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COORDINATE SYSTEMS FOR THE SPACE SHUTTLE PROGRAM

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16. Abstract

This document comprises a minimal set of well-defined coordinate systems necessary for the interchange of data within the Space Shuttle Program. The basic document format consists of four parts: (a) a list of the subscripts identifying the coordinate systems, (b) a glossary explaining the terms used within the coordinate-system definitions, (c) figures defining, both graphically and verbally, each coordinate system, and (d) an appendix (published separately) showing the relationships (transformations) between similar coordinate systems.

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By Larry D. Davis
Lyndon B. Johnson Space Center

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COORDINATE SYSTEMS FOR THE SPACE SHUTTLE PROGRAM

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INTRODUCTION

In 1965, a standard set of coordinate systems was established to facilitate the exchange of data among participants of the Apollo Program. Similarly, this document establishes a standard set of coordinate systems for the Space Shuttle Program. This document provides a minimum set of well-defined coordinate systems that are required for the practical exchange of data among participants of the Shuttle Program.

This document was compiled by Larry Davis, Mission Planning and Analysis Division, NASA Lyndon B. Johnson Space Center; however, several individuals in this division and one individual in the Propulsion and Power Division were also responsible for defining coordinate systems included in this document. The individuals contributing to this document and their areas of responsibility are as follows.

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O. Hill	Topocentric Topodetic Body axes Stability axes Wind axes Trajectory axes
G. L. Carman	Landing field
S. A. Kamen R. L. McHenry A. D. Long	Plumbline U, V, W
E. W. Henry J. B. Williamson	Aries mean of 1950, Cartesian Aries mean of 1950, polar Aries true of date, Cartesian

	Aries true of date, polar Greenwich true of date (geographic) Geodetic Orbital element Inertial measurement unit (IMU) stable member Radar azimuth-elevation mount Tactical air navigation (TACAN) Radar X-Y mount, 30-foot dish Radar X-Y mount, 85-foot dish
J. R. Thibodeau III	Inertial measurement unit (IMU) stable member
T. J. Blucker	Navigation base Optical base Star tracker optics
T. B. Murtagh	Pilot (body fixed), Cartesian
H. C. Sullivan	Software development review
W. L. Brasher	Space shuttle main engine (SSME) structural body
L. D. Davis	Orbiter structural body Solid rocket booster (SRB) structural body External tank (ET) or integrated vehicle structural body Payload reference
M. E. Bonneau	Document artwork

STANDARD SUBSCRIPTS

The standard subscripts used to identify the coordinate systems are as follows.

Subscript	Coordinate System
M	Aries mean of 1950, Cartesian (fig. 1)
M	Aries mean of 1950, polar (fig. 2)
TR	Aries true of date, Cartesian (fig. 3)
TR	Aries true of date, polar (fig. 4)

Subscript	Coordinate System
G	Greenwich true of date (geographic) (fig. 5)
None Required	Geodetic (fig. 6)
None Required	Orbital element (fig. 7)
PL	Plumbline (fig. 8)
None Required	U, V, W (fig. 9)
LO	Local orbital (fig. 10)
LF	Landing field (fig. 11)
BY	Body axes (fig. 12)
SB	Stability axes (fig. 13)
W	Wind axes (fig. 14)
TJ	Trajectory axes (fig. 15)
TC	Topocentric (fig. 16)
TD	Topodetic (fig. 17)
BY	Look angle (fig. 18)
NB	Navigation base (fig. 19)
I	Inertial measurement unit (IMU) stable member (fig. 20)
OB	Optical base (fig. 21)
None Required	Star tracker optics (fig. 22)
O	Orbiter structural body (fig. 23)
B	Solid rocket booster (SRB) structural body (fig. 24)
T	External tank (ET) or integrated vehicle structural body (fig. 25)
None Required	Radar azimuth-elevation mount (fig. 26)
None Required	Tactical air navigation (TACAN) (fig. 27)
F	Radar X-Y mount, 30-foot dish (fig. 28)

Subscript	Coordinate System
J	Radar X-Y mount, 85-foot dish (fig. 29)
PD	Payload reference (fig. 30)
PB	Pilot (body fixed), Cartesian (fig. 31)
ME	Space shuttle main engine (SSME) structural body (fig. 32)

GLOSSARY OF TERMS

The terms used within the coordinate-system definitions are defined as follows.

Inertial coordinate system: A system whose coordinate axes are fixed, relative to the stars, at infinite distances. That is, the rotation rates about all axes, relative to the stars, are zero.

Quasi-inertial system: A system that rotates with time from an inertial system and whose instantaneous rates of rotation and translational velocity between respective origins are, by definition, equal to zero. Thus, a velocity-vector transformation between quasi-inertial systems does not include the rotation rates of axes; hence, velocity magnitudes are invariant under such a transformation.

Nonrotating systems: An inertial or quasi-inertial system. That is, any system whose rates of rotation about all axes, relative to any inertial system, are zero.

Rotating systems: A reference frame that varies with time from an inertial system and whose rates of rotation about axes are included in transformations of velocity vectors to derive relative velocity.

Cartesian system: A system whose reference frame consists of a triad of mutually-perpendicular directed lines originating from a common point, in which a vector is expressed by components that are scalar magnitude projections along each axis.

Slant range: The minimum or straight-line distance between two points expressed in the same coordinate system.

Perigee and apogee: The unique points in an elliptic orbit about the Earth, wherein the object achieves minimum and maximum distance, respectively, from the center of the Earth.

Osculating conic: A two-body approximation to non-two-body motion that is derived from conditions existing at some instant of time but that is exact only for that instant. An osculating-conic trajectory is one that is tangent to the true trajectory at the defining instant.

Geodetic local vertical: A reference ellipsoid of revolution that approximates the figure of the Earth is presumed. Then the local vertical at any point is along the unique line that is normal to the ellipsoid surface and that contains the point of interest.

Mean versus true systems: The line of intersection of the ecliptic plane (the instantaneous plane of motion of the Earth and Sun) and the celestial equator (mean Earth equator) precesses among the fixed stars with a rate of one revolution in 26 000 years. Additionally, the Earth wobbles slightly on its axis, relative to its mean position, with periods of oscillations of only a few years. The former phenomenon is called precession; the latter is called nutation. A mean system conveys the concept that precession is included when relating that system to another system at a different time, but the nutation phenomenon is not included. A true system, however, conveys the concept that a mean system at any specific instant of time is converted to a true system at the same instant of time by including terms associated with the nutation phenomenon.

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Houston, Texas, October 1, 1974
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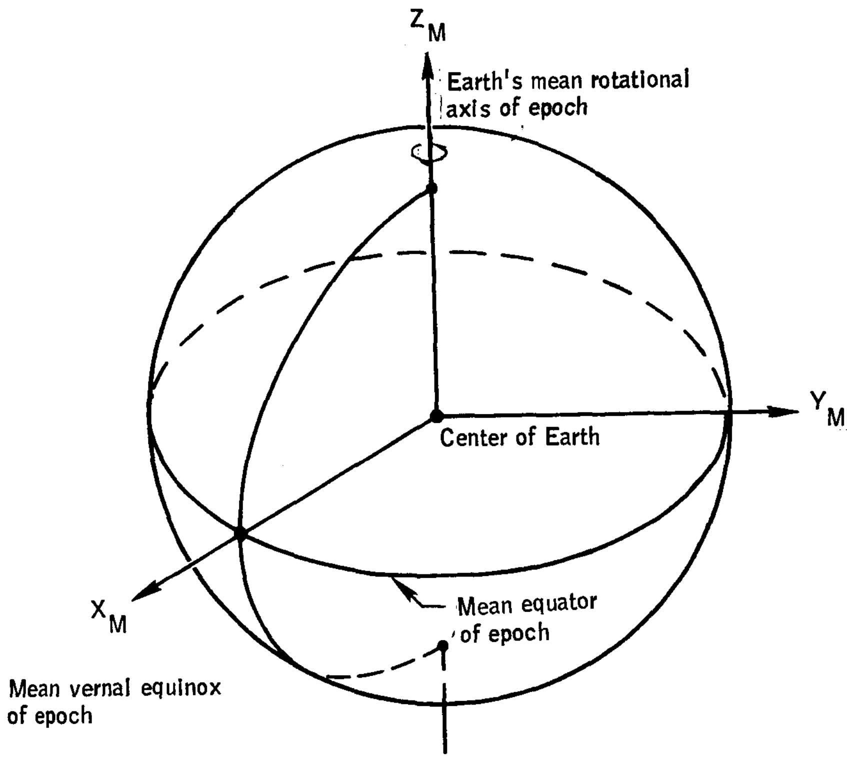


NAME: Aries-mean-of-1950, Cartesian, coordinate system.

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.

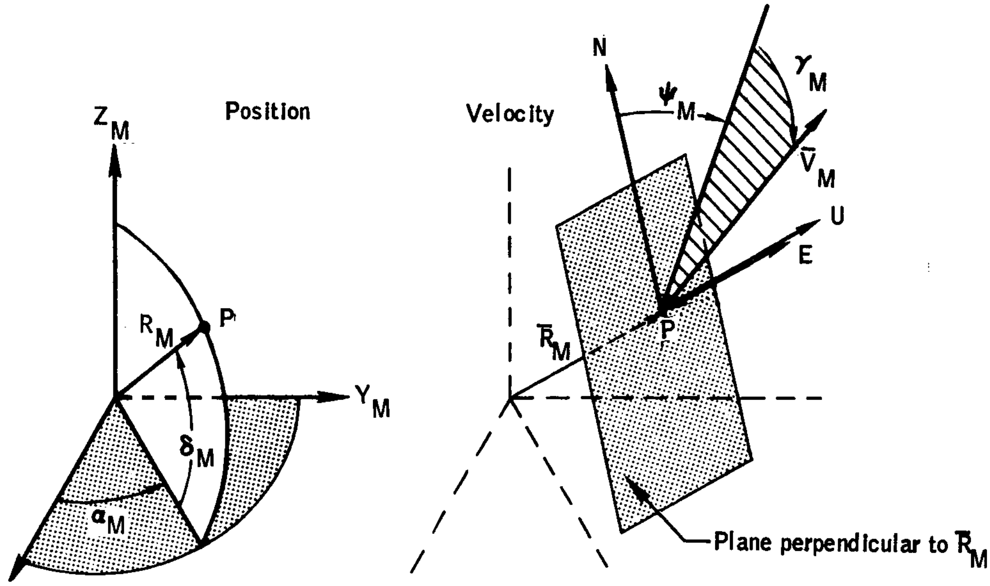
The X_M axis is directed towards the mean vernal equinox of epoch.

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 1.- Aries mean of 1950, Cartesian.



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 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 northlerly along the meridian containing P.

Polar position coordinates of P are:

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

δ_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:

Let U, E, N denote up, east, and north directions; then:

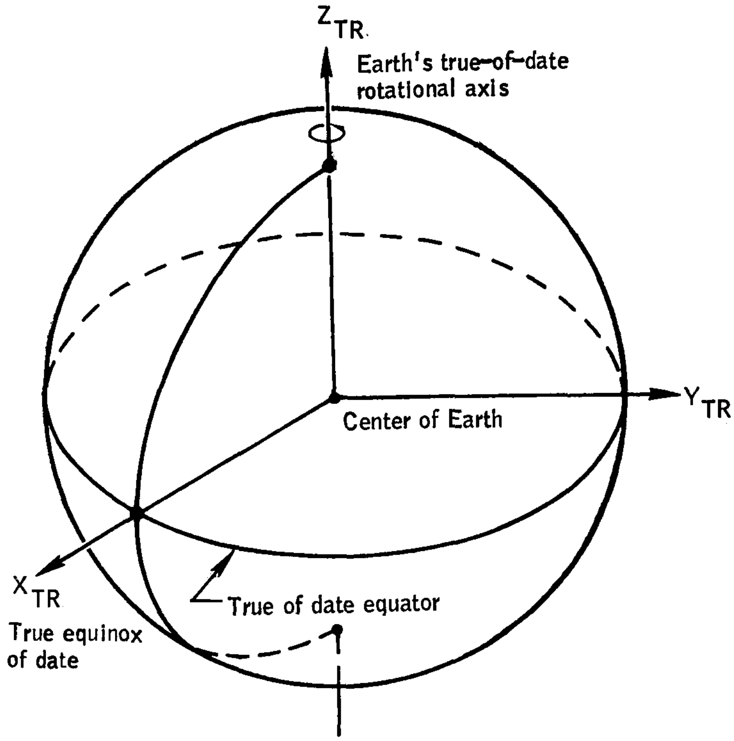
Ψ_M, azimuth, is the angle from north to the projection of $\bar{V}_M$ on the reference plane, positive toward east.

γ_M, flight-path 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.

