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Mars Exploration Rover (MER) Project
Pointing, Positioning, Phasing & Coordinate Systems (PPPCS)

Section a (Initial Release)

MER Coordinate Systems

Document Custodian:

Martin Greco
Section 313

Approved by:

Rob Manning
Systems PEM

Scott Doudrick
Section 313

Randy Lindemann
Rover Mechanical Lead

Joanathan Stabb
Launch Vehicle Integration

James Baughman
Cruise/EDL Mechanical Lead

Justin Maki
Imaging Investigation Scientist

August 28, 2002

Jet Propulsion Laboratory
California Institute of Technology

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1 Purpose, Scope and Background

1.1 Relationship to Other Documents

The MER Pointing, Positioning, Phasing & Coordinate System document is part of the MER document structure at level 3.

The MER Pointing, Positioning, Phasing & Coordinate System document consist of multiple documents under individual signature control. These documents are as follows with this document bolded.

Document Name	MER Document Number	Document D Number	Custodian
MER Pointing, Positioning, Phasing & Coordinate Systems Master	MER420-2-431	D-19720	Doudrick
MER Coordinate Systems	**MER420-2-431.a**	**D-20506**	**Greco**
MER Phasing	MER420-2-431.b	D-20507	Swenka
MER Spin Rate & Cruise Pointing Error Budgets	MER420-2-431.c	D-20508	Swenka
MER TCM and Residual Error Budgets	MER420-2-432.d	D-20509	Greco
MER Turn to Entry Error Budget	MER420-2-431.e	D-20510	Swenka
MER Bridle Cut Altitude Error Budgets	MER420-2-431.f	D-20511	
MER Surface Attitude Estimation Error Budgets	MER420-2-431.g	D-20512	Swenka
MER HGA Pointing Error Budgets	MER420-2-431.h	D-20513	Doudrick
MER Instrument Positioning System (IPS) Pointing and Positioning Budgets	MER420-2-431.i	D-20514	Greco
MER Surface Navigation Error Budgets	MER420-2-431.j	D-20515	Doudrick
MER PanCam to Mini-TES Coregistration Error Budgets	MER420-2-431.k	D-20516	Doudrick

1.2 Purpose & Scope

The objective of the MER Pointing, Positioning, Phasing & Coordinate System (PPPCS) document is to respond to accuracy requirements levied on the MER flight system and to define the MER flight system coordinate systems and phasing. This section specifically addresses system level accuracy requirements pertaining to the cruise phase of the MER mission. MER subsystems, software and/or assemblies are allocated accuracy requirements to meet those system-level requirements. Then through the process of error budgeting, all the contributing error sources are summarized as a system capabilities and compared to systems requirements. Discrepancies between the requirements and capabilities are then reconciled through negotiations and documented here in this document.

This documents also provides the Mars Exploration Rover team members with a common document for coordinate frame definition for the duration of the mission. The document includes the coordinate frame orientation, directions, as well as rotational and translational matrices between frames. Time System and Tilt Angle definitions are also included.

1.3 Derived Requirements

Requirements derived from the error budgets are listed after each error budget along with any assumptions that were made. These requirements are also summarized at the end of this document in Section 3.

2 MER Coordinate Systems

2.1 Foreword

Dimensions are taken or derived from design drawings; actual dimensions will be known upon completion of the metrology.

2.2 Background

In this document, the concepts of frame orthogonality and right-handed polarity are utilized. Although these are simple and commonplace concepts, they will be defined here to ensure a mutual understanding of the frame definitions.

Let a frame U be defined by the unit vectors $\underline{u}_1$, $\underline{u}_2$, and $\underline{u}_3$. Then the U frame is orthogonal if

$$u_i \bullet u_j = 0, for \quad i \neq j$$

$$u_i \bullet u_j = 1, for \quad i = j$$

where i = 1, 2, 3, and j = 1, 2, 3.

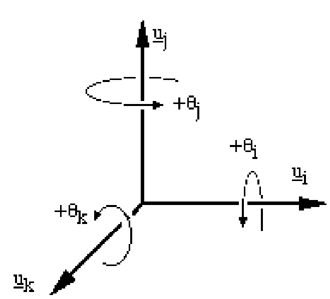
Since $\underline{u}_i \bullet \underline{u}_j = \cos\theta$, where θ is the angle defined by $\underline{u}_i$ and $\underline{u}_j$, the axes of the U frame are exactly 90° apart. Furthermore, the U frame is right-handed if

$$u_i \times u_j = u_k$$

where i, j, k = 1, 2, 3 or 2, 3, 1 or 3, 1, 2 (i.e. cyclic permutation).

The import of the right-handed definition is with regard to rotation angles about the frame axes. An angle measured as a rotation about $\underline{u}_k$ has a positive polarity if the right thumb is directed along $\underline{u}_k$ and the fingers curl in the direction of rotation as shown in Figure 2-1.

Figure 2-1 Right Hand Polarity



2.2.1 Coordinate Transformation Convention

The coordinate frame transformation convention for this document will be as follows:

To transform from the A frame to the B frame,

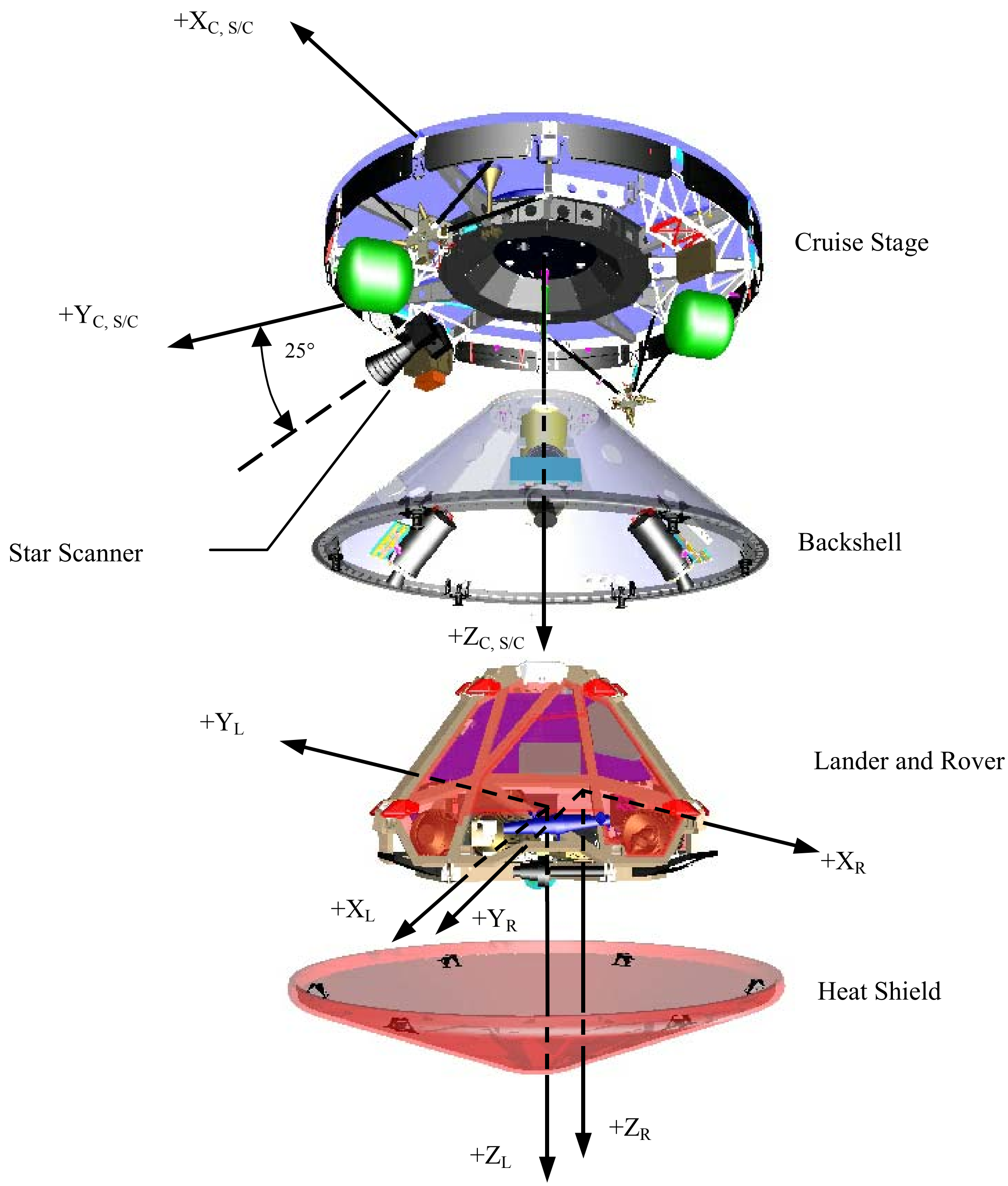
Xb = bCa Xa

The transformation is read from right to left.

2.2.2 Coordinate System Integration

Figure 2-2 shows the various integrations of the Mars Exploration Rover coordinate frames that will be covered in detail in the following sections.

Figure 2-2 Integration of Various Mars Exploration Rover Coordinate Frames.



2.3 Coordinate & Time Systems Applicable Across All Mission Phases

2.3.1 J2000 Coordinates (J Frame)

The J2000 coordinate system is right handed, orthogonal, and defined by axes X_J, Y_J, and Z_J. It is defined as the standard coordinate frame for all in-flight, ground and ephemeris processing during all phases of the mission, where the origin is defined at the center of the Earth (reference body) and,

$X_J \equiv$ lying in the Earth equatorial plane (X_J/Y_J plane – reference plane) and directed along the vernal equinox of Earth's mean orbit (reference direction).

$Y_J \equiv$ lying in the equatorial plane and orthogonal to X_J and Z_J.

$Z_J \equiv$ through the North Pole and perpendicular to the Earth equatorial plane.

2.3.2 Universal Time (UT)

UT is defined as the time at 0° longitude, the Greenwich meridian, i.e. Midnight in Greenwich, England, it is also midnight (00:00:00.000000) in UT.

2.3.3 Earth Relative Time (ERT)

TBS (same as MPF)

2.3.4 Generic Mars Sol Time (GMST)

TBS

Will allows for using sequences at the same Mars time on different sols.

2.4 Launch Phase

2.4.1 Launch Vehicle Upper Stage Coordinates (L/V-Frame)

Table 2-1 Launch Vehicle / MER Cruise Stage Coordinate System Axes Relative Orientation

Figure 2-3 Launch Vehicle Upper Stage Configuration.

2.4.1.1 Launch Vehicle Adapter (LVA Plane)

Figure 2-4 LVA and Launch Vehicle Separation Plane

2.4.2 LV HVL Coordinate Frame (HVL)

2.4.3 Spacecraft Spin Vector

Figure 2-5 Mars Exploration Rover Spin Direction.

2.5 Cruise Phase

2.5.1 Cruise Stage and Spacecraft Coordinate Frame (C and S/C - Frames)

The MER Cruise and Spacecraft coordinate frames are equal. The cruise coordinate system is right handed, orthogonal, and defined by axes X_C, Y_C, and Z_C, where the X_C/Y_C plane is defined as the plane of the entry vehicle interface pads located at the top of the Backshell Interface Plate (BIP, also known as entry vehicle separation plane), and containing the points R, S and T. The coordinate systems and primary datum for the spacecraft are fully defined by the three points that are located between the BIP and the Cruise Stage on the BIP side of the interface.

The origin of the coordinate system is defined by the center of the circle defined by these three points. The $+Z_C$ axis emanates from the origin in the X_C/Y_C plane, is normal to the X_C/Y_C plane and points toward the end of the aeroshell. This is the launch direction. The $+Y_C$ axis emanates from the origin in the X_C/Z_C plane, bisects the line between points S and R, and points in the direction of the Star Scanner Assembly (SSA). (Figure 2-6, Figure 2-7, Figure 2-8, Figure 2-9 and Figure 2-10)

Figure 2-6 Mars Exploration Rover Spacecraft Coordinate Definition - View 1.

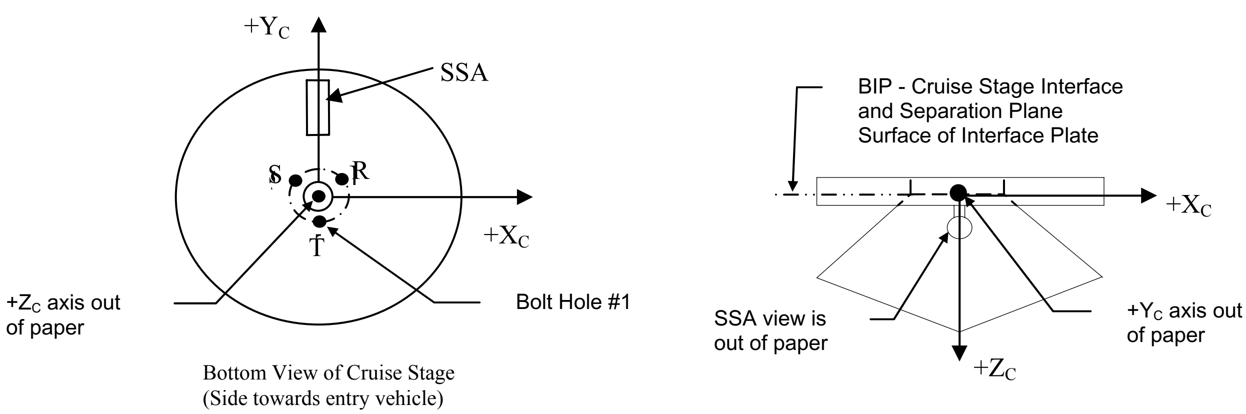


Figure 2-7 Mars Exploration Rover Cruise Stage Coordinate Definition – View 2.

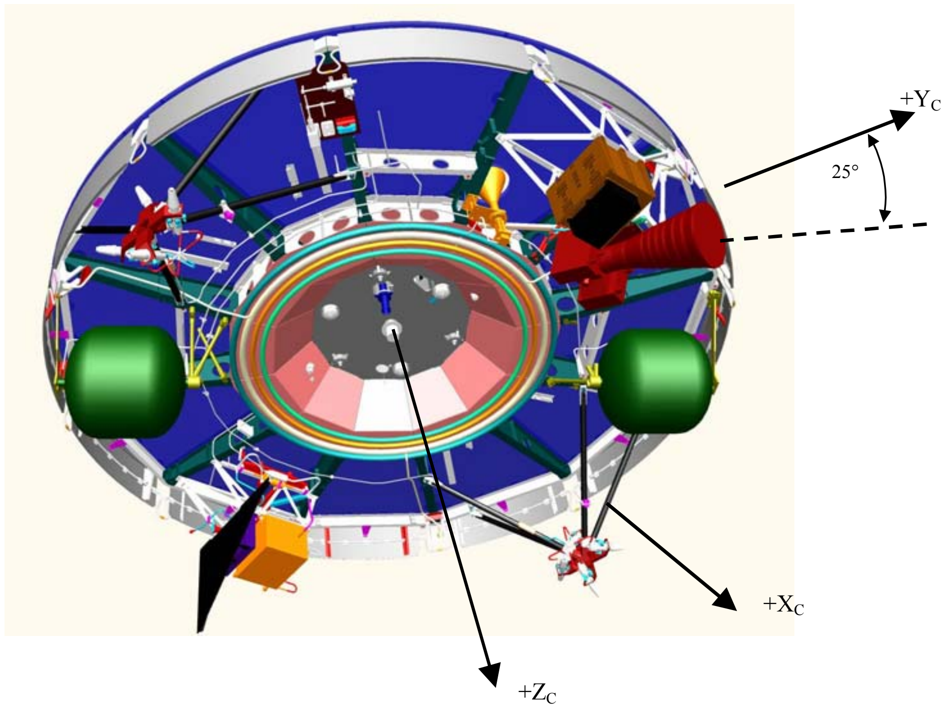


Figure 2-8 MER Cruise Stage Coordinate Definition - View 3.

