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# OFT Ascent/Descent Ancillary Data Requirements Document

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Lyndon B. Johnson Space Center
Houston, Texas

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SHUTTLE PROGRAM

# OFT ASCENT/DESCENT ANCILLARY DATA REQUIREMENTS DOCUMENT

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CONTENTS





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TABLES

## FIGURES

## ACRONYMS

| | |
|---|---|
| A/D | ascent/descent |
| AOA | abort once around |
| ATO | abort to orbit |
| Att. | attitude |
| BET | best estimated trajectory |
| CCT | Computer compatible tape |
| DFI | development flight instrumentation |
| DRC | data reduction complex |
| ET | external tank |
| FTR | flight test requirement |
| G&N | guidance and navigation |
| GDSD | Ground Data Systems Division |
| GMT | Greenwich mean time |
| HS | high-speed |
| IDSD | Institutional Data Systems Division |
| IMU | inertial measurement unit |
| lb | pounds (force) |
| MCC | Mission Control Center |
| MECO | main engine cutoff |
| MPAD | Mission Planning and Analysis Division |
| MPB | Mathematical Physics Branch |
| NMC | National Meteorological Center |
| OFT | orbital flight test |
| OI | operational instrumentation |
| OMS | orbital maneuvering system |
| RTLS | return-to-landing site |
| SRB | solid rocket booster |
| TM | telemetry |

OFT ASCENT/DESCENT ANCILLARY
DATA REQUIREMENTS DOCUMENT

By A. C. Bond, Jr., Mathematical Physics Branch

## 1.0 INTRODUCTION

This document contains requirements for the ascent/descent (A/D) navigation and attitude-dependent ancillary data products to be generated for the Space Shuttle Orbiter by the Mathematical Physics Branch/Mission Planning and Analysis Division (MPB/MPAD) in support of orbital flight test (OFT) flight test requirements (FTR's), MPAD guidance and navigation (G&N) performance assessment, and the mission evaluation team. It is intended that this document serve as the sole requirements control instrument between MPB/MPAD and the A/D ancillary data users. The requirements presented herein are primarily functional in nature, but some detail level requirements are also included.

## 2.0 ASCENT/DESCENT ANCILLARY DATA SUPPORT SCOPE

The A/D ancillary data support for OFT mission evaluation activities shall be confined to providing postflight position, velocity, attitude, and associated navigation and attitude derived parameters for the Orbiter over the flight phases and time intervals shown in figure 1. No ancillary data support related to the external tank (ET) or the solid rocket boosters (SRB's) shall be provided. In addition, the A/D ancillary data products delivered shall be confined to those described in section 5.0 of this document.

## 3.0 DATA PROCESSING APPROACH (FOR INFORMATION)

This section summarizes the A/D ancillary data processing approach in terms of the functional flow diagram shown in figure 2. The approach is presented primarily for information purposes to acquaint prospective ancillary data users with the current data reduction plan. Elements of the approach are subject to change, pending further analyses of data processing techniques and procedures.

### 3.1 INPUT DATA SOURCES AND INITIAL DATA PRODUCTS (TIER 1)

Raw, high-speed, C- and S-band tracking data shall be obtained from the OFT Mission Control Center (MCC) through the facilities of the Ground Data Systems Division (GDSD). Selected onboard navigation and attitude telemetry data shall be obtained from the Institutional Data Systems Division/Data Reduction Complex (IDSD/DRC).

Phototheodolite data shall not be processed in this task.

## 3.2 INTERMEDIATE DATA PRODUCTS (TIER 2)

Preprocessing or conditioning of the input tracking and telemetry data shall be accomplished by using interactive computer graphics techniques to perform data smoothing, editing, and gap filling. Ground and onboard clock times shall be tabulated to implement correlation of sensor data from the two input sources. Special event times will be provided by the JSC Instrumentation Integration Branch (WC6).

## 3.3 FINAL PROCESSING AND DELIVERED OUTPUT DATA PRODUCTS (TIERS 3, 4, AND 5)

At the tier-3 level, an ephemeris solution (position, velocity, and acceleration) shall be generated first, using a navigation filter procedure that combines onboard and ground tracking data in the A/D flight regions area. (Both sources are available.) In regions where ground tracking is precluded (e.g., during entry blackout), the solution shall be obtained by using onboard inertial measurement unit (IMU) data to propagate the state vector computed at the terminus of the navigation filter solution. Attitude data are then time-correlated with overall ephemeris solution, and this result shall provide the basis for the delivered output products indicated in tier 4.

Tier-4 processing shall include the computation of the remaining navigation and attitude-related parameters needed to complete the parameter set established for the output product; i.e., the product intended to satisfy the ancillary data users. Ascent quick-look output data will be provided in this tier. The basic computation for the ascent quick-look outputs is the same as the final outputs with the exception of the refinement of the input meteorological data. The final descent best estimated trajectory (BET) is developed in tier 4 and reflects the meteorological data supplied to MPAD by WC6.

The IDSD via WC6 will also provide the meteorological data for the ascent segment of the OFT flights. These data will be obtained by IDSD through the Kennedy Space Center in two stages - quick-look and final (1 day and 3 weeks after flight phase termination, respectively). The meteorological data for the descent phase will be supplied by the National Meteorological Center (NMC) 3 weeks after the OFT flight via WC6. The NMC requires plots and tabulation of the descent ground track based on telemetry (TM) vectors for generating the meteorological data. A time history of center-of-gravity data for the ascent segment of the OFT flights will also be provided by WC6. This information will be reflected in the ascent final and quick-look product.

In association with the descent BET, a set (table I) of navigation parameter accuracies will be generated as a special product that gives an estimate of the error associated with the tier-3 outputs, which includes the uncertainty associated with the observed meteorological data provided by the NMC via WC6.

## 4.0 REQUIRED INPUTS

Raw, high-speed, C- and S-band tracking data shall be obtained from the OFT MCC through the facilities of the GDSD. Selected onboard navigation and attitude telemetry data shall be obtained from the IDSD/DRC. The IDSD via WC6 will also provide the meteorological data for the ascent segment of the OFT flights. These data will be obtained by the IDSD through KSC in two stages - quick-look and final (1 day and 3 weeks after flight phase termination, respectively).

Meteorological data and associated accuracies for the descent phase will be supplied by the NMC 3 weeks after the OFT flight. The NMC requires plots and tabulation of the descent ground track (latitude and longitude) based on TM vectors for generating the meteorological data. Special event times will be provided by WC6.

In order that the task provide velocity and acceleration vector data with respect to the vehicle center of mass, the task requires as input a table that defines the location of the center of mass with respect to the navigation base. The definition of the center of mass with respect to the IMU navigation base will be coordinated through WC6.

## 5.0 GENERAL ORBITER ASCENT/DESCENT OUTPUT PRODUCTS

Functional as well as some detail level characteristics are presented here for the Orbiter ascent/descent ancillary output products. Both general and special ancillary output products are addressed in terms of the following output requirement items:

a. Parameters

b. Coordinate systems

c. Units

d. Accuracies

e. Time correlation

f. Output data frequency

g. Output data forms

h. Data product delivery schedules

i. Data product distribution

## 5.1 GENERAL OUTPUT PRODUCTS

The output product described below is designed to provide Orbiter ascent/descent ancillary data to satisfy users with a single product. The product output parameters and format will be common to all Orbiter ascent and descent flight phases (fig. 1).

### 5.1.1 Parameters, Coordinate Systems, and Units

The product output parameters and their associated coordinate systems and units are given in table I. Definitions of the relevant coordinate systems are given in the Appendix, together with equations for selected output parameters to supplement their tabular descriptions. Note that the product ephemeris parameters in table I all describe the motion of the Orbiter in navigation base and in terms of the center of mass and that only contact (nongravitational) accelerations are included in the ephemeris data.

Table II presents the "one-time-only" parameters for block outputs. These parameters will remain constant during the duration of the mission phase.

### 5.1.2 Accuracies

The product generated by this task will satisfy the FTR accuracy requirements to the extent possible based on the quality of the onboard and ground navigation sensor data available.

### 5.1.3 Time Correlation

Time correlation of the product output variables shall be accomplished as indicated in sections 3.2 and 3.3.

### 5.1.4 Output Data Frequency

Product output data shall be generated at one sample per second on the even seconds Greenwich mean time (GMT) and at requested event times provided by WC6.

### 5.1.5 Output Data Forms

Product output data shall be delivered on Univac 1108 computer-compatible tape(s) (CCT's) accompanied by computer printout and microfilm listings. Updates to this document will provide detail description of the output materials including the range and resolution of the output parameters.

