“High Accuracy” Orientation and Body-fixed Frames for the Moon and Earth

January 2009

Topics

- Introduction
- Earth binary PCKs
- Lunar binary PCKs
- Lunar Frames Kernel
  - Frame specifications
  - Frame alias names
- Binary PCK file format
- Using Binary PCKs
- Backup
  - Earth and Moon frame association kernels

Introduction-1

- Now that you are an expert in "standard" PCKs and FKs you may want to learn about several "special" PCKs and FKs dealing with the Earth and the Moon.
- While it is ultimately up to you, in most cases you should use the PCK and FK kernels described here when working with the Moon or the Earth.

Introduction-2

- NAIF provides "High accuracy" orientation data for the Earth and Moon in binary PCKs.
  - For the Earth
    - » High accuracy, frequently updated file
      - Contains high accuracy historical data and fairly accurate, short-term predict data
    - » High accuracy, infrequently updated historical file
    - » Lower accuracy long term predict file
  - For the Moon, there's a long-term file for each JPL "Developmental Ephemeris" (DE) version. The current version is DE-421.
    - » Contains accurate historical and predict data
- To use these kernels:
  - Select PCKs with required time coverage
    - » unlike text PCKs, the time span covered by binary PCKs is limited
  - Load the PCK(s) via FURNSH
  - For the Moon, also load the Lunar FK
  - Reference the Earth body-fixed frame using the name 'ITRF93'
  - Reference the high-accuracy Lunar body-fixed frames using one of these names:
    - » MOON_ME (Moon Mean Earth/Rotation axis frame)
    - » MOON_PA (Moon Principal Axes frame)
    - » IAU_MOON (can not be used to reference high-accuracy lunar orientation data)

