National Aeronautics and
Space Administration

CxP 70138

REV A

RELEASE DATE: TBD

CONSTELLATION PROGRAM
LEVEL 2 COORDINATE SYSTEMS

REVISION AND HISTORY PAGE

Status	Revision No.	Change No.	Description	Release Date
Baseline	-		Baseline (Reference CxCBD 000142/1-1, dated 9/6/07)	09/25/07
Revision	001		Rev. A – Various updates and new material including: ALTAIR and ARES I Body/GNC Coordinate Systems, Euler Sequence and Quaternion Standards, Summary Vehicle Body/GNC/Structural Coordinate System Table, and Summary Body/GNC Mated Configuration Coordinate System Tables	TBD

NOTE: Updates to this document, as released by numbered changes (Change XXX), are identified by a black bar on the right margin.

TABLE OF CONTENTS

PARAGRAPH **PAGE**

APPENDIX

TABLE

FIGURE

1.0 INTRODUCTION

This document defines the coordinate systems, Euler Sequences, and Quaternions standards used in inter-element information exchange across the Constellation Program.

The coordinate systems are defined by the appropriate project or Systems Integration Group (SIG). The defining organization for each coordinate system is identified in the description of the coordinate system in this document, as the "Owner Organization." The coordinate systems in this document are configuration-controlled at Level 2 by the Constellation Analysis Working Group. Any changes to the coordinate systems in this document, additions of new frames to this document, or deletions of frames from this document require approval of the Analysis Working Group.

1.1 PURPOSE

The purpose of this document is to ensure consistency and compatibility in inter-element and inter-SIG analyses and communication.

1.2 SCOPE

All pertinent geometric technical data that are exchanged between Constellation Level 3 Projects and Systems Integration Groups (SIGs) shall be in the coordinate systems described in this document. Level 3 Projects and SIGs may use coordinate systems that are not in this document for internal (intra-Project, intra-SIG) communication and analysis. Interface agreements between organizations will specify which of these coordinate systems are used to exchange information.

1.3 CHANGE AUTHORITY

Proposed changes to this document shall be submitted by a Constellation Program Change Request (CR) to the appropriate Constellation Control Board for consideration and disposition.

All such requests will adhere to the Constellation Program Configuration Management Change Process.

The appropriate NASA Office of Primary Responsibility (OPR) identified for this document is the Level 2 System Engineering and Integration Office in the Constellation Program Office.

2.0 TRAJECTORY COORDINATE SYSTEMS

This section contains a description of the coordinate systems that should be used to convey or communicate vehicle states between elements of the Constellation Program. The first portion of the text is a brief review of the relevant nomenclature and how some of the basic terms will be used or interpreted in this section.

Coordinate System Attributes

The primary attributes of any coordinate system are the coordinate frame or orientation of the axes of the coordinate system and the coordinate center or origin of the coordinate system.

The coordinate center is the easier of the two attributes to define and in trajectory-related coordinate systems is often taken to be the center of mass of natural solar system bodies such as the Earth, the Moon, or Mars. Precise definition of the coordinate frame, however, usually takes much more effort. As a result, the primary purpose of this section is to provide a detailed description of a number of different coordinate frames commonly used in lunar and Mars mission analysis. All of the coordinate frames described in this section are standard, right-handed coordinate frames with orthogonal axes at the origin.

In general, the coordinate frame and the coordinate center are independent quantities. In other words, multiple coordinate systems can be defined using the same coordinate center (with different frames) or the same coordinate frame (with different centers). In order to simplify interfaces within the Constellation Program, an attempt has been made to minimize the number of coordinate systems used for inter-element communication. There are, however, a few instances in this document in which multiple coordinate centers are specified for the same coordinate frame. In these cases, each of the different coordinate systems is considered important.

In general, the coordinate systems described in this section are organized by coordinate frame with similar coordinate frames being grouped together.

Realizations and Relationships

The definitions of the coordinate systems given here are conceptually useful but theoretical. A coordinate system can only be useful in a practical way if it is tied to observations of real, physical objects and its relationship to other coordinate systems is known. The tie between the coordinate system and the physical universe is called a realization and in some sense is its “real” definition.

For example, the International Celestial Reference System (ICRF) is defined by IAU resolution in terms of where the Earth’s mean equator was at a particular epoch, but it is “really” defined by having ICRF coordinates for the locations of a selection of quasars and other distant bright radio objects. Then the ICRF becomes realized as “the coordinate system in which the defining objects have the given coordinates.”

Inertial vs. Non-Rotating

In a strict sense, the word “inertial”, when used to describe a coordinate system, means that that coordinate system is unaccelerated. Thus, the only truly unaccelerated coordinate system in our solar system is a non-rotating coordinate frame centered at the solar system barycenter. The common usage of the word “inertial”, however, when applied to a coordinate system, usually only refers to the attributes of the coordinate frame, not the coordinate system (i.e. the coordinate center and coordinate frame). Thus, while technically incorrect, if the axes of the coordinate frame are non-rotating (i.e. the axes point in directions that are inertially fixed in space), the coordinate system as a whole is often referred to as an “inertial coordinate system”.

For this reason, while slightly compromising on technical accuracy, but following the conventions used by most readers, this section will use the same terminology to describe the coordinate frame and coordinate system. For example, non-rotating coordinate frames, wherever they are centered, will be referred to as non-rotating/”inertial” (with the word inertial in quotes) coordinate frames and coordinate systems.

Rotating vs. Non-Rotating

All of the coordinate frames described in this section are, by necessity, either rotating or non-rotating coordinate frames. The non-rotating (or “inertial”) coordinate frames are defined by taking a “snapshot” of the orientation of a particular set of right-handed, orthogonal axes at a specific epoch or time. In other words, the non-rotating coordinate frame, however it is defined, is frozen or fixed at a specific time - for all time. These non-rotating coordinate frames are referred to as “of Epoch” coordinate frames.

For rotating coordinate frames, the same concept of a “snapshot” taken at a specific time is used to define the orientation of a set of axes, but in this case the frame rotates about the instantaneous spin axis of the coordinate frame at a rate consistent with the definition of the rotating frame. Thus, at any time specified by the user, the orientation of the frame, orientation of the spin axis, and rotation rate of the frame are re-evaluated. The rotating coordinate frames are referred to as “Body-fixed” or “Rotating” - depending on the particular coordinate frame.

Vehicle State vs. Vehicle Attitude

In this section, the term “vehicle state” generally refers to the position and velocity or orbital state of a vehicle expressed relative to some natural body. Some of the coordinate systems (or coordinate frames) described in this section are, however, also useful for conveying vehicle attitude and instrument or sensor pointing information. In a few instances, the coordinate center or origin of the coordinate system is taken to be the vehicle center of mass.

It's important to note that while this document specifies the coordinate systems to be used to convey vehicle state and vehicle attitude information between elements of the Constellation Program, it does not specify what type of representation of the vehicle state (e.g., Cartesian position and velocity or orbital elements - including a reference epoch) or vehicle attitude must be used.

Summary of Trajectory Coordinate Systems

The following table indicates the trajectory-related coordinate systems described in this document and recommended for inter-element communication within the Constellation Program.

TABLE 2.0-1 TRAJECTORY COORDINATE SYSTEMS

Section	Coordinate Center	Coordinate Frame	Frame Type
2.1	**Earth Coordinate Systems**		
2.1.1	Earth-Centered Sun-Centered Vehicle-Centered	International Celestial Reference Frame	Non-Rotating "Inertial"
2.1.2	Earth-Centered	International Terrestrial Reference Frame	Rotating
2.1.3	Earth-Centered	Earth True Equator and Prime Meridian of Epoch	NR/"Inertial"
2.1.4	Earth-Centered	Earth Mean Equator and Prime Meridian	Rotating
2.2	**Lunar Coordinate Systems**		
2.2.1	Moon Centered	Lunar Principal Axis of Epoch	NR/"Inertial"
2.2.2	Moon Centered	Lunar Principal Axis Body-Fixed	Rotating
2.2.3	Moon Centered	Lunar Mean Earth Body-Fixed	Rotating
2.3	**Three-Body Rotating Coordinate Systems**		
2.3.1	Sun-Centered Earth-Centered	Sun-Earth Rotating	Rotating
2.3.2	Earth-Centered Moon Centered	Earth-Moon Rotating	Rotating
2.4	**Mars Coordinate Systems**		
2.4.1	Mars-Centered	Mars Mean Equator and IAU-Node of Epoch	NR/"Inertial"
2.4.2	Mars-Centered	Mars Mean Equator and Prime Meridian Body-Fixed	Rotating
2.5	**Local Vertical Local Horizontal Coordinate Systems**		
2.5.1	Vehicle-Centered	Local Vertical Local Horizontal	Rotating
2.5.2	Vehicle-Centered	Local Vertical Curvilinear	Rotating

NOTE: NR = Non-Rotating

The material presented in this section was based heavily on the information provided in Reference 1.

2.1 EARTH COORDINATE SYSTEMS

2.1.1 International Celestial Reference Frame (ICRF)

Also Known As: Earth Mean Equator and Equinox of J2000 (EME2000)

Owner Organization: Flight Performance SIG

Coordinate Frame: Non-Rotating/“Inertial”

Z-axis: Defined as the pole vector of the Earth Mean Equator of J2000 (where J2000 = Julian date 2451545.0 TDB (Barycentric Dynamical Time)).

X-axis: Defined as the cross product of the Z-axis (as defined above) and the Earth mean orbit pole of J2000 (i.e. the ecliptic pole of J2000). The X-axis of this coordinate frame is the Earth vernal equinox of J2000.

Y-axis: Completes a standard, right-handed coordinate frame.

Realization: The International Celestial Reference Frame (ICRF) was defined in 1995 with locations given for 22 quasars and other bright radio objects. This definition was extended by the addition of more sources in 2000. See Reference 8 for further information.

Relationships: The ICRF is the best-determined and most stable reference frame and is the “root” frame—other reference frames are often given with respect to the ICRF.

Coordinate Systems: **Earth-Centered, ICRF**
Sun-Centered, ICRF
Solar-System-Barycentered, ICRF (used for ephemerides)
Vehicle-Centered, ICRF *(used only for vehicle attitude)*

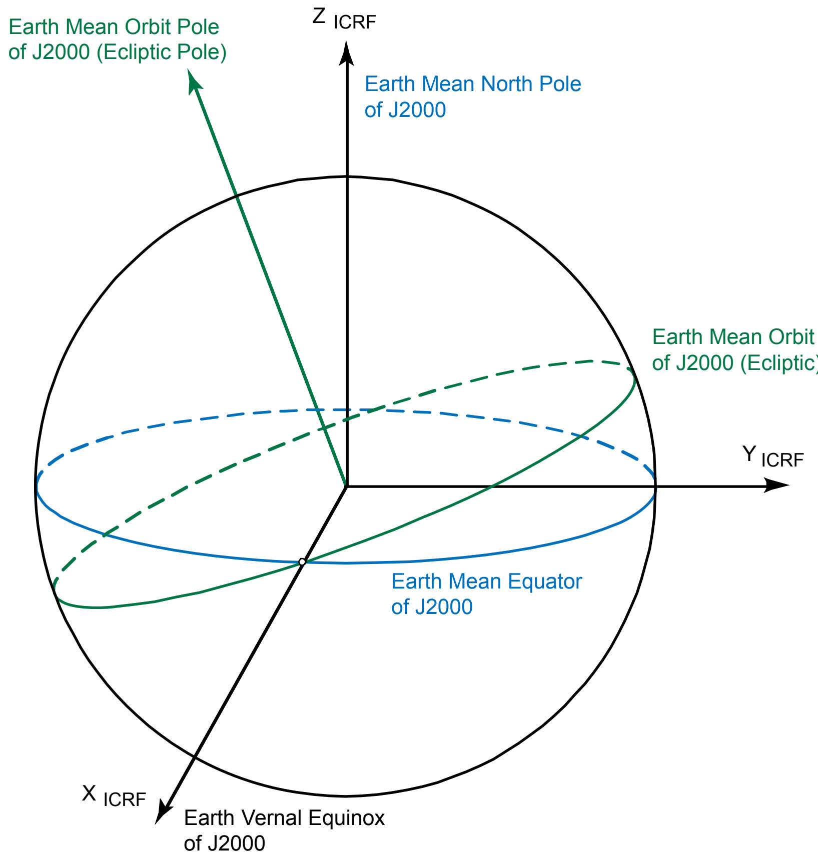


FIGURE 2.1.1-1 COORDINATE FRAME: INTERNATIONAL CELESTIAL REFERENCE FRAME (ICRF)

Also known as Earth Mean Equator and Equinox of J2000 (EME2000)

(Non-Rotating/“Inertial”)

NOTE: The vehicle-centered, EME2000 coordinate system is useful for vehicle attitude determination since the positions of stars in star catalogs used with star trackers and other celestial sensors are generally expressed in the EME2000 coordinate frame. However, caution must be exercised here since the EME2000 frames realized in the past by various star catalogs (such as FK5) and ephemerides (such as DE205) were actually slightly different frames because estimates of the actual location EME2000 changed with improvements in models and new data. For this reason the ICRF is the recommended standard.

NOTE: The celestial reference frame used in the development of the JPL-generated planetary ephemerides since DE400 is the International Celestial Reference Frame (ICRF) maintained by the International Earth Rotation and Reference Systems Service (IERS), which we have here identified as the recommended realization of the EME2000 frame; this identification is consistent with the definition of ICRS adopted by the IAU General Assembly in 1997. It should be noted, however, that our knowledge of the "actual" Earth Mean Equator depends on observations which are not exact and which then are analyzed using models which continue to be improved, so our understanding of where the "real" Earth Mean Equator and vernal equinox were in J2000 changes with time. Reference 2, for example, indicates that the pole of the mean Earth at J2000 differs from the ICRF pole by ~18 milliarcseconds (mas) and the right ascension of the vernal equinox at J2000 differs from the right ascension of ICRF X-axis by 78 mas, whereas Reference 8, paragraph 2.1.2, reports that analysis of lunar laser ranging observations has found a 55 mas difference between the vernal equinox of J2000 and the ICRF X-axis.

2.1.2 International Terrestrial Reference Frame (ITRF)

Also Known As: Earth True Equator and Prime Meridian Body Fixed

Owner Organization: Flight Performance SIG

Coordinate Frame: Rotating

Z-axis: The rotation pole of the Earth.

X-axis: The intersection of the prime meridian and the rotation equator of the Earth.

Y-axis: Completes a standard, right-handed coordinate frame.

Realization: The International Terrestrial Reference Frame (ITRF) is realized by the locations of a set of points or stations on a tide-free Earth. As measurements and models have improved or changed, these locations have been changed also and the ITRF has moved slightly with respect to the physical Earth every few years; ITRF93 is recommended [TBR] (see Note below).

Relationships: At current levels of accuracy and precision the location of the ITRF at any point in time with respect to the ICRF (see 2.1.1 above) cannot be predicted because the Earth (and its weather!) are not modeled that accurately. The location of the true pole depends on modeling precession and nutation and then measuring the actual rotation pole relative to the modeled pole with respect to both the ITRF and the ICRF. One can use either the NASA Deep Space Network's models and file of pole locations, which also includes timing information to tell where the prime meridian was **OR** one can use the IERS models and file of pole locations and timing called the Earth Orientation Parameters (EOP) file **BUT NOT BOTH**, e.g., do not use the IERS EOP with the DSN models for precession and nutation. The IERS information is more publicly available and is recommended. See Reference 8 for more information, including the relationships between the various ITRF frames.

Coordinate Systems: Earth-Centered, ITRF

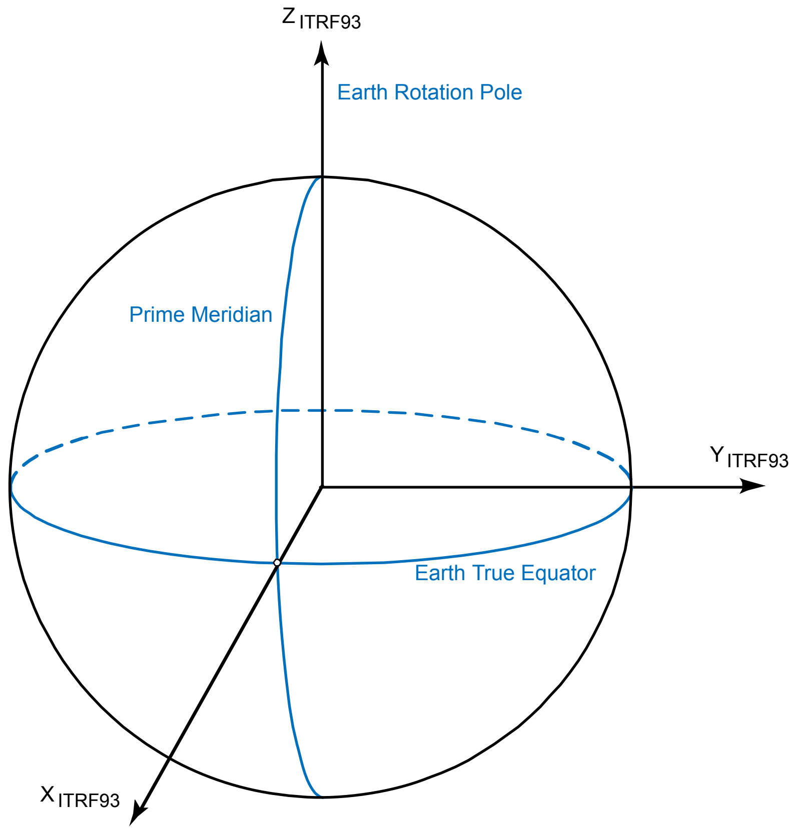


FIGURE 2.1.2-1 COORDINATE FRAME: INTERNATIONAL TERRESTRIAL REFERENCE FRAME (ITRF)

Also known as Earth True Equator and Prime Meridian Body Fixed

(Rotating)

NOTE: ITRF93 is the reference frame used for station locations by NASA's Deep Space Network. It is formally defined by the positions given in the ITRF for selected locations on the Earth with conventional tide-free correction. Ten different ITRFs have been defined through ITRF2000, beginning with ITRF88, with changes in the length scale caused by time scale changes between Terrestrial Time (TT) and Geocentric Coordinate Time (TCG) and back again, and different precession and nutation models. Since 1992 the differences between these frames have been less than a few centimeters (see Table 4.1 in Reference 8). The position of the actual rotation pole of the Earth varies unpredictably and can be on the order of meters away from the ITRF93 Z-axis; this position is tracked by the International Earth Rotation and Reference Systems Service (IERS) and reported in the Earth Orientation Parameters (EOP) file.

