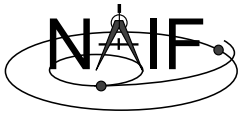




Dynamic Reference Frames

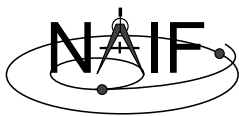
October 2007



Topics

Navigation and Ancillary Information Facility

- **Introduction to Dynamic Reference Frames**
- **Terminology**
- **Parameterized Dynamic Reference Frames**
- **Defining Dynamic Reference Frames**
 - Two-Vector Frame Concepts
 - Two-Vector Frame Examples
 - "Of-Date" Frames
 - Euler Frames
 - Frozen Dynamic Frames
 - Inertial Dynamic Frames
- **Generic Dynamic Reference Frame Kernel**
- **Backup**



Introduction to Dynamic Frames - 1

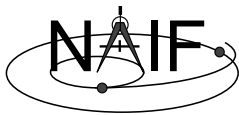
Navigation and Ancillary Information Facility

- **The Dynamic Reference Frames subsystem is an extension to the SPICE Frames system.**
 - First introduced in the N0058 SPICE Toolkit, released in January 2005.
- **What are "dynamic reference frames"?**
 - Dynamic reference frames ("dynamic frames" for short) have time-dependent orientation.
 - Dynamic frames are specified via a frame kernel (FK).
 - CK and PCK frames are not considered to be dynamic frames (although they are time-varying).
- **The Dynamic Frames capability enables the SPICE system to conveniently use a wide variety of frames that are not "built in" to SPICE. Examples include:**
 - Nadir-oriented frame for planetary orbiter
 - Geocentric Solar Ecliptic (GSE)
 - Solar Magnetic (SM)

(continued on next page)

Dynamic Frames

3



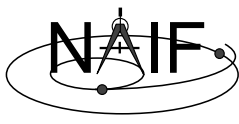
Introduction to Dynamic Frames - 2

Navigation and Ancillary Information Facility

- Spacecraft-centered roll-celestial frame
- Geocentric Solar Magnetospheric (GSM)
- Geomagnetic (MAG)
 - » Using constant north centered geomagnetic dipole
 - » Using dipole direction defined by time-dependent Euler angles
- Geocentric Solar Equatorial (GSEQ)
- Solar Equatorial frame for any ephemeris object
- Orbital frame for any ephemeris object
- Earth mean equator and equinox of date
- Earth true equator and equinox of date
- Earth mean ecliptic and equinox of date
- RTN ("radial, tangential, normal") frames
- And many more...

Dynamic Frames

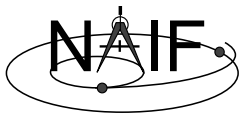
4



Introduction to Dynamic Frames - 3

Navigation and Ancillary Information Facility

- **Using already defined dynamic frames in a SPICE-based program is straightforward.**
 - At program initialization:
 - » Load one or more dynamic frame kernels to make frame definitions known to SPICE.
 - » Load any kernels on which the dynamic frames depend.
 - Some dynamic frames are defined using data from SPK, FK, PCK, CK or other SPICE kernels.
 - Then, refer to the dynamic frame or frames by name in calls to SPICE routines:
 - » Just as you would do with built-in frames such as "J2000."



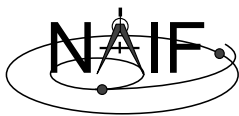
Introduction to Dynamic Frames - 4

Navigation and Ancillary Information Facility

- » For example, find the 6x6 matrix to transform states from the J2000 frame to the Geocentric Solar Ecliptic (GSE) frame at the TDB epoch given by ET.

```
CALL SXFORM( 'J2000', 'GSE', ET, XFORM )
```
- » Or look up the state of Jupiter relative to the earth in the GSE frame:

```
CALL SPKEZR( 'JUPITER', ET, 'GSE',  
             'NONE', 'EARTH', STATE, LT )
```
- You can refer to dynamic frames in SPK or CK files, for example:
 - When you create an SPK file, you can have an SPK segment reference its ephemeris data to the true earth equator and equinox of date reference frame.
 - » However, some restrictions apply to use of dynamic frames in SPICE kernels (see Backup slides).



Introduction to Dynamic Frames - 5

Navigation and Ancillary Information Facility

- To define dynamic frames via a frame kernel, a fairly detailed understanding of the SPICE dynamic frame capability is required.
- A good understanding of the basic SPICE system (in particular, the SPK and Frame systems) is also a prerequisite for defining dynamic frames.
- See the Frames Required Reading for the most detailed documentation available.
- The rest of this tutorial is concerned with:
 - explaining the SPICE dynamic frames capability.
 - showing how to create dynamic frame kernels.
 - » We present many frame definition examples.



Terminology - 1

Navigation and Ancillary Information Facility

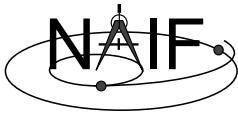
- Terms involving reference frames and vectors:
 - "Frame" is short for "reference frame."
 - A frame can be thought of as a set of three mutually orthogonal, unit-length vectors.
 - » These vectors are called "basis vectors." The lines containing the basis vectors are the "axes" of the frame.
 - » The basis vectors indicate the "positive" axis directions; we label these vectors +X, +Y, and +Z. The negatives of these vectors are labeled -X, -Y, and -Z.
 - » We number the axes as follows:
 $X = \text{axis 1}; Y = \text{axis 2}; Z = \text{axis 3}$
 - All of the frames we'll deal with are "right-handed": this means +Z is the cross product $+X \times +Y$.
 - A reference frame's orientation is always defined relative to another specified frame: the "base frame."



Terminology - 2

Navigation and Ancillary Information Facility

- When we say that a frame is "time-dependent" or "time-varying," we mean:
 - » The orientation of the frame is time-dependent.
 - » Equivalently, the rotation between the frame and its base frame is time-dependent.
- By "evaluating" a frame or "evaluating the orientation of a frame," we mean computing the rotation between the frame and its base frame.
 - » An epoch is required in order to evaluate a dynamic frame.
- In the SPICE system, frames are considered to have "centers."
 - » The center of a frame is always an ephemeris object, something whose location can be specified with an SPK file.
 - » Frame centers come into play when light time corrections are used: the apparent orientation of a time-dependent frame as seen by an observer is affected by the one-way light time between the frame's center and the observer.



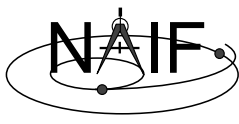
Terminology - 3

Navigation and Ancillary Information Facility

- When we say that a vector is "aligned" with another vector, we mean that the angular separation between the two vectors is zero.
- We use the terms "defining a frame" and "specifying a frame" interchangeably. Both refer to creating a frame definition in a frame kernel.
- Other definitions:
 - The term "API" stands for "Application Programming Interface." This term refers to the set of SPICE routines that are intended to be called directly by SPICE-based programs.
 - The notation

$[\text{theta}]_n$

indicates a frame rotation of theta radians about axis n, where n is one of {1, 2, 3}. This transformation rotates vectors by $-\text{theta}$ radians about axis n.