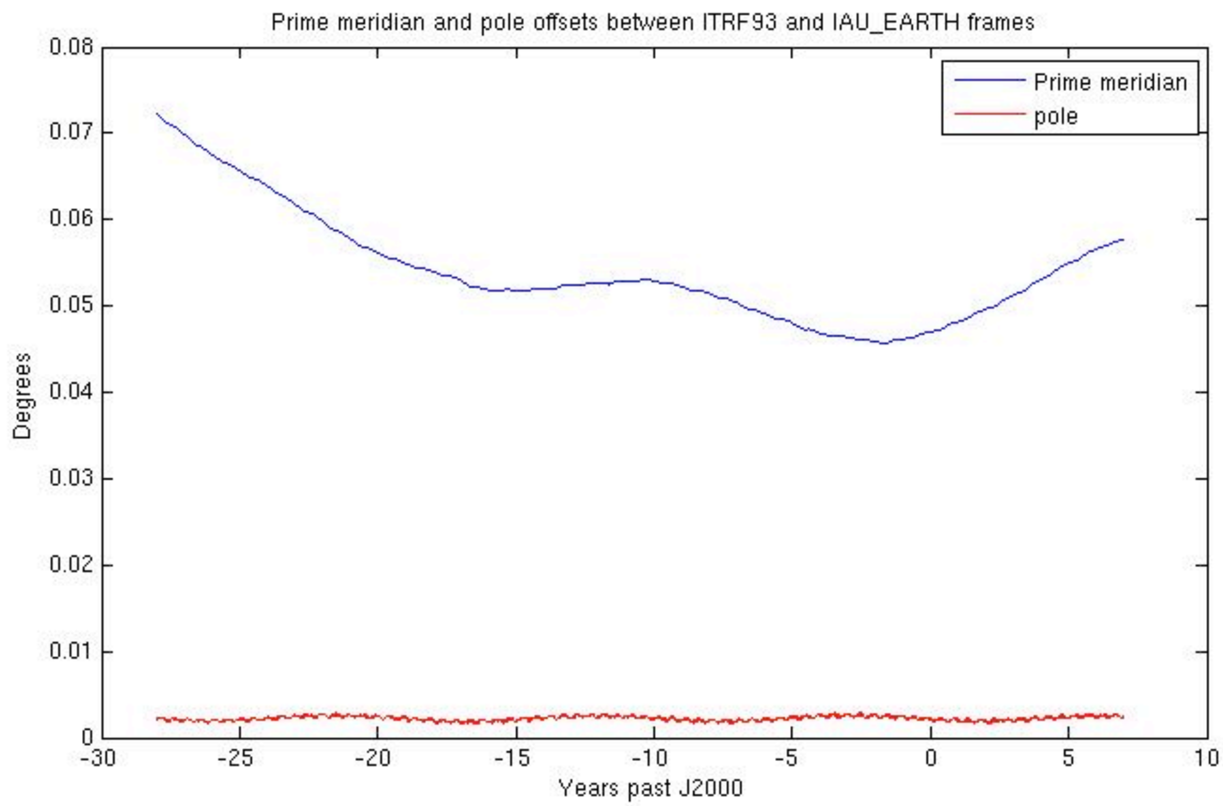
Earth Binary PCKs

"High Accuracy" Earth Rotation Model

- The ITRF93 high accuracy Earth rotation model takes into account:
  - Precession: 1976 IAU model due to Lieske.
  - Nutation: 1980 IAU model, with IERS corrections due to Herring et al.
  - True sidereal time using accurate values of TAI-UT1
  - Polar motion
- It is more accurate than the IAU rotation models found in text PCKs.
  - See the plot on the next slide comparing orientation of the ITRF93 frame to that of the IAU_EARTH frame.
    - » IAU_EARTH frame orientation error is ~1 milliradian, or ~6km on a great circle!
- The highest accuracy is obtainable only for past epochs.
  - Unpredictable variations of UT1-TAI and polar motion limits the accuracy of predicted Earth orientation. See plot on page 8.