2.1.3 Earth True Equator and Prime Meridian of Epoch

Owner Organization: Flight Performance SIG

Coordinate Frame: Non-Rotating/“Inertial”

Z-axis: The rotation pole of the Earth, in the ICRF and at the epoch given.

X-axis: The intersection of the prime meridian and the rotation equator of the Earth, in the ICRF and at the epoch given.

Y-axis: Completes a standard, right-handed coordinate frame.

Realization: The International Terrestrial Reference Frame as defined for 1993 (ITRF93), as located in the ICRF at the epoch given using a consistent set of precession, nutation, and timing and polar motion models. (See 2.1.2 above.)

Relationships: See 2.1.2 above. This frame is useful as an intermediate frame in relating a launch frame (fixed at an epoch near launch time) to the ICRF.

Coordinate Systems: **Earth-Centered**

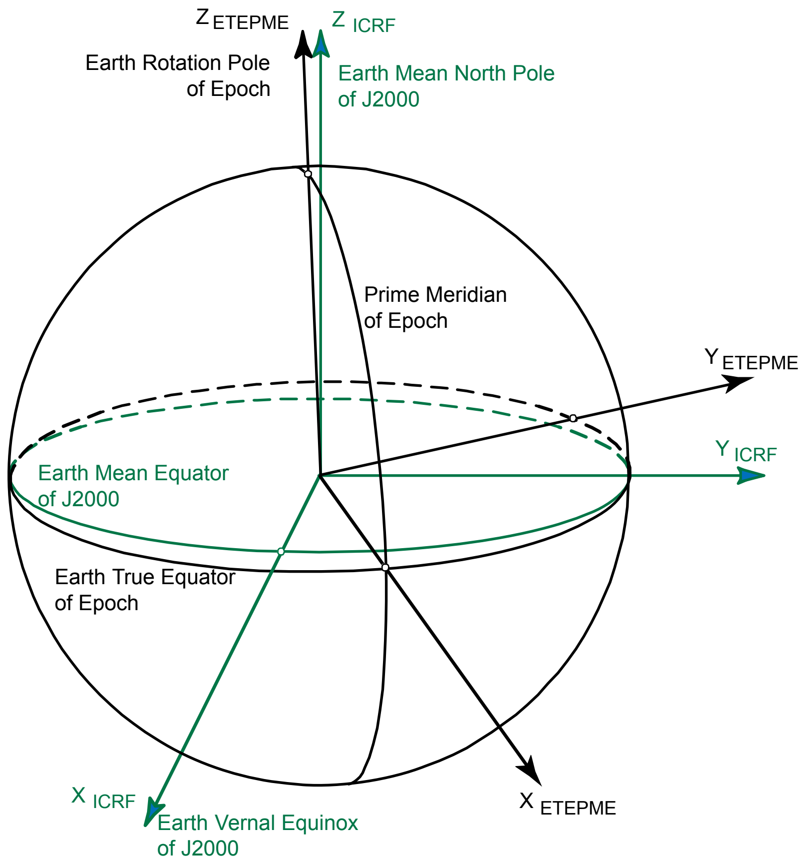


FIGURE 2.1.3-1 COORDINATE FRAME: EARTH TRUE EQUATOR AND PRIME MERIDIAN OF EPOCH (ETEPME)

(Note that the difference between the Mean Equator of J2000 and the True Equator of Epoch is greatly exaggerated.)

(Non-Rotating/“Inertial”)

NOTE: The relationship between ITRF and ICRS is discussed extensively in Reference 8. Different models of this relationship are used. The NASA Deep Space Network uses the Lieske precession model (1976) and the corresponding nutation model is realized by nutations provided on DE405; the corresponding timing and polar motion data as measured for times past are maintained in internal files at the Jet Propulsion Laboratory. The IERS has proposed use of more recent precession (two flavors available) and nutation models and publishes timing and polar motion data for times past in its Earth Orientation Parameters (EOP) file available at http://www.iers.org. Either algorithm should be sufficiently accurate and it should be stated which is being used. However, the data and models must not be mixed. Do not, for example, use IERS EOP data with the Lieske precession model and DE405 nutations.

2.1.4 Earth Mean Equator and Prime Meridian

Owner Organization: Flight Performance SIG

Coordinate Frame: Rotating

Z-axis: The mean rotation pole of the Earth, in the ICRF and as a function of time.

X-axis: The intersection of the prime meridian and the rotation equator of the Earth, in the ICRF and as a function of time.

Y-axis: Completes a standard, right-handed coordinate frame.

Realization and Relationships: This frame is realized from the ICRF, precessed and rotated according to the formulae in IAU2000, Reference 5.

Coordinate Systems: **Earth-Centered**

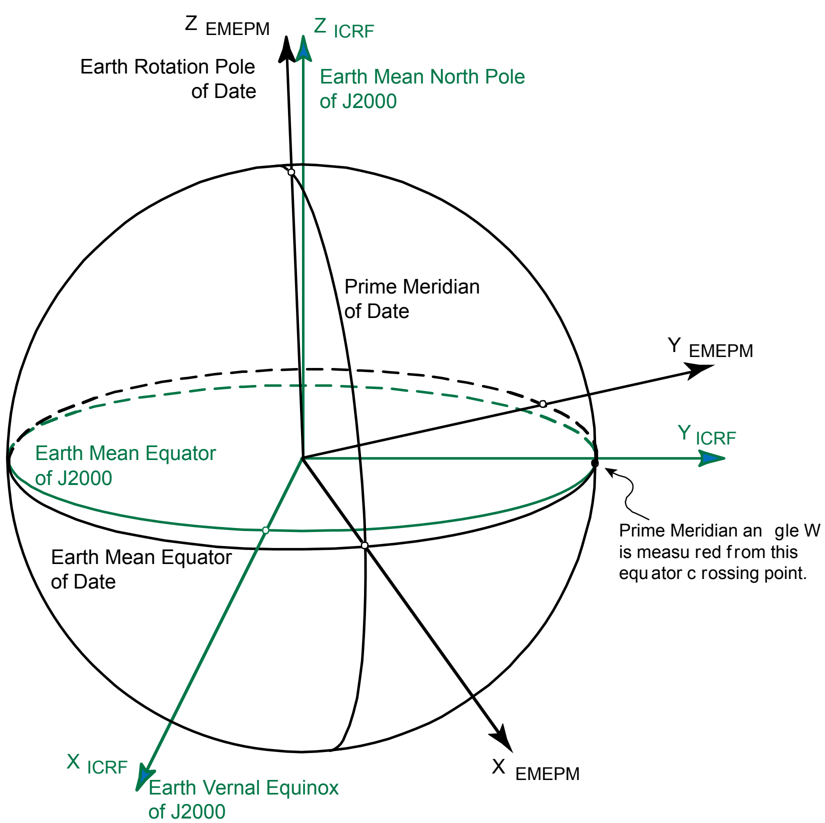


FIGURE 2.1.4-1 COORDINATE FRAME: EARTH MEAN EQUATOR AND PRIME MERIDIAN (EMEPM)

(Rotating)

NOTE: Reasonable alternatives include the ICRF precessed and rotated according to any standard precession model, but since the “mean” is an approximation, it seems not worthwhile to additional computation to this definition. Although Reference 5 specifies TCB (Barycentric Coordinate Time), this in fact was an error introduced late in the preparation of the paper; the correct time scale for use in the IAU formulae given in Table 2.0-1 in the paper is TDB (Barycentric Dynamical Time, i.e., ephemeris time) and the standard epoch is 2451545.0 TDB.

2.2 LUNAR COORDINATE SYSTEMS

Two slightly different coordinate frames are commonly used to define the orientation of the axes of a lunar body-fixed coordinate system: a mean Earth/rotation frame and a principal axis coordinate frame. The mean Earth/rotation frame (sometimes called the "mean Earth/polar axis" frame) is a lunar body-fixed coordinate frame with the X-axis aligned with the mean direction from the Moon to the Earth and the Z-axis aligned with the mean axis of rotation of the Moon. The principal axis frame is a lunar body-fixed coordinate frame aligned with the principal axes of the Moon. Due to the fact that the Moon is synchronously rotating but is not exactly symmetric, the principal axes and the mean Earth/rotation axes of the Moon do not coincide. References 3 and 4 describe and compare the two different Moon-centered coordinate systems and indicate that the axes of the two systems differ by just less than 1 km when expressed as a distance along a great circle on the Moon's surface. In other words, the locations of surface features may differ by as much as nearly 1 km in the two coordinate systems.

The Constellation Program will use the more accurate (and readily available) principal axis-based lunar coordinate frame to define the directions of the Moon's rotation pole and prime meridian. It's worthwhile to note, however, that the reports published by International Astronomical Union/International Association of Geodesy (IAU/IAG) Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites provide a method to estimate the direction of the Moon's north pole and prime meridian of the mean Earth/rotation system, with the time-dependent rotation from the International Celestial Reference Frame (ICRF) to the mean Earth/rotation frame approximated by a (truncated) series (see Reference 5). (See the note at the end of the previous section regarding the ICRF reference frame).

NOTE: The coordinates of surface features displayed on most lunar maps and the locations of terrestrial hardware deposited on the Moon (e.g. at the Apollo landing sites) are generally expressed relative to the mean Earth/rotation system. It is important to keep in mind that the construction of lunar maps introduces errors associated with the uncertainty in the placement of images on to a lunar body-fixed coordinate system - often called "map tie errors". These types of errors are not addressed here.

The Principal Axis (PA) based lunar coordinate frame is defined in conjunction with the development of a particular lunar ephemeris. In other words, the PA frame is updated every time a new lunar ephemeris is developed. This means that lunar surface positions expressed in a PA based coordinate system will change slightly (probably on the order of a few tens of meters, though much larger changes have occurred in the past) when a new ephemeris is developed.

The updated PA frame is rotated from the previous PA frame by a small constant amount. This rotation represents an update in knowledge, i.e., it is not the result of tracking some type of time-dependency. Thus, as more data are collected, the knowledge of the PA frame will improve and the resulting differences in subsequent lunar PA frames will diminish.

The planetary ephemeris file that contains the current, best lunar ephemeris for general mission and navigation analyses is the JPL generated DE421(Developmental Ephemeris 421) [6]. See Reference 1 and the following website, http://ssd.jpl.nasa.gov/iau-comm4/, for more information on DE421 and how to obtain a copy of the ephemeris file in the JPL external export format or the “SPICE” SPK format. (See the text at the end of this section for more information about the SPICE software).

The numerically integrated physical librations of the Moon can be obtained directly from the DE421 ephemeris file. Reference 7 defines three (Euler) angles that describe the orientation of the principal axes of the Moon relative to the ICRF reference frame as follows:

The three Euler angles are

a. ϕ, the angle along the ICRF “equator”, from the ICRF X-axis to the ascending node of the lunar equator

b. θ, the inclination of the lunar equator to the ICRF “equator”

c. ψ, the angle along the lunar equator from the node to the selenographic prime meridian

The three Euler angles (or libration angles) are illustrated in Figure 2.3.1-1.

Polynomials for the three libration angles and their rates are stored on the ephemeris file. The ephemeris reader outputs the libration angles and their rates in the following order ϕ, θ, ψ, $\dot{\phi}$, $\dot{\theta}$, $\dot{\psi}$, where the angles are expressed in radians and the angle rates in radians/day. The transformation from the ICRF coordinate frame to the lunar principal axis coordinate frame is given by the following equation.

$$\begin{bmatrix} \hat{X}_{Moon\text{-}PA} \\ \hat{Y}_{Moon\text{-}PA} \\ \hat{Z}_{Moon\text{-}PA} \end{bmatrix} = [R_Z(\psi)]\,[R_X(\theta)]\,[R_Z(\phi)] \begin{bmatrix} \hat{X}_{ICRF\text{-}J2000} \\ \hat{Y}_{ICRF\text{-}J2000} \\ \hat{Z}_{ICRF\text{-}J2000} \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{X}_{ICRF\text{-}J2000} \\ \hat{Y}_{ICRF\text{-}J2000} \\ \hat{Z}_{ICRF\text{-}J2000} \end{bmatrix}$$

Another common way to describe the orientation of a particular coordinate frame is to simply define the direction of the pole vector (or Z-axis) and the prime meridian vector (or X-axis) relative to a known coordinate frame. For reference, the three principal axis lunar libration angles described above are related to the directions of the Moon's PA frame pole and prime meridian vectors by the following equations [3]

$$\alpha_{Moon\text{-}PA} = \phi - 90^o$$

$$\delta_{Moon\text{-}PA} = 90^o - \theta$$

$$W_{Moon\text{-}PA} = \psi$$

where $\alpha_{Moon\text{-}PA}$ and $\delta_{Moon\text{-}PA}$ are the right ascension and declination (respectively) of the Moon's Z-axis in the PA frame and $W_{Moon\text{-}PA}$ is the angle to the Moon's X-axis in the PA frame. The $Z_{Moon\text{-}PA}$-axis is nearly aligned with the mean axis of rotation of the Moon and the $X_{Moon\text{-}PA}$-axis is nearly aligned with the mean direction to the Earth, which are the Moon's ME frame pole and prime meridian vectors.

For those familiar with the Navigation and Ancillary Information Facility (NAIF) "SPICE" software, the same lunar libration data (and thus the same lunar PA coordinate frame) can be accessed using the SPICE Toolkit. This requires the use of a binary PcK (Planetary Constants Kernel) file and a Frames Kernel (FK) file. In the absence of such PcK and FK files, the default lunar body-fixed frame in the SPICE Toolkit is the mean Earth rotation frame as related to the ICRF using the approximation provided by the IAU/IUG Working Group in Reference 5. As mentioned earlier, the lunar ephemeris can also be accessed using a binary SPK (Spacecraft and Planet Kernel) file.

For more information about the NAIF/SPICE software and how to use these files, please see the following website, http://naif.jpl.nasa.gov/naif. The files can be downloaded from the following directories within the NAIF anonymous ftp site:

Path:	ftp://naif.jpl.nasa.gov/pub/naif/generic_kernels/spk/planets/	
Filename:	de421.bsp	(binary SPK file)
Path:	ftp://naif.jpl.nasa.gov/pub/naif/generic_kernels/pck	
Filename:	moon_pa_de421_1900-2050.bpc	(binary PcK file)
Path:	ftp://naif.jpl.nasa.gov/pub/naif/generic_kernels/fk/satellites	
Filename:	moon_080317.tf	(ASCII FK file)

A detailed description of the contents of these files is not provided here, since the files are extensively documented. The Frames Kernel file is an ASCII file and can be viewed with any text editor. The SPK and PcK files are binary files, but they also contain descriptive text of interest to the user. The text can be viewed using a SPICE utility called commnt.

2.2.1 Lunar Principal Axis of Epoch (LPAE)

Owner Organization: Flight Performance SIG

Coordinate Frame: Non-Rotating/“Inertial”

Lunar coordinate frame aligned with the principal axes of the Moon at a specific Epoch.

Z-axis: Points in the direction of the Moon’s North pole principal axis of Epoch (maximum moment of inertia).

X-axis: Points in the direction of the Moon’s prime meridian principal axis of Epoch (minimum moment of inertia).

Y-axis: Completes a standard, right-handed coordinate frame.

NOTE: Finding the principal axes depends on solving for the dynamics of the Moon’s orientation, which must be done in conjunction with solving for its motion in space, though the Moon’s motion in space can also be solved for independently. The terms “north pole” and “prime meridian” are loosely used for the Z and X axes respectively of both this and the Lunar Mean Earth (Section 2.2.3) frames, which are indistinguishable in the scale of Figure 2.2.1-1.

