRAN and CODAP for use on the CDC-1604 computer and utilizes subroutines of the CO-OP library. The program is designed to handle up to a ten-stage vehicle for both powered and unpowered flight with provisions to calculate the trajectories of the separated "expended" stages.

The main program computes the powered portion of the trajectory and controls entry into the various subroutines. All unpowered flight trajectories are computed in the two subroutines "TWO BOD" and "IMPACT." Both of these subroutines have the capability to calculate the trajectory of all the separated stages and of the payload. TWO BOD is a Keplerian trajectory program with provisions for calculating look angles of various tracking stations, while IMPACT integrates the equation of a point mass with drag.

The main program uses a five-degree-of-freedom, three-dimensional system with the sixth degree constrained by a table of spin rates that are read into the program. An oblate rotating earth and associated gravitational potential, standard 1962 atmosphere, and altitude-dependent wind provisions are also incorporated into the program. The position vector is calculated in a rotating Earth-centered coordinate system, while the angular positions are calculated in a launch-centered coordinate system.
The procedure includes provisions for coasting periods between stages, which are terminated by time. Thrust is computed from thrust vs. time tables and corrected for atmosphere back pressure.

Aerodynamic forces and moments about the center of mass are interpolated from a table of Mach number dependent coefficients.

Computations are carried out using either the Adams or the Runge-Kutta method of numerical integration. Both methods can be used in either fixed or variable step size-mode.

The program has the provision for writing two special output tapes. One, a plot tape, is designed to be used with a special plot program for use on the AFSWC plotter and can plot any output variable against any other output variable. The second, a BATT tape, is used with the BATT program to prepare magnetic tapes to meet specified Atlantic Missile Range formats.

The program running time is approximately 3 to 4 minutes for a four-stage vehicle similar to the SLV-1B. The integration and atmosphere routines are compiled separately in octal locations 6000 to 7514. The rest of the program is compiled in fixed binary mode starting at octal location 10050. The two parts are then put together to be read into the computer. This method has the advantage that the integration and atmosphere routines are not recompiled every time a change is made in the rest of the program.

The program is stored in core according to the following octal addresses.

<table>
<thead>
<tr>
<th>Octal Location</th>
<th>Octal Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>7142</td>
<td>Integration Routine</td>
</tr>
<tr>
<td>7300</td>
<td>7514</td>
<td>Atmosphere Routine</td>
</tr>
<tr>
<td>7660</td>
<td>10026</td>
<td>SQRTF, EXPF, &amp; LOGF Routines</td>
</tr>
<tr>
<td>10050</td>
<td>34102</td>
<td>SPURT Routine (main program)</td>
</tr>
<tr>
<td>34103</td>
<td>34262</td>
<td>SETTAB Routine</td>
</tr>
<tr>
<td>34263</td>
<td>34350</td>
<td>ECLOCK Routine</td>
</tr>
<tr>
<td>34351</td>
<td>34364</td>
<td>SCLOCK Routine</td>
</tr>
<tr>
<td>34365</td>
<td>56750</td>
<td>TWO BOD Routine</td>
</tr>
<tr>
<td>56751</td>
<td>61516</td>
<td>IMPACT Routine</td>
</tr>
<tr>
<td>61517</td>
<td>61615</td>
<td>GEODED Routine</td>
</tr>
<tr>
<td>61616</td>
<td>62006</td>
<td>ROTATE Routine</td>
</tr>
<tr>
<td>62013</td>
<td>67420</td>
<td>LIBRARY Routines</td>
</tr>
<tr>
<td>70037</td>
<td>71343</td>
<td>COMMON</td>
</tr>
</tbody>
</table>

This method has the advantage that the integration and atmosphere routines are not recompiled every time a change is made in the rest of the program.
2. **EQUATIONS.**

### SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Axial moment of inertia</td>
<td>ft$^2$ - slug</td>
</tr>
<tr>
<td>$A_E$</td>
<td>EXIT area of nozzle</td>
<td>in$^2$</td>
</tr>
<tr>
<td>$A_w$</td>
<td>Azimuth angle* of the wind</td>
<td>deg</td>
</tr>
<tr>
<td>$Ax$</td>
<td>Azimuth angle of the $X_L$ axis</td>
<td>deg</td>
</tr>
<tr>
<td>$a_E$</td>
<td>Equatorial radius of the Earth</td>
<td>ft</td>
</tr>
<tr>
<td>$B$</td>
<td>Longitudinal moment of inertia</td>
<td>ft$^2$ - slug</td>
</tr>
<tr>
<td>$C_A$</td>
<td>$1/\sqrt{1-(2f - f^2)\sin^2 \theta_G}$ (Ref 6)</td>
<td>ft</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Drag coefficient</td>
<td>None</td>
</tr>
<tr>
<td>$C_{DB}$</td>
<td>Powered flight drag coefficient</td>
<td>None</td>
</tr>
<tr>
<td>$C_{DC}$</td>
<td>Coasting flight drag coefficient</td>
<td>None</td>
</tr>
<tr>
<td>$C_{Na}$</td>
<td>$(\frac{\partial C_N}{\partial \alpha})$ Normal force coefficient with respect to angle of attack</td>
<td>per radian</td>
</tr>
<tr>
<td>$C_{Ma}$</td>
<td>Moment coefficient with respect to angle of attack</td>
<td>None</td>
</tr>
<tr>
<td>$C_P$</td>
<td>Center of pressure of the missile**</td>
<td>ft</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter of the missile</td>
<td>ft</td>
</tr>
<tr>
<td>$D$</td>
<td>Total drag on the missile</td>
<td>lb$^f$</td>
</tr>
<tr>
<td>$d$</td>
<td>Derivative of a variable</td>
<td>None</td>
</tr>
<tr>
<td>$d$</td>
<td>Reference length</td>
<td>ft</td>
</tr>
<tr>
<td>$e_E$</td>
<td>Eccentricity of the Earth</td>
<td>None</td>
</tr>
<tr>
<td>$F$</td>
<td>Total force vector on the missile</td>
<td>lb$^f$</td>
</tr>
<tr>
<td>$f$</td>
<td>Flattening of the Earth</td>
<td>None</td>
</tr>
</tbody>
</table>

* All azimuth angles are measured clockwise from true north.
** Measured from the tail.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>Missile center of gravity*</td>
<td>ft</td>
</tr>
<tr>
<td>$g_E$</td>
<td>Acceleration of gravity constant</td>
<td>$32.174 \frac{lb\cdot m}{ft\cdot \sec^2}$</td>
</tr>
<tr>
<td>$G_i$</td>
<td>Initial center of gravity of the missile*</td>
<td>ft</td>
</tr>
<tr>
<td>$G_M$</td>
<td>Overturning moment of the missile</td>
<td>ft-lbs</td>
</tr>
<tr>
<td>$G_M$</td>
<td>Gravitational constant of the Earth</td>
<td>$ft^3/\sec^2$</td>
</tr>
<tr>
<td>$G_P$</td>
<td>Center of gravity of the propellant*</td>
<td>ft</td>
</tr>
<tr>
<td>$G_x, G_y, G_z$</td>
<td>Gravitational attraction components</td>
<td>ft/\sec^2</td>
</tr>
<tr>
<td>$H$</td>
<td>Angular momentum vector</td>
<td>lb-ft-sec</td>
</tr>
<tr>
<td>$H_G$</td>
<td>Geodetic altitude</td>
<td>ft</td>
</tr>
<tr>
<td>i, j, k</td>
<td>Unit vectors along X, Y, Z</td>
<td>None</td>
</tr>
<tr>
<td>J</td>
<td>Earth oblateness constant</td>
<td>None</td>
</tr>
<tr>
<td>K</td>
<td>Earth oblateness constant = f(J)</td>
<td>$ft^2$</td>
</tr>
<tr>
<td>$K_{AP}$</td>
<td>Propellant axial radius of gyration</td>
<td>ft</td>
</tr>
<tr>
<td>$K_{BP}$</td>
<td>Propellant transverse radius of gyration</td>
<td>ft</td>
</tr>
<tr>
<td>M</td>
<td>Mass of the missile</td>
<td>slugs</td>
</tr>
<tr>
<td>$M_i$</td>
<td>Initial mass of the missile</td>
<td>slugs</td>
</tr>
<tr>
<td>$M_P$</td>
<td>Mass of the propellant</td>
<td>slugs</td>
</tr>
<tr>
<td>M, N.</td>
<td>Mach number of the missile</td>
<td>None</td>
</tr>
<tr>
<td>N</td>
<td>Spin rate of the vehicle</td>
<td>rad/\sec</td>
</tr>
<tr>
<td>N, E</td>
<td>North and east directions at the launch site</td>
<td>None</td>
</tr>
<tr>
<td>$P_a$</td>
<td>Pressure of the atmosphere</td>
<td>$lb_f/in^2$</td>
</tr>
<tr>
<td>$P_{aT}$</td>
<td>Pressure of the atmosphere at which the thrust is measured</td>
<td>$lb_f/in^2$</td>
</tr>
<tr>
<td>$P_E$</td>
<td>Constant in the $R_E$ equation</td>
<td>None</td>
</tr>
<tr>
<td>$\vec{R}$</td>
<td>Position vector of the missile</td>
<td>ft</td>
</tr>
</tbody>
</table>

* Measured from the tail.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_E)</td>
<td>Radius of the Earth</td>
<td>ft</td>
</tr>
<tr>
<td>(S)</td>
<td>Reference area of the missile</td>
<td>ft²</td>
</tr>
<tr>
<td>(S^A)</td>
<td>(C \ (1 - f^2)) (Ref 6)</td>
<td>ft</td>
</tr>
<tr>
<td>(\vec{T})</td>
<td>Thrust vector of the missile</td>
<td>lb (_f)</td>
</tr>
<tr>
<td>(t)</td>
<td>Time - independent variable</td>
<td>sec</td>
</tr>
<tr>
<td>(T_{AS})</td>
<td>Reference temperature of the atmosphere</td>
<td>(^\circ_K)</td>
</tr>
<tr>
<td>(T_A)</td>
<td>Temperature of the atmosphere</td>
<td>(^\circ_K)</td>
</tr>
<tr>
<td>(T_{Tt})</td>
<td>Thrust known for input data</td>
<td>lb (_f)</td>
</tr>
<tr>
<td>(T_{TV})</td>
<td>Vacuum thrust of the missile</td>
<td>lb (_f)</td>
</tr>
<tr>
<td>(V)</td>
<td>Velocity of the missile</td>
<td>ft/sec</td>
</tr>
<tr>
<td>(V_{SD})</td>
<td>Speed of sound</td>
<td>ft/sec</td>
</tr>
<tr>
<td>(V_{SDS})</td>
<td>Reference speed of sound</td>
<td>ft/sec</td>
</tr>
<tr>
<td>(V_x, V_y, V_z)</td>
<td>Velocity components along (X, Y, Z)</td>
<td>ft/sec</td>
</tr>
<tr>
<td>(V_{wx}, V_{wy}, V_{wz})</td>
<td>Wind velocity components along (X, Y, Z)</td>
<td>ft/sec</td>
</tr>
<tr>
<td>(V_1, V_2)</td>
<td>Velocity components along axis 1 &amp; 2</td>
<td>ft/sec</td>
</tr>
<tr>
<td>(X, Y, Z)</td>
<td>Geocentric coordinate system</td>
<td>ft</td>
</tr>
<tr>
<td>(X_L, Y_L, Z_L)</td>
<td>Launch coordinate system</td>
<td>ft</td>
</tr>
<tr>
<td>(X_1, X_2, X_3)</td>
<td>Missile nonrotating coordinate system</td>
<td>None</td>
</tr>
<tr>
<td>(X'_1, X'_2, X'_3)</td>
<td>Missile rotating coordinate system</td>
<td>None</td>
</tr>
</tbody>
</table>

**GREEK LETTERS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>Angle between east and (X_L) axis</td>
<td>deg</td>
</tr>
<tr>
<td>(\delta_T)</td>
<td>Thrust misalignment angle</td>
<td>rad</td>
</tr>
<tr>
<td>(\theta)</td>
<td>Euler angle as shown in figure 2</td>
<td>deg</td>
</tr>
<tr>
<td>(\theta_C)</td>
<td>Geocentric latitude</td>
<td>deg</td>
</tr>
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</table>
### Symbols and Their Meanings

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_G$</td>
<td>Geodetic latitude</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of the atmosphere</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>Summation sign</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Euler angle as shown in figure 2</td>
</tr>
<tr>
<td>$\phi_A$</td>
<td>Angle at which the thrust misalignment acts in the $X_2, X_3$ plane</td>
</tr>
<tr>
<td>$\phi_T$</td>
<td>Angle at which the thrust misalignment acts in the $X_1', X_3'$ plane</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular velocity of missile in the $X_1', X_2, X_3$ coordinate system</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular velocity of the missile in the $X_1, X_2, X_3$ coordinate system</td>
</tr>
<tr>
<td>$\omega_E$</td>
<td>Angular velocity of the Earth</td>
</tr>
</tbody>
</table>

### Dimensions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_G$</td>
<td>deg</td>
</tr>
<tr>
<td>$\rho$</td>
<td>slugs/ft$^3$</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>None</td>
</tr>
<tr>
<td>$\phi_A$</td>
<td>deg</td>
</tr>
<tr>
<td>$\phi_T$</td>
<td>rad</td>
</tr>
<tr>
<td>$\omega$</td>
<td>rad/sec</td>
</tr>
<tr>
<td>$\omega_E$</td>
<td>rad/sec</td>
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</table>

### Subscripts

<table>
<thead>
<tr>
<th>Subscript</th>
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<tbody>
<tr>
<td>C</td>
<td>Geocentric</td>
</tr>
<tr>
<td>E</td>
<td>The Earth</td>
</tr>
<tr>
<td>G</td>
<td>Geodetic</td>
</tr>
<tr>
<td>i</td>
<td>Initial</td>
</tr>
<tr>
<td>L</td>
<td>Launch system</td>
</tr>
<tr>
<td>P</td>
<td>Propellant</td>
</tr>
<tr>
<td>S</td>
<td>Reference conditions</td>
</tr>
<tr>
<td>T</td>
<td>Thrust</td>
</tr>
<tr>
<td>V</td>
<td>Vacuum</td>
</tr>
<tr>
<td>X</td>
<td>$X_L$ - Axis</td>
</tr>
<tr>
<td>X, Y, Z</td>
<td>$X, Y, Z$ Coordinate system</td>
</tr>
<tr>
<td>W</td>
<td>Wind</td>
</tr>
<tr>
<td>1, 2, 3</td>
<td>$X_1, X_2, X_3$ Coordinate system</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Angle of attack</td>
</tr>
</tbody>
</table>
An arrow over a variable indicates that the variable is a vector.

A dot over a variable indicates the time derivative of that variable.
a. **Linear equations of motion.**

(1) Coordinate systems.

(a) Earth-centered coordinate system \((X, Y, Z)\).

A right-handed, Earth-centered, Cartesian coordinate system is used. The \(X\), \(Y\), and \(Z\) axes, shown in figure 1 are oriented as follows:

The \(X\) axis is the node of the equatorial plane and the plane containing the \(Z\) axis and Greenwich Meridian.

The \(Y\) axis also lies in the equatorial plane and is at right angles to the \(X\) and \(Z\) axes.

The \(Z\) axis lies along the spin axis of the Earth and is at right angles to the \(X\) and \(Y\) axes.

(b) Launch coordinate system \((X_L, Y_L, Z_L)\).

A right-hand coordinate system with the \(X_L, Y_L\) plane tangent to an oblate Earth at the launch point is used. The \(X_L, Y_L, Z_L\) axes are oriented as follows:

The \(X_L\) axis is in the direction of the initial launch azimuth.

The \(Y_L\) axis is counterclockwise 90° from the \(X_L\) axis.

The \(Z_L\) axis is positive along the local geodetic vertical.

(2) Development.

(a) Newton second law for a rotating coordinate system.

The fundamental equation of motion for a particle moving in a rotating coordinate system such as the Earth is

\[
\frac{d^2 \vec{R}}{dt^2} = \frac{\Delta \vec{F}}{M} + 2 \left( \frac{d\vec{R}}{dt} \times \vec{\omega}_E \right) - \vec{\omega}_E \times \left( \vec{\omega}_E \times \vec{R} \right)
\]  

(1) (Reference 2)
Figure 1. Coordinate systems for trajectory equations.
where \( \vec{R} \) is the vector distance from the origin of the rotating X-Y-Z coordinate system to the particle, 

\[
(\vec{R} = iX + jY + kZ)
\]

\( \frac{d\vec{R}}{dt} \) and \( \frac{d^2\vec{R}}{dt^2} \) are the velocity and acceleration, respectively, of the particle measured with respect to the rotating axes.

\[
\frac{d\vec{R}}{dt} = iX + jY + kZ \quad \text{and} \quad \frac{d^2\vec{R}}{dt^2} = iX + jY + kZ. \quad (2)
\]

\( \vec{\omega}_E \) is the angular velocity of the Earth (axis system) and is along the Z axis, \((\vec{\omega} = k\omega_E)\). \( \Sigma \vec{F} \) is the vector sum of the forces acting on the particle: thrust, drag, and gravity, \((\Sigma \vec{F} = i\Sigma F_x + j\Sigma F_y + k\Sigma F_z)\). \( M \) is the total instantaneous mass of the particle, \( 2(\frac{d\vec{R}}{dt} \times \vec{\omega}_E) \) is the coriolis pseudo-acceleration of the axis system due to the rotation of the Earth; 

\( -\vec{\omega}_E \times (\vec{\omega}_E \times \vec{R}) \) is the centrifugal pseudo-acceleration of the axis system due to the rotation of the Earth.

\[
\vec{dR} \times \vec{\omega}_E = \omega_E \begin{vmatrix} i & j & k \\ \frac{dX}{dt} & \frac{dY}{dt} & \frac{dZ}{dt} \\ 0 & 0 & 1 \end{vmatrix}
\]

\( 2(\frac{d\vec{R}}{dt} \times \vec{\omega}_E) = 2\omega_E \begin{vmatrix} i & j & k \\ \frac{dX}{dt} & \frac{dY}{dt} & \frac{dZ}{dt} \\ 0 & 0 & 1 \end{vmatrix} 
\)

\[
(\vec{\omega}_E \times \vec{R}) = \omega_E \begin{vmatrix} i & j & k \\ X & Y & Z \\ 0 & 0 & 1 \end{vmatrix} = \omega_E(-jY + jX)
\]

\[
\vec{\omega}_E \times (\vec{\omega}_E \times \vec{R}) = \omega_E^2 \begin{vmatrix} i & j & k \\ -Y & X & 0 \\ 0 & 0 & 1 \end{vmatrix} = \omega_E^2(-iX - jY)
\]

(3)
From equations 2 and 3 the components of equation 1 can be expressed:

\[
\begin{align*}
\frac{d^2 X}{dt^2} &= \Sigma F_x - \omega_E^2 X \\
\frac{d^2 Y}{dt^2} &= \Sigma F_y - \omega_E^2 Y \\
\frac{d^2 Z}{dt^2} &= \Sigma F_z \\
\end{align*}
\]

The program assumes that there are three forces acting on a rocket vehicle: thrust, drag, and gravity. Thrust is assumed to act along the longitudinal axis of the rocket vehicle. Drag is assumed to act opposite the velocity vector. Gravity is assumed to be directed toward the center of mass of an oblate Earth.

(b) Gravitational attraction equations.

The equations of gravitational attraction are obtained from reference 8, and converted to a Cartesian coordinate system. They are as follows:

\[
\begin{align*}
G_x &= -GM \frac{X}{R^3} \left[ 1 + \frac{3K}{R^2} - \frac{15}{R^4} \right] \\
G_y &= -GM \frac{Y}{R^3} \left[ 1 + \frac{3K}{R^2} - \frac{15}{R^4} \right] \\
G_z &= -GM \frac{Z}{R^3} \left[ 1 + \frac{5K}{R^3} - \frac{15}{R^4} \right]
\end{align*}
\]

Finally, the equations for total acceleration components along \( X \), \( Y \), and \( Z \) axes can be written as follows:
\[ \ddot{x} = \frac{T_x}{M} - \frac{D}{M} \dot{x} - g_x + 2 \omega_E \dot{y} + \omega_E^2 x \]

\[ \ddot{y} = \frac{T_y}{M} - \frac{D}{M} \dot{y} - g_y - 2 \omega_E \dot{x} + \omega_E^2 y \]

\[ \ddot{z} = \frac{T_z}{M} - \frac{D}{M} \dot{z} - g_z \]

where

\[ \dot{R} = (\dot{x}^2 + \dot{y}^2 + \dot{z}^2)^{\frac{1}{2}} \]

\[ \ddot{R} = (\ddot{x}^2 + \ddot{y}^2 + \ddot{z}^2)^{\frac{1}{2}} \]

(c) Thrust and mass.

The mass \( M \) of the rocket vehicle and the thrust \( T_{Tt} \) at air pressure \( P_{at} \) are assumed to be known functions of time. In general these functions will be nonlinear and discontinuous. The thrust \( T \) corresponding to air pressure \( P_a \) may be computed from the equation

\[ T = T_{Tt} + (P_{at} - P_a)A_e \]

where \( A_e \) is the nozzle exit area. (\( A_e \) is measured in square inches; therefore, \( P_{at} \) and \( P_a \) are absolute pressures in lb/in\(^2\).)

In this trajectory-computation program, the thrust function is evaluated by table look-up and interpolation. Since this function is discontinuous, a set of tables is needed for each stage of the rocket vehicle. The tables in the working storage are changed each time a stage is dropped.

The thrust function \( T_{Tt} \) vs. \( t \) is given, but the mass function \( M \) vs. \( t \) is computed by
\[ M = M_i - M_p \int_{t_i}^{t} T_{Tv} \, dt - M_p \int_{b}^{t} T_{Tv} \, dt \]

where \[ T_{Tv} = T_{Tt} + P_{at} A_e \] (9)

Subscript \( i \) indicates values at ignition, \( b \) denotes values at burnout, and \( M_p \) is the mass of the propellant. For clarity, subscript \( n \) denoting the configuration number has been omitted from the subscripted symbols.

\( d \) Aerodynamic drag.

The aerodynamic drag may be computed from the equation

\[ D = \frac{1}{2} \rho S V^2 C_D (M.N.) \] (11)

where

\( \rho \) = Density of the air about the rocket vehicle, slugs/ft\(^3\)

\( C_D (M.N.) \) = Drag coefficient, assumed to be a function of Mach number only in this report (dimensionless)

\( S \) = Cross-section area of the rocket vehicle, ft\(^2\)

\( M.N. = \) Mach number = \( V/V_{SD} \)

\( V_{SD} \) = Velocity of sound in the air about the rocket vehicle, ft/sec.

It should be noted that each stage of the rocket vehicle could have a different diameter. The diameter of the largest stage in the assembly that has not dropped off will be used.

Two drag coefficients for each configuration of the rocket vehicle are needed. It is assumed that the drag of a configuration during powered flight is different from (less than) the drag before ignition or after burnout by the amount of the base drag. The drag coefficients for
the powered and coasting conditions will be denoted by $C_{DB}$ and $C_{DC}$, respectively, with numerical subscripts added to denote the configuration or stage number. Thus, up to six different drag coefficients will be needed for a three-stage rocket vehicle: $C_{DB1}$, $C_{DB2}$, $C_{DB3}$, $C_{DC1}$, $C_{DC2}$, $C_{DC3}$. $C_{DC1}$ and/or $C_{DC2}$ are not needed, of course, if the first and/or second configuration do not coast.

The neglect of yaw angle in determining the drag coefficient is justified by the fact that the thrust will dominate the motion so that fairly large errors in the aerodynamics will have little effect on the trajectory. Also, the yaw angle (and its effect on the coefficients) will presumably be small.

(e) Atmosphere and wind.

The values of $\rho$, $V_{SD}$, and $P_a$ are available from the COESA 1962 model atmosphere or from launch site soundings. Actually $V_{SD}$ is not measured directly; instead, the air temperature $T_a$ is recorded and $V_{SD}$ is computed from the equation

$$V_{SD} = V_{SDs} \left(\frac{T_a}{T_{as}}\right)^{1/2}$$  \hspace{1cm} (12)

where $V_{SDs}$ is the standard velocity of sound (ft/sec) corresponding to standard air temperature $T_{as}$, and the units of $T_a$ and $T_{as}$ should be °K.

If a wind is blowing, it will have an important effect on the trajectory of a multistage unguided rocket vehicle. The effect is most pronounced during the first stage, and decreases thereafter. After burnout of the last stage, the effect will be fairly small and can be neglected. The wind may be taken into account by computing the velocity components from the following equations:

$$V_X = \ddot{X} - V_{WX}$$

$$V_Y = \ddot{Y} - V_{WY}$$

$$V_Z = \ddot{Z} - V_{WZ}$$  \hspace{1cm} (13)
where \( V_{WX}, V_{WY}, V_{WZ} \) are the wind components in the Earth-centered axis system. The total velocity \( V \) with respect to the air mass may be computed from

\[
V = (V_X^2 + V_Y^2 + V_Z^2)^{1/2}
\]  

Equations 13 follow from the definition of \( V_X, V_Y, \) and \( V_Z \) as components of the velocity of the rocket vehicle with respect to the air mass.

It is assumed that the wind velocity is a function of \( H_G \) only and is horizontal (that is, \( V_{WZ} = 0 \)). If the wind velocity is exactly horizontal, then \( V_{WZ} \neq 0 \) for \( R_{XY} \neq 0 \). Setting \( V_{WZ} = 0 \) may be thought of as a flat-earth approximation, but unless \( R_{XY} \) is very large, it is doubtful whether \( V_W \) can be measured accurately enough for the approximation to be questionable.

The meteorological data taken before a launch should include the wind velocity \( V_W \) and the wind azimuth angle \( A_W \) as well as \( \rho, T_a, \) and \( P_a \) vs. altitude. By convention \( A_W \) is defined to be the azimuth angle, measured clockwise from the North, from which the wind is blowing; then \( A_W \) is also the azimuth angle, measured clockwise from the South, to which the wind is blowing. It will be seen that \( V_{WX_L} \) and \( V_{WY_L} \) may be computed from the following equations:

\[
V_{WX_L} = V_W \cos (A_W - A_X_L)
\]
\[
V_{WY_L} = V_W \sin (A_W - A_X_L)
\]

\( V_{WX_L} \) and \( V_{WY_L} \) are then rotated into the Earth-centered components \( V_{WX}, V_{WY} \) and \( V_{WZ} \).

The presentation of the linear acceleration equations for
the burning period has now been completed.

b. **Angular equations of motion.**

(1) **Coordinate systems.**

(a) **Nonrotating body axis** ($X_1, X_2, X_3$).

A right-hand Cartesian coordinate system which is fixed to, but does not spin with the body. The $X_1$ axis is along the spin axis. The $X_2$ axis lies in the vertical plane, while the $X_3$ axis lies in the horizontal plane. This axis system is related to the reversed ($-Y_L$) launch coordinate system by the two Euler angles $\theta$ and $\phi$.

(b) **Rotating body axis** ($X_1', X_2', X_3'$).

A body fixed coordinate system with the same origin as the $X_1, X_2, X_3$ system. Axes $X_2'$ and $X_3'$ are along the transverse principal axis of the rocket vehicle.

(2) **Development.**

(a) **Body axis equations.**

The angular acceleration equations of the rocket vehicle may be developed from the vector equation of reference 1. The only torque considered is the overturning moment. All other moments including pitch and jet damping are assumed to be small and will be neglected; the rocket vehicle is spun to reduce the effects of any misalignments, asymmetries, or unbalances, but such a spin is not large enough to develop an appreciable Magnus moment. The vector equation of angular motion is then as follows:

$$\frac{d\vec{H}}{dt} = \frac{d\vec{H}}{dt} + \vec{\omega} \times \vec{H} = \vec{G}_M$$  \hspace{1cm} (16)

where

$$\vec{H} = \text{Angular momentum vector, lb-ft-sec}$$

$$\vec{G}_M = \text{Overturning moment (vector), lb-ft}$$

$$\vec{\omega} = \text{Angular velocity of the } X_1, X_2, X_3 \text{ system, rad/sec}$$
The angular velocity of the missile is denoted by $\dot{\mathbf{\omega}}$; the components of $\dot{\mathbf{\omega}}$ in the $X_1, X_2, X_3$ system are $\Omega_1 + N, \Omega_2, \Omega_3$, where $N$ is the axial spin of the missile and $\Omega_1, \Omega_2, \Omega_3$ are the components of $\dot{\mathbf{\omega}}$. Then equations for $\dot{\mathbf{\omega}}$ and $\dot{\mathbf{H}}$ are as follows: (reference 1.)

$$
\dot{\mathbf{\omega}} = \mathbf{I}_1 \Omega_1 + \mathbf{I}_2 \Omega_2 + \mathbf{I}_3 \Omega_3
$$

$$
\dot{\mathbf{H}} = \mathbf{I}_1 A(\Omega_1 + N) + \mathbf{I}_2 B\Omega_2 + \mathbf{I}_3 B\Omega_3
$$

where

$A = \text{moment of inertia of the rocket vehicle about the longitudinal principal axis, slug-ft}^2$

$B = \text{moment of inertia of the rocket vehicle about a transverse axis through the center of mass, slug-ft}^2$

It is assumed that the mass distribution is symmetric, so the moment of inertia is the same about any transverse axis through the center of mass.

(b) Moments of inertia.

It is assumed that an internal-burning solid propellant is used. Approximate values of $A$ and $B$ during burning are computed by use of the following formulas:

$$
A = A_i - k_{AP}^2 (M_i - M)
$$

$$
B = B_i - M_i (G - G_i) (G_i - G_P) - (M_i - M)k_{BP}^2
$$

where

$$
G = G_i + (G_i - G_P) (M_i - M)/M
$$

As before, subscript $i$ indicates values at time of ignition and $P$ denotes a property of the propellant; $k_{AP}$ is the radius of gyration of the propellant grain about its longitudinal axis (ft), $k_{BP}$ is the radius of gyration of the propellant grain about a transverse axis through its center of mass (ft), and $G$ is the distance from the base to the center of mass of the rocket vehicle (ft). The quantities $G_P, k_{AP}$ and $k_{BP}$ are assumed to be constant for an internal burning grain; $A_i, B_i, G_i$, and $M_i$ are, of course, constant, so $M$ is the only variable.
Equations 19 and 20 cannot be used for an end-burning grain unless formulas are added for $k_{BP}$ and $G_p$. None of these equations apply for liquid propellant rockets.

(c) Aerodynamic moment.

The expression for $\vec{G}_M$ is as follows:

$$\vec{G}_M = \frac{1}{2} \rho d S V C_{Ma} \left( \hat{1}_2 V_3 - \hat{1}_3 V_2 \right)$$

(21)

For the present application $C_{Ma}$ is the static stability derivative (dimensionless) and is a negative number which can be computed by use of the equation:

$$C_{Ma} = C_{Na} \frac{(C_D - G)}{d}$$

(22)

where

$$C_{Na} = \text{Normal force coefficient (dimensionless)}$$

$$C_p = \text{Distance from the base of the rocket to the normal force center of pressure, feet}$$

In this report $C_{Ma}$, $C_{Na}$, and $C_p$ are assumed to be functions of Mach number only. In the trajectory-computation program these functions and $C_D$ are evaluated by table look-up and interpolation.

(d) Euler angle relation.