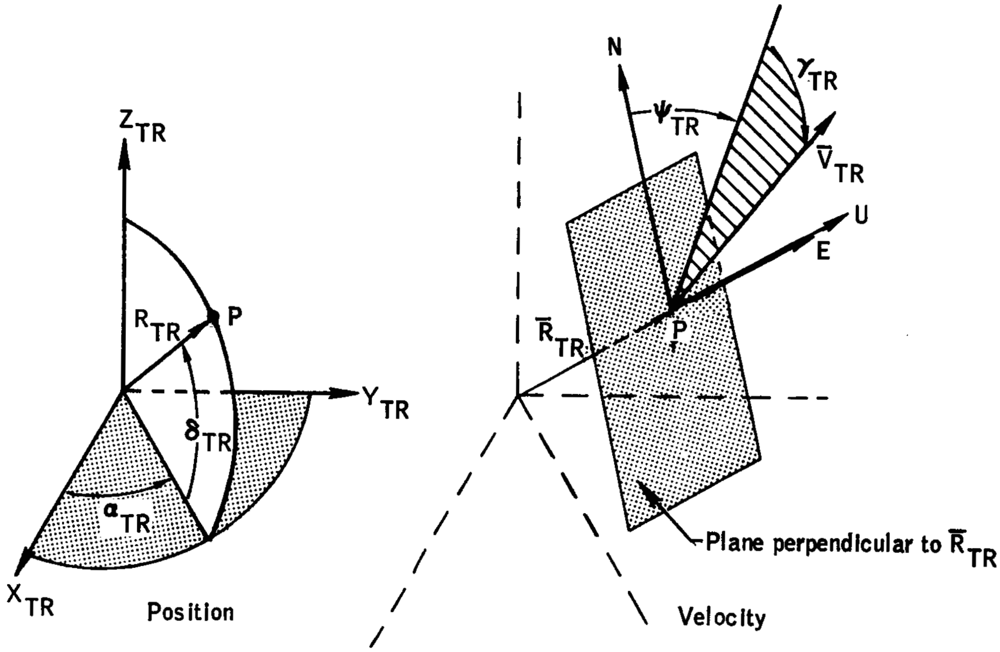
CHARACTERISTICS: Inertial.

Figure 2.- Aries mean of 1950, polar.



NAME:	Aries true of date, Cartesian, coordinate system.
ORIGIN:	The center of the Earth.
ORIENTATION:	The epoch is the current time of interest.
	The X_{TR}-Y_{TR} plane is the Earth's true equator of epoch.
	The X_{TR} axis is directed towards the true vernal equinox of epoch.
	The Z_{TR} axis is directed along the Earth's true rotational axis of epoch and is positive north.
	The Y_{TR} axis completes the right-handed system.
CHARACTERISTICS:	Quasi-inertial, right-handed Cartesian.

Figure 3.- Aries true of date, Cartesian.



NAME: Aries true of date, polar, coordinate system.

ORIGIN: For position - the center of the Earth.
For velocity - the point of interest, $P(X_{TR}, Y_{TR}, Z_{TR})$.

ORIENTATION: For position - same as in Aries true of date, Cartesian.
For velocity -
Reference plane is perpendicular to radius vector $\bar{R}_{TR}$ from center of Earth to point P of interest.

Reference direction is northerly along the meridian containing P.

Polar position coordinates of P are:

α_{TR}, right ascension, is the angle between projection of radius vector in the equatorial plane and the true vernal equinox of epoch, measured positive toward the east.

δ_{TR}, declination, is the angle between the radius vector and the Earth time equatorial plane, of epoch, positive toward the north.

R_{TR}, is the magnitude of $\bar{R}_{TR}$.

Figure 4.- Aries true of date, polar.

ORIENTATION (Concluded): Polar velocity coordinates of P are:

Let U, E, N denote up, east, and north directions; then:

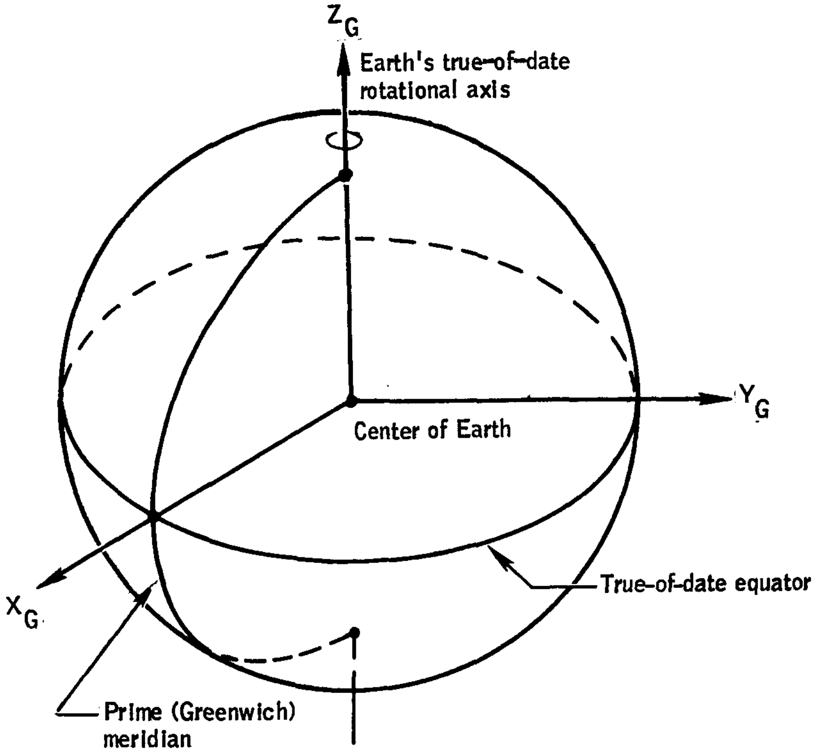
Ψ_{TR}, azimuth, is the angle from north to the projection of $\bar{V}_{TR}$ on the reference plane, positive toward east.

γ_{TR}, flight-path angle, is the angle between the reference plane and $\bar{V}_{TR}$; positive sense toward U.

V_{TR}, magnitude of $\bar{V}_{TR}$, is always positive.

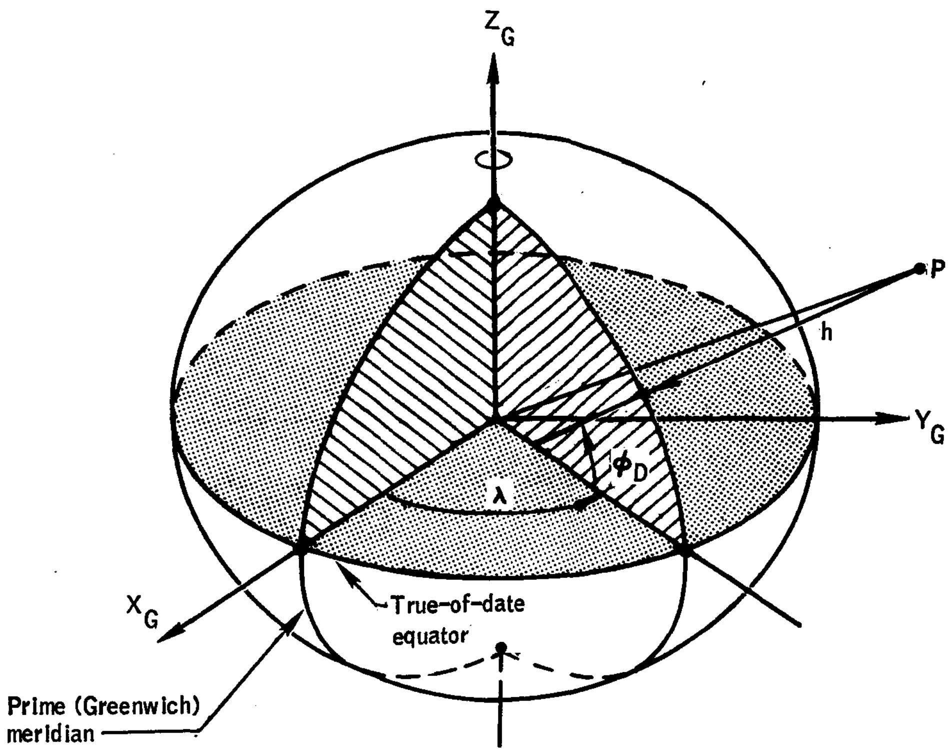
CHARACTERISTICS: Quasi-inertial.

Figure 4.- Aries true of date, polar - concluded.



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.

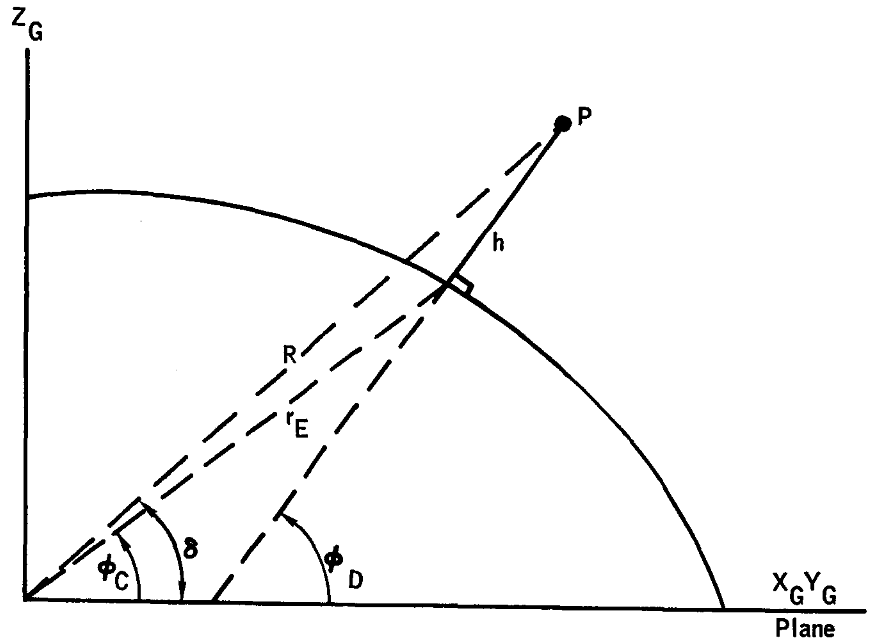
Figure 5.- Greenwich true of date (geographic).



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 a 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 which 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.
	λ 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.
	ϕ 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 6(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 6.- 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.

ϕ_D is the geodetic latitude of point P.

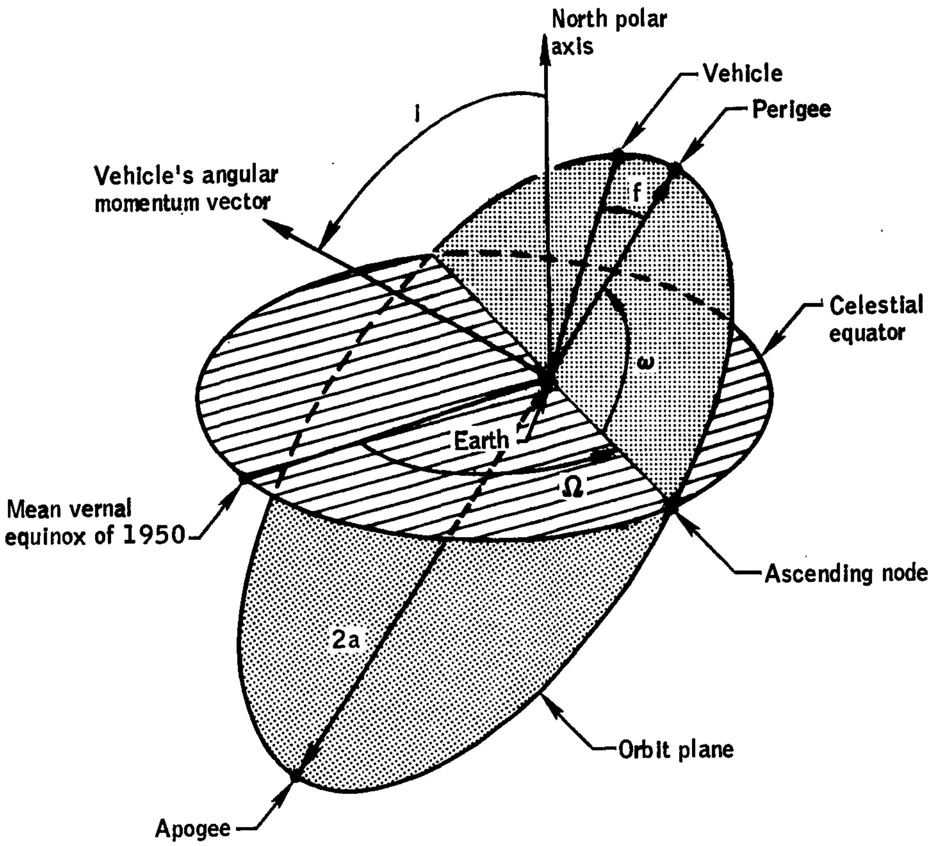
ϕ_C is the geocentric latitude of point P.