Coordinate Systems: Moon-Centered, LPAE

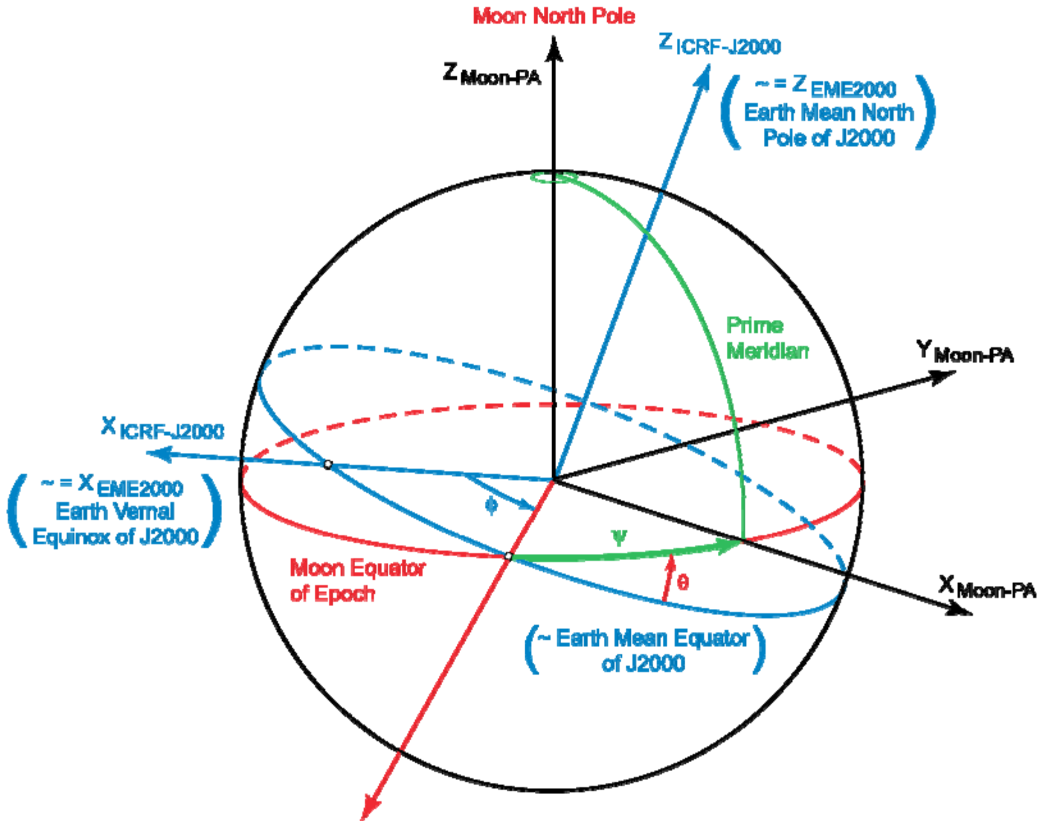


FIGURE 2.2.1-1 COORDINATE FRAME: LUNAR PRINCIPAL AXIS OF EPOCH (LPAE) (NON-ROTATING/"INERTIAL") OR BODY-FIXED (LPABF) (ROTATING)

2.2.2 Lunar Principal Axis Body-Fixed (LPABF)

Owner Organization: Flight Performance SIG

Coordinate Frame: Rotating

Lunar body-fixed coordinate frame aligned with the principal axes of the Moon.

Z-axis: Points in the direction of the Moon's North pole principal axis (maximum moment of inertia).

X-axis: Points in the direction of the Moon's prime meridian principal axis (minimum moment of inertia).

Y-axis: Completes a standard, right-handed coordinate frame.

Realization: This is a fixed rotation from LMEBF (see 2.2.3 below), given in Reference 11 and quoted in Reference 9.

Relationships: The location of the LPABF in the ICRF is solved for in conjunction with solving for the Moon's motion in space, and is given in DE421. Data for lunar orientation from this ephemeris has been extracted and made available as a SPICE pck file [TBD] as described in Section 2.2 above.

NOTE: Lunar gravity fields are defined in this frame.

NOTE: Finding the principal axes depends on solving for the dynamics of the Moon's orientation, which must be done in conjunction with solving for its motion in space, though the Moon's motion in space can also be solved for independently. The terms "north pole" and "prime meridian" are loosely used for the Z and X axes respectively of both this and the Lunar Mean Earth (Section 2.2.3) frames, which are indistinguishable in the scale of Figure 2.2.1-1. The published lunar orientation data changed after DE403 but DE415 returned to the orientations published in DE403. A major revision in lunar orientation models and a corresponding fully integrated solution for lunar orientation and lunar and planetary motion has been completed and is realized in DE421. The new solution includes a rotation of the DE421 LPABF of about 4 arcsec (or a maximum of about 34 m on the lunar surface) from the DE403 LPABF (Reference 13).

Coordinate Systems: Moon-Centered, LPABF

See Figure 2.2.1-1

2.2.3 Lunar Mean Earth Body-Fixed (LMEBF)

Owner Organization: Flight Performance SIG

Coordinate Frame: Rotating

Lunar body-fixed coordinate frame aligned with the rotation axis of the Moon.

Z-axis: Points in the direction of the Moon's North rotation pole (mean rotation axis).

X-axis: Points in the direction of the Moon's historical prime meridian (mean direction toward Earth).

Y-axis: Completes a standard, right-handed coordinate frame.

Realization: This is realized by the locations of the three Apollo and one Lunakhod laser ranging retroreflectors given in Reference 13.

Relationships: The location of the LMEBF is a fixed rotation from the LPABF given in J.G. Williams, et al., Reference 13: " If M is a vector of Cartesian coordinates in the mean Earth/mean rotation (MER) axis frame and P is a coordinate vector in the principal axis (PA) frame, then… For DE421 the rotation between frames is $M = R_x(-0.30'') R_y(-78.56'') R_z(-67.92'') P$."

NOTE: Historical data and surface maps are given in this frame.

NOTE: Finding the rotation axes and principal axes depends on solving for the dynamics of the Moon's orientation, which must be done in conjunction with solving for its motion in space, though the Moon's motion in space can also be solved for independently. The published lunar orientation data changed after DE403 but DE415 returned to the orientations published in DE403. A major revision in lunar orientation models and a corresponding fully integrated solution for lunar orientation and lunar and planetary motion has been completed and is realized in DE421. The new solution includes a rotation of the DE421 LMEBF of about 0.6 arcsec (or a maximum of about 5 m on the lunar surface) from the DE403 LMEBF (Reference 13).

NOTE: Using the traditional terminology and syntax for trajectory-related coordinate frames, this frame probably could have been called "Moon True Equator and Prime Meridian Body-Fixed" since the mean rotation and mean Earth axes directions represent the best (or "true") orientations of the Moon's pole and prime meridian at any given time. The Moon's principal axes are slightly rotated away from these axes because the Moon is tidally locked to Earth so that perturbations from higher order terms in the gravity field are not averaged out by rotation.

Coordinate Systems: Moon-Centered, LMEBF

See Figure 2.2.1-1. On the scale of this figure, LMEBF is indistinguishable from LPABF

2.3 THREE-BODY ROTATING COORDINATE SYSTEMS

The lunar coordinate systems described in Section 2.2 are primarily used when operating in close proximity to the Moon. There are, however, a few additional coordinate systems that are also useful when analyzing (and depicting) trajectories in the vicinity of the Earth-Moon system. They are rotating coordinate systems associated with two different three-body systems: the Sun-Earth-spacecraft system and the Earth-Moon-spacecraft system.

The Sun-Earth and Earth-Moon rotating coordinate frames are defined as follows. The pole vector or Z-axis of the coordinate frame is set equal to the instantaneous orbit normal of the secondary (smaller) body about the primary (larger) body and the X-axis is set equal to the vector from the primary body center of mass (CM) to the secondary body CM. The X-axis rotates at a rate equal to the instantaneous rotation rate of the secondary body about the primary body.

2.3.1 Sun-Earth Rotating (SE-ROT)

Owner Organization: Flight Performance SIG

Coordinate Frame: Rotating

Z-axis: Points in the direction of the instantaneous orbit normal of the Earth about the Sun.

X-axis: Points in the direction of the vector from the Sun to the Earth.

Y-axis: Completes a standard, right-handed coordinate frame.

Coordinate Systems: **Sun-Centered, SE-ROT**
Earth-Centered, SE-ROT, used for illustrating motion near Earth
Sun-Earth-Barycentered, SE-ROT, for calculating Jacobi’s constant

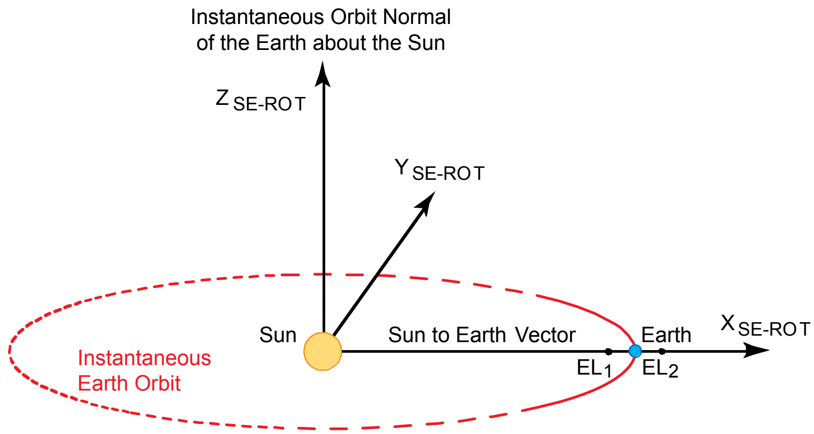


FIGURE 2.3.1-1 COORDINATE FRAME: SUN-EARTH ROTATING (SE-ROT)

Earth-Centered, SE-ROT

NOTE: In this coordinate frame, the two collinear Lagrange points EL_1 and EL_2 (sometimes called Libration points) both lie along the positive X-axis approximately 1.5 million kilometers from the Earth. The EL_1 point lies on the X-axis between the Earth and the Sun and the EL_2 point lies on the X-axis on the other side of the Earth away from the Sun. See Reference 1 for more information about Lagrange points.

2.3.2 Earth-Moon Rotating (EM-ROT)

Owner Organization: Flight Performance SIG

Coordinate Frame: Rotating

Z-axis: Points in the direction of the instantaneous orbit normal of the Moon about the Earth.

X-axis: Points in the direction of the vector from the Earth to the Moon.

Y-axis: Completes a standard, right-handed coordinate frame.

Coordinate Systems: **Earth-Centered, EM-ROT**
Moon-Centered, EM-ROT, used for illustrating motion near Earth
Earth-Moon-Barycentered, EM-ROT, for calculating Jacobi's constant

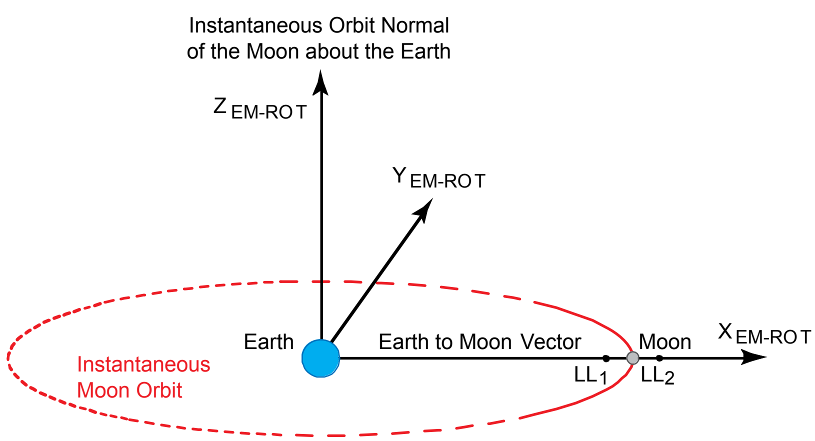


FIGURE 2.3.2-1 COORDINATE FRAME: EARTH-MOON ROTATING (EM-ROT)

Moon-Centered, EM-ROT

NOTE: In this coordinate frame, the two collinear Lagrange points LL_1 and LL_2 (sometimes called Libration points) both lie along the positive X-axis approximately 60000 kilometers from the Moon. The LL_1 point lies on the X-axis between the Moon and the Earth and the LL_2 point lies on the X-axis on the other side of the Moon away from the Earth. See Reference 1 for more information about Lagrange points.

2.4 MARS COORDINATE SYSTEMS

2.4.1 Mars Mean Equator and IAU-Node of Epoch (MMEIAUE)

Owner Organization: Flight Performance SIG

Coordinate Frame: Non-Rotating/“Inertial”

Z-axis: Defined as the pole vector of the Mars Mean Equator of Epoch.

X-axis: Defined as the cross product of the ICRF Z-axis with the Z-axis (as defined above).

Y-axis: Completes a standard, right-handed coordinate frame.

Realization and Relationships: This frame is realized from the ICRF, precessed and rotated according to the formulae in IAU2000, Reference 5.

Coordinate Systems: Mars-Centered, MMEIAUE

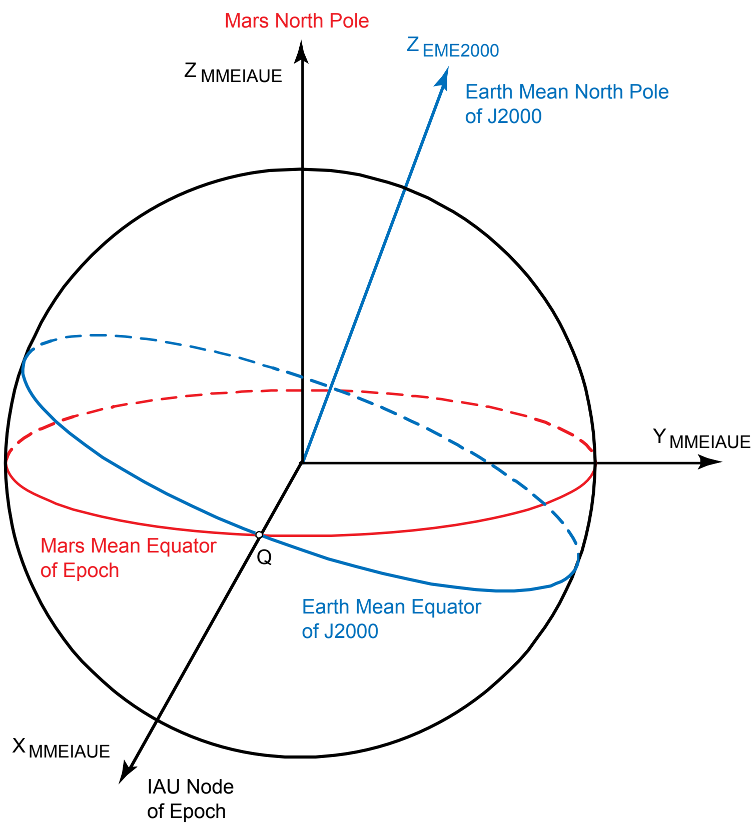


FIGURE 2.4.1-1 COORDINATE FRAME: MARS MEAN EQUATOR AND IAU-NODE OF EPOCH (MMEIAUE) (NON-ROTATING/"INERTIAL")

2.4.2 Mars Mean Equator and Prime Meridian Body-Fixed (MMEPMBF)

Owner Organization: Flight Performance SIG

Coordinate Frame: Rotating

Mars body-fixed coordinate frame with the Mars North pole and prime meridian directions defined by the IAU/IAG [5].

Z-axis: Defined as the pole vector of the Mars Mean Equator.

X-axis: Points in the direction of the prime meridian of Mars.

Y-axis: Completes a standard, right-handed coordinate frame.

Realization and Relationships: This frame is realized from the ICRF, precessed and rotated according to the formulae in IAU2000, Reference 5.

Coordinate Systems: Mars-Centered, MMEPMBF

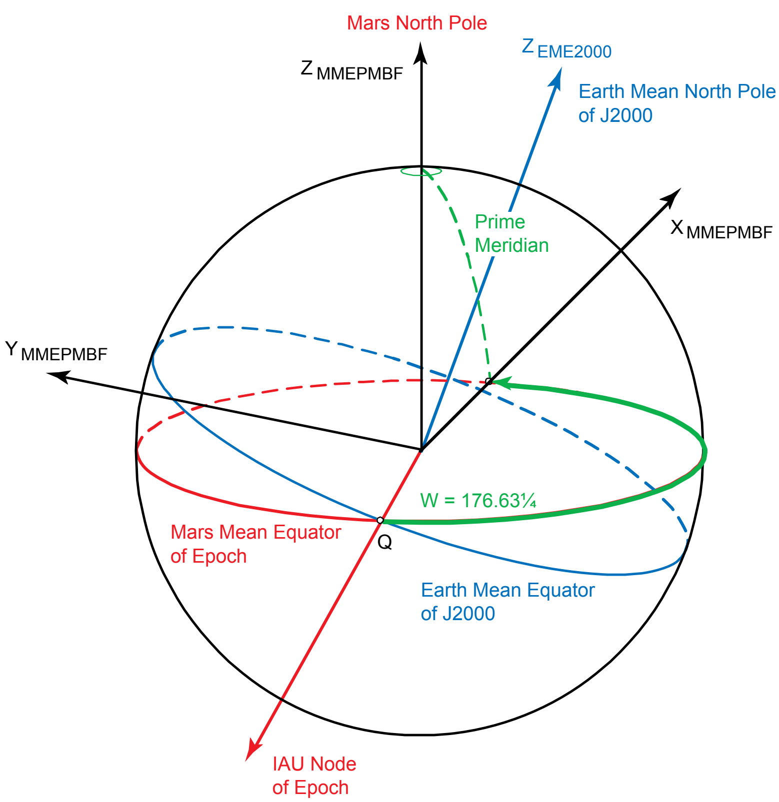


FIGURE 2.4.2-1 COORDINATE FRAME: MARS MEAN EQUATOR AND PRIME MERIDIAN BODY-FIXED (MMEPMBF) (ROTATING) - (SHOWN AT THE J2000 EPOCH)

2.5 LOCAL VERTICAL LOCAL HORIZONTAL COORDINATE SYSTEMS

2.5.1 Local Vertical Local Horizontal (LVLH)

Owner Organization: Flight Performance SIG

Coordinate Frame: Rotating

Z-axis: Defined as a line that lies along the radius vector from the central body center to the vehicle center-of-mass and is positive toward the central body center.