Parameterized Dynamic Frames - 1

Navigation and Ancillary Information Facility

- **Parameterized dynamic frames**

- This is the only frame definition style currently supported by the dynamic frames subsystem.
 - » Future versions of SPICE might support additional styles.
- Frames are defined via parameterized formulas
 - » The code implementing the formulas is built into SPICE.
 - » The parameters are specified in a frame kernel.
- Parameterized dynamic frames are grouped into frame "families". Each family corresponds to a distinct, parameterized geometric formula providing a frame definition. The families are:
 - » **Two-Vector Frames**
 - » **Mean Equator and Equinox of Date Frames**
 - » **True Equator and Equinox of Date Frames**
 - » **Mean Ecliptic and Equinox of Date Frames**
 - » **Euler Frames**

Dynamic Frames

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Parameterized Dynamic Frames - 2

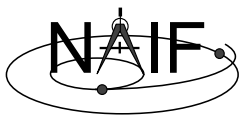
Navigation and Ancillary Information Facility

- **Defining Parameterized Dynamic Frames**

- Parameterized Dynamic frames are defined using "keyword=value" assignments in a frame kernel.
- The following items must be specified in the frame definition:
 - » **Frame name**
 - » **Frame ID code**
 - The range 1400000-2000000 is reserved for people outside of the NAIF group
 - » **Class** (=5 for dynamic frames)
 - » **Class ID code** (=frame ID code for dynamic frames)
 - » **Frame center** (=NAIF ID code for central body)
 - » **Frame definition style** (='PARAMETERIZED')
 - » **Base frame**
 - Frame definition specifies mapping from dynamic frame to the base frame.
 - » **Frame family**
 - » **Family-specific assignments**

Dynamic Frames

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Parameterized Dynamic Frames - 3

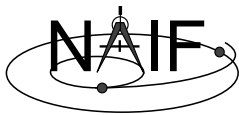
Navigation and Ancillary Information Facility

» Rotation state

- Possible states are 'ROTATING' and 'INERTIAL'.
 - Frame is treated as rotating or inertial for the purpose of velocity transformations.
- The default dynamic frame rotation state is 'ROTATING'.
- For rotating two-vector and Euler frames, the rotation state assignment can be omitted from the frame definition.
- For "of-date" frames, the frame definition must either specify the rotation state or designate the frame as "frozen" at a specified epoch.

» Freeze epoch.

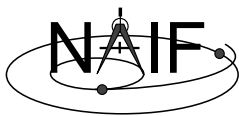
- Presence of this optional assignment in a frame kernel indicates that the frame orientation, relative to the base frame, is held constant ("frozen") at the specified epoch.
- Most dynamic frames are not frozen.



Two-Vector Frame Concepts - 1

Navigation and Ancillary Information Facility

- Two-vector frames are defined using two time-dependent vectors: the "primary" and "secondary" vectors.
 - Each of the primary and secondary vectors may be defined by a variety of geometric means. Each vector may be a
 - » Position vector
 - » Target near point vector
 - » Velocity vector
 - » Constant vector
- The user associates specified positive or negative axes of the two-vector frame with the primary and secondary vectors.
 - Two-vector frames are always right-handed and have orthogonal axes, so two non-parallel vectors and associations of axes with these vectors suffice to define the orientation of a frame.

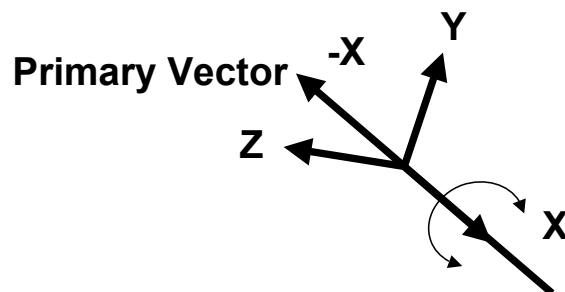


Two-Vector Frame Concepts - 2

Navigation and Ancillary Information Facility

• Primary Vector

- A specified positive or negative axis of the two-vector frame is aligned with this vector.
 - » The frame kernel creator assigns to this vector one of the axis designations { +X, -X, +Y, -Y, +Z, -Z }.
- Two degrees of freedom of the frame orientation are removed by association of an axis with the primary vector. The third degree of freedom is the frame's rotation about the primary vector.
- Example: a frame's -X axis is aligned with the primary vector:



Dynamic Frames

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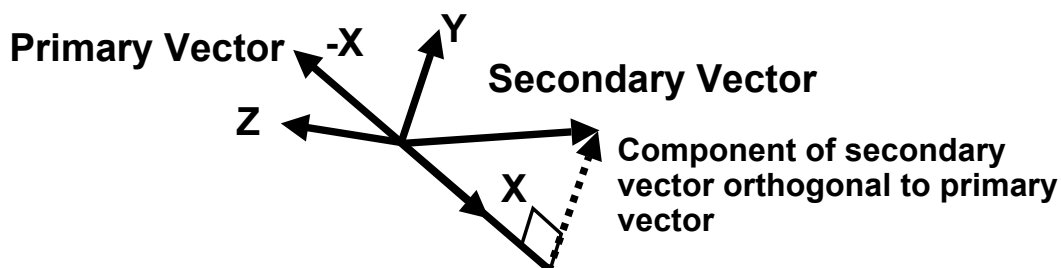


Two-Vector Frame Concepts - 3

Navigation and Ancillary Information Facility

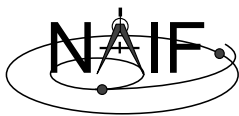
• Secondary Vector

- A specified positive or negative axis of the two-vector frame is aligned with the component of the secondary vector orthogonal to the primary vector.
 - » The frame kernel creator associates with this vector one of the axis designations { +X, -X, +Y, -Y, +Z, -Z }, where the axis is orthogonal to that associated with the primary vector.
- Example, continued: the frame's +Y axis is associated with the secondary vector. The component of the secondary vector orthogonal to the primary vector is aligned with the frame's +Y axis. The secondary vector thus lies in the frame's X-Y plane.



Dynamic Frames

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Two-Vector Frame Concepts - 4

Navigation and Ancillary Information Facility

• Secondary Vector, continued

- Typically the secondary vector itself is not orthogonal to the primary vector.
- The secondary vector must be linearly independent of the primary vector.
 - » Near-degenerate geometry can lead to extreme loss of precision.
 - This problem can be difficult to diagnose.
 - » SPICE enforces independence using a default angular separation tolerance of 1 milliradian. The angular separation of the primary and secondary vectors may not differ from 0 or Pi radians by less than this tolerance.
 - » A frame kernel creator can specify a different tolerance value. The frame kernel assignment for this is:

```
FRAME_<frame_ID>_ANGLE_SEP_TOL = <tolerance>
```

where the tolerance is given in radians.
- Designers of two-vector frames should ensure that the primary and secondary vectors can't become nearly parallel for any realistic evaluation epoch.