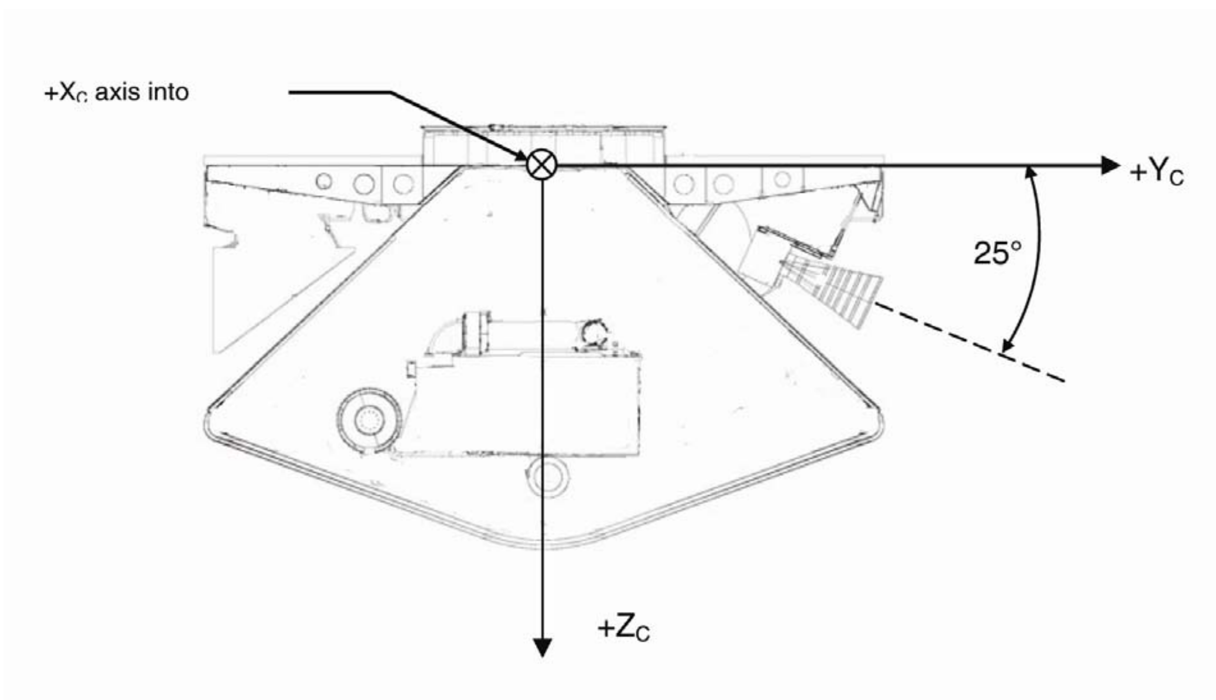


Figure 2-9 MER Cruise Stage Coordinate Definition - View 4.

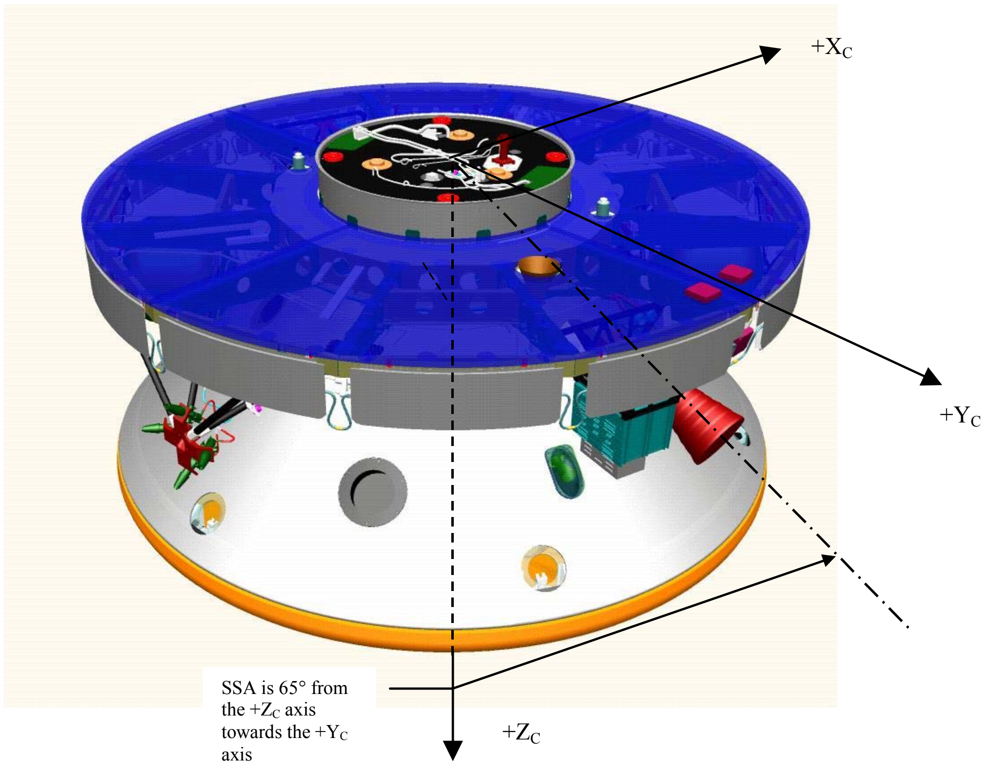
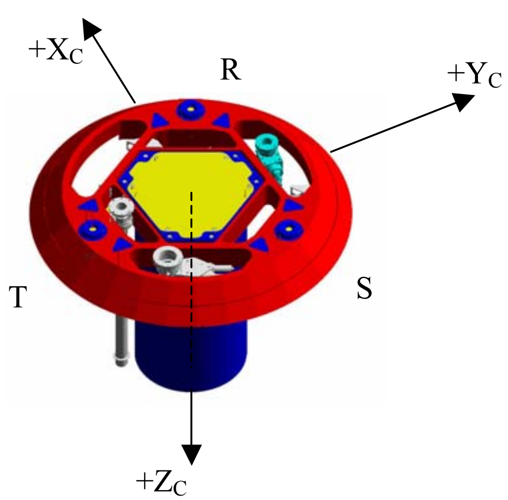