If equations 17 and 21 are substituted into equation 16, the $X_2$ and $X_3$ components of the resulting vector equation will be as follows:

$$B \dot{\Omega}_2 + B \dot{\Omega}_2 + (A - B) \Omega_1 \dot{\Omega}_3 + A \dot{\Omega}_3 = \frac{1}{2} \rho V d S C_{Ma} V_3$$

$$B \dot{\Omega}_3 + B \dot{\Omega}_3 + (B - A) \Omega_1 \dot{\Omega}_2 - A \dot{\Omega}_2 = -\frac{1}{2} \rho V d S C_{Ma} V_2$$

(23)

It is desirable to replace $\Omega_1$, $\Omega_2$, $\Omega_3$, $\dot{\Omega}_2$, $\dot{\Omega}_3$ in these equations by functions of $\phi$ and $\theta$. This may be done by use of the following relations:

$$\Omega_1 = -\dot{\phi} \sin \theta$$

18
These equations neglect the angular velocity of the Earth \((\omega_E)\); they are written by inspection of figure 2. It will be seen that

\[
\begin{align*}
\dot{\Omega}_2 &= -\dot{\theta} \\
\dot{\Omega}_3 &= -\ddot{\phi} \cos \theta + \dot{\phi} \dot{\theta} \sin \theta
\end{align*}
\]
Substitution of equations 24 and 25 into equations 23 yields the required angular acceleration equations as follows:

\[-B\ddot{\theta} - B\dot{\theta} + (A - B) \dot{\phi}^2 \sin \theta \cos \theta - AN \dot{\phi} \cos \theta\]

= \(\frac{1}{2} \rho VSD \frac{C_{Ma}}{V_3}\)

\[-B\ddot{\phi} \cos \theta - B\dot{\phi} \cos \theta + (2B - A) \ddot{\phi} \sin \theta + AN \dot{\phi}\]

= \(-\frac{1}{2} \rho VSD \frac{C_{Ma}}{V_2}\)

These equations are dynamically exact, except for the neglect of \(\omega_E\) which is negligibly small compared to \(\dot{\phi}, \dot{\theta}\), and \(N\).

Equations 26 may be put in a form more suitable for computation by dividing through by \(B\). The equations become

\[\dot{\theta} + (\dot{B}/B) \dot{\theta} + (1 - (A/B)) \dot{\phi}^2 \sin \theta \cos \theta + (A/B)N \dot{\phi} \cos \theta\]

= \(-\frac{1}{2} \rho VdS \frac{C_{Ma}}{V_3}\)

\[\ddot{\phi} \cos \theta + (\dot{B}/B) \dot{\phi} \cos \theta - (2 - (A/B)) \ddot{\phi} \sin \theta - (A/B)N \dot{\phi}\]

= \(\frac{1}{2} \rho dS \frac{C_{Ma}}{V_2}\)

(27)

(e) \(\dot{B}\) Terms.

For an internal burning solid-propellant rocket, the following formulas are used to compute the \(\dot{B}\) terms:

\[\dot{B} = \dot{M} \left[ (M_i^2/M^2) (G_i - G_p)^2 + k_{BP}^2 \right]\]

where

\[\dot{M} = -T_{Tv} \left\{ M_{Pl} \int_{t_1}^{t_b} T_{Tv} dt \right\}\]

(28)

These formulas are easily derived from equations 9 and 19.
(f) Body-cross wind components.

A coordinate transformation is needed to compute $V_2$ and $V_3$ from $V_{X_L}$, $V_{Y_L}$, $V_{Z_L}$. The following equations can be written from inspection of figure 2:

$$V_2 = -V_{X_L} \cos \varphi + V_{Z_L} \sin \varphi$$

$$V_3 = -V_{X_L} \sin \varphi \sin \theta - V_{Y_L} \cos \theta - V_{Z_L} \cos \varphi \sin \theta$$

(29)

This completes the derivation of the equations of motion during burning.

c. Summary of equations of motion.

If the rocket is assumed to have thrust misalignments, additional terms are added to the equations to account for the new forces and moments created. For convenience, the equations are restated here with the new terms added.

$$\ddot{X} = \frac{1}{M} \left[ T_x - \frac{D}{R} \dot{X} \right] + G_x + 2 \omega E \dot{Y} + \omega_e^2 X$$

$$\ddot{Y} = \frac{1}{M} \left[ T_y - \frac{D}{R} \dot{Y} \right] + G_y - 2 \omega E \dot{X} + \omega_e^2 Y$$

$$\ddot{Z} = \frac{1}{M} \left[ T_z - \frac{D}{R} \dot{Z} \right] + G_z$$

$$\ddot{\phi} = -\frac{B}{B} \dot{\phi} + \left\{ \left[ \left( 2 - \frac{A}{B} \right) \phi \sin \theta + \frac{A}{B} N \right] \dot{\phi} \right\}$$

$$+ \frac{\tau}{\theta} \rho C_{Na} \left( C_P - G \right) \frac{D^2 V}{B} + \frac{T G \delta T \cos \varphi A}{B} \frac{1}{\cos \theta}$$

$$\ddot{\theta} = -\frac{B}{B} \dot{\theta} - \left\{ \left[ \left( 1 - \frac{A}{B} \right) \phi \sin \theta + \frac{A}{B} N \right] \dot{\theta} \cos \theta \right\}$$

$$- \frac{\tau}{\theta} \rho C_{Na} \left( C_P - G \right) \frac{D^2 V}{B} - \frac{T G \delta T \sin \varphi A}{B}$$

(30)
where

\[ \delta_T = \text{thrust misalignment angle, radians} \]
\[ \varphi_T = \text{orientation angle of jet misalignment force; measured in the } \mathbf{X}' - \mathbf{X}'_3 \text{ plane from the } \mathbf{X}'_2 \text{ axis and positive in the sense of a counterclockwise rotation as seen from the positive } \mathbf{X}'_1 \text{ axis, radians.} \]
\[ \varphi_A = \theta_T + \int_0^t N dt \text{ measured in the } \mathbf{X}_2 - \mathbf{X}_3 \text{ plane from the } \mathbf{X}_2 \text{ axis and positive in the sense of a counterclockwise rotation as seen from the positive } \mathbf{X}_1 \text{ axis, radians.} \]

These equations require a table of roll rate \((N = \phi)\) vs. time.

The thrust vector is given in the launch coordinate system and rotated to the Earth-centered system by the use of a matrix rotation. The thrust vector in the launch coordinate system is

\[
T_{xL} = T \left[ \cos \theta \sin \varphi - \delta_T (\cos \varphi_A \cos \varphi + \sin \varphi_A \sin \varphi \sin \theta) \right]
\]
\[
T_{yL} = -T \left[ \sin \theta + \delta_T \sin \varphi_A \cos \theta \right]
\]
\[
T_{zL} = T \left[ \cos \theta \cos \varphi + \delta_T (\cos \varphi_A \sin \varphi - \sin \varphi_A \cos \varphi \sin \theta) \right]
\]

(31)

d. Geocentric relationships.

(1) Shape of the Earth.

Figure 3 shows a meridian section of the earth where \(a_E\) is the semi-major (equatorial) axis, \(\theta_c\) is the geocentric latitude, and \(R_E\) is a radius vector from center to the surface of the earth. \(R_E\) is a function of the geocentric latitude and is given as
\[ R_E = \frac{a_E}{\sqrt{1 + P_E \sin^2 \theta_c}} \]

where
\[ P_E = \frac{e_E^2}{1 - e_E^2} \]

(32)

Figure 3

(2) Geodetic sublatitude and altitude.

Figure 4 shows the geometric relation between the geodetic and geocentric latitude and altitude.

\[ \theta_G - \text{Geodetic Latitude} \]

\[ H_G - \text{Geodetic Altitude} \]

Figure 4
To convert geodetic latitude and altitude to geocentric latitude and radius:

\[ \tan \theta_c = \left[ \frac{S + H_G}{C + H_G} \right] \tan \theta_G \]  

(33)

where

\[ C \triangleq \frac{a_E}{(1 - e_E^2 \sin^2 \theta_G)^{1/2}} \quad S \triangleq C(1 - e_E^2) \]  

(34)

\[ R = \left( (C + H_G)^2 \cos^2 \theta_G + (S + H_G)^2 \sin^2 \theta_G \right)^{1/2} \]  

(35)

to convert geocentric latitude and radius to geodetic latitude and altitude:

\[ \theta_G = \theta_c + \sin^{-1} \left[ \frac{a_E}{R} \left( f \sin^2 \theta_c + f^2 \sin 4 \theta_c \left( \frac{a_E}{R} - \frac{1}{4} \right) \right) \right] \]  

\[ H_G = R - a_E \left[ 1 - f \sin^2 \theta_c - \frac{1}{2} \sin^2 2 \theta_c \left( \frac{a_E}{R} - \frac{1}{4} \right) \right] \]  

(36)

The following geocentric constants were used in the program.

Adopted Geocentric Constants (1961) (reference 8)

\[ a_E = 20,925,647.12 \text{ ft} \]

\[ GM = 1.4076427 \times 10^{16} \text{ ft}^3/\text{sec}^2 \]

\[ = 2.316686 \times 10^{12} \text{ NM} (\text{ft/sec})^2 \]

\[ g_E = 32.174 \text{ ft/sec}^2 \]

\[ 1/f = 298.30 \pm 0.05 \]
$e_E = 0.0818133302$

$J = (1623.42 \pm 0.5) \times 10^{-6}$

$P_E = 0.00673852$

$\omega_E = 7.292115 \times 10^{-5} \text{ rad/sec}$
3. **DATA INPUT AND PROGRAM USAGE.**

**INPUT DATA**

All input data are read into SPURT at one time and in one "read" block. This includes data for the subroutines (two-body and impact). Most data, except for special cases and control integers, are read in a FORTRAN 7F10.0 format. This format is for seven data words (of ten digits each) per card. The decimal point is always punched in the field. On Repeat Blocks, as many words will be read as specified by a previously read integer.
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<th>Column</th>
<th>Mode</th>
<th>Remarks</th>
</tr>
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<td>I</td>
<td>1 Card</td>
</tr>
<tr>
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<td>pounds</td>
<td>3 - 15</td>
<td>V</td>
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</tr>
<tr>
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<td>Hollerith</td>
<td>1 Card</td>
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<tr>
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<td>1 - 10</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Initial longitude</td>
<td>degrees (+E)</td>
<td>11 - 20</td>
<td>V</td>
<td></td>
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<tr>
<td>Initial altitude</td>
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<td>V</td>
<td></td>
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<tr>
<td>Initial azimuth</td>
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<td>31 - 40</td>
<td>V</td>
<td>1 Card</td>
</tr>
<tr>
<td>Initial X</td>
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<td>V</td>
<td></td>
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<tr>
<td>Initial Y</td>
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<td>51 - 60</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Initial Z</td>
<td>feet</td>
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<td>V</td>
<td></td>
</tr>
<tr>
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<td>1 - 10</td>
<td>V</td>
<td></td>
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<tr>
<td>Initial ( \dot{Y} )</td>
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<td>11 - 20</td>
<td>V</td>
<td></td>
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<td>Initial ( \dot{Z} )</td>
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<td>21 - 30</td>
<td>V</td>
<td></td>
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<td>V</td>
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<td>V</td>
<td></td>
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<tr>
<td>Initial ( \dot{\phi} )</td>
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<td>51 - 60</td>
<td>V</td>
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<td>1 - 10</td>
<td>V</td>
<td>1 Card</td>
</tr>
<tr>
<td>Time of last stage B.O.</td>
<td>seconds</td>
<td>11 - 20</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Master control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>Control 1</td>
<td>none</td>
<td>1-2</td>
<td>I</td>
<td>metro &amp; wind</td>
</tr>
<tr>
<td>Control 2</td>
<td>none</td>
<td>3-4</td>
<td>I</td>
<td>print input data</td>
</tr>
<tr>
<td>Control 3</td>
<td>none</td>
<td>5-6</td>
<td>I</td>
<td>write BATT tape</td>
</tr>
<tr>
<td>Control 4</td>
<td>none</td>
<td>7-9</td>
<td>I</td>
<td>two body sub.</td>
</tr>
<tr>
<td>Control 5</td>
<td>none</td>
<td>9-10</td>
<td>I</td>
<td>lines/page</td>
</tr>
<tr>
<td>Control 6</td>
<td>none</td>
<td>11-12</td>
<td>I</td>
<td>write plot tape</td>
</tr>
<tr>
<td>Control 7</td>
<td>none</td>
<td>13-14</td>
<td>I</td>
<td>right hand cord.</td>
</tr>
<tr>
<td>Control 8</td>
<td>none</td>
<td>15-16</td>
<td>I</td>
<td>impact sub.</td>
</tr>
<tr>
<td>Control 9</td>
<td>none</td>
<td>17-18</td>
<td>I</td>
<td>all this</td>
</tr>
<tr>
<td>Control 10</td>
<td>none</td>
<td>19-20</td>
<td>I</td>
<td>block on</td>
</tr>
</tbody>
</table>

| No. of spin values | none | 21-22 | I |
| Output tape No.   | none | 23-24 | I |
| Deg. of interpolation | none | 25-26 | I |

| Spin time table  | seconds 77.0 | V | N spin values |
| Spin rate table  | rev/sec 77.0 | V | N spin values |

| Stage number | none | 1-2 | I | N0 |
| Size of thrust table | none | 3-4 | I | N(1,J) |
| Size of CDD table | none | 5-6 | I | N(2,J) |
| Size of CDC table | none | 7-8 | I | N(3,J) |
| Size of Cp table | none | 9-10 | I | N(4,J) |
| Size of CNa table | none | 11-12 | I | N(5,J) |
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Thrust time  seconds  7F10.0  V  N (1,J) values

Thrust  pounds force  7F10.0  V  N (1,J) values

C_{D_{N_{0}}}  none  7F10.0  V  N (2,J) values

if the last word of C_{DB} L,N. is (-1), skip  Skip Aerodynamics

Powered drag coeff.  none  7F10.0  V  N (2,J) values

C_{D_{C}} Mach No.  none  7F10.0  V  N (3,J) values

Coasting drag coeff.  none  7F10.0  V  N (3,J) values

C_{P} Mach No.  none  7F10.0  V  N (4,J) values

C_{P}  feet  7F10.0  V  N (4,J) values

C_{N_{a}} Mach No.  none  7F10.0  V  N (5,J) values

C_{N_{a}}  per/rad  7F10.0  V  N (5,J) values
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Units</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure at thrust meas.</td>
<td>pounds/in²</td>
<td>1 - 10</td>
</tr>
<tr>
<td>Exit area</td>
<td>inch²</td>
<td>11 - 20</td>
</tr>
<tr>
<td>Stage diameter</td>
<td>feet</td>
<td>21 - 30</td>
</tr>
<tr>
<td>Missile C.G.</td>
<td>feet</td>
<td>31 - 40</td>
</tr>
<tr>
<td>Stage fuel C.G.</td>
<td>feet</td>
<td>41 - 50</td>
</tr>
<tr>
<td>Fuel axial I/²</td>
<td>feet²</td>
<td>51 - 60</td>
</tr>
<tr>
<td>Fuel transverse I/²</td>
<td>feet²</td>
<td>61 - 70</td>
</tr>
<tr>
<td>Missile axial I</td>
<td>slug*ft²</td>
<td>1 - 10</td>
</tr>
<tr>
<td>Missile transverse I</td>
<td>slug*ft²</td>
<td>11 - 20</td>
</tr>
<tr>
<td>Stage weight</td>
<td>pounds</td>
<td>21 - 30</td>
</tr>
<tr>
<td>Stage consumed wt</td>
<td>pounds</td>
<td>31 - 40</td>
</tr>
<tr>
<td>Orientation of T.M.A.</td>
<td>radians</td>
<td>41 - 50</td>
</tr>
<tr>
<td>Thrust misalign angle</td>
<td>radians</td>
<td>51 - 60</td>
</tr>
<tr>
<td>- OHT -</td>
<td></td>
<td>61 - 70</td>
</tr>
<tr>
<td>Ignition time from launch</td>
<td>seconds</td>
<td>1 - 10</td>
</tr>
<tr>
<td>Burnout time from launch</td>
<td>seconds</td>
<td>11 - 20</td>
</tr>
<tr>
<td>TCC from launch</td>
<td>seconds</td>
<td>21 - 31</td>
</tr>
</tbody>
</table>

Repeat from A' for each stage (NS)
WIND AND METEOROLOGY INPUT DATA:

1. Skip Metro Data
   - NO: KMRL 1 = 1, 2
   - YES:
     - KMRL 1 = 2

2. No. of altitude values
   - None
   - 1-2
   - I
   - KMETRO

3. Altitude values
   - feet
   - 7F10.C
   - V
   - WAIT

4. YES: is KMRL 1 = 2

5. Temperature
   - °C
   - 7F10.0
   - V
   - No. = KMETRO

6. Density
   - kg/m³
   - 7F10.0
   - V
   - No. = KMETRO

7. Pressure
   - Millibars
   - 7F10.0
   - V
   - No. = KMETRO

8. Wind velocity
   - feet/sec
   - 7F10.0
   - V
   - No. = KMETRO

9. Wind azimuth
   - °C from north
   - 7F10.0
   - V
   - No. = KMETRO
WIND AND METEOROLOGY INPUT DATA:

Skip Metro Data

- **is** KMTNL l = 1, 2
  - **YES**
    - **No. of altitude values** None 1-2 I KMETRO
      - **Altitude values** feet 7F10.0 V WALT
    - **YES is** KMTNL l = 2
      - **NO**
        - **Temperature** °C 7F10.0 V No. = KMETRO
        - **Density** KGM/m³ 7F10.0 V No. = KMETRO
        - **Pressure** Millibars 7F10.0 V No. = KMETRO
        - **Wind velocity** feet/sec 7F10.0 V No. = KMETRO
        - **Wind azimuth** deg. from north 7F10.0 V No. = KMETRO
INPUT DATA FOR KEPPELIAN TRAJECTORY AND LOCK ANGLES:

1. SKIP KEPPELIAN

No. of Time changes
None 1 I JTB1

No. of ORBITS
None 2-11 V TB2

ATI
seconds
1-10 V TB3

END of ATI
seconds
11-20 V TB4

Repeat JTB1 Times

No. of Lock Stations
None 1-3 I JTB5

Station name
None 1-24 Hollerith TB6

Station latitude
Degrees (+N) 25-34 V TB7

Station longitude
Degrees (+E) 35-44 V TB8

Station altitude
feet 45-54 V TB9

Repeat JTB5 Times
DATA FOR SUBROUTINE IMPACT

Skip Subroutine Impact

```
                  YES

                  NO

                       is

                  KNTRL 8=1

No. of stages for DRAG
None 1-2 I NXIM

Table size
Print time increment
None 1-2 1-15 V DELPR

Mach No. for DRAG
None 7F10.0 V RXCH

DRAG coefficient
None 7F10.0 V CDM
```

Repeat for each stage to be used in impact

END

I = INTEGER - Fixed point numbers
V = VARIABLE - Floating point numbers
MASTER CONTROL NUMBERS

These numbers control various options of the program as follows:

**Control 1.** When KNTRL(1) = 1*, the program will read in the temperature, pressure, and density and use them to compute the aerodynamic forces and moments. Otherwise, the standard 1962 atmosphere is used.

When KNTRL(1) = 1 or 2, the program will read in wind velocity and wind azimuth vs. altitude. The program will compute the path of the missile due to the winds.

**Control 2.** When KNTRL(2) = 1, the input data are printed out.

**Control 3.** When KNTRL(3) = N, the program will write tape number N for input to the BATT program.

**Control 4.** When KNTRL(4) = 1, the program will use the Keplerian (TWO-BOD) subroutine for coasting flight on the last stage. If KNTRL(4) = 2, it will use it on all stages.

**Control 5.** When KNTRL(5) = NO, the program will write NO lines of output per page.

**Control 6.** When KNTRL(6) = N, the program will prepare an input tape (N) for the plot program.

**Control 7.** When KNTRL(7) = 1, the launch coordinate system printed out is a right-hand one instead of a left-hand one.

**Control 8.** If KNTRL(8) = 1, the integrating unpowered flight trajectory is computed for all stages except the last one. If KNTRL(8) = 2, the trajectory is computed for all stages.

**Control 9.** Not used.

**Control 10.** Not used.

* When a KNTRL number is left blank, that option will be ignored.
4. **VARIABLES USED IN SPURT.**

**INPUTS**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Initial axial moment of inertia for each stage (slug-ft$^2$)</td>
</tr>
<tr>
<td>AALT</td>
<td>Initial geodetic altitude (ft)</td>
</tr>
<tr>
<td>AAZIM</td>
<td>Initial launch azimuth (deg)</td>
</tr>
<tr>
<td>AAZ12</td>
<td>Initial launch azimuth (rad)</td>
</tr>
<tr>
<td>ACODE</td>
<td>Integration code</td>
</tr>
<tr>
<td>ACODES</td>
<td>Integration code table</td>
</tr>
<tr>
<td>AE</td>
<td>Exit area of rocket for each stage (in$^2$)</td>
</tr>
<tr>
<td>ALAT</td>
<td>Initial geodetic latitude (deg)</td>
</tr>
<tr>
<td>ALA2</td>
<td>Initial geodetic latitude (rad)</td>
</tr>
<tr>
<td>ALON</td>
<td>Initial longitude (deg)</td>
</tr>
<tr>
<td>ALO2</td>
<td>Initial longitude (rad)</td>
</tr>
<tr>
<td>ALT</td>
<td>Geocentric altitude (ft)</td>
</tr>
<tr>
<td>AN1</td>
<td>$\frac{x}{2} +$ longitude (rad)</td>
</tr>
<tr>
<td>AN2</td>
<td>Colatitude (rad)</td>
</tr>
<tr>
<td>AXLM</td>
<td>Axial moment of inertia (slug-ft$^2$)</td>
</tr>
<tr>
<td>AXLMB</td>
<td>Axial moment of inertia over transverse moment of inertia</td>
</tr>
<tr>
<td>B</td>
<td>Initial transverse moment of inertia for each stage (slug-ft$^2$)</td>
</tr>
<tr>
<td>BAZIM</td>
<td>AAZ12 - $\frac{x}{2}$ (rad)</td>
</tr>
<tr>
<td>BDOT</td>
<td>Rate of change of the transverse moment of inertia, B (slug-ft$^2$/sec)</td>
</tr>
<tr>
<td>BDOTB</td>
<td>$\dot{B}/B$ (sec$^{-1}$)</td>
</tr>
<tr>
<td>BL</td>
<td>Integration data storage</td>
</tr>
<tr>
<td>BLON</td>
<td>$\frac{x}{2} +$ ALO2 (rad)</td>
</tr>
<tr>
<td>C</td>
<td>$\frac{\Delta}{\sqrt{1 - e_E^2 \sin^2 \theta_G}}$ (ft)</td>
</tr>
<tr>
<td>CALAT</td>
<td>Cosine of the initial latitude</td>
</tr>
<tr>
<td>CBLOCK</td>
<td>Common block for integration</td>
</tr>
<tr>
<td>CDM</td>
<td>$C_D A/m$ - drag parameter used for empty stages (ft$^2$/slug)</td>
</tr>
</tbody>
</table>

**Note:** Some variables are marked with a plus sign (+), indicating they are stored in common.
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INPUTS

CHECK Flag for integration check
CN * Input table of normal force coefficient $C_{N_a}$ (rad$^{-1}$)
CNI Normal force coefficient used in calculation
CNMACH * Input CN Mach table
CNMTAB Inverted CN Mach table
CNTAB Inverted CN table
COEF Coefficient used in aerodynamic moment =

$$C_{N_a} \left( C_p - C_{G} \right) \frac{D^2 V_o}{B}$$

COLAT Initial co-latitude = $\frac{\pi}{2} - ALA2$ (rad)
COTHC Co-geocentric latitude = $\frac{\pi}{2} - THC$ (rad)
CP * Initial center of pressure table (feet from tail)
CPHI Cosine of PHI
CPHT Cosine of PHT
CPI Center of pressure used in calculation
CPMACH * Initial Mach No. table for center of pressure
CPMTAB Inverted CP Mach No. table
CPTAB Inverted CP table (ft)
CTHC Cosine of initial geocentric latitude = Cos (THC) +
CTHET Cosine of THETA
D * Diameter of each stage (ft)
DIMACH * Input Mach No. table for burning drag coefficient
D2MACH * Input Mach No. table for coasting drag coefficient
DC Direction cosines matrix
DELPR * Print times used in impact (sec)
DELTH Difference between $\theta_c$ and $\theta_g$ (rad)
DMTAB Inverted drag Mach table
DRAG1 * Input table of burning drag coefficient
DRAG2 * Input table of coasting drag coefficient
DT Print interval (sec)
DTAB Inverted drag table

+ Stored in common
**INPUTS**

- **DUM**  * Dummy variable
- **ERR**  Integration error
- **FDRAG**  Drag force (lb)
- **FORCE**  Vacuum thrust (lb)
- **FT**  Thrust on vehicle (lb)
- **FTT**  Total impulse (lb - sec)
- **GI**  Center of gravity at any given time (feet from tail)
- **GK**  Earth oblateness term $a_E^2 J$ (ft$^2$)
- **GM**  Gravitational constant for the Earth (ft$^3$/sec$^2$)
- **GO**  * Initial CG of the remaining missile for a given state (ft)
- **GOP**  Difference between GO and GP (ft)
- **GP**  * Initial CG of the fuel for a given stage (ft)
- **GRAVO**  Gravity constant (32.174 ft/sec$^2$)
- **GRV**  Term used to compute gravity components
- **GRVX**  Gravity component along the X axis (ft/sec$^2$)
- **GRVY**  Gravity component along the Y axis (ft/sec$^2$)
- **GRVZ**  Gravity component along the Z axis (ft/sec$^2$)
- **H**  Velocity vector (no wind) (ft/sec)
- **HALFPI**  $rac{x^2}{2}$
- **I**  Utility index
- **ICODE**  Code used to determine integration method
- **II**  Utility index
- **III**  Utility index
- **INTN**  * Order of interpolation
- **IRA**  Utility index
- **IT**  Print table count
- **J**  Utility index
- **JP**  Lines per page count for output
- **JTB1**  * Two Body input (number of time changes) +
- **JTB5**  * Two Body input (number of look-angle stations) +
- **K**  Utility index
- **KBATT**  Tape number for BATT tape = KNTRL(3) +
- **KIX**  Number of stages for subroutine impact

+ Stored in common
**INPUTS**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>KMETRO</td>
<td>Size of Metro tables</td>
</tr>
<tr>
<td>KNTRL(10)</td>
<td>Controls</td>
</tr>
<tr>
<td>KPLOT</td>
<td>Tape number of PLOT tape = KNTRL(6)</td>
</tr>
<tr>
<td>L</td>
<td>Stage count</td>
</tr>
<tr>
<td>LSkip</td>
<td>Skip aerodynamics</td>
</tr>
<tr>
<td>N</td>
<td>Table size</td>
</tr>
<tr>
<td>NO</td>
<td>Input card check</td>
</tr>
<tr>
<td>N1</td>
<td>Thrust table size for different stages</td>
</tr>
<tr>
<td>N2</td>
<td>Burning drag table size for different stages</td>
</tr>
<tr>
<td>N3</td>
<td>Coasting drag table size for different stages</td>
</tr>
<tr>
<td>N4</td>
<td>CP table size for different stages</td>
</tr>
<tr>
<td>N5</td>
<td>CN table size for different stages</td>
</tr>
<tr>
<td>NAME</td>
<td>Page title (up to 80 Hollerith characters)</td>
</tr>
<tr>
<td>NOE</td>
<td>Number of equations used in integration</td>
</tr>
<tr>
<td>NOT</td>
<td>Output tape number</td>
</tr>
<tr>
<td>NNX</td>
<td>Table of NRAT values</td>
</tr>
<tr>
<td>NRAT</td>
<td>Table size for each stage in impact</td>
</tr>
<tr>
<td>NS</td>
<td>Number of stages (NS &lt; 10)</td>
</tr>
<tr>
<td>NSPIN</td>
<td>Spin table size (NSPIN &lt; 100)</td>
</tr>
<tr>
<td>NXIM</td>
<td>Number of stages read in impact drag table</td>
</tr>
<tr>
<td>OMEG</td>
<td>Spin rate of Earth = $\omega_E$ (rad/sec)</td>
</tr>
<tr>
<td>OMEG2</td>
<td>Earth spin rate squared = $\omega_E^2$ (rad$^2$/sec$^2$)</td>
</tr>
<tr>
<td>OUT</td>
<td>Variable used for output</td>
</tr>
<tr>
<td>P1</td>
<td>Pressure times exit area (lb)</td>
</tr>
<tr>
<td>PAT</td>
<td>Pressure at which thrust is measured (lb/in$^2$)</td>
</tr>
<tr>
<td>PHI</td>
<td>Euler angle used in equations (rad)</td>
</tr>
<tr>
<td>PHID</td>
<td>First derivative of PHI (rad/sec)</td>
</tr>
<tr>
<td>PHIDD</td>
<td>Second derivative of PHI (rad/sec$^2$)</td>
</tr>
<tr>
<td>PH+</td>
<td>Orientation angle of thrust misalignment (rad)</td>
</tr>
<tr>
<td>PI</td>
<td>$\pi$</td>
</tr>
<tr>
<td>PRES</td>
<td>Atmospheric pressure (lb/ft$^2$)</td>
</tr>
<tr>
<td>PRTIME</td>
<td>Time at which to print (sec)</td>
</tr>
</tbody>
</table>

+ Stored in common
**INPUTS**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWGT *</td>
<td>Stage input weight (lb)</td>
</tr>
<tr>
<td>PWGTC *</td>
<td>Stage fuel weight (lb)</td>
</tr>
<tr>
<td>PX</td>
<td>Earth centered position vector used in integration (ft)</td>
</tr>
<tr>
<td>PXD</td>
<td>First derivative of position vector (ft/sec)</td>
</tr>
<tr>
<td>PXDD</td>
<td>Second derivative of position vector (ft/sec^2)</td>
</tr>
<tr>
<td>PXL</td>
<td>Position vector in launch coordinate system (ft)</td>
</tr>
<tr>
<td>PXLD</td>
<td>Velocity vector in launch coordinate system (ft/sec)</td>
</tr>
<tr>
<td>PXLDD</td>
<td>Acceleration vector in launch coordinate system (ft/sec^2)</td>
</tr>
<tr>
<td>PXND</td>
<td>Velocity vector in local coordinate system (ft/sec)</td>
</tr>
<tr>
<td>PYL WGT *</td>
<td>Payload weight (lb)</td>
</tr>
<tr>
<td>R</td>
<td>Distance from Earth center to vehicle (ft)</td>
</tr>
<tr>
<td>RA *</td>
<td>Fuel axial radius of gyration squared for each stage (ft^2)</td>
</tr>
<tr>
<td>RANGE</td>
<td>Range at burnout of each stage (N.M.)</td>
</tr>
<tr>
<td>RANGE1</td>
<td>Dummy variable used for impact (N.M.)</td>
</tr>
<tr>
<td>RAD</td>
<td>Radius of Earth as a function of latitude (ft)</td>
</tr>
<tr>
<td>RB *</td>
<td>Fuel transverse radius of gyration squared for each stage (ft^2)</td>
</tr>
<tr>
<td>RE</td>
<td>Equatorial radius of the Earth (ft)</td>
</tr>
<tr>
<td>REE</td>
<td>Distance from Earth center to launch pt (ft)</td>
</tr>
<tr>
<td>REL</td>
<td>Atmosphere density (slugs/ft^3)</td>
</tr>
<tr>
<td>RHO</td>
<td>Matrix from launch to Earth centered coordinates</td>
</tr>
<tr>
<td>ROT</td>
<td>&quot;COMMON&quot; rotation matrix</td>
</tr>
<tr>
<td>ROT1</td>
<td>Dummy variable used in X integration</td>
</tr>
<tr>
<td>R1X</td>
<td>Dummy variable used in Y integration</td>
</tr>
<tr>
<td>R2X</td>
<td>Dummy variable used in Z integration</td>
</tr>
<tr>
<td>R3X</td>
<td>Dummy variable used in ( \phi ) integration</td>
</tr>
<tr>
<td>R4X</td>
<td>Dummy variable used in ( \theta ) integration</td>
</tr>
<tr>
<td>R5X</td>
<td>Distance squared from Earth center to vehicle (ft^2)</td>
</tr>
<tr>
<td>R2</td>
<td>Distance squared from Earth center to vehicle (ft^2)</td>
</tr>
<tr>
<td>S</td>
<td>( \frac{\pi}{180} ) C (1 - ( e^2 )) (ft)</td>
</tr>
<tr>
<td>SILAT</td>
<td>Sine of the initial latitude</td>
</tr>
</tbody>
</table>