Two-Vector Frame Concepts - 5

Navigation and Ancillary Information Facility

• Position Vector

- Is defined by the position of one ephemeris object relative to another. The frame kernel creator specifies:
 - » the target
 - » the observer
 - » the aberration correction
 - The vector may optionally be corrected for light time and stellar aberration.
- The epoch at which the position vector is computed is supplied via a call to a SPICE API routine:
 - » as an input to an SPK routine, e.g. SPKEZR, SPKPOS.
 - » as an input to a frame system routine, e.g. SXFORM, PXFORM.
- The reference frame relative to which the vector is expressed is not specified by the frame kernel creator.
 - » SPICE automatically selects this frame.



Two-Vector Frame Concepts - 6

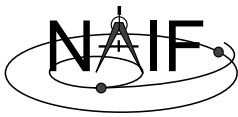
Navigation and Ancillary Information Facility

• Target Near Point Vector

- Is defined as the vector from an observer to the nearest point on a specified extended target body to that observer. The frame kernel creator specifies:
 - » the target
 - » the observer
 - » the aberration correction
 - The vector may optionally be corrected for light time and stellar aberration.
 - When light time correction is used, both the position and orientation of the target body are corrected for light time.
- The extended target body is modeled as a triaxial ellipsoid.
 - » Size and shape data are given by a PCK.
- The epoch is supplied via a SPICE API call, as for position vectors.
- The reference frame relative to which the vector is expressed is not specified by the frame kernel creator.
 - » SPICE automatically selects this frame.

Dynamic Frames

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Two-Vector Frame Concepts - 7

Navigation and Ancillary Information Facility

• Velocity Vector

- Is defined by the velocity of a target ephemeris object relative to an observing ephemeris object. The frame kernel creator specifies:
 - » the target
 - » the observer
 - » the velocity reference frame
 - This frame may be distinct from the base frame.
 - Different velocity frame choices can lead to radically different two-vector frame definitions.
 - » the aberration correction
 - The velocity vector may optionally be corrected for light time and stellar aberration.
 - Use of light time correction also implies evaluation of the velocity vector's frame at a light-time corrected epoch: the epoch is corrected for light time between the velocity frame's center and the observer, if the velocity frame is non-inertial.
- The epoch is supplied via a SPICE API call, as for position vectors.

Dynamic Frames

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Two-Vector Frame Concepts - 8

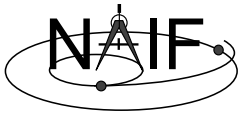
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• Constant Vector

- The vector is constant in a frame specified by the kernel creator.
 - » The constant vector's frame may be time-dependent.
 - » This frame may be distinct from the base frame.
- The vector may be specified in a variety of coordinate systems.
 - » Cartesian
 - » Latitudinal
 - » Right ascension/declination (RA/DEC)
- An observer may optionally be associated with a constant vector for the purpose of defining aberration corrections.
 - » The orientation of the constant vector's frame may optionally be corrected for light time between the frame's center and the observer: if the frame is non-inertial, it is evaluated at a light-time corrected epoch.

Dynamic Frames

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Two-Vector Frame Concepts - 9

Navigation and Ancillary Information Facility

- » A constant vector may optionally be corrected for stellar aberration due to motion of observer relative to solar system barycenter.
 - Stellar aberration can be specified without light time correction; the string indicating stellar aberration correction alone is
'S'
 - This correction specification is not supported elsewhere in the SPICE Toolkit API.
- The epoch is supplied via a SPICE API call, as for position vectors.
 - » If the constant vector's frame is time-dependent, that frame is evaluated at this epoch, optionally adjusted for light time.

Dynamic Frames

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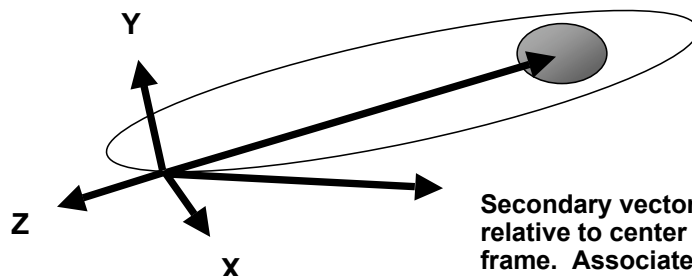


Two-Vector Frame Examples - 1

Navigation and Ancillary Information Facility

Nadir-Oriented Spacecraft-Centered Frame

$Y = Z \times X$, completing the right-handed frame.



Primary vector: spacecraft nadir direction vector. Associated with nadir frame's -Z axis in frame kernel.

Nadir vector can be defined to point to either:

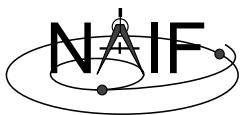
- closest point to spacecraft on ellipsoid
- center of mass of orbited body

Secondary vector: spacecraft velocity relative to center of motion in J2000 frame. Associated with nadir frame's +X axis in frame kernel.

Normalized component of secondary vector orthogonal to primary vector. This vector is aligned with the nadir frame's +X axis.

Dynamic Frames

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Two-Vector Frame Examples - 2

Navigation and Ancillary Information Facility

Nadir-Oriented Spacecraft-Centered Frame: Frame kernel specification.

The -Z axis points from the spacecraft toward the closest point on Mars.

The component of inertially referenced spacecraft velocity vector orthogonal to Z is aligned with the +X axis.

The +Y axis is the cross product of the +Z axis and the +X axis.

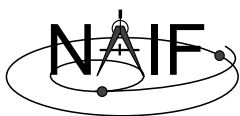
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```
FRAME <frame_name> = <frame_ID>
FRAME <frame_ID> NAME = <frame_name>
FRAME <frame_ID> CLASS = 5
FRAME <frame_ID> CLASS_ID = <frame_ID>
FRAME <frame_ID> CENTER = <orbiter_ID>
FRAME <frame_ID> RELATIVE = 'J2000'
FRAME <frame_ID> DEF_STYLE = 'PARAMETERIZED'
FRAME <frame_ID> FAMILY = 'TWO-VECTOR'
FRAME <frame_ID> PRI_AXIS = '-Z'
FRAME <frame_ID> PRI_VECTOR_DEF = 'TARGET NEAR POINT'
FRAME <frame_ID> PRI_OBSERVER = <orbiter_ID/name>
FRAME <frame_ID> PRI_TARGET = 'MARS'
FRAME <frame_ID> PRI_ABCORR = 'NONE'
FRAME <frame_ID> SEC_AXIS = 'X'
FRAME <frame_ID> SEC_VECTOR_DEF = 'OBSERVER_TARGET_VELOCITY'
FRAME <frame_ID> SEC_OBSERVER = 'MARS'
FRAME <frame_ID> SEC_TARGET = <orbiter_ID/name>
FRAME <frame_ID> SEC_ABCORR = 'NONE'
FRAME <frame_ID> SEC_FRAME = 'J2000'
```

<frame_name> = user-specified frame name
 <frame_ID> = integer frame ID code
 <orbiter_ID> = NAIF ID code of spacecraft
 <orbiter_ID/name> = NAIF ID code or name of spacecraft

Dynamic Frames

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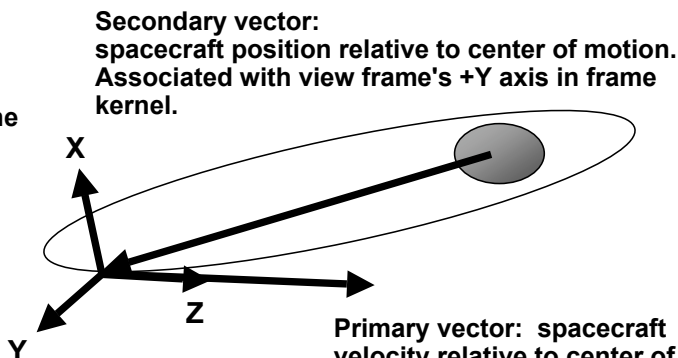


Two-Vector Frame Examples - 3

Navigation and Ancillary Information Facility

Spacecraft "View Frame"

$X = Y \times Z$, completing the right-handed frame.
("Out of plane" direction)

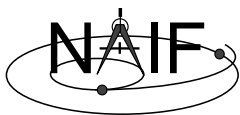


Normalized component of secondary vector orthogonal to primary vector. This vector is aligned with the view frame's +Y axis. ("In plane" direction)

Primary vector: spacecraft velocity relative to center of motion in J2000 frame. Associated with view frame's +Z axis in frame kernel. ("Down track" direction)

Dynamic Frames

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Two-Vector Frame Examples - 4

Navigation and Ancillary Information Facility

Spacecraft "View Frame": Frame kernel specification.

The +Z axis is aligned with the J2000-referenced velocity of the spacecraft relative to Mars.

The component of the spacecraft position orthogonal to +Z is aligned with the +Y axis.

The +X axis is the cross product of the +Y axis and the +Z axis.

\begindata