X-axis: Defined as a line that is normal to the orbit plane, positive in the direction opposite to the instantaneous orbit angular momentum vector.

Y-axis: Completes a standard, right-handed coordinate frame and is positive in the direction of vehicle motion.

Realization and Relationships: Defined by the position and velocity vectors associated with a vehicle and thus directly related to the coordinate system in which those vectors are expressed.

Coordinate Systems: Vehicle-Centered, LVLH

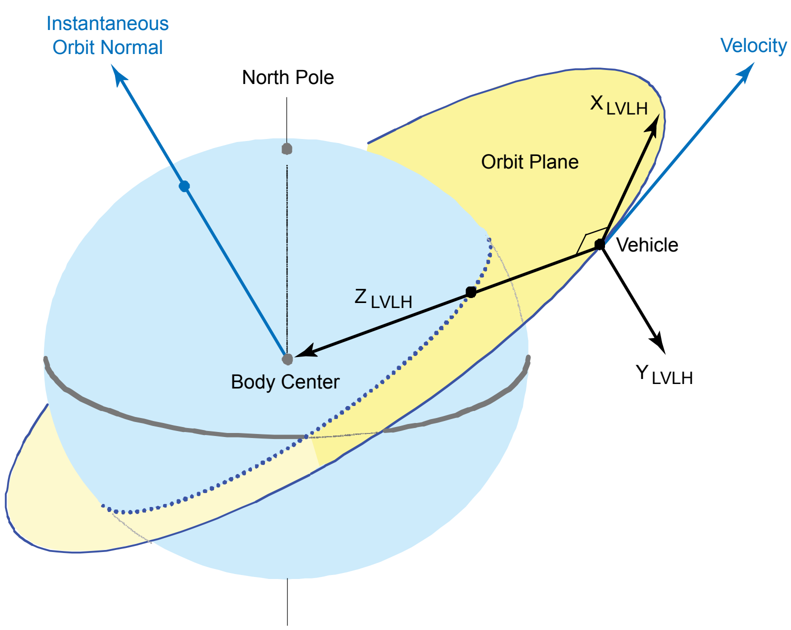


FIGURE 2.5.1-1 COORDINATE FRAME: LOCAL VERTICAL LOCAL HORIZONTAL (LVLH) (ROTATING)

2.5.2 Local Vertical Curvilinear (LVC)

Owner Organization: Flight Performance SIG

Coordinate Frame: Rotating, non-Euclidean

Since this coordinate system is non-Euclidean, the axes are not defined by vectors but are lines and circles in space through an origin at a vehicle in orbit around a central body.

Z-axis: Defined as the line through the vehicle center-of-mass and the central body center, positive toward the central body center.

X-axis: Defined as the circle that intersects the vehicle center-of-mass, is centered on the central body center, and lies in the vehicle orbit plane, positive in the direction of motion.

Y-axis: Defined as the line that intersects the vehicle center-of-mass and is normal to the vehicle orbit plane, positive opposite the direction of the orbit angular momentum vector (thus completing a right-handed coordinate system).

Let *P* be a point whose LVC coordinates we wish to determine, let *N* be the line through the central body center which is normal to the orbit plane of the vehicle (so that *N* is parallel to the Y-axis), and let *C* be the circular cylindrical surface containing the X and Y axes (so that *N* is the axis of *C* and the vehicle lies on *C*). Then the X,Y,Z LVC coordinates of *P* are determined as follows:

Z coordinate: Defined as the distance from the central body center to the vehicle center-of-mass minus the distance between *P* and *N*; equivalently, the radius of *C* minus the radius of the projection of *P* onto the vehicle orbit plane.

X coordinate: Defined as the distance on *C* between the radial projection of *P* onto *C* and the Y-axis; this is taken to be positive if *P* is on the same side from the Y-Z plane as the vehicle velocity vector points and negative otherwise. Equivalently, if we let θ be the central-body-centered angle from the vehicle to the projection of *P* onto the orbit plane (measured positively in a right-handed sense with respect to the vehicle orbit angular momentum), then the x-coordinate of the point is θ (in radians) times the radius of the vehicle. Note that the LVC x-coordinate is arbitrary for P located on N.

Y coordinate: Defined as the distance from the orbit plane, positive on the side opposite the angular momentum direction.

NOTE: For points close to the vehicle, the LVLH and LVC coordinates are approximately the same. See Reference 10 for further discussion.

Realization and Relationships: Defined by the position and velocity vectors associated with a vehicle and thus directly related to the coordinate system in which those vectors are expressed.

Coordinate Systems: Centered, LVC

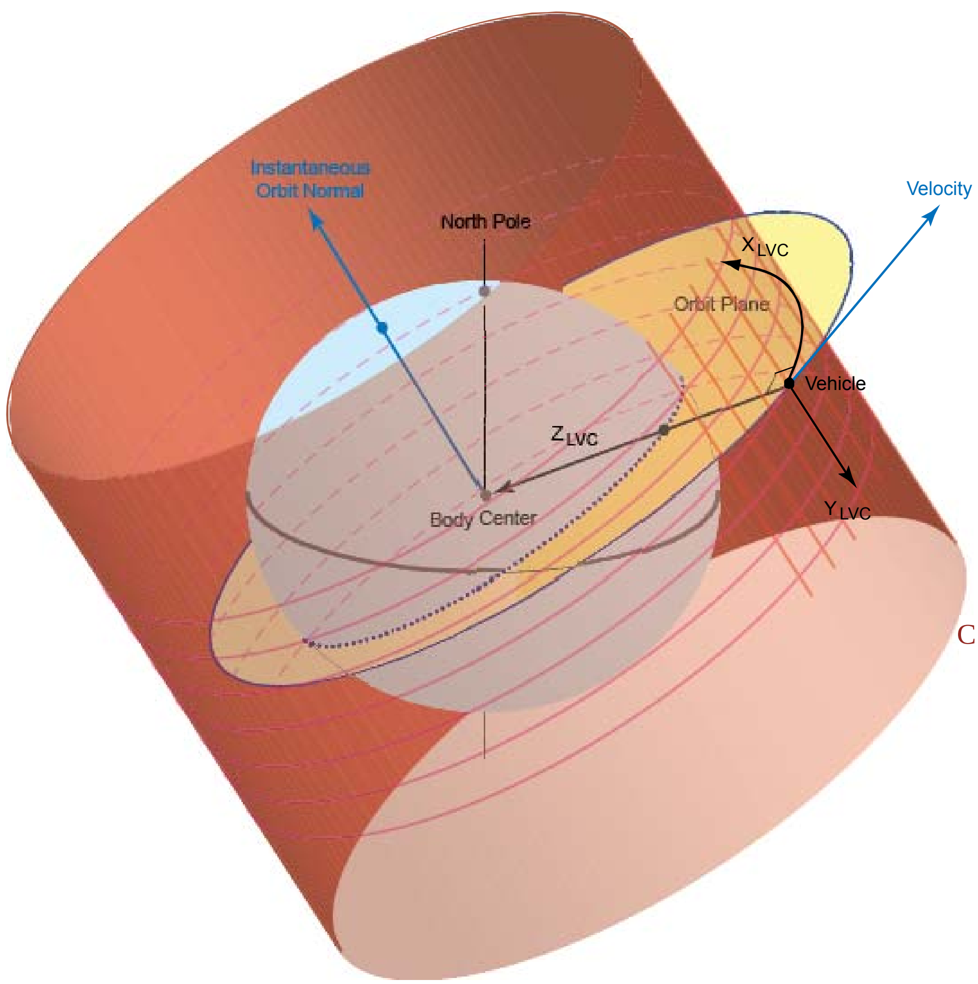


FIGURE 2.5.2-1 COORDINATE FRAME: LOCAL VERTICAL CURVILINEAR (LVC)

The cylinder C is the X-Y surface (where *z=0*).

(Rotating)

3.0 VEHICLE COORDINATE SYSTEMS

3.1 ORION

3.1.1 Orion Crew Module Structural Coordinate System

The Orion Crew Module Structural Coordinate System is typically used for Orion mechanical configuration and mass properties information.

Owner Organization: Orion Project

Origin: At the theoretical apex of the crew module conical shape. This places the origin 4.0204 meters (158.28 inches) from the crew module maximum diameter plane.

X-axis: The X-axis coincides with the centerline of the cone and is positive from the cone apex toward the heatshield. This orientation is dictated by the use of heritage Shuttle hardware as components of the Ares I stack.

Z-axis: The Z-axis lies in the plane containing the origin and a line equidistant between the 2 windows. The positive Z direction corresponds to the "feet to head" direction for the seated crew.

Y-axis: Completes the right-handed system, resulting in the positive direction toward the crew's right when the crew is seated facing the cone apex.

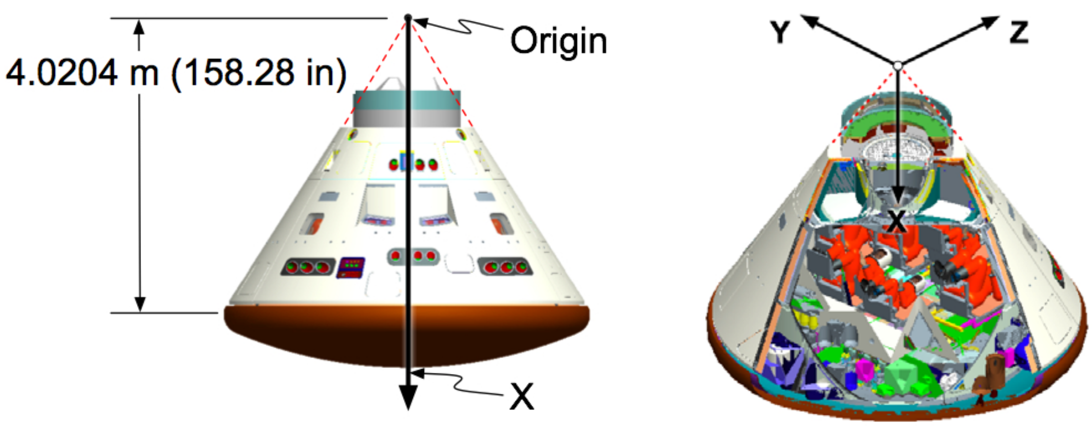


FIGURE 3.1.1-1 ORION CREW MODULE STRUCTURAL COORDINATE SYSTEM

Orion reports data to Ares in the Ares 1/Orion Crew Module Structural Frame.

Relationship Between Ares I Structural and Orion Crew Module Structural Coordinate Systems:

Translation: The Orion Crew Module Structural Coordinate System origin is 9.6327 m (379.24 in) forward of the Orion-Ares I Interface Plane (i.e., the Interface Plane is at (x=9.6327 m, y=0, z=0) in the Orion Crew Module Structural System). The Ares I Structural Coordinate System origin is 25.4 m (1000.0 in) forward of the Orion-Ares I Interface Plane. Therefore, the Ares I Structural Coordinate System origin is 15.7673 m (630.475 in) forward of the Orion Crew Module Structural Coordinate System origin. This translation value is valid for the 606C configuration and is subject to change. Users need to check with the Orion configuration group before applying this translation.

Rotation: None. The Orion Crew Module Structural Coordinate System and the Ares I Structural Coordinate System are parallel.

The transformation from CEV Structural Coordinates to Ares I Structural Coordinates is:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\text{Ares I Structural}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\text{Orion Crew Module Structural}} + \begin{bmatrix} 15.7673\text{ m} \\ 0 \\ 0 \end{bmatrix}$$

3.1.2 Orion GN&C Body Coordinate System

Owner Organization: Orion Project

Origin: At the instantaneous center-of-mass of the combination of all "Orion relevant objects." The center-of-mass of all Orion relevant objects is dynamic and therefore the origin location is dynamic.

The following objects are considered Orion relevant objects when they are directly or indirectly rigidly attached to the Orion CM: CM, SM, LAS, Spacecraft Adapter, CM cargo, SM cargo while SM is attached to CM, CM consumables, SM consumables while SM is attached to CM, crew while inside CM, parachutes while packed in CM, and any other objects directly or indirectly rigidly attached to CM or SM.

The following objects are not Orion relevant objects and thus do not affect the origin location: Ares I, Altair, Altair-AS, EDS, ISS, crew while outside of the CM, parachutes when deployed (outside of the CM).

X-axis: Parallel but opposite in direction to the Orion Crew Module Structural Coordinate System X-axis, positive towards the Orion Crew Module cone apex.

Y-axis: Parallel to the Orion Crew Module Structural Coordinate System Y-axis, positive toward the crew's right when the crew is seated facing the cone apex.

Z-axis: Completes the right-handed system. Parallel to the Orion Crew Module Structural Coordinate System Z-axis, positive in the direction pointing away from the windows and "down" relative to a seated crew member.

Rotation Definitions:
Roll is defined as positive about the +X axis.
Pitch is defines as positive about the +Y axis.
Yaw is defines as positive about the +Z axis.

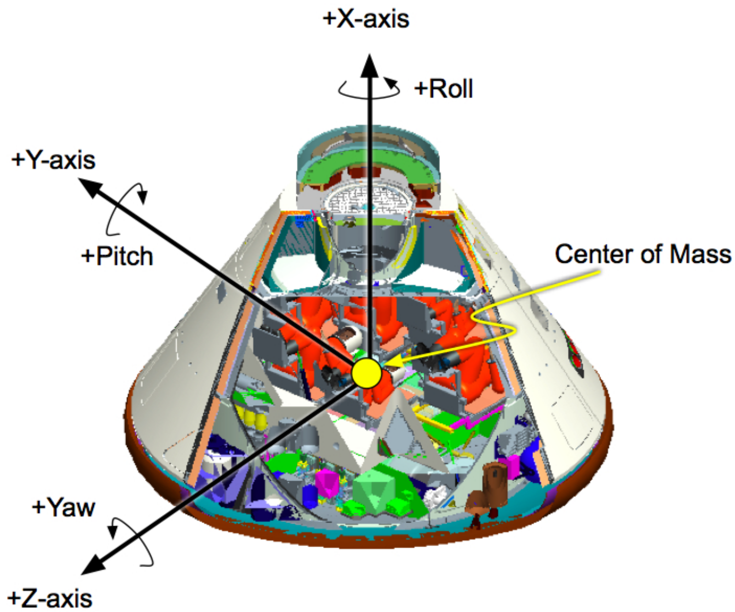


FIGURE 3.1.2-1 ORION GN&C BODY COORDINATE SYSTEM

3.1.3 Orion Spacecraft Structural Coordinate System

Also Known as: Ares I Structural Coordinate System

The Orion Spacecraft Structural Coordinate System is an identical copy of the Ares I Structural Coordinate System and is defined as a convenience for use both within the Orion project and when communicating information, e.g. mass properties, between the Orion and Ares I Projects. Between these two coordinate systems, the Ares System is authoritative in the sense that the Orion System is a copy of the Ares System.

3.2 ARES I

3.2.1 Ares I Structural Coordinate System

The Ares I Structural Coordinate System is the standard system for integration and coordination of configuration and mass properties for the Ares I launch vehicle and all elements and components that are launched on the Ares I. Elements and components report their configuration and mass property information to the Ares I Project in the Ares I Structural Coordinate System. The Ares I Project then integrates the configuration and mass property information in this Coordinate System.

This coordinate system is also known as the Orion Spacecraft Structural Coordinate System.

Owner Organization: Ares I Project

Origin: On the vehicle longitudinal axis, 25.4 m (1000.0 in) forward of the forward external edge of the Ares I Instrument Unit.

X-axis: Along the longitudinal axis of the vehicle, positive in the direction opposite to nominal vehicle thrust.

Y-axis: In the plane containing the origin and the center of the upper stage LH2 feed line, positive in the direction of the upper stage LH2 feed line.

Z-axis: Completes the right-handed system.

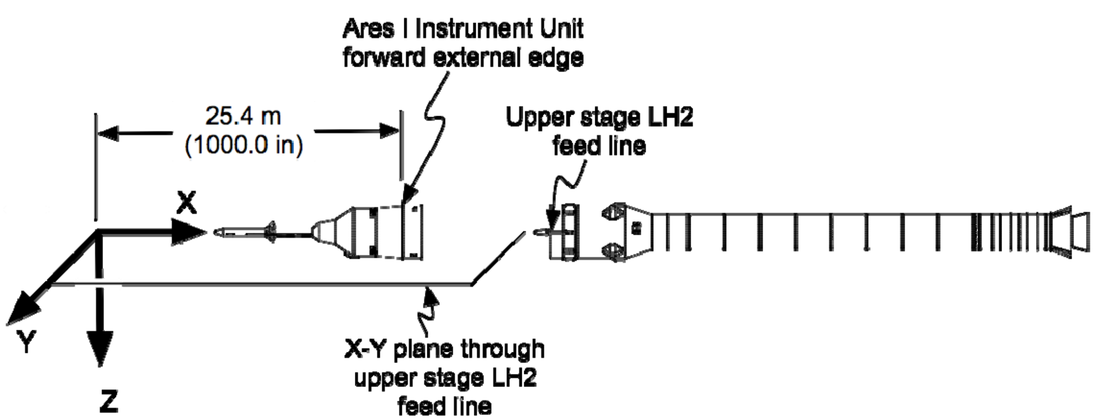


FIGURE 3.2.1-1 ARES I STRUCTURAL COORDINATE SYSTEM

3.2.2 Ares I GN&C Body Coordinate System (Also called CLV Control Body Coordinate System)

Owner Organization: Ares I Project.