+ Stored in common

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**TDR-63-11**

**INPUTS**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAX</td>
<td>Maximum integration step size (sec)</td>
</tr>
<tr>
<td>SMIN</td>
<td>Minimum integration step size (sec)</td>
</tr>
<tr>
<td>SPHI</td>
<td>Sine of PHI</td>
</tr>
<tr>
<td>SPHI</td>
<td>Sine of PHT</td>
</tr>
<tr>
<td>SPI</td>
<td>Inverted spin table</td>
</tr>
<tr>
<td>SPIN</td>
<td>Input spin table (rad/sec)</td>
</tr>
<tr>
<td>SPIT</td>
<td>Integrated spin table (rad)</td>
</tr>
<tr>
<td>SPT</td>
<td>Inverted spin time table</td>
</tr>
<tr>
<td>SPTIME</td>
<td>Input spin time table (sec)</td>
</tr>
<tr>
<td>SS</td>
<td>Integration step size (sec)</td>
</tr>
<tr>
<td>STARTT</td>
<td>Start time or launch time (sec)</td>
</tr>
<tr>
<td>STHC</td>
<td>Sine of the initial geocentric latitude</td>
</tr>
<tr>
<td>STHET</td>
<td>Sine of THETA</td>
</tr>
<tr>
<td>STP</td>
<td>Initial PHI (deg)</td>
</tr>
<tr>
<td>STPD</td>
<td>Initial PHI DOT (deg/sec)</td>
</tr>
<tr>
<td>STT</td>
<td>Initial THETA (deg)</td>
</tr>
<tr>
<td>STTD</td>
<td>Initial THETA DOT (deg/sec)</td>
</tr>
<tr>
<td>STX</td>
<td>Initial position vector in launch coordinate system (ft)</td>
</tr>
<tr>
<td>STXD</td>
<td>Initial velocity vector in launch coordinate system (ft/sec)</td>
</tr>
<tr>
<td>SW</td>
<td>Angle between wind azimuth and X axis (rad)</td>
</tr>
<tr>
<td>T</td>
<td>Thrust vector in launch coordinate system (lb)</td>
</tr>
<tr>
<td>TABLE</td>
<td>Table of printout times</td>
</tr>
<tr>
<td>TB2</td>
<td>Number of orbits</td>
</tr>
<tr>
<td>TB3</td>
<td>Time increment ( \Delta t ) (sec)</td>
</tr>
<tr>
<td>TB4</td>
<td>Ending time (sec)</td>
</tr>
<tr>
<td>TB6</td>
<td>Name of look-angle station (up to 24 Hollerith characters)</td>
</tr>
<tr>
<td>TB7</td>
<td>Latitude of look-angle station (deg)</td>
</tr>
<tr>
<td>TB8</td>
<td>Longitude of look-angle station (deg)</td>
</tr>
<tr>
<td>TB9</td>
<td>Altitude of look-angle station (ft)</td>
</tr>
<tr>
<td>TDEL</td>
<td>Thrust misalignment angle (rad)</td>
</tr>
<tr>
<td>TFIMP</td>
<td>Stage drop time (sec)</td>
</tr>
<tr>
<td>THC</td>
<td>Initial geocentric latitude (rad)</td>
</tr>
</tbody>
</table>

+ Stored in common

42
### INPUTS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>THETA</td>
<td>Euler angle in the horizontal plane (rad)</td>
</tr>
<tr>
<td>THETD</td>
<td>First derivative of THETA (rad/sec)</td>
</tr>
<tr>
<td>THETDD</td>
<td>Second derivative of THETA (rad/sec^2)</td>
</tr>
<tr>
<td>THRUST</td>
<td>Input thrust table (lb)</td>
</tr>
<tr>
<td>THTAB</td>
<td>Inverted thrust table</td>
</tr>
<tr>
<td>TIME</td>
<td>Time (dependent variable) (sec)</td>
</tr>
<tr>
<td>TIMET</td>
<td>Time table for thrust (sec)</td>
</tr>
<tr>
<td>TMBO</td>
<td>Burnout time for each stage (sec)</td>
</tr>
<tr>
<td>TMCC</td>
<td>Time to change coefficients for each stage (sec)</td>
</tr>
<tr>
<td>TMI</td>
<td>Ignition time for each stage (sec)</td>
</tr>
<tr>
<td>TOMEQ</td>
<td>Twice the Earth spin rate = 2 ( \omega_E ) (rad/sec)</td>
</tr>
<tr>
<td>TP</td>
<td>Intermediate variables used in output block</td>
</tr>
<tr>
<td>TP1</td>
<td>Intermediate variables used in output block</td>
</tr>
<tr>
<td>TP2</td>
<td>Intermediate variables used in output block</td>
</tr>
<tr>
<td>TPHO</td>
<td>Orientation angle of thrust misalignment at a given time (rad)</td>
</tr>
<tr>
<td>TRERR</td>
<td>Integration truncation error</td>
</tr>
<tr>
<td>TRVM</td>
<td>Transverse moment of inertia at any time (ft^2 - slug)</td>
</tr>
<tr>
<td>TSTOP</td>
<td>Preset time to stop powered portion of program (sec)</td>
</tr>
<tr>
<td>TT</td>
<td>Thrust vector in Earth centered coordinate system (lb)</td>
</tr>
<tr>
<td>TTTAB</td>
<td>Inverted thrust time table</td>
</tr>
<tr>
<td>TWOP1</td>
<td>2 ( \pi )</td>
</tr>
<tr>
<td>V</td>
<td>Velocity of vehicle (ft/sec)</td>
</tr>
<tr>
<td>VA</td>
<td>Velocity of sound (ft/sec)</td>
</tr>
<tr>
<td>V2</td>
<td>Cross wind perpendicular to the velocity vector (ft/sec)</td>
</tr>
<tr>
<td>V3</td>
<td>Cross wind perpendicular to the velocity vector (ft/sec)</td>
</tr>
<tr>
<td>V MACH</td>
<td>Mach number of vehicle</td>
</tr>
<tr>
<td>VWX</td>
<td>Wind components in Earth-centered system (ft/sec)</td>
</tr>
<tr>
<td>VWY</td>
<td>Wind components in Earth-centered system (ft/sec)</td>
</tr>
<tr>
<td>VWZ</td>
<td>Wind components in Earth-centered system (ft/sec)</td>
</tr>
<tr>
<td>VX</td>
<td>Velocity vector with wind in Earth-centered system (ft/sec)</td>
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<tr>
<td>WALT</td>
<td>Input metro altitude table (ft)</td>
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</table>
### INPUTS

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>WALTU</td>
<td>Inverted metro altitude table (ft)</td>
</tr>
<tr>
<td>WDEN</td>
<td>Input metro atmosphere density (kgm/m$^3$)</td>
</tr>
<tr>
<td>WDU</td>
<td>Inverted metro atmosphere density (slugs/ft$^3$)</td>
</tr>
<tr>
<td>WGT</td>
<td>Mass of remaining missile for each stage (slugs)</td>
</tr>
<tr>
<td>WGTAB</td>
<td>Inverted mass table (slugs)</td>
</tr>
<tr>
<td>WGTC</td>
<td>Mass of fuel for each stage (slugs)</td>
</tr>
<tr>
<td>WGTCI</td>
<td>Mass expelled from ignition (slugs)</td>
</tr>
<tr>
<td>WINDA</td>
<td>Mass at a given time WGTI = WGT - WGTCI (slugs)</td>
</tr>
<tr>
<td>WINDV</td>
<td>Local wind azimuth (deg from North, clockwise)</td>
</tr>
<tr>
<td>WINDV</td>
<td>Local wind velocity (ft/sec)</td>
</tr>
<tr>
<td>WMAX</td>
<td>Maximum altitude of metro table (ft)</td>
</tr>
<tr>
<td>WPU</td>
<td>Input metro pressure table (millibars)</td>
</tr>
<tr>
<td>WPRES</td>
<td>Inverted metro pressure table (lb/ft$^2$)</td>
</tr>
<tr>
<td>WTEMP</td>
<td>Input metro temperature table (°C)</td>
</tr>
<tr>
<td>WTEMP</td>
<td>Inverted speed of sound table (ft/sec)</td>
</tr>
<tr>
<td>WX</td>
<td>Wind component parallel to Earth-centered X axis (ft/sec)</td>
</tr>
<tr>
<td>WY</td>
<td>Wind component parallel to Earth-centered Y axis (ft/sec)</td>
</tr>
<tr>
<td>WZ</td>
<td>Wind component parallel to Earth-centered Z axis (ft/sec)</td>
</tr>
<tr>
<td>X1X</td>
<td>Variables used in geodetic to geocentric conversion</td>
</tr>
<tr>
<td>X1Y</td>
<td>Variables used in geodetic to geocentric conversion</td>
</tr>
<tr>
<td>XDIMP</td>
<td>Velocity vector at burnout for impact (ft/sec)</td>
</tr>
<tr>
<td>XIMPA</td>
<td>Position vector at burnout for impact (ft)</td>
</tr>
<tr>
<td>XJ</td>
<td>First harmonic coefficient for oblateness</td>
</tr>
<tr>
<td>XMACH</td>
<td>Mach number table for $C_DA/m$</td>
</tr>
<tr>
<td>XSP</td>
<td>Spin rate at any given time (rad/sec)</td>
</tr>
<tr>
<td>XSPT</td>
<td>Integrated spin at any given time (rad)</td>
</tr>
<tr>
<td>XVX</td>
<td>Variable used in calculation of PX</td>
</tr>
<tr>
<td>ZZ</td>
<td>Lines-per-page count for Two Body output</td>
</tr>
</tbody>
</table>

+ Stored in common
5. **SPURT FLOW DIAGRAMS.**
INSTRUCTION SUM ROUTINES THERE ARE FOUR
EXITS FROM THIS ROUTINE
1. E Go EQUATION OF MOTION
2. EXIT EXITS ON EVERY INTEGRATION STEP
3. EXIT EXITS ON PRINT TIME
4. EXIT EXITS ON CRITERION FAILURE

- SENSE SWITCH 1
- SENSE SWITCH 2
- SENSE LIGHT 1
- SENSE LIGHT 2
- PRINT INTERMEDIATE RESULTS
- DOWN 500
- UP
- EXIT
- RETURN
- RETURN
- PRINT CRITERION FAILURE
- TWIN
- EXIT
6. **SUBROUTINES.**
a. **Atmosphere subroutine.**

The 1962 COESA standard atmosphere is incorporated as a subroutine of SPURT. This atmosphere uses the equations derived for the 1959 ARDC model atmosphere. These equations are

1. **Molecular-scale temperature**

\[ T_m = (T_m)_b + L_m (H - H_b) \]

2. **Pressure - altitude**

\[
P = P_b \left[ \frac{(T_m)_b}{(T_m)_b + L_m (H - H_b)} \right] \frac{G M_o}{R^* L_m} \quad \text{for } L_m \neq 0
\]

\[
P = P_b \exp \left[ \frac{-G M_o (H - H_b)}{R^* (T_m)_b} \right] \quad \text{for } L_m = 0
\]

3. **Density - altitude**

\[ \rho = 3.236598 \times 10^{-4} \frac{P}{T_m} \]

4. **Speed of sound**

\[ V_s = 1116.4437 \sqrt{\frac{T_m}{T_m_0}} \]

where \( b \) = subscript that refers to the quantity at the base of the constant-gradient layer.

\[ G M_o / R^* = \text{constant of the air gas} \]

\[ H = \text{geopotential altitude in meters} \]

\[ H_b = \text{geopotential altitude in meters at the base of a constant gradient layer} \]

\[ L_m = \frac{dT_m}{dH} = \text{the gradient of the molecular scale temperature} \]

\[ P = \text{pressure} \]
P_b = pressure at the base of a particular layer

T_m = the molecular scale temperature

(T_m)_b = the value of T_m at the base of a particular layer

V_s = speed of sound (ft/sec)

ρ = density of the air (slugs/ft^3)

The skeleton of the COESA is from reference 15 and is given in table 1.

### TABLE 1.

SKELETON OF THE U.S. STANDARD ATMOSPHERE—1962

Defining temperature and molecular weights of the proposed U.S. Standard Atmosphere and computed pressures and densities, where h = geopotential altitude, z = geometric altitude, T = kinetic temperature, N = mean molecular weight, L = gradient of molecular scale temperatures, (T_m)_b = the value of T_m at the base of a particular layer, and N_b = sea-level value of N.

<table>
<thead>
<tr>
<th>L, km</th>
<th>h, km</th>
<th>N_b, K</th>
<th>L</th>
<th>T, K</th>
<th>P, ab</th>
<th>P_b, g/cm^3</th>
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<tr>
<td>0.000</td>
<td>0.000</td>
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<td>-6.5</td>
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<td>1.0</td>
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<td>2.6</td>
<td>288.16</td>
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<td>0.0</td>
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<td>288.16</td>
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<table>
<thead>
<tr>
<th>L, km</th>
<th>h, km</th>
<th>N_b, K</th>
<th>L</th>
<th>T, K</th>
<th>P, ab</th>
<th>P_b, g/cm^3</th>
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</table>

*Power of 10 by which preceding number must be multiplied.

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This routine must be called by the CODAP symbolic language as follows:

```
LDA  ALT
RTJ  ATMOS
TEM  OCT
PRES OCT
RHO  OCT
VA   OCT
ERR
N. R.
```

where

- ALT is the altitude in feet
- TEM is the temperature
- PRES is the pressure
- RHO is the density
- VA is the speed of sound
- ERR is the error return
- N. R. is the normal return
b. **Subroutine E_clock and subroutine S_clock.**

These subroutines are incorporated to compute the time used by the computer in computing a typical trajectory. These subroutines are written in the CODAP symbolic language and are callable by FORTRAN. The S clock subroutine will initialize the computer clock to zero, and the E clock subroutine will stop the clock and print out the elapsed time in hours, minutes, and seconds.

To use the S clock subroutine:

```
CALL SCLOCK
```

To use the E clock subroutine:

```
CALL ECLOCK(N) where time is printed on tape number N.
```
c. **Subroutine GEODED.**

The subroutine converts geocentric latitude and radius to geodetic latitude and altitude by use of the following equations.

\[ \theta_G = \theta_c + \sin^{-1} \left( \frac{a_E}{r} \left[ f \sin 2\theta_c + f^2 \sin^4 \frac{\theta_c}{2} \left( \frac{a_E}{r} - 1 \right) \right] \right) \]

\[ H_G = r - a_E \left[ 1 - f \sin^2 \theta_c - \frac{r^2}{2} \sin^2 2\theta_c \left( \frac{a_E}{r} - 1 \right) \right] \]

where

- \( a_E \) = equatorial radius of the Earth
- \( f \) = flattening of the Earth
- \( r \) = geocentric position vector
- \( H \) = geodetic altitude
- \( \theta \) = latitude
- \( c \) = refers to geocentric
- \( G \) = refers to geodetic

This subroutine is callable by FORTRAN.

To use:

CALL GEODED (A, B, C, D)

where

- \( A \) is the geocentric latitude (radians)
- \( B \) is the geocentric position vector (feet)
- \( C \) is the geodetic latitude (radians)
- \( D \) is the geodetic altitude (feet)
d. Impact subroutine.

The Impact subroutine is a point mass three-degree-of-freedom trajectory subroutine. This routine is incorporated primarily to compute the trajectories of the "separated" expended stages.

The vector form of the equation of motion is the geocentric position equation derived in section 2 of this report and is

$$\frac{d^2 \vec{R}}{dt^2} = \frac{\vec{\omega}_E}{M} + 2 \left( \frac{d\vec{R}}{dt} \times \vec{\omega}_E \right) - \vec{\omega}_E \times \left( \vec{\omega}_E \times \vec{R} \right)$$

The atmosphere subroutine is used along with the oblate Earth described in section 2. The drag parameter \((C_d A/M)\) vs. Mach number table for the expended stages are read in the main program and placed in common for use by the Impact subroutine.

The Integration routine will use the same option as the main portion of the program (powered flight) uses. When the altitude is negative, the Impact subroutine will punch a card containing the name, stage number, impact latitude, and longitude. The routine will then terminate and return to the main program. To use the Impact subroutine, control number 8 must be set equal to 1 or to 2.
## VARIABLES USED IN IMPACT SUBROUTINE

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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<td>Not used in impact</td>
</tr>
<tr>
<td>AC</td>
<td>Not used in impact</td>
</tr>
<tr>
<td>ACODE</td>
<td>Integration code</td>
</tr>
<tr>
<td>ACODES</td>
<td>Integration code table</td>
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<tr>
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</tr>
<tr>
<td>AE</td>
<td>Equatorial radius of the Earth</td>
</tr>
<tr>
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</tr>
<tr>
<td>AH</td>
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<tr>
<td>AI</td>
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</tr>
<tr>
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<tr>
<td>AN1</td>
<td>Variables used for output parameters</td>
</tr>
<tr>
<td>AN2</td>
<td>Variables used for output parameters</td>
</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>ARG</td>
<td>Argument used for gravitational computation</td>
</tr>
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<td>Block reserved for integration</td>
</tr>
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<td>CDM</td>
<td>$C_{DA/M}$ - drag parameter</td>
</tr>
<tr>
<td>CHECK</td>
<td>Check used in integration</td>
</tr>
<tr>
<td>COSRA</td>
<td>Cosine of the range angle</td>
</tr>
<tr>
<td>DELPR</td>
<td>Print time increment</td>
</tr>
<tr>
<td>DM</td>
<td>Drag over mass parameter</td>
</tr>
<tr>
<td>DRA</td>
<td>Variable used in computing drag</td>
</tr>
<tr>
<td>DRAG</td>
<td>Drag parameter of empty stage</td>
</tr>
<tr>
<td>DUMB1</td>
<td>Not used in impact</td>
</tr>
<tr>
<td>ERR</td>
<td>Integration error</td>
</tr>
<tr>
<td>FMN</td>
<td>Mach number of empty stage</td>
</tr>
</tbody>
</table>

* Stored in common  
+ Equivalence with AL
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM</td>
<td>Gravitational constant</td>
</tr>
<tr>
<td>GX</td>
<td>X component of gravitational attraction</td>
</tr>
<tr>
<td>GY</td>
<td>Y component of gravitational attraction</td>
</tr>
<tr>
<td>GZ</td>
<td>Z component of gravitational attraction</td>
</tr>
<tr>
<td>H</td>
<td>Variable used for first time increment</td>
</tr>
<tr>
<td>I</td>
<td>Utility index</td>
</tr>
<tr>
<td>ICODE</td>
<td>Code for method of integration</td>
</tr>
<tr>
<td>II</td>
<td>Utility index</td>
</tr>
<tr>
<td>JP</td>
<td>Page count</td>
</tr>
<tr>
<td>J1</td>
<td>Number of stage being computed</td>
</tr>
<tr>
<td>J6</td>
<td>Number of lines per page</td>
</tr>
<tr>
<td>K</td>
<td>Utility index</td>
</tr>
<tr>
<td>KAA</td>
<td>Not used in impact</td>
</tr>
<tr>
<td>KAF</td>
<td>Not used in impact</td>
</tr>
<tr>
<td>KAZ</td>
<td>Not used in impact</td>
</tr>
<tr>
<td>N</td>
<td>Number of values in drag table</td>
</tr>
<tr>
<td>NAME</td>
<td>Name stored in common</td>
</tr>
<tr>
<td>NN</td>
<td>Integer for drag selection</td>
</tr>
<tr>
<td>NOE</td>
<td>Number of equations for integration</td>
</tr>
<tr>
<td>NOT</td>
<td>Number of output tape</td>
</tr>
<tr>
<td>OUT</td>
<td>Dimensioned output variables</td>
</tr>
<tr>
<td>PE</td>
<td>Earth flattening constant</td>
</tr>
<tr>
<td>PI</td>
<td>$\pi = 3.1415927$</td>
</tr>
<tr>
<td>PRTIM1</td>
<td>Print time for integration routine</td>
</tr>
<tr>
<td>R</td>
<td>Length of position vector</td>
</tr>
<tr>
<td>RAD</td>
<td>$= \pi/180. = 1/57.2957795$</td>
</tr>
<tr>
<td>RANGE</td>
<td>Great circle range from launch point</td>
</tr>
<tr>
<td>R2</td>
<td>Position vector squared</td>
</tr>
<tr>
<td>SIT</td>
<td>Sine of the latitude</td>
</tr>
<tr>
<td>SMAX</td>
<td>Maximum integration step size</td>
</tr>
<tr>
<td>SMIN</td>
<td>Minimum integration step size</td>
</tr>
</tbody>
</table>

* Stored in common
+ Equivalence with AL
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SS       Integration step size       +
T        Time, independent variable    +
TFIMP    Initial time for Impact computation  *
THET     Latitude of position vector  +
TRERR    Integration truncation error  *
VA       Velocity of sound  +
VD       Vector used for matrix rotation  +
VEL      Velocity of empty stage  *
W        Rotational velocity of the Earth  *
WD       Vector used for matrix rotation  *
W²      = W squared
X       Component of position vector  *
XALT     Altitude from GEOD subroutine  *
XD       Velocity vector component  *
XDD      Second derivative of the motion equation  *
XDIMP    Input velocity vector  *
XD1      Velocity used in integration routine  *
XIMPA    Input position vector  *
XK2      Oblateness constant
XLAT     Geodetic latitude from GEOD subroutine  *
XMACH    Mach number table for drag  *
XMN      Stage Mach number table  *
XX       Vector for computing range  *
XXD      Velocity vector  *
Y        Component of position vector  *
YD       Velocity vector component  *
YDD      Second derivative of the motion equation  *
YD1      Velocity used in integration routine  *
Z        Component of position vector  *
ZD       Velocity vector component  *
ZDD      Second derivative of the motion equation  *
ZD1      Velocity used in integration routine  *
Z²       Number of lines per page  *

* Stored in common
+ Equivalence with AL
e. **Integration.**

A. **IDENTIFICATION**

**TITLE:** Numerical Integration of Ordinary Differential Equations with Error Control  
**CO-OP ID:** D2 CODA NMI 2  
**PROGRAMMER:** Roger Johnson  
**DATE:** February 27, 1961

B. **PURPOSE**

To integrate a set of \( N \) simultaneous first order differential equations of the form:

\[
\frac{dx_i}{dt} = f_i(t, x_1, x_2, \ldots x_N), \ i = (1, 2, \ldots N).
\]

The user has the option of either a Runge-Kutta or Adams-Moulton integration scheme. The integration step size, \( \Delta t \), may be a variable step size under error control or a fixed step size. A print option causes printing of the initial conditions and various parameters before the start of the integration to help define each case. The user also has an option to break into the program at exact specified values of the independent variable \( t \).

C. **USAGE**

The index registers are saved. No internal checks of arithmetic faults (exponential overflow, underflow, etc.) are made. When the print option is used, the differential equation routine removes the selection of interrupt on arithmetic faults before printing and does a clear arithmetic faults after printing. The differential equations routine should not cause an arithmetic fault unless the \( x_i \)'s exceed the range of the floating point format.
1. Calling Sequence -

The calling sequence used to start or restart; if parameters are changed, the integration of a set of differential equation is

<table>
<thead>
<tr>
<th>Loc</th>
<th>OPN</th>
<th>B</th>
<th>M</th>
<th>OPN</th>
<th>B</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>BETA</td>
<td>SLJ</td>
<td>4</td>
<td>ADAMS</td>
<td>0</td>
<td>P</td>
<td>DERIV</td>
</tr>
<tr>
<td>BETA+1</td>
<td>0</td>
<td>0</td>
<td>TEXIT</td>
<td>0</td>
<td>0</td>
<td>T</td>
</tr>
<tr>
<td>BETA+2</td>
<td>0</td>
<td>0</td>
<td>DATA</td>
<td>0</td>
<td>0</td>
<td>COMMON</td>
</tr>
<tr>
<td>BETA+3</td>
<td>0</td>
<td>0</td>
<td>EXIT</td>
<td>0</td>
<td>0</td>
<td>TMIN</td>
</tr>
<tr>
<td>BETA+4</td>
<td>ERROR RETURN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Parameters -

The upper part of the first instruction of the calling sequence is a return jump command SLJ 4 ADAMS, to the first location of differential equation routine.

If \( P \) is unequal to zero the differential equation routine will print the initial conditions and the parameters in the DATA region using the Generalized Listable Output Routine (J5 LMSD OUTPUT). If \( P \) is zero no printing takes place.

**DATA**: starts a block of \( 3N+8 \) locations that the user sets up with the parameters and variables. The location and description of the parameters and variables are as follows:

**DATA** contains the integration scheme code which is a fixed point binary integer (binary point at the far right) set up by the user.

a) If code = 0: The integration scheme is the Runge-Kutta mode with a fixed \( \Delta t \).

b) If code = 1: The integration scheme is the Runge-Kutta predictor-corrector mode with a variable \( \Delta t \).
c) If code = 2: The integration scheme is the Adams-Moulton mode with a fixed $\Delta t$.

d) If code = 3: The integration scheme is the Adams-Moulton predictor-corrector mode with a variable $\Delta t$.

e) If the code is negative or any binary digit greater than 3, the code is out of range. If this occurs, the AC is set to the binary integer 2 and a jump is made to the error return in BETA+ 4.

$DATA_{+1}$ contains the floating point number $A$ used in the variable step mode to prevent unnecessary halving of $\Delta t$ when $x_i$ becomes small in magnitude. If $A$ is positive then a positive floating point number $A_i$ must be determined for each $x_i$, ($i = 1, 2, \ldots, N$), and be set up by the user in the following locations:

$$A_1 \text{ in } DATA + 2N + 8$$
$$A_2 \text{ in } DATA + 2N + 9$$
$$A_N \text{ in } DATA + 3N + 7$$

If $A$ is a negative floating point number then the absolute value of $A$ is set in location $DATA + 2N + 8$ and used for all $A_i$ ($i = 1, 2, \ldots, N$). If $A$ is zero then location $DATA + 2N + 8$ is set to zero and $A$ is ignored in the halving and doubling option.

$DATA_{+2}$ contains a positive floating point number $E$ used in the truncation error test in the predictor-corrector variable $\Delta t$ mode. If $E$ is set to $10^{-h}$ approximately $h$ significant figures are asked for in the truncation error test. ($10^{-1} \leq E \leq 10^{-8}$) is the suggested range of $E$.

$DATA_{+3}$ contains a positive floating point number called MINIMUM DT. If in the truncation error test, after a step $\Delta t$, one or more of the variables doesn't meet the convergence test and $\Delta t$ is less than or equal to MINIMUM DT, the differential
equation routine does a return jump to the user's subroutine starting at TMIN. The location of TMIN is given in the calling sequence. The user may stop and do some checking or do an unconditional jump to TMIN to return to the differential equation routine. The differential equation after the return accepts the step $\Delta t$ ignoring the failure of the convergence test and continues the integration.

**DATA+4** contains the positive floating point number MAXIMUM DT. If in the truncation error test all the variables have converged so well that doubling is indicated but $\Delta T$ is already greater or equal to MAXIMUM DT then $\Delta T$ is not doubled and the next integration step is still $\Delta T$.

**DATA+5** contains a positive fixed point integer $N$, the number of differential equations to be solved.

**DATA+6** contains the floating point number DELTA T. In the fixed $\Delta T$ mode the whole integration is done with the fixed integration step DELTA T. In the halving and doubling mode the initial trial step is $\Delta T$ but if the convergence test fails, the initial step will be redone at half $\Delta T$ and this halving will continue until the convergence test is passed. If the convergence test indicates doubling the next step made will be $2\Delta T$. If on entering the differential equation routine DELTA T is zero or negative the AC is set to the binary integer +1 and an unconditional jump is made to the error return BETA +4.

**DATA+7** is the location of independent variable $t$. The user must set up an initial value of $t$ (a floating point number) that can be negative, zero, or positive. The differential equation will advance $t$ by some $\Delta t$ during each integration step.

**DATA+8** is the beginning of the $N$ locations containing the dependent variable $x_1$ through $x_N$. The user sets them up to their initial values at the start of a problem. The differential equation integrates them with step $\Delta t$ and replaces
them with their new values.

\[
\begin{align*}
    x_1 & \text{ is in location DATA } + 8 \\
    x_2 & \text{ is in location DATA } + 9 \\
    \cdots \cdots \cdots \cdots \cdots \\
    x_N & \text{ is in location DATA } + N + 7 \\
\end{align*}
\]

\( \text{DATA } + N + 8 \) is the beginning of the \( N \) locations of the derivatives of \( x_i \) or \( f_i(t, x_1, x_2, \ldots, x_N) \). The user must code a subroutine starting at location DERIV (given in the calling sequence) to calculate the derivatives of \( x_i \) using the values of \( t, x_1, x_2, \ldots, x_N \) in their DATA locations and then store the derivatives in their locations in the DATA region. As the DERIV subroutine is entered by a return jump from the differential equations routine, an unconditional jump to location DERIV gives the return to the differential equations routine so it can continue the solution. The DATA locations of \( f_i \), or the derivatives are:

\[
\begin{align*}
    \frac{dx_1}{dt} &= f_1 \text{ is in location DATA } + N + 8 \\
    \frac{dx_2}{dt} &= f_2 \text{ is in location DATA } + N + 9 \\
    \frac{dx_N}{dt} &= f_N \text{ is in location DATA } + 2N + 7
\end{align*}
\]

\( \text{DATA } + 2N + 8 \) is the beginning of the \( N \) locations of \( A_i \).

These are the last locations used in the DATA region. A description of the \( A_i \)'s has already been given under the discussion of DATA + 1.

DERIV is the beginning of a subroutine to be coded by the user. The user's DERIV subroutine function uses the variables \( t \) and \( x_i \) in the DATA regions to calculate the derivatives, \( f_i \), and stores them in the DATA region. The location of the variables
in the DATA region have been described before, but to repeat:

\[ t \text{ is in } \text{DATA+} + 7 \]
\[ x_1 \text{ is in } \text{DATA+} + 8 \]
\[ x_2 \text{ is in } \text{DATA+} + 9 \]
\[ \ldots \ldots \ldots \]
\[ x_N \text{ is in } \text{DATA+} + N + 7 \]
\[ f_1 \text{ is in } \text{DATA+} + N + 8 \]
\[ f_2 \text{ is in } \text{DATA+} + N + 9 \]
\[ \ldots \ldots \ldots \]
\[ f_N \text{ is in } \text{DATA+} + 2N + 7 \]

After calculating and storing the \( f_i \)'s the DERIV routine does an unconditional jump to DERIV which causes a return to the differential equations routine so it can continue the solution. No printing should be done in this routine as the \( x_i \)'s in the DATA region may be just preliminary estimates.

EXIT is the beginning of a subroutine coded by the user to perform printing. When \( t \) and the \( x_i \)'s have been integrated a step \( \Delta t \) and the \( x_i \)'s have satisfied the convergence conditions, the differential equation routine goes to the DERIV subroutine which calculates the derivatives of the new \( x_i \)'s. The differential equation routine then executes a return jump instruction, SLJ 4 EXIT, to the users subroutine for possible printing. The user's subroutine can just bump a counter and do printing just every \( k \) steps or can print at each step. The user can take selected values of \( t, x_i \) and the derivatives of \( x_i \) from the DATA region, or calculate functions of these variables and print them or save them for future interpolation.

If the Generalized Listable Output Routine is used the user should remove the selection of interrupt on arithmetic fault before printing as the output routine often causes arithmetic faults not related to computational errors. After printing, a
clear arithmetic faults instruction should be given to clear possible arithmetic faults from the output routine. At the end of the EXIT subroutine the user does an unconditional jump to EXIT to return control to the differential equation routine.

TEXIT and T are set up by the user to get points on the solution of the differential equation for specified values of the independent variable t. The way it works is if the independent variable t is equal to or greater than the contents of location T, the differential equation routine will do a return jump to TEXIT with the contents of location T minus the independent variable t in the AC. In using this feature the contents of location T should be always set greater than the independent variable t. Because if the next integration step will make t larger than the contents of location T the differential equation routine does a special Runge-Kutta integration step with a value of Δt to advance t and calculate xₙ and the derivatives of xₙ. Δt is such that t is equal to the contents of location T. After this special Δt step the old Δt is restored and the differential equation routine does a return jump, SLJ 4 TEXIT, to the user's TEXIT subroutine and as t equals the contents of location T the AC is zero. The user's subroutine, TEXIT, may do printing, keeping in mind the suggestions given in the EXIT subroutine. It should then advance the contents of T to the next break point. To exit, an unconditional jump to TEXIT returns to the differential equation routine.

If the contents of T are less than the independent variable t because of improper updating or some other oversight, the differential equation routine still executes the instruction, SLJ 4 TEXIT, but with the AC minus to show that the break point has been passed in t. The break point features of the differential equation routine will be ignored if T or the contents of location T are set to zero, then no jump to TEXIT will ever occur. If both T and the contents of
location $T$ are nonzero, but TEXIT is zero, the differential equations routine will go to its error return with a fixed integer -1 in the AC because no subroutine can start at zero.