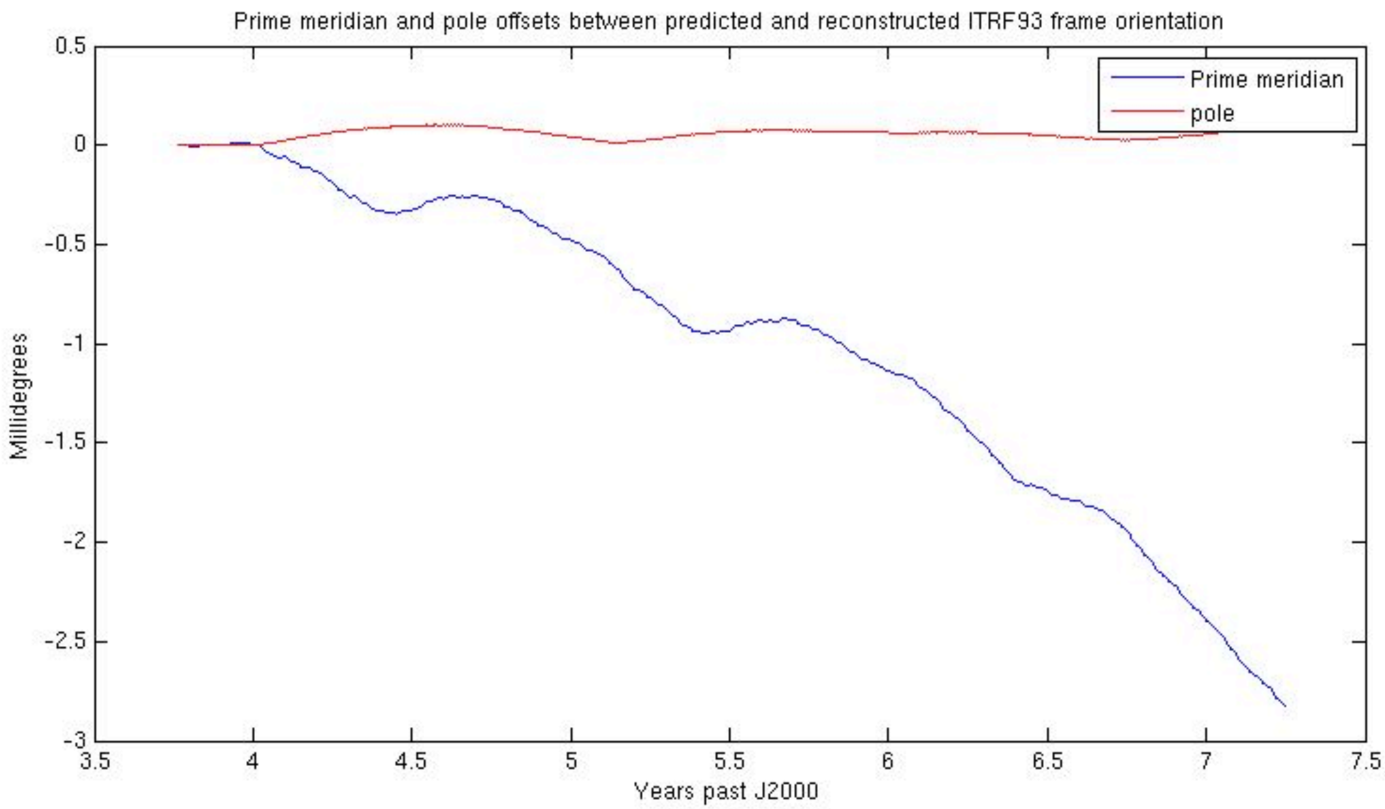
IAU_EARTH vs ITRF93 Comparison Plot

Difference between the IAU_Earth frame and the ITRF93 frame



Earth Predicted vs Reconstructed ITRF93 Plot

Difference between predicted and reconstructed orientation of ITRF93 frame



Data Source for Earth "High Accuracy" Model

- **Data for the Earth come from a JPL Earth Orientation Parameters file (EOP).**
  - **Binary Earth PCKs represent the orientation of an Earth ITRFxx body-fixed reference frame relative to the ICRF*.**
    - **ITRF* frames are defined by the International Earth Rotation Service (IERS).**
    - **Currently only the ITRF93 frame is supported within SPICE.**

ICRF = International Celestial Reference Frame, often referred to in SPICE as the "J2000" frame, and also often referred to as the EME 2000 frame. This is an inertial frame.
ITRF = International Terrestrial Reference Frame

Earth PCK Production Scheme

- Three versions of the "high accuracy" binary Earth PCK are produced
  - "The latest," using each new release of a reconstructed EOP file by JPL
    - » Covers well into the past and approximately two months into the future beyond the production date
    - » Accuracy of the future data degrades rapidly past the production date
    - » Produced several times per week using an automatic script
  - Long term predict, for future uses not requiring high accuracy
    - » Produced infrequently
    - » Covers several years into the past and approximately 30 years into the future
    - » Accuracy at epochs in the future is low compared to that for past epochs, but any of it is far better than what is obtained from the IAU rotation model for the Earth provided in any text PCK
  - History file, containing only high accuracy historical data
- All are in the pck directory under generic_kernels on the NAIF server: ftp://naif.jpl.nasa.gov/pub/naif/generic_kernels/pck/
  - Read the "aareadme" file to see the file naming schema and more details

Accurate Earth Surface Locations

- High accuracy determination of surface locations relative to an inertial frame involves motions in addition to Earth rotation, including:
  - tectonic plate motion
  - tidal effects
  - ocean and atmospheric loading
  - relativistic effects
- Tectonic plate motion is accounted for in NAIF's DSN and some non-DSN station SPK files.
- The other non-rotational effects affecting surface locations are NOT accounted for by a PCK or any other SPICE component.