Origin: At the instantaneous center-of-mass of the combination of all "CLV relevant objects." The center-of-mass of all CLV relevant objects is dynamic and therefore the origin location is dynamic.

The following objects are considered CLV relevant objects when they are directly or indirectly rigidly attached to the CLV: CM, SM, LAS, Spacecraft Adapter, CM cargo, SM cargo while SM is attached to CM, CM consumables, SM consumables while SM is attached to CM, crew while inside CM, parachutes while packed in CM, and any other objects directly or indirectly rigidly attached to CM or SM.

The following objects are not CLV relevant objects and thus do not affect the origin location: Ares I, Altair, Altair-AS, EDS, ISS, crew while outside of the CM, parachutes when deployed (outside of the CM).

X-axis: +X is the axis of symmetry and points forward
Parallel but opposite in direction to the Orion Crew Module Structural Coordinate System X-axis, positive towards the Orion Crew Module cone apex.

Y-axis: +Y is in the direction of the US LH_2 Feed line directly opposite Systems Tunnel
Parallel to the Orion Crew Module Structural Coordinate System Y-axis, positive toward the crew's right when the crew is seated facing the cone apex.

Z-axis: +Z completes the right-hand rule and is in the direction directly opposite the CEV windows
Completes the right-handed system. Parallel to the Orion Crew Module Structural Coordinate System Z-axis, positive in the direction pointing away from the windows and "down" relative to a seated crew member.

Rotation Definitions:

Roll is defined as positive about the +X axis.
Pitch is defines as positive about the +Y axis.
Yaw is defines as positive about the +Z axis.

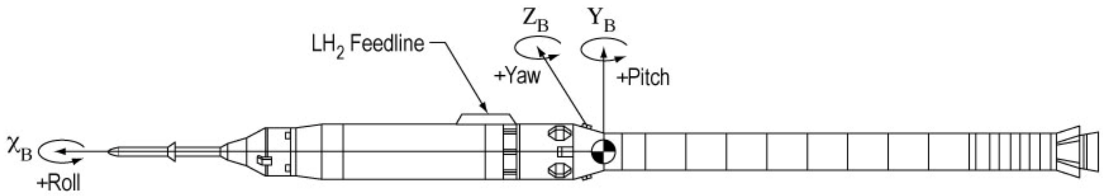


FIGURE 3-1: ARES I GN&C BODY COORDINATE SYSTEM / CLV CONTROL BODY COORDINATE SYSTEM

3.2.3 Ares V Structural Coordinate System

Owner Organization: CaLV/Ares V Project

The Ares V Structural Coordinate System is the standard system for integration and coordination of configuration and mass properties for the Ares V launch vehicle and all elements and components that are launched on the Ares V. Elements and components report their configuration and mass property information to the Ares V Project in the Ares V Structural Coordinate System. The Ares V Project then integrates the configuration and mass property information in this Coordinate System.

Origin: On the vehicle longitudinal axis, 25.4 m (1,000 in) forward of the forward external edge of the EDS Forward Skirt.

X-axis: Along the longitudinal axis of the vehicle, opposite the direction of nominal vehicle thrust.

Y-axis: Towards the centerline of Solid Rocket Booster 1 (to be defined).

Z-axis: Completes the right-handed system.

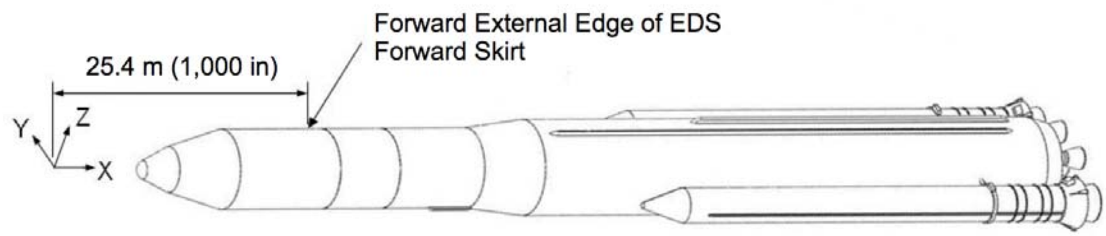


FIGURE 3.3.1-1 ARES V COORDINATE SYSTEM

Relationship Between Ares V Structural and Earth Departure Stage Coordinate Systems:

Translation: None.

Rotation: None.

The Ares V Structural and Earth Departure Stage Coordinate Systems are coincident.

Relationship Between Ares V Structural and Lunar Surface Access Module Coordinate Systems:

Translation: To Be Determined.

Rotation: To Be Determined.

The transformation from Lunar Surface Access Module Coordinates to Ares V Structural Coordinates is (TBS = To Be Supplied):

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\text{Ares V Structural}} = \begin{bmatrix} \text{TBS} & \text{TBS} & \text{TBS} \\ \text{TBS} & \text{TBS} & \text{TBS} \\ \text{TBS} & \text{TBS} & \text{TBS} \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{\text{LSAM Structural}} + \begin{bmatrix} \text{TBS} \\ \text{TBS} \\ \text{TBS} \end{bmatrix}$$

3.3 INTERNATIONAL SPACE STATION

3.3.1 Space Station Analysis Coordinate System

Owner Organization: ISS Program

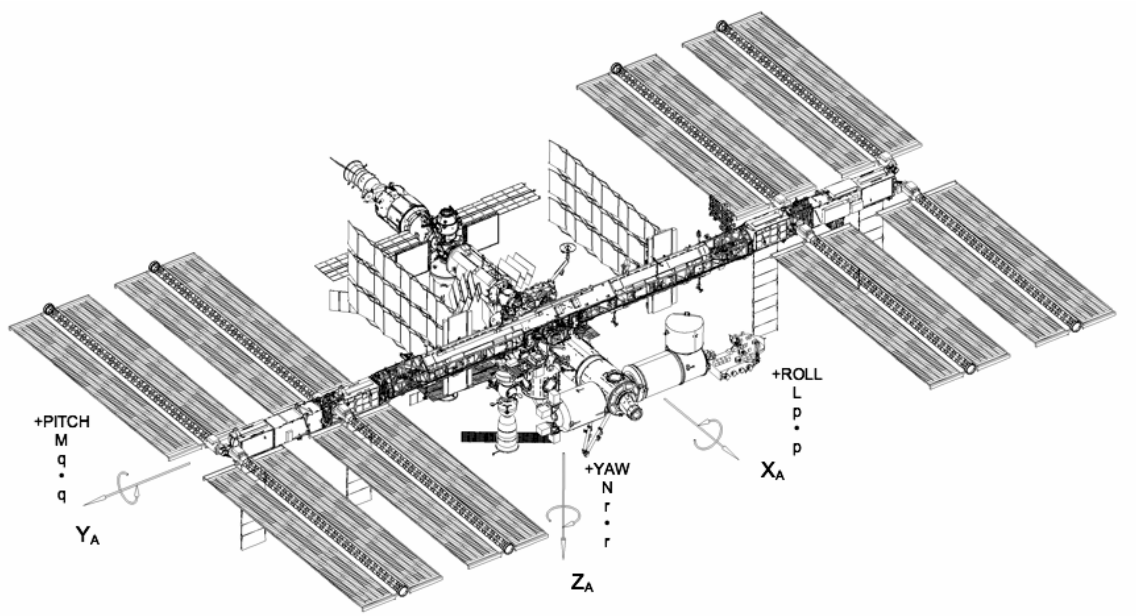


FIGURE 3.4.1-1 SPACE STATION ANALYSIS COORDINATE SYSTEM

Type: Right-Handed Cartesian, Body-Fixed

Description: This coordinate system is derived using the Local Vertical Local Horizontal (LVLH) flight orientation. When defining the relationship between this coordinate system and another, the Euler angle sequence to be used is a yaw, pitch, roll sequence around the Z_A, Y_A, and X_A axes, respectively.

Origin: The origin is located at the geometric center of Integrated Truss Segment (ITS) S0 and is coincident with the S0 Coordinate frame.

Orientation: X_A The X-axis is parallel to the longitudinal axis of the module cluster. The positive X-axis is in the forward direction.

Y_A The Y-axis is identical with the S_O axis. The nominal alpha joint rotational axis is parallel with Y_A. The positive Y-axis is in the starboard direction.

Z_A The positive Z-axis is in the direction of nadir and completes the right-handed Cartesian system.

L, M, N: Moments about X_A, Y_A, and Z_A axes, respectively.

p, q, r: Body rates about X_A, Y_A, and Z_A axes, respectively.

• • •

p, q, r: Angular body acceleration about X_A, Y_A, and Z_A axes, respectively.

Subscript: A

3.3.2 Space Station Reference Coordinate System

Owner Organization: ISS Program

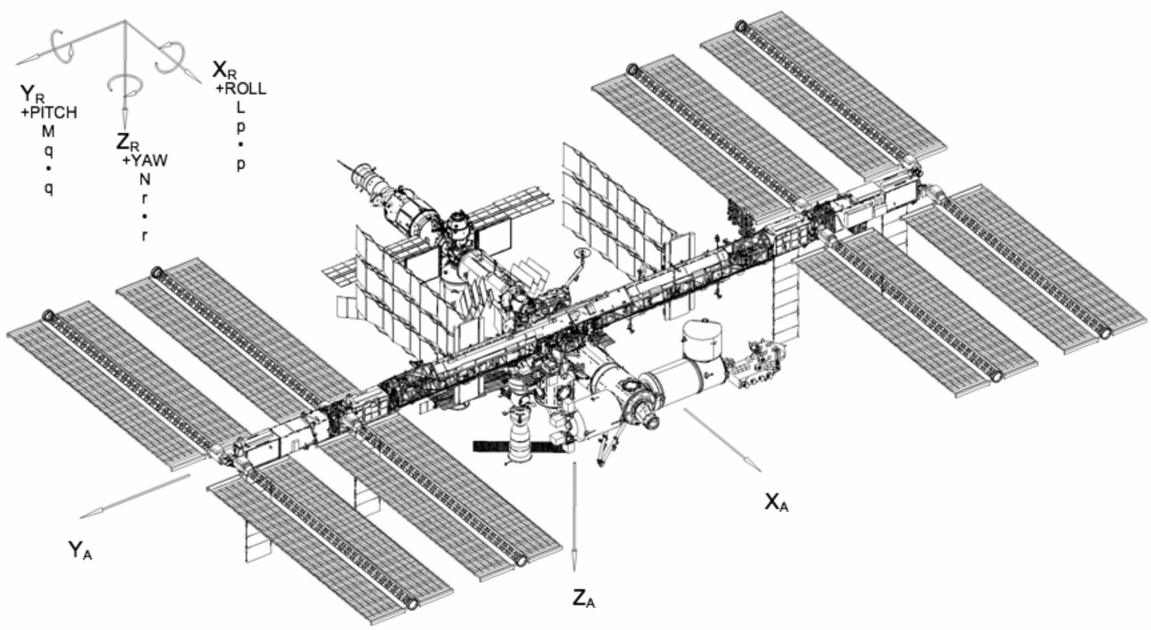


FIGURE 3.4.2-1 SPACE STATION REFERENCE COORDINATE SYSTEM

Type: Right-Handed Cartesian, Body-Fixed

Description: This coordinate system is derived using the LVLH flight orientation.

Origin: The datum point is located at the origin of the Space Station Analysis Coordinate System frame. The origin of the Space Station Reference Coordinate System is located such that the datum point is located at X_R=100, Y_R=0, and Z_R=100 meters.

Orientation:

X_R The X-axis is parallel to the X_A. The positive X-axis is in the forward direction.

Y_R The Y-axis is parallel with the nominal alpha joint rotational axis which is coincident to Y_A. The positive Y-axis is in the starboard direction.

Z_R The positive Z-axis is parallel to Z_A and is in the direction of nadir and completes the rotating right-handed Cartesian system.

L, M, N: Moments about X_R, Y_R, and Z_R axes, respectively.

p, q, r: Body rates about X_R, Y_R, and Z_R axes, respectively.

• • •

p, q, r: Angular body acceleration about X_R, Y_R, and Z_R axes, respectively.

Subscript: R

3.3.3 Space Station Body Coordinate System

Owner Organization: ISS Program

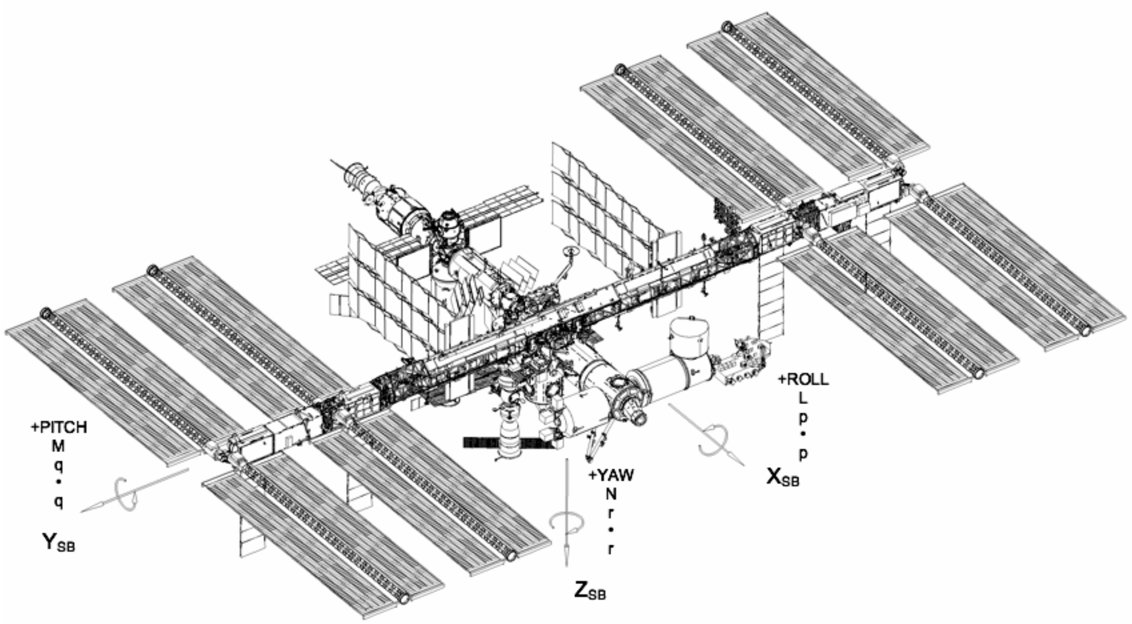


FIGURE 3.4.3-1 SPACE STATION BODY COORDINATE SYSTEMF

Type: Right-handed Cartesian system, Body−Fixed

Description: When defining the relationship between this coordinate system and another, the Euler angle sequence to be used is a yaw, pitch, roll sequence around the Z_{SB}, Y_{SB}, and X_{SB} axes, respectively.

Origin: The origin is located at the Space Station center of mass.

Orientation: The X_{SB} axis is parallel to the X_A axis. Positive X_{SB} is in the forward flight direction.

The Y_{SB} axis is parallel to the Y_A. Positive Y_{SB} is toward starboard.

The Z_{SB} axis is parallel with the Z_A. Positive Z_{SB} is approximately toward nadir and completes the right-handed system X_{SB}, Y_{SB}, Z_{SB}.

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

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

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

Subscript: SB

3.4 ALTAIR

3.4.1 Altair Structural Coordinate System

Owner Organization: Altair Project

Origin: On the vehicle longitudinal (centerline) axis, at the Altair-CEV docking interface plane. Notionally, the zero point of the x-axis is at the fixed docking mechanism docking plane.

X-axis: Along the longitudinal axis (centerline) of the vehicle, positive in the direction opposite of nominal vehicle thrust.

Z-axis: Assuming that the Altair has piloting windows on the forward face of the vehicle, the positive Z-axis would pass in the direction of the windows (between the two crew windows). Notionally, the X-Z plane would intersect the windows.

Y-axis: Completes the right-handed triad system.