```
FRAME <frame_name>           = <frame_ID>
FRAME <frame_ID> NAME         = <frame_name>
FRAME <frame_ID> CLASS        = 5
FRAME <frame_ID> CLASS_ID     = <frame_ID>
FRAME <frame_ID> CENTER       = <orbiter_ID>
FRAME <frame_ID> RELATIVE     = 'J2000'
FRAME <frame_ID> DEF_STYLE    = 'PARAMETERIZED'
FRAME <frame_ID> FAMILY       = 'TWO-VECTOR'
FRAME <frame_ID> PRI_AXIS     = 'Z'
FRAME <frame_ID> PRI_VECTOR_DEF = 'OBSERVER_TARGET_VELOCITY'
FRAME <frame_ID> PRI_OBSERVER  = 'MARS'
FRAME <frame_ID> PRI_TARGET   = <orbiter_ID/name>
FRAME <frame_ID> PRI_ABCORR   = 'NONE'
FRAME <frame_ID> PRI_FRAME    = 'J2000'
FRAME <frame_ID> SEC_AXIS     = 'Y'
FRAME <frame_ID> SEC_VECTOR_DEF = 'OBSERVER_TARGET_POSITION'
FRAME <frame_ID> SEC_OBSERVER  = 'MARS'
FRAME <frame_ID> SEC_TARGET   = <orbiter_ID/name>
FRAME <frame_ID> SEC_ABCORR   = 'NONE'
```

<frame_name>	= user-specified frame name
<frame_ID>	= integer frame ID code
<orbiter_ID>	= NAIF ID code of spacecraft
<orbiter_ID/name>	= NAIF ID code or name of spacecraft

Dynamic Frames

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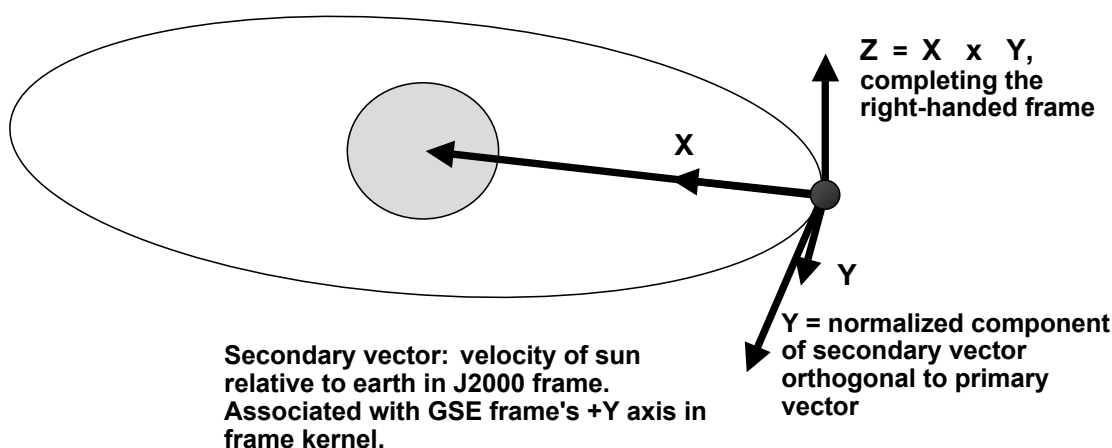


Two-Vector Frame Examples - 5

Navigation and Ancillary Information Facility

Geocentric Solar Ecliptic Frame (GSE)

Primary vector: position of sun relative to earth
Associated with GSE frame's +X axis in frame kernel.



Secondary vector: velocity of sun relative to earth in J2000 frame.
Associated with GSE frame's +Y axis in frame kernel.

Dynamic Frames

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Two-Vector Frame Examples - 6

Navigation and Ancillary Information Facility

Geocentric Solar Ecliptic (GSE) frame:

- +X is parallel to the geometric earth-sun position vector.
- +Y axis is the normalized component of the geometric earth-sun velocity vector orthogonal to the GSE +X axis.
- +Z axis is parallel to the cross product of the GSE +X axis and the GSE +Y axis.

\begindata