Kernel Usage Summary: Earth

- To use high accuracy Earth orientation data
  - Load one or more binary Earth PCKs
    - If a long-term predict is used, load this kernel *before* loading any kernel containing reconstructed data so that the reconstructed data have precedence during the overlap period.
  - If your application uses any of the old, pre-N0062 APIs that make use of the default Earth body-fixed frame (see Backup slides), load an Earth frame association kernel making ITRFxx the default earth body-fixed frame.
    - But best to switch to use the "new" APIs that require you to specify which frame to use.
      - New APIs: ILUMIN, SINCPT, SUBPNT, SUBSLR
- If you're using SPICE to access Earth size and shape information, you'll also need to load a text PCK file containing these data.
  - Typically use the latest generic text PCK: pck000xx.tpc

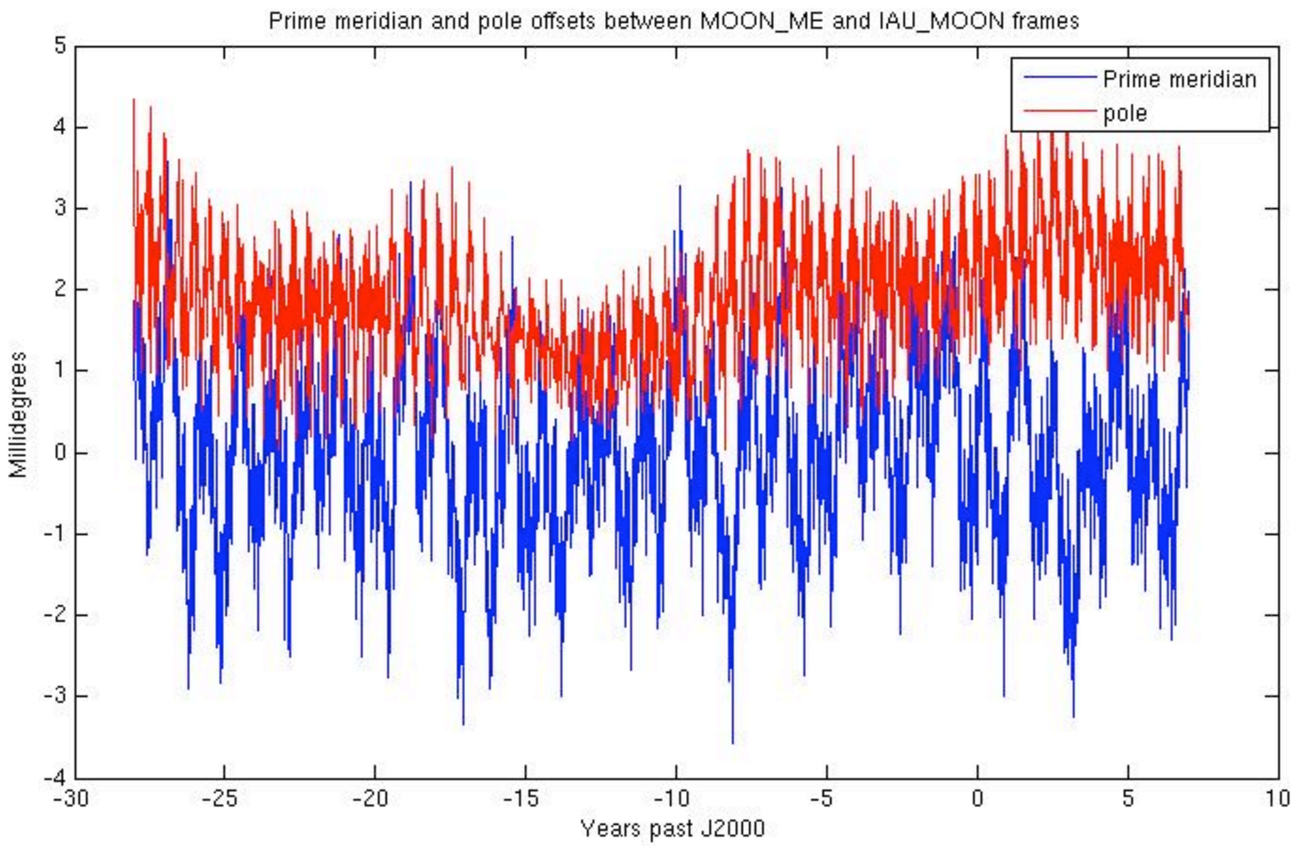
Lunar Binary PCKs

"High Accuracy" Lunar Rotation Model

- **More accurate than the IAU rotation models found in text PCKs.**
  - Rotation error between IAU_MOON and corresponding "high accuracy" MOON_ME (mean Earth/rotation axis) frame is, for the DE-421 and 2000 IAU data sets and the time period 2000-2020, approximately
    - » Worst case: ~0.0051 degrees, or ~155m on a great circle
    - » Average: ~0.0025 degrees, or ~76m on a great circle
  - Error is due to truncation of the libration series in the IAU model
  - Error is not nearly as large as that for IAU_EARTH vs ITRF93
  - See the plot in the following chart comparing the IAU lunar rotation model to the integrated DE-421 model.
    - » Note that the IAU_MOON model was developed in 2000, published in 2002 (see documentation in pck00008.tpc).

IAU_Moon vs MOON_ME Comparison Plot

Difference between the IAU_Moon frame and the Moon_ME frame (equivalent to the Moon_ME_DE421 frame)



Lunar Rotation Model Effects

- **The DE421 high accuracy lunar orientation model represents the result of a simultaneous numerical integration of lunar rotation and orbit, and of orbits of the planets.**
  - The DE421 integration model includes*:
    - » A "solid Moon"
    - » Torques on Moon from the static gravity field of degree 2-4. Torque is due to Earth, Sun, Venus, and Jupiter.
    - » Torques on Moon and moments of inertia due to (degree 2) tides raised by Earth
    - » Dissipation effects on torques and moments due to tides on the Moon.
    - » Torques due to Earth J2 interacting with Moon degree 2 (J2 and C22).