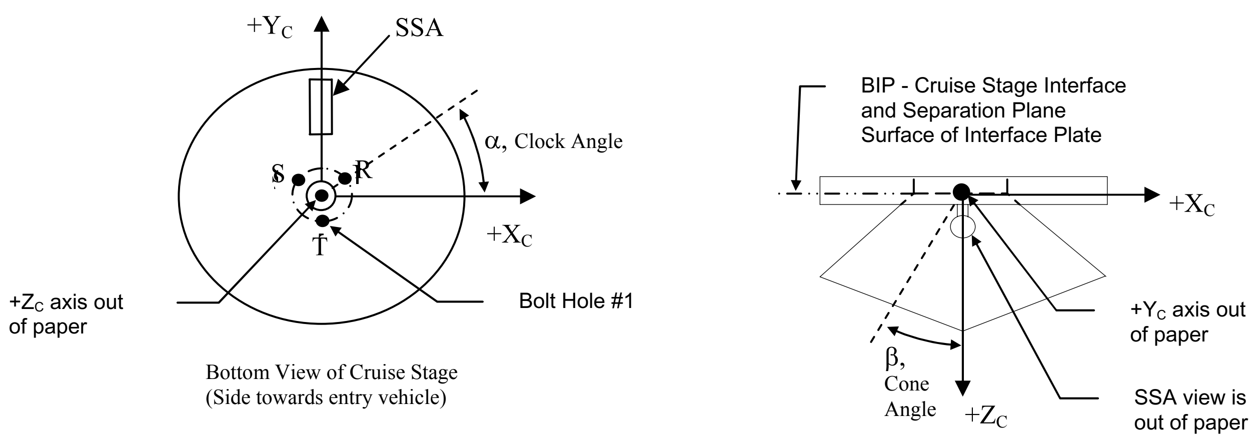
Figure 2-10 MER Backshell Interface Plate (BIP)



2.5.2 Angle Definitions

The clock and cone angles for all Mars Exploration Rover coordinate systems are identical in definition, except for the Rover that uses pitch, roll and yaw. The cone angle β (where 0≤β≤180 degrees) is defined as the angle at the origin of the coordinate system, from the Z_C axis to the specified object or vector. The clock angle is defined as the angle α (where 0≤α≤360 degrees) between the intersection of the plane containing the Z_C axis and the specified object or vector located in the X_C/Y_C plane. This angle is defined as positive in the clockwise direction from the X_C axis when viewing toward the Z_C direction. The angle definitions can be seen graphically in Figure 2-11 utilizing the cruise stage as an example.

Figure 2-11 Spacecraft Angle Definitions



2.6 Entry Phase

2.6.1 Entry Vehicle Coordinates (E Frame)

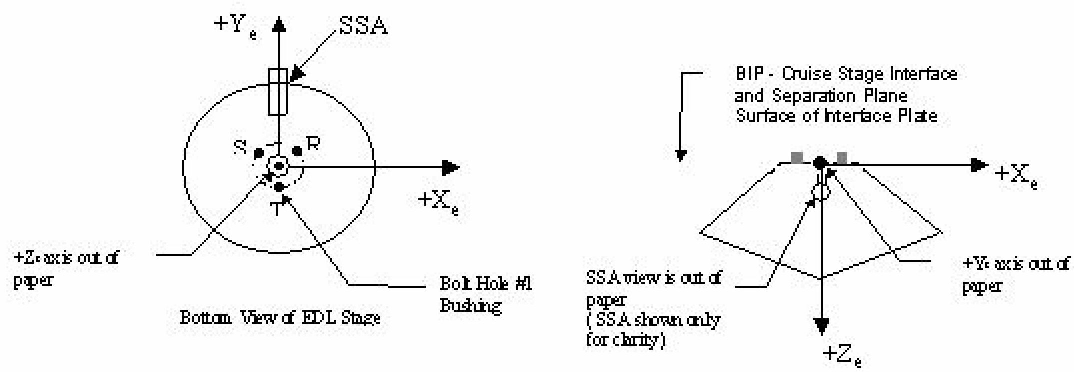
The coordination frames of the Mars Exploration Rover entry vehicle are shown in Figure 2-12. It is right handed, orthogonal, and defined by axes X_e, Y_e, and Z_e, where the origin of the entry vehicle frame is identical to the one for the cruise coordinate frame. The X_e/Y_e plane is defined as the plane of the entry vehicle interface pads located at the top of the backshell interface plate, and

$X_e \equiv X_c$ lying in the entry vehicle separation plane (X_e/Y_e plane), positively directed outward in the entry vehicle separation plane outward from the Z_e axis and orthogonal to Y_e and Z_e.

$Y_e \equiv Y_c$ lying in the X_e/Y_e plane and positively directed outward in the entry vehicle separation plane outward from the Z_e axis toward the SSA when the entry vehicle and the cruise stage are attached to each other ($-Y_e$ lies in the direction of interface bushing #1).

$Z_e \equiv Z_c$ coincident with the nominal spacecraft spin axis, through the geometric center of the three interface bushing holes for connecting the entry vehicle to the cruise stage, and positively directed outward from the spacecraft center of mass towards the heatshield.

Figure 2-12 Mars Exploration Rover Entry Vehicle Coordinate Definition.



2.7 Surface Phase

2.7.1 Lander Coordinate Frame (L Frame)

Figure 2-13 Lander Coordinate Frame - View 1.

Figure 2-14 Lander Coordinate Frame - View 2.

2.7.1.1 Lander Tilt Angle Definitions

Figure 2-15 Lander Cone Angle Definition

Figure 2-16 Lander Clock Angle Definition

2.7.2 Rover Coordinate Frames

There are two coordinate frames for the MER rover. The Rover Mechanical Frame is used by mechanical for the rover design. The Rover Traverse Coordinate Frame is used by the navigation and imaging teams during testing and mission operations see Section 2.7.3.5.

2.7.2.1 Rover Mechanical Coordinate Frame (R Frame)

The MER rover coordinate system is right handed, orthogonal, and defined by axes X_R, Y_R, and $Z_{R.}$ The $+Z_R$ axis emanate from the origin in the X_R/Y_R plane, is normal to the X_C/Y_C plane and points toward the end of the aeroshell, this is the launch direction. The origin of the coordinate system is offset from the cruise and lander coordinate frames as described below for the rover in stowed and deployed configurations.

2.7.2.1.1 Rover Pre-Deployed -Middle wheel restrains still attached- RPD

Figure 2-17 Rover Mechanical Coordinate Definition – View 1 (Stowed)