```
FRAME_GSE = <frame_ID>
FRAME <frame_ID> NAME = 'GSE'
FRAME <frame_ID> CLASS = 5
FRAME <frame_ID> CLASS_ID = <frame_ID>
FRAME <frame_ID> CENTER = 399
FRAME <frame_ID> RELATIVE = 'J2000'
FRAME <frame_ID> DEF_STYLE = 'PARAMETERIZED'
FRAME <frame_ID> FAMILY = 'TWO-VECTOR'
FRAME <frame_ID> PRI_AXIS = 'X'
FRAME <frame_ID> PRI_VECTOR_DEF = 'OBSERVER_TARGET_POSITION'
FRAME <frame_ID> PRI_OBSERVER = 'EARTH'
FRAME <frame_ID> PRI_TARGET = 'SUN'
FRAME <frame_ID> PRI_ABCORR = 'NONE'
FRAME <frame_ID> SEC_AXIS = 'Y'
FRAME <frame_ID> SEC_VECTOR_DEF = 'OBSERVER_TARGET_VELOCITY'
FRAME <frame_ID> SEC_OBSERVER = 'EARTH'
FRAME <frame_ID> SEC_TARGET = 'SUN'
FRAME <frame_ID> SEC_ABCORR = 'NONE'
FRAME <frame_ID> SEC_FRAME = 'J2000'
```

<frame_ID> = integer frame ID code

Dynamic Frames

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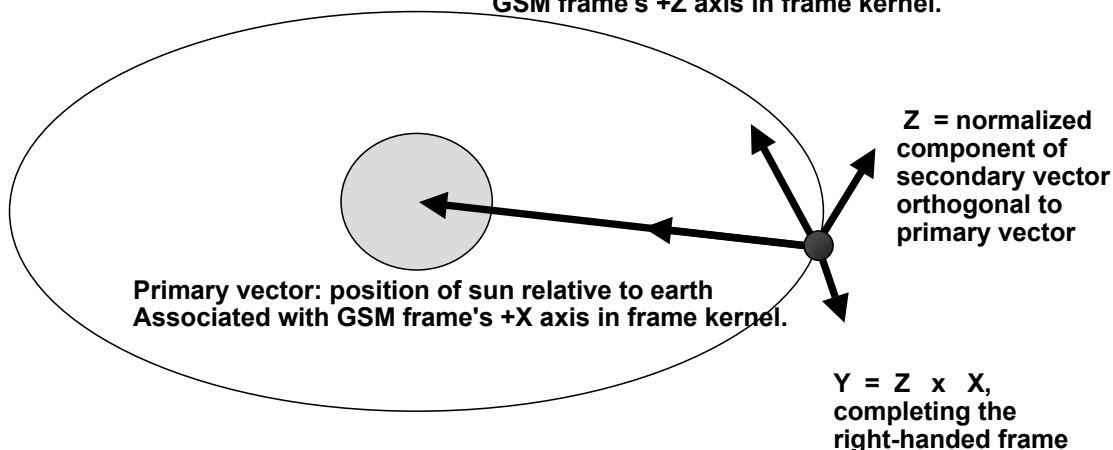


Two-Vector Frame Examples - 7

Navigation and Ancillary Information Facility

Geocentric Solar Magnetospheric Frame (GSM)

Secondary vector: North geomagnetic centered dipole in IAU_EARTH frame. Associated with GSM frame's +Z axis in frame kernel.



Dynamic Frames

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Two-Vector Frame Examples - 8

Navigation and Ancillary Information Facility

Geocentric Solar Magnetospheric (GSM) frame:

+X is parallel to the geometric earth-sun position vector.

+Z axis is normalized component of north centered geomagnetic dipole vector orthogonal to GSM +X axis.

+Y completes the right-handed frame.

\begindata

```

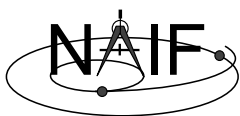
FRAME_GSM                                = <frame_ID>
FRAME_<frame_ID>_NAME                     = 'GSM'
FRAME_<frame_ID>_CLASS                     = 5
FRAME_<frame_ID>_CLASS_ID                 = <frame_ID>
FRAME_<frame_ID>_CENTER                   = 399
FRAME_<frame_ID>_RELATIVE                  = 'J2000'
FRAME_<frame_ID>_DEF_STYLE                 = 'PARAMETERIZED'
FRAME_<frame_ID>_FAMILY                   = 'TWO-VECTOR'
FRAME_<frame_ID>_PRI_AXIS                  = 'X'
FRAME_<frame_ID>_PRI_VECTOR_DEF            = 'OBSERVER_TARGET_POSITION'
FRAME_<frame_ID>_PRI_OBSERVER              = 'EARTH'
FRAME_<frame_ID>_PRI_TARGET                = 'SUN'
FRAME_<frame_ID>_PRI_ABCORR                = 'NONE'
FRAME_<frame_ID>_SEC_AXIS                  = 'Z'
FRAME_<frame_ID>_SEC_VECTOR_DEF            = 'CONSTANT'
FRAME_<frame_ID>_SEC_FRAME                 = 'IAU_EARTH'
FRAME_<frame_ID>_SEC_SPEC                  = 'LATITUDINAL'
FRAME_<frame_ID>_SEC_UNITS                 = 'DEGREES'
FRAME_<frame_ID>_SEC_LONGITUDE             = 288.43
FRAME_<frame_ID>_SEC_LATITUDE              = 79.54

```

<frame_ID> = integer frame ID code

Dynamic Frames

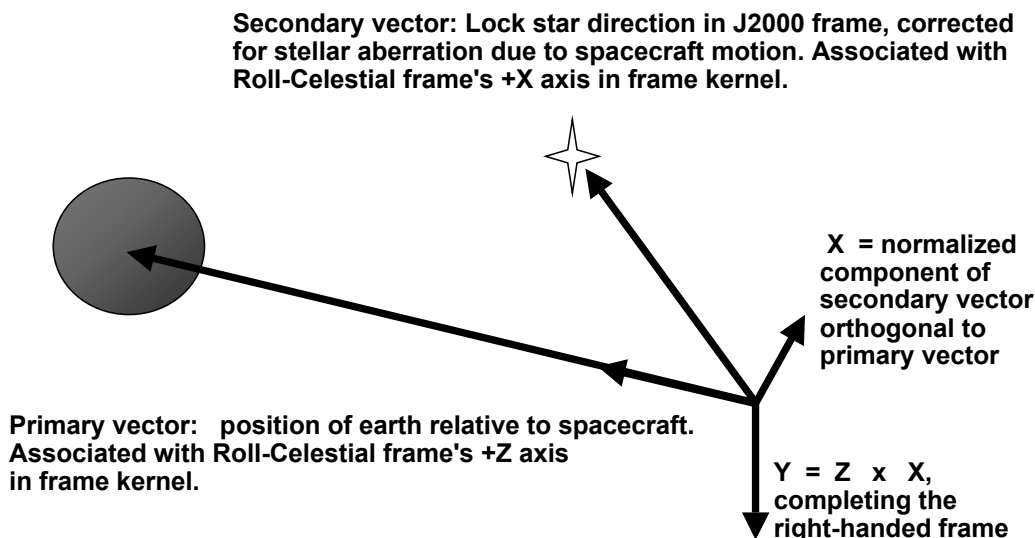
30



Two-Vector Frame Examples - 9

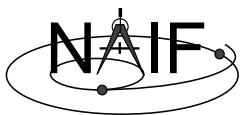
Navigation and Ancillary Information Facility

Spacecraft-Centered Roll-Celestial Frame



Dynamic Frames

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Two-Vector Frame Examples - 10

Navigation and Ancillary Information Facility

Spacecraft-centered roll-celestial frame:

+Z is parallel to the geometric earth-sun position vector.

+X axis is normalized component of star direction orthogonal to Z axis. The star direction is corrected for stellar aberration due to motion of the spacecraft.

+Y completes the right-handed frame.