  - Lunar quantities fit for DE421 include
    - » Initial conditions for lunar orbit and rotation of body
    - » Moment of inertia difference (C-A)/B and (B-A)/C
    - » Third-degree gravity field coefficients
    - » Tidal Love numbers and dissipation
    - » Locations of four laser retroreflector arrays
- **It is anticipated that further improvements in the orientation of the moon will become available in new Dexxx-based kernels in the future.**

*Description provided by James G. Williams (JPL)

Data Sources for “High Accuracy” Models

- Data for the Moon come from JPL’s DExxx planet/lunar ephemeris (e.g. DE421).
  - Binary lunar PCKs represent the orientation of the Moon’s “principal axis” reference frame, MOON_PA_DExxx, relative to the ICRF*.

ICRF = International Celestial Reference Frame, often referred to in SPICE as the “J2000” frame, and also often referred to as the EME 2000 frame. This is an inertial frame.
ITRF = International Terrestrial Reference Frame

Lunar Frames Kernel

Lunar Frames Kernel

- **A lunar frames kernel is maintained and available from NAIF. It has four functions.**
  1. **Make two lunar frames–Principal Axes (PA) and Mean Earth/Polar Axis (ME)–known to the SPICE system.**
     - » **Within SPICE their names are MOON_PA_DExxx and MOON_ME_DExxx**
     - » **These frames are unique to a particular JPL-produced lunar and planetary ephemeris (DE/Lexxx, which is often referred to as simply DExxx).**
  2. **Connect the MOON_PA_DExxx frame name to the high accuracy lunar orientation PCK data that implement the PA orientation (relative to the ICRF).**
  3. **Provide specifications, in the SPICE context, for implementing the rotation between the PA frame and the ME frame.**
     - » **Makes the MOON_ME_DExxx frame available to SPICE.**
  4. **Provide generic frame names, aliased to the MOON_PA_DExxx and MOON_ME_DExxx frame names.**
     - » **The generic frame names are simply MOON_PA and MOON_ME.**
     - » **The generic names need not be changed in your programs when the MOON_PA_Dexxx and MOON_ME_DExxx names change due to use of new defining data.**
       - » **The DE-specific frames to which these aliases “point” will be updated by NAIF whenever a new binary lunar orientation PCK is produced. NAIF will release a new lunar FK at that time.**
- **To access the PA or ME frame you must load the lunar FK into your program in addition to the lunar binary PCK that implements the lunar PA frame orientation.**