δ is the angle between radius vector and equatorial plane (declination).

λ is the longitude of point P. Angle (+ east) between plane of the figure and the plane formed by the Greenwich meridian.

(b) Detailed explanation.

Figure 6.- Geodetic - concluded.



NAME: Orbital element coordinate system.

ORIGIN: The center of the Earth.

ORIENTATION AND DEFINITIONS: The reference for computing osculating orbital elements is the Aries mean of 1950 coordinate system.

a is the semimajor axis of the orbit.

e is the eccentricity of the orbit.

i, the inclination of the orbital plane, is the angle between the north polar axis and the orbital angular momentum vector.

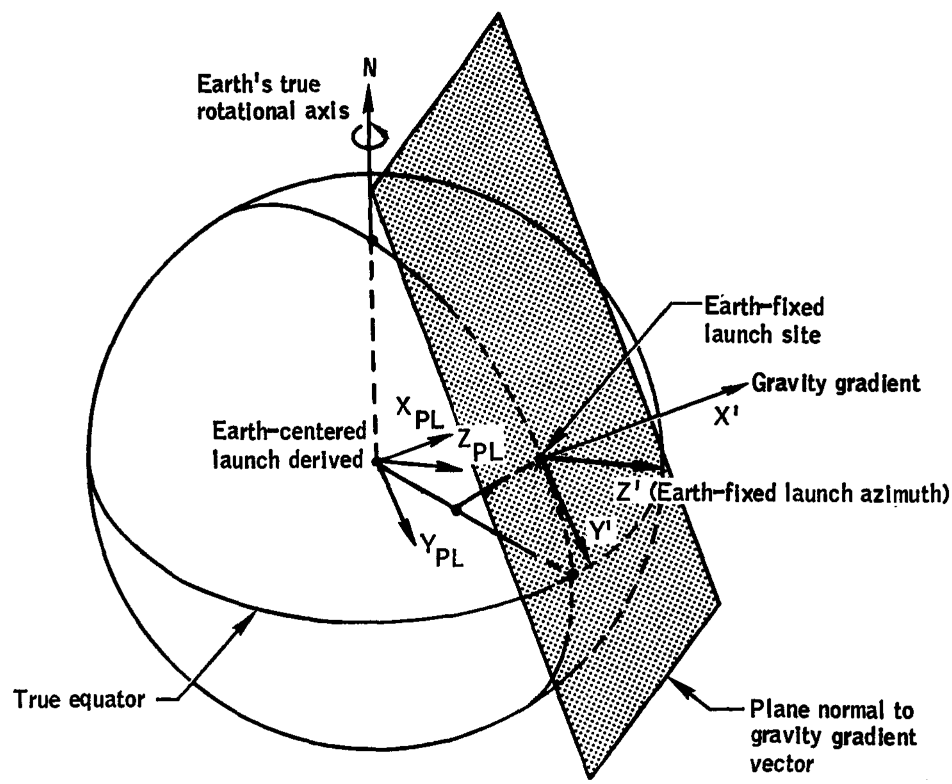
Ω, the right ascension of the ascending node, is the angle measured eastward from the vernal equinox along the equator to that intersection with the orbit plane where the vehicle passes from south to north. In the case where inclination equals zero, the ascending node is defined to be the X axis of the reference system.

ω, the argument of perigee, is the angle measured in the orbit plane between the ascending node and perigee, positive in the direction of travel in the orbit. In the case where eccentricity equals zero, perigee is defined to be at the ascending node.

f, the true anomaly, is the geocentric angular displacement of the vehicle measured from perigee in the orbit plane, and positive in the direction of travel in the orbit.

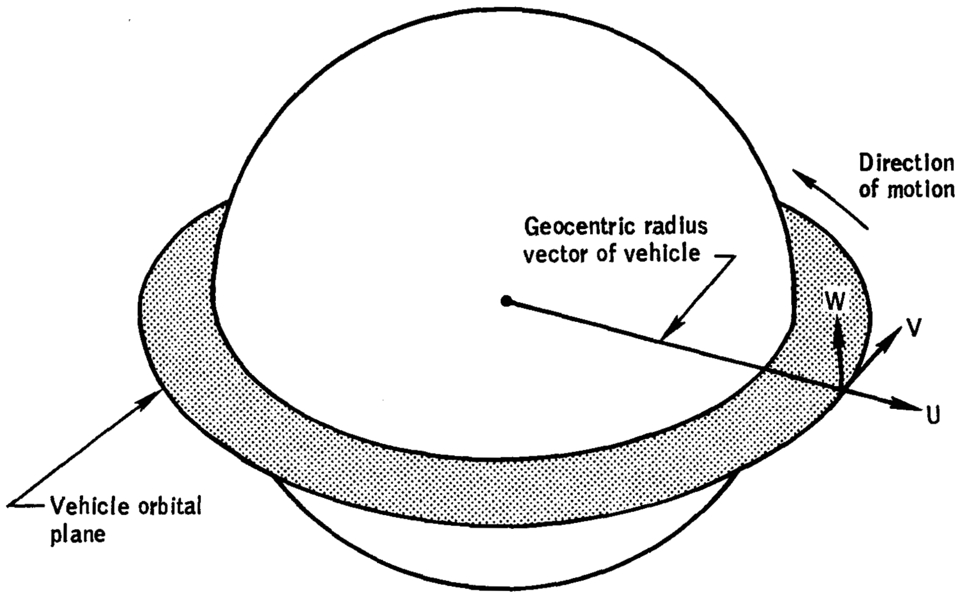
CHARACTERISTICS: Quasi-inertial.

Figure 7.- Orbital elements.



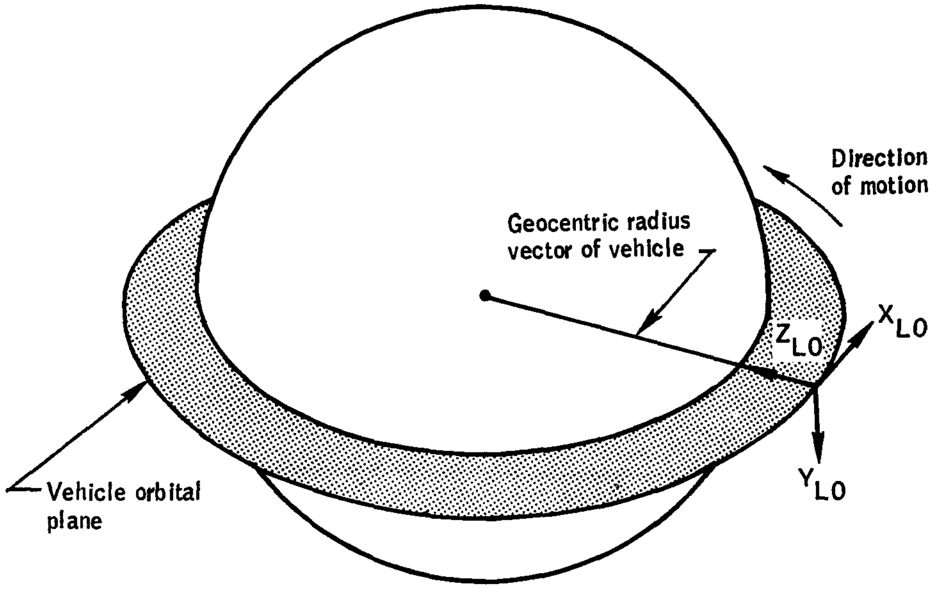
NAME:	Plumbline coordinate system.
ORIGIN:	At the center of the Earth.
ORIENTATION AND DIRECTIONS:	The X_{PL} axis is parallel to the gravity gradient (X'), which passes through the launch site and is positive toward the launch site. The X_{PL} axis is fixed at a specifically stated time. The Z_{PL} axis is parallel to, and positive in the same direction as the chosen Earth-fixed launch azimuth direction (Z'). The Y_{PL} axis is parallel to the Y' and completes a standard right-handed system. The Y_{PL}-Z_{PL} plane is normal to launch site gravity gradient vector.
CHARACTERISTICS:	Inertial, right-handed, Cartesian.

Figure 8.- Plumbline.



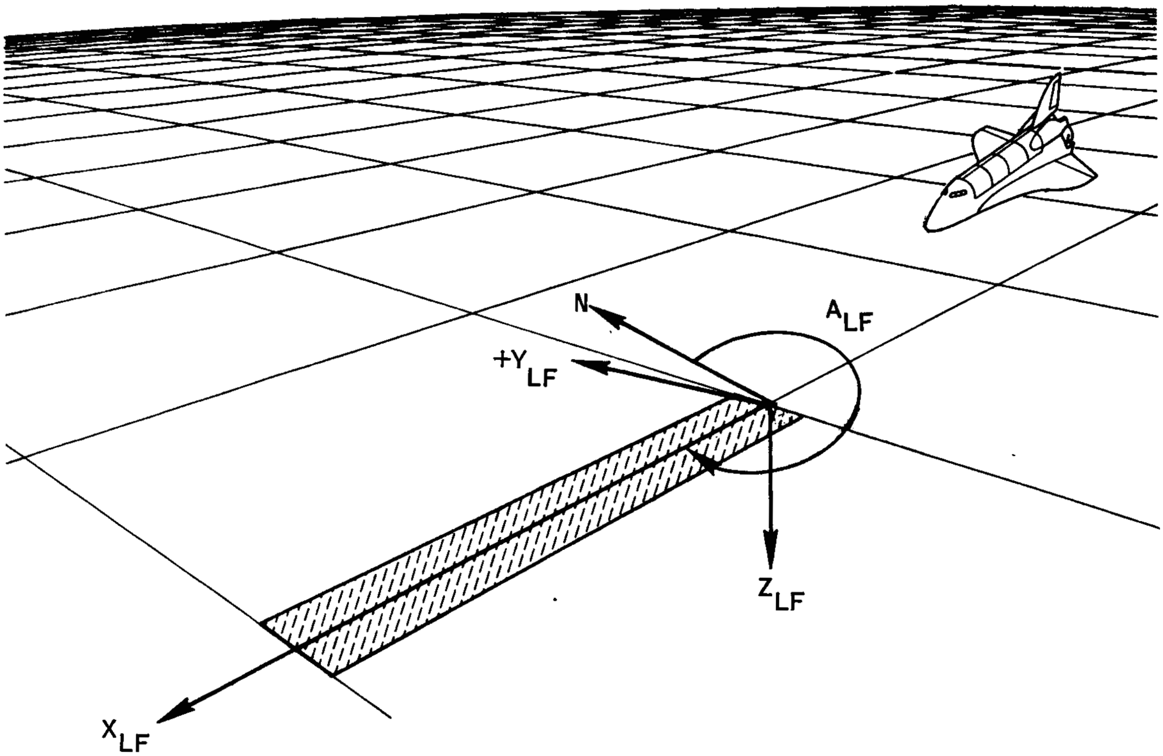
NAME:	U, V, W coordinate system.
ORIGIN:	Point of interest.
ORIENTATION:	The U-V plane is the instantaneous orbit plane at epoch.
	The U axis lies along the geocentric radius vector to the vehicle and is positive radially outward.
	The W axis lies along the instantaneous orbital angular momentum vector at epoch and is positive in the direction of the angular momentum vector.
	The V axis completes a right-handed system.
CHARACTERISTICS:	Quasi-inertial, right-handed, Cartesian coordinate system. This system is quasi-inertial in the sense that it is treated as an inertial coordinate system, but it is redefined at each point of interest.

Figure 9.- U, V, W.



NAME:	Local orbital coordinate system.
ORIGIN:	Vehicle center of mass.
ORIENTATION:	The X_{LO}-Z_{LO} plane is the instantaneous orbit plane at the time of interest. The Z_{LO} axis lies along the geocentric radius vector to the vehicle and is positive toward the center of the Earth. The X_{LO} axis lies in the vehicle orbital plane, perpendicular to the Z_{LO} axis, and positive in the direction of vehicle motion. The Y_{LO} axis is normal to the orbit plane and completes the right-handed orthogonal system.
CHARACTERISTICS:	Quasi-inertial, right-handed, Cartesian coordinate system.

Figure 10.- Local orbital.



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.