If, when $t$ equals the contents of location $T$ the formulas to compute the derivatives of $x$ are changed or it is wished to change some of the parameters in the DATA region, the solution of the differential equation must be restarted by either going to a new calling sequence or back to the start of the old calling sequence.

If $t$ is at the end of a case, the next case can be set up and the differential equation routine restarted with a calling sequence. Only in the user's EXIT and TEXIT subroutines can the values of the variables be trusted either for printing or restarting the solution by going to a calling sequence.

BETA + 4 is the error return for the differential equation routine. An unconditional jump is made to BETA + 4, with a fixed point binary integer in the AC which tells the type of error, if a parameter is obviously bad. To correct this, the bad parameter should be changed and the case rerun. When at location BETA + 4, if:

- AC is 0: then $N$, the number of equations to be solved, (location DATA + 5) has been set to zero, a negative number, or is greater than 200.
- AC is +1: then $\Delta t$ (location DATA + 6) is either zero, negative, or not in normalized floating point form.
- AC is +2: then the integration code in location DATA is either negative or greater than +3.
- AC is -1: Both $T$ and the contents of $T$ are nonzero, but TEXIT is zero. This means the exact $t$ break feature is being used but the user's subroutine, TEXIT, starts at location zero. This is invalid.
COMMON is a block of 14N + 5 locations starting at COMMON that the user must reserve for the differential equation routine. When command has been transferred to the user EXIT subroutine the first N location of COMMON contain the predictor values of the new \( x_i \). The truncation error of the last step for the variable \( x_i \) is about \( \frac{1}{14} (x_{p,i} - x_i) \) in magnitude. The locations of the variables \( x_{p,i} \) and \( x_i \) are:

\[
\begin{align*}
  x_{p,1} & \text{ is in location COMMON} \\
  x_{p,2} & \text{ is in location COMMON + 1} \\
  \ldots & \ldots \\
  x_{p,N} & \text{ is in location COMMON + N-1}
\end{align*}
\]

If the user needs the values of \( t \) and the variables \( x_i \) of the last step for interpolation they can be found in the locations:

\[
\begin{align*}
  t & \text{ in COMMON + N} \\
  x_1 & \text{ in COMMON + N + 1} \\
  x_2 & \text{ in COMMON + N + 2} \\
  \ldots & \ldots \\
  x_N & \text{ in COMMON + 2N}
\end{align*}
\]

As already described in the writeup, the current \( x_i \)'s are in the DATA locations:

\[
\begin{align*}
  x_1 & \text{ in DATA + 8} \\
  x_2 & \text{ in DATA + 9} \\
  \ldots & \ldots \\
  x_N & \text{ in DATA + N + 7}
\end{align*}
\]

TMIN is the first location of a subroutine coded by the user that the differential equation goes to if the convergence test has failed and \( \Delta t \) is less than or equal to \text{MINIMUM DT}.
Its use is discussed later in this writeup.

3. SPACE REQUIRED - is about 700 locations not including the 610 locations of the Generalized Listable Output routine.

4. TEMPORARY STORAGE - none. The two blocks of storage DATA (3N+8 locations) and COMMON (14 N+5 locations) cannot be used by the programer to store numbers.

7. ERROR STOPS - the error return is described before. It is in location BETA + 4 in the calling sequence.

9. PRINT INFORMATION - If the print option is used the "General Listable Output Routine" must be in the computer and its symbol location, OUTPUT, in 70412B. At the head of the assembly is the card

```
OUTPUT EQU 70412B
```

The symbolic location ADTAPE, in the differential equation routine determines the channel number of the output tape, the tape number, and 1607 number. The print option sets up words for the write BCD tape calling sequence by using ADTAPE after inserting the proper carriage control in the lower address. Therefore, to change the channel number, tape number, or 1607 number, just modify the contents of ADTAPE in the differential equation routine. At present:

- CN or channel number of the output tape is 4
- TN or tape number of the output tape is 4
- UN or 1607 number is 2

D. METHOD

To compute the change of $x_i$ with the integration step $\Delta t$ the fourth order Runge-Kutta method gives the formulas:
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\[ k_1, i = (\Delta t) \ f_i (t, x_1, x_2, \ldots, x_n) \]

\[ k_2, i = (\Delta t) \ f_i (t + \frac{1}{2} \Delta t, x_1 + \frac{1}{2} k_1, i, \ldots, x_n + \frac{1}{2} k_1, n) \]

\[ k_3, i = (\Delta t) \ f_i (t + \frac{1}{2} \Delta t, x_1 + \frac{1}{2} k_2, i, \ldots, x_n + \frac{1}{2} k_2, n) \]

\[ k_4, i = (\Delta t) \ f_i (t + \Delta t, x_1 + k_3, i, \ldots, x_n + k_3, n) \]

\[ \Delta x_i = \frac{1}{6} (k_1, i + 2k_2, i + 2k_3, i + k_4, i) \]

The calculation: \( x_i^c (t + \Delta t) = x_i (t) + \Delta x_i \) is done in double precision to help control rounding errors. All other calculations are performed in single precision. Programers at STL didn't feel the Gill or other modifications to control rounding errors to be of much value so the standard Runge-Kutta method was programed.

The Adams-Moulton method requires the derivatives of \( x_i \) three equal steps behind. To start the Adams-Moulton integration, several Runge-Kutta integrations are required. The Adams-Moulton predictor-corrector formulas are:

\[ x_i^p, k+1 = x_i, k + \frac{\Delta t}{24} (55 f_i, k - 59 f_i, k-1 + 37 f_i, k-2 - 9 f_i, k-3) \]

\[ \Delta x_i, k = \frac{\Delta t}{24} (9 f_i^p, k+1 + 19 f_i, k+1 - 5 f_i, k+1 + f_i, k-2) \]

Again the calculation \( x_i^c, k+1 = x_i, k+1 + \Delta x_i, k \) is done in double precision to help control rounding errors.

Both Adams-Moulton and Runge-Kutta have error terms of the order \( (\Delta t)^5 \) but the Runge-Kutta step requires four references to the derivatives against just two references in an Adams-Moulton step; so for most problems the Adams-Moulton integration method is to be preferred.

In integrating a differential equation numerically, it is replaced with a difference equation and we solve this difference equation. If the integration steps used are small and an integration scheme like
Adams-Moulton or Runge-Kutta which have favorable stability properties is used, the solution of the difference equation is usually close to the solution of the differential equation. However, if some of the variables \( x_i \) given by the differential equation routine have either odd oscillations or increase very rapidly with the physical problem not suggesting such behavior, the solution is probably unstable and greatly in error. In long problems with many integration steps a slight instability will cause the solution to slowly drift from the true solution of the differential equation. An unstable solution can often be made stable by integrating with a smaller step \( \Delta t \) or by forcing a smaller step by asking for more accuracy in the predictor-corrector mode. The reason for this is that different step sizes change the parameters relating to the stability of the difference equation. Therefore, if two solutions with different step sizes are similar and close together, both solutions can be accepted as correct. The routine also makes it easy to do checking by running the same case over using both the Runge-Kutta and Adams-Moulton integration methods. Usually the truncation error requirements in solving a set of differential equations dictate integration steps sufficiently small to insure stability.

HALFING AND DOUBLING MODE

When doing an Adams-Moulton integration step \( \Delta t \) to advance the dependent variables from \( x_i(t) \) to \( x_i(t + \Delta t) \) for each variable, we first calculate the predicted value \( x_i^p(t + \Delta t) \) for each variable. The users DERIV routine is used to calculate the predictor derivatives, \( f_i(t + \Delta t, x_1^p(t + \Delta t), \ldots, x_n^p(t + \Delta t)) \). Using the predicted derivatives the step is finished by calculating \( x_i^c(t + \Delta t) \) the corrector. An estimate of the magnitude of the truncation error of each variable in the last step is:

\[
\frac{1}{14} \left| x_i^c(t + \Delta t) - x_i^p(t + \Delta t) \right|
\]

To get an estimate of the truncation error in the Runge-Kutta mode
we first do a Runge-Kutta integration step of $2\Delta t$ to get the predictor, $x^P_i(t + 2\Delta t)$. Then restarting with the variables $x_i(t)$ we do two Runge-Kutta integration steps each of length $\Delta t$ to get the corrector, $x_i(t + 2\Delta t)$. An estimate of the magnitude of the truncation error for each variable in the step from $x_i(t)$ to $x_i(t + 2\Delta t)$ is:

$$\frac{1}{15} \left| x^C_i(t + 2\Delta t) - x^P_i(t + 2\Delta t) \right| .$$

Going from $x_i(t)$ to $x_i(t + 2\Delta t)$ requires 4 references to the derivatives using the Adams-Moulton integration scheme and 12 references to the derivatives using the Runge-Kutta scheme.

The convergence test uses the parameters $A_i$ and $E$ described before in the writeup of the DATA region. Using the predictor, $x^P_i$, and corrector, $x^C_i$, of each variable from the last integration step (for either the Runge-Kutta or Adams-Moulton method) if the inequality:

$$\frac{|x^C_i - x^P_i|}{\max[A_i, |x^P_i|, |x^C_i|]} < E$$

is satisfied for all $i$ ($i = 1, 2, \ldots, N$) then we say the convergence test has been passed and the results of the last integration step will be accepted by the differential equation routine. If the inequality doesn't hold for any one of the $i$, then the convergence test has failed and the results of the last integration step are not accepted. If $E$ in the above inequality is replaced by $E/M$, "where $M$ is in symbolic location ADC + 2 and set to the value 20 in floating point format", and the above inequality is still satisfied for every $i$, we say the convergence test to double has passed. Again, if when $E$ is replaced by $E/M$ in the above inequality and the inequality doesn't hold for any one of the $i$ we say the convergence test to double has failed.

If the convergence test is satisfied but the convergence test to double has failed, then the integration step $\Delta t$ is left unchanged and
the differential equation routine goes to users subroutine EXIT for possible printing. Upon return to the differential equation routine it integrates the variables again by the same step $\Delta t$.

If the convergence test to double is satisfied the differential routine goes to the users subroutine EXIT for possible printing of the accepted $x_i^C$ but on return a set up may be made to make the next integration step $2\Delta t$. Even though the convergence test to double is satisfied, sometimes $\Delta t$ is not doubled. For instance, if $\Delta t$ is already greater than or equal to the number, MAXIMUM DT in DATA + 4, then $\Delta t$ is not doubled. If $\Delta t$ was halved within the last four steps in the Runge-Kutta mode, controlled by the fixed point binary number 4 in symbolic location ADC, no doubling of $\Delta t$ is done or if $\Delta t$ was halved within the last six steps in the Adams-Moulton mode, controlled by the fixed point binary number 6 in symbolic location ADC + 1, no doubling is done. The above delays are inserted to save machine time that might be wasted in halving and doubling oscillations.

In the Runge-Kutta mode doubling can take place every integration step but in the Adams-Moulton mode sufficient delays may not exist to do the next integration step at $2\Delta t$. To integrate with the next step $2\Delta t$; first $x_i(t + \Delta t)$ becomes $x_i(t*)$, where $t^* = t + \Delta t$ the advanced independent variable, and $\dot{x}_i(t - 5\Delta t)$ becomes $x_i(t^* - 3(2\Delta t))$. Therefore, after any halving or doubling operation in the Adams-Moulton mode $\Delta t$ cannot be doubled until 3 integration steps of the same length are made to get the delays needed for the next integration step $2\Delta t$.

If the convergence test has failed $\Delta t$ is usually halved. The only case where $\Delta t$ is not halved, is if $\Delta t$ is less than or equal to the floating point number, MINIMUM DT set up by the user in location DATA + 3. As described before in this writeup then $\Delta t$ is supposed to half but it is already less than or equal to MINIMUM DT. If a return jump is made to the users subroutine TMIN and if the user returns to the differential equation routine by an unconditional jump to TMIN,
then \( x_i(t + \Delta t) \) is accepted and the next integration step will also be \( \Delta t \).

If the convergence test has failed and \( \Delta t \) is greater than MINIMUM DT the \( x_i(t + \Delta t) \) in the Adams-Moulton mode and \( x_i(t + 2\Delta t) \) in the Runge-Kutta mode are not accepted and the differential equation routine goes back to variables \( x_i(t) \) and the next integration step is \( .5\Delta t \). In the Runge-Kutta mode the differential equation routine restores the old \( x_i(t) \) and its derivatives it had saved in COMMON storage and takes the saved result of the first RK step \( x_i(t + \Delta t) \) and makes it the new predictor. It then enters the RK predictor-corrector mode at the point it computes the two Runge-Kutta steps, now each of length \( .5\Delta t \) to get the corrector.

In the Adams-Moulton mode after \( \Delta t \) is halved the derivatives of \( x_i(t - .5\Delta t) \) and \( x_i(t - 1.5\Delta t) \) are needed for the next integration step of length \( .5\Delta t \). Using \( \dot{x}_i(t) \), \( \dot{x}_i(t - \Delta t) \), \( \dot{x}_i(t - 2\Delta t) \), \( \dot{x}_i(t - 3\Delta t) \), and \( \dot{x}_i(t - 4\Delta t) \) in the five point interpolation formula of Lagrange; \( \dot{x}_i(t - .5\Delta t) \) and \( \dot{x}_i(t - 1.5\Delta t) \) are computed. The five point formula was used as its error term is of the same order \( (\Delta t)^5 \) as the error terms in the Runge-Kutta and Adams-Moulton integration methods with integration steps of length \( \Delta t \). After interpolation, the routine restores \( x_i(t) \) and returns to the Adams-Moulton mode in the routine to the part where the Adams-Moulton step will be done over with the new step \( .5\Delta t \). As referred to before, no doubling of \( \Delta t \) will take place after a halving in Adams-Moulton mode until sufficient delays exist for doubling \( \Delta t \). Tags were set to delay 4 steps in the Runge-Kutta mode and 6 steps in the Adams-Moulton mode to save machine time.

The five point Lagrange Interpolation Formulas came from page 118 of "Introduction to Numerical Analysis" by F. Hildebrand. In the same book can be found the formulas of Runge-Kutta on page 237 and Adams-Moulton on page 200.
SETTING PARAMETERS

In solving a set of differential equations we are interested in keeping the error at all points of the solution within certain specified limits. However, by setting the parameters $A_i$ and $E$, the truncation error is only controlled for each single step in the predictor-corrector mode. The total error is a combination of the truncation and rounding errors of many steps. The truncation error per step for the variable $x_i$ is less than $\frac{1}{14} E x_i$ if the absolute value of $x_i$ is greater than the value of $A_i$ or less than $\frac{1}{14} E A_i$ if $A_i$ is larger of the two. As most problems are only a few thousand integration steps and are well behaved, the truncation error per step is suggested to be set to one fiftieth of the total error allowed.

Two examples for setting $A$ and $E$ are:

1) Integrate $\dot{x} = \cos t$ with truncation error per step less than $10^{-5}$. As the truncation error requirement is independent of the magnitude of the variable $x$, set $A$ to 1 which is equal to or greater than the absolute value of $x$ at any time. As $\text{MAX} (A, |x^c_i|, |x^p_i|) = 1$, set $E = 14(10^{-5})$.

2) Integrate $\dot{x} = e^t$, where $x(0) = 1$, with truncation error per step less than $x(10^{-5})$. As the truncation error requirement per step is some proportion of the variable $x$ set $A$ to zero. As $\text{MAX} (A, |x^c_i|, |x^p_i|) = x^c_i$ set $E = 14(10^{-5})$. If when integrating the last case to $t_f$ seconds we set $A = e^{tf}$, As $\text{MAX} (A, |x^c_i|, |x^p_i|) = A = e^{tf}$ we would have large $\Delta t$ steps at the beginning resulting in great relative errors that would be carried through the whole solution.

To avoid unnecessary halving of $\Delta t$; each value of $A_i$ should be set slightly less than the average magnitude of its corresponding variable $x_i$, but, if the solution tends to be inaccurate or unstable when some of the variables are small the value of $A_i$ corresponding to these variables must be decreased.
When trying to see the effects of the range of a parameter to check for the total error of an integration; change the parameter at least by a factor of 10 to make sure it reruns with a different step size and change $E$ or some of the $A_i$'s only to isolate the effect. When running a problem the user is not too familiar with; a typical case, or the extreme cases plus a few middle cases, should be run with different values of the parameters $A_i$ and $E$. Then after comparing the solutions of the same case which has been run with different parameters $A_i$ and $E$, run the rest of the cases with the values of the parameters $A_i$ and $E$ that gave satisfactory total error bounds. Sometimes when $E$ is decreased the greater number of integration steps can increase the total rounding error until it is so much greater than the total truncation error that the solution with the smaller $E$ has greater total error than the solution with the larger $E$; however, as the variables $x_i$ are accumulated in double precision and since the Control Data computer has a 36 bit mantissa then only when $E$ becomes less than $10^{-8}$ are the total errors likely to increase when $E$ is further decreased.

When solving some problems a part of the solution may have very small truncation errors; then $\Delta t$ can become so large that the solution becomes unstable. The parameter MAXIMUM DT, in DATA + 4, is used to prevent $\Delta t$ from becoming too large. As an example, when a trajectory was being calculated in a region of very thin air, integration steps of 15 seconds passed the truncation error test but the solution soon became unstable and did false large oscillations. By setting a limit on the integration step to a few seconds the rerun solution was stable.

**BREAK POINTS**

As described before in the writeup the contents of $T$ and $TEXIT$ can be set up by the user to get points of the solution of the differential equation for specified values of the independent variable $t$. 

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One use of this feature is to do printing every $h$ seconds of $t$. Initially, the contents of $T$ are set to $h$. Then the $k$-th time the differential equation routine does a return jump to the user's TEXIT subroutine the user prints the solution, where $t = kh$, then bumps location $T$ by $h$ and does a return jump to the differential equation routine so it can calculate to the next $t$ break, $t = (k+1)h$.

Another use of this feature is when starting a solution, if some of the variables are initially equal to zero, a different set of parameters is required for a small value of $t$. At the start of the problem the contents of $T$ are set to a value $t_p$, slightly greater than the initial value of $t$ and the starting parameters are set up. When $t$ equals $t_p$, the users TEXIT subroutine is used to modify the parameters.

When just the contents of $T$ or any of the convergence parameters like $E$, $A_i$, MINIMUM DT, or MAXIMUM DT are changed in the middle of a case by a user's subroutine the user's normal return, which is an unconditional jump to the beginning of his subroutine may be used in returning to the differential equation routine. However, almost any other kind of change in a user's subroutine requires a jump back to the beginning of the calling sequence or a new calling sequence. Such changes by the user requiring a return to a calling sequence are: if the calling sequence is to be modified, either $N$, code, or $\Delta t$ is changed, changes of the variable $t$ or $x_i$. This is necessary because parameter setups from the calling sequence are done only at the beginning of the routine and the logic of the differential equation routine depends on the code to tell where it has stored the variables and delays of the derivatives of $x_i$ in COMMON. The delays are also assumed to be integral multiples of the present $\Delta t$ in DATA + 6.

To return to examples in the use of the time interrupt feature. One way to start solutions where some of the initial values of the variables $x_i$ are zero is to run in the fixed $\Delta t$ mode with a small
At until the solution is started. Then, after the solution is assumed started at time \( t_p \), change to the predictor-corrector mode by modifying the code, and restart the solution at \( t = t_p \) by entering a new calling sequence. At the same time TEXIT could be changed to a new TEXIT subroutine that does printing. To accurately simulate a missile in the velocity range of zero to a few hundred feet per second when it is under the influence of torques that change its direction (like crosswinds or controllers) requires small integration steps of the order .01 second or large errors in the orientation of the missile occur from the integration process.

The last use of time interrupt discussed is when there are discontinuities of the variables or their derivatives at specified times. An example is when a rocket engine burns out at \( t_p \). By setting \( t_p \) in location \( T \) then the user in his TEXIT routine must modify his DERIV routine to omit the thrust term and the change the drag calculations. As such changes cause discontinuities in the derivatives of \( x_i \) the differential equation routine should be restarted by going to a new calling sequence.

Another case similar to the above is in the staging of missiles, there should be a break when a missile separates into two sections, a break at the end of free flight of the second stage, and at the time of burnout of the rocket engine; whose firing terminated the free flight of the second stage. When controllers are turned on and off they can cause discontinuities in the derivatives of the variables \( x_i \) or even in \( x_i \) if the controllers are impulse functions, so the differential equation routine should be restarted by entering a calling sequence at such times. When interpolating through nonsmooth functions with discontinuous derivatives to maintain accuracy the differential equation routine halves \( \Delta t \) many times using a great deal of machine time; it may also cause an exit to the users TMIN subroutine because \( \Delta t \) is less than or equal to MINIMUM DT and the error requirements are not satisfied. In runs with controllers even though the errors in interpolating variables through nonsmooth functions may be small in terms of the magnitudes of the variables
$x_i$, as the error term driving the controller is a function of the difference of some ideal $x_i$ and actual $x_i$, this error may jump several hundred percent making the rest of the controller or guidance simulation useless.

**USERS INTERPOLATIONS**

The user may require other breaks than time breaks. He may wish to print the output every 1000 feet of altitude or turn on or off a controller when the error, which is a function of the $x_i$'s, becomes equal to some critical value. To do this the user could save several values of the functions at different times and for some interpolation formulas also the derivatives of the functions and do an inverse interpolation to find the time when the function of the error reached the critical point. The interpolation formula used should have an error term of the order $(\Delta t)^5$ to have about the same accuracy as the differential equation routine.

After the time of the break $t$ (break), is known by inverse interpolation the user can interpolate for all the other variables, if he has saved enough delays, then change the method of calculating the derivatives to include the new status of the controller and re-start the differential equation routine by going to a calling sequence. If the user hasn't saved enough delays of the variables to do sufficiently accurate interpolation, he could let the differential equation routine do the interpolation. The user is in his EXIT routine, the time of break is between the current $t$ in DATA + 7 and the $t$ that was in DATA + 7 at the time of the last entry into the EXIT routine as the break occurred between steps. The user first moves the old $t$ and the old variable $x_i$ from COMMON in this way:

old $t$ from COMMON + N to $t$ in DATA + 7

old $x_i$ from COMMON + N + 1 to $x_i$ in DATA + 8

..............

old $x_n$ from COMMON + 2N to $x_n$ in DATA + N + 7
Then set the new $\Delta T = t(\text{BREAK}) - t(\text{old})$ in DATA + 6 and change the code to zero, by setting zero in location DATA, and go to a calling sequence to restart the differential equations routine. The first return to users EXIT will be with $t = t(\text{old})$ but in the second return to EXIT the variables and $x_i$ will be advanced to the break point. The user then makes the necessary changes in his DERIV subroutine that happen at the break point, restores the old code and $\Delta t$ and goes to a calling sequence to restart the differential equation.

The user shouldn't turn on the controller or ignite the rocket motor in the simulations until he has all his variables interpolated at the break time or he will have serious errors in his interpolations because of the nonsmooth functions introduced. If the user hasn't saved delays of the function that determines the break point he could calculate the old value of the function from $t$ and the variables $x_i$ in COMMON + N through COMMON + 2N and do a linear interpolation for the break point. Then advance $t$ and the variables $x_i$ to the estimated break from linear interpolation by a Runge-Kutta step as before. Then the estimated $t$ break from linear interpolation and the new variable $x_i$ with a new interpolation can be used to get a better estimate of the break time and this process repeated until the break point is calculated to sufficient accuracy. The user should note the process will iterate closer and closer to the break point but may not go past it so the exit from above process should be done when an estimate of the $t$ (break) is close to the actual $t$ (break).

**TMIN SUBROUTINE**

If in the predictor-corrector mode one of the variables has failed the convergence test and $\Delta T$ is less than or equal to MINIMUM DT the differential equation routine does a return jump to the users subroutine TMIN.

If the user has a problem he knows can be integrated to sufficient accuracy using a step, $\Delta T$, he can set MINIMUM DT to $\Delta T$ and in the TMIN subroutine do an unconditional jump to TMIN.
to cause the return to the differential equation. The differential equation routine accepts the last step integrated with the last $\Delta T$ and also does the next step with the same $\Delta T$. Therefore, machine time is not wasted with a $\Delta T$ much smaller than $\Delta T$ and if in other regions of the problem, where truncation error is small $\Delta T$ may be much larger than $\Delta T$. The regions of small $\Delta T$ could be caused by slight discontinuities in curve fits of the empirical data that determine the coefficients of the differential equation or the values of $A_i$ are too small.

If the user has a problem that isn't too familiar, MINIMUM DT should be set very small. Then the TMIN subroutine should stop the problem so it can be examined. The user may find derivatives changing rapidly or which are very large because they are not calculated correctly or an unnoticed singular is making a derivative infinite. Also the user may be changing variables because of program errors, or if the differential equation has impulse functions the variables were changed but the differential equation routine wasn't restarted. If the value of MINIMUM DT was only a factor of 10 smaller than the $\Delta T$ that runs most of the problem accurately, an exit to TMIN could mean, discontinuous derivatives being integrated through a point where the differential equation routine should have been restarted. Another possibility with MINIMUM DT a factor of 10 smaller than the standard DT, if in TMIN when some of the variables are small; the values of some of the $A_i$ could be increased and the problem reran with both a smaller MINIMUM DT and the old $A_i$'s and the old MINIMUM DT and the larger $A_i$'s and the solution compared to see if the shorter machine time in running with larger $A_i$'s gives sufficiently accurate solutions.

**RUNNING A PROBLEM IN REVERSE**

If a user wishes to run a problem backwards in time, as $\Delta t$ cannot be made negative in this routine, the method described below must be used.
Given the standard set of $N$ simultaneous differential equations to be integrated we have:

$$\frac{dx_i}{dt} = f_i \left[ t, x_1(t), x_2(t), \ldots x_N(t) \right]$$

Let the initial value of $t$ be $t_o$ and its final value be $t_f$. To run this same set of differential equations backwards we make the transformation $T = t_f - t$, to the new independent variable $T$. Let the initial value of $T$ be 0, then $t = t_f$ and the initial values of the variables $x_i$ is $x_i(t_f)$. Then the final value of $T$ is $t_f - t_o$ and this corresponds to $t = t_o$ and the final value of the variables $x_i$ is $x_i(t_o)$. The derivatives of the variables $x_i$ with respect to $T$ are:

$$\frac{dx_i}{dT} = -f_i \left[ t_f - T, x_1(t_f - T), x_2(t_f - T), \ldots x_N(t_f - T) \right]$$

as $t = t_f - T$ and $dT = -dt$.

E. TEST CASE

To help clarify the writeup, a simple test case is inserted. I am integrating the three equations:

$$\frac{dx_1}{dt} = x_2$$

$$\frac{dx_2}{dt} = -4x_1$$

$$\frac{dx_3}{dt} = 2x_3$$
Let $x_1(0) = 0$, $x_2(0) = 2$, and $x_3(0) = 1$. The solutions of the above differential equations are:

$$
x_1 = \sin 2t
$$
$$
x_2 = 2 \cos 2t
$$
$$
x_3 = e^{2t}
$$

Using the T break feature printing is done every second. At $t$ equal one second,

$$
x_1 = \sin 2 = 0.909297427 \text{ the routine gives } 0.9092974248
$$
$$
x_2 = 2 \cos 2 = -0.832293674 \text{ the routine gives } -0.8322936859
$$
$$
x_3 = e^{2t} = 7.38905610 \text{ the routine gives } 7.389056142
$$

The last printout is $t = 5$ seconds.

$$
x_1 = \sin 10 = -0.544021111 \text{ the routine gives } -0.544021143
$$
$$
x_2 = 2 \cos 10 = -1.678143058 \text{ the routine gives } 1.678143027
$$
$$
x_3 = e^{10} = 22026.4658 \text{ the routine gives } 22026.46649
$$
**TEST CASE CODING**

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<td>ZRO 1 DERIV B NOT ZERO SO PRINT</td>
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<td>SIX DEC 6. 7.</td>
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<tr>
<td>M FOUR DEC -4. -4.</td>
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<td>DATA DEC 3. CODE IS 3</td>
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<td>DEC 1. A IN DATA+1 IS PLUS</td>
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<td>DEC 1. D-8 E IN DATA+2 IS .000001</td>
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<td>DEC 1. MAX DT IN DATA+4 IS 1.</td>
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TDR-63-11

DEC 3 N IS 3 IN DATA+5
DEC 5, D-3 INITIAL DT IS .005
DEC 0, 0, 0, 0, 0, 0 + X1, X2, X3 and DERIV X1, X2, X3
DEC .1, .1, 1. A1, A2, A3
COMMON BSS 47 14 W+5 IS 47
T BSS 1 T BREAK
TMIN SLS TMIN STOP IF DT TOO SMALL
COUNT BSS 1
DERIV SLJ 0
LDA DATA+ 9
STA DATA+ 11 DERIV X1 IS X2
LDA M FOUR
FMU DATA+ 8
STA DATA+ 12 DERIV X2 IS -4 X 1
LDA DATA+ 10
FAD DATA+ 10
STA DATA+ 13 2X3 IS DERIV X3
SLJ DERIV
EXIT SLJ 0 EXIT EACH DT STEP
SLJ EXIT
TEXIT SLJ 0
SLJ 4 OUTPUT PRINT TITLE
A3 SLS A3
+ 03 BCD SUBSCRIPT
  00 2021
+ 03 BCD+2
  00 1029 X
+ 03 BCD+3
  00 1047 DERIV X
+ 03 BCD+4
  00 1070 T
+ 01 4 4
00 2 10 PRINT TITLE

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ENI 1 0

LOOP SLJ 4 OUTPUT

A4 SLS A4

+ 04 COUNT COUNT 1 TO 3

00 10

+ 06 1 DATA+8

00 10030 X1

+ 06 1 DATA+11

00 10050 DERIV X1

+ 06 DATA+7

00 10070 TIME

+ 01 4 4

00 2 16 PRINT X, DERIV X, AND T

RAO COUNT EVERY SEC

+ ISK 1 2 BUMP 1

SLJ LOOP

LDA T END PRINT

FAD ONE

STA T

FSB SIX

AJP M TEXIT

STOP SLS STOP IF DATA+7 OR T IS 7 STOP

BCD BCD 2SUBSCRIPT

BCD 1X

BCD 1 DERIV X

BCD 1 T

END TEST
### TEST CASE OUTPUT

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<td>.3027208220 +1</td>
<td>.2000000000 + 1</td>
</tr>
<tr>
<td>3</td>
<td>.5459815071 +2</td>
<td>.1091963721 +3</td>
<td>.2000000000 + 1</td>
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<th>DERIV ( X )</th>
<th>( T )</th>
</tr>
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<tr>
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<th>( T )</th>
</tr>
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<td>-.2909987991 +0</td>
<td>.4000000000 + 1</td>
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<tr>
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<td>3</td>
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<table>
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<th>DERIV ( X )</th>
<th>( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>-.1678143115 +1</td>
<td>.5000000000 + 1</td>
</tr>
<tr>
<td>2</td>
<td>-.1678143027 +1</td>
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<td>.5000000000 + 1</td>
</tr>
<tr>
<td>3</td>
<td>.2202646649 +5</td>
<td>.4405293659 +5</td>
<td>.5000000000 + 1</td>
</tr>
</tbody>
</table>
f. INTERPF.

A. IDENTIFICATION

TITLE: Divided Difference Interpolation or Extrapolation Routine
CATEGORY: Mathematical Subroutine
PROGRAMER: Sanford Elkin, William Silverman, and Ed Fleming
MODIFIED: June 1961

B. PURPOSE:

Given a table of M values in floating point which define a function, and given a floating point argument X, this routine approximated the functional value Y of that argument by a polynomial interpolation or extrapolation.

C. USAGE:

1. Calling sequence:

CALL INTERPF (X, M, N, a, b)

Interpolate, find Y for X, X Flt argument
where various X vs. Y given
in table.

M Size of the table
N Degree of interpolation
a Table of X values
b Table of Y values

Where M is in fixed integer form, N is the order of interpolation or extrapolation desired — in fixed integer form.