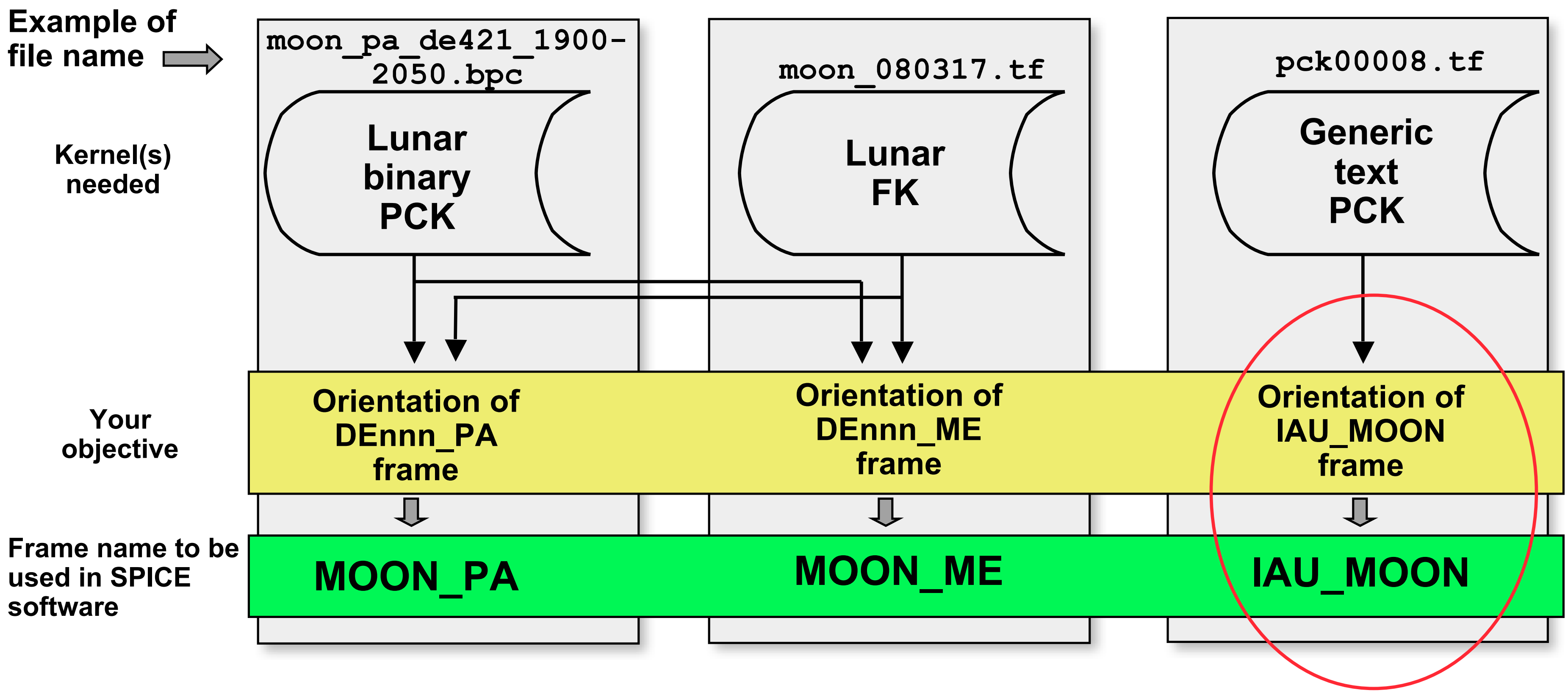
Kernel Usage Summary: Moon

- **To use high accuracy Moon orientation data**
  - Load the current binary lunar PCK
  - Load the current lunar FK
  - If your application uses any of the old, pre-N0062 APIs that make use of the <u>default</u> lunar body-fixed frame (see Backup), load a moon frame association kernel making either MOON_ME or MOON_PA the default lunar body-fixed frame.
    - » But best to switch to use the "new" APIs that require you to specify which frame to use.
      - New APIs: ILUMIN, SINCPT, SUBPNT, SUBSLR

- **If you're using SPICE to access Moon size and shape information, you'll also need to load a text PCK file containing these data.**
  - Typically use the latest generic text PCK, such as pck00008.tpc

Lunar PCK/FK Summary

Which kernels are needed to access each of the three lunar body-fixed reference frames providing lunar orientation?



Usually a bad choice for the moon!

Binary PCK File Format

Binary PCK File Format

- **SPICE binary PCK files are used to accommodate "high accuracy" rotation models.**
  - Just as for SPKs and CKs, the data are held in SPICE Double Precision Array files (DAF)
  - Multiple types are supported
    - » Type 2: Chebyshev polynomials are used to represent Euler angles giving orientation as a function of time. Rates are obtained by differentiating polynomials. Coverage intervals have fixed length.
      - Used for the Earth and the Moon
    - » Type 3: Separate sets of Chebyshev polynomials are used to represent Euler angles and their rates. Coverage intervals have variable length.
      - Not currently used for Earth or Moon
  - Binary PCKs include a "comment area" for storing descriptive metadata
    - » Access the comment area using the Toolkit's *commnt* utility program
  - Binary PCKs support high-speed direct access
    - » Cheby polynomials are fit to source Euler angles; these evaluate very quickly

Using Binary PCKs

Precedence Rules for Text and Binary PCKs

Navigation and Ancillary Information Facility