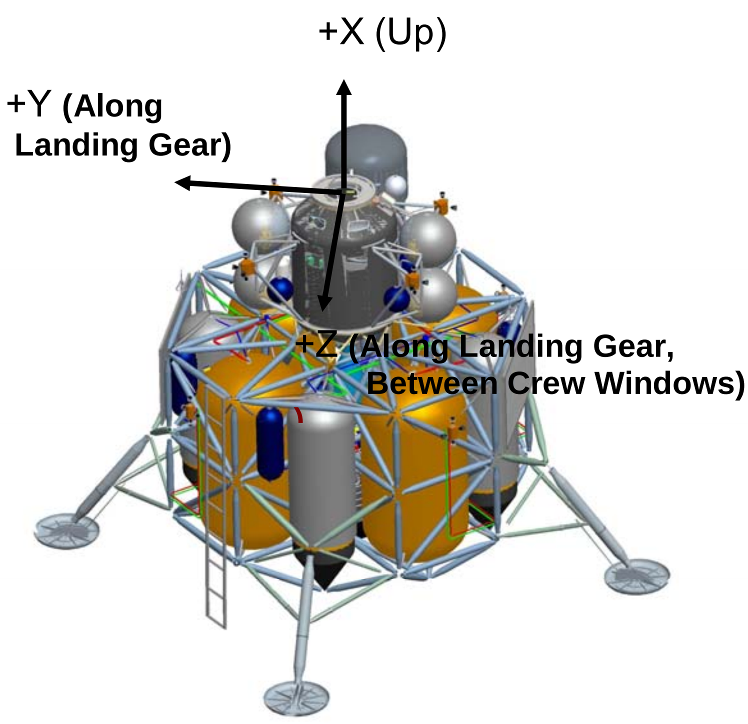


FIGURE 3.5.1-1 ALTAIR STRUCTURAL COORDINATE SYSTEM

3.4.2 Altair Body/GNC Coordinate System

Owner Organization: Altair Project

Origin: On the vehicle longitudinal (centerline) axis , at the ALTAIR-CEV docking interface plane. Notionally, the zero point of the x-axis is at the fixed docking mechanism docking plane.

X-axis: Along the longitudinal (centerline) axis of the vehicle, positive in the direction opposite of nominal vehicle thrust.

Z-axis: Assuming that the ALTAIR has piloting windows on the forward face of the vehicle, the positive Z-axis would pass in the direction of the windows. Notionally, the X-Z plane would intersect the windows (between the two crew windows).

Y-axis: Completes the right-handed triad system.

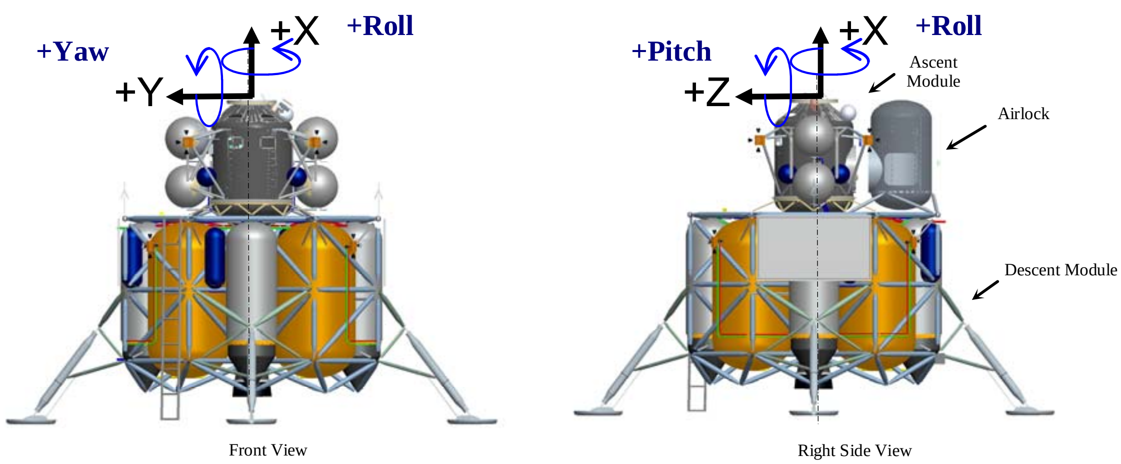


FIGURE 3.5.1-1 ALTAIR BODY/GNC COORDINATE SYSTEM

3.5 EARTH DEPARTURE STAGE

3.5.1 Earth Departure Stage Structural Coordinate System

Owner Organization: CaLV/Ares V Project

Origin: On the vehicle longitudinal axis, 25.4 m (1,000 in) forward of the forward external edge of the EDS Forward Skirt.

X-axis: Along the longitudinal axis of the vehicle, positive in the direction opposite to nominal vehicle thrust.

Z-axis: The attach point of the solar panel defines the Z-axis.

Y-axis: Completes the right-handed system.

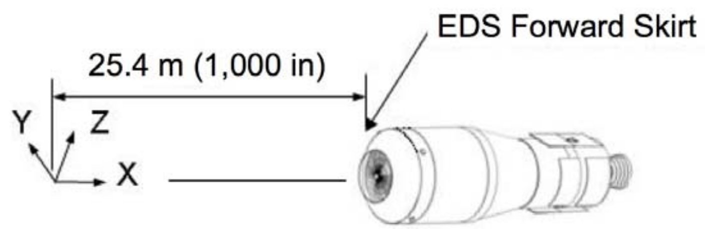
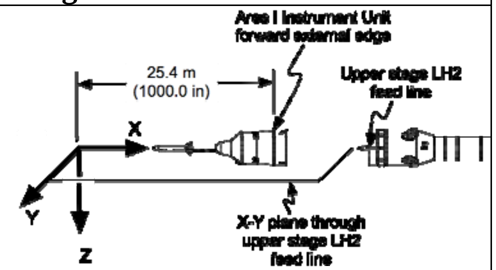
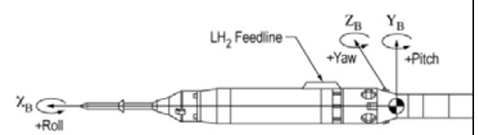


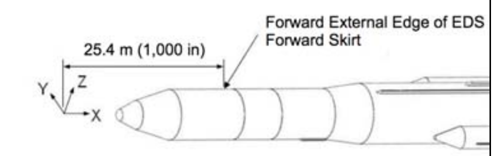
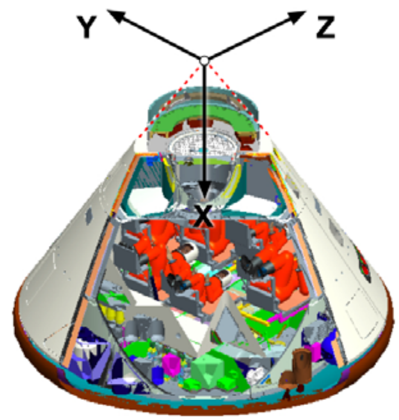
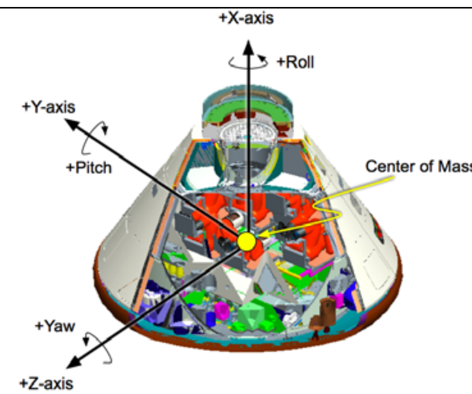
FIGURE 3.6.1-1 EARTH DEPARTURE STAGE STRUCTURAL COORDINATE SYSTEM

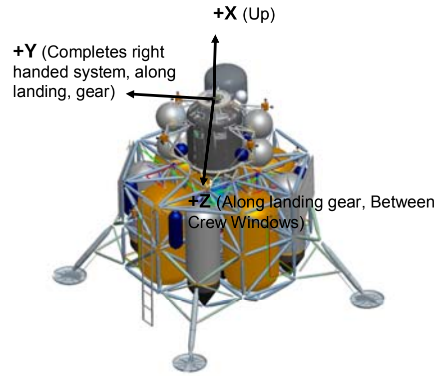
3.6 SUMMARY OF VEHICLE COORDINATE SYSTEMS

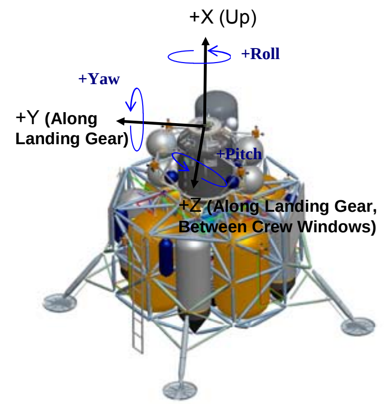
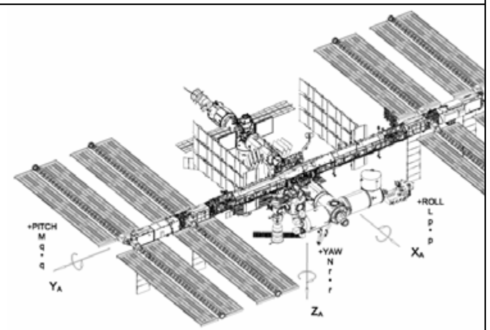
This section contains a summary table which provides a one-stop location to allow easy comparison of the differences in vehicle Body/GNC and Structural coordinate systems.

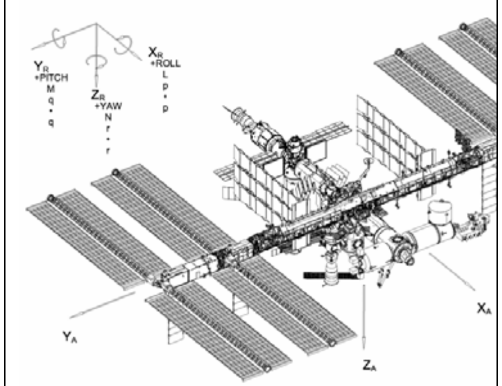
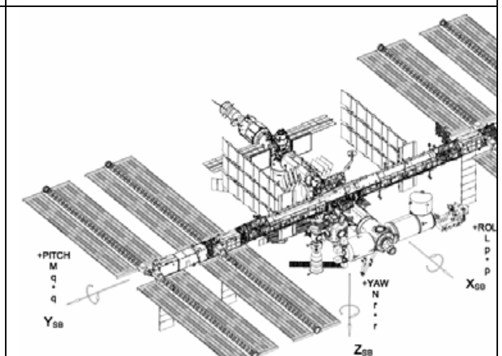
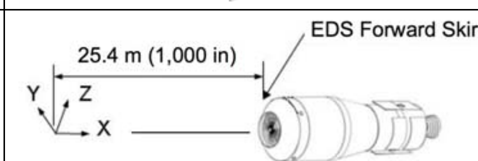
Body and Structural Coordinate SystemS

	X-Axis	Y-Axis	Z-Axis	Origin	Owner	Diagram
ARES I - Structural	Along the longitudinal axis of the vehicle, positive in the direction opposite to nominal vehicle thrust.	In the plane containing the origin and the center of the upper stage LH2 feed line, positive in the direction of the upper stage LH2 feed line.	Completes the right-handed system	On the vehicle longitudinal axis, 25.4 m (1000.0 in) forward of the forward external edge of the Ares I Instrument Unit.	Ares I Project – See section 3.2.1 for more details	
ARES I - Body/GNC	+X is the axis of symmetry and points forward	+Y is in the direction of the US LH_2 Feed line directly opposite Systems Tunnel	+Z completes the right-hand rule and is in the direction directly opposite the CEV windows	At the instantaneous center-of-mass of the combination of all "CLV relevant objects." The center-of-mass of all CLV relevant objects is dynamic and therefore the origin location is dynamic.	Ares I Project – See section 3.2.2 for more details	

	X-Axis	Y-Axis	Z-Axis	Origin	Owner	Diagram
ARES V - Structural	Along the longitudinal axis of the vehicle, opposite the direction of nominal vehicle thrust.	Towards the centerline of Solid Rocket Booster 1 (to be defined).	Completes the right-handed system	On the vehicle longitudinal axis, 25.4 m (1,000 in) forward of the forward external edge of the EDS Forward Skirt.	CaLV / Ares V Project – See section 3.2.3 for more details	
Orion - Structural	Coincides with the centerline of the cone and is positive from the cone apex toward the heatshield.	Completes the right-handed system, resulting in the positive direction toward the crew's right when the crew is seated facing the cone apex.	The Z-axis lies in the plane containing the origin and a line equidistant between the 2 windows. The positive Z direction corresponds to the "feet to head" direction for the seated crew.	At the theoretical apex of the crew module conical shape. This places the origin 4.0204 meters (158.28 inches) from the crew module maximum diameter plane	Orion Project – See section 3.1.1 for more details	
Orion – Body/GNC	Parallel but **opposite** in direction to the Orion Crew Module Structural Coordinate System X-axis, positive towards the Orion Crew	Parallel to the Orion Crew Module Structural Coordinate System Y-axis, positive toward the crew's right when the crew is seated facing the cone apex.	Completes the right-handed system. Parallel to the Orion Crew Module Structural Coordinate System Z-axis, positive in the direction	At the instantaneous center-of-mass of the combination of all "Orion relevant objects." The center-of-mass of all Orion relevant objects is dynamic and therefore the	Orion Project – See section 3.1.2 for more details	

	X-Axis	Y-Axis	Z-Axis	Origin	Owner	Diagram
	Module cone apex		pointing away from the windows and "down" relative to a seated crew member.	origin location is dynamic.		
Altair Structural	Along the longitudinal (centerline) axis of the vehicle, positive in the direction opposite of nominal vehicle thrust.	Completes the right-handed triad system.	Assuming that the Altair has piloting windows on the forward face of the vehicle, the vehicle, the positive Z-axis would pass in the direction of the windows. Notionally, the X-Z plane would intersect the windows.	On the vehicle longitudinal (centerline) axis, at the Altair-CEV docking interface plane. Notionally, the zero point of the x-axis is at the fixed docking mechanism docking plane.	Altair Project – See section 3.4.1 for more details	

	X-Axis	Y-Axis	Z-Axis	Origin	Owner	Diagram
Altair Body/GNC	Along the longitudinal (centerline) axis of the vehicle, positive in the direction opposite of nominal vehicle thrust.	Completes the right-handed triad system.	Assuming that the ALTAIR has piloting windows on the forward face of the vehicle, the positive Z-axis would pass in the direction of the windows. Notionally, the X-Z plane would intersect the windows.	On the vehicle longitudinal (centerline) axis, at the Altair-CEV docking interface plane. Notionally, the zero point of the x-axis is at the fixed docking mechanism docking plane.	Altair Project – See section 3.4.2 for more details	
Space Station Analysis	The X-axis is parallel to the longitudinal axis of the module cluster. The positive X-axis is in the forward direction.	The Y-axis is identical with the SO axis. The nominal alpha joint rotational axis is parallel with YA. The positive Y-axis is in the starboard direction.	The positive Z-axis is in the direction of nadir and completes the right-handed Cartesian system.	The origin is located at the geometric center of Integrated Truss Segment (ITS) S0 and is coincident with the S0 Coordinate frame.	ISS Program. – See Section 3.3.1 for details	

	X-Axis	Y-Axis	Z-Axis	Origin	Owner	Diagram
Space Station Referenc e	The X-axis is parallel to the XA. The positive X-axis is in the forward direction.	The Y-axis is parallel with the nominal alpha joint rotational axis which is coincident to YA. The positive Y-axis is in the starboard direction.	The positive Z-axis is parallel to ZA and is in the direction of nadir and completes the rotating right-handed Cartesian system.	The datum point is located at the origin of the Space Station Analysis Coordinate System frame. The origin of the Space Station Reference Coordinate System is located such that the datum point is located at XR=100, YR=0, and ZR=100 meters.	ISS Program . – See Section 3.3.2 for details	
Space Station Body	The *XSB* axis is parallel to the *XA* axis. Positive *XSB* is in the forward flight direction.	The *YSB* axis is parallel to the *YA*. Positive *YSB* is toward starboard.	The *ZSB* axis is parallel with the *ZA*. Positive *ZSB* is approximately toward nadir and completes the right-handed system *XSB, YSB, ZSB*.	The origin is located at the Space Station center of mass	ISS Program . – See Section 3.3.3 for details	
Earth Departure Stage Structural	Along the longitudinal axis of the vehicle, positive in the direction opposite to	Completes the right-handed system.	The attach point of the solar panel defines the Z-axis.	On the vehicle longitudinal axis, 25.4 m (1,000 in) forward of the forward external edge of the EDS	CaLV / Ares V Project – See section 3.5.1 for	

	X-Axis	Y-Axis	Z-Axis	Origin	Owner	Diagram
	nominal vehicle thrust.			Forward Skirt.	more details	

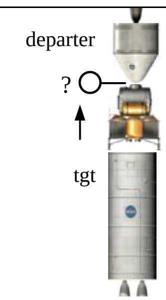
3.7 SUMMARY OF MATED VEHICLE COORDINATE SYSTEMS

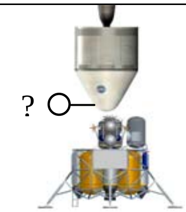
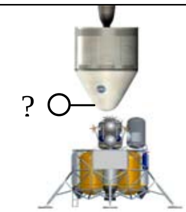
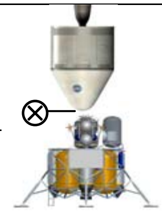
3.7.1 Lunar Sortie BODY/GNC Coordinate Systems – Breakout by Flight Phase

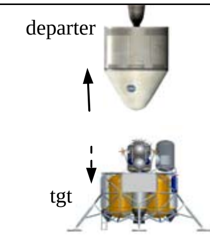
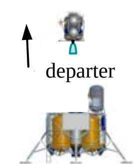
The following table describes the different possible vehicle combinations during a Lunar Sortie, and indicates which vehicles are designated as "Controlling" and "Backup". The Controlling vehicle's coordinate system is to be used for targeting, navigation, guidance, and control as noted below. During contingency and abort situations, it may be necessary to switch to a backup coordinate system. Those cases are noted by the "Backup" designations in the table.