The X's and Y's must be in floating format and the table of X values must be stored in decreasing order.
D. MATHEMATICAL METHOD: (reference 19)

\[ Y = \frac{1}{x_n - x_0} \left| \begin{array}{c} I_0, 1, \ldots, n-1(x) \ x_0 - x \\ I_1, 2, \ldots, n(x) \ x_n - x \end{array} \right| \]

\[ Y = I_0, 1, \ldots, n(x) \text{ is equivalent to Lagrange's Formula} \]

\[ Y = \psi(x) = \frac{(x-x_1)(x-x_2)\ldots(x-x_n)}{(x_0-x_1)(x_0-x_2)\ldots(x_0-x_n)} Y_0 + \frac{(x-x_0)(x-x_2)\ldots(x-x_n)}{(x_1-x_0)(x_1-x_2)\ldots(x_1-x_n)} Y_1 + \cdots + \frac{(x-x_0)(x-x_1)\ldots(x-x_{n-1})}{(x-x_0)(x-x_1)\ldots(x-x_{n-1})} Y_n \]

which yield a polynomial of degree such that \( (x_0) = Y_0, \psi(x_1) = y_1, \ldots, \psi(x_n) = Y_n \), as is easily demonstrated by an induction proof.

When \( x \) is within the limits of the table, the points \( x_0, x_1, \ldots, x_n \) are spaced about it to best advantage, but if \( x \) is outside the limits of the table, the nearest \( n+1 \) points in the table are used in the formula.
TITLE: Read Data, Fixed Formats
ID: RDF
Classification: Input Routine
Programers: W. Silverman and R. E. Mann

PURPOSE:
To load data from Hollerith cards through the 088 card reader, or from 80 character records on BCD tape. The data are on symbolic cards of the types used for the pseudo operations DEC, OCT, and BCD as described in the assembly routine.

USAGE:
1. Calling Sequence
   
   ENA A
   ENQ B
   a RTJ RDF
   a+1 NOP L(LTN)
   a+2 Error Return
   a+3 Normal Return

   L(LTN) = Location of Logical Tape Number
   LTN (Logical Tape Number) = 1-48 for tape input
   = 49 for card input

   After a description of the input formats, the function of A and B will be discussed.

2. Input Formats:
   Load is controlled by a symbolic operation code in columns 10, 11, 12 of the input cards (or records). There are five permissible operation codes.

   1. SLJ--This operation always causes loading to be terminated. A transfer address may appear in decimal or octal
beginning in column 20. The address is assumed decimal if it is followed by a D or blank, and octal if it is followed by a B. If index modification of the transfer address is desired, column 17 or 18 may contain an index register number. Control is transferred to the (modified) transfer address, or if there is no transfer address, control is returned to \( a + 3 \) in the calling sequence.

2. REM-- This record will be skipped. No conversion or operation results. REM cards may be used as spacers or tags in the data deck.

Conversion operations:

3. BCD--n words of binary coded decimal information beginning in column 21 are loaded into consecutive memory locations. \( n \) is in column 20, \( 1 \leq n \leq 7 \). The information runs through column 20 + 8n.

4. OCT--Octal data beginning in column 20 and terminating with the first blank column are interpreted as octal integers, and converted to binary integers. Successive words are separated by commas and loaded into consecutive locations. Each word may consist of a + or - sign and up to 16 octal digits. If no sign appears, a + sign is assumed.

5. DEC--Decimal data beginning in column 20 and terminating with the first blank column are loaded. Successive words are separated by commas and loaded into consecutive locations. Each word may consist of a sign, + or - or none, up to 15 decimal digits with a decimal point if desired, a D or E followed by a signed or unsigned decimal scale factor, and a B followed by a signed or unsigned binary scale factor. Presence of a binary scale factor will cause the number to be loaded as a fixed point decimal number with the binary point to the right of the bit position given by the binary scaling. If a decimal scale factor or decimal point is present, the number will be loaded as a fixed point number as above if
a binary scaling is present, or as a (scaled) floating point number if no binary scaling is present. If a binary scaling is present, it must lie between -47 and 47, and the decimal scaling, if any, must lie between -28 and 28. If no decimal point or scale factor is present, the number will be loaded as an integer. A few illustrative examples follow:

1) 1.2345 will be loaded as floating point 1.2345
2) 12345E-3 will be loaded as floating point 12.345
3) 1.2345D-2 will be loaded as floating point .012345
4) 12345 will be loaded as integer 12345
5) 12345B15 will be loaded as fixed point 12345.0 with binary point to the right of bit position 15.
6) 12.345D2B13 will be loaded as fixed point 1234.5 with binary point to the right of bit position 13.
7) 12345B-3 will be loaded as fixed point 12345.0 with binary point to the right of bit position -3, that is as (rounded) integer 1543 = 12345/8 to the nearest integer.

Any data card BCD, OCT, or DEC may have an absolute numerical address in columns 1-8. The data on the card is loaded relative to that address. The address is treated as octal or decimal according to the same conventions used for the transfer address on the SLJ card.

e. g. The card

2000B  BCD  2ABCDEFGHJKLMNOP

will be loaded so that:

(2000B) = ABCDEFGH

(2001B) = IJKLMNOP

A and B (the addresses in the accumulator and quotient registers upon entry to RDF) condition where the data on cards with blank address fields is loaded and the number of words actually loaded by RDF.

If A ≠ 0, the first card with a blank address field is loaded relative to A, the data going into addresses A, A+1, ...
A+n-1, where n is the number of data words on the card. The data from the next card with a blank address field is loaded relative to A into locations A+n, A+n+1, ..., A+n+m-1 where m is the number of data words on the card. And so on, each card with a blank address field being loaded relative to A.

If A = 0, the first card must have an absolute numerical address in columns 1-8. Loading proceeds relative to the last such address. Thus if the first data card has the address 2000B, the second card has a blank address field, the third has the address 3000B, and the remaining data cards have blank address fields, the data from the first cards will go into consecutive addresses starting at 3000B. If B ≠ 0, B-A+1 words will be loaded unless the load is terminated by an SLJ card or an error (see errors below).

If B = 0, an indefinite number of words will be loaded until the routine is terminated by an SLJ card or an error.

3. RDF requires 397 locations
4. RDF uses 19 common erasable storage locations
5. Errors:
   1. End of file on tape or card.
      The end of file flag (77713B) is set non-zero and if no other errors occurred, control is returned to A+3 in the calling sequence.
   2. Parity error on tape.
      The RTT flag (77712B) is set non-zero, and the routine continues, although the conversion of the record on which the parity error occurred may be inaccurate. When the routine is terminated, control is returned to the error return, A+2, in the calling sequence, with the number of records which had parity errors in the upper address of the A register, and the transfer address, if
any, in the Q register.

3. Illegal punch on card.

The RTT flag is set with 1's in bits 0 through 39 corresponding to erroneous columns on the card (these may apply to the first or second half of the card, but not both). Control is returned to a + 2 in the calling sequence, with the upper address of A set to 1.

4. Format error:

This may be caused by an illegal operation code in columns 10, 11, 12; an illegal address; an illegal character in column 17 or 18 of an SLJ card; or an illegal character in column 20 of a BCD card. Control is restored to a + 2 in the calling sequence with bit 47 of A set to 1.

5. Data error:

This may be caused by an illegal character in a numerical field; more than 16 digits in an octal numerical field, or more than 14 in a decimal numerical field; more than one sign in a numerical field or a sign which is preceded by a number in the field; more than one decimal point in a decimal numerical field; too large a scale factor; a decimal number which when scaled does not fit the A register, or which is too large or too small for the floating point format

\[ (\geq 2^{-1023} \text{ or } \leq -2^{-1023}) \]

In case of a data error, the word in storage corresponding to the erroneous field is set equal to minus zero, and loading continues. At the end of the routine, control is returned to a + 2 in the calling sequence, with the number of erroneous fields in the lower address of the A register.

6. Termination of loading:

An SLJ card, an end-of-file, or a format error automatically terminates loading. If \( B \neq 0 \) (in the Q register
of entry), loading is terminated when \( B - A + 1 \) words have been loaded. The program then hunts forward through the remaining cards (or records on tape) to the first SLJ card, or end-of-file. The tape or card reader is left set to read the next succeeding record or card. Normal return in this case is to \( a + 3 \) in the calling sequence.

7. All conversions are performed rapidly enough so that the 1607 tape mechanism (or the 088 card reader) can be operated at full speed; 3000 records per minute on tape or 650 cards per minute through the 088.

8. Floating point numbers with large negative exponents may be accurate to only 35 bits.
h. **Rotate.**

**MATRIX ROTATION**

The following transformation was used as a subroutine to transform from one Cartesian coordinate system to another Cartesian coordinate system.

1. Rotation of the initial system by an angle $\phi$ counterclockwise about the Z axis.

2. Rotation of the primed system by the angle $\theta$ counterclockwise about the $X'$ axis.

3. Rotation of the double primed system by the angle $\psi$ counterclockwise about the $Z''$ axis.

$$
\begin{bmatrix}
X^1' \\
Y^1' \\
Z^1'
\end{bmatrix} =
\begin{bmatrix}
A & X \\
Y & Z
\end{bmatrix}
$$

$$
A =
\begin{bmatrix}
\cos \phi \cos \psi & -\cos \theta \sin \psi & -\sin \psi \cos \phi & \cos \theta \sin \phi & \sin \theta \sin \phi \\
\cos \phi \sin \psi & \cos \theta \cos \psi & -\sin \psi \cos \phi & \cos \theta \sin \phi & \sin \theta \cos \phi \\
\sin \theta \sin \phi & -\sin \theta \cos \phi & \cos \phi & \sin \theta \sin \phi & \sin \theta \cos \phi \\
\sin \theta \cos \phi & \cos \theta & 0 & \sin \theta \sin \phi & \sin \theta \cos \phi \\
0 & 0 & 0 & \cos \theta
\end{bmatrix}
$$

Figure 6.
This program is callable by FORTRAN.

To use:

CALL ROTATE (A, B, C, D, E)

where

A = The angle $\varphi$
B = The angle $\theta$
C = The angle $\psi$
D = The input 3 component vector
E = The output 3 component vector
i. SETTAB

The Subroutine SETTAB is used to set up a table of print times. This table includes both even increment print times and abnormal print times such as ignition, drop stages, and burnout.

The subroutine is callable by FORTRAN. To use:

```
CALL SETTAB (NS, TMI, TMCC, TMBO, DT, TABLE, IX)
```

where

- **NS** = number of stages
- **TMI** = table of ignition times
- **TMCC** = table of coefficient change times
- **TMBO** = table of burnout time
- **DT** = even time increments
- **TABLE** = resulting table
- **IX** = size of the table
## SYMBOLS

### ENGLISH

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>a</td>
<td>Semi-major axis of orbit</td>
<td>(NM)</td>
</tr>
<tr>
<td>a_E</td>
<td>Equatorial radius of the earth</td>
<td>(NM)</td>
</tr>
<tr>
<td>b</td>
<td>Semi-minor axis of orbit</td>
<td>(NM)</td>
</tr>
<tr>
<td>C</td>
<td>Earth parameter defined by equation 3-1</td>
<td>(NM)</td>
</tr>
<tr>
<td>e</td>
<td>Eccentricity of the orbit</td>
<td></td>
</tr>
<tr>
<td>e_E</td>
<td>Eccentricity of the earth ((e_E^2 = 2f - f^2))</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Eccentric anomaly</td>
<td>(RAD)</td>
</tr>
<tr>
<td>f</td>
<td>Flattening of the earth</td>
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</tr>
<tr>
<td>GM</td>
<td>Gravitational constant of the earth</td>
<td>((FT^3/SEC^2))</td>
</tr>
<tr>
<td>h_G</td>
<td>Geodetic altitude</td>
<td>(NM)</td>
</tr>
<tr>
<td>h_x, h_y, h_z</td>
<td>Angular momentum about subscripted axis</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>Total angular momentum</td>
<td></td>
</tr>
<tr>
<td>h_A</td>
<td>Apogee altitude</td>
<td>(NM)</td>
</tr>
<tr>
<td>h_p</td>
<td>Perigee altitude</td>
<td>(NM)</td>
</tr>
<tr>
<td>H</td>
<td>Energy parameter defined by equation 2-2</td>
<td>(DEG)</td>
</tr>
<tr>
<td>i</td>
<td>Inclination of orbit plane to equatorial plane</td>
<td></td>
</tr>
<tr>
<td>k</td>
<td>Constant used to obtain period ((2\pi/\sqrt{GM}))</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Mean anomaly</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Period of the orbit</td>
<td>(MIN)</td>
</tr>
<tr>
<td>R</td>
<td>Geocentric radius from center of earth to vehicle</td>
<td>(NM)</td>
</tr>
<tr>
<td>iR</td>
<td>Change in R with respect to time</td>
<td>(NM/SEC)</td>
</tr>
<tr>
<td>R'_i</td>
<td>Geocentric radius used for earth's velocity</td>
<td>(NM)</td>
</tr>
<tr>
<td>S</td>
<td>Earth parameter defined by equation 3-2</td>
<td>(NM)</td>
</tr>
<tr>
<td>t_o</td>
<td>Time of entry into orbit</td>
<td>(SEC)</td>
</tr>
</tbody>
</table>
SYMBOLS

T - Time of perigee passage (SEC)
t_i - Time at i\textsuperscript{th} point in orbit (SEC)
V_E - Velocity of vehicle with respect to the earth (FPS)
V_R - Velocity of earth's surface below vehicle (FPS)
V_I - Velocity of vehicle with respect to non-rotating earth (FPS)
\(x_b', y_b', z_b\) - Earth centered coordinates of the space vehicle (Figure 3)
x, y, z - Geodetic coordinate system at vehicle (Figure 4)
x', y', z' - Geodetic coordinate system below vehicle on surface of the earth (Figure 4)
x'', y'', z'' -Coordinate system in orbit plane (Figure 2)
X, Y, Z - Earth centered coordinate system (Figure 1)
x_s', y_s', z_s - Coordinates of the look station (Figure 3)

GREEK

\(\alpha\) - Angle between geodetic east axis and X axis of coordinate system tangent to a geodetic earth; also the aspect angle (DEG)
\(\beta\) - Initial azimuth (positive c. w. from north) (DEG)
\(\gamma\) - Initial flight path angle (positive up) (DEG)
\(\gamma_I\) - Inertial flight path angle (positive up) (DEG)
\(\omega\) - Argument of perigee (DEG)
\(\omega_E\) - Rotational rate of the earth (RAD/SEC)
\(\Omega\) - Longitude of ascending node (DEG)
\(\varphi\) - Longitude (DEG)
\(\theta_G\) - Geodetic latitude (DEG)
\(\theta_c\) - Geocentric latitude from vehicle (DEG)
\(\theta_c'\) - Geocentric latitude from earth's surface (DEG)
\(\mu\) - Argument of latitude (DEG)
\(\nu\) - True anomaly (DEG)
SUBSCRIPTS

b - refers to space vehicle
c - refers to geocentric
E - refers to the earth
G - refers to geodetic
i - refers to ith point in orbit
I - refers to nonrotating earth
o - refers to initial or burnout values
R - refers to rotational velocity radius
s - refers to look station
x, y, z - refers to X, Y, Z, coordinate system
1 - refers to coordinate system at station parallel to equatorial plane
2 - refers to coordinate system at look station

A dot over a variable indicates the time derivative of that variable.
A delta (Δ) in front of a variable indicates a difference in that variable.
1. **INTRODUCTION.**

   a. **Inputs.**

   The inputs are a position and velocity vector in a right-hand Earth-centered coordinate system with the X axis along the node of the equatorial plane and the Greenwich meridian and the Z axis along the north polar axis. The number of time increments, changes, and look-angle stations must be in COMMON. To use the subroutine, control number 4 must be set equal to 1 or 2.

   b. **Printout time changes.**

   Since some portions of the trajectory are more important than others, provisions are included for changing the time increment, with the use of a maximum of five different time increments. If the ellipse intersects the earth, the trajectory computation stops at this time. If it does not intersect the earth, the computation will continue for a prespecified number of orbits.

   c. **TWO-BOD computer program.**

   The program computes the classical orbital elements $(a, b, e, P, h_A, h_P, i, \omega, \Omega, \nu, E_0)$. After the orbital elements are computed, a matrix-rotation is set up to transfer from the orbital plane to the equatorial plane coordinate system. Time is incremented and a new true anomaly is obtained.

   The corresponding orbit plane coordinates are then transformed by a matrix rotation to the equatorial coordinate system. The latitude and longitude are obtained by taking "arc tangents" and adding the effects of a rotating earth. These values are stored along with the radius vector to the vehicle and are used to find the "look angles" at various stations.

   The matrix subroutine described in rotate is used for the coordinate transformation.
2. EQUATIONS OF CELESTIAL MECHANICS.

a. Semi-major axis.

\[
V_I = \sqrt{x^2 + y^2 + z^2}
\]  

\[
H = \frac{RV_I^2}{GM}, \text{ if } H \geq 2, \text{ the rocket escapes}
\]  

\[
a = \frac{R}{2-H}
\]

b. Angular momentum.

\[
h_x = Y\dot{Z} - Z\dot{Y}
\]  

\[
h_y = Z\dot{X} - X\dot{Z}
\]  

\[
h_z = X\dot{Y} - Y\dot{X}
\]  

\[
h = \sqrt{h_x^2 + h_y^2 + h_z^2}
\]

c. Orbital elements.

\[
i = \cos^{-1} \left( \frac{h_z}{h} \right)
\]  

\[
\Omega = \tan^{-1} \left( \frac{h_x}{-h_y} \right) \text{ If } (-h_y) \text{ is negative,} \\
\Omega = \Omega + 180^\circ
\]  

\[
R = \frac{XX + YY + ZZ}{R}
\]  

\[
e = \left( 1 - \frac{h^2}{GMa} \right)^{1/2}
\]
\[
\cos v_o = \frac{h^2}{RGM} - 1 \tag{9}
\]
\[
\sin v_o = \frac{\dot{h}}{GM} \tag{10}
\]
\[
v_o = \tan^{-1} \left( \frac{\sin v_o}{\cos v_o} \right) \quad \text{If } (\cos v_o) \text{ is negative, } \quad v_o = v_o + 180^o \tag{11}
\]
\[
\cos \mu = \frac{(Y h_x - X h_y)}{h} \tag{12}
\]
\[
\mu = \tan^{-1} \left( \frac{Z}{\cos \mu} \right) \quad \text{If } (\cos \mu) \text{ is negative} \quad \mu = \mu + 180^o \tag{13}
\]
\[
\omega = \mu - v_o \tag{14}
\]
\[
b = a \sqrt{1 - e^2} \tag{15}
\]
\[
P = k a^{3/2} \tag{16}
\]
\[
h_A = a (1 + e) - a_e \tag{17}
\]
\[
h_P = a (1 - e) - a_e \tag{18}
\]
\[
E_o = 2 \tan^{-1} \left( \frac{\sqrt{1 - e}}{1 + e} \tan \frac{v_o}{2} \right) \tag{19}
\]
\[
t_o - T = \frac{(E_o - e \sin E_o) P}{2\pi} \tag{20}
\]
d. **Trajectory points.**

\[ t_{1+1} = t_i + \Delta t \]  
\[ M = \frac{2\pi}{P} (t_i - T) \]  
\[ E_2 = E_1 - \frac{(E_1 - e \sin E_1 - M)}{1 - e \cos E_1} \]

Iterate until \( E_2 = E_1 \)

\[ v_i = 2 \tan^{-1} \left( \sqrt{\frac{1 + e}{1 - e}} \tan \frac{E_i}{2} \right) \]

\[ R_i = \frac{a(1 - e^2)}{1 + e \cos v_i} \]

\[ V_i = \left[ GM \left( \frac{2}{R_i} - \frac{1}{a} \right) \right]^{1/2} \]

\[ \gamma_i = \tan^{-1} \left[ \frac{e \sin v_i}{1 + e \cos v_i} \right] \]

\[ x'' = \cos v_i \]

\[ y'' = \sin v_i \]

\[ z'' = 0 \]
\[
\begin{align*}
X &= x''(\cos \Omega \cos \omega - \sin \Omega \cos i \sin \omega) - y''(\cos \Omega \sin \omega + \sin \Omega \cos i \cos \omega) \\
Y &= x''(\sin \Omega \cos \omega + \cos \Omega \cos i \sin \omega) - y''(\sin \Omega \sin \omega - \cos \Omega \cos i \cos \omega) \\
Z &= x''(\sin i \sin \omega) + y''(\sin i \cos \omega)
\end{align*}
\]

\( (30) \)

\[
\theta_c = \tan^{-1} \frac{Z}{\sqrt{X^2 + Y^2}}
\]

\( (31) \)

\[
\phi_c = \tan^{-1} \left( \frac{Y}{X} \right) \quad \text{If } X \text{ is negative, } \phi_c = \phi_c + 180^\circ
\]

\( (32) \)

\[
\phi_c = \phi_c - \omega_E (t_i - t_o)
\]

\( (33) \)

e. Geocentric to geodetic.

\[
\theta_G = \theta_c + \sin^{-1} \left\{ \frac{a_E}{R_i} \left[ f \sin 2\theta_c + f^2 \sin 4\theta_c \left( \frac{a_E}{R_i} - \frac{1}{4} \right) \right] \right\}
\]

\( (34) \)

\[
h_G = R_i - a_E \left[ 1 - f \sin^2 \theta_c - \frac{f^2}{2} \sin^2 2\theta_c \left( \frac{a_E}{R_i} - \frac{1}{4} \right) \right]
\]

\( (35) \)

f. Range.

The great circle range is obtained by computing the range angle. This angle is obtained by taking the dot product of the launch vector with the radius vector at any given time.

\[
R.A. = \cos^{-1} \left\{ \frac{a_E}{R_i} \left[ (X_L X + Y_L Y + Z_L Z) / \sqrt{X_L^2 + Y_L^2 + Z_L^2} \right] \right\}
\]

\[
\text{Range} = R_E \text{ (avg) (R.A.)}
\]

\( (36) \)
Figure 3
g. Look angles.

Station given station \((h_G, \theta_G, \varphi_s)\)

\[
C_s = \frac{a_E}{(1 - e_E^2 \sin^2 \theta_G)^{1/2}} \quad S_s = C_s(1 - e_E^2)
\]

\[
|\vec{R_E}| = \left[ (S_s + h_G)^2 \sin^2 \theta_G + (C_s + h_G)^2 \cos^2 \theta_G \right]^{1/2}
\]

\[
\theta_{c_s} = \tan^{-1} \left[ \left( \frac{S_s + h_G}{C_s + h_G} \right) \tan \theta_G \right]
\]

\[
R_E \begin{cases} 
  x_s = R_E \cos \theta_{c_s} \\
  y_s = 0 \\
  z_s = R_E \sin \theta_{c_s}
\end{cases}
\]

\[
R_b \begin{cases} 
  x_b = R_b \cos \theta_{c_b} \cos \Delta \varphi \\
  y_b = R_b \cos \theta_{c_b} \sin \Delta \varphi \quad \text{where } \Delta \varphi = \varphi_b - \varphi_s \\
  z_b = R_b \sin \theta_{c_b}
\end{cases}
\]

\[
\vec{R_b} = \vec{R_E} + \vec{\rho}
\]

\[
\vec{\rho} = \vec{R_b} - \vec{R_E}
\]
The aspect angle is defined as the angle between the spin axis of the space vehicle and the vector from the look station to the vehicle. This program assumes the vehicle remains fixed in space. The angle is obtained by the following equations:

$$\alpha = \cos^{-1}\left[\frac{\dot{x}x_1 + \dot{y}y_1 + \dot{z}z_1}{\sqrt{x_1^2 + \dot{y}_1^2 + \dot{z}_1^2}}/\sqrt{x_1^2 + y_1^2 + z_1^2}\right]$$

(47)
### VARIABLES USED IN TWO BODY SUBROUTINE

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALT</td>
<td>Geocentric radius to vehicle</td>
</tr>
<tr>
<td>AMU</td>
<td>Argument of latitude</td>
</tr>
<tr>
<td>ANS</td>
<td>Output vector</td>
</tr>
<tr>
<td>ANT</td>
<td>Aspect angle</td>
</tr>
<tr>
<td>APOGEE</td>
<td>Apogee altitude of the orbit</td>
</tr>
<tr>
<td>ARA</td>
<td>Average radius of the Earth</td>
</tr>
<tr>
<td>AX</td>
<td>X Component of inertial burnout position vector</td>
</tr>
<tr>
<td>AXDOT</td>
<td>X Component of inertial burnout velocity vector</td>
</tr>
<tr>
<td>AY</td>
<td>Y Component of inertial burnout position vector</td>
</tr>
<tr>
<td>AYDOT</td>
<td>Y Component of inertial burnout velocity vector</td>
</tr>
<tr>
<td>AZ</td>
<td>Z Component of inertial burnout position vector</td>
</tr>
<tr>
<td>AZDOT</td>
<td>Z Component of inertial burnout velocity vector</td>
</tr>
<tr>
<td>AZIM</td>
<td>Azimuth of look vector</td>
</tr>
<tr>
<td>A1</td>
<td>Burnout position vector</td>
</tr>
<tr>
<td>A2</td>
<td>Burnout velocity vector</td>
</tr>
<tr>
<td>A1A</td>
<td>Not used in two body *</td>
</tr>
<tr>
<td>A1B</td>
<td>Not used in two body *</td>
</tr>
<tr>
<td>C</td>
<td>$\Delta = \frac{R_e}{\sqrt{1 - e^2 \sin^2 \theta_c}}$</td>
</tr>
<tr>
<td>CAPO</td>
<td>Longitude of ascending node</td>
</tr>
<tr>
<td>CLAL</td>
<td>Cosine of the launch latitude *</td>
</tr>
<tr>
<td>CLOL</td>
<td>Cosine of the launch longitude</td>
</tr>
<tr>
<td>CMU</td>
<td>Cosine of MU</td>
</tr>
<tr>
<td>CSLANT</td>
<td>Cosine of inclination angle</td>
</tr>
<tr>
<td>CT</td>
<td>Cosine of geocentric latitude</td>
</tr>
<tr>
<td>CTRVA</td>
<td>Cosine of true anomaly</td>
</tr>
<tr>
<td>DELTAT</td>
<td>Stored time increment *</td>
</tr>
<tr>
<td>DPHI</td>
<td>Difference in longitude</td>
</tr>
<tr>
<td>DUMTB</td>
<td>Not used in two body *</td>
</tr>
<tr>
<td>E</td>
<td>Eccentricity of the Earth</td>
</tr>
</tbody>
</table>

* Stored in COMMON
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELEV</td>
<td>Elevation of look angle vector</td>
</tr>
<tr>
<td>ENDT</td>
<td>End of time increment *</td>
</tr>
<tr>
<td>ER</td>
<td>Size of allowable error</td>
</tr>
<tr>
<td>ETA</td>
<td>Anomaly = period/2π</td>
</tr>
<tr>
<td>EX</td>
<td>Orbital eccentricity</td>
</tr>
<tr>
<td>EXANOM</td>
<td>Eccentric anomaly</td>
</tr>
<tr>
<td>EXIMP</td>
<td>Impact eccentric anomaly</td>
</tr>
<tr>
<td>E1</td>
<td>Used to compute eccentric anomaly</td>
</tr>
<tr>
<td>E2</td>
<td>Used to compute eccentric anomaly</td>
</tr>
<tr>
<td>F</td>
<td>Flattening of the Earth</td>
</tr>
<tr>
<td>FMIN</td>
<td>Output - time in minutes</td>
</tr>
<tr>
<td>FMINF</td>
<td>Function for obtaining FMIN</td>
</tr>
<tr>
<td>FPA</td>
<td>Flight path angle</td>
</tr>
<tr>
<td>FX</td>
<td>Output vector from Rotate</td>
</tr>
<tr>
<td>GM</td>
<td>Earth gravitational attraction constant</td>
</tr>
<tr>
<td>GM1</td>
<td>Earth gravitational attraction constant</td>
</tr>
<tr>
<td>H</td>
<td>Angular momentum parameter</td>
</tr>
<tr>
<td>HH</td>
<td>Angular momentum squared</td>
</tr>
<tr>
<td>HOUR</td>
<td>Output time in hours</td>
</tr>
<tr>
<td>HOURH</td>
<td>Function for obtaining HOUR</td>
</tr>
<tr>
<td>HX</td>
<td>X Component of angular momentum</td>
</tr>
<tr>
<td>HY</td>
<td>Y Component of angular momentum</td>
</tr>
<tr>
<td>HZ</td>
<td>Z Component of angular momentum</td>
</tr>
<tr>
<td>H1</td>
<td>Angular momentum</td>
</tr>
<tr>
<td>I</td>
<td>Utility index</td>
</tr>
<tr>
<td>IT</td>
<td>Utility index</td>
</tr>
<tr>
<td>J</td>
<td>Utility index</td>
</tr>
<tr>
<td>K</td>
<td>Utility index</td>
</tr>
<tr>
<td>KBATT</td>
<td>Number of Batt output tape *</td>
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<tr>
<td>MEX</td>
<td>Utility index</td>
</tr>
<tr>
<td>MM</td>
<td>Utility index</td>
</tr>
<tr>
<td>NAME</td>
<td>Name stored in common *</td>
</tr>
</tbody>
</table>

* Stored in COMMON
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAT</td>
<td>Number of output tape</td>
<td>*</td>
</tr>
<tr>
<td>NOST</td>
<td>Number of look angle stations</td>
<td>*</td>
</tr>
<tr>
<td>NOT</td>
<td>Number of time changes</td>
<td>*</td>
</tr>
<tr>
<td>NIC</td>
<td>Not used in two body</td>
<td>*</td>
</tr>
<tr>
<td>ORBT</td>
<td>Number of orbits of orbital vehicle</td>
<td>*</td>
</tr>
<tr>
<td>PERIGEE</td>
<td>Perigee altitude of the orbit</td>
<td></td>
</tr>
<tr>
<td>PERIOD</td>
<td>Time to make one revolution of orbit</td>
<td></td>
</tr>
<tr>
<td>PHI</td>
<td>Stored longitude</td>
<td></td>
</tr>
<tr>
<td>PHIX</td>
<td>Used to compute longitude</td>
<td></td>
</tr>
<tr>
<td>PI</td>
<td>$\pi = 3.141592654$</td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>Page count</td>
<td></td>
</tr>
<tr>
<td>POP</td>
<td>Earth flattening constant</td>
<td></td>
</tr>
<tr>
<td>PRALT</td>
<td>Geodetic latitude of the vehicle</td>
<td></td>
</tr>
<tr>
<td>PRLAT</td>
<td>Geodetic altitude of the vehicle</td>
<td></td>
</tr>
<tr>
<td>PRLON</td>
<td>Longitude of the vehicle</td>
<td></td>
</tr>
<tr>
<td>PRTIME</td>
<td>Time from launch</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>Length of position vector n. m.</td>
<td></td>
</tr>
<tr>
<td>RADIUS</td>
<td>$\pi /180. = 1/57.2957795$</td>
<td></td>
</tr>
<tr>
<td>RANGE</td>
<td>Great circle range on surface of Earth</td>
<td></td>
</tr>
<tr>
<td>RDOT</td>
<td>Rate of change along R with respect to time</td>
<td></td>
</tr>
<tr>
<td>RE</td>
<td>Radius of Earth $f(\theta c)$</td>
<td></td>
</tr>
<tr>
<td>REE</td>
<td>Equatorial radius of Earth - n. m.</td>
<td></td>
</tr>
<tr>
<td>RF</td>
<td>Length of position vector (ft)</td>
<td></td>
</tr>
<tr>
<td>RLAU</td>
<td>Radius to launch point</td>
<td>*</td>
</tr>
<tr>
<td>RS</td>
<td>Radius of look station</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>$\triangle C (1 - e^2)$</td>
<td></td>
</tr>
<tr>
<td>SEC</td>
<td>Output time in seconds</td>
<td></td>
</tr>
<tr>
<td>SECF</td>
<td>Function for obtaining output time in seconds</td>
<td></td>
</tr>
<tr>
<td>SHT</td>
<td>Look station altitude</td>
<td></td>
</tr>
<tr>
<td>SLAL</td>
<td>Sine of the launch latitude</td>
<td>*</td>
</tr>
<tr>
<td>SLANT</td>
<td>Orbital inclination angle</td>
<td></td>
</tr>
<tr>
<td>SLOL</td>
<td>Sine of the launch longitude</td>
<td></td>
</tr>
<tr>
<td>SLR</td>
<td>Distance from tracking station to vehicle</td>
<td></td>
</tr>
</tbody>
</table>

* Stored in COMMON
TDR-63-11

SMAJ  Semi major axis
SMIN  Semi minor axis
SMON  Argument of perigee
SPH   Look station longitude
SSLANT Sine of inclination angle
ST    Sine of theta
STH   Look station latitude
STHC  Look station geocentric latitude
STRVA Sine of the true anomaly
SX    Orbital plane coordinate system vector
S1    Variables used to compute output variables
S2    Variables used to compute output variables
S3    Variables used to compute output variables
S4    Variables used to compute output variables
S5    Variables used to compute output variables
SP6   Used to calculate aspect angle
TAG   Not used in two body *
THETA Geocentric latitude
TIME  Independent variable
TIMP  Time to impact
TINCR Time increment
TOPP  Time of perigee passage
TRANOM Initial true anomaly
TRIMP Impact point true anomaly
TRUNU True anomaly
VELOC Velocity at any point of the orbit
VI    Initial inertial velocity
WE    Rotational velocity of the Earth
X     X Component of look vector
XAZ   Azimuth of look vector
XEL   Elevation of look vector
XIM   X Component of position vector for range computations

* Stored in COMMON
XLAV X Component of launch vector
XLLO Launch longitude *
XM Mean anomaly
XP Used in matrix rotation
XSHT Stored tracking station altitude *
XSPH Stored tracking station longitude *
XSTH Stored tracking station latitude *

XX \[= \sqrt{\frac{1 - e}{1 + e}}, \text{ storage variable}\]

XX1 Sine of station geodetic latitude
XX2 Cos of Station geodetic Latitude
XX3 Used in station radius calculation
XX4 Used in station radius calculation
Y Y Component of look vector
YIM Y Component of position vector for range computation
YLAU Y Component of launch vector
YY Storage variable
Z Z Component of look vector
ZIM Z Component of position vector for range computation
ZIZ Range angle
ZLAU Z Component of launch vector
ZP Used in matrix rotation
Z2 Number of lines per page *

* Stored in COMMON
A. IDENTIFICATION

TITLE: WRITE ON TAPE
CO-OP ID: WOTF
CATEGORY: General Tape Handler
Programer: J. W. Vise
Date: August 4, 1961

B. PURPOSE:

This routine is used to write a record of arbitrary length on a magnetic tape in either binary or BCD mode

C. USAGE:

1. Calling Sequence

CALL WOTF (a, b, n, m)

\[
\begin{align*}
  n & = 1-48, \text{ MT} \\
  m & = 0, \text{ BINARY} \\
  m & = 1, \text{ BCD} \\
  a & = \text{First LOCN} \\
  b & = \text{Last LOCN}
\end{align*}
\]
CLASSIFICATION: Utility Routine

TITLE: SAVE TAPE

ID: SAVF

PURPOSE: To inform the operator that a tape is to be saved and to rewind the tape with interlock. E.O.F. and 9ssssssENDsssss 0FssssssTAPEssss is written on the tape. (Here s represents blanks).