Figure 2-18 Rover Mechanical Coordinate Definition – View 2

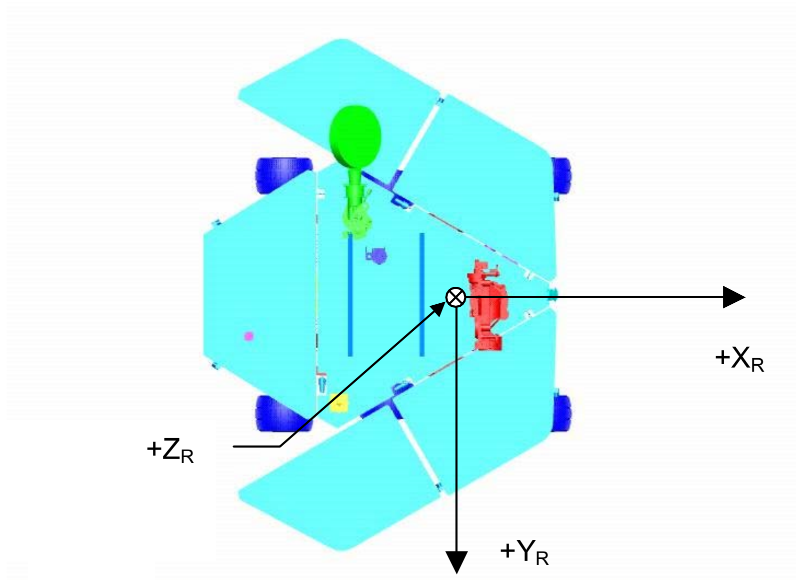
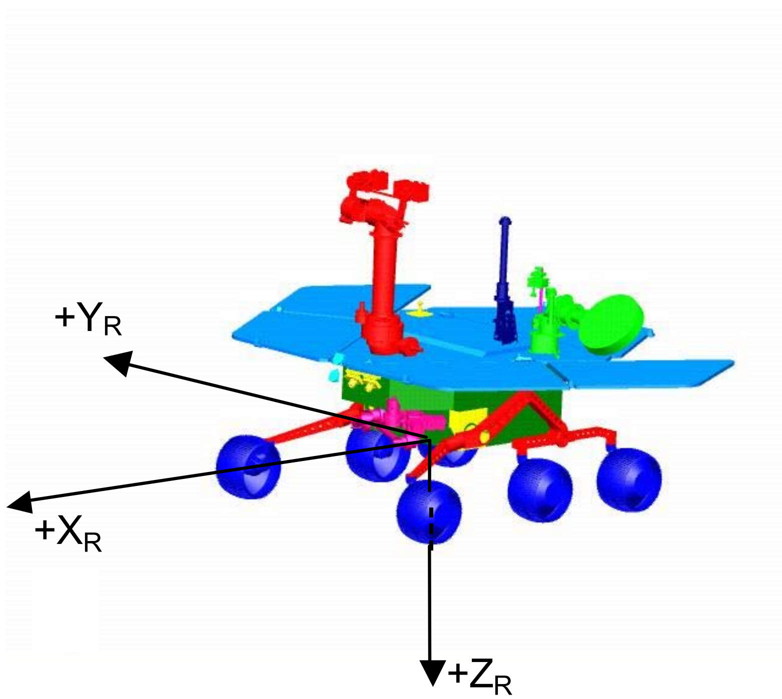


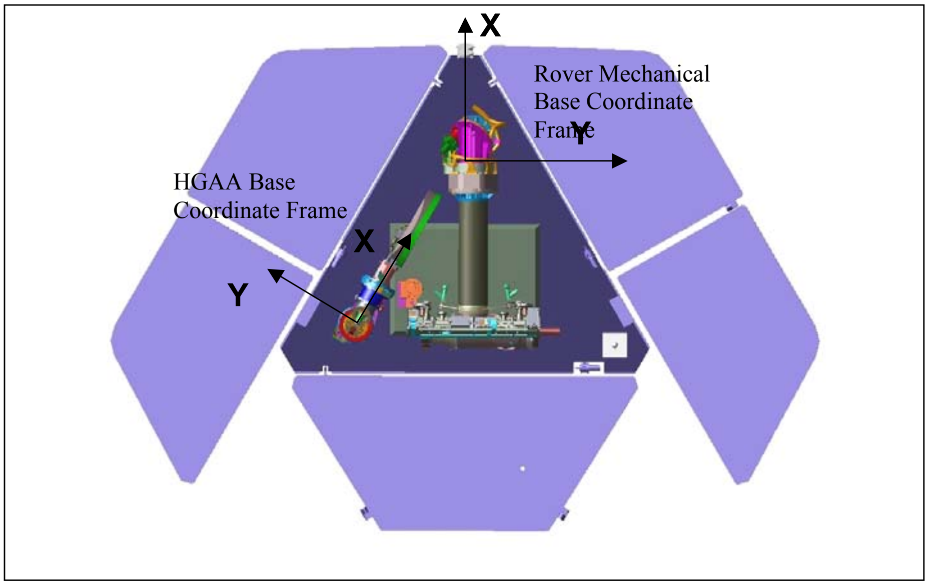
Figure 2-19 Rover Mechanical Coordinate Frame Definition - View 3



2.7.2.2 HGA Frame (HGA)[i]

The HGA is mounted on the top of the RED and the coordinate frame is defined by the following. The HGA coordinate system is right handed, orthogonal, and defined by axes X_{HGA} Y_{HGA}, and Z_{HGA}, where the X_{HGA}/Y_{HGA} plane is defined interface mounting plane between HGAA and RED as seen in Figure 2-21. The $+Z_{HGA}$ axis emanates from the origin in the X_{HGA}/Y_{HGA} plane, is anti-normal to the X_R/Y_R plane and points toward the cruise stage.

Figure 2-20 HGA Frame



2.7.2.3 IDD Frame (IDD Frame)

Figure 2-21 IDD Coordinate Frame Definitions 1

Figure 2-22 IDD Coordinate Frame Definitions 2

Figure 2-23 IDD Coordinate Frame Definitions 3

Figure 2-24 IDD Coordinate Frame Definitions 4

2.7.2.4 PMA Frame (PMA)

Figure 2-25 PMA Frame

2.7.3 Mars Surface Coordinate Frames and Time Systems

2.7.3.1 Mars Body Fixed Coordinate Frame (MBF Frame)

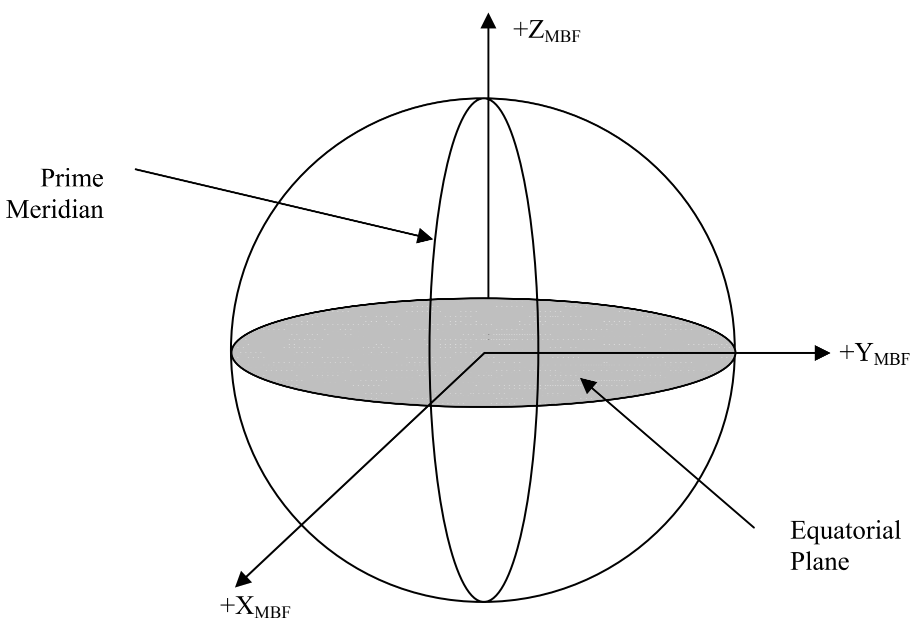
The Mars body fixed reference axes have their origin at the Mars center-of-mass and are aligned with the spin axis and prime meridian as defined by the IAU[ii] see Figure 2-26. This frame is described as the following:

$+Z_{mbf} \equiv$ Mars spin axis, pointing toward Martian North Pole.

$+X_{mbf} \equiv$ Vector lies in the Mars equatorial plane and intersects the prime meridian.

$+Y_{mbf} \equiv$ Vector lies in the Mars equatorial plane and completes a right handed coordinate system.

Figure 2-26 Mars Body Fixed Coordinate Frame



2.7.3.2 Mars Local Level Coordinate Frame (M Frame)

The Mars Local Level Coordinate Frame (M Frame) is right handed, orthogonal, and defined by axes X_M, Y_M, and Z_M. It is described as a North, East, Nadir frame whose origin is coincident with the Lander L frame. There are no translations in any directions with respect to the L frame. It is defined relative to the Mars body fixed frame using radius, r, aerocentric latitude, ϕ, and aerocentric longitude, λ, of the rover frame as follows:

The origin is coincident with the Rover Frame origin, or

$$r[\cos(\phi)\cos(\lambda) \quad \cos(\phi)\sin(\lambda) \quad \sin(\phi)]$$

with respect to the Mars Body Fixed Frame.