```
\begindata
FRAME <frame_name>          = <frame_ID>
FRAME <frame_ID> NAME        = <frame_name>
FRAME <frame_ID> CLASS        = 5
FRAME <frame_ID> CLASS ID     = <frame_ID>
FRAME <frame_ID> CENTER       = <spacecraft_ID>
FRAME <frame_ID> RELATIVE     = 'J2000'
FRAME <frame_ID> DEF STYLE     = 'PARAMETERIZED'
FRAME <frame_ID> FAMILY       = 'TWO-VECTOR'
FRAME <frame_ID> PRI_AXIS      = 'Z'
FRAME <frame_ID> PRI_VECTOR_DEF = 'OBSERVER TARGET POSITION'
FRAME <frame_ID> PRI_OBSERVER  = <spacecraft_ID/name>
FRAME <frame_ID> PRI_TARGET    = 'EARTH'
FRAME <frame_ID> PRI_ABCORR    = 'NONE'
FRAME <frame_ID> SEC_AXIS      = 'X'
FRAME <frame_ID> SEC_VECTOR_DEF = 'CONSTANT'
FRAME <frame_ID> SEC_FRAME     = 'J2000'
FRAME <frame_ID> SEC_SPEC      = 'RA/DEC'
FRAME <frame_ID> SEC_UNITS     = 'DEGREES'
FRAME <frame_ID> SEC_RA        = <star right ascension in degrees>
FRAME <frame_ID> SEC_DEC       = <star declination in degrees>
FRAME <frame_ID> SEC_OBSERVER  = <spacecraft_ID/name>
FRAME <frame_ID> SEC_ABCORR    = 'S'
```

<frame_name>	= user-specified frame name
<frame_ID>	= integer frame ID code
<spacecraft_ID>	= NAIF ID code of spacecraft
<spacecraft_ID/name>	= NAIF ID code or name of spacecraft

Dynamic Frames

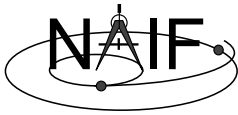
32



"Of-Date" Frames - 1

Navigation and Ancillary Information Facility

- **Of-date frames are associated with user-specified bodies and are based on user-selected dynamical models.**
 - Implementations of models are built into SPICE.
- **The currently supported "of-date" frame families are**
 - Mean Equator and Equinox of Date
 - True Equator and Equinox of Date
 - Mean Ecliptic and Equinox of Date
- **The earth is the only currently supported body.**



"Of-Date" Frames - 2

Navigation and Ancillary Information Facility

- **The currently supported types of models are**
 - Precession
 - Nutation
 - Mean obliquity
- **The of-date frame implementation is intended to be flexible:**
 - The set of supported bodies can grow over time.
 - The set of supported models can grow over time.
 - » **SPICE is not forever locked into using a single hard-coded implementation, such as the 1976 IAU precession model**
 - The set of supported frame families can grow, if necessary.



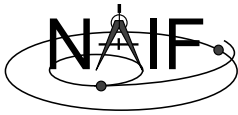
"Of-Date" Frames - 3

Navigation and Ancillary Information Facility

- **Mean Equator and Equinox of Date Family**
 - **For all reference frames in this family:**
 - » The frame's relationship to the J2000 frame is given by a precession model.
 - » The frame kernel creator selects a precession model from those built into the SPICE software.
 - Currently supported only for the earth
 - 1976 IAU precession model (aka Lieske model)
 - » The frame kernel creator must either specify the frame's rotation state or must designate the frame "frozen" at a specified "freeze epoch."

Dynamic Frames

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"Of-Date" Frames - 4

Navigation and Ancillary Information Facility

Earth mean equator and equinox of date frame:

+Z axis is perpendicular to mean equator of date and points north.

+X axis is parallel to the cross product of the +Z axis and the north-pointing vector normal to the mean ecliptic of date.

+Y axis completes the right-handed frame.

\begindata

```
FRAME <frame_name>          = <frame_ID>
FRAME <frame_ID>_NAME        = <frame_name>
FRAME <frame_ID>_CLASS        = 5
FRAME <frame_ID>_CLASS_ID     = <frame_ID>
FRAME <frame_ID>_CENTER       = 399
FRAME <frame_ID>_RELATIVE      = 'J2000'
FRAME <frame_ID>_DEF STYLE     = 'PARAMETERIZED'
FRAME <frame_ID>_FAMILY        = 'MEAN EQUATOR_AND_EQUINOX_OF_DATE'
FRAME <frame_ID>_PREC MODEL    = 'EARTH_IAU_1976'
FRAME <frame_ID>_ROTATION STATE = 'ROTATING'
```

<frame_name>	= user-specified frame name
<frame_ID>	= integer frame ID code

Dynamic Frames

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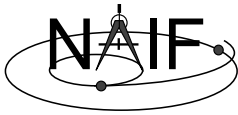
"Of-Date" Frames - 5

Navigation and Ancillary Information Facility

- **True Equator and Equinox of Date Family**
 - For all reference frames in this family:
 - » The frame's relationship to the J2000 frame is given by a precession model and a nutation model.
 - » The frame kernel creator selects models from those built into the SPICE software.
 - Currently supported only for the earth
 - 1976 IAU precession model (aka Lieske model)
 - 1980 IAU nutation model
 - » The frame kernel creator must either specify the frame's rotation state or must designate the frame "frozen" at a specified "freeze epoch."

Dynamic Frames

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"Of-Date" Frames - 6

Navigation and Ancillary Information Facility

Earth true equator and equinox of date frame:

+Z axis is perpendicular to true equator of date and points north.

+X axis is parallel to the cross product of the +Z axis and the north-pointing vector normal to mean ecliptic of date.

+Y axis completes the right-handed frame.

\begindata

```
FRAME <frame_name>          = <frame_ID>
FRAME <frame_ID>_NAME        = <frame_name>
FRAME <frame_ID>_CLASS        = 5
FRAME <frame_ID>_CLASS_ID     = <frame_ID>
FRAME <frame_ID>_CENTER       = 399
FRAME <frame_ID>_RELATIVE      = 'J2000'
FRAME <frame_ID>_DEF STYLE     = 'PARAMETERIZED'
FRAME <frame_ID>_FAMILY        = 'TRUE EQUATOR AND EQUINOX OF DATE'
FRAME <frame_ID>_PREC MODEL    = 'EARTH IAU 1976'
FRAME <frame_ID>_NUT MODEL     = 'EARTH IAU 1980'
FRAME <frame_ID>_ROTATION STATE = 'ROTATING'
```

<frame_name>	= user-specified frame name
<frame_ID>	= integer frame ID code

Dynamic Frames

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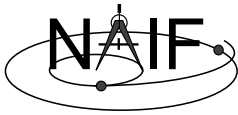
"Of-Date" Frames - 7

Navigation and Ancillary Information Facility

- **Mean Ecliptic and Equinox of Date Family**
 - For all reference frames in this family:
 - » The frame's relationship to the J2000 frame is given by a precession model and an obliquity model.
 - » The frame kernel creator selects models from those built into the SPICE software.
 - » Currently supported only for the earth
 - 1976 IAU precession model (aka Lieske model)
 - 1980 IAU mean obliquity model
 - » The frame kernel creator must either specify the frame's rotation state or must designate the frame "frozen" at a specified "freeze epoch."

Dynamic Frames

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"Of-Date" Frames - 8

Navigation and Ancillary Information Facility

Earth mean ecliptic and equinox of date frame:

+Z axis is perpendicular to mean ecliptic of date and points toward ecliptic north.

+X axis is parallel to the cross product of +Z axis and the north-pointing vector normal to mean ecliptic of date.

+Y axis completes the right-handed frame.

\begindata