USAGE:
1. Calling Sequence:
   This routine is used with the following FORTRAN calling sequences:

   CALL SAVF (N), or
   DUMMY = SAVF (N)

   where N is the number, 1-48, of the logical tape to be saved.
7. PROGRAM LISTING
*** SPURT ***
SEPTEMBER 19, 1962 MOD OF AUG. 21, 1962
IF KNTRL (1) = 1, USE METRO DATA
IF KNTRL (1) = 2, USE WINDS ONLY
IF KNTRL (2) = 1, PRINT INPUT DATA
IF KNTRL (3) = N, WRITE OUTPUT FOR BATT ON TAPE N
IF KNTRL (4) = 1, USE TBODY FOR LAST STAGE ONLY
IF KNTRL (4) = 2, USE TBODY FOR ALL STAGES
IF KNTRL (5) = NO IS NUMBER OF LINES ON OUTPUT PAGE
IF KNTRL (6) = N, PLOT TAPE IS WRITTEN ON TAPE N
IF KNTRL (7) = 1, A RIGHT HAND COORDINATE SYSTEM
IS PRINTED OUT
IF KNTRL (8) = 1, USE IMPACT FOR N-1 STAGES
IF KNTRL (8) = 2, USE IMPACT FOR ALL STAGES
SENSE SWITCH 4 PRINTS INTERMEDIATE RESULTS
SENSE SWITCH 5 REINITIALIZES ON CRITERION FAILURE
A NEG NO. IN FIRST POSITION OF BURNING DRAG-MACH NO.
TABLE IgNORES AERODYNAMICS FOR THAT STAGE

*** DIMENSION BLOCK ***

DIMENSION NAME(10), KNTRL(10), TMCC(10), SPTIME(100), SPIN(100), TIMET
1(21,10), THRUST(21,10), DIMACH(21,10), DRAG1(21,10), D2MACH(21,10), DRA
2G2(21,10), CPMACh(21,10), CP[21,10], CMMACH(21,10), CN(21,10), FTT(10),
3AE(10), PAT(10), D(10), GO(10), GP(10), R(10), A(10), B(10), PWGT(10), PWGT
4C(10), TMI(10), TMB0(10), WTEMP(96), WDEN(96), WPRES(96), WINDV(96), WIND
5A(96), WGT(10), WGT(10), WALTU(98), DC (3,3), ACODES(10), PXLDD(3)
6, SPT(100), SPI(100), WALT(96), WUTU(96), WOUT(96), WPU(96),
7STX(3), STXD(3), PX(3), PXD(3), WX(98), WY(98), WZ(98), ROT(3,3), RA(10),
8RB(10), TTAB(21), THTAB(21), DMAB(21), DMTAB(21), CPMTAB(21), CPTAB(21)
9CNMTAB(21), CNTAB(21), WGTAB(21), SPT1(100), G0P(10), N(6,10)
DIMENSION ROT1(3,3), T(3), T(3), DEL(10), PHT(10), PXDD(3)
1, OUT (25,50), PXL(3), PXLD(3), PXND(3), XVX(3), BL(38), TABLE(500), CBLOCK
2(150), VX(3), TB3(5), TB4(5), TB6(3,50), TB7(50), TB8(50), TB9(50)
3XMACH(10,10), CDM(10,10), NNX(10), XIMPA(3,10), XDIMP(3,10), TFIMP(10)
4, RANGE(10), DELPR(10)

*** COMMON BLOCK ***

COMMON ROT1, NAME, KBATT, JTB1, JTB2, TB2, TB3, TB4, JTB5, TB6, TB7, TB8, TB9, Z2
1, STHC, CTHC, AL02, REL, XMACH, CDM, NNX, NOT, RANGE, XIMPA, XDIMP, TFIMP, DELP
2R
*** EQUIVALENCE BLOCK ***

EQUIVALENCE (BL(1),ICODE),(BL(2),ACODE),(BL(3),TRERR),(BL(4),SMIN
1),(BL(5),SMAX),(BL(6),NOE),(BL(7),SS),(BL(8),TIME),(BL(9),PX (1))
2(BL(12),PHI),(BL(13),THETA),(BL(14),R1X),(BL(15),R2X),(BL(16),R3X)
3,(BL(17),R4X),(BL(18),R5X),(BL(19),PXD(1)2),(BL(22),PHID),(BL(23),T
4HETD),(BL(24),PXDD(1)),(BL(27),PHDD),(BL(28),THETDD),(BL(29),ACOD
5ES(1))

RADF(A)=SQRTF(A(1)*A(1)+A(2)*A(2)+A(3)*A(3))

ADAMS EQU 6000B
ATMOS EQU 7300B
SQRDF EQU 7660B

*** FORMAT BLOCK ***

1 FORMAT(10A8)
2 FORMAT(3512)
3 FORMAT(12,7F13.0)
5 FORMAT(7F10.0)
6 FORMAT(612)
7 FORMAT(17H1 INPUT TABLE 10A8)
8 FORMAT(5X5F15.4,4X10I2)
9 FORMAT(12H1 STAGE NO. I2,11X4HTIME,5X6HTHRUST,5X8HMACH NO.,5X6HCD
1(B),3X8HMACH NO.,5X6HCD(C),3X8HMACH NO.,6X2HCP,6X8HMACH NO.,4X8H
2CN/ALPHA/)
10 FORMAT(14H0 SPIN TABLE/(8F10.3))
11 FORMAT(23H1 INPUT ERROR IN STAGE12)
12 FORMAT(5X10F11.3)
13 FORMAT(1H0,9X15STAGE WEIGHT = F26.2,4H LBS 6X20HSTAGE FUEL WEIGH
1T = F30.2,4H LBS/10X16HIGNITION TIME = F25.2,4H SEC 6X15BBURNOUT
2TIME = F35.2,4H SEC/10X13HMISSEI CG = F29.4,3H FT 6X16HSSTAGE FUE
3L CG = F35.4,3H FT/10X12HEXIT AREA = F26.2,7H SQ IN. 6X34HPRESSUR
4E AT THRUST MEASUREMENT = F9.4,11H LBS/SQ IN./10X28HLONGITUDINAL
5 I OF MISSILE = F7.2,10H FT2 SLUGS6X26HTRANSVERSE I OF MISSILE = F
618.2,10H FT2 SLUGS/10X24HFUEL LONGITUDINAL I/M = F17.4,4H FT26X22
7HFLUEL TRANSVERSE I/M = F28.4,4H FT2/
14 FORMAT(10X28HTHRUST MISALIGNMENT ANGLE = F13.2,4H RAD 6X43HORIENTA
1TION ANGLE OF THRUST MISALIGNMENT = F7.2,4H RAD10X11HDIAMETER =
2F31.4,3H FT6X30HTIME TO CHANGE COEFFICIENTS = F20.2,4H SEC
15 FORMAT(21H1 INTEGRATION ERROR 016)
16 FORMAT(21H0 **CRA FAILURE ATF9.4,7H SEC***)
FORMAT (1H0F10.4,9E12.3/(5X10F11.3))
FORMAT(2H1 10A8)
FORMAT(/19X23HLOCAL FLIGHT PARAMETERS/3X4HTIME4X8HLATITUDE4X9HLON
GITUDE3X8HALITUDE2X8VEL0CITY2X7HAZIMUTH3X3HPA/4X3HSEC7X3HDEG10X3
2HDEG7X4HEET4X6HT/SEC6X3HDEG5X3HDEG/
FORMAT(/83H TIME RANGE DEFORMATION ALTITUDE VELOCITY
1 PHI THEETA /83H SEC N.MILES N.MILES
2 N.MILES FT/SEC DEG. DEG. DEG. /
FORMAT(/3X4HTIME5X6HTHRUST5X6HWEIGHT4X12HTOTAL ACCEL.4X12HDYNAMI
C1PRES4X5H DRAG7X5H MACH/4X3HSEC7X3HLBS8X3HLBS5X12HACCEL./GRAV.6X8HL
2BS/5QFT7X3HLBS9X3HNO.)
FORMAT(/4X4HTIME9X1HX12X1HY12X1HZ10X5HX-DOT8X5HY-DOT8X5HZ-DOT/4X3H
1SEC9X4HEET9X4HEET8X6HFT/SEC7X6HFT/SEC7X6HFT/SEC/)
FORMAT(F8.2,2F12.4,F9.0,F9.0,2F9.2)
FORMAT(F8.2,F10.3,2F12.3,F11.1,2F8.3)
FORMAT(F8.2,2F12.2,2F12.3,2F13.2)
FORMAT(F8.2,6F13.0)
FORMAT(11,F10.6)
FORMAT(2F10.0)
FORMAT(13)
FORMAT(3A8,3F10.0)
ORG 100508

**** CONSTANTS ****

PI=3.141592654
TWOPI=2.*PI
HALFPI=0.5*PI
RAD=PI/180.
REE=20925647.
GM=1.40764E16
XJ=.0016234
GRAV0=32.174
TMEG=7.292111E-5
TMEG2=2.*TMEG
TMEG2=TMEG*TMEG
GK= XJ*REE*REE
ICODE=3
TRERR=1.E-3
ACODE=1.0
ACODES(1)=1.0
ACODES(2)=1.0
ACODES(3)=1.0
ACODES(4)=0.1
ACODES(5)=0.1
ACODES(6)=1.0
ACODES(7)=1.0
ACODES(8)=1.0
ACODES(9)=0.01
ACODES(10)=0.01
DT=1.
SMIN=.01
SMAX=1.
NOE=10
SS=1./16.

*** INPUT BLOCK ***

100 CALL SCLOCK
   KIX = 0
   READ 3,NS,PYLWGT
   IF(NS)120,110,140
110 IF(NOT) 111,112,111
111 CALL SAVF(NOT)
112 STOP
120 NS=NS
   ENA = 0
   ENQ = 0
   RTJ = RDF
   NOP =49
   RTJ = ERROR.
130 GO TO 183
140 READ 1,(NAME(I),I=1,10)
   READ 5,ALAT,ALON,AALT,AAZIM,(STX(I),I=1,3),(SIXD(I),I=1,3),STP,STT
   1,STPD,STTD,START,TSTOP
   READ 2,(KNTRL(I),I=1,10),NSPIN,NOT,INTN
   IF(NOT) 113,114,113
113 REWIND NOT
114 READ 5,(SPTIME(I),I=1,NSPIN)
   READ 5,(SPIN(I),I=1,NSPIN)
   DO 150 J=1,NS
150 READ 6,NO,(N(I,J),I=1,5)
   NI=N(I,J)
N2=N(2,J)
N3=N(3,J)
N4=N(4,J)
N5=N(5,J)
READ 5,(TIME(I,J),I=1,N1)
READ 5,(THRU(I,J),I=1,N1)
READ 5,(D1MACH(I,J),I=1,N2)
IF (D1MACH(I,J)) 142,141,141
141 READ 5,(DRAG1(I,J),I=1,N2)
READ 5,(D2MACH(I,J),I=1,N3)
READ 5,(DRAG2(I,J),I=1,N3)
READ 5,(CPMACH(I,J),I=1,N4)
READ 5,(CP(I,J),I=1,N4)
READ 5,(CMACH(I,J),I=1,N5)
142 READ 5,(PAT(J),AE(J),D(J),G0(J),GP(J),RA(J),RB(J),A(J),B(J),PWGT(J)
1,PWGTC(J),PHT(J),TDEL(J),DUM,TM1(J),TM0(J),TMCC(J)
IF (NO-J) 149,150,149
149 PRINT 11,J
STOP
150 CONTINUE
IF (KNTRL(1)) 190,190,160
160 READ 2, KMETER
READ 5,(WALT(I),I=1,KMETER)
IF (KNTRL(1)-1) 190,170,180
170 READ 5,(WTEMP(I),I=1,KMETER)
READ 5,(WDEN(I),I=1,KMETER)
READ 5,(WRES(I),I=1,KMETER)
180 READ 5,(WINDV(I),I=1,KMETER)
READ 5,(WINDA(I),I=1,KMETER)
190 IF (KNTRL(4)) 188,188,187
187 READ 30, JTB1,TB2
READ 31, (TB3(I),TB4(I),I=1,JTB1)
READ 32, JTB5
DO 189 I=1,JTB5
189 READ 33,(TB6(I1,I),I1=1,3),TB7(I),TB8(I),TB9(I)
188 IF (KNTRL(8)) 183,183,184
184 READ 6,NXIM
DO 185 J=1,NXIM
READ 3, NRAT,DELP(J)
NX(J)= NRAT
READ 5,(XMACH(I,J),I=1,NRAT)
READ 5, (CDM(I,J), I=1, NRAT)
185 CONTINUE
183 IF (KNTRL(2)) 200, 200, 192
192 WRITE OUTPUT TAPE NOT, 7, (NAME(I), I=1, 10)
   WRITE OUTPUT TAPE NOT, 8, PYLWGT, ALAT, ALON, AALT, AAZIM, (KNTRL(I), I=1, 110)
   WRITE OUTPUT TAPE NOT, 10, (SPTIME(I), SPIN(I), SPTIME(I+25), SPIN(I+25)
   SPTIME(I+50), SPIN(I+50), SPTIME(I+75), SPIN(I+75), I=1, 125)
   DO 191 J=1, NS
   WRITE OUTPUT TAPE NOT, 9, J
   WRITE OUTPUT TAPE NOT, 12, (TIMET(I,J), THRUST(I,J), DIMACH(I,J), DRAG1
   DRAG2(I,J), CPMACH(I,J), CP(I,J), CNMACH(I,J), CN(I, 2J), I=1, 21)
   WRITE OUTPUT TAPE NOT, 13, PWGT(J), PWGTC(J), TMI(J), TMBO(J), GO(J),
   2GP(J), AE(J), PAT(J), A(J), B(J), RA(J), RB(J)
191 WRITE OUTPUT TAPE NOT, 14, TDEL(J), PHT(J), D(J), TMCC(J)
   *** GEODETIC TO GEOCENTRIC ***
200 ALA2=ALAT*RAD
   ALO2=ALON*RAD
   AAZI2=AAZIM*RAD
   COLAT=HALFPFI-ALA2
   BLON=ALO2+HALFPFI
   BAZIM=AAZI2-HALFPFI
   CALAT=COSF(ALA2)
   SILAT=SINF(ALA2)
   C=REE/SQRTF(1.-.006693421*SILAT*SILAT)
   S=.99330658*C
   X1X=(C+ALAT)*CALAT
   X1Y=(S+ALAT)*SILAT
   REL=SQRTF(X1X*X1X+X1Y*X1Y)
   THC=ATANF(X1Y/X1X)
   STHC = SINF (THC)
   CT0HC=HALFPFI-THC
   CTHC=COSF (THC)
   CALL ROTATE(BAZIM, DELTH, 0., STX, XVX)
   XVX(3)=XVX(3)+REL
   CALL ROTATE(0.,-CT0HC,-BLON,XVX,PX)
   DELTH=ALA2-THC
   CALL ROTATE (BAZIM, -COLAT, -BLON, STXD, PXD)
   DO 201 I=1, 3
DO 201 J=1,3
   R0T(I,J)=ROT(I,J)
201   Z2=KNTRL(5)
   PH1=TP*RAD
   PHI=STP*RAD
   THETA=STT*RAD
   R1X=PSD(1)
   R2X=PSD(2)
   R3X=PSD(3)
   R4X=TPD*RAD
   R5X=STD*RAD
   LSKIP=0
   JP=1
   L=0
   TIME = STARTT
KBATT = 0
   KPLOT = 0
202   IF (KNTRL(3)) 202,203,202
203   KBATT = KNTRL(3)
   REWIND KBATT
204   IF (KNTRL (6)) 204,205,204
204   KPLOT = KNTRL (6)
   REWIND KPLOT

*** SET UP INPUT TABLES ***

205   WGT(NS+1)=PYLWGT/GRAV0
   DO 210 J=1,NS
      K=NS-J+1
      WGT(K)=PWT(K)/GRAV0+WTG(K+1)
   WGC(T(J)=PWGTC(J)/GRAV0
210   G0P(J)=G0(J)-GP(J)
   DO 220 I=1,NSPIN
      K=NSPIN-I+1
      SPT(K)=SPTIME(I)
220   SPI(K)=SPIN(I)
      SPIT(NSPIN)=0.
   DO 221 I=2,NSPIN
      K=NSPIN-I+1
221   SPI(K)=SPI(K+1)+SPI(K)+SPI(K+1))*(SPT(K)-SPT(K+1))/2.
   IF(KNTRL(1))229,229,230
229   WMAX = 0.
   GO TO 260
DO 251 I=1,KMETRO
   K = KMETRO-I+1
   WALTU(K) = WALT(I)
   IF(KNTRL(I)-1)260,240,250
240   WTU(K) = 1116.4*SQRTF((WTEMP(I)+273.16)/288.16)
   WDU(K) = WDEN(I)*.00194032
   WPU(K) = WPRES(I)*2.088544
250   SW=WINDA(I)*RAD-BAZIM+HALFPI
   VWX=COSF(SW)
   VWY=SINF(SW)
   WX(K)=WINDV(I)*(ROT(1,1)*VWX+ROT(1,2)*VWY)
   WY(K)=WINDV(I)*(ROT(2,1)*VWX+ROT(2,2)*VWY)
251   WZ(K)=WINDV(I)*(ROT(3,1)*VWX+ROT(3,2)*VWY)
   WMAX = WALTU(I)
260   CALL SETTAB(NS,TMI,TMCC,TMBO,DT,TABLE,IT)
   GO TO 281
270   IF(TIME-TMBO(L))410,271,273
271   DO 272 I=1,N3
272   K=N3-I+1
   DMTAB(K)=D2MACH(I,L)
   DTAB(K)=DRAG2(I,L)*D(L)*D(L)*PI/8.
   DMTAB(I)=10.E10
   DTAB(I)=DTAB(2)
   BDOT=0.
   FT=0.
   WGTCl=WGTCL(L)
   SENSE LIGHT 1
   IF(KNTRL(4)-2)280,279,280
279   CALL TWP08D(TIME,PX,PXD)
280   KIX=KIX+1
   DO 274 I=1,3
   XIMP(A,I,KIX)=PX(I)
274   XDIMP(A,I,KIX)=PXD(I)
   TFXMP(A,I,KIX)=TIME
   RANGE(KIX)=RANGE1
273   IF(TIME-TMCC(L))999,281,410
281   L=L+1
   WGTCl=0.
   GI=GO(L)
   N1=N1(L)
   N2=N2(L)+1
   N3=N3(L)+1
N4=N(4,L)+1
N5=N(5,L)+1
P1=PA(T,L)*AE(L)
DO 400 I=1,N1
K=N1-I+1
TTTAB(K)=TIMFT(I,L)+TM1(I,L)
400 THTAB(K)=THRUST(I,L)+P1
WGTAB(N1)=0.
DO 404 I=2,N1
K=N1-I+1
404 WGTAB(K)=WGTAB(K+1)+(THTAB(K)+THTAB(K+1))*(TTTAB(K)-TTTAB(K+1))*.0.
15
FTT(L)=WGTAB(1)
DO 405 I=1,N1
405 WGTAB(I)=WGTAB(I)*WGTC(L)/FTT(L)
IF(DIMACH(1,L))406,407,407
406 LSKI=1
GO TO 410
407 LSKI=0
DO 401 I=1,N2
K=N2-I+1
401 DTA(B(K))=DRAG1(I,L)*D(L)*D(L)*PI/8.
DO 402 I=1,N4
K=N4-I+1
402 CPTAB(K)=CMACH(I,L)
402 CPMTAB(K)=CPMACH(I,L)
DO 403 I=1,N5
K=N5-I+1
403 CNMTAB(K)=CNMACH(I,L)
CNMTAB(K)=CNMACH(I,L)
403 CNTAB(K)=CN(I,L)*PI/8.
DMTAB(1)=10.E10
DTAB(1)=DTAB(2)
CPMTAB(1)=10.E10
CPTAB(1)=CPTAB(2)
CNMTAB(1)=10.E10
CNTAB(1)=CNTAB(2)
410 IF(TIME-TMI(L))999,411,411
411 SENSE LIGHT 0
411 IF(TIME)412,412,999
412 CHECK=PX(1)
RTJ TEXIT
(999) RTJ ADAMS INTEGRATION
ZRO EQN CALLING
ZRO TEXIT SEQUENCE
ZRO PRTIME
ZRO BL
ZRO CBLOCK
ZRO EXIT
ZRO TMIN
STA ERR
PRINT 15, ERR STOP

C *** EQUATIONS OF MOTION ***
C
C EQN SLJ **
PXD(1)=R1X
PXD(2)=R2X
PXD(3)=R3X
PHID=R4X
THETD=R5X
R2=PX(1)*PX(1)+PX(2)*PX(2)+PX(3)*PX(3)
R=SQRTF(R2)
RE=REE/SQRTF(1.+0.00673852*PX(3)/R*PX(3)/R)
ALT=R-RE
IF(LSKIP)1050,1001,1050
1001 IF(ALT-WMAX)1000,1030,1030
1000 IF(KNTRL(1)-1)1030,1010,1020
1010 RHO = INTERPF(ALT,KMETRO,INTN,WALTU,WDU)
VA = INTERPF(ALT,KMETRO,INTN,WALTU,WTU)
PRES = INTERPF(ALT,KMETRO,INTN,WALTU,WPU)
1020 VWX = INTERPF(ALT,KMETRO,INTN,WALTU,WX)
VWY = INTERPF(ALT,KMETRO,INTN,WALTU,WY)
VWZ = INTERPF(ALT,KMETRO,INTN,WALTU,WZ)
IF (KNTRL(1)-1) 1031,1040,1031
1030 VWX = 0.
VWY = 0.
VWZ = 0.
(1031) LDA ALT ATMOSPHERE
RTJ ATMOS CALL
TEM OCT RUTINE
PRES OCT
RH0 OCT
VA OCT
GO TO 1050
1040 VX(1) = PXD(1)-VWX
VX(2) = PXD(2)-VWY
VX(3) = PXD(3)-VWZ
V = RADF(VX)
VMACH=V/VA
FDRAF=INTERPF(VMACH,N2,INTN,DMTAB,DTAB)*V*V*RHO
CPI=INTERPF(VMACH,N4,INTN,CPTAB,CPTAB)
CNI=INTERPF(VMACH,N5,INTN,CNMTAB,CNTAB)
GO TO 1060
1050 FDRAG=0.
CPI=0.
CNI=0.
VMACH=0.
RHO=0.
1060 IF(SENSE LIGHT 1)1061,1062
1061 SENSE LIGHT 1
GO TO 1063
1062 FORCE=INTERPF(TIME,N1,INTN,TTTAB,THTAB)
WGTCL=INTERPF(TIME,N1,INTN,TTTAB,WGTAB)
FT=FORCE-PRES*AE(L)/144.
BDOT=FORCE*WGTCL/FTT(L)*(WGT(L)*GOP(L)/WGTI*WGT(L)*GOP(L)/WGTI+W1RB(L))
1063 GRV=GM/(R2*R)*(1. +3.*GK/R2-15.*GK* PX(3)/R2* PX(3)/R2)
WGTI=WGT(L)-WGTCL
G1=G0(L)+GOP(L)*WGTCL/WGTI
GRVX=GRV*PX(1)
GRVY=GRV*PX(2)
GRVZ=(GRV+G1*R2*G2*G3)*PX(3)
IF(TIME-TMI(L))1082,1080,1082
1080 AXLM=A(L)
TRVM=B(L)
GO TO 1083
1082 AXLM=A(L)-RA(L)*WGTCL
TRVM=B(L)-WGT(L)*(G1-G0(L))*G0P(L)-WGTCL*R(B(L)
1083 BDOTB=BDOT/TRVM
AXLMB=AXLM/TRVM
COEF=CNI*(CPI-GI)*D(L)*D(L)*V/RHO/TRVM
XSP=INTERPF(TIME,NSPIN,INTN,SPT,SPIT)
XSP=MODF(INTERPF(TIME,NSPIN,INTN,SPT,SPIT),TWOP1)
SPHI=SINF(PHI)
CPHI=COSF( PHI )
STHET=SINF( THETA )
CTHET=COSF( THETA )
TPH0=PHT(L)+XSPT
CPHT=COSF( TPH0 )
SPHT=SINF( TPH0 )
IF(LSKIP)1091,1089,1091
1089 DO 1090 I=1,3
  T(1)=0.
  DO 1090 J=1,3
1090  T(1)=ROT(J,I)*VX(J)+T(1)
       V2=-T(1)*CPHI+T(3)*SPHI
       V3=-T(1)*SPHI*STHET+T(2)*CTHET-T(3)*CPHI*STHET
1091  T(1)=FT*(CTHET*SPHI-TDEL(L)*(CPHT*CPHI+SPHT*SPHI*STHET))
       T(2)=-FT*(STHET+TDEL(L)*SPHT*CTHET)
       T(3)=FT*(CTHET*CPHI+TDEL(L)*(CPHT*SPHI-SPTH*CPHI*STHET))
       DO 1100 I=1,3
       TT(I)=0.
       DO 1100 J=1,3
1100  TT(I)=ROT(I,J)*T(J)+TT(I)
       H = RADF(PXD)
1101  PXDD(1)=T(1)-FDRAG*PXD(1)/H+GVT+GRT*OME8*PXD(2)+OME8*PX(1)
       PXDD(2)=T(2)-FDRAG*PXD(2)/H+GVT+GRT*OME8*PXD(1)+OME8*PX(2)
       PXDD(3)=T(3)-FDRAG*PX(3)/H+GVT+GRT
       PHIDD=BD0T*PHID+(( (2.-AXLMB)*STHET*PHID+AXLMB*XSP)*THEA+COE8*V2
       1+FT*G1*TDEL(L)*CPHT/TRVM/CTHET
       THEA=-BD0T*THEA-((1.-AXLMB)*STHET*PHID+AXLMB*XSP)*PHID*CTHET-F
       1*TG1*TDEL(L)*SPHT/TRVM-COE8*V3
       GO TO EQN
EXIT  SLJ
502  CHECK=PX(1)
      IF(SENCH SWITC14)500,505
500  PRINT 17, TIME,( PX(I), I=1,3 ),(PXD(I), I=1,3),(AXLMB(I), I=1,3),PHI,TH
       ETA,PHID,THEA,HIDDD,THEA,ALT,V,VMACH,FT,GRVX,GRVY,GRVZ,WGTI,FDR
       2AG,CPI,CNL,AXLMB,TRVM,BDOT
505  IF(SENCH LIGHT 2) 999,EXIT
TMIN  SLJ
      PRINT 16,TIME
      IF (SENCH SWITC15) 550, TMIN
550  SENSE LIGHT 2
      GO TO TMIN
EXIT  SLJ
IF(PX(1)-CHECK)4000,3999,4000
(3999) RTJ EQN

*** OUTPUT BLOCK ***

C
C
4000 DO 4001 I=1,3
PXLD(I)=0.
DO 4001 J=1,3
PXLD(J)=PXD(J)+PXLD(I)
CALL ROTATE(BLO, COTH, 0., PX, XVX)
XVV(3)=XVV(3)-REL
CALL ROTATE(0.,-DELT,-BAZIM, XVV, PXL)
OUT(1,JP)=TIME
TP=RADF(PX)
TP=ASINF(PX(3)/TP1)
CALL GEODED(TP,TP1,TP2,OUT(4,JP))
OUT(2,JP)=TP2/RAD
OUT(3,JP)=ATANF(PX(2)/PX(1))/RAD
IF(PX(1)) 4010,4011,4011
4011 AN1=OUT(3,JP)*RAD+HALFP1
AN2=HALFP1-TP2
CALL ROTATE(AN1,AN2,0.,PXD,PXND)
OUT(5,JP)=RADF(PXND)
IF (TIME) 4015,4015,4016
4015 OUT(6,JP)=AAZIM
OUT(7,JP)=(HALFP1-PHI)/RAD
GO TO 4019
4016 OUT(6,JP)=ATANF(PXND(1)/PXND(2))/RAD
IF(PXND(2)) 4020,4021,4021
4020 OUT(6,JP)=OUT(6,JP)+180.
4021 OUT(7,JP)=ASINF(PXND(3)/OUT(5,JP))/RAD
4019 IF (TIME=12.) 4023,4023,4022
4022 AN1=SINF((THC+TP)/2.)
OUT(8,JP)=REE/6076.1033*ACOSF(STHC*PX(3)/TP1+COTH*COSF(TP)*COSF(TP)*OUT(3,JP)*RAD))/SQRFT(1.'00673852*AN1*AN1)
GO TO 4024
4023 OUT(8,JP)=PXL(1)/6076.1033
4024 OUT(9,JP)=PXL(2)/6076.1033
RANGE1=OUT(8,JP)
OUT(10,JP)=OUT(4,JP)/6076.1033
OUT(11,JP)=RADF(PXLD)
OUT(12,JP)=PHI/RAD
OUT(13,JP)=THETA/RAD
OUT(14,JP)=FT
OUT(15,JP)=WGT*GRAV
OUT(16,JP)=RADF(PXDD)/GRAV
OUT(17,JP)=.5*RHO*OUT(5,JP)*OUT(5,JP)
OUT(18,JP)=FDRAG
OUT(19,JP)=VMACH
OUT(20,JP)=PXL(1)
OUT(21,JP)=PXL(2)
OUT(22,JP)=PXL(3)
OUT(23,JP)=PXL(1)
OUT(24,JP)=PXL(2)
OUT(25,JP)=PXL(3)
IF(KNTRL(7)) 40241,40241,40241