5.1.6 Data Product Delivery Schedules

The ascent quick-look product output shall be made available for distribution nominally 1 week after the flight phase. The final output product for ascent will be delivered 4 weeks after the flight phase and for descent, 5 weeks after the flight phase. All deliverables are dependent on receiving the required inputs.

5.1.7 Data Product Distribution

Distribution of the product output shall be accomplished as follows:

a. WC6 shall serve as the sole distribution center for all product output.

b. Requests for the data shall be made to WC6 where the appropriate JSC facilities will be directed to generate the required number of tape copies and/or listings of the tape(s).

c. MPB shall provide WC6 with the appropriate tape reel numbers, a computer printout listing of the tape(s), and a microfilm of the listing.

d. MPB shall provide IDSD with a copy of the actual tape(s).

e. MPB shall maintain the responsibility for proper archiving of the ascent/descent ancillary data.

5.2 SPECIAL OUTPUT PRODUCTS

Special output products are defined to be those requested by a small number of postflight analysts whose ancillary data requirements are not satisfied by the general output product.

5.2.1 Parameters, Coordinate Systems, and Units

Time histories of the estimated accuracy associated with a subset of the general product parameters of table I shall be provided. The subset is for descent only and defined by the flagged parameters in the table. The accuracy estimates of the BET will reflect the uncertainties associated with the measured winds and atmospheric parameters. Plots and tabulations of the descent ground track will be provided to NMC via WC6 for the development of the entry wind and atmosphere profile. Another support item that will be provided under special output is a quick-look time history of the altitude and Earth-fixed velocity magnitude of the descent trajectory based on downlinked telemetry data.

Special product outputs shall be limited to the descent trajectory. Coordinate systems and units of the latitude, longitude, altitude, and Earth-fixed velocity magnitude and navigation parameter accuracy outputs shall be identical to those defined for the general product parameters.

### 5.2.2 Accuracies

The product generated by this task will satisfy the FTR accuracy requirements to the extent possible based on the quality of the onboard and ground navigation sensor data available.

### 5.2.3 Time Correlation

There is no requirement for the special outputs to be time correlated with respect to each other, but they shall be time tagged.

### 5.2.4 Output Data Frequency

The parameter accuracy estimates output rates will be at least approximately every 20 seconds. Outputs for the ground track and stripped telemetry parameters will be at the rate of the downlink data.

### 5.2.5 Output Data Forms

Output data forms will consist of computer printout CCT plots based on the appropriate user requirements.

### 5.2.6 Data Product Delivery Schedules

The ground track and stripped telemetry parameters will be available 1 week after the flight. The accuracy estimates shall be distributed 3 weeks after delivery of the descent general product.

### 5.2.7 Data Product Distribution

Distribution of the discrete event special product shall be accomplished as discussed in section 5.1.7.

TABLE I.- ORBITER PRODUCT OUTPUT PARAMETERS

| Parameter | | Appendix figure reference | Units |
|---|---|---|---|
| Symbol | Description | | |
| GET | Ground elapsed time | NA | sec |
| GMT | Greenwich mean time | NA | day:hr:min:sec |
| SGMT | Shuttle Greenwich mean time | NA | day:hr:min:sec |
| $X_M, Y_M, Z_M$; $\dot{X}_M, \dot{Y}_M, \dot{Z}_M$; $\ddot{X}_M, \ddot{Y}_M, \ddot{Z}_M$ | Inertial (Mean of 1950) position, velocity, and contact acceleration components | A-1 | ft<br>fps<br>fps$^2$ |
| $X_{MC}, Y_{MC}, Z_{MC}$ $\dot{X}_{MC}, \dot{Y}_{MC}, \dot{Z}_{MC}$ $\ddot{X}_{MC}, \ddot{Y}_{MC}, \ddot{Z}_{MC}$ | Inertial (Mean of 1950) position, velocity, and contact acceleration components (center of mass) | A-1 | ft<br>fps<br>fps$^2$ |
| $X_G, Y_G, Z_G$; $\dot{X}_G, \dot{Y}_G, \dot{Z}_G$; $\ddot{X}_G, \ddot{Y}_G, \ddot{Z}_G$ | Earth-fixed (Greenwich true of date) position, velocity, and contact acceleration components | A-3 | ft<br>fps<br>fps$^2$ |
| $\dot{X}_{GW}, \dot{Y}_{GW}, \dot{Z}_{GW}$ | Wind relative (Greenwich true of date) velocity | A-3 | fps |
| $X_{GC}, Y_{GC}, Z_{GC}$ $\dot{X}_{GC}, \dot{Y}_{GC}, \dot{Z}_{GC}$ $\ddot{X}_{GC}, \ddot{Y}_{GC}, \ddot{Z}_{GC}$ | Earth-fixed (Greenwich true of date) position, velocity, contact accelerations (center of mass) | A-3 | ft<br>fps<br>fps$^2$ |
| $\dot{X}_{GWC}, \dot{Y}_{GWC}, \dot{Z}_{GWC}$ | Wind relative (Greenwich true of date) (center of mass) | A-3 | fps |
| $X_{LF}, Y_{LF}, Z_{LF}$; $\dot{X}_{LF}, \dot{Y}_{LF}, \dot{Z}_{LF}$; $\ddot{X}_{LF}, \ddot{Y}_{LF}, \ddot{Z}_{LF}$ | Runway position, velocity, and contact acceleration components | A-6 | ft<br>fps<br>fps$^2$ |
| $\dot{X}_{TD}, \dot{Y}_{TD}, \dot{Z}_{TD}$; $\ddot{X}_{TD}, \ddot{Y}_{TD}, \ddot{Z}_{TD}$ | Topodetic velocity and contact acceleration components | A-5 | fps<br>fps$^2$ |
| $\dot{X}_{TDW}, \dot{Y}_{TDW}, \dot{Z}_{TDW}$ | Wind-relative topodetic velocity components | A-5 | fps |

TABLE I.- Continued

| Parameter | | Appendix figure reference | Units |
|---|---|---|---|
| Symbol | Description | | |
| $\dot{x}_B, \dot{y}_B, \dot{z}_B$<br>$\ddot{x}_B, \ddot{y}_B, \ddot{z}_B$ | Earth-relative velocity and contact acceleration components in body coordinate system | A-8 | fps<br>$fps^2$ |
| $\dot{X}_{BW}, \dot{Y}_{BW}, \dot{Z}_{BW}$ | Wind-relative body velocity components | A-8 | fps |
| $\theta_A$<br>$\theta_P$<br>$\theta_R$ | Inner (azimuth), middle (pitch), and outer (roll) gimbal angles, respectively of gimbal case with respect to IMU stable member | A-7 | deg<br>deg<br>deg |
| $X_E, Y_E, Z_E$<br>$\dot{X}_E, \dot{Y}_E, \dot{Z}_E$<br>$\ddot{X}_E, \ddot{Y}_E, \ddot{Z}_E$ | Plumbline Earth-fixed launch site coordinates, position, velocity, and contact acceleration components | A-13 | ft<br>fps<br>$fps^2$ |
| $\dot{X}_{EW}, \dot{Y}_{EW}, \dot{Z}_{EW}$ | Wind-relative plumbline components | A-13 | fps |
| $X_{EC}, Y_{EC}, Z_{EC}$<br>$\dot{X}_{EC}, \dot{Y}_{EC}, \dot{Z}_{EC}$<br>$\ddot{X}_{EC}, \ddot{Y}_{EC}, \ddot{Z}_{EC}$ | Plumbline Earth-fixed launch site coordinates, position, velocity, and contact acceleration components (center of mass) | A-13 | ft<br>fps<br>$fps^2$ |
| $\dot{X}_{EWC}, \dot{Y}_{EWC}, \dot{Z}_{EWC}$ | Wind-relative plumbline components (center of mass) | A-13 | fps |
| $\psi$<br>$\theta$<br>$\phi$ | Body yaw, pitch, and roll Euler angles, respectively. Orientation of body axes with respect to local vertical/local horizontal | A-8 | deg<br>deg<br>deg |
| P<br>Q<br>R | Roll, pitch, and yaw body rates, respectively | A-8 | deg/sec<br>deg/sec<br>deg/sec |
| $\lambda$<br>$\phi_D$<br>h (2) | Longitude<br>Geodetic latitude<br>Geodetic altitude | A-4 | deg<br>deg<br>ft |