Its orientation with respect to the Mars Body Fixed Frame is defined by the Z followed by Y sequence of rotations:

$\mathbf{C}_2(-\pi/2\text{-Lat})\mathbf{C}_3(\text{Lon})$

Where $\mathbf{C}_2$ and $\mathbf{C}_3$ are the matrices of rotation about the Y and Z-axes, respectively.

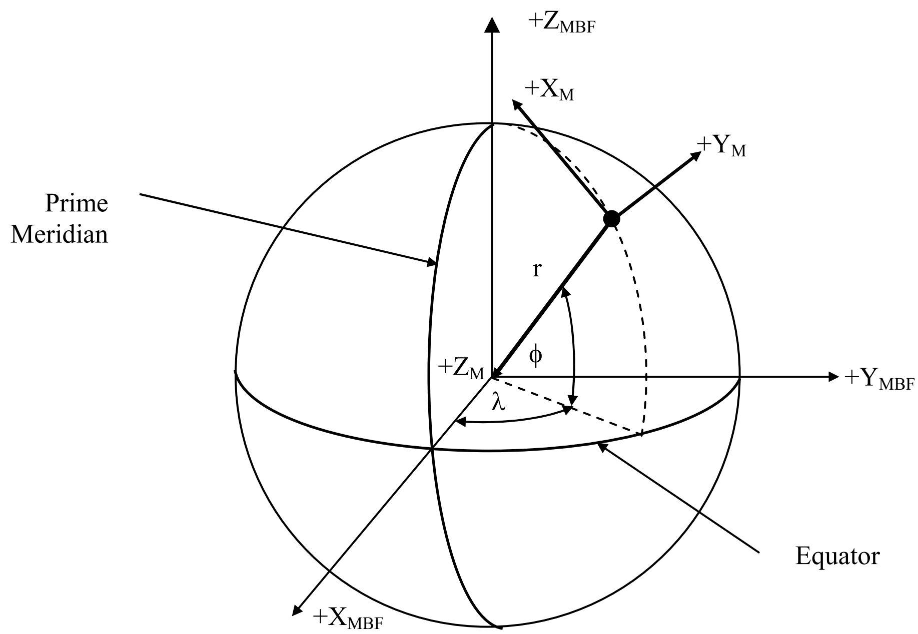
Within the this subsystem, sign conventions for latitude, ϕ, and longitude, λ, shall be:

$-90 < \phi < 90$ deg (positive in northern hemisphere), and

$0 < \lambda < 360$ deg (positive east)

Since west longitude is often used by the science community, all MER data products should clearly state whether the east or west convention is being used for longitude. See Figure 2-27

Figure 2-27 Mars Local Level Coordinate Frame Description



2.7.3.3 Surface Fixed Coordinate Frame (S Frame)

The Surface Fixed Frame (S) is described as a North, East, Nadir frame whose origin is initially coincident with the Rover (R) frame and is initially equivalent to the Mars Local Level Frame (M). After the Lander petals have been deployed and Rover orientation has been initially estimated (through accelerometer measurements located in the rover IMU and sun search performed by the cameras), this frame is fixed with respect to the Mars Body Fixed Frame (MBF) and is no longer assumed coincident with the R frame or equivalent to the M frame. The initial S frame shall be fixed thereafter.

$Z_S \equiv$ unit vector that is normal to the Mars IAU[iii] Reference Ellipsoid, which originates at the Lander (L) origin at the time of or immediately prior to the Sun search, and which points down into the Ellipsoid. This is the Nadir vector.

$X_S \equiv$ unit vector that points toward the North Spin Axis, that lies in the plane tangent to the reference ellipsoid, and which originates as given above in the Z_S definition.

$Y_S \equiv$ unit vector that is orthogonal to X and Z that completes a right hand coordinate frame. In addition, this originates as given above in the Z_S definition. This is the Nominal East Vector.

2.7.3.4 Mars Local Solar Time (MLST)

Local solar time: Time relative to the time of maximum solar elevation (local noon) at a point on the Martian surface. This time is expressed in Mars solar seconds (there are 86400 Mars solar seconds in a sol).

Martian sol: The mean solar day for Mars (88775.245 Earth solar seconds).

2.7.3.5 Rover Traverse Coordinate Frames

2.7.3.5.1 Rover Navigation Frame (N Frame)

The rover N frame is used for rover surface navigation. The N coordinate system is right handed, orthogonal, and defined by axes X_N Y_N, and Z_N, where the X_N/Y_N plane is coincident with the X_R/Y_R plane. The $+Z_N$ axis emanates from the origin in the X_N/Y_N plane, is anti-normal to the X_R/Y_R plane and points away the cruise stage. The Y_N axis is aligned with the middle wheel rotation axis for deployed rover and suspension system on flat plane (gravity vector parallel to Z_N). See Figure 2-28 and Figure 2-29

Figure 2-28 N Frame ISO

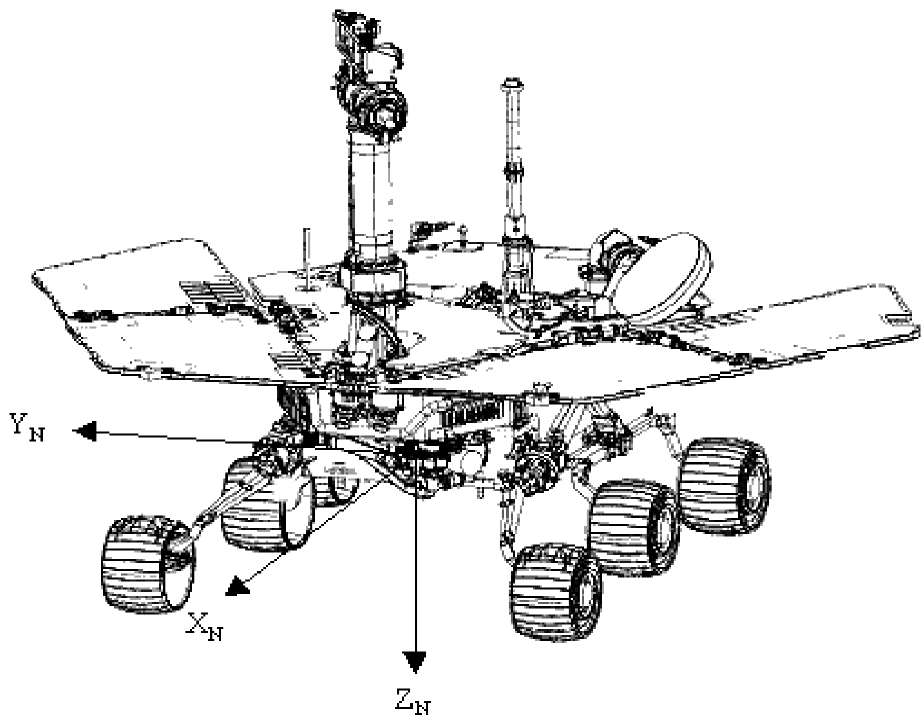
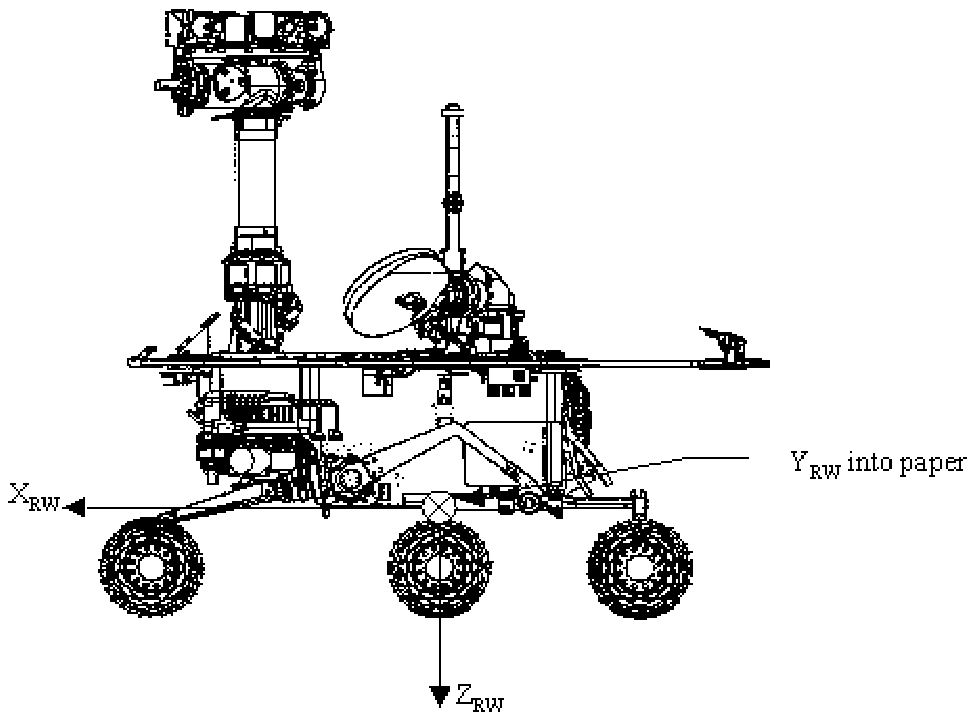