40242 OUT(21,JP)=OUT(21,JP)
OUT(24,JP)=OUT(24,JP)

40241 IF(KNTRL(6)) 4026,4026,4025
4025 CALL WOTF (OUT(1,JP),OUT(25,JP),KPLMT,0)
4026 IF(KNTRL(3)) 4029,4029,4027

4027 AN1=HALFPI-PHI
AN2=HALFPI+THETA
CALL ROTATE (HALFPI,AN1,AN2,T,TT)
DO 4028 I=1,3
PXLDD(I)=0.
DO 4028 II=1,3
DC(I,II)=0.
PXDD(I)=ROT(I1,1)*PXDD(I1)+PXLDD(I)
DO 4028 III=1,3
4029 DC(I1,II1)=ROT(I1,II1)*ROT1(I11,II1)+DC(I,II)
WRITE TAPE KBATT{OUT(JP),I=1,25},(PXSDL(I1),I=1,3),
1((DC(I,II1),II=1,3),I1=1,3),((PXI(I),I=1,3),I1=1,3)

4029 IF(JP-KNTRL(5)) 4030,4031,4031
4030 IF(TIME=TSTOP) 4039,4031,4031
4031 WRITE OUTPUT TAPE NOT,18,(NAME(I),I=1,10)
WRITE OUTPUT TAPE NOT,20
WRITE OUTPUT TAPE NOT,24,((OUT(I1,II),I=1,7),II=1,JP)
WRITE OUTPUT TAPE NOT,18,(NAME(I),I=1,10)
WRITE OUTPUT TAPE NOT,21
WRITE OUTPUT TAPE NOT,25,OUT(I1,II),OUT(I1,II),I=8,13,II=1,JP
WRITE OUTPUT TAPE NOT,18,(NAME(I),I=1,10)
WRITE OUTPUT TAPE NOT,22
WRITE OUTPUT TAPE NOT,26,(OUT(1,11),OUT(1,11),I=14,19),II=1,JP)
WRITE OUTPUT TAPE NOT,18,(NAME(I),I=1,10)
WRITE OUTPUT TAPE NOT,23
WRITE OUTPUT TAPE NOT,27,(OUT(1,11),OUT(1,11),I=20,25),II=1,JP)
JP=1
4036 IF(TIME-TSTOP) 4060,4037,4037
4037 IF(KNTRL(3)) 4039,4039,4038
4038 END FILE KBATT
4039 IF(KNTRL(6)) 4040,4040,40391
40391 END FILE KPLOR
4040 IF(KNTRL(8)-2) 4071,4070,4071
4070 KIX = KIX + 1
DO 4073 I = 1,3
XIMPA(I,KIX) = PX(I)
4073 XDIMP(I,KIX) = PXD(I)
TFIMP(KIX) = TIME
RANGE(KIX) = RANGE1
4071 IF(KNTRL(8)) 5010,5010, 5011
5011 DO 5009 I=1,KIX
IRA=1
CALL IMPACT (IRA)
5009 CONTINUE
5010 IF(KNTRL(4)) 4041,4050,4041
4041 CALL TWOBOD (TIME,PX,PXD)
4050 IF(KNTRL(3)) 4052,4052,4051
4051 CALL SAVF (KBATT)
4052 IF(KNTRL(6)) 4054,4054,4053
4053 CALL SAVF (KPLOR)
4054 CALL ECLOK(OUT)
GO TO 100
4059 JP=JP+1
4060 IT=IT-1
PRTIME=TABLE(IT)
IF(MOCF(TABLE(IT+1),DT))270,TEXIT,270
RDF LIB RDF
END
C:
C
SUBROUTINE SETTAB (NS, TMI, TMCC, TMBO, DT, TABLE, IX)
C   THIS SUBROUTINE SETS UP THE PRINT TIME TABLE
R   DIMENSION TMI(10), TMCC(10), TMBO(10), TABLE(500)
   NSS=NS-1
   IX=(TMBO(NS)+1.)/DT
   TABLE(Ix)=0.
   DO 1 I=2,IX
   K=IX-I+1
1   TABLE(K)=TABLE(K+1)+DT
   DO 2 I=2,NS
   U=TMI(I)
   RTJ
2   TMI(I)=U
   DO 3 I=1,NS
   U=TMBO(I)
   RTJ
3   TMBO(I)=U
   DO 4 I=1,NSS
   U=TMCC(I)
   RTJ
4   TMCC(I)=U
5   RETURN
   DUM=MODF(DUM,1.)
INS
   SLJ **
   SIL 6 INS3
   LDA  U
   LIL 6 IX
   TS 6 TABLE
   INI 6 -1
   INI 6 1
   FSB 6 TABLE
   AJP 1 INS1
   LDA 6 TABLE
   LDQ  DT
   RTJ MODF
   RTJ ERROR.
+   AJP N *+3
   LDA 6 TABLE
   FAD INS3+1
   STA 6 TABLE
   STA  U
+   LIL 6 INS3
SUBROUTINE ECLOCK(ITAPE)

C THIS PROGRAM COMPUTES THE MACHINE TIME FOR ONE TRAJECTORY RUN

DIMENSION X(3)

+ EXF 0 02000B
  LDA 0
  SCM MASK1
  FAD ZERO
  FDV F216M
  STA X+1
  ENA X+1
  RTJ INTF

+ NOP
+ STA X
  LDA X+1
  FSB X
  FMU F60
  STA X+2
  ENA X+2
  RTJ INTF

+ NOP
+ STA X+1
  LDA X+2
  FSB X+1
  FMU F60
  STA X+2

NOP

WRITE OUTPUT TAPE ITAPE,2,(X(I), I=1,3)

2 FORMAT(16HOELAPSED TIME = F3.1,7H HOURS F4.1,10H MINUTES F6.3,8H
1SECONDS)

RETURN

MASK1 OCT 20440000000000000
F60 DEC 60.
F216M DEC 216000.
ZERO DEC 0
INTF LIB INTF

END
SUBROUTINE SCLOCK

EXF  0 02000B
ENA  0
STA  0B

EXF  0 01000B

RETURN

END

STOP THE CLOCK

START THE CLOCK AFTER SETTING=0
SUBROUTINE TWOBOO (TBO,A1,A2)
  THIS SUBROUTINE COMPUTES A KEPLERIAN TRAJECTORY ALONG WITH
   LOOK ANGLES FROM VARIOUS STATIONS
  1ALT(2000),DELTAT(5),ENDT(5),TAG(3,50),SX(3),FX(3),XSTH(50)
  2,DUMTB(9),A1(3),A2(3),XSPH(50),XSHT(50),A1A(10,10),A1B(10,10),N1C(310)
COMMON DUMTB,NME,KBATT,NOT,ORBT,DELTAT,ENDT,NOST,NAME,XSTH,
  1XSPH,XSTH,ZC,SLAL,CLAL,XLLO,RLAU,A1A,A1B,N1C,NAT
SECF(X)=MODF(X,60.)
FMINTF(X)=MODF(INTF(X/60.),60.)
HOURF(X)=INTF(X/3600.)
REE=3443.9255
WE=7.292115E-5
E=.08181333
GM=1.4076427E+16
GMI=GM/6076.1033
PI=3.141592654
RAD=PI/180.0
F=1.0/298.3
ER=0.000005
POP=E*E/(1.0-E*E)
SLOL=SINF(XLLO)
CLOL=COF(XLLO)
XLAU=CLAL*CLOL
YLAL=CLAL*SLOL
ZLAL=SLAL
AX=A1(1)
AY=A1(2)
AZ=A1(3)
AXDOT=A2(1)-AY*WE
AYDOT=A2(2)+AX*WE
AZDOT=A2(3)
RF=SQRTF(AX*AX+AY*AY+AZ*AZ)
R=RF/6076.1033
VI=SQRTF(AXDOT*AXDOT+AYDOT*AYDOT+AZDOT*AZDOT)
H=R*VI*VI/GMI
IF(H-2.0)104,110,110
110 WRITE OUTPUT TAPE NAT,200,(NAME(1),I=1,9)
WRITE OUTPUT TAPE NAT,202
GO TO 190
104 SMAJ=R/(2.0-H)
HX=AY*AZDOT-AZ*AYDOT
HY=AZ*AXDOT-AX*AZDOT
HZ=AX*AYDOT-AY*AXDOT
HH=HX*HY*HY*HY+HZ*HZ
H1=SQRTF(HH)
SLANT=ACOSF(HZ/H1)
CAP0=ATANF(-HX/HY)
IF(HY)106,106,105
105
CAP0=PI+CAP0
106
RDOT=(AX*AXDOT+AY*AYDOT+AZ*AZDOT)/RF
EX=SQRTF(1.0-H1*H1/(SMAJ*GM*6076.1033))
CTRUA=H1/RF*H1/GM-1.0
STRAU=H1*RDOT/GM
TRANOM=ATANF(STRAU/CTRUA)
IF(CTRUA)111,112,112
111
TRANOM=PI+TRANOM
112
CMU=(AY*HX-AX*HY)/H1
AMU=ATANF(AZ/CMU)
IF(CMU)1120,1121,1121
1120
AMU=PI+AMU
1121
SMOM=AMU-TRANOM
SMIN=SMAJ*SQRTF(1.0-EX*EX)
PERIOD=4.184624E-4*SMAJ**1.5
ETA=PERIOD*60./(2.*PI)
APOGEE=SMAJ*(1.0+EX)-REE
PERGEE=SMAJ*(1.0-EX)-REE
XX=SQRTF((1.0-EX)/(1.0+EX))
EXANOM=2.0*ATANF(XX*TANF(TRANOM/2.0))
TOPP=(EXANOM-EX*SINF(EXANOM))*ETA
WRITE_OUTPUT TAPE NAT,200,(NAME(1),I=1,9)
ANS(1)=SLANT/RAD
ANS(2)=SMOM/RAD
ANS(3)=CAP0/RAD
ANS(4)=TRANOM/RAD
ANS(5)=EXANOM/RAD
WRITE_OUTPUT TAPE NAT,201,SMAJ,SMIN,EX,PERIOD,APOGEE,PERGEE,(ANS(1),I=1,5)

TRACERY POINTS
IF(PERGEE)1123,1124,1124
1123
TRIMP=ACOSF(((1.-EX*EX)*SMAJ/REE-1.)/EX)
EXIMP=2.*PI-2.*ATANF(XX*TANF(TRIMP/2.))
TIMP=(EXIMP-EX*SINF(EXIMP))*ETA
GO TO 1127
1124 IF(ORB1)1125,1125,1126
1125 TIMP=PERIOD*60.
GO TO 1127
1126 TIMP=ORB1*PERIOD*60.
1127 SSLANT=SINF(SLANT)
CSSLANT=COSF(SLANT)
E1=EXANOM
TIME=TOPP
PN=-1.0
J=0
TINC0=0.0
MEX=0
MM=1
GO TO 117
113 TINC0=60.*(INTF(TB0/60.)+1.)-TB0
MM=2
GO TO 117
114 MM=3
115 MEX=MEX+1
TINC0=DELTAT(MEX)
116 IF(TIME+TB0-TOPP-EDNT(MEX)+.01)117,115,115
117 J=J+1
TIME=TIME+TINC0
IF(TIME-TIMP)118,118,1171
1171 TIME=TIMP
118 XM=TIME/ETA
119 E2=E1-(E1-EX*SINF(E1)-XM)/(1.0-EX*COSF(E1))
IF(ABS(E2-E1)-ER)121,121,120
120 E1=E2
GO TO 119
121 TRUNU=2.0*ATANF(TANF(E2/2.0)/XX)
R=SMAJ*(1.0-EX*EX)/(1.0+EX*COSF(TRUNU))
VELOC=SQRTE(GM1*(2./R-1./SMAJ))
FPA=ATANF(EX*SINF(TRUNU)/(1.0+EX*COSF(TRUNU)))/RAD
SX(1)=COSF(TRUNU)
SX(2)=SINF(TRUNU)
SX(3)=0.0
CALL ROTATE(-SMOM,-SLANT,-CAP0,SX,FX)
THETA(J)=ATANF(FX(3)/SQRTE(FX(1)*FX(1)+FX(2)*FX(2)))
PH1X=ATANF(FX(2)/FX(1))
IF(FX(1))122,123,124
122  PHI=PI+PHI
123  PHI=PHI-WE*(TIME-T0PP)
   PHI(J)=MODF(PHI,2.*PI)
   STH=SIGN(THETA(J))
   ALT(J)=R

C  GEOCENTRIC TO GEODETIC (TRAJECTORY POINTS)
124  S1=STH
    S2=SIGN(2.0*THETA(J))
    S3=SIGN(4.0*THETA(J))
    S4=F*S2+F*F*S3*(REE/R-0.25)
    S5=1.0-F*S1*S1-0.5*F*F*S2*S2*(REE/R-0.25)
    PRLAT=THETA(J)+ASINF(REE*S4/R)
    PRLAT=R-REE*S5
    PRLAT=PRLAT/RAD
    PRLO=PHI(J)/RAD
    PRTIME(J)=TIME+TB0-T0PP+.01
    XIM=COSF(THETA(J))*COSF(PHI(J))
    YIM=COSF(THETA(J))*SINF(PHI(J))
    ZIM=SINF(THETA(J))
    ARA=(RLAU/6076.1033+REE*S5)/2.
    ZLZ=XLAU*XIM+YLAU*YIM+ZLAU*ZIM
    RANGE=ARA*ACOSF(ZLZ)
1241  WRITE TAPE KBATT,FX(1),1=1,3,PRTIME(J),PRLAT,PRLO,PRLAT,VELOC,
      1FPA,R
1242  SEC=SECF(PRTIME(J))
      FM=FMINF(PRTIME(J))
      HOUR=HOURF(PRTIME(J))
      PN=PN+1.0
      IF(MODF(PN,Z2))126,125,126
125  WRITE OUTPUT TAPE NAT,200,(NAME(1),I=1,9)
      WRITE OUTPUT TAPE NAT,205
126  WRITE OUTPUT TAPE NAT,206,HOUR,FM,SEC,PRLAT,PRLO,VELOC,
      1FPA,RANGE
      IF(TIME-TIMP)1261,127,127
1261  GO TO(113,114,116),MM
C  LOOK ANGLE
127  DO 135 IT=1,NOST
    STH = XSTH(IT)*RAD
SPH = XSPH(IT)*RAD  
SHT = XSHT(IT)/6076.1033  

C GEODETIc TO GEOCENTRIC (STATION)  
XX1=SINF(STH)  
XX2=COSF(STH)  
C=REE/SQRTF(1.0-E*E*XX1*XX1)  
S=C-C*E*E  
XX3=S+SHT  
XX4=C+SHT  
STHC=ATANF(XX1/XX2*XX3/XX4)  
RS=SQRTF(XX1*XX1*XX3*XX3+XX2*XX2*XX4*XX4)  
PN=-1.0  

K=1  
IF(PRTIME(K)-TBO+TDEP-TIMP)=1311,135,135  
DPHI=PHI(K)-SPH  
ST=SINF(THETA(K))  
CT=COSF(THETA(K))  
X=ALT(K)*CT*COSF(DPHI)-RS*COSF(STHC)  
Y=ALT(K)*CT*SINF(DPHI)  
Z=ALT(K)*ST-RS*SINF(STHC)  
XP=X*XX1-Z*XX2  
ZP=X*XX2-Z*XX1  
ELEV=ATANF(ZP/SQRTF(XP*XP+Y*Y))  
AZIM=ATANF(-Y/XP)  
IF(XP)=132,132,130  
AZIM=PI+AZIM  
IF(AZIM)=1321,1322,1322  
AZIM=AZIM+2.*PI  
XAZ=AZIM/RAD  
XEL=ELEV/RAD  
SEC=SECF(PRTIME(K))  
FMIN=FMINF(PRTIME(K))  
HOUR=HOURF(PRTIME(K))  
RE=REE/SQRTF(1.+POF*ST*ST)  
PRALT=ALT(K)-RE  
PRLAT=THETA(K)/RAD  
PRLON=PHI(K)/RAD  
SLR=SQRTF(X*X+Y*Y+Z*Z)  
SP6=SPH+WE*(PRTIME(K)-PRTIME(1))  
XX=X*COSF(SP6)-Y*SINF(SP6)  
YY=X*SINF(SP6)+Y*COSF(SP6)
ANT = ACOSF((XX*AXDOT+YY*AYDOT+ZZ*AZDOT)/(SQRTF(XX+YY+ZZ)*SQRTF(AXDOT*AXDOT+AYDOT*AYDOT+AZDOT*AZDOT)))/RAD
PN = PN+1.0
IF(MODF(PN,Z2)) 134,133,134
133 WRITE OUTPUT TAPE NAT,200,(NAME(I),I=1,9)
WRITE OUTPUT TAPE NAT,209,(TAG(I,IT),I=1,3),XSTH(IT),XSPH(IT),XSHT(I)
134 WRITE OUTPUT TAPE NAT,210,HOUR,FMIN,SEC,PRALT,PRLAT,PRLON,
1XAZ,XEL,SLR,ANT
K=K+1
GO TO 131
135 CONTINUE
190 IF(KBATT)192,192,191
191 END FILE KBATT
192 RETURN
200 FORMAT(1H19A8)
201 FORMAT(39H ORBITAL ELEMENTS /17H SEMIMAJ)
1R AXISE28.8,5H N.M./17H SEMIMINOR AXISE28.8,5H N.M./15H ECCE
2NTRICITY30.8//9H PERIODE36.8,5H MIN./18H APOGEE ALTITUDE27.
38,5H N.M./19H PERIGEE ALTITUDE26.8,5H N.M./14H INCLINATION
431.8,5H DEG./22H ARGUMENT OF PERIGEE23.8,5H DEG./25H LONGIT
5UDE OF ASCENDING/23H NODE AT BURNOUT TIME22.8,5H DEG./23H IN
6ITIAL TRUE ANOMALYE22.8,5H DEG./28H INITIAL ECCENTRIC ANOMALE1
77.8,5H DEG.)
202 FORMAT(16HVEHICLE ESCAPES)
205 FORMAT(39H KEPLERIAN TRAJECTORY /52X22HINERTIAL
1 INERTIAL /7TH H M S ALTITUDE(NM) LATITUDE LONGITUDE
2 VEL.(FPS) FLT PATH ANG RANGE(NM)/)
206 FORMAT(1H F3.0,F3.0,E14.5,2F12.5,F12.2,F13.5,F13.2)
209 FORMAT(13H0 STATION - 3A8/26XF12.3,6H N.LATF12.3,7H E.LONGF12.0,4
1H FT./20X23HTRAJECTORY (GEOCENTRIC)13X11HL00K ANGLES7X5HSLANT5X6H
2ASPECT/6X4HTIME4XHALTITUDE4X8HLATITUDE3X9HLONGITUDE7X7HAZIMUTH2X9
3ELEVATION3X5HRANGE5X5HANGLE/4X18HH M S N.MILES6X3HDEG9X3HDEG
412X3HDEGTX3HDEG8X2HNM7X3HDEG)
210 FORMAT(F5.0,2F3.0,F10.0,2F12.2,5X2F10.3,F9.0,F10.2)
SQRTF EQU 7660B
END
SUBROUTINE IMPACT(JJ)
  THIS SUBROUTINE COMPUTES THE TRAJECTORY OF THE EMPTY STAGES

  ** ** DIMENSION BLOCK ** **

  DIMENSION XX(3),XXD(3),CDM(10,10),XMACH(10,10),AL(26),CBLACK(150),
  1NAME(10),OUT(8,42),WD(3),DRA(10),XMN(10),NN(10),DELP(10),VD(3),
  2ACODES(6),DUMB1(3,3),AC(5),AD(5),AG(3,50),AH(50),AK(50),AI(50),
  3XIMPA(3,10),XDIMP(3,10),TFIMP(10),RANGE(10)

  ** ** COMMON BLOCK ** **

  COMMON DUMB1,NAME,KAA,KAZ,AB,AC,AD,KAF,AG,AH,AK,AL,AP,AM,AN,AO,
  1AP,XMACH,CDM,NN,NOT,RANGE,XIMPA,XDIMP,TFIMP,DELP

  ** ** EQUIVALENCE BLOCK ** **

  EQUIVALENCE (AL(1),ICODE),(AL(2),ACODE),(AL(3),TRERR),(AL(4),SMIN)
  1,(AL(5),SMA),(AL(6),NOE),(AL(7),SS),(AL(8),T),(AL(9),XD),(AL(10),
  2YD),(AL(11),ZD),(AL(12),X),(AL(13),Y),(AL(14),Z),(AL(15),XDD),(AL(16),
  YDD),(AL(17),ZDD),(AL(18),XD1),(AL(19),YD1),(AL(20),ZD1),(AL(21),ACODES)

  ** ** FORMAT BLOCK ** **

  1 FORMAT(12)
  2 FORMAT(7F10.0)
  3 FORMAT(21H1 INTEGRATION ERROR 016)
  4 FORMAT(19H0 CRT FAILURE AT F9.4,7H SFC***)
  5 FORMAT(2H1 10A8)
  6 FORMAT(3X4HTIME4X8HLATITUDE4X9HLONGITUDE4X8HALITUDE4X5HRANGE/4X3H)
  7 SEC7X3HDEG9X3HDEG9X2HNM9X2HNM/
  8 FORMAT(F8.2,2F12.4,F12.2,F10.2)
  9 FORMAT(3X4HTIME4X8HEL0CITY6X3HFPA6X7HAZIMUTH/4X3HSEC6X3HFPS9X3HDE
  1G8X3HDEG/)
  10 FORMAT(F8.2,F11.1,F10.2,F12.2)
  11 FORMAT(10X7HSTAGE I2)

  J6=Z2
  T=TFIMP(JJ)
  X=XIMPA(1,JJ)
  Y=XIMPA(2,JJ)
  Z=XIMPA(3,JJ)
XD=XDIMP(1,JJ)
YD=XDIMP(2,JJ)
ZD=XDIMP(3,JJ)
XX(1)=X
XX(2)=Y
XX(3)=Z
XXD(1)=XD
XXD(2)=YD
XXD(3)=ZD
JP=1
ICODE=3
TRERR=1.E-3
ACODE=1.0
ACODES(1)=1.
ACODES(2)=1.
ACODES(3)=1.
ACODES(4)=1.
ACODES(5)=1.
ACODES(6)=1.
DT=1.
SMIN=.01
SMAX=1.
NOE=6
SS=1./16.
H=T-INTF(T)
H=1.-H
IF(H) 50,51,50
50 PRTIM1=T+H
GO TO 52
51 PRTIM1=T+DELPR(JJ)
52 AE=20925647.
W=7.292115E-5
W2=W*W
XK2=AE*AE*.00162342
GM=1.4076427E16
PI=3.1415927
RAD=PI/180.
PE=.00673852
VEL=SQRTF(XD*XD+YD*YD+ZD*ZD)
R2=X*X+Y*Y+Z*Z
R=SQRTF(R2)
THET=ATANF(Z/SQRTF(X*X+Y*Y))
SIT=SINF(THET)
ALT=R-AE/SQRTF(1.+PE*SIT*SIT)
N=NN(JJ)
DO 30 I=1,N
  K=N-I+1
  DRA(K)=CDM(I,JJ)
  XMN(K)=XMACH(I,JJ)
30

C

**INTEGRATION CALL ROUTINE**

C

RTJ  TEJI
RTJ  ADAMS
ZRO  EQN1
ZRO  TEXI
ZRO  PRTIM1
ZRO  AL
ZRO  CBLACK
ZRO  EXIT1
ZRO  TMIN1
STA  ERR

PRINT 3,ERR

C

**EQUATIONS OF MOTION**

EQN1  SLJ

XD1=XD
YD1=YPD
ZD1=ZD
VEL=SQRTF(XD*XD+YD*YD+ZD*ZD)
R2=X*X+Y*Y+Z*Z
R=SQRTF(R2)
ARG=(1.+3.*XK2/R2-15.*XK2*Z/Z/R2/R2)/R2/R
GX=-GM*ARG*X
GY=-GM*ARG*Y
GZ=-GM*(ARG+6.*XK2/R2/R2/R)*Z
THET=ATANF(Z/SQRTF(X*X+Y*Y))
SIT=SINF(THET)
ALT=R-AE/SQRTF(1.+PE*SIT*SIT)
IF(ALT) 79,81,81
79  JP=JP-1
   GO TO 4031
81  IF(ALT-500000.) 82,82,83
82  LDA  ALT
    RTJ  ATMOS
TEMP  OCT
PRES  OCT
RHO  OCT
VA  OCT
NOP
NOP

85 FMN=VEL/VA
   DRAG = INTERPF(FMN,N,2,XMN,DRA)
   DM=.5*RHO*VEL*VEL*DRAG
   GO TO 84
83 DM=0.
84 XDD=DM*XD/VEL+GX+2.*W*YD+D2*X
   YDD=DM*YD/VEL+GY-2.*W*XD+W2*Y
   ZDD=DM*ZD/VEL+GZ
   GO TO EQN1
EXIT1 SLJ **
502 CHECK=X
   IF(SENSE LIGHT 2) 999, EXIT1
TMN1 SLJ **
   PRINT 4,T
   IF(SENSE SWITCH 5)550,TMN1
550 SENSE LIGHT 2
   GO TO TMN1
TEX1 SLJ **
   IF(X-CHECK) 4000,3999,4000
(3999) RTJ EQN1
C COMPUTE THE OUTPUT BLOCK
4000 OUT(1,JP)=T
   CALL GEDODTHET,R,XLAT,XALT)
   OUT(2,JP)=XLAT/RAD
   OUT(4,JP)=XALT/6076.1033
   OUT(3,JP)=ATANF(Y/X)/RAD
   IF(X) 6000,6000,6001
6000 OUT(3,JP)=OUT(3,JP)+180.
6001 OUT(6,JP)=VEL
   VD(1)=XD
   VD(2)=YD
   VD(3)=ZD
   AN1=OUT(3,JP)*RAD+PI/2.
   AN2=PI/2.-XLAT
   CALL ROTATE(AN1,AN2,0.,VD,W)
   OUT(7,JP)=ATANF(WD(3)/SQRTF(WD(1)*WD(1)+WD(2)*WD(2)))/RAD
OUT(8,JP)=ATANF(WD(1)/WD(2))/RAD
IF(WD(2)) 6002,6002,6003
6002 OUT(8,JP)=OUT(8,JP)+180.
6003 COSRA=(X*XX(1)+Y*XX(2)+Z*XX(3))/SQRTF(X*X+Y*Y+Z*Z)/SQRTF(XX(1)*XX(1)+XX(2)*XX(2)+XX(3)*XX(3))
OUT(5,JP)=RANGE(JJ)+3440.*ACOSF(COSRA)
IF (JP=J6) 4030,4031,4031
4030 IF(ALT)4031,4059,4059
C WRITE OUTPUT BLOCK
4031 WRITE OUTPUT TAPE NOT,5,(NAME(I),I=1,10)
WRITE OUTPUT TAPE NOT,11,JJ
WRITE OUTPUT TAPE NOT,6
WRITE OUTPUT TAPE NOT,7,((OUT(I,II),I=1,5),II=1,JP)
WRITE OUTPUT TAPE NOT,5,(NAME(I),I=1,10)
WRITE OUTPUT TAPE NOT,11,JJ
WRITE OUTPUT TAPE NOT,8
WRITE OUTPUT TAPE NOT,9,((OUT(I,II),I=6,8),II=1,JP)
IF(ALT) 4037,4061,4061
4061 JP=1
GO TO 4060
C STORE IMPACT POINT FOR PUNCH AND RETURN
4037 PUNCH 10,(NAME(I),I=1,6),JJ,OUT(2,JP), OUT(3,JP)
RETURN
4059 JP=JP+1
4060 PRTIM1=PRTIM1 + DELPR(JJ)
4064 GO TO TEX1
ADAMS EQU 6000B
ATMOS EQU 7300B
SQRTF EQU 7660B
RDF LIB RDF
END
C
C
SUBROUTINE GEODED(A,B,C,D)
C      THIS SUBROUTINE CONVERTS THE GEOCENTRIC COORDINATES TO
C      GEODETIC COORDINATES
S1=SINF(A)
S2=SINF(2.*A)
S3=SINF(4.*A)
S4=20925647./B-.25
S5=S2/298.3+S3/88982.89*S4
S6=1.-S1*S1/298.3-S2*S2*S4/177965.78
C=A+ASINF(20925647.*S5/B)
D=B-20925647.*S6
RETURN
END
SUBROUTINE ROTATE (PHI, THETA, PSI, U, V)

C THIS SUBROUTINE GIVES A ROTATION OF CARTESIAN COORDINATES
DIMENSION U(3), V(3), A(3, 3), BLOCK(700)
COMMON A, BLOCK
T1=SINF(PHI)
T2=SINF(THETA)
T3=SINF(PSI)
T4=COSF(PHI)
T5=COSF(THETA)
T6=COSF(PSI)
A(1,1)=T6*T4-T5*T1*T3
A(1,2)=T6*T1+T5*T4*T3
A(1,3)=T3*T2
A(2,1)=-T3*T4-T5*T1*T6
A(2,2)=-T3*T1+T5*T4*T6
A(2,3)=T6*T2
A(3,1)=T2*T1
A(3,2)=-T2*T4
A(3,3)=T5

1 DO 2 I=1, 3
   V(I)=0.0
2 DO 2 J=1, 3
   V(I)=A(I, J)*U(J)+V(I)
5 RETURN
END 10050B
<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ORG 6000B</td>
<td>NUMERICAL INTEGRATION</td>
</tr>
<tr>
<td>REM SOL OF DIFF EQ</td>
<td></td>
</tr>
<tr>
<td>ADAMS SLJ 0</td>
<td>RUNGE KUTTA STARTER FOR</td>
</tr>
<tr>
<td>SIU 1 AD+13</td>
<td>ADAMS MOLTON DIFF EQ</td>
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<tr>
<td>SIL 2 AD+13</td>
<td>EVALUATOR</td>
</tr>
<tr>
<td>LIU 1 ADAMS</td>
<td>BETA+1 IN INDEX 1</td>
</tr>
<tr>
<td>LDA 1 1</td>
<td>C(BETA+2) INAC</td>
</tr>
<tr>
<td>ENQ 0</td>
<td>COMMON TO AD+10</td>
</tr>
<tr>
<td>STQ AD+10</td>
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<tr>
<td>SAL AD+10</td>
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<tr>
<td>ARS 24</td>
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<tr>
<td>STQ AD+9</td>
<td>DATA TO AD+9</td>
</tr>
<tr>
<td>SAL AD+9</td>
<td>DATA IN AC</td>
</tr>
<tr>
<td>LDA AD+9</td>
<td></td>
</tr>
<tr>
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<td>1 TO INDEX: 2</td>
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STA ADDR
LIL 1 AD+12
ENA 0

ADTC2
STA 1 0
IJP 1 ADTC2
ENA 6
STA AD+1
STA AD+3
ENA 0
STA AD
STA AD+2
STA AD+4
LDA AD+5
AJP Z AD17
SLJ AD17

NO PRINT IF P IS ZERO
CARD LOU ADDED FOR NO PRINTING

ADF1
DEC 1
OCT 777777777707777
ADD P LIL 1 AD+12
ENA 0
STA AD+4

BEGIN DP LOOP
DT + TK LOWER IS B IN TEMP+1

ADTC
LDA 1 0
FAD 1 0
LDQ 1 0
STQ ADTEMP
STA ADTEMP+1
ENI 2 0
QJP P AD70
ENI 2 1

AD70
FAD ADTEMP
AJP P AD74
INI 2 -1

AD74
STA ADTEMP+2
ENQ 0
IJP 2 ADXDP
LDA ADTEMP
AJP P AD63
ENQ 1

SCM ADA7
STQ ADSC
ENQ 0
LLS 12

ABS VALUE C
STORE SIGN C
POWER TO MQ
SCL ADDS
STA ADDCC2
LDL AD3777
THS AD1777
SLJ AD64
SCM ADNB
AD65 ADCE
LDA ADTEMP+1
ENQ 0
AJP P AD60
ENQ 1
SCM ADA7
STQ ADSB
ENQ 0
LLS 12
ARS 3
SCL ADDS
STA ADB
LDL AD3777
THS AD1777
SLJ AD61
SCM ADNB
AD62 ADBE
SUB ADCE
AJP M AD71
AD67 ADTEMP+2
ENQ 0
SLJ ADXDP
AD61 INA -2000B
SLJ AD62
AD64 INA -2000B
SLJ AD65
AD71 SCM ADA7
SAU AD69
THS AD72D
ENQ 0
LDA ADB
AD69 LRS 0
STA ADB
STQ ADL
LDA ADSB