TABLE I.- Continued

| Parameter | | Appendix figure reference | Units |
|---|---|---|---|
| Symbol | Description | | |
| $R_M$ | Magnitude of Mean of 1950 position vector | A-2 | ft |
| $V_M$ | Inertial velocity magnitude | A-2 | fps |
| $\gamma_M$ | Inertial flightpath angle | A-2 | deg |
| $\Psi_M$ | Inertial azimuth (heading) angle | A-2 | deg |
| $R_S$ | Slant range from vehicle to launch pad (ascent) or to runway coordinate system origin (descent) | A-6 | ft |
| A (3X3) | Direction cosines Mean of 1950 to body | NA | ND |
| $V_{TD}$[a,b] | Relative velocity magnitude | A-5 | fps |
| $\gamma_{TD}$[a,b] | Relative (local) flightpath angle | A-5 | deg |
| $\Psi_{TD}$[a,b] | Relative (local) azimuth heading angle | A-5 | deg |
| S | Earth surface range from vehicle to launch pad (ascent) or to runway coordinate system origin (descent) | A-9 | ft |
| $\alpha$[a,b] | Angle of attack | A-8 | deg |
| $\beta$[a,b] | Sideslip angle | A-8 | deg |
| $\bar{q}$[a,b] | Dynamic pressure | A-10 | $lb/ft^2$ |
| $\bar{q}$[a]$\alpha$ | Pitch dynamic pressure | NA | $lb\text{-}deg/ft^2$ |
| $\bar{q}\beta$[a] | Yaw dynamic pressure | NA | $lb\text{-}deg/ft^2$ |

[a]Wind relative velocity shall be used in evaluating these parameters.

[b]Navigation estimation accuracy shall be computed for these parameters.

TABLE I.- Concluded

| Parameter | | Appendix figure reference | Units |
|---|---|---|---|
| Symbol | Description | | |
| $M$[a,b] | Mach number | A-10 | n.d. |
| $\bar{V}_\infty$[a,b] | Viscous parameter | A-11 | n.d. |
| T | Ambient temperature | NA | deg R |
| P | Ambient pressure | NA | psf |
| $\rho$[a] | Density | NA | slugs/$ft^3$ |
| EAS[a,b] | Equivalent airspeed | A-12 | fps |
| L[a] | Total load factor | A-12 | n.d. |
| D/M[a] | Drag arc | A-12 | $fps^2$ |
| LOD[a] | Lift over drag | A-12 | n.d. |

[a]Wind relative velocity shall be used in evaluating these parameters.

[b]Navigation estimation accuracy shall be computed for these parameters.

TABLE II.- NAVIGATION BLOCK OUTPUT PARAMETERS

| Symbol | Description | Units |
|---|---|---|
| GRR | Time of guidance release | sec |
| CG/T | c.g. locations vs. time table | ft, sec |
| SET | Special event times | sec |
| REF | Refsmat | |
| MET | MET DATA | |
| TRAC | Tacan, MLS, tracker locations, orientation, and runway | |

Note: Other parameters to be defined

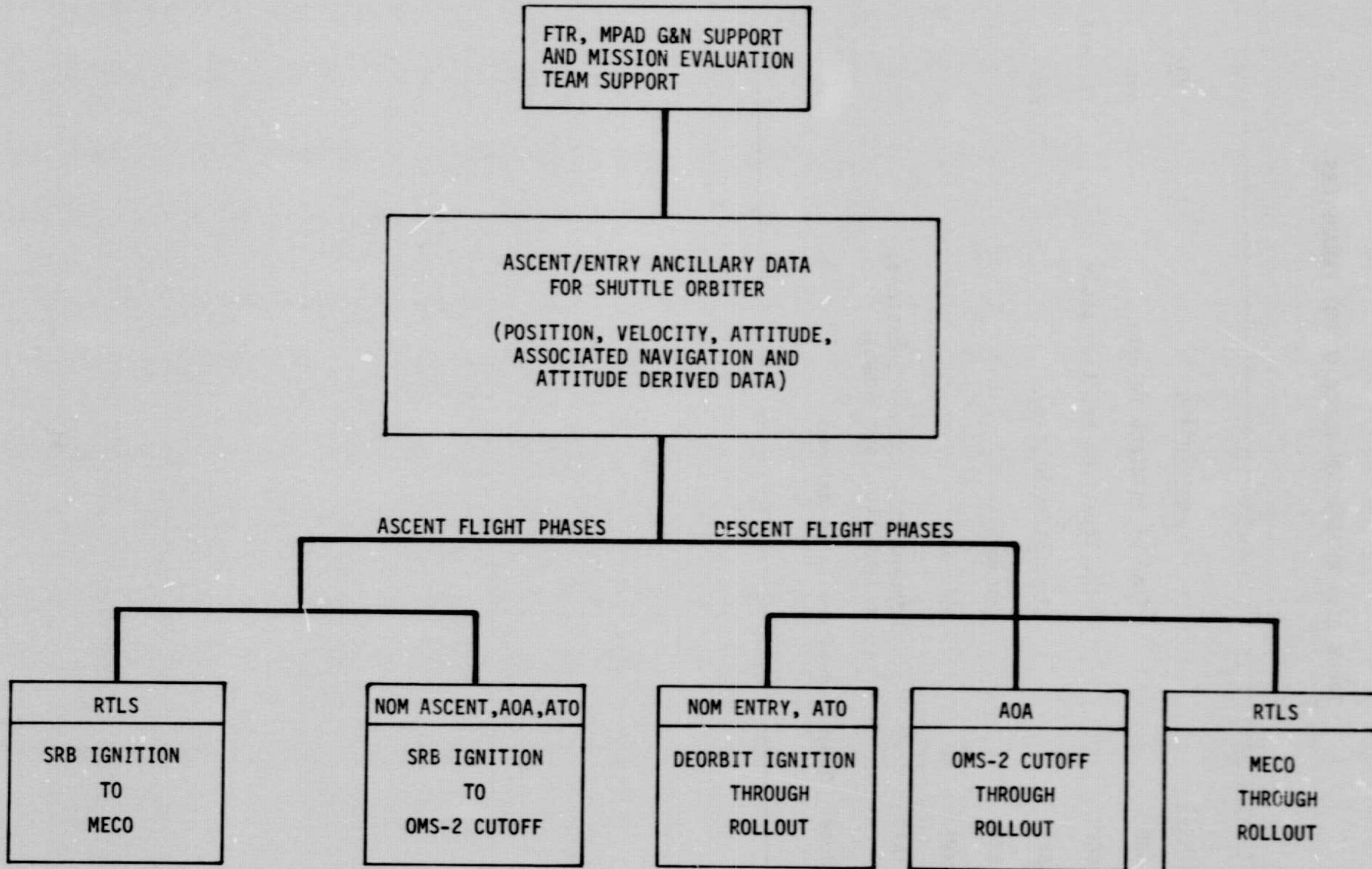



Figure 1.- Ascent/descent ancillary support task.