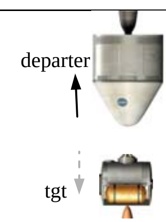
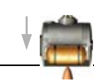
Flight Phase	**Elements**	**Target**	**Navigation**	**Guidance**	**Control**	**Key / Notes**	**Diagrams**
CALV Ascent (*Launch to Insertion)*	Altair					C = Controlling coordinate system B = Backup coordinate system Ab = Abort Cases Navigation = Monitor and Detect	 
	EDS		C	C	C		
	CaLV						
	MCC		B - EDS				
LEO Loiter *(EDS/Altair Stack)*	Altair						
	EDS		C	C	C		
	MCC	C - EDS	C - EDS				
CLV Ascent *Launch to SECO*	CEV/LAS						
	CEV/CM	B	B	B / Ab	B / Ab		
	CEV/SM						
	CLV – 2^{nd} stage		C	C	C		
	CLV – 1^{st}						

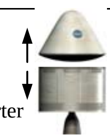
Flight Phase	Elements	Target	Navigation	Guidance	Control	Key / Notes	Diagrams
	stage						
	MCC		B - CLV				
CEV Insertion	CEV / CM	B	C	C	C	C = Controlling coordinate system B = Backup coordinate system Ab = Abort Cases Navigation = Monitor and Detect	
	CEV / SM						
	MCC	C - CEV / CM	B - CEV / CM				
LEO Rendezvous	CEV / SM						
	CEV / CM	C	C	C	C		
	Altair						
	EDS		C	C	C		
	MCC	B - CEV / CM	B - CEV / CM				
ERO / pre-TLI	CEV / SM					○ - Hatch Open	
	CEV / CM	Ab	B	Ab	Ab		
	Altair		B				
	EDS		C	C	C		
	MCC	C - EDS	C - EDS				

Flight Phase	Elements	Target	Navigation	Guidance	Control	Key / Notes	Diagrams
TLI	CEV / SM					C = Controlling coordinate system B = Backup coordinate system Ab = Abort Cases Navigation = Monitor and Detect ⊗ - Hatch Closed **EDS will not perform TLI targeting onboard. Targets will nominally be uplinked from the ground, or commanded from CEV under contingency (CEV-Guidance will be evaluating the burn	
	CEV / CM	**	B	B	B / Ab		
	Altair		B	B			
	EDS		C	C	C		
	MCC	C - EDS	C - EDS				
EDS Sep	CEV / SM					See above ○ - Hatch Open	
	CEV / CM	B	B	B / Ab	B / Ab		
	Altair		C	C	C		
	EDS		C	C	C		
	MCC	C –Altair & EDS	C – Altair & EDS				
EDS Disposal	*EDS		C	C	C	* Scenario is independent from CEV	

Flight Phase	Elements	Target	Navigation	Guidance	Control	Key / Notes	Diagrams
	MCC	C - EDS	C - EDS				
Trans-Lunar / TCMs	CEV / SM					C = Controlling coordinate system B = Backup coordinate system Ab = Abort Cases Navigation = Monitor and Detect ○ - Hatch Open *** For potential swingby / return maneuver	
	CEV / CM	B / Ab***	B	B / Ab	B / Ab		
	Altair		C	C	C		
	MCC	C - Altair	C - Altair				
LOI (-1,-2,-3)	CEV / SM					○ - Hatch Open	
	CEV / CM	B	B	B / Ab	B / Ab		
	Altair	C	C	C	C		
	MCC	C - Altair	C – Altair				
LOI Coast	CEV / SM					○ - Hatch Open	
	CEV / CM	B	B	B / Ab	B / Ab		
	Altair	C	C	C	C		
	MCC	C - Altair	C - Altair				
LLO Pre-Undock	CEV / SM					⊗ - Hatch Closed	
	CEV /	B	B	B / Ab	B / Ab		

Flight Phase	**Elements**	**Target**	**Navigation**	**Guidance**	**Control**	**Key / Notes**	**Diagrams**
	CM						
	Altair	C	C	C	C		
	MCC	C - Altair	C - Altair				
LLO Pre-Undock	CEV / SM					C = Controlling coordinate system B = Backup coordinate system Ab = Abort Cases Navigation = Monitor and Detect	
	CEV / CM		C	C	C		
	Altair	B	C	C	C		
	MCC	C - CEV / CM	C – CEV/CM & Altair				
Lunar Descent	*Altair / AS	C	C	C	C	* Scenario is independent from CEV	
	*Altair / DS						
	MCC	B – Altair/AS	B – Altair/AS				
Lunar Ascent	*Altair-AS	C	C	C	C	* Scenario is independent from CEV	
	*Altair-DS						
	MCC	B – Altair/AS	B – Altair/AS				
LLO Rendezvous (nominal)	CEV / SM						
	CEV / CM		C	C	C		
	Altair-AS	C	C	C	C		

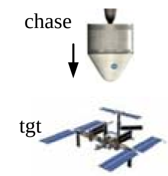
Flight Phase	Elements	Target	Navigation	Guidance	Control	Key / Notes	Diagrams
	MCC	B – Altair/AS	B – Altair/AS & CEV/CM				
LLO Rendezvous (contingency)	CEV / SM					C = Controlling coordinate system B = Backup coordinate system Ab = Abort Cases Navigation = Monitor and Detect	
	CEV / CM	C	C	C	C		
	Altair-AS		C	C	C		
	MCC	B – CEV/ CM	B – Altair/AS & CEV/CM				
LLO (post-dock, pre-disposal)	CEV / SM					⊗ - Hatch Closed	
	CEV / CM		C	C	C		
	Altair-AS		B				
	MCC	C - CEV /CM	C - CEV/CM				
LLO Sep	CEV / SM					⊗ - Hatch Closed	
	CEV / CM		C	C	C		
	Altair-AS		C	C	C		
	MCC	C - Altair/AS & CEV/CM	C - Altair/AS & CEV/CM				
Altair-AS Disposal	*Altair-AS	B	C	C	C	* Scenario is independent from CEV	

Flight Phase	Elements	Target	Navigation	Guidance	Control	Key / Notes	Diagrams
	MCC	C - Altair/AS	C				
Trans-Earth Injection (TEI)	CEV / SM					C = Controlling coordinate system B = Backup coordinate system Ab = Abort Cases Navigation = Monitor and Detect	
	CEV / CM	C	C	C	C		
	MCC	C – CEV/CM	C – CEV/CM				
Trans-Earth TCMs	CEV / SM						
	CEV / CM	C	C	C	C		
	MCC	C – CEV/CM	C – CEV/CM				
CM / SM Sep	CEV / CM		C	C	C		departer 
	CEV / SM				C		
	MCC	C – CEV/CM	C – CEV/CM				
SM Disposal	CEV / SM						
	MCC	C - CEV / SM	C - CEV / SM				
CM Disposal	CEV / CM	B / Ab	C	C	C		

Flight Phase	Elements	Target	Navigation	Guidance	Control	Key / Notes	Diagrams
	MCC	B - - CEV / CM	B - - CEV / CM				

3.7.2 ISS DRM Unigue GNC Roles – Breakout by Flight Phase

The following table describes the different possible vehicle combinations during an ISS mission (only those unique combinations above and beyond what is already covered in the Lunar Sortie Section 3.7.1), and indicates which vehicles are designated as “Controlling” and “Backup”. The Controlling vehicle’s coordinate system is to be used for targeting, navigation, guidance, and control as noted below. During contingency and abort situations, it may be necessary to switch to a backup coordinate system. Those cases are noted by the “Backup” designations in the table.

Flight Phase	Elements	Target	Navigation	Guidance	Control	Key / Notes	Diagrams
LEO Rendezvous	CEV / SM					C = Controlling coordinate system B = Backup coordinate system Ab = Abort Cases Navigation = Monitor and Detect	
	CEV / CM	C	C	C	C		
	ISS		C	C	C		
	MCC	B – CEV/CM	B – CEV/CM & ISS				
LEO Undock	CEV / SM						
	CEV / CM		C	C	C		
	ISS		C	C	C		
	MCC	B – CEV/CM & ISS	B – CEV/CM & ISS				
LEO Deorbit	CEV / SM						
	CEV / CM	C	C	C	C		

Flight Phase	Elements	Target	Navigation	Guidance	Control	Key / Notes	Diagrams
	MCC	C - CEV/CM	C - CEV/CM				
CM Raise Maneuver	CEV / CM		C	C	C	C = Controlling coordinate system B = Backup coordinate system	
	MCC	B - CEV/CM	B - CEV/CM				

4.0 GROUND COORDINATE SYSTEMS

4.1 LAUNCH SITE COORDINATE SYSTEM

Owner Organization: Ground Operations Project

X-axis: Vertically down, normal to the Earth reference ellipsoid. The X-axis is parallel with the launch vehicle centerline when the vehicle is in the launch position. It is recognized that there is a slight misalignment between the reference ellipsoid normal vector and the gravity vector, but this difference is considered to be negligible.

Z-axis: Due east.

Y-axis: Completes the right-handed system (north).

Origin: In the Y-Z (horizontal) plane, the origin is centered between Mobile Launcher Mount Mechanisms 1 and 4 (see Figure 4.1-1). Mount Mechanisms 1 and 4 are the 2 northernmost mount mechanisms. In the X (vertical) direction, the origin is 166.73 meters (6,564 inches) above the launch pad surface.

NOTES:

The Mobile Launcher "0 deck" is at X = 152.4 meters (500 feet).

There is a difference in launch pad surface altitude between Launch Complex 39 pads A and B.

An X-axis referenced to the Mobile Launcher mount mechanisms, independent of Launch Vehicle X axis, was chosen because there may be differences positions, relative to the launch pad, for different vehicles and missions.

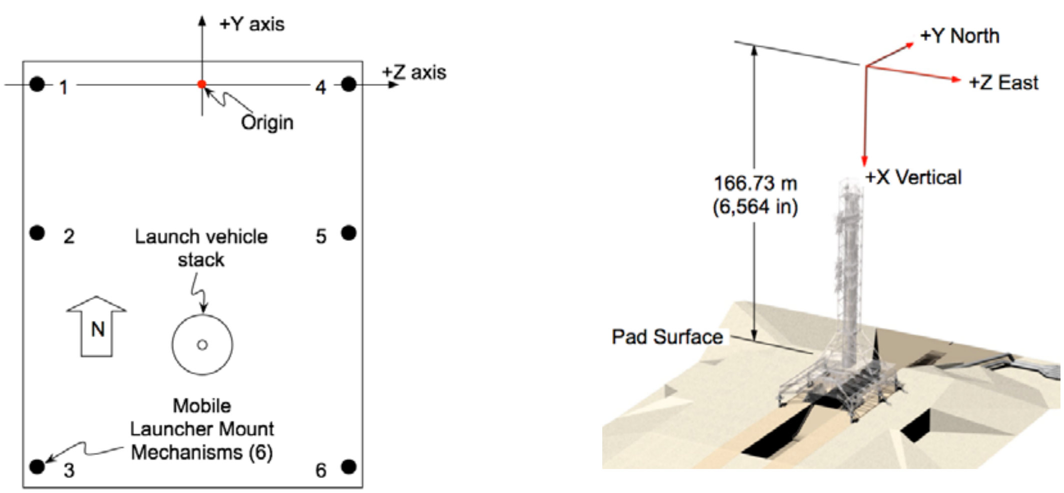


FIGURE 4.1-1 LAUNCH SITE COORDINATE SYSTEM

5.0 EULER SEQUENCE & QUATERNION STANDARDS

5.1 EULER SEQUECES

This section contains a description of the Euler Sequence standards to be used by the Constellation Program. These sequences are a series of three rotations that describe the movement from one coordinate frame to a second frame. Euler sequences have the advantage of being easy to understand and display and are therefore used by ground and flight crews when discussing maneuvers. However, because singularities exist when certain axes are pointed to zero, these sequences are not used in flight software and are instead replaced by quaternions (see Section 5.2 for more details on quaternions).

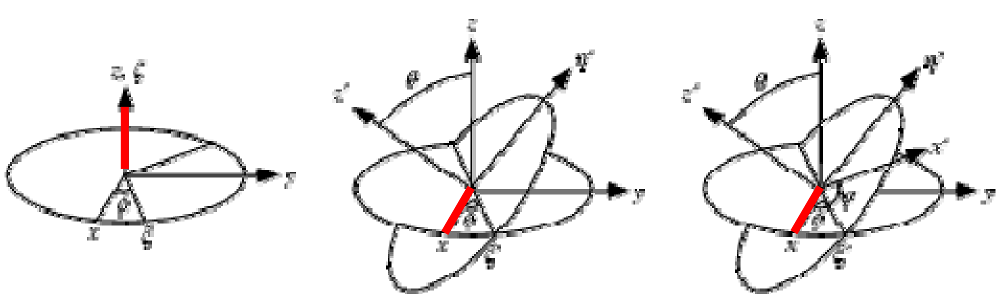
According to Euler's rotation theorem, any rotation may be described using three angles. If the rotations are written in terms of rotation matrices B, C, and D, then a general rotation A can be written as:

$$A = B\,C\,D.$$

Write the matrix A as:

$$A \equiv \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}.$$

The three angles giving the three rotation matrices are called Euler angles. There are several conventions for Euler angles, depending on the axes about which the rotations are carried out.



In the example illustrated above, the rotation given by Euler angles (ϕ, θ, ψ), where the first rotation is by an angle ϕ about the z-axis, the second is by an angle $\theta \in [0, \pi]$ about the x-axis, and the third is by an angle ψ about the z-axis (again). This is known as a 3-1-3 rotation, or Z-X-Z, or in aerospace terminology Yaw-Roll-Yaw (where Roll is about the X-axis, Pitch about the Y-axis, and Yaw about the Z-axis).

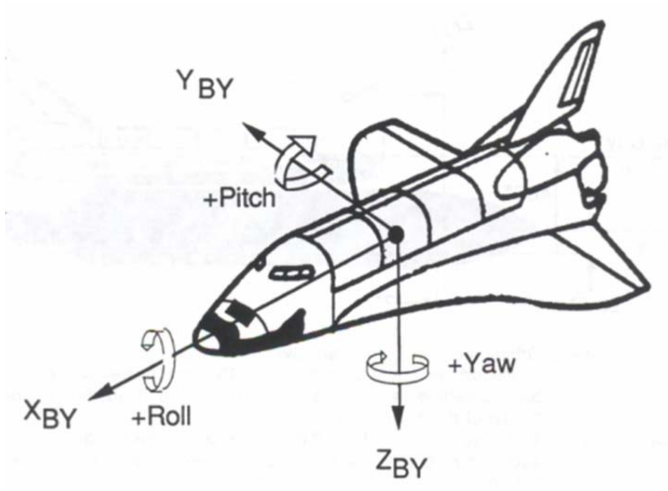
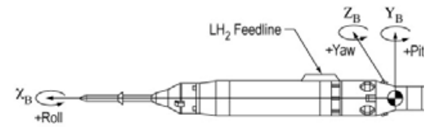
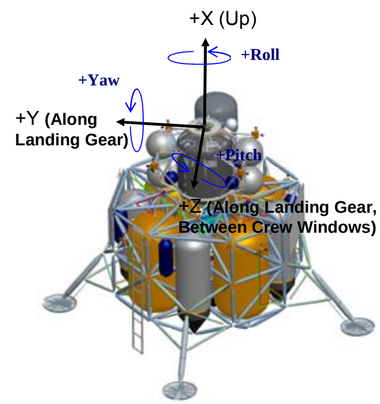
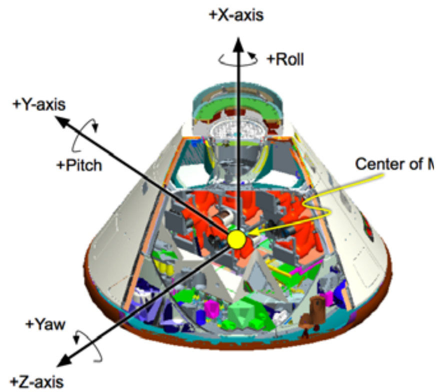
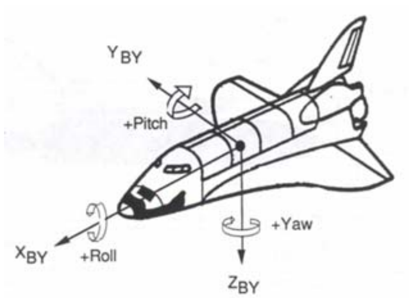


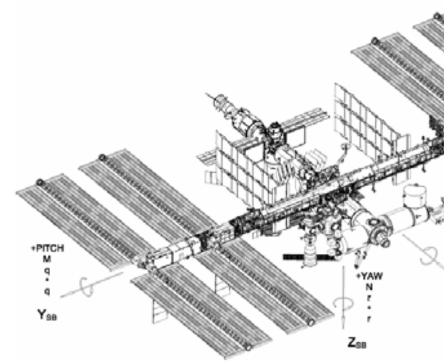
Figure 5-1: Example Shuttle Roll, Pitch, Yaw Axes

For Constellation, a group consensus was reached between Orion, ARES, Altair, MOD, FP-SIG, KSC, Ops Integration, and ATA to adopt a single standard to be used to reduce errors in data transmission between groups and simplify inter-element communication. The standard chosen was PYR (Pitch-Yaw-Roll) and it is to be used in all occasions except those noted in the table below (most exceptions come from pre-existing Shuttle/Station vehicle rules). In addition, when communicating information between elements, data is to be written and transmitted in X,Y,Z format before applying any Euler Sequences, so there is a known starting point for each transformation.