Figure 2-29 RW Frame Left



2.7.3.5.2 Rover Tilt Angle Definitions

Eulerian angles will be used to define the rover tilt angle definitions. Relating the rover orientation from the Mechanical frame (body frame) see Section 2.7.2.1 to the Surface Fixed frame (inertial frame) see Section 2.7.3.3 and Section 2.7.3.5.3.

The order of rotations used will be the system that is widely employed in aeronautical engineering, where ψ is defined as the heading angle, θ is defined as the attitude angle and ϕ is defined as the bank angle.

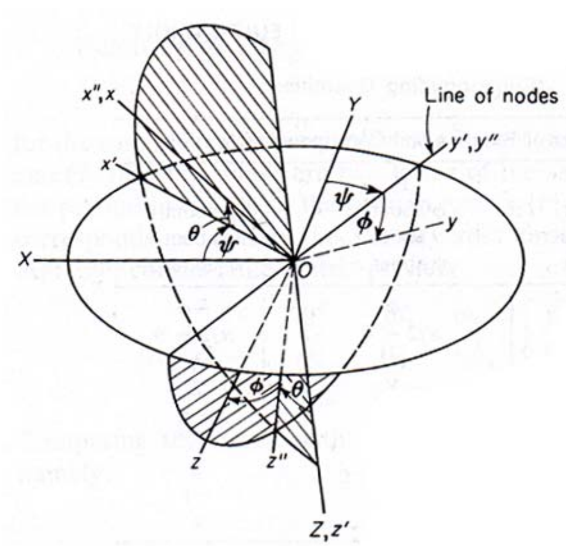
1. Positive rotation ψ about the Z_S axis, resulting in the primed system.

2. Positive rotation θ about the y' axis, resulting in the double primed system.

3. Positive rotation ϕ about the x'' axis, resulting in the final unprimed system.

See Figure Figure 2-30.

Figure 2-30 Eulerian Angles



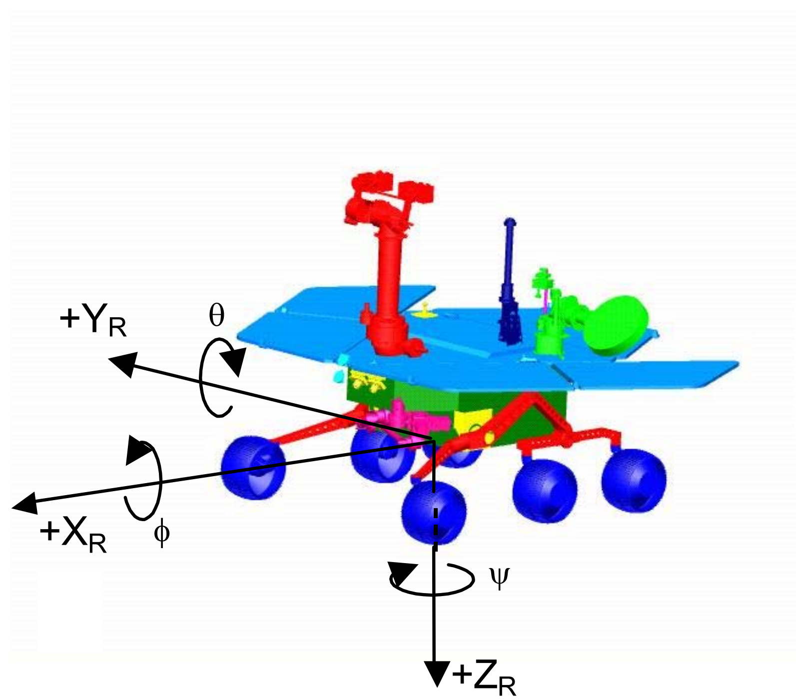
The rotational matrix is included in Table Table 2-2.

Table 2-2 Euler Angles Rotational Matrix (1-2-3)

$$\begin{Bmatrix} X_R \\ Y_R \\ Z_R \end{Bmatrix} = \begin{bmatrix} C\psi C\theta & C\psi S\theta S\phi + S\psi C\phi & -C\psi S\theta C\phi + S\psi S\phi \\ -S\psi C\theta & -S\psi S\theta S\phi + C\psi C\phi & S\psi S\theta C\phi + C\psi S\phi \\ S\theta & -C\theta S\phi & C\theta C\phi \end{bmatrix} \begin{Bmatrix} X_S \\ Y_S \\ Z_S \end{Bmatrix}$$