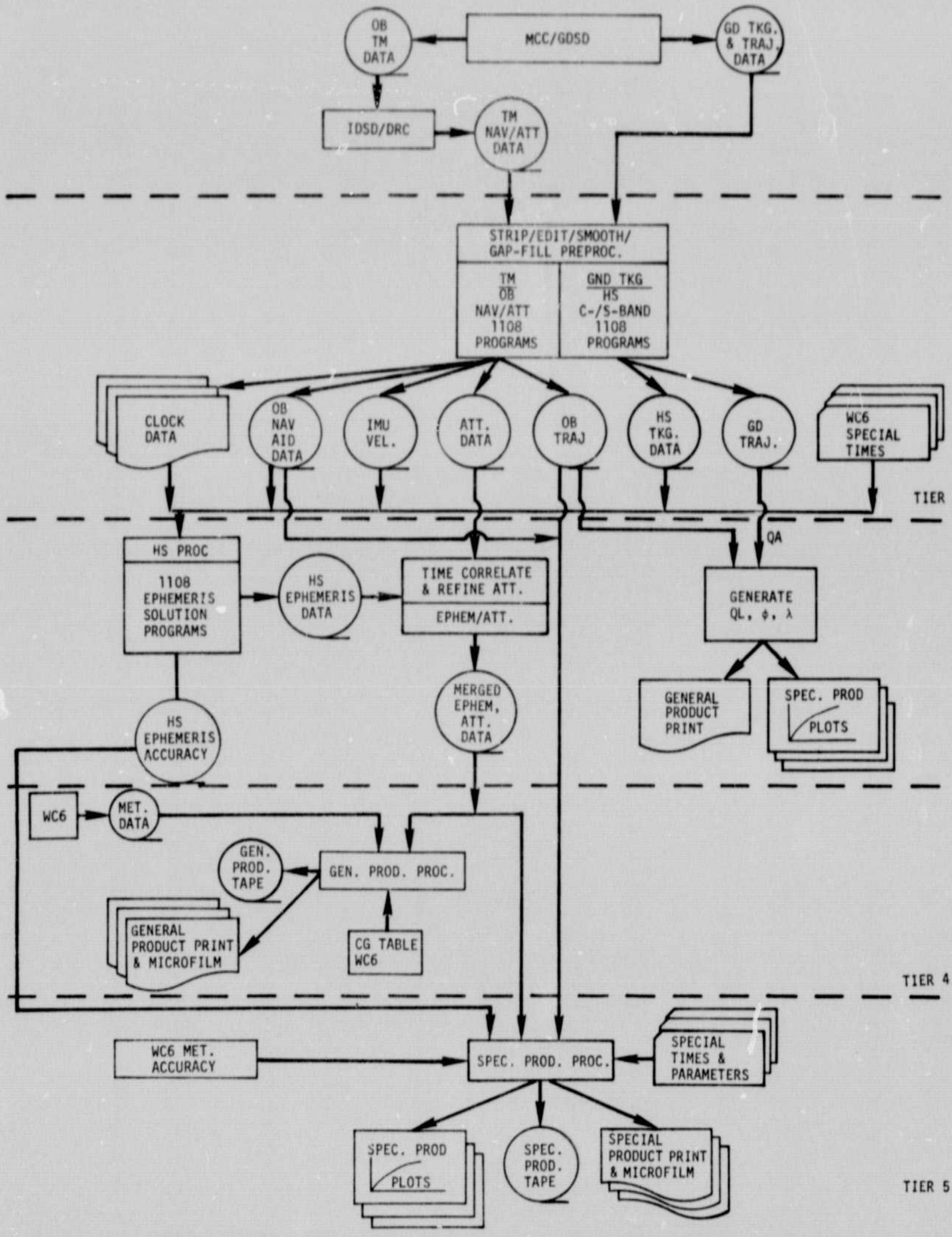



Figure 2.- Data processing functional flow, Orbiter ascent/descent ancillary data (for information).

APPENDIX

COORDINATE SYSTEM DEFINITIONS

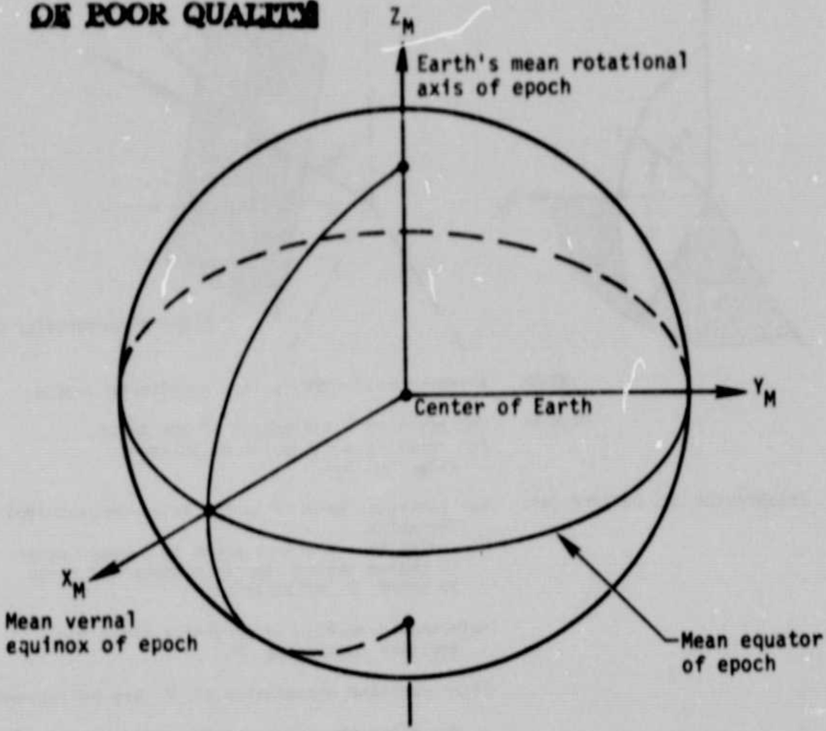
AND

OUTPUT PARAMETER EQUATIONS

This appendix contains definitions of the coordinate systems listed in table I. The definitions were obtained from reference A-1. In addition to the coordinate systems definitions, equations for selected table I output parameters are given to supplement their tabular descriptions.

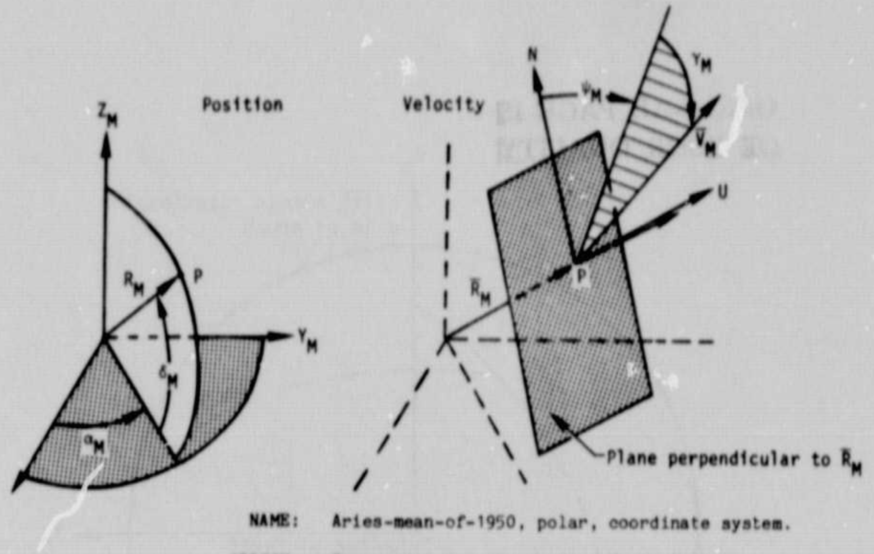
## REFERENCE

A-1 Davis, Larry D.: Coordinate Systems for the Space Shuttle Program. NASA TM X-58153, 1974.




| | |
|---|---|
| NAME: | Aries-mean-of-1950, Cartesian, coordinate system. |
| ORIGIN: | The center of the Earth. |
| ORIENTATION: | The epoch is the beginning of Besselian year 1950 or Julian ephemeris date 2433282.423357. |
| | The $X_M$-$Y_M$ plane is the mean Earth's equator of epoch. |
| | The $X_M$ axis is directed towards the mean vernal equinox of epoch. |
| | The $Z_M$ axis is directed along the Earth's mean rotational axis of epoch and is positive north. |
| | The $Y_M$ axis completes a right-handed system. |
| CHARACTERISTICS: | Inertial, right-handed, Cartesian system. |

Figure A-1.- Aries-mean-of-1950, Cartesian, coordinate system.




**NAME:** Aries-mean-of-1950, polar, coordinate system.

**ORIGIN:** For position - the center of the Earth.
For velocity - the point of interest, $P(X_M, Y_M, Z_M)$.

**ORIENTATION AND DEFINITIONS:** For position, same as in the Aries-mean-of-1950, Cartesian.
For velocity, reference plane is perpendicular to radius vector $\bar{R}_M$ from center of Earth to point P of interest.

Reference direction is northerly along the meridian containing P.

Polar position coordinates of P are as follows.

$\alpha_M$, right ascension, is the angle between the projection of the radius vector in the equatorial plane and the vernal equinox of epoch.

$\delta_M$, declination, is the angle between the radius vector and the mean Earth's Equator of epoch.

$R_M$, magnitude of $\bar{R}_M$.

Polar velocity coordinates of P are as follows.