EXP TO AC
JUMP+EXP
EXTEND SIGN - EXP
STORE + EXP
B IN AC
1 TO MQ
ABS VALUE B
STORE SIGN B
CLEAR LEAD 3 BITS
STORE CHAR P
ENTEND SIGN NEG POWER
STORE POWER B
POWER B - POWER C
IF NEG POWERS IS GREATER
IF C SAME, OR LESS
CLEAR LESSER
REMOVE BIAS EXP B
REMOVE BIAS EXPC
EXP (-EXP B, ALSO EXP C LARGER
SHIFT IN ADDRESS
POWDER DIFF GREATER THAN, SKIP
CHAR B
UPPER BITS SCALED B
LOWER BITS SCALED B
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**AD75**

- **SCM** ADSC
- **AJP** N AD66
- **LDA** ADCC2
- **ADD** ADB
- **LDQ** ADL
- **SCQ** 2 72
- **LRS** 11
- **ALS** 11
- **STA** ADH
- **QRS** 1
- **LDL** ADMP
- **STA** ADHL
- **INI** 2 -70
- **LDA** ADCE
- **INA** 2 0
- **STA** ADHE
- **LDQ** ADSC
- **QLS** 1
- **QJP** Z AD68
- **ENQ** 77777B
- **STQ** ADSC

**AD68**

- **AJP** M AD72
- **INA** 2000B
- **STA** ADTM
- **LDA** ADHE
- **INA** -44B
- **AJP** M AD73
- **INA** 2000B
- **LDQ** ADHL
- **LLS** 36
- **SCM** ADSC
- **STA** ADTM+1
- **LDA** ADTM
- **LDQ** ADH
- **QLS** 1
- **LLS** 36
- **SCM** ADSC
- **LDQ** ADTM+1
- **SLJ** ADXDP
- **AD72** INA -6000B
- **STA** ADTM
- **LDA** ADHE

**AD75**

- Jump if sign B diff from sign C
- Add char B to char C
- 36 bit char B + C in AC
- Lead 36 bits B+C
- 0.xxx 1 lead bit MQ
- Clear lead bit
- Lower bits of B+C
- Diff exp of C and B+C in 2
- Exp largest operand
- Exp of C+B
- Sign C same as sign C+B
- If sign C neg
- Set adce to -0 for SCM
- Jump exp C-
- + exp +bias, upper part
- Exp lower
- Lower exp- jump
- Exp+ bias, least sign part
- Lower power
- Lower char
- Floated lower
- Upper exp
- Upper char
- Floated upper
- Exp - upper B+C
- Set bias, clear sign bit of
- Exp and number to get bias
IN A  -44B  EXP LOWER PART B+C
AD73  INA  -6000B  SET BIAS
SLJ  AD76
ADXDP STA  1 0  UPPER PART IN DATA
ADTC1 STO  1 0  LOWER PART IN COMMON
IJP  1 ADTC  END DOUBLE PRE LOOP
SLJ  AD17
ADMS OCT  7000000000000000  USE OT CLEAR LEAD 3 BIT OF CHAR
ADNB OCT  7777777777776000  USE TO EXTEND SIGN - POWER
ADA7 OCT  7777777777777777  USE TO ALT SIGN
ADMP OCT  3777777777777777  MAX POS NUMBER
ADTEMP BSS  3  FLOATED C,B, C+B
AD3777 OCT  3777  LOGICAL MASK EXP
AD1777 OCT  1777  CHECK SIGN EXP
AD72D DEC  72
ADSB BSS  1  SIGN B
ADB BSS  1  CHAR B
ADBE BSS  1  EXP B
ADSC BSS  1  SIGN C
ADCC BSS  1  EXP C
ADL BSS  1  LOWER PART CHAR B
ADH BSS  1  UPPER CHAR B+C
ADHL BSS  1  LOWER CHAR B+C
ADHE BSS  1  EXP B+C
ADTM BSS  2
AD66 LDA  ADCC2
SUB  ADB
INA  -1
LQC  ADL
SLJ  AD75
AD17 LIU  1 AD+13
LIL  2 AD+13
ADY SLJ  4 0  CALC YK
ADEXIT SLJ  4 0  TO EXIT
+ SIU  1 AD+13
SIL  2 AD+13
LIL  1 AD+12  H TO INDEX 1
ADTS LDA  1 0  SAVE DATA TK, YK, IN COMMON
STA  1 0
IJP  1 ADTS
LDA  AD+2  AMC TO AC
AJP  N AD18
LDA  AD+6
AJP  N AD19
LDA  ADDR+7
SLJ  AD20
INA  -1
AJP  Z AD21
INA  -1
AJP  N AD22
ENA  ADDR+3
SUB  AD
SAA  AD23
LDA  0
C(ADDR+3-RKC) IS ADDRESS YK
AD23
SAL  ADYR
SAU  ADYR1
SAL  ADYK
ENA  0
STA  AD+4
LIL  1 AD+21
AD20
N-1 TO INDEX 1
SAL  AD+4
STA  1 0
SAVE YK, AMC=0, RKC IS ZERO OR 2
IJP  1 ADYK
SLJ  4 ADTI
TO INTERRUPT SUBROUTINE
+  SLJ  AD27
+  SLJ  4 ADRK
+  LDA  AD+6
AJP  Z ADDP
LDA  AD
C(CODE)
ADK  AD+6
AJP  Z AD24
RAO  AD
SLJ  ADDP
AD24
ENA  1
RKC IS 2
STA  AD+2
SET AMC TO 1, NEXT STEP IS AM
SLJ  ADDP
AD21
LDA  ADDR+5
SLJ  AD25
CODE IS 1
AD22
ENA  ADDR+4
AD21
SUB  AD
SAU  AD26
AD22
LDA  0
SLJ  AD25
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SAU  ADYR1
SAL  ADYM
LIU  1 AD+13
LIL  2 AD+13
SLJ  4 0
+   SIU  1 AD+13
SIL  2 AD+13
LIL  1 AD+21
ADYM  LDA  1 0
ADXH LDA  1 0
STA  1 0
STA  1 0
IJP  1 ADYM
ENA  1
STA  AD+4
LDA  7 AD+20
STA  7 ADTK
SLJ  4 ADTI
SLJ  AD30
+   SLJ  4 ADRK
+   SLJ  4 ADCV
+AJP N AD31
RA0  AD+1
AD37 LIL  1 AD+12
ADXS1 LDA  1 0
STA  1 0
IJP  1 ADXS1
LDA  AD+28
AJP  Z AD32
AD34 LDA  AD+6
INA  -1
AJP  Z ADDP
LDA  AD
INA  -3
AJP  Z AD33
RA0  AD
SLJ  ADDP
AD33 ENA  1
STA  AD+2
SLJ  ADDP
AD32 LDA  AD+1
SUB  ADC
SEC RK STEP CODE 1,3
SAVE YK+.5
CALC YK+.5
N-1 TO INDEX 1
DAVE YK+.5
XK+5 DATA TO COMMON
RKD IS SET 1
TK+.5
TK+.6 TO COMMON
TO INTERRUPT SUP, RK SEC STEP
RK STEP DONE, INTERRUPT
NO RK STEP IN INTERRUPT
AFTER RK STEP DT, CONVTEST
JUMP CONV TEST FAILED
RKH+1 TO RKH
N TO INDEX 1
RESTORE XK FROM ADDR+7
DOUBLE TAG
JUMP IF CONV INDICATES DOUBLE
NO DOUBLE
CODE-1 TO AC
CODE IS 1, NEXT STEP
CODE IS 3
RKC-3
RKC+1 TO RKC
NEXT STEP
RK C IS 3, CHANGE TO AN STEP
SET AMC TO 1
DOUBLE TAG ZERO
RKH-4, CHECK LAG IN DOUBLE
AJP       M AD34
LDA       7 AD+19
FAD       7 AD+19
STA       AD+45
FSB       7 AD+17
AJP       M AD35
AJP       N AD34
AD35      LDA       AD+45
STA       7 AD+19
ENA       0
STA       AD
SLJ       ADDP
AD31      LDA       7 AD+16
FSB       7 AD+19
AJP       M AD36
LIU       1 AD+13
LIL       2 AD+13
ADTMN     SLJ       4
+          SIL       2 AD+13
SIU       1 AD+13
ENA       1
STA       AD+28
ENA       0
STA       AD+1
SLJ       AD37
AD36      ENA       0
LDQ       AD
STQ       AD+7
STA       AD+4
STA       AD
STA       AD+1
LDA       AD+6
INA       -1
AJP       Z AD38
LDA       AD+7
INA       -1
AJP       Z AD38
LIL       1 AD+21
ADYRH     LDA       1 0
STA       1 0
IJP       1 ADYRH
AD38      ENI       1 0

IF NEG NO DOUBLE
LDT
2DT-DT(MAX)
SKIP DOUBLE IF 2DT TO LARGE
DOUBLE DT
2DT TO DT
RKC TO ZERO
CONV TEST FAILED
-DT +DT(MIN)
SEE LAST PAGE
DT EQUAL OR LESS MIN(DT)
DOUBLE TAG SET NON ZERO
RKH TO ZERO
CLEAR RKD, RKC, RCH
N-1 TO INDEX 1
YK IN ADDR+2 MOVED TO ADD+4
MOVE YK FROM RKC 2 TO 0
CLEAR INDEX 1
LDA 7 AD+19
FMU AD+10
STA 7 AD+19
LDA 7 ADXS
STA 7 ADTS
LIL 1 AD+21
ADXPS
LDA 1 0
STA 1 0
ADXXS
LDA 1 0
STA 1 0
IJP 1 ADXPS
LDA AD+6
INA -1
AJP Z AD399
LDA ADDR+4
AD388
SAL ADYR
SAU ADYR1
SLJ AD39
AD399
LDA ADDR+5
SLJ AD388
AD18
LDA ADDR
SAL ADYAS
LIL 1 AD+21
ADYAS
LDA 1 0
STA 1 0
IJP 1 ADYAS
ADMSET ENS 0
STA AD+4
LDA ADDR
SAL ADYR
SAU ADYR1
SAU ADYMP
SAL ADYMC
LDA ADDR+1
SAU ADYMP1
SAL ADYMC1
LDA ADDR+2
SAU ADYMP2
SAU ADYMC2
LDA ADDR+3
SAL ADYMP3
SLJ 4 ADTI

.5DT TO DT (COMMON)
INDEX 1 IS ZERO
RESTORE TK-1 TO TK
N-1 TO INDEX 1
XK+.5 TO XP IF DT AALF
XK RESTORED IF DT AALF
CODE 3
REDO RK STEP, HALF DT
CODE 1 ADDRESS TK
AMC NOT ZERO
BEGIN AM STEP
N-1 TO INDEX 1
SAVE YK IN ADDR
CLEAR RKD
ADDRESS SETUP AM STEP
YAM SET FOR RK STEP
AM STEP
YAM-1
YAM-2
YAM-3
GO TO INTERRUPT SUBROUTINE
+     ENI  0
+     SLJ  4 AADMP
+     LDA  AD+6
     INA  -2
     AJP  N AD40
    AD40  SLJ  4 ADCV
     AJP  Z AD43
     ENA  0
     STA  AD+3
     ENA  1
     STA  AD+2
     LDA 7 AD+16
     FSB 7 AD+19
     AJP  P ADINT
     LIU 1 AD+13
     LIL 2 AD+13
     ADTMC SLJ  4 0
    AD43  SII 1 AD+13
    SIL 2 AD+13
    SLJ  AD42
     LDA  AD+28
     AJP  N AD41
     LDA  AD+2
     INA  -4
     AJP  M AD41
     LDA  AD+3
     SUB  ADC+1
     AJP  M AD41
     LDA 7 AD+19
     FAD 7 AD+19
     STA  AD+45
     FSB 7 AD+17
     AJP  P AD44

EXIT SAME LOGIC EXIT +1
DO AM STEP
CODE IN AC
JUMP IF CODE 3
CODE 2, YAM IN AC
SHIFT ADDRESS YAM
ADDRESS YAM TO YAM-1
ADDRESS YAM-1 TO YAM-2
ADDRESS YAM-2 TO YAM-3
ADDRESS YAM-3 TO YAM
NEXT STEP
JUMP IF YK+1 CONV
CONV TEST FAILED
SET AMH TO 0
SET AMC TO 1
DT(MIN)-DT
HALF DT IF MINUS
DT TO SMALL DO NOT HALF DT
ACCEPT DT STEP
DOUBLE TAG
IF NO DOUBLE JUMP
NO DOUBLE IF AMC LESS THAN 4
NO DOUBLE IF AMH LESS THAN 6
2DT
2DT-MAX DT
STEP TO LARGE NO DOUBLE
AD46 LDA AD+45  DOUBLE DT
    STA 7 AD+19  2DT TO DT
EN4 STA AD+2    AMC TO 1
LDA ADDR+2     ADJ ADDRESS YK FOR DOUBLE
LDQ ADDR+2
STA ADDR+2     YAM-3 TO YAM-2
LDA ADDR+5     YAM-5 TO YAM-3
STA ADDR+3     YAM-2 TO YAM-5
STQ ADDR+5     YAM-7 TO YAM-4
STQ ADDR+4
LDQ ADDR+4
STA ADDR+4     YAM TO YAM-1
STQ ADDR+1     YAM-1 TO YAM-2
LDA ADDR+1     YAM-2 TO YAM-3
STQ ADDR+2     YAM-3 TO YAM-4
LDQ ADDR+2
STQ ADDR+3     YAM-5 TO YAM-6
LDQ ADDR+4
STA ADDR+6
LDA ADDR+7     YAM-5 TO YAM-7
STQ ADDR+7     YAM-6 TO YAM-7
STA ADDR+7     YAM-7 TO YAM
SLJ ADDP
AD44 AJP 2 AD46  IF 2DT EQ DT MAX, DOUBLE
SLJ AD41
AD41 RAO AD+2    DT STEP ONLY
RAO AD+3     BUMP AMC AND AMH BY 1
AD42 LDQ ADDR     SHIFT ADDRESS YAM
LDA ADDR+1
STQ ADDR+1     YAM TO YAM-1
LDQ ADDR+2
STA ADDR+2     YAM-1 TO YAM-2
LDA ADDR+3     YAM-2 TO YAM-3
LDQ ADDR+4
STA ADDR+4     YAM-3 TO YAM-4
LDA ADDR+5
STQ ADDR+5
LDQ ADDR+6     YAM-5 TO YAM-6
STQ ADDR+6
LDA ADDR+7
STQ ADDR+7     YAM-5 TO YAM-7
STA ADDR+7     YAM-6 TO YAM-7
SLJ ADDP
AD30 ENA 0        RK STEP IN INTERRUPT SECRKSTEP
STA AD         CLEAR RKC
LIL 1 AD+12    RESTORE OLD TK, XK FROM
ADTIRK LDA 1 0    ADDR+7 TO STANDARD COMMON
STA 1 0         DUM FIRST DT STEP + INT RK STEP
IJP 1 ADTIRK
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<td>FMU ADC+10</td>
<td>0.5DT TO AD+22</td>
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<td>ADYR LDA AD+22</td>
<td>LOOP TO GET XK+.5DT(YK)</td>
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<td>ADK2 LDA 1</td>
<td>LOOP TO GET X IN ARG K3</td>
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<td>CALC Y IN K3, RK STEP</td>
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<td>FDV ADC+11</td>
<td>DIV DT BY 6</td>
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**ADY6**

SLJ 4 CALC Y IN K4, RK STEP

SIU 1 AD+13

SIL 2 AD+13

LIL 1 AD+21

**ADK22**

LDA 1 0 N-1 TO INDEX 1

FAD 1 0 K2, LOOP TO CALC DT

STA AD+27 K2+K3

FAD AD+27 2K2+2K3

**ADYR1**

FAD 1 0 +K1

FAD 1 0 +K4

FMU AD+24 .1666DT(K1+2K2+3K3+K4)

LDQ AD+4 RKD IN MQ

**ADDX1**

QJP N AD3 RKD IS ZERO, STORE DX

STA 1 0

SLJ ADXR3

**AD3**

STA AD+27 RKD NOT ZERO

**ADDX2**

FAD 1 0 SAVE DX THIS STEP

STA 1 0 CUMULATE DX

LDA AD+27 RESTORE DX THIS STEP

**ADXR3**

FAD 1 0 ADD XK TO DX

STA 1 0 STORE YK+1 IN DATA

IJP 1 ADK22 END LOOP TO CALC DT, IN RK

LDA 7 AD+19 DT IN AC

LDQ AD+4 RKD IN MQ

**QJP N ADDT3**

**ADDT3**

STA 7 ADDT3 DT TO DT COMMON IF RRD IS ZERO

SLJ ADRK

**ADCV**

SLJ 0 CONV SUBROUTINE

ENA 0 CLEAR DOUBLE TAG

STA AD+28 N-1 TO INDEX 1

LIL 1 AD+21 SAVE INDEX 3

SIU 3 AD+33

LDA 7 AD+15 E

STA AD+34 E TO AD+34

FDV ADC+2 DIV E BY DOUBLE FACTOR

STA AD+35 STORE DOUBLE ERROR

LDA 7 AD+14 A IN AC

**AJP Z ADA** JUMP IF A ZERO

AJP P AD4
SCM  ADMASK

ADA  ENI  2  0
    STA  0
    SLJ  ADA1

AD4  LIL  2  AD+21

ADA1 LDA  2  0
    STA  AD+30

ADXP2 LDA  1  0
     AJP  P  ADXC

SCM  ADMASK

ADXC STA  AD+29
    LDA  1  0
    ENI  3  2
    AJP  P  AD5
     SCM  ADMASK

AD5  THS  3  AD+29
     SLJ  AD6
     LDA  3  AD+29
     ENQ  3  0
     QJP  N  AD5

AD6  STA  AD+32
     AJP  Z  AD7

ADXP3 LDA  1  0
     FSB  1  0
     FDV  AD+32
     AJP  P  AD8
     SCM  ADMASK

AD8  FSB  AD+35
     AJP  M  AD7
     AJP  Z  AD7
     STA  AD+28
     FSB  AD+34
     AJP  P  AD10

AD7  IJP  2  AD9

AD9  IJP  1  ADA1
     ENA  0

AD57 LIU  3  AD+33
     SLJ  ADCV

AD10 ENA  0
     SLJ  AD57

ADMASK OCT  3
     SLJ  0

SUBROUTINE AM STEP
LIL  1 AD+21  N-1 TO INDEX 1
LDA  7 AD+19  DT
FDV  ADC+3  DIV DT BY 24, PUT IN AD+25
STA  AD+25

ADYMP3 LAC  ADC+4  LOOP TO CALC XP
FMU  1 0
STA  AD+26
LDA  ADC+5

ADYMP2 FMU  1 0  -.9YAM-3
STA  AD+26
LDA  ADC+6
FAD  AD+26

ADYMP1 FMU  1 0  37 YAM-2
STA  AD+26
LDA  ADC+6
FAD  AD+26

ADYMP FMU  1 0  -59YAM-1
STA  AD+26
LDA  ADC+7
FAD  AD+26

ADXM FMU  AD+25  55.YAM
FAD  1 0  (55YAM-59YAM-1+37YAM-2-9YAM-3)

ADXP STA  1 0  ADD XK IN COMMON
STA  1 0  XP TO DATA
STA  1 0  YP TO COMMON
IJP  1 ADYMP3  END LOOP TO CALC XP
LDA  AD+19  DT IN DATA

ADTK STA  7 ADDT3  DT TO DT COMMON REGION
FAD  0 1 ADYMP3  DT IN DATA
STA  AD+20  DT FROM COMMON
L1U  AD+13  TAT TO T IN DATA
LIL  2 AD+13  RESTORE INDEX

ADY3 SLJ  4 0  CALC YP IN AM
+ 1 AD+13  SAVE INDEX
SIU  1 AD+13
SIL  2 AD+13  N-1 TO INDEX 1
LIL  AD+21  5YAM-1

ADYMCI LDA  ADC+8  LOOP TO CALC XC
FML  1 0  -5YAM-1
ADYM2 FAD  1 0  YAM-2 -5YAM-1
FAD  AD+26
STA  AD+26
ADYM FMU  AD+9  19YAM
LDA  ADC+4

ADYP LDA  ADC+4
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9YP
MULT BY DT OVER 24
STORE DX
ADD XK FROM COMMON
STORE YK+1 IN DATA
END LOOP TO CALC XC
EXIT AM STEP SUBROUTINE
INTERPOLATE FOR HALF STEP
ADDRESS YAM
ADDRESS YAM-1
ADDRESS YAM-2
ADDRESS YAM-3
ADDRESS YAM-4
ADDRESS YAM-5
N-1 TO INDEX 1
BEGIN INTERPOLATE LOOP
.0234575YAM-4
-.15625YAM-3
.703125YAM-2
.46875YAM-1
-.0390625YAM-4
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SLJ      AD14
AD13     
LIU      1 AD+13
LIL      2 AD+13
ADEXL    
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SIL      2 AD+13
LDA      7 ADT1
FSB      7 ADTK
FSB      7 AD+19
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ADDT2    
STA      1 0
IJP      1 ADDT1
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SLJ      ADT1
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DEC      -5.19.,.5,6.
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DEC      .703125,.46875
DEC      -.0390625,.21875
DEC      -.546875,1.09375
DEC      .2734375
AD       BSS 50
ADDR     BSS 9

IF C(T)-TK IS 0 OR - EXIT INT-KOOP
C(T)-TK IN COMMON
C(T)-TK-DT
EXIT INTERRUPT IF +
LOOP INTERRUPT
IF C(T)-TK ZERO OR -
INTERRUPT WITHOUT RK STEP
IS NEW PRINT TIEM WITHIN DT OF
PRESENT TIME
NO, NORMAL EXIT +1 INTERRUPT
YES8 DO RK STEP WITH MODIFIED DT
RESTORE RKD
SKIP RESTORE IF RKD IS ZERO
N TO INDEX 1
DX+OLD DX TO DX
CUMULATE AND RESTORE DT
ID RKD IS 1
EXIT, RK STEPS DONE
20. IS DOUBLE FACTOR
ALTITUDE IN GEOPOTENTIAL METERS

ATMOS ORG 7300B
ZRO 0
FDV MTOFEET
*** EQU 0
STA COMP+1
FAD HFACT
STA COMP+2
LDA COMP+1
FMU HFACT
FDV COMP+2
STA COMP
LDA ATMOS
ARS 24
SAL TEMPEXT
ADD OCTONE
SAU PRESEXT
ADD OCTONE
SAL RHOEXT
ADD OCTONE
SAL VSNDEXT
ADD OCTONE
SAL EXIT
ADD OCTONE
SAL EXIT2
SIU 1 OCTONE
ENI 1 0
CAT LDA 1 TABLE
FSB COMP
AJP Z EQUAL
AJP P EQUAL
+
ISK 1 22
SLJ 0 CAT
EXIT LIU 1 OCTONE
SLJ 0 ***
EQUAL LDA COMP
FSB 1 TABLE-1
FMU 1 TABLE1X
FAD 1 TABLE2X
TEMPEXT STA COMP+1
STA ***
LDA 1 TABLE1X
AJP N NONZERO
LDA 1 TABLE-1
FSB COMP
FMU QCONST
FDV 1 TABLE2X
SLJ 0 AROUND
NONZERO LDA 1 TABLE2X
FDV COMP+1
STA COMP+3
ENAA COMP+3
RTJ 0 LOGF
QCONST DEC 3.41647942D-02
+ FMU QCONST
FDV 1 TABLE1X
AROUND STA COMP+3
ENAA COMP+3
RTJ 0 EXPF
MTOFEET DEC 3.2808333333
+ FMU 1 TABLE3X
PREEXT STA ***
FDV COMP+1
RHOEXT FMU RHOCNT
STA ***
LDA COMP+1
FDV TABLE2X
STA COMP+3
ENAA COMP+3
RTJ 0 SQRTF
CSZERO DEC 1116.4437
VSNDEXT FMU CSZERO
STA ***
EXIT2 LIU 1 OCTONE
SLJ 0 ***
RHOCNT DEC 3.2365983D-04
OCTONE OCT 00000000001
COMP BSS 4
HFACT DEC 6356766.
DEC 0.0
TABLE DEC 0.11000.20000.
DEC 32000.47000.52000.
DEC 61000.79000.88743.
DEC 98451.108129.117777.
DEC 146542.156071.165572.
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8. SPURT SAMPLE PRINTOUT DATA.
SPURT SAMPLE PRINTOUT DATA

1. INPUT DATA - Launch Parameters and Spin Table
2. INPUT DATA - Stage Weight and Aerodynamic Parameters -- 1 page per Stage
3. SPURT OUTPUT DATA
4. SPURT OUTPUT DATA
5. SPURT OUTPUT DATA
6. SPURT OUTPUT DATA
7. TWO-BODY OUTPUT DATA - Orbital Elements
8. TWO-BODY OUTPUT DATA - Keplerian Trajectory
9. TWO-BODY OUTPUT DATA - Look-Angles
10. IMPACT OUTPUT DATA - Position Information
11. IMPACT OUTPUT DATA - Velocity Information
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STAGE WEIGHT = 9443.20 Lbs
STAGE FUEL WEIGHT = 7447.10 Lbs
IGNITION TIME = 0.00 SEC
BURNOUT TIME = 37.00 SEC
MISSILE CG = 16.6750 FT
STAGE FUEL CG = 11.3100 FT
EXIT AREA = 904.00 SQ IN.
PRESSURE AT THRUST MEASUREMENT = 14,600 LBS/SQ IN.
LONITUDINAL I OF MISSILE = 362.00 FT2 SLUGS
TRANSVERSE I OF MISSILE = 45277.00 FT2 SLUGS
FUEL LONITUDINAL I/N = 0.9660 FT2
FUEL TRANSVERSE I/N = 29.6870 FT2
THRUST MISALIGNMENT ANGLE = 0.00 RAD
ORIENTATION ANGLE OF THRUST MISALIGNMENT = 0.00 RAD
DIAMETER = 2.5050 FT
TIME TO CHANGE COEFFICIENTS = 46.00 SEC
DEFINITIONS

All trajectories are with respect to an oblate earth.

A left hand orthogonal cartesian coordinate system with the XY plane tangent to an oblate earth at the launch point. The Z axis is positive upward along the local vertical and the X axis is positive along the launch azimuth.

TIME (Sec): Relates to the first motion of the vehicle off the launch site.

LATITUDE (Deg): Angle between the normal to the reference spheroid passing through the vehicle and the equatorial plane. Positive in the northern hemisphere.

LONGITUDE (Deg): Angular distance measured from the foot of the Greenwich meridian to the vehicle sub-point meridian. West of Greenwich is negative and East is positive.
ALTITUDE (Feet): Distance from vehicle to the surface of a geodetic earth below the vehicle.

VELOCITY (fps): Velocity of vehicle with respect to a point on a rotating earth directly below the vehicle.

AZIMUTH (Deg): Angle from North the velocity vector makes with the local meridian. Measured positive C. W. from North.

F. P. A. (Deg): Flight path angle. The angle the velocity vector makes with the local horizon; positive upward.

RANGE (N. M.): Arc distance from launch to the point under the vehicle measured along the surface of the earth.

DEFLECTION (N. M.): Distance the vehicle has deviated from the launch axis in the XY plane.

PHI (Deg): Euler angle between the longitudinal axis of the vehicle and the Z axis in the range coordinate system.

THETA (Deg): Euler angle between the longitudinal axis of the vehicle and the XZ plane measured in the rotated X'Y' plane.

THRUST (Lbs): Thrust of the rocket motor with thrust increase due to pressure decrease included.

WEIGHT (Lbs): Weight of the remaining portion of the vehicle. Given in terms of sea level pounds.
TOTAL ACCEL (g'): Absolute total acceleration of the vehicle normalized by the gravitational constant $g_0$.

DYNAMIC PRESSURE (Lb/Ft²): The classical dynamic pressure on the vehicle given by $\frac{1}{2}$ of the density times the velocity squared.

DRAG (Lbs): Aerodynamic drag on the vehicle.

MACH NO: Mach number of the vehicle.

X, Y, Z (Ft): Position vector of vehicle in range coordinate system.

X-DOT, Y-DOT, Z-DOT (ft/s): Velocity vector of vehicle in range coordinate system.

ORBITAL ELEMENTS: (Ref 3) The parameters of a classical Keplerian ellipse based on an inverse square gravitational field.

SEMI MAJOR AXIS (a): One half of the longest diameter of the Keplerian ellipse.

SEMI MINOR AXIS (b): One half of the smallest diameter of the Keplerian ellipse.

ECCENTRICITY (e): A measure of the flattening of the Keplerian ellipse.

PERIOD (p): The time that a space vehicle takes to make one complete orbit.

APOGEE ALTITUDE (hA): The distance to the highest point on the ellipse from the surface of the Earth.

PERIGEE ALTITUDE (hp): The radius of the point on the ellipse closest to the Earth, minus the radius of the Earth.
INCLINATION (i):
The angle between the orbit plane and the equatorial plane.

ARGUMENT OF PERIGEE (ω):
The angular distance measured in the orbit plane from the line of nodes to the line of apsides.

LONGITUDE OF THE ASCENDING NODE AT BURNOUT TIME (Ω):
The angular distance measured at burnout time from Greenwich eastward in the equatorial plane to the point of intersection of the orbit plane where the vehicle crosses from south to north.

INITIAL TRUE ANOMALY (V₀):
The angle measured at burnout time at the center of the Earth between the line of apsides and the radius vector to the vehicle measured from perigee in the direction of motion.

INITIAL ECCENTRIC ANOMALY (E₀):
The angle at the center of the ellipse between the line of apsides and radius vector of the auxiliary circle through a point which has a projection of the ellipse corresponding to the initial true anomaly.

H. M. S.:
Time in hours, minutes, and seconds of the vehicle from launch.

INERTIAL VELOCITY (fps):
The velocity of the vehicle with respect to a coordinate system fixed to, but not rotating with, the Earth.
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<td>The angle at any given time the inertial velocity vector makes with respect to the perpendicular to the radius vector at that time.</td>
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<td><strong>LOOK ANGLES:</strong></td>
<td>The direction to position a tracking antenna at a given station.</td>
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<td><strong>AZIMUTH (Deg):</strong></td>
<td>The angle that the projection in the horizontal plane of the vector pointing to the vehicle makes with the North direction.</td>
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<td><strong>ELEVATION (Deg):</strong></td>
<td>The angle from the horizon to the vector pointing to the vehicle.</td>
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<td><strong>SLANT RANGE (N. M.):</strong></td>
<td>The distance from the tracking station to the vehicle.</td>
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<td><strong>ASPECT ANGLE (Deg):</strong></td>
<td>Angle between the vehicle spin axis and a vector from a given station to the vehicle.</td>
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### 32 LB PAYLOAD

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**DATE:** NOVEMBER 15, 1962

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2 Commanding Officer, US Army Signal Research & Development Laboratory, ATTN: SIGRA/SL-SAT-1, Weapons Effects Section, Fort Monmouth, NJ

2 Research Analysis Corp., ATTN: Document Control Office, 6935 Arlington Road, Bethesda, Md., Wash 14, DC

2 Director, Army Research Office, Arlington Hall Sta, Arlington, Va

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SPURT is a five-degree-of-freedom trajectory digital computer program for spinning unguided space probe vehicles. The program was written for the Control Data Corporation 1644 digital computer. SPURT will compute trajectories for a vehicle up to a maximum of ten stages and has provision for computing the trajectories of the separated stages.

This generalised program computes the trajectory over an oblate spheroidal, rotating Earth with atmosphere, in a geocentric rectangular coordinate system.
Coasting flight trajectories are computed in two subroutines. The first is a Keplerian solution, which also computes orbital elements and "look angles" for various tracking stations. The second uses three-degree-of-freedom point mass equations solved by numerical integrations.

The program will prepare two special output tapes. One is used in plotting output data and the other is used to prepare a special tape for the Atlantic Missile Range.

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