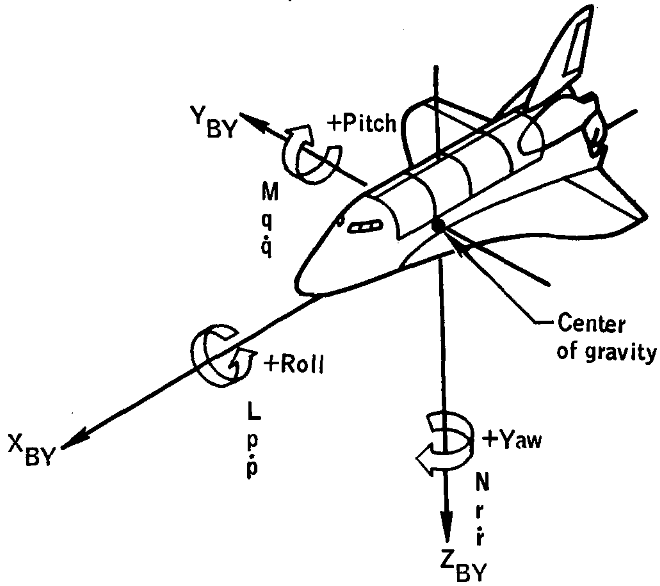
X_{LF} axis is perpendicular to the Z_{LF} axis and lies in a plane containing the Z_{LF} axis and the runway centerline. (positive in the direction of landing).

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

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

CHARACTERISTICS: Rotating, Earth-referenced.

Figure 11.- Landing field.



NAME:	Body axis coordinate system.
ORIGIN:	Center of mass.
ORIENTATION:	X_{BY} axis is parallel to the orbiter structural body X_0 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 ψ = yaw, θ = pitch, and ϕ = 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.

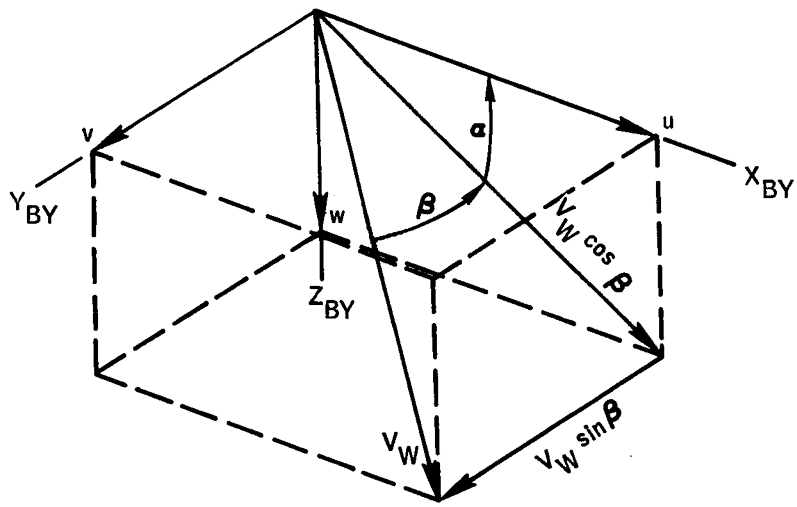
Figure 12.- Body axes.

The body axis system and the velocity vector (V_W) with components U, V, and W [see fig. 12(b)] can be used to define the stability, wind, and trajectory axes systems.

A similar system can be defined for the solid rocket boosters and integrated vehicle.

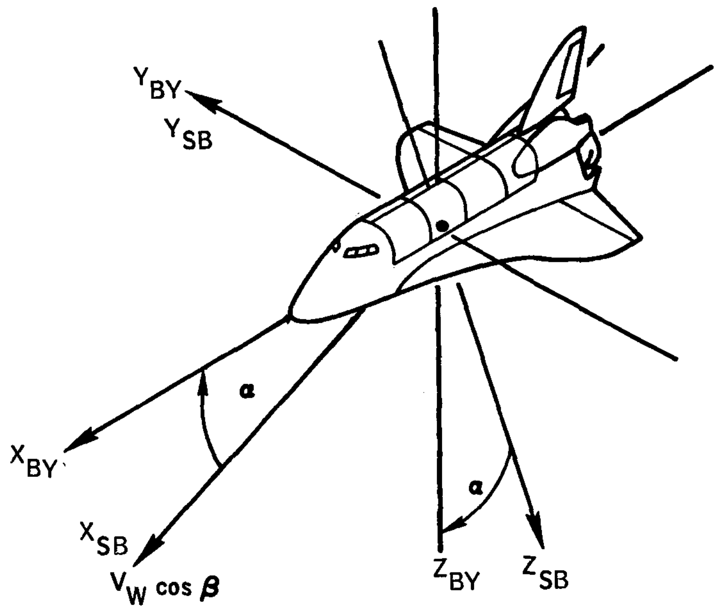
(a) Basic definition - concluded.

Figure 12.- Body axes - continued.



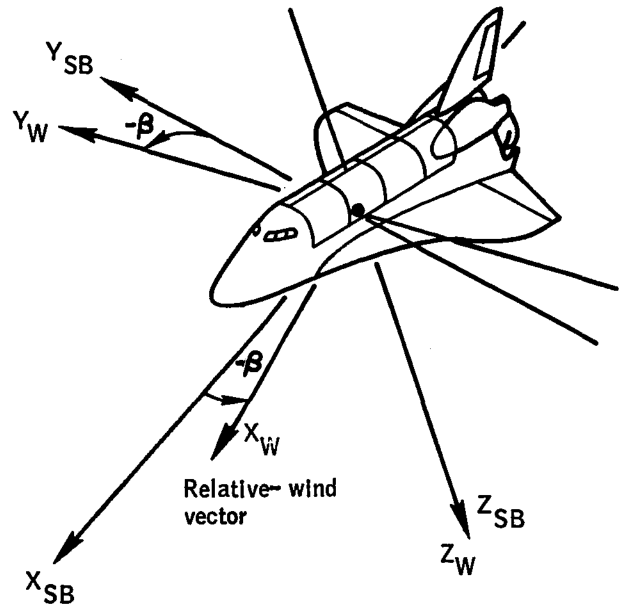
(b) Resolution of relative wind into components along vehicle body axes.

Figure 12.- Body axes - concluded.



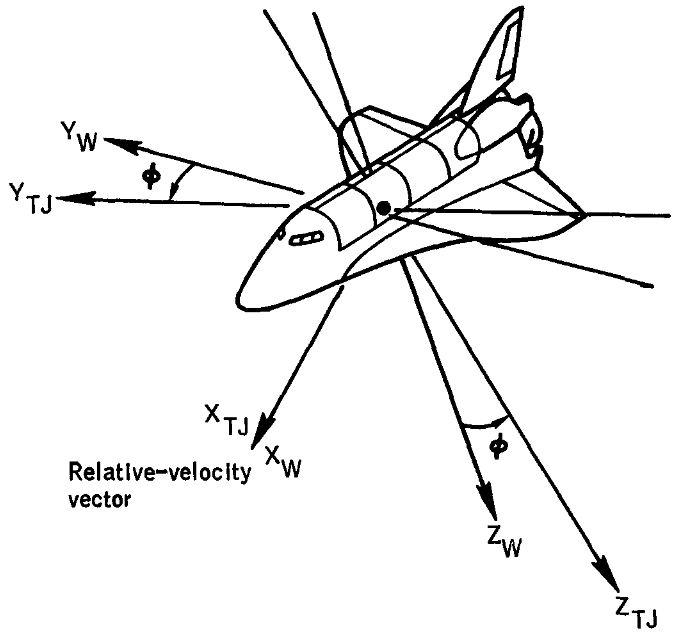
NAME:	Stability axis coordinate system.
ORIGIN:	Center of mass.
ORIENTATION:	X_{SB} lies in the X_{BY}, Z_{BY} plane positive in the direction of the relative velocity and coincident with the projection of the relative wind on the orbiter plane of symmetry. Z_{SB} lies in a plane parallel to the orbiter plane of symmetry, perpendicular to X_{SB}, positive down with respect to the orbiter fuselage.
	Y_{SB} completes the right-handed system.
	The stability axis system is obtained from the body axis system by a rotation about the $+Y_{BY}$ axis through the angle of attack , $-\alpha$.
CHARACTERISTICS:	Rotating, right-handed, Cartesian. See figure 12(b).

Figure 13.- Stability axes.



NAME:	Wind axes coordinate system.
ORIGIN:	Center of mass.
ORIENTATION:	X_W is coincident with the relative-wind vector, positive in the direction of the relative velocity. Z_W is the Z_{SB} axis. Y_W completes the right-handed system. The wind axis system is obtained from the stability system by a rotation about the Z_{SB} axis through the angle of side slip β.
CHARACTERISTICS:	Rotating, right-handed, Cartesian. The relative-wind vector may be resolved into components along the vehicle body axes as shown in figure 12(b). A similar system can be defined for the solid rocket boosters and the integrated vehicle.

Figure 14.- Wind axes.



NAME: Trajectory axis coordinate system.

ORIGIN: Center of mass.

ORIENTATION: X_{TJ} is coincident with the Earth relative-velocity vector positive in the direction of the velocity.

Z_{TJ} is contained in the plane of the relative velocity and the geodetic altitude [see fig. 6(b)] normal to the X_{TJ} axis positive downward.

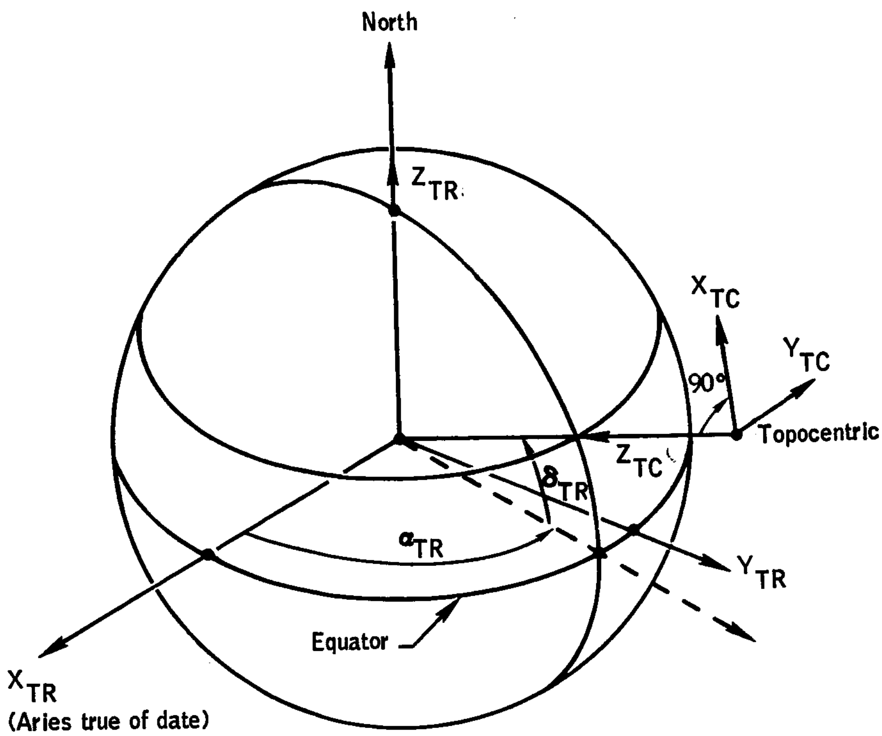
(NOTE: For high speed flight, Z_{TJ} is normally considered as being in a plane containing the velocity vector and the center of the Earth. V_e and V_W are considered coincidental.)

Y_{TJ} completes the right-handed orthogonal system.

The trajectory axis system is obtained from the wind system by a rotation about the $+X_W$ axis through the angle roll (ϕ), positive ϕ is defined by the right-handed rule.

CHARACTERISTICS: Rotating, right-handed, Cartesian system. The Euler sequence that is associated with this system is a roll, yaw, pitch sequence where ϕ = roll, ψ = yaw, and α = pitch. The sequence is commonly used in three-degree-of-freedom simulation of aircraft flight with the assumption that $\beta = \psi = 0$ for symmetric flight.

Figure 15.- Trajectory axes.



NAME: Topocentric coordinate system.

ORIGIN: Orbiter center of mass.

ORIENTATION: Z_{TC} is positive along radius vector toward Earth center.

X_{TC} is perpendicular to Z_{TC} axis and positive northward along the meridian plane containing the orbiter.