Let U, E, N denote up, east, and north directions. Then

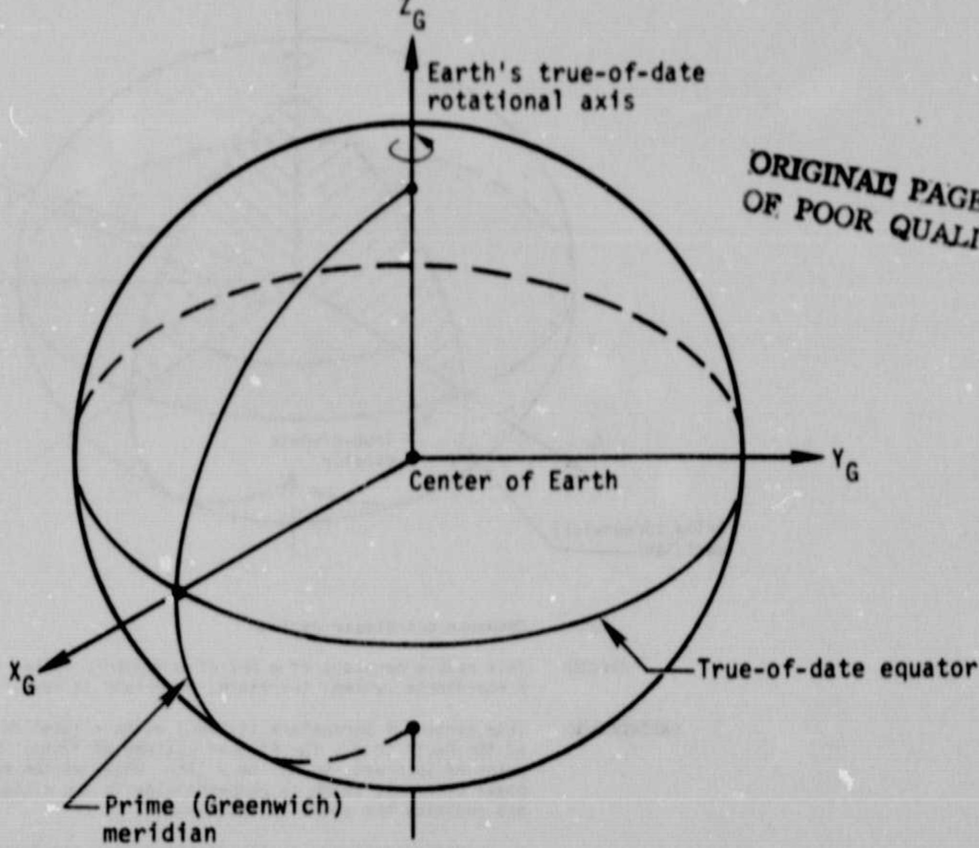
$\psi_M$, azimuth, is the angle from north to the projection of $\bar{V}_M$ on the reference plane, positive toward east.

$\gamma_M$, flightpath angle, is the angle between the reference plane and $\bar{V}_M$; positive sense toward U.

$V_M$, magnitude of $\bar{V}_M$ is always positive.

**CHARACTERISTICS:** Inertial.

Figure A-2.- Aries-mean-of-1950, polar, coordinate system.






NAME: Greenwich true of date (geographic) coordinate system.

ORIGIN: The center of the Earth.

ORIENTATION: The $X_G$–$Y_G$ plane is the Earth's true-of-date equator.

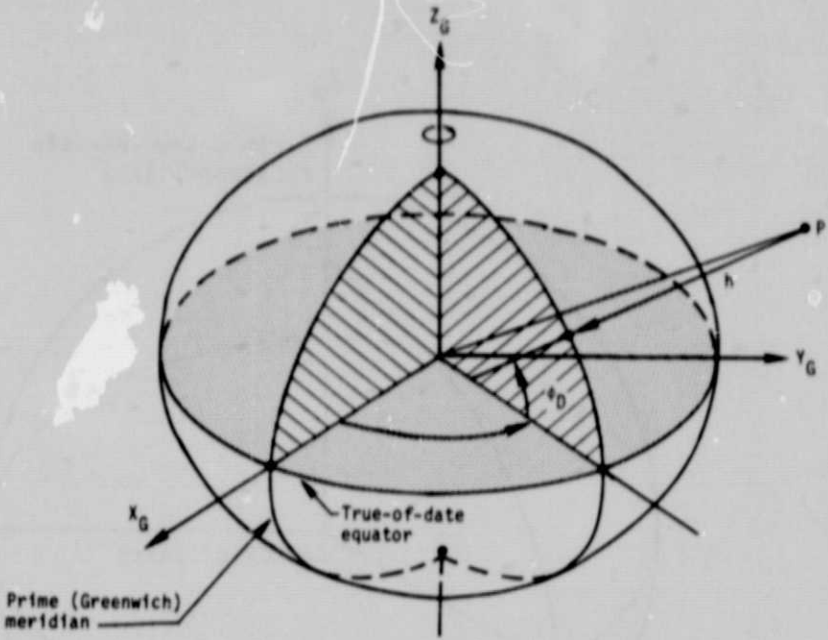
The $Z_G$ axis is directed along the Earth's true-of-date rotational axis and is positive north.

The $+X_G$ axis is directed toward the prime meridian.

The $Y_G$ axis completes a right-handed system.

CHARACTERISTICS: Rotating, right-handed, Cartesian. Velocity vectors expressed in this system are relative to a rotating reference frame fixed to the Earth, whose rotation rates are expressed relative to the Aries-mean-of-1950 system.

Figure A-3.- Greenwich true of date (geographic).




**NAME:** Geodetic coordinate system.

**ORIGIN:** This system consists of a set of parameters rather than a coordinate system; therefore, no origin is specified.

**ORIENTATION:** This system of parameters is based on an ellipsoidal model of the Earth (e.g., the Fischer ellipse of 1960). For any point of interest, we define a line, known as the geodetic local vertical, which is perpendicular to the ellipsoid and contains the point of interest.

h, geodetic altitude, is the distance from the point of interest to the reference ellipsoid, measured along the geodetic local vertical and is positive for points outside the ellipsoid.

$\lambda$ is the longitude measured in the plane of the Earth's true equator from the prime (Greenwich) meridian to the local meridian, measured positive eastward.

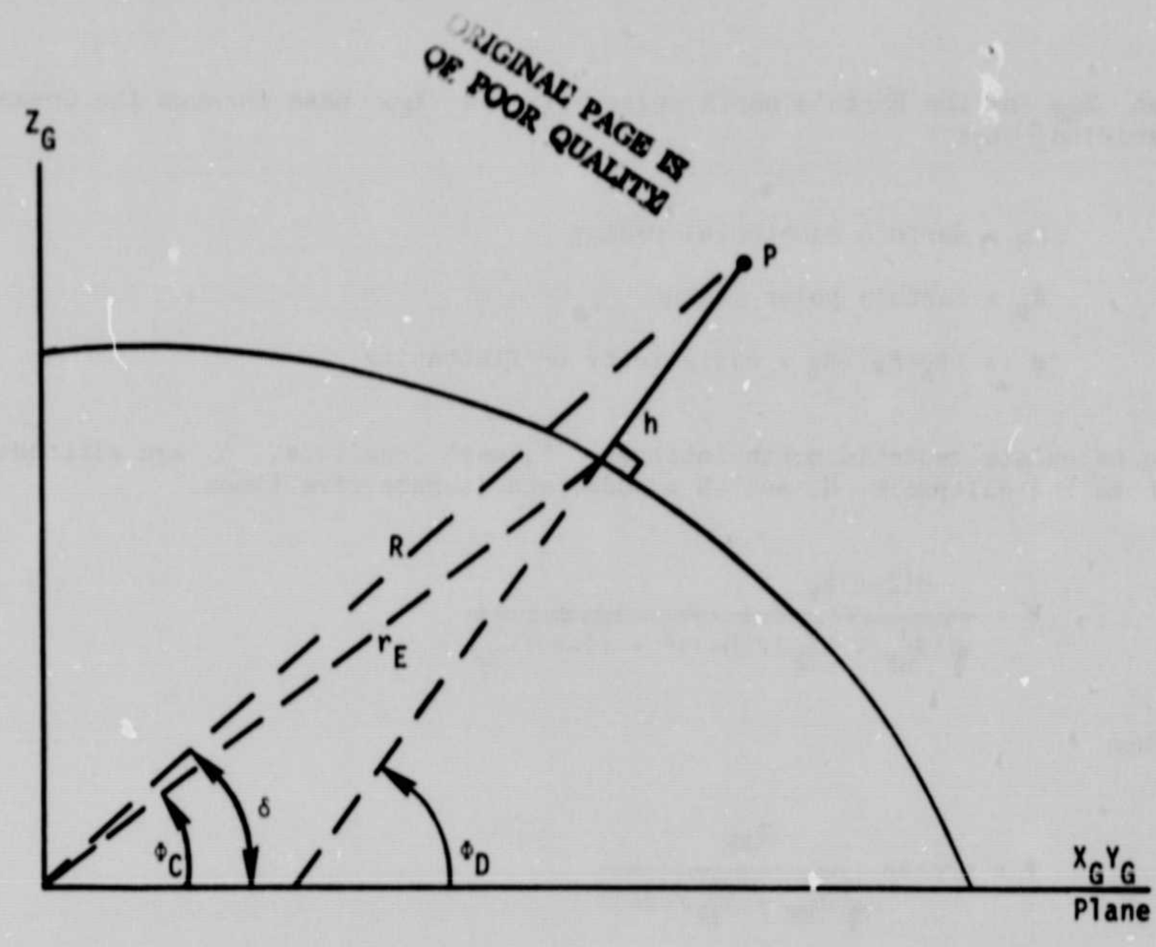
$\phi$ is the geodetic latitude, measured in the plane of the local meridian from the Earth's true equator to the geodetic local vertical, measured positive north from the equator.