Constellation Euler Sequence Standards

Vehicle	Ascent	Orbit	Entry	Lunar Orbit Rendezvous	Lunar Descent	Attached Ops.	Diagrams
Ares I	PYR	PYR	PYR	PYR	PYR	PYR	
Altair	PYR	PYR	PYR	PYR	PYR	PYR	

Vehicle	Ascent	Orbit	Entry	Lunar Orbit Rendezvous	Lunar Descent	Attached Ops.	Diagrams
Orion	PYR	PYR	Topodetic Pitch / Roll	NA	NA	NA	
Space Shuttle	PYR for: Inertial frame, LVLH & Stored Reference frame YPR for LVIY*	PYR for: Inertial frame, LVLH & Stored Reference frame (Includes transition phase)	Topodetic Pitch & Roll. Yaw fixed at zero (Includes TAEM, A/L, and touchdown phase)	NA	NA		

Vehicle	Ascent	Orbit	Entry	Lunar Orbit Rendezvous	Lunar Descent	Attached Ops.	Diagrams
Space Station	NA	YPR relative to LVLH or Inertial	NA	NA	NA	NA	

* LVIY is a specialized convention similar to LVLH. LVIY fixes yaw at zero, is referenced to MECO targets, and uses a YAW, PITCH, ROLL rotational sequence. In contrast, LVLH is based on the current (instantaneous) position and uses a PITCH, YAW, ROLL rotation sequence. (Reference 14)

5.2 QUATERNIONS

Quaternion Introduction

It follows from Euler's theorem that the relative orientation of any pair of coordinate systems may be specified by a set of four numbers. Three of these numbers are the direction cosines that orient the eigenvector. The fourth is the angle about the eigenvector that separates the two sets of coordinates. Such a set of four numbers is called a quaternion.

A general quaternion q consists of a scalar component q_s (one element) and a vector component $\vec{q}_v$ (three elements) for a total of four elements.

$$q = \{q_s, \vec{q}_v\} \qquad \text{or} \qquad q = \left\{ q_s, \begin{bmatrix} q_x \\ q_y \\ q_z \end{bmatrix} \right\}.$$

Unlike Euler Sequences, Quaternions contain no singularities throughout the full 360 deg. rotation of any axis, and are therefore used in flight software calculations.

The following material describes the Quaternion standards to be used in inter-element transformation of Coordinate System data on the Constellation Program. (Reference 15)

===

Positive Rotation standard **..** Right-handed

===

To/From Written Notation standard

from to from to

$${}^{A}q^{B} = {}^{A}\{q_s, \vec{q}_v\}^{B}$$

Note: this To/From notation reinforces the need to stack right-hand quaternions to the right when computing sequential rotations using the standard quaternion multiply. The inner superscripts of adjacent quaternions match and the outer superscripts are the same on both sides of the equation.

1st rot 2nd rot 3rd rot

$${}^{A}\vec{q}^{D} = {}^{A}\vec{q}^{B} \otimes {}^{B}\vec{q}^{C} \otimes {}^{C}\vec{q}^{D}$$

===

Scalar location standard

Unambiguous structure where possible

The written notation should maintain an unambiguous scalar element by indicating with a q_s. How it is "placed" relative to the vector element $\vec{q}_v = \lfloor q_x, q_y, q_z \rfloor$ is not critical.

$$\{q_s, \vec{q}_v\} = \{\vec{q}_v, q_s\} = \begin{Bmatrix} \vec{q}_v \\ q_s \end{Bmatrix} = \begin{Bmatrix} q_s \\ \vec{q}_v \end{Bmatrix}$$

Note: should deliberately avoid 1,2,3,4 or 0,1,2,3 as subscripts as this has ambiguity on the scalar location.

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = \left\{ \begin{bmatrix} q_s \\ q_x \\ q_y \\ q_z \end{bmatrix} or \begin{bmatrix} q_x \\ q_y \\ q_z \\ q_s \end{bmatrix} \right\} ? \text{ Similarly, } \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} = \left\{ \begin{bmatrix} q_s \\ q_x \\ q_y \\ q_z \end{bmatrix} or \begin{bmatrix} q_x \\ q_y \\ q_z \\ q_s \end{bmatrix} \right\} ?$$

Scalar first where needed

If the four elements need to be put in a one-dimensional array for the sake of external user consumption (put on a display or in a bit stream in telemetry), the standard it to put the scalar first, and then the x, y, z elements of the vector.

$$\lfloor q_s, q_x, q_y, q_z \rfloor \text{ or } \begin{bmatrix} q_s \\ q_x \\ q_y \\ q_z \end{bmatrix}$$

===

Scalar Sign Standard

Scalar element to always be positive.

Some algorithms might assume a positive scalar element and not be written robustly to handle a negative scalar.

$$q \triangleq -q$$

Negating ALL the elements of that quaternion produces an equivalent quaternion. We can use the property to maintain the scalar element to be positive.

==

Code Standard – Structure + Naming Convention

QR_frameA_to_frameB.s
QR_frameA_to_frameB.v[3]

Psuedocode Example:

```
//structure definition
typedef struct QUAT_TAG{................s    ; // scalar element
                         v[3] ; // vector element
                    } QUAT_TYPE;

//Declaration (using variable name convention)
QUAT_TYPE QR_frameA_to_frameB


//Variable assignment example
//Note: deliberately listed with “scalar last” to show
independence of //order
QR_frameA_to_frameB.v[0] = 0.5;
QR_frameA_to_frameB.v[1] = 0.0;
QR_frameA_to_frameB.v[2] = 0.0;
QR_frameA_to_frameB.s    = 0.5;
```

NOTE:

The byte order of the quaternion elements in memory is dependent on:
(a) the order of the structure members and..
(b) the possibly variability between compilers and operating systems.

Therefore, telemetry should not assume how the structure members will be ordered in memory.

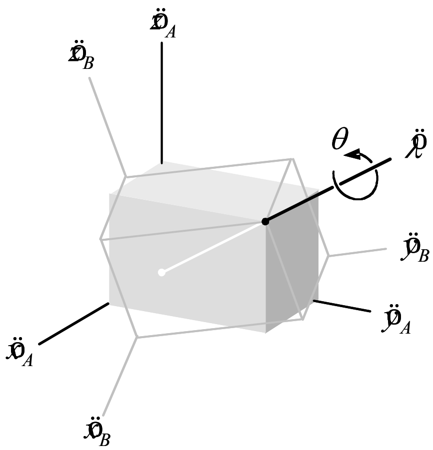
Telemetry should explicitly address both the scalar and vector elements.

===

Back up – Positive Rotation Standard

When an attitude quaternion is constructed from an eigen-axis and eigen-angle, a standard for positive rotation needs to be defined. The options are “right-handed” or “left-handed”.

Consider the figure below.



Imagine that frame B is originally aligned with frame A*, then imagine rotating frame B about $\hat{\lambda}$ through the angle θ. Doing so would have frame B end up in the orientation shown. It can be shown that any two arbitrary frames can be related via a single Eigen axis/ Eigen angle combination.

Let us define the positive sense of the eigen-angle θ **rotation in a right-handed sense**. That is, if you were to point your right-thumb in the direction of the eigen-axis $\hat{\lambda}$, your fingers would curl in the direction of a positive eigen-angle θ. Using this polarity standard for eigen-angle wrt eigen-vector…

a **right-hand quaternion** is constructed as…

$$q_s = cos\left(\tfrac{1}{2}\theta\right)$$

$$\vec{q}_v = +\hat{\lambda} \cdot sin\left(\tfrac{1}{2}\theta\right) = \begin{bmatrix} q_x \\ q_y \\ q_z \end{bmatrix} = \begin{bmatrix} +\lambda_x sin\left(\tfrac{1}{2}\theta\right) \\ +\lambda_y sin\left(\tfrac{1}{2}\theta\right) \\ +\lambda_z sin\left(\tfrac{1}{2}\theta\right) \end{bmatrix}.$$

a **left-hand quaternion** is constructed as…

$$q_s = cos\left(\tfrac{1}{2}, \right)$$

---

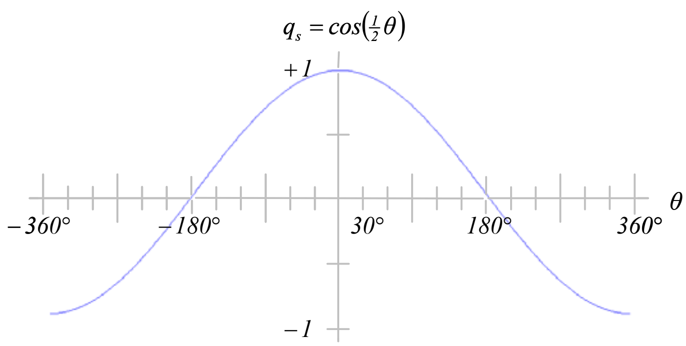
* Notice that frame A and frame B are both right-hand systems. If you curl your right hand’s fingers from the $\hat{x}$ axis toward the $\hat{y}$ axis, your right thumb points along $\hat{z}$.

$$\vec{q}_v = -\hat{\lambda} \cdot sin\left(\tfrac{1}{2}\theta\right) = \begin{bmatrix} q_x \\ q_y \\ q_z \end{bmatrix} = \begin{bmatrix} -\lambda_x sin\left(\tfrac{1}{2}\theta\right) \\ -\lambda_y sin\left(\tfrac{1}{2}\theta\right) \\ -\lambda_z sin\left(\tfrac{1}{2}\theta\right) \end{bmatrix}.$$

===

Back up – Eigen Angle domain

Note: If the Eigen angle is constrained between $0°$ and $180°$ then the scalar component of the attitude quaternion is guaranteed to be positive (or zero in the case of an exact $180°$ rotation).



An attitude quaternion that has a negative scalar component reflects a rotation that exceeds $180°$.

6.0 REFERENCES

1. "Lunar Constants and Models Document", R. Roncoli, JPL D-32296, September 23, 2005, *http://ssd.jpl.nasa.gov/?lunar_doc*.
2. "The adoption of ICRS on 1 January 1998: meaning and consequences", Letter to the Editor, M. Feissel and F. Mignard, Astronomy and Astrophysics, 331, L33-L36, 1998, *http://adsabs.harvard.edu/cgi-bin/nph-bib_query?bibcode=1998A%26A...331L..33F&db_key=AST&data_type=HTML&format=* .
3. "Recent Gravity Models as a Result of the Lunar Prospector Mission", A. S. Konopliv, S. W. Asmar, E. Carranza, W. L. Sjogren, and D. N. Yuan, Academic Press, Icarus 150, 1-18 (2001).
4. "Lunar Laser Ranging Science: Gravitational Physics and Lunar Interior and Geodesy", J. G. Williams, S. G. Turyshev, D. H. Boggs, and J. T. Ratcliff, 35th COSPAR Scientific Assembly, Paris, France, July 18-24, 2004, Advances in Space Research, in press 2005, *http://arxiv.org/abs/gr-qc/?412049*.
5. "Report of the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites: 2000", P.K. Seidelmann, V. K. Abalakin, M. Bursa, M. E. Davies, C. DeBergh, J. H. Lieske, J. Oberst, J. L. Simon, E. M. Standish, P. Stooke, and P. C. Thomas, Celestial Mechanics and Dynamical Astronomy 82: 83-110, 2002. [For those with access to the following website *http://springerlink.metapress.com*, follow the links from "Browse by Online Libraries (subject areas)", then "Physics and Astronomy", then "Celestial Mechanics and Dynamical Astronomy", then "Volume 82 - Number 1/January 2002", then follow the links to download the paper].
6. "The Planetary and Lunar Ephemeris DE 421," W. M. Folkner, J. G. Williams, D. H. Boggs, JPL IOM 343R-08-003, March 31, 2008, *http://ssd.jpl.nasa.gov/iau-comm4/de421iom/*.
7. "Estimation of the Lunar Physical Librations", X. X. Newhall and J. G. Williams, Celestial Mechanics and Dynamical Astronomy 66: 21-30, 1997, *http://adsabs.harvard.edu/abs/1997CeMDA..66...21N* .
8. IERS Conventions (2003), D. D. McCarthy and Gérard Petit (eds.), IERS Technical Note No. 32, 2004; *http://www.iers.org/iers/publications/tn/tn32*.
9. "Lunar coordinates in the regions of the Apollo lander," M. E. Davies and T. R. Coltin, Journal Of Geophysical Research, V. 105, No. E8, Pages 20, 277-20, 280, August 25, 2000.

10. “A Meaningful Relative Motion Coordinate System For Generic Use,” D. R. Adamo, AAS Paper No. 05-306, presented at the AAS/AIAA Astrodynamics Specialists Conference, Lake Tahoe, California, August 7 - 11, 2005.

11 “Lunar moments, tides, orientation, and coordinate frames,” J. G. Williams, X. X. Newhall, and J. O. Dickey, Planet. Space Sci. 44:1077-1080, 1996.

12 Weisstein, Eric W. "Euler Angles." From MathWorld--A Wolfram Web Resource. *http://mathworld.wolfram.com/EulerAngles.html* .

13 “DE421 Lunar Orbit, Physical Librations, and Surface Coordinates,” J. G. Williams, D. H. Boggs and W. M. Folkner, JPL IOM 335-JW,DB,WF-20080314-001, March 14, 2008,
de421_lunar_ephemeris_and_orientation.pdf in ftp://naif.jpl.nasa.gov/pub/naif/generic_kernels/spk/planets/

14 “**(Shuttle) Flight Procedures Handbook”,** Ascent/Aborts (OI-30), Revision F, March 2005, JSC-10559, Additional Detail in Section 3.4.1.1

15 “Quaternions and Rotation Sequences: A Primer with Applications to Orbits, Aerospace, and Virtual Reality,” Jack B. Kuipers, Princeton University Press, 1999.

APPENDIX A
ACRONYMS AND ABBREVIATIONS
AND GLOSSARY OF TERMS

A1.0 ACRONYMS AND ABBREVIATIONS

AS	Ascent Stage
CEV	Crew Exploration Vehicle
CM	Center of Mass
EDS	Earth Departure Stage
EM-ROT	Earth-Moon Rotating
EOP	Earth Orientation Parameters
FK	Frames Kernel
GN&C	Guidance, Navigation, and Control
IAG	International Association of Geodesy
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
IERS	International Earth Rotation and Reference Systems Service
ISS	International Space Station
ITRF	International Terrestrial Reference Frame
ITS	Integrated Truss Segment
JPL	Jet Propulsion Laboratory
LAS	Launch Abort System
LMEBF	Lunar Mean Earth Body-Fixed
LPABF	Lunar Principal Axis Body-Fixed
LPAE	Lunar Principal Axis of Epoch
LSAM	Lunar Surface Access Module
LVC	Local Vertical Curvilinear
LVLH	Local Vertical Local Horizontal
M	Mean
mas	milliarcseconds
MMEIAUE	Mars Mean Equator and IAU-Node of Epoch
MMEPMBF	Mars Mean Equator and Prime Meridian Body-Fixed

NAIF	Navigation and Ancillary Information Facility
NASA	National Aeronautics and Space Administration
NR	Non-Rotating
OPR	Office of Primary Responsibility
P	Principal
PA	Principal Axis
PCK	Planetary Constants Kernel
SE-ROT	Sun-Earth Rotating
SIG	Systems Integration Group
SM	Service Module
SPK	Spacecraft and Planet Kernel
TBD	To Be Determined
TBR	To Be Resolved
TCB	Barycentric Coordinate Time
TCG	Geocentric Coordinate Time
TDB	Barycentric Dynamical Time
TT	Terrestrial Time

A2.0 GLOSSARY OF TERMS

Term	Description
None	

APPENDIX B
OPEN WORK

B1.0 TO BE DETERMINED

Table B1-1 lists the specific To Be Determined (TBD) items in the document that are not yet known. The TBD is inserted as a placeholder wherever the required data is needed and is formatted in bold type within brackets. The TBD item is numbered based on the section where the first occurrence of the item is located as the first digit and a consecutive number as the second digit (i.e., **<TBD 4-1>** is the first undetermined item assigned in Section 4 of the document). As each TBD is solved, the updated text is inserted in each place that the TBD appears in the document and the item is removed from this table. As new TBD items are assigned, they will be added to this list in accordance with the above described numbering scheme. Original TBDs will not be renumbered.

TABLE B1-1 TO BE DETERMINED ITEMS

TBD	Section	Description
None		

B2.0 TO BE RESOLVED

Table B2-1 lists the specific To Be Resolved (TBR) issues in the document that are not yet known. The TBR is inserted as a placeholder wherever the required data is needed and is formatted in bold type within brackets. The TBR issue is numbered based on the section where the first occurrence of the issue is located as the first digit and a consecutive number as the second digit (i.e., **<TBR 4-1>** is the first unresolved issue assigned in Section 4 of the document). As each TBR is resolved, the updated text is inserted in each place that the TBR appears in the document and the issue is removed from this table. As new TBR issues are assigned, they will be added to this list in accordance with the above described numbering scheme. Original TBRs will not be renumbered.

TABLE B2-1 TO BE RESOLVED ISSUES

TBR	Section	Description
None		