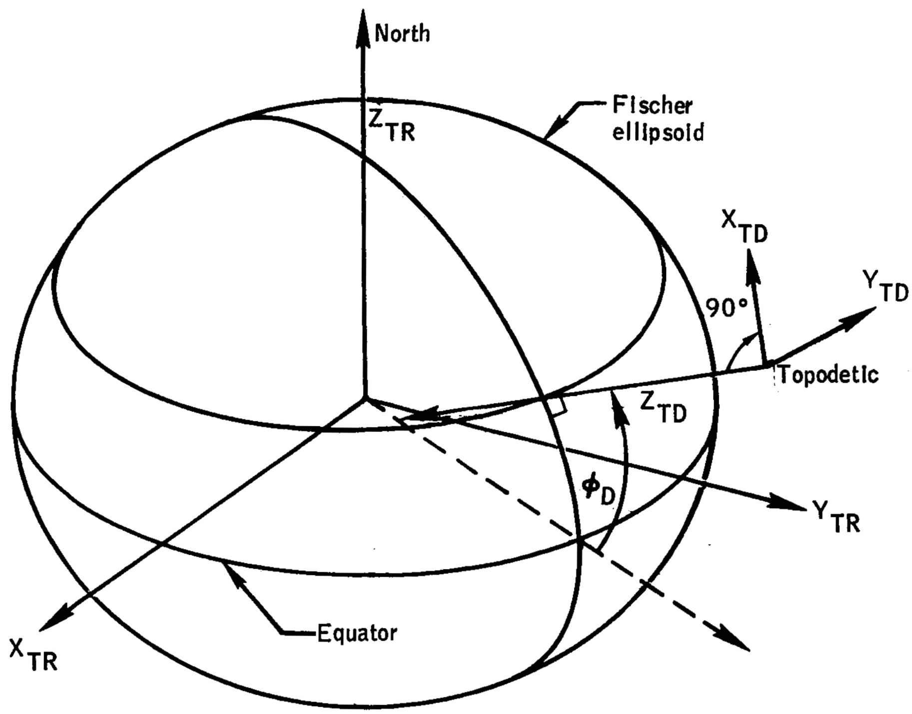
Y_{TC} completes right-handed orthogonal system.

α_{TR} is right ascension.

δ_{TR} is declination.

CHARACTERISTICS: Rotating, right-handed, Cartesian system. Velocity vectors are expressible in this system for the orbiter.

Figure 16.- Topocentric.



NAME: Topodetic coordinate system.

ORIGIN: Orbiter center of mass[a].

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 $\overline{V}_{TD}$ in this system.

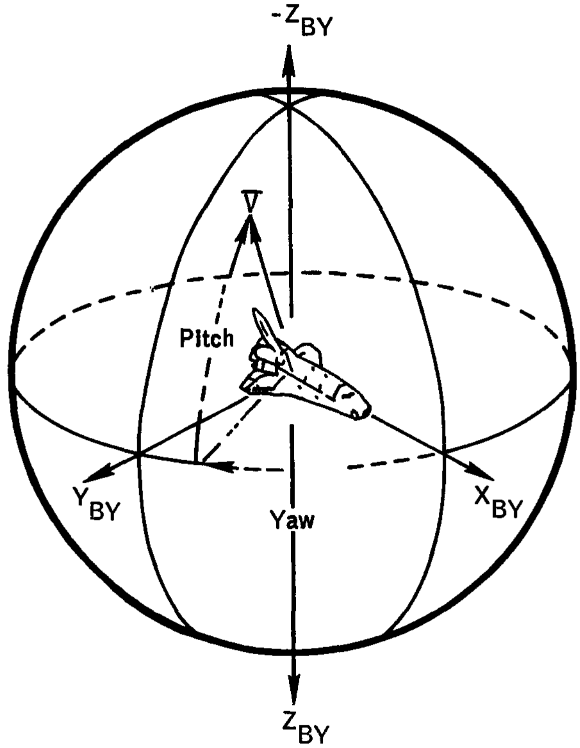
$$\gamma_{TD} = \sin^{-1}\left(\frac{-\dot{Z}_{TD}}{V_{TD}}\right)$$

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

ϕ_D = geodetic latitude [also see fig. 6(b)]

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

Figure 17.- Topodetic.



NAME: Look angle coordinate system.

(NOTE: The definition of this system is identical to the body axis system, but it is presented as a separate system to clarify a second class of uses.)

ORIGIN: Orbiter center of mass.

ORIENTATION: X_{BY} axis is in a plane parallel to the orbiter structural body axis (X_0), positive toward the nose.

Z_{BY} axis lies in a plane 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.

Look angles define a vector direction relative to the body axes of the vehicle. Since only direction is involved, the origin is translatable to any point on the body.

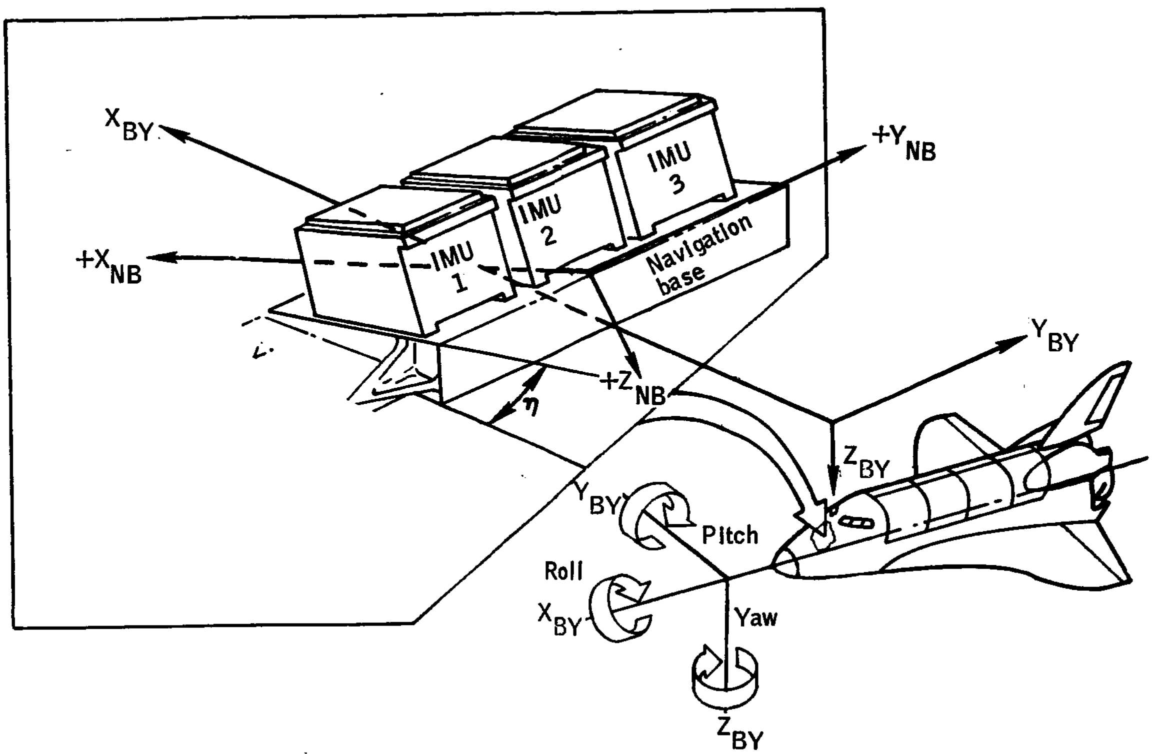
$\overline{V}$ is any vector line of sight.

Yaw is measured from the vehicle X_{BY} axis to the projection of $\overline{V}$ onto the X_{BY}, Y_{BY} plane. Yaw, from 0 to 360°, is a right-handed rotation about the Z_{BY} axis.

Figure 18.- Look angle.

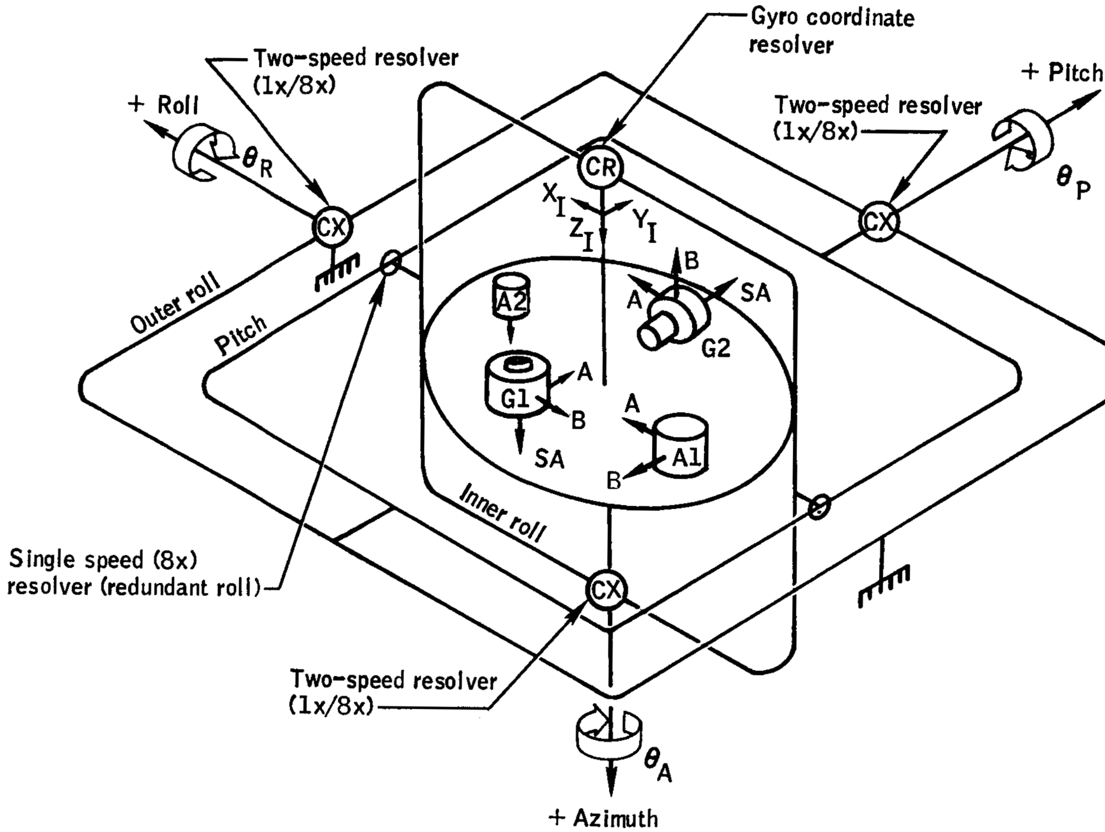
ORIENTATION: Concluded	Pitch is the angle between the vector $\overline{V}$ and its projection onto the X_{BY}, Y_{BY} plane. Pitch is formed by a right-handed rotation about the previously rotated Y_{BY} axis and is positive toward $-Z_{BY}$.
CHARACTERISTICS:	Rotating, right-handed, Cartesian system. Direction of celestial objects, ground stations, other orbiting vehicles, etc., from the orbiter can be reported in this system. A unit vector along X_{BY} will be made to coincide with $\overline{V}$ by rotating the vector through the yaw angle about the Z_{BY} axis, then through the pitch angle, about the Y'_{BY} axis, in that order. Y'_{BY} is the Y_{BY} location resulting from the first location. This coordinate system can be used as an instrument pointing coordinate system when the origin is translated to the instrument center location. A third rotation, analogous to body roll, is used to establish the instrument index referenced to the body coordinate system. This system may be used as a basic for defining orbiter-antenna radiation-distribution patterns.

Figure 18.- Look angle - concluded.



NAME:	Navigation base coordinate system.
ORIGIN:	The origin is TBD (probably on the upper surface of the navigation base in a plane parallel to the plane of symmetry of the orbiter).
ORIENTATION:	The X_{NB}, Y_{NB} plane is the upper surface of the navigation base.
	The X_{NB} axis lies in a plane parallel to the plane of symmetry of the orbiter and is positive forward.
	The Z_{NB} is perpendicular to the upper surface of the navigation base and is positive downward.
	The Y_{NB} axis completes the right-handed system.
	η is the angle between the mounted navigation base plane and the X_{BY}, Y_{BY} plane.
CHARACTERISTICS:	Rotating, right-handed, Cartesian.

Figure 19.- Navigation base.



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 IAs are parallel to the X_I axis.

The Y accelerometer and Y gyro IAs are parallel to the Y_I axis.

The Z accelerometer and Z gyro IAs are parallel to the Z_I axis.

Figure 20.- Inertial measurement unit 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.