Note: A detailed explanation of declination, geodetic latitude, and geocentric latitude is provided in figure A-4(b).

**CHARACTERISTICS:** Rotating polar coordinate parameters. Only position vectors are expressed in this coordinate system. Velocity vectors should be expressed in the Aries-mean-of-1950, or the Aries true-of-date, polar for inertial or quasi-inertial representations, respectively. The Fischer ellipsoid model should be used with this system.

(a) Basic definitions.

Figure A-4.- Geodetic.




NAME: Geodetic coordinate system of point P.

DEFINITIONS: h is the altitude of point P measured perpendicular from the surface of the referenced ellipsoid.

$\phi_D$ is the geodetic latitude of point P.

$\phi_C$ is the geocentric latitude of point P.

$\delta$ is the angle between the radius vector and the equatorial plane (declination).

$\lambda$ is the longitude of point P angle (+ east) between the plane of the figure and the plane formed by the Greenwich meridian.

(b) Detailed explanation.

Figure A-4.- Continued.

Let $Z_{EF}$ be the Earth's north polar axis and $X_{EF}$ pass through the Greenwich meridian. Let

$R_E$ = Earth's equatorial radius

$R_p$ = Earth's polar radius

$e = (R_E - R_p)/R_E$ = ellipticity or flattening

To calculate geodetic north latitude, $\phi$, east longitude, $\lambda$, and altitude above the ellipsoid H, set B = .0067 and iterate five times.

$$B = \frac{e(2-e)R_E}{\sqrt{(X_{EF}^2 + Y_{EF}^2)/(B+1)^2 + (1-e)^2 Z_{EF}^2}}$$

Then

$$\phi = \arctan \frac{Z_{EF}}{\sqrt{X_{EF}^2 + Y_{EF}^2/(B+1)}}$$

$$\lambda = \arctan (Y_{EF}/X_{EF})$$

$$H = 1 - B\,\frac{(1-e)^2}{e(2-e)} \qquad \sqrt{(X_{EF}^2 + Y_{EF}^2)/(B+1)^2 + Z_{EF}^2}$$

A very good approximation for H is

$$H = X_{EF}^2 + Y_{EF}^2 + Z_{EF}^2 \quad - \quad \frac{R_E(1-e)\sqrt{X_{EF}^2 + Y_{EF}^2 + Z_{EF}^2}}{\sqrt{(1-e)^2(X_{EF}^2 + Y_{EF}^2) + Z_{EF}^2}}$$

(c) Definitions of $\phi$, $\lambda$, H.

Figure A-4.- Concluded.

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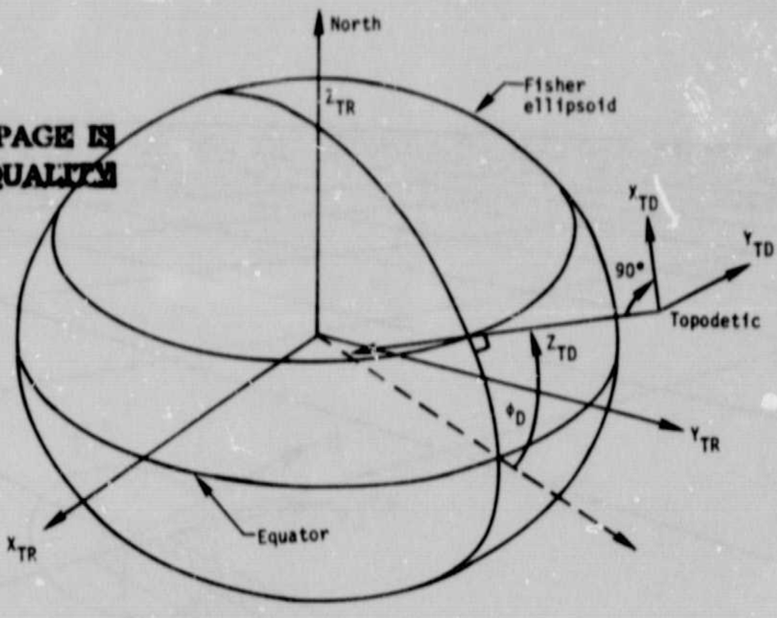


NAME: Topodetic coordinate system.

ORIGIN: Orbiter center of mass[a] or navigation base.

ORIENTATION: $Z_{TD}$ is normal to a geodetic local tangent plane and is positive toward the Earth's center.

$X_{TD}$ is perpendicular to $Z_{TD}$ axis and is positive northward along the meridian plane containing the Orbiter.

$Y_{TD}$ completes the right-handed orthogonal system.

CHARACTERISTICS: Rotating, right-handed, Cartesian system. Velocity vectors are expressible in this system for the Orbiter, given relative velocity $V_{TD}$ in this system.

$$V_{TD} = (\dot{X}_{TD}^2 + \dot{Y}_{TD}^2 + \dot{Z}_{TD}^2)^{1/2} = \text{magnitude of } \bar{V}_{TD}$$

$$\gamma_{TD} = \sin^{-1}\left(\frac{-\dot{Z}_{TD}}{V_{TD}}\right) = \text{flightpath angle (relative)}$$

$$\psi_{TD} = \tan^{-1}\left(\frac{\dot{Y}_{TD}}{\dot{X}_{TD}}\right) = \text{azimuth angle (relative)}$$

$\phi_D$ = geodetic latitude

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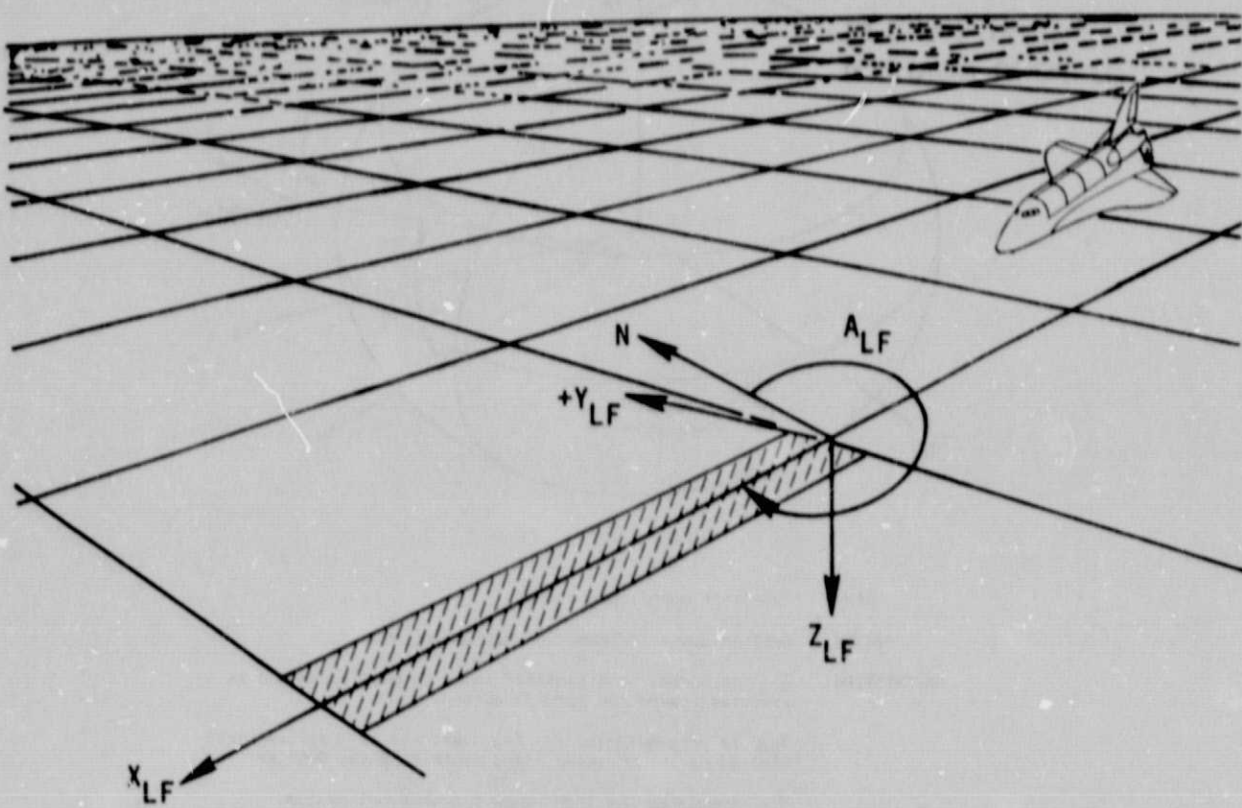
[a]A similar system may be defined for any point of interest.