See Figure 2-31

Figure 2-31 Yaw, Pitch and Roll Definitions



2.7.3.5.3 Site Indexing Surface Fixed Frame[iv]

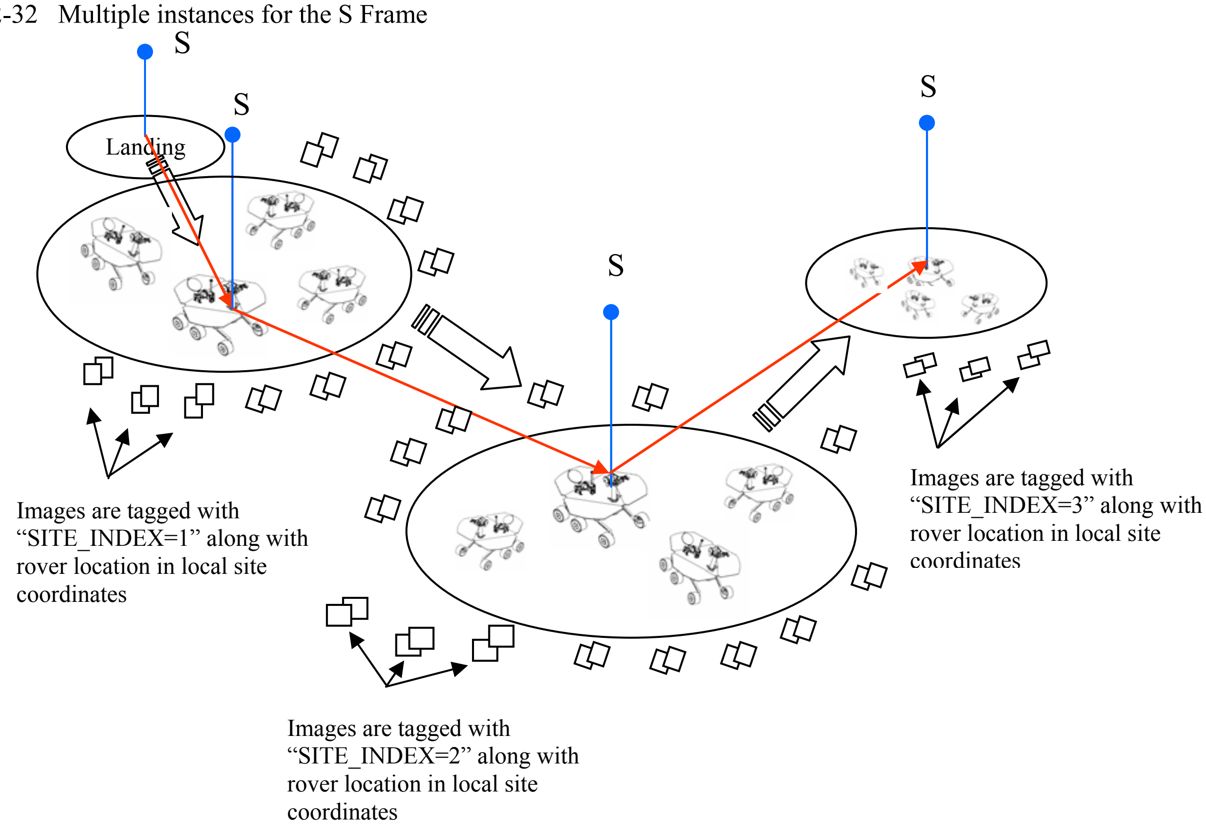
MER extends the use of the MPF coordinate systems by including multiple instances of the Surface Fixed frame (S Frame) described in section 2.7.3.3. Upon landing (and before Rover egress), the origin of the first instance of the S Frame (S_0) is coincident with the origin of the R Frame. When the Rover egresses from the lander, the S_0 Frame stays fixed in space, the L Frame stays attached to the lander (in both position and orientation), and the Local Level and R Frame origins move with the Rover. The positional offset between the S_0 and R Frames is simply the location of the Rover in the S_0 Frame.

As the Rover traverses across the surface, it accumulates an error of its position and orientation in the S_0 Frame. The error in orientation is periodically corrected by measurements of the position of the Sun at a known time. The error in position is corrected by examining images from the surface navigation cameras and comparing the locations of objects that are also contained within images acquired before the traverse. These corrections (position updates) are uplinked to the Rover.

In the simplest case, an entire surface mission could be conducted using one instance of the S Frame. Pathfinder used this approach because the lander camera was essentially fixed to the S_0 frame origin (the lander didn't move). For MER however, the cameras will regularly move relative to the S Frame origin - and the knowledge of Rover absolute position (relative to the local S Frame) degrades over time. Because of this degradation in position knowledge, the image data acquired over time become misaligned.

To prevent the accumulated Rover positional error from propagating into the image data, the Surface frame is “zeroed out” (reset) at strategic locations (defined as a new *site*) during the mission by the Surface operations team (nominally just prior to the acquisition of a large image data set, e.g., a panorama). As with all new S Frames, the origin initially coincides with the R Frame origin, and the orientation is aligned with the Local Level (S_L) orientation. This new S Frame becomes the operational coordinate system for activities within that site.

Figure 2-32 Multiple instances for the S Frame



2.7.3.5.4 Site to Site Translations

Site to site translations are performed using site offset vectors. A site offset vector is defined to be the offset between two Surface frame origins. See figure 2-38.

Figure 2-33 Site Vector Example

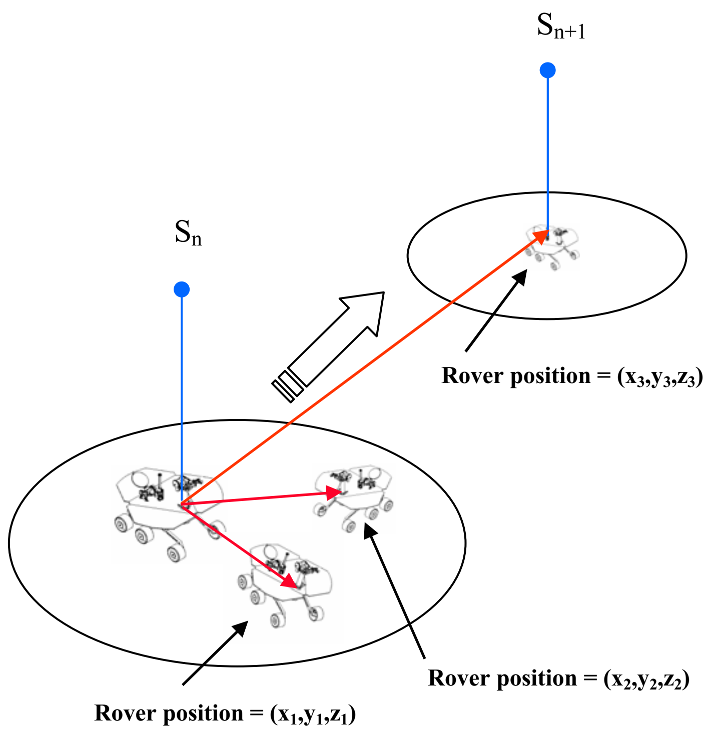


Figure x.x. Site Vector Example: $\mathbf{S_n}$ is Surface Frame *n,* $\mathbf{S_{n+1}}$ is Surface Frame *n* +1. The site vector joining $\mathbf{S_n}$ and $\mathbf{S_{n+1}}$ is the 3D rover position (in the $\mathbf{S_n}$ coordinate frame) at the time of $\mathbf{S_{n+1}}$ creation. For this example, the vector joining site frame $\mathbf{S_n}$ and $\mathbf{S_{n+1}}$ is [x_3,y_3,z_3], given in S_n coordinates. Note: usage of quaternions for orientation conversion is assumed.

3 Requirements

None

4 References

1. “MARS PATHFINDER AIM PHASING AND COORDINATE FRAME DOCUMENT” J.Mellstrom, K. Lau, April 9, 1996, JPL Document D12103 PF-300-4.0-04, Version 4

2. “Mars Exploration Rover Mechanical Subsystem Preliminary Design Review “, Various, January 22-24, 2001

3. Meetings, e-mails and/or conversations with the following: Scott Doudrick, Ed Swenka, Justin Maki, Rob Manning, Jonathan Stabb, Jake Matijevic, Miguel SanMartin, Larry Lee, Barry Nakazono, Joe Melko, Shawn Goodman, Jim Baughman, Ed Motts, Rick Welch, Sam Sirlin, Bruce Bon. February 2001 to August 2002

4. “10208291-IDD_ICD_Draft_5-31-01”, Alliance Spacesystems, Inc. Pasadena CA, March 5, 2001

5 Endnotes

[i] "High Gain Antenna Gimbal (Hgag)/Rover Electronics Module Interface Change Log"; MER-420-3-480.m/JPL D-20261; 2/6/02-Rev A

[ii] "Report of the IAU/IAG/COSPAR Working Group on Cartographic Coordinates and Rotational Elements of Planets and Satellites: 1994"; M. Davies et al.; published in Celestial Mechanics.

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