```
FRAME_<frame_name>          = <frame_ID>
FRAME_<frame_ID>_NAME        = <frame_name>
FRAME_<frame_ID>_CLASS       = 5
FRAME_<frame_ID>_CLASS_ID    = <frame_ID>
FRAME_<frame_ID>_CENTER      = 399
FRAME_<frame_ID>_RELATIVE     = 'J2000'
FRAME_<frame_ID>_DEF_STYLE    = 'PARAMETERIZED'
FRAME_<frame_ID>_FAMILY       = 'MEAN_ECLIPTIC_AND_EQUINOX_OF_DATE'
FRAME_<frame_ID>_PREC_MODEL   = 'EARTH_IAU_1976'
FRAME_<frame_ID>_OBLIQ_MODEL  = 'EARTH_IAU_1980'
FRAME_<frame_ID>_ROTATION_STATE = 'ROTATING'
```

<frame_name>	= user-specified frame name
<frame_ID>	= integer frame ID code

Dynamic Frames

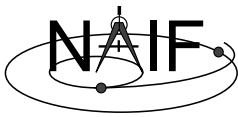
40



Euler Frames - 1

Navigation and Ancillary Information Facility

- **Euler frames are defined by a time-dependent rotation relative to a base frame.**
 - The rotation from an Euler frame to its base frame is given by three Euler angles.
 - Each angle is given by a separate polynomial.
 - » The polynomials may have different degrees.
 - » The independent variable is a time offset, in TDB seconds, from an epoch specified by the frame kernel creator.
 - » The units associated with the angles are specified by the frame kernel creator. Angles are converted to radians internally by SPICE.
 - » The sequence of rotation axes is specified by the frame kernel creator.
 - The central axis must differ from the other two.
 - The rotation from the Euler frame to the base frame is $[\text{angle_1}]_{\text{axis_1}} [\text{angle_2}]_{\text{axis_2}} [\text{angle_3}]_{\text{axis_3}}$ (units are radians)



Euler Frames - 2

Navigation and Ancillary Information Facility

- **Examples of applications:**
 - Dynamic version of earth magnetospheric frame (MAG)
 - » Latitude and longitude of the north centered geomagnetic dipole are given by polynomials.
 - Spinning spacecraft frame
 - » The base frame could be a:
 - Built-in inertial frame
 - C-kernel frame
 - Roll-celestial frame (using lock star)
 - Nadir frame
 - Topocentric frames for tracking stations for which plate motion is modeled
 - » The frame rotation keeps the frame orientation consistent with the changing station location.



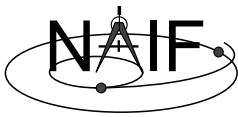
Euler Frames - 3

Navigation and Ancillary Information Facility

- Mean or true body equator and earth equinox of date frame, where the body is a planet or satellite other than the earth
 - » The base frame is an IAU_<body> frame.
 - » The Euler frame "removes" the body's rotation about the spin axis.
- Variation on supported "of date" frame
 - » An existing supported "of date" frame is used as the base frame.
 - » Perturbations to the "of date" frame are expressed using Euler angles.

Dynamic Frames

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Euler Frames - 4

Navigation and Ancillary Information Facility

As an example, we construct an Euler frame called IAU_MARS_EULER. Frame IAU_MARS_EULER is mathematically identical to the PCK frame named IAU_MARS. The PCK data defining the underlying IAU_MARS frame are:

```
BODY499_POLE_RA = ( 317.68143  -0.1061 0. )
BODY499_POLE_DEC = ( 52.88650  -0.0609 0. )
BODY499_PM       = ( 176.630   350.89198226 0. )
```

Relative to the angles used to define the IAU_MARS frame, the angles for our Euler frame definition are reversed and the signs negated. Angular units are degrees. Rate units are degrees/second, unlike the PCK units of degrees/day.

PCK:	angle_3 is 90 + RA	Euler Frame:	angle_1 is -90 - RA
	angle_2 is 90 - Dec		angle_2 is -90 + Dec
	angle_1 is PM		angle_3 is - PM

```
\begindata
FRAME IAU_MARS_EULER           = <frame_ID>
FRAME <frame_ID>_NAME          = 'IAU_MARS_EULER'
FRAME <frame_ID>_CLASS          = 5
FRAME <frame_ID>_CLASS_ID      = <frame_ID>
FRAME <frame_ID>_CENTER        = 499
FRAME <frame_ID>_RELATIVE       = 'J2000'
FRAME <frame_ID>_DEF_STYLE      = 'PARAMETERIZED'
FRAME <frame_ID>_FAMILY        = 'EULER'
FRAME <frame_ID>_EPOCH          = @2000-JAN-1/12:00:00
FRAME <frame_ID>_AXES           = ( 3 1 3 )
FRAME <frame_ID>_UNITS          = 'DEGREES'
FRAME <frame_ID>_ANGLE_1_COEFFS = ( -47.68143 0.33621061170684714E-10 )
FRAME <frame_ID>_ANGLE_2_COEFFS = ( -37.1135 -0.19298045478743630E-10 )
FRAME <frame_ID>_ANGLE_3_COEFFS = ( -176.630 -0.40612497946759260E-02 )
```

<frame_ID> = integer frame ID code

Dynamic Frames

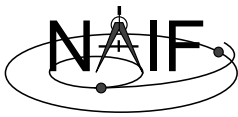
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Frozen Dynamic Frames - 1

Navigation and Ancillary Information Facility

- A frozen dynamic frame is a "Snapshot" of a dynamic frame at a specified epoch.
 - The frame is frozen relative to the base frame specified by the frame kernel creator in the frame kernel definition.
 - The rotation from the frozen frame to the base frame is constant.
 - The rotation is not frozen with respect to inertial frames unless the base frame is inertial.
 - A frame is designated frozen by the presence of a "freeze epoch" specification in the frame definition, for example:
`FRAME_<FRAME_ID>_FREEZE_EPOCH = @1949-DEC-31/22:09:46.861901`
 - The freeze epoch is given in SPICE text kernel format, as is used in a leapseconds kernel.



Frozen Dynamic Frames - 2

Navigation and Ancillary Information Facility

Frozen version of Earth mean equator and equinox of date frame:

+Z axis is perpendicular to mean equator of date.

+X axis is parallel to cross product of +Z axis and vector normal to mean ecliptic of date.

+Y axis completes the right-handed frame.

\begindata