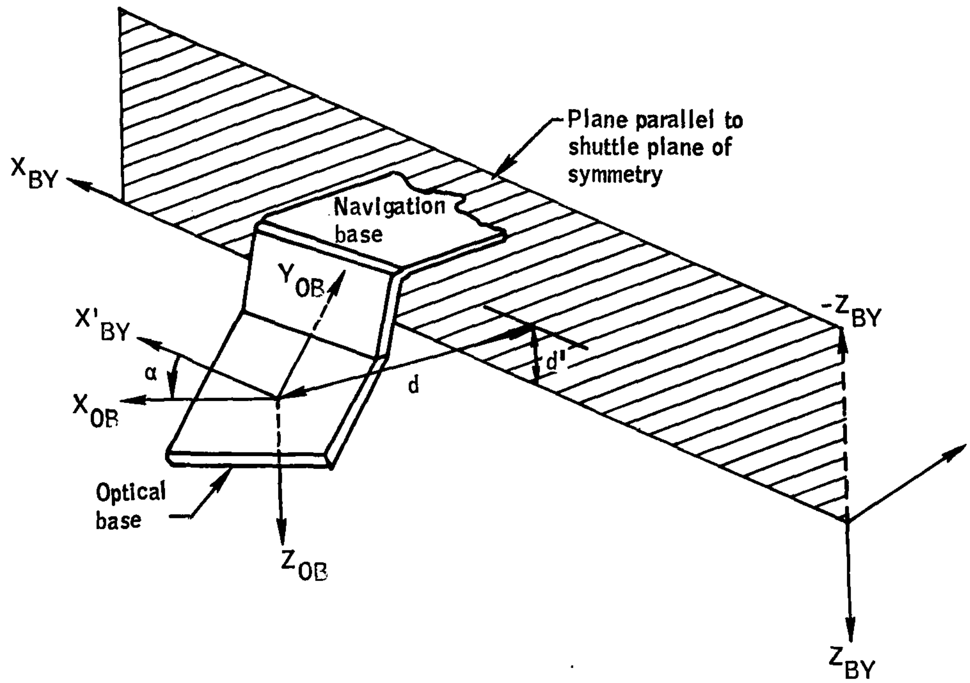
The outer roll axis and the X_I-axis will be parallel to X_{NB}. Positive X_I will be in the forward direction. Positive roll gimbal angles will be in the sense of a right-handed rotation of the gimbal case relative to the platform about the plus outer roll axis.

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 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.

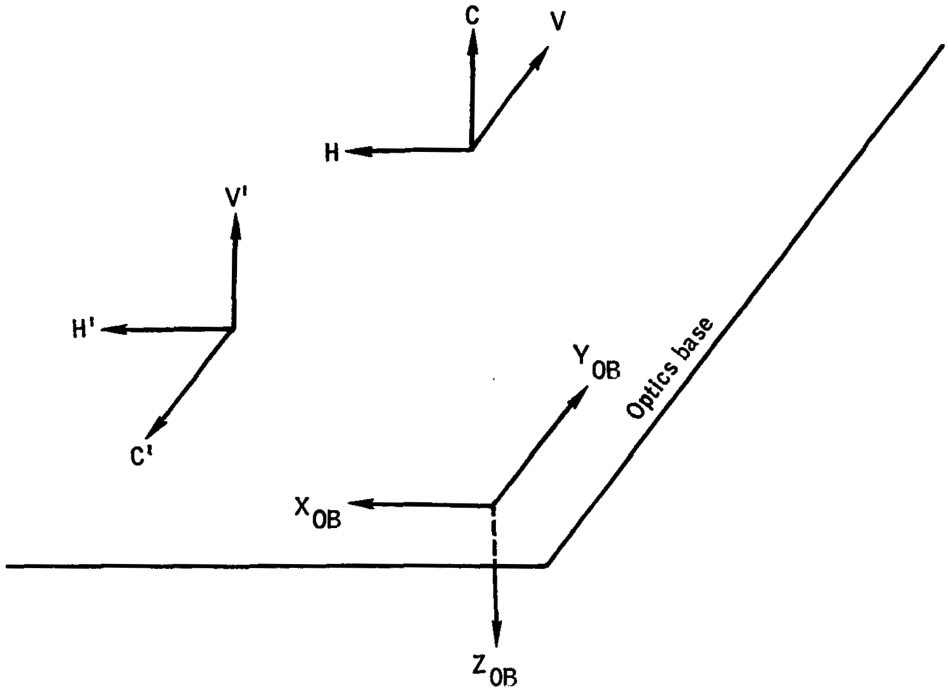
The azimuth axis and Z_I will be parallel to Z_{NB}. Positive Z_I will be down relative to an observer standing in the vehicle. Positive azimuth gimbal angles will be in the sense of a right-handed rotation of the gimbal case relative to the platform about the plus azimuth axis.

Figure 20.- Inertial measurement unit stable member - concluded.



NAME:	Optical base coordinate system.
ORIGIN:	On upper surface of optical base d units to pilot's left of the X_{BY}, Z_{BY} plane and d' units from the X_{BY}, Y_{BY} plane of the shuttle.
ORIENTATION:	The X_{OB}, Y_{OB} plane is the upper surface of the optical base. The Z_{OB} axis is perpendicular to the upper surface of the optical base (nominally parallel to the shuttle body axis Z_{BY}) and is positive downward. The X_{OB} axis is $\alpha°$ from the X_{BY}, Z_{BY} plane and the Y_{OB} axis completes the right-handed system.
	α is the angle displacement of X_{OB} axis from the X_{BY} axis.
	X'_{BY} is the X_{BY} axis displaced to the optical base coordinate system origin.
	d' is the perpendicular distance from optical base coordinate system origin to the X_{BY}, Y_{BY} plane.
	d is the perpendicular distance from the optical base coordinate system orgin to the X_{BY}, Z_{BY} plane (i.e., shuttle plane of symmetry).
CHARACTERISTICS:	Rotating, right-handed, Cartesian.

Figure 21.- Optical base.



NAME:	Star tracker optics coordinate system.
ORIGIN:	A point on the face of star tracker assembly.
ORIENTATION:	Star Trackers 1 and 2:

The C axis is parallel to the Z_{OB} axis and oppositely directed.

The V axis is parallel to the Y_{OB} axis and positive in same direction.

The H axis completes the CVH right-handed system.

Star Tracker 3:

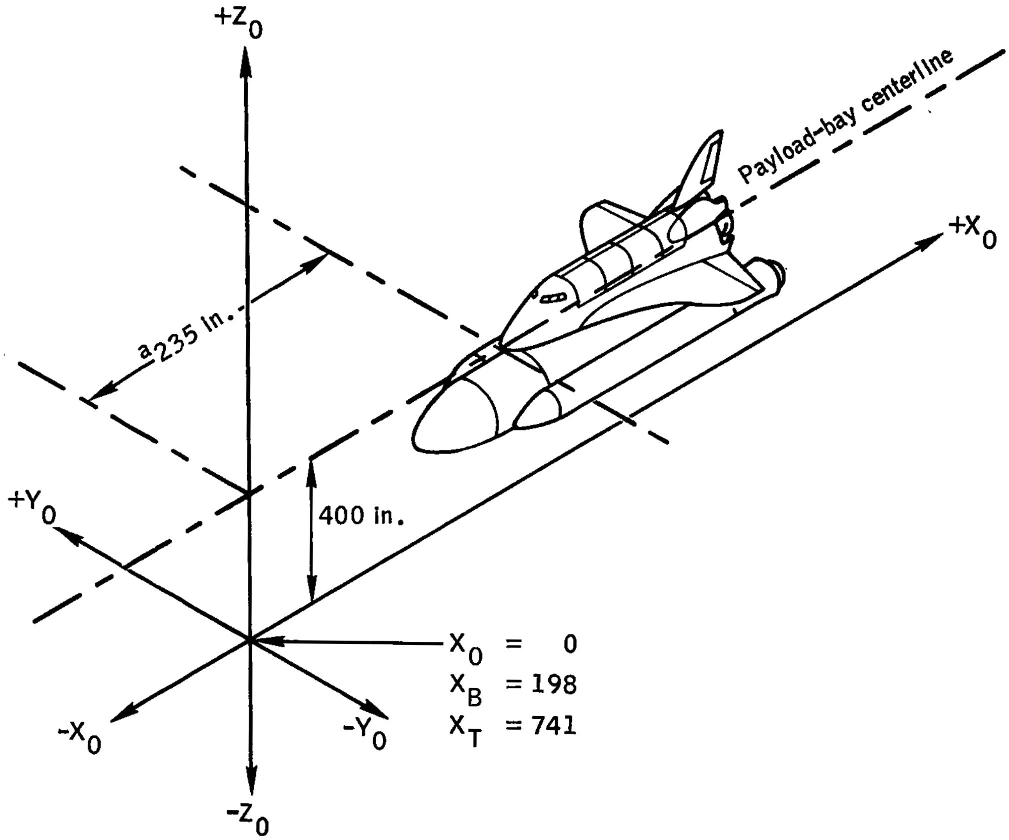
The C' axis is parallel to the Y_{OB} axis and oppositely directed.

The V' axis is parallel to the Z_{OB} axis and oppositely directed.

The H' axis completes the C'V'H' right-handed system.

CHARACTERISTICS: Rotating, right-handed, Cartesian.

Figure 22.- Star tracker optics.



NAME: Orbiter structural body coordinate system.

ORIGIN: In the orbiter plane of symmetry, 400 inches below the center line of the payload bay and 235 inches[a] forward of the tip of the orbiter nose fairing.

ORIENTATION: The X_0 axis is in the vehicle plane of symmetry, parallel to and 400 inches below the payload bay centerline. Positive sense is from the nose of the vehicle toward the tail.

The Z_0 axis is in the vehicle plane of symmetry, perpendicular to the X_0 axis. Positive upward in landing attitude.

The Y_0 axis completes a right-handed system.

CHARACTERISTICS: Rotating, right-handed, Cartesian.

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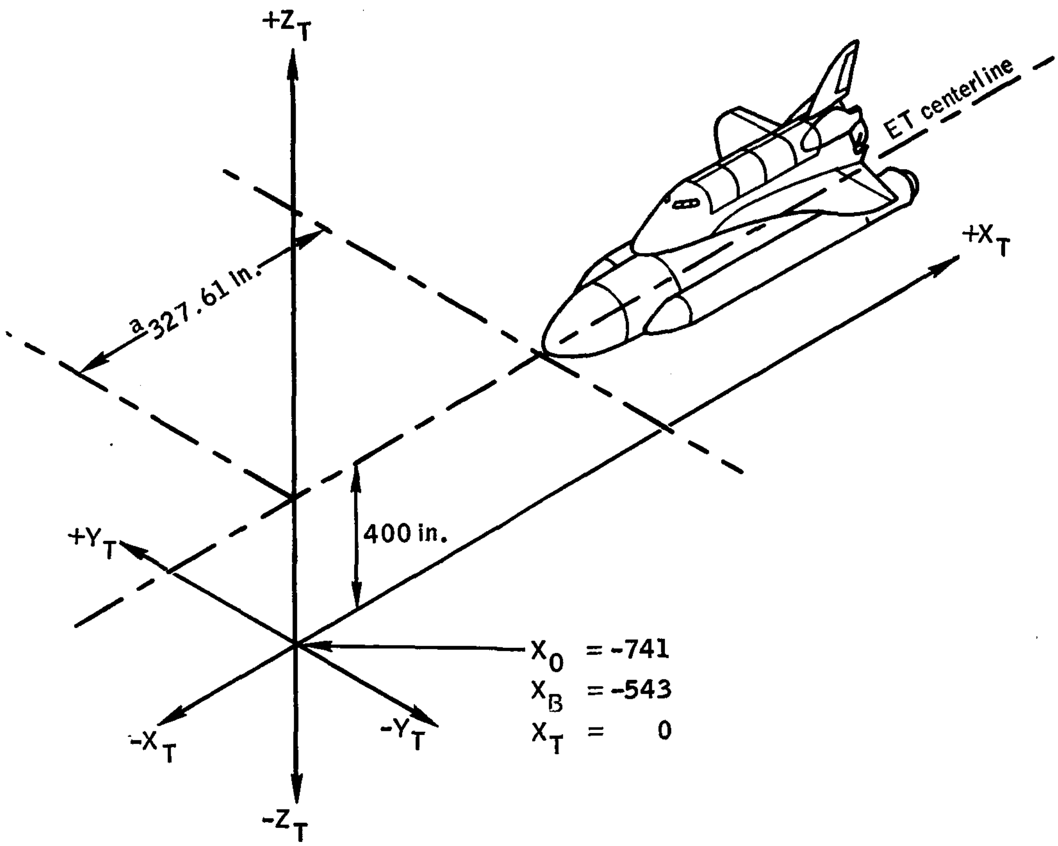
[a]This distance is valid as of October 8, 1974, but may require updating as the orbiter vehicle becomes better defined.