Figure A-5.- Topodetic.




NAME: Landing field coordinate system.

ORIGIN: Runway center at approach threshold.

ORIENTATION AND DEFINITIONS: $Z_{LF}$ axis is normal to the ellipsoid model through the runway centerline at the approach threshold and positive toward the center of the Earth.

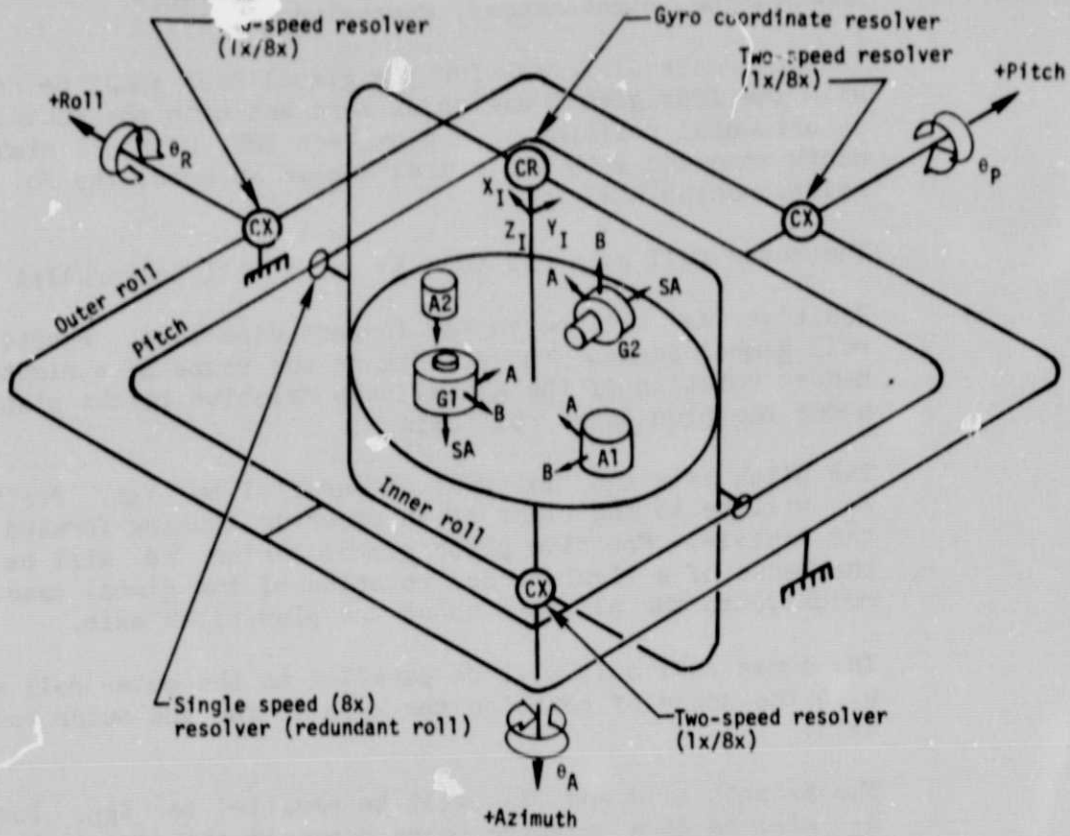
$X_{LF}$ axis is perpendicular to the $Z_{LF}$ axis and lies in a plane containing the $Z_{LF}$ axis and the runway centerline (positive in the direction of landing).

$Y_{LF}$ axis completes the right-handed system.

$A_{LF}$ is the runway azimuth measured in the $X_{LF}Y_{LF}$ plane from true north to the $+X_{LF}$ axis (positive clockwise).

CHARACTERISTICS: Rotating, Earth-referenced.

Figure A-6.- Landing field.




NAME: Inertial measurement unit (IMU) stable member coordinate system.

ORIGIN: The intersection of the innermost gimbal axis and the measurement plane of the XY two-axis accelerometer.

ORIENTATION: The $Z_I$ axis is coincident with the innermost gimbal axis.

The $X_I$ axis is determined by the projection of the X accelerometer input axis (IA) onto a plane orthogonal to $Z_I$. $Y_I$ completes a right-handed triad.

In a perfect IMU, with all misalinements zero, these relationships hold:

The X accelerometer and X gyro IA's are parallel to the $X_I$ axis.

The Y accelerometer and Y gyro IA's are parallel to the $Y_I$ axis.

The Z accelerometer and Z gyro IA's are parallel to the $Z_I$ axis.

Figure A-7.- IMU stable member.

CHARACTERISTICS: Nonrotating, right-handed, Cartesian system.

The reference alinement for the gimbal case shall be defined with the four gimbal angles at zero and with the vehicle in a horizontal position. In a perfect IMU, with all misalinements zero and with all gimbal angles at zero, the following relationships hold.

The outer roll axis and the $X_I$ axis will be parallel to $X_{NB}$.

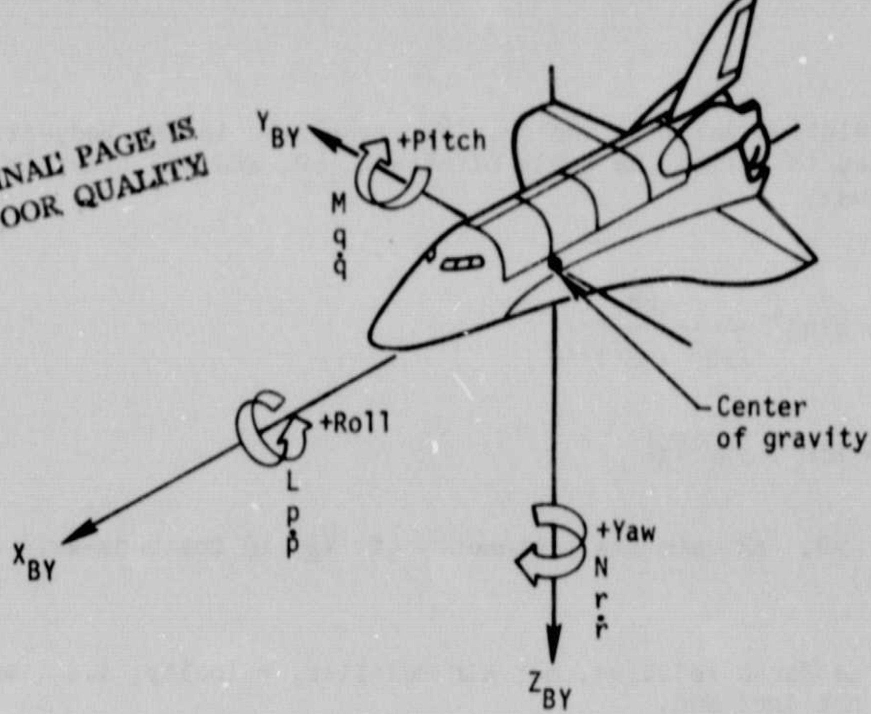
Positive $X_I$ will be in the forward direction. Positive roll gimbal angles $\theta_R$ will be in the sense of a right-handed rotation of the gimbal case relative to the platform about the plus outer roll axis.

The pitch axis and $Y_I$ will be parallel to $Y_{NB}$. Positive $Y_I$ will be to the right of an observer looking forward in the vehicle. Positive pitch gimbal angles $\theta_P$ will be in the sense of a right-handed rotation of the gimbal case relative to the platform about the plus pitch axis.

The inner roll axis will be parallel to the outer roll axis, with the sense of rotation the same as for the outer roll axis.

The azimuth axis and $Z_I$ will be parallel to $Z_{NB}$. Positive $Z_I$ will be down relative to an observer standing in the vehicle. Positive azimuth gimbal angles $\theta_A$ will be in the sense of a right-handed rotation of the gimbal case relative to the platform about the plus azimuth axis.

Figure A-7.- Concluded.




NAME: Body axis coordinate system.

ORIGIN: Orbiter center of mass or navigation base.

ORIENTATION: $X_{BY}$ axis is parallel to the Orbiter structural body $X_O$ axis; positive toward the nose.

$Z_{BY}$ axis is parallel to the Orbiter plane of symmetry and is perpendicular to $X_{BY}$, positive down with respect to the Orbiter fuselage.