```
FRAME <frame_name>          = <frame_ID>
FRAME <frame_ID>_NAME        = <frame_name>
FRAME <frame_ID>_CLASS        = 5
FRAME <frame_ID>_CLASS_ID     = <frame_ID>
FRAME <frame_ID>_CENTER       = 399
FRAME <frame_ID>_RELATIVE      = 'J2000'
FRAME <frame_ID>_DEF_STYLE     = 'PARAMETERIZED'
FRAME <frame_ID>_FAMILY        = 'MEAN EQUATOR_AND_EQUINOX_OF_DATE'
FRAME <frame_ID>_PREC_MODEL    = 'EARTH_IAU_1976'
FRAME <frame_ID>_FREEZE_EPOCH = @1949-DEC-31/22:09:46.861901
```

<frame_name>	= user-specified frame name
<frame_ID>	= integer frame ID code



Inertial Dynamic Frames - 1

Navigation and Ancillary Information Facility

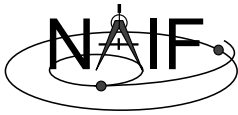
- Inertial dynamic frames are specified by setting the rotation state to 'INERTIAL' in the rotation state assignment:

FRAME_<FRAME_ID>_ROTATION_STATE = 'INERTIAL'

- The 'INERTIAL' state implies the frame is treated as inertial for the purpose of velocity transformations.
- The state transformation between any inertial frame and "inertial dynamic frame" has zero derivative block: the state transformation matrix has the form

$$\begin{array}{c|c} R(t) & 0 \\ \hline 0 & R(t) \end{array}$$

where $R(t)$ is a time-dependent rotation.



Inertial Dynamic Frames - 2

Navigation and Ancillary Information Facility

- In contrast, for any rotating frame $R(t)$, the state transformation between any inertial frame and $R(t)$ has a corresponding matrix of the form

$$\begin{array}{c|c} R(t) & 0 \\ \hline dR(t)/dt & R(t) \end{array}$$

- The inertial rotation state
 - » Simplifies velocity transformations: velocities are transformed by a rotation.
 - » May be useful for maintaining consistency with other dynamic frame implementations.
 - » Only makes sense if the "inertial" dynamic frame actually rotates very slowly!



Inertial Dynamic Frames - 3

Navigation and Ancillary Information Facility

Inertial version of Earth true equator and equinox of date frame:

+Z axis is perpendicular to true equator of date.

+X axis is parallel to cross product of +Z axis and vector normal to mean ecliptic of date.

+Y axis completes the right-handed frame.

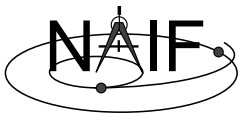
\begindata

```
FRAME <frame_name>           = <frame_ID>
FRAME <frame_ID>_NAME         = <frame_name>
FRAME <frame_ID>_CLASS        = 5
FRAME <frame_ID>_CLASS_ID     = <frame_ID>
FRAME <frame_ID>_CENTER       = 399
FRAME <frame_ID>_RELATIVE      = 'J2000'
FRAME <frame_ID>_DEF STYLE     = 'PARAMETERIZED'
FRAME <frame_ID>_FAMILY        = 'TRUE EQUATOR AND EQUINOX OF DATE'
FRAME <frame_ID>_PREC MODEL    = 'EARTH_IAU_1976'
FRAME <frame_ID>_NUT MODEL     = 'EARTH_IAU_1980'
FRAME <frame_ID>_ROTATION_STATE = 'INERTIAL'
```

<frame_name>	= user-specified frame name
<frame_ID>	= integer frame ID code

Dynamic Frames

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Generic Dynamic Frames Kernel

Navigation and Ancillary Information Facility

- **NAIF is developing a "generic" dynamic frames kernel.**
 - Will contain widely applicable dynamic frame definitions.
 - Analogous to generic PCK file.
 - Examples of included frames:
 - » GSE, GSM, MAG
 - » Earth mean equator and equinox of date, 1976 version
 - » Earth true equator and equinox of date, 1980 version

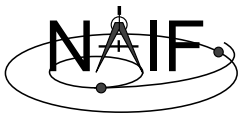
Dynamic Frames

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Backup

- **Rationale**
- **Numerical Issues**
- **Limitations**



Rationale

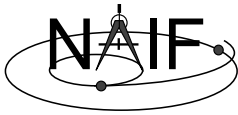
- **Why provide dynamic frames?**
 - User could build C-kernel for *any* frame.
 - SPICE could provide a limited number of "built-in" dynamic frames which wouldn't require a frame kernel.
 - Users can (and do) create their own routines to implement dynamic frames.
- **Benefits**
 - **Convenience:** using a formula rather than a C-kernel avoids C-kernel creation, dissemination, storage, and consistency issues
 - **Flexibility:** the dynamic frame mechanism enables creation of a vast variety of reference frames
 - **Integration:** once defined, and once supporting kernels are loaded, dynamic frames may be referenced in SPICE API calls.



Numerical Issues - 1

Navigation and Ancillary Information Facility

- **Two-vector frame derivatives may be inaccurate.**
Let $R(t)$ represent a time-dependent rotation:
 - If $R(t)$ depends on CK data, $dR(t)/dt$ may be inaccurate because CK rates frequently have low accuracy.
 - If $R(t)$ depends on velocity vectors, then $dR(t)/dt$ depends on acceleration determined via numerical differentiation. Typically such derivatives suffer loss of accuracy.
 - » However, if velocities are "well-behaved," numerically derived acceleration can be quite good. Example: GSE frame.
 - If $R(t)$ depends on position vectors, the velocities associated with those vectors by the SPK system may not be mathematically consistent with the positions. This can happen for SPK types with separate polynomials for position and velocity, such as types 3, 8, 9, and 14.
 - If $R(t)$ depends on aberration-corrected vectors, the associated velocities may be inaccurate due to accuracy limitations of the aberration corrections applied to velocities by the SPK system.



Numerical Issues - 2

Navigation and Ancillary Information Facility

- **Recommendations**
 - Avoid using aberration corrections in two-vector frame definitions, if accurate velocity transformations are required.
 - Be aware of the accuracy of the data on which two-vector frames are based.

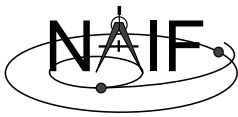


Limitations - 1

Navigation and Ancillary Information Facility

- **Simulated recursion:**

- ANSI Fortran 77 doesn't support recursion, so the SPICE dynamic frame system implements limited, simulated recursion.
 - » Basically, two levels of recursion are supported for selected SPK and Frame System routines.
- Users must avoid requesting "deeper" recursion than the SPICE dynamic frame system can support.
 - » When defining dynamic frames:
 - Choose J2000 as the base frame for two-vector frames.
 - Except for Euler frames, avoid using dynamic frames as base frames.
 - Try to avoid choosing a dynamic frame as the frame associated with a velocity or constant vector.
 - » In SPK, CK, or PCK kernels, don't use two-vector frames as the base frame relative to which ephemeris or attitude data are specified.
 - "Of-date" or Euler frames are OK for this purpose.



Limitations - 2

Navigation and Ancillary Information Facility

- **Run-time efficiency:**

- Dynamic frame evaluation typically requires more computation than is needed for CK or PCK frames.
 - » For example, evaluation of a two-vector frame may involve several SPK calls.
 - » Euler frames are an exception: these are fairly efficient as long as they don't have a base frame that requires a lot of computation to evaluate.
- To minimize the performance penalty:
 - » Use J2000 as the base frame for two-vector frames.
 - » Use the simplest frames possible for association with velocity or constant vectors in two-vector frame definitions.
 - Prefer non-dynamic frames to dynamic frames and inertial frames to non-inertial frames where there is a choice.