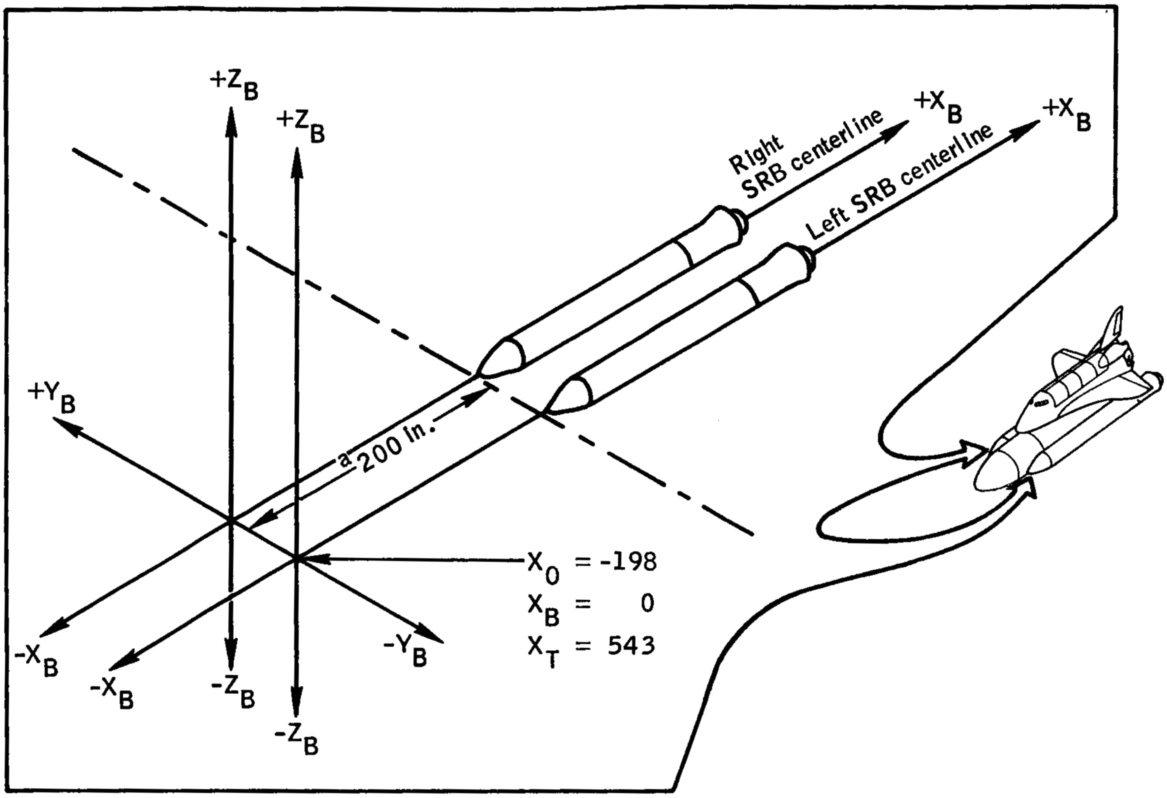
Figure 23.- Orbiter structural body.



NAME:	External tank (ET) or integrated vehicle structural body coordinate system.
ORIGIN:	In the integrated vehicle plane of symmetry, 400 inches below the centerline of the external tank in the integrated configuration and 327.61 inches[a] forward of the tip of the ET nose fairing.
ORIENTATION:	The X_T axis is in the integrated vehicle plane of symmetry, parallel to and 400 inches below the external tank centerline in the integrated configuration. Positive sense from the nose toward aft end of ET.
	The Z_T axis is in the integrated vehicle plane of symmetry, perpendicular to the X_T axis. Positive sense from ET toward orbiter when in integrated configuration.
	The Y_T axis completes a right-handed system.
CHARACTERISTICS:	Rotating, right-handed, Cartesian.

[a]This distance is valid as of October 8, 1974, but may require updating as the ET becomes better defined.

Figure 24.- External tank or integrated vehicle structural body.



NAME: Solid rocket booster (SRB) structural body coordinate system.

ORIGIN: Right SRB - On the right SRB center line 200 inches[a] forward of the tip of the SRB nose fairing.

Left SRB - On the left SRB center line 200 inches forward of the tip of the SRB nose fairing.

ORIENTATION: Right SRB - The X_B axis is coincident with the right SRB center line, with positive sense from the nose toward the tail of the vehicle.

The Z_B axis is parallel to the integrated vehicle plane of symmetry and perpendicular to X_B. Positive sense is from ET toward the orbiter when in the integrated configuration.

The Y_B axis completes a right-handed system.

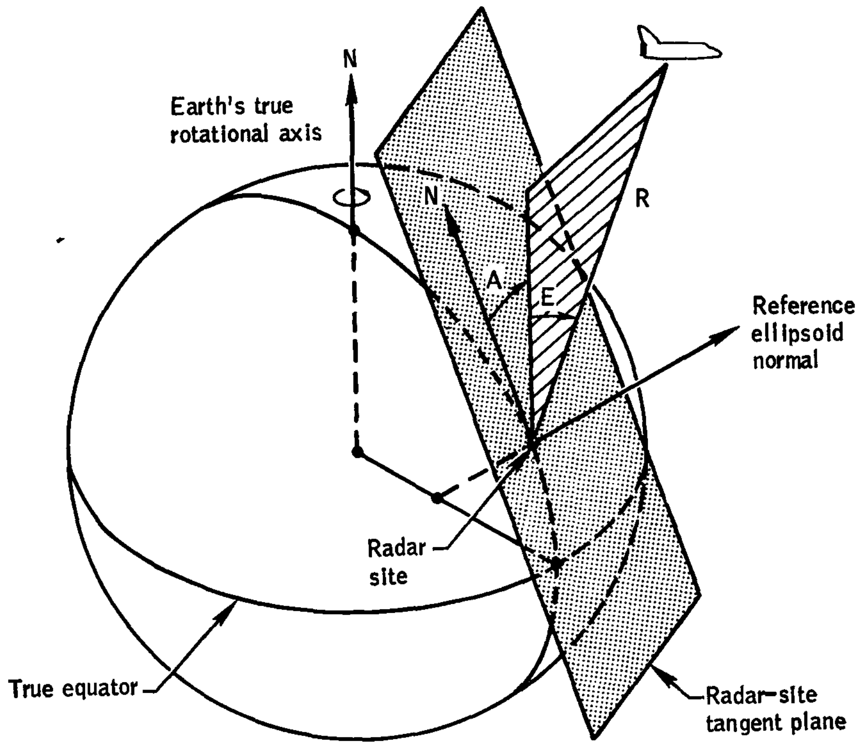
Left SRB - The X_B axis is coincident with the left SRB center line, with positive sense from the nose toward the tail of the vehicle.

Figure 25.- Solid rocket booster structural body.

ORIENTATION: (concluded)	The Z_B axis is parallel to the integrated vehicle plane of symmetry and perpendicular to the X_B axis. Positive sense is from ET toward the orbiter when in the integrated configuration.
	The Y_B axis completes a right-handed system.
CHARACTERISTICS:	Both systems are rotating, right-handed, Cartesian.

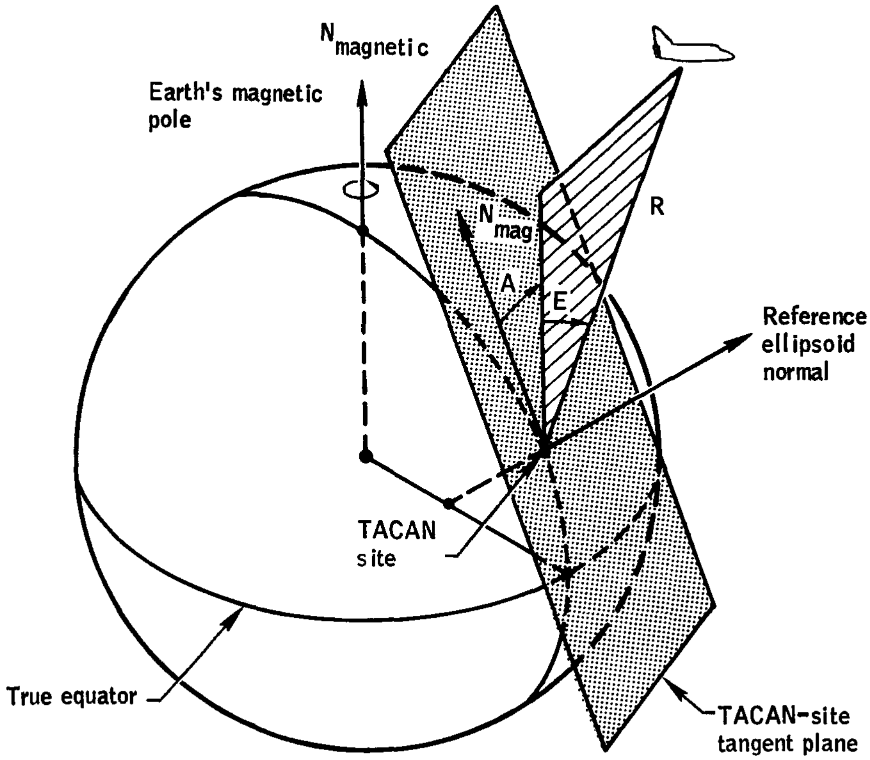
[a]This distance is valid as of October 8, 1974, but may require updating as the SRB becomes better defined.

Figure 25.- Solid rocket booster structural body - concluded.



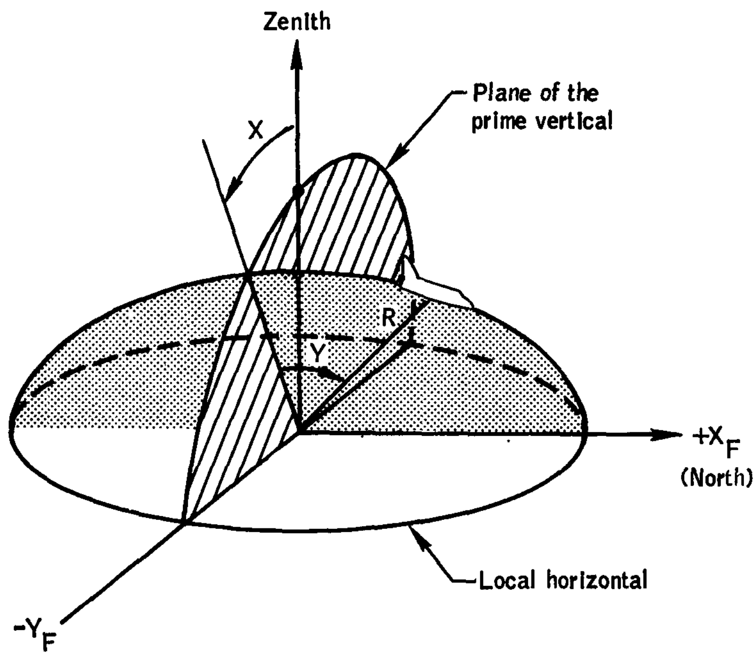
NAME:	Radar azimuth-elevation mount coordinate system.
ORIGIN:	The intersection of the radar axes.
ORIENTATION AND DEFINITIONS:	The radar-site tangent plane contains the site and is perpendicular to the reference ellipsoid normal which passes through the radar site. R is the slant range to the vehicle. A is the azimuth angle measured clockwise from true north to the projection of the slant range vector into the radar-site tangent plane. E is the elevation angle measured positive above the radar-site tangent plane to the slant range vector.
CHARACTERISTICS:	Rotating, Earth-referenced.

Figure 26.- Radar azimuth-elevation mount.



NAME:	Tactical air navigation (TACAN) coordinate system.
ORIGIN:	TACAN antenna
ORIENTATION AND DEFINITIONS:	The TACAN-site tangent plane contains the site and is perpendicular to the reference ellipsoid normal which passes through the TACAN site. R is the slant range to the vehicle. A is the azimuth angle measured clockwise from magnetic north to the projection of the slant range vector into the TACAN site tangent plane. E is the elevation angle measured positive above the TACAN site tangent plane to the slant range vector.
CHARACTERISTICS:	Elevation is not transmitted by TACAN. The TACAN azimuth of the earth's true North Pole is minus variation and is a geographic station constant (true bearing - variation = magnetic bearing). The TACAN is fixed to the Earth and is therefore a rotating system.

Figure 27.- Tactical air navigation.



NAME:	Radar X-Y mount 30-ft dish coordinate system.
ORIGIN:	At the intersection of the X_F axis and the plane of the Y_F axis gear.
ORIENTATION AND DEFINITIONS:	R is the slant range from the radar site to the vehicle.

The X_F axis lies along the intersection of the horizontal plane and the meridian plane at the radar site. The Y_F axis is perpendicular to the X_F axis.