$Y_{BY}$ axis completes the right-handed orthogonal system.

CHARACTERISTICS: Rotating, right-handed, Cartesian system.

L, M, N: Moments about $X_{BY}$, $Y_{BY}$, and $Z_{BY}$ axes, respectively.

p, q, r: Body rates about $X_{BY}$, $Y_{BY}$, and $Z_{BY}$ axes, respectively.

$\dot{p}$, $\dot{q}$, $\dot{r}$: Angular body acceleration about $X_{BY}$, $Y_{BY}$, and $Z_{BY}$ axes, respectively.

The Euler sequence that is commonly associated with this system is a yaw, pitch, roll sequence, where $\Psi$ = yaw, $\theta$ = pitch, and $\phi$ = roll or bank. This attitude sequence is yaw, pitch, and roll around the $Z_{BY}$, $Y_{BY}$, and $X_{BY}$ axes, respectively.

(a) Basic definition.

Figure A-8.- Body axes.

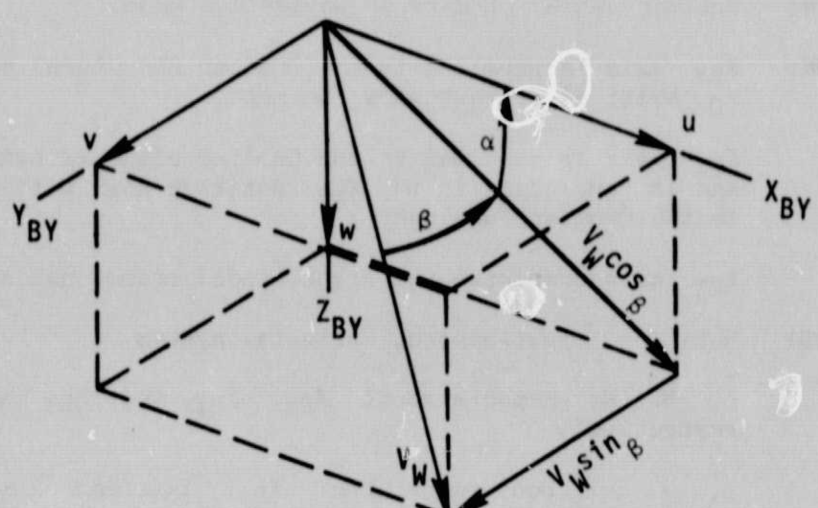
The Earth relative velocity vector, $\bar{V}_E$, expressed in the body-axis system. shall be used to define the angle of attack, $\alpha$, and the sideslip angle, $\beta$, as follows:

$$\alpha = \sin^{-1} \frac{\dot{z}B}{(\dot{x}B^2 + \dot{z}^2)^{1/2}}$$

$$\beta = \sin^{-1} \dot{y}_B / |\bar{V}_E|$$

where $\dot{x}B$, $\dot{y}B$, $\dot{z}B$ are the components of $\bar{V}_E$ in the body-axis system (see fig. A-8(b)).

Note: $\bar{V}_E$ is Earth relative, not air relative, velocity; i.e., wind effects are not included.




(b) Resolution of Earth relative velocity along vehicle body axes.

Figure A-8.- Concluded.

Earth surface range. S, shall be defined as the product of (1) the magnitude of the Earth-fixed position vector to the launch or landing site and (2) the central angle between the site vector and the Earth-fixed position vector to the Orbiter; i.e.,

$$S = |\bar{R}_{SITE}|\ \theta_E$$

where $\theta_E = \cos^{-1} \dfrac{\bar{R}_{SITE} \cdot \bar{R}_{ORB}}{|\bar{R}_{SITE}|\ |\bar{R}_{ORB}|}$ = central angle

$\bar{R}_{SITE}$ = Earth-fixed position vector to launch pad (ascent) or to runway coordinate system origin (descent)

$\bar{R}_{ORB}$ = Earth-fixed position vector to Orbiter

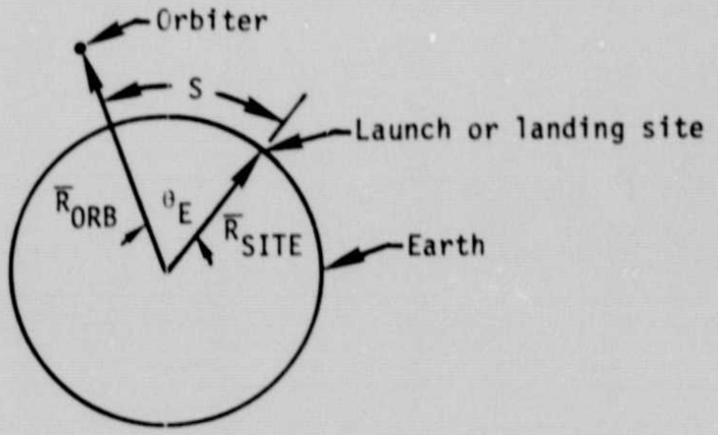



Figure A-9.- Definition of Earth surface range.

Dynamic pressure $\bar{q}$ shall be defined as

$$\bar{q} = 1/2\ \rho\ |\bar{V}_E|^2$$

and Mach number M shall be defined as

$$M = |\bar{V}_E|/a$$

where $|\bar{V}_E|$ = magnitude of Earth relative velocity

$\rho$ = atmospheric density

a = speed of sound

Figure A-10.- Definition of dynamic pressure and Mach number.

$$T' = 726.97 + .468T_\infty + 3.4098447 \times 10^{-6} V_\infty^2 \qquad (^\circ K)$$

$T_\infty$ in $^\circ$K → from flightpath atmosphere

$V_\infty$ in fps → wind relative (true) airspeed

$$C'_\infty = \left(\frac{T'}{T_\infty}\right)^{.5} \left[\frac{T_\infty + 122.1 \times 10^{-(5/T_\infty)}}{T' + 122.1 \times 10^{-(5/T')}}\right] \qquad (N/D)$$

$$\mu = \frac{3.0449939 \times 10^{-8} T_\infty{}^{1.5}}{(T_\infty + 110.4)} \qquad (lbf\text{-}sec/ft^2)$$

$$Re_{\infty L_B} = \frac{V_\infty \rho_\infty L_B}{\mu} \qquad (N/D)$$

$\rho_\infty$ in slug/ft$^3$ → from flightpath atmosphere

$L_B$ = body length = 107.5 ft

$$M_\infty = \frac{V_\infty}{a} = \frac{V_\infty}{\sqrt{\gamma R T_\infty}} = \frac{V_\infty}{\sqrt{4289.05 T_\infty}} \qquad (N/D)$$

$$\bar{V}'_\infty = M_\infty \sqrt{\frac{C_\infty'}{Re_{\infty L_B}}} \qquad (N/D)$$

Figure A-11.- Hypersonic viscous parameter.

Drag over mass (D/M) is calculated as follows:

$$D/M = \frac{\Delta\bar{V}_S}{\Delta t} \cdot \frac{\bar{V}_{REL}}{|\bar{V}_{REL}|}$$

where $\bar{V}_{REL}$ is the Earth relative velocity vector

$= \bar{V}_{inertial} - \omega X \bar{R}_{inertial}$

and $\omega$ is the Earth rotation rate

$\bar{R}_{inertial}$ = Mean of 50 position vector

$\bar{V}_{inertial}$ = Mean of 50 velocity vector

$|\bar{V}_{REL}|$ = magnitude of the Earth relative vector

$\Delta\bar{V}_S$ = sensed change in velocity from IMU output

$\Delta t$ = time interval over which $\Delta V_S$ is determined

$$ACC\_LIFT = \frac{\Delta\bar{V}_S}{\Delta t} \cdot \frac{[\bar{Y}\_BD\_UNIT \; X \; \bar{V}_{REL}]}{|\bar{Y}\_BD\_UNIT \; X \; \bar{V}_{REL}|}$$

$\bar{Y}$_BD_UNIT is unit vector passing through Y body (right wing). It is the second column of the transformation matrix body to M50.

LOD = ACC_LIFT/(D/M)

LOD = lift over drag

$$LOAD\_TOTAL = \left|\frac{\Delta\bar{V}_S}{\Delta t}\right| / 32.174$$

Load total is total load factor. It is total acceleration expressed in g's of 32.174 $fps^2$.

Equivalent airspeed (EAS) = 17.1865 $\sqrt{1/2 \, \rho \, V_e^2}$ knots

p = atmospheric density in $slug/ft^3$

$V_e$ = relative speed in fps

Figure A-12.- Calculations for drag acceleration, lift of drag, total load factor, and equivalent airspeed.