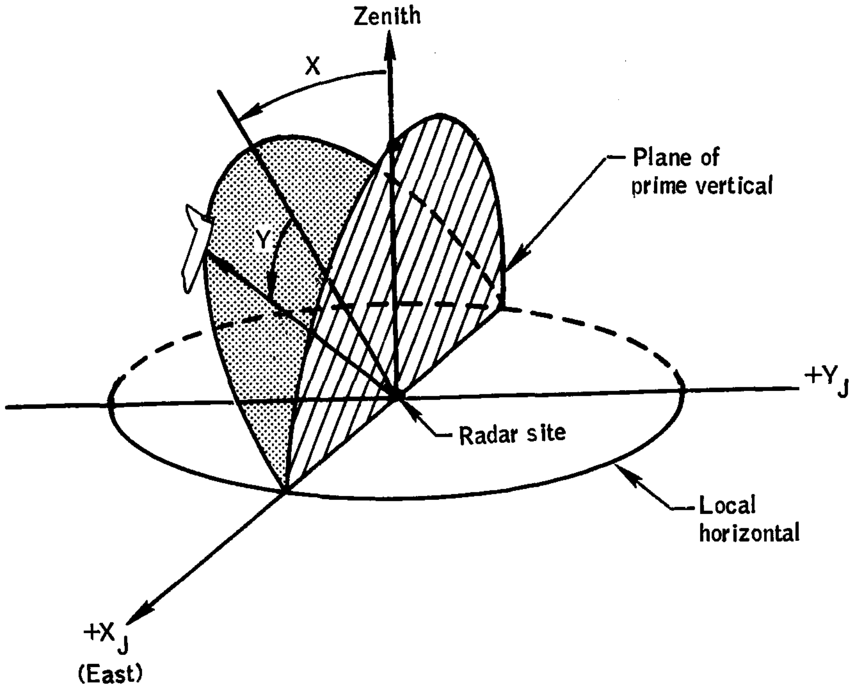
X is the angle measured in the plane of the radar site prime vertical from the zenith to the projection of the slant range vector onto this plane, positive eastward.

Y is the angle between the slant range vector and its projection onto the plane of the radar site prime vertical, positive when the slant range vector is north of the plane and negative when it is south of it.

(When the radar antenna is directed toward the zenith, the X and Y angles are zero and the Y_F axis is perpendicular to the radar site meridian plane).

CHARACTERISTICS: Rotating, polar coordinates.

Figure 28.- Radar X-Y mount, 30-ft dish.



NAME: Radar X-Y mount, 85-ft dish coordinate system.

ORIGIN: At the intersection of the X_J axis and the plane of the Y_J axis gear.

ORIENTATION AND DEFINITIONS: R is the slant range from the radar site to the vehicle.

The X_J axis lies along the intersection of the horizontal plane and the plane of the prime vertical at the radar site. The Y_J axis is perpendicular to the X_J axis.

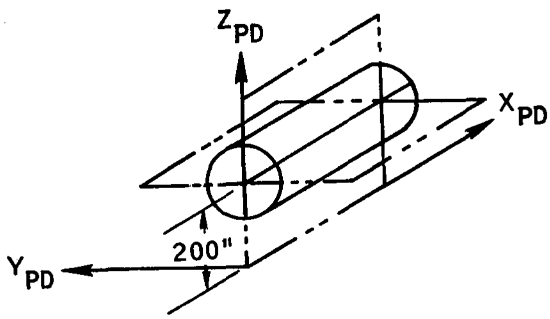
X is the angle measure in the meridian plane of the radar site from the zenith to the projection of the slant range vector onto this plane, positive southward.

Y is the angle between the slant range vector and its projection onto the meridian plane of the radar site, positive when the slant range vector is east of the meridian plane and negative when it is west of it.

(When the radar antenna is directed toward the zenith, the X and Y angles are zero and the Y_J axis is perpendicular to the radar site prime vertical plane.)

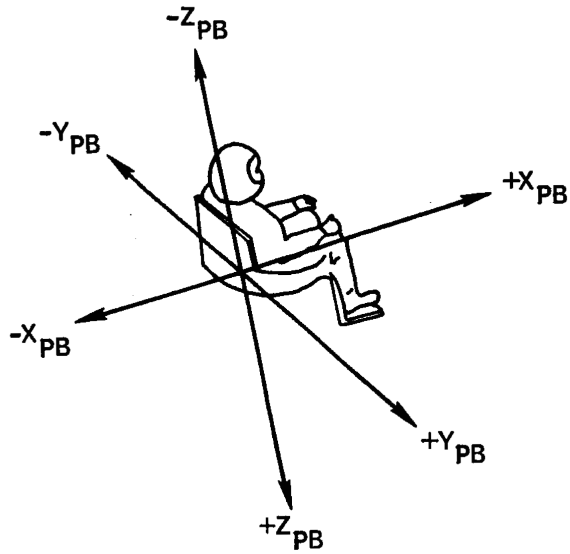
CHARACTERISTICS: Rotating, polar coordinates.

Figure 29.- Radar X-Y mount, 85-ft dish.



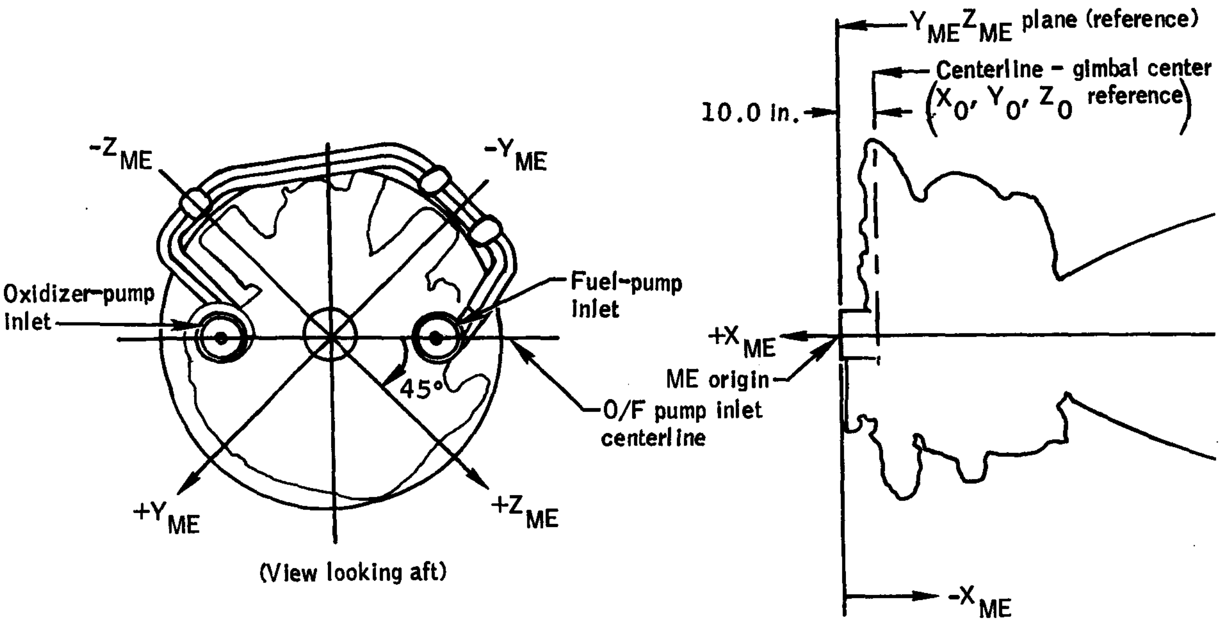
NAME:	Payload reference coordinate system.
ORIGIN:	200 inches below the payload centerline at the forward end of the payload.
ORIENTATION:	The X_{PD} axis is parallel to the orbiter payload-bay centerline and positive toward the tail of orbiter. The Z_{PD} axis is parallel to the orbiter plane of symmetry and is positive upward in the orbiter landed position. The Y_{PD} axis completes the right-handed system.
CHARACTERISTICS:	Right-handed, Cartesian.

Figure 30.- Payload reference.



NAME:	Pilot-body-fixed coordinate system.
ORIGIN:	Pilot center of mass.
ORIENTATION:	$+X_{PB}$ is forward, $+Y_{PB}$ is to the pilot's right, and $+Z_{PB}$ is down.
CHARACTERISTICS:	Rotating, right-handed, Cartesian.

Figure 31.- Pilot-body-fixed.



NAME:	Space shuttle main engine (SSME) structural body coordinate system.
ORIGIN:	The intersection of the engine geometric centerline and the Y_{ME}, Z_{ME} interface plane formed by the orbiter/SSME mounting surface, which is perpendicular to the engine geometric centerline (X_{ME}) and is located 10 inches forward of the engine gimbal center.
ORIENTATION:	Vehicle mounted SSME X_{ME}, Y_{ME}, Z_{ME} axes orientation relative to orbiter X_0, Y_0, Z_0 axes is as follows:

Engine no. 1 (top engine)

X_{ME} axis is canted at an angle of 16° in a pitch-up position with respect to orbiter X_0 axis.

Y_{ME} and Z_{ME} axes are in the same plane of symmetry as the orbiter Y_0 and Z_0 axes.

Engine no. 2 (lower left, looking forward)

X_{ME} axis is canted at an angle of 10° in a pitch-up position and 3.5° yaw outboard position with respect to orbiter X_0 axis.

Y_{ME} and Z_{ME} axes are rotated 90° counterclockwise with respect to the Y_0, Z_0 plane of symmetry.

(a) Basic definition.

Figure 32.- Space shuttle main engine structural body.

ORIENTATION (Concluded): Engine no. 3 (lower right, looking forward)

X_{ME} axis canted at an angle of 10° in a pitch-up position and 3.5° yaw outboard position with respect to orbiter X_0 axis.

Y_{ME} and Z_{ME} axes are in the same plane of symmetry as the orbiter Y_0 and Z_0 axes.

SSME gimbal center locations relative to the orbiter s structural body coordinates are:

Engine no. 1 $X_0 = 1445$

$Y_0 = 0$

$Z_0 = 443$

Engine no. 2 $X_0 = 1468.17$

$Y_0 = -53.0$

$Z_0 = 342.64$

Engine no. 3 $X_0 = 1468.17$

$Y_0 = +53.0$

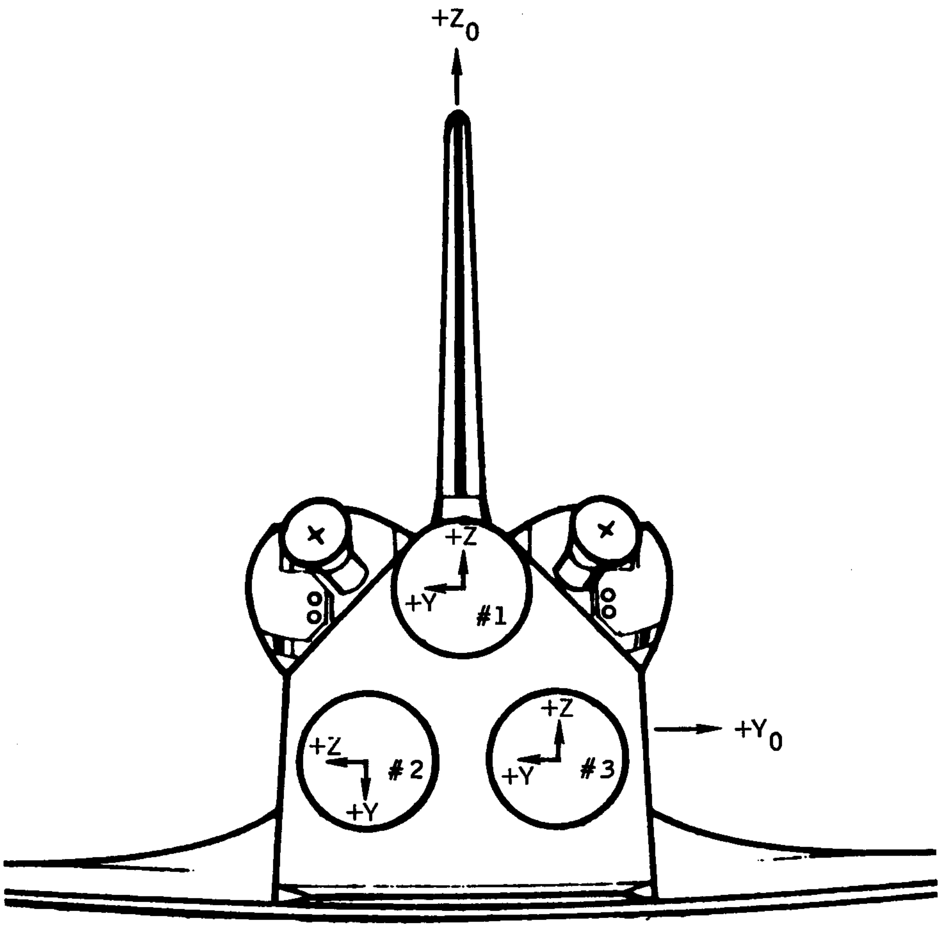
$Z_0 = 342.64$

Note: The relationship of the uncanted SSME to the orbiter is shown in figure 32(b).

CHARACTERISTICS: Rotating, right-handed, Cartesian.

(a) Basic definition - concluded.

Figure 32.- Space shuttle main engine structural body - continued.



(b) Systems shown uncanted for clarity (view looking forward).

Figure 32.- Space shuttle main engine structural body - concluded.

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