- If two (or more) binary PCKs with functionally equivalent data are loaded, a later loaded file takes precedence.
- Loading one text PCK that supersedes another can lead to errors if data from the "old" PCK remain in the kernel pool.
  - It's essential to unload the old text PCK before loading the new one.
    - » Use UNLOAD or KCLEAR to unload the old text PCK.
  - This problem doesn't apply to binary PCKs.
- If both a binary and a text PCK provide orientation for the same frame, data available from the binary PCK always take precedence over data available from the text PCK.
  - This is independent of file loading order
  - The binary PCKs discussed in this tutorial define earth-fixed and moon-fixed frames different from those defined by a NAIF text PCK (e.g. pck00008.tpc), so there is no conflict.

Tools for use with Binary PCKs

- Use the *commnt* utility to access a binary PCK comment area
  - Read, extract or insert metadata
- Use the *brief* or *spacit* utility to summarize a binary PCK
  - *brief* is easier to use; *spacit* provides more information
- Non-native binary PCKs can be read without first being converted to the native binary form
  - If you need to write to a non-native binary PCK you must first convert it to native binary form using *bingo* or the pair of *toxfr* and *tobin*
    - » *toxfr* and *tobin* are avaiable in each Toolkit; bingo is available only from the NAIF website
  - Converting a non-native binary PCK to native form will also speed up data access somewhat

Backup

Association Frames Kernels for the Earth and the Moon

Association FKs: Introduction

Navigation and Ancillary Information Facility

- **In most SPICE modules that deal with one or more reference frames the name(s) of that/those frame(s) must be provided as input argument(s), for example:**
  - `CALL SPKEZR (target,time, frame, observer, correction,`
    `state, lighttime)`
- **NAIF's SPICE developers assumed there would be only one body-fixed reference frame associated with each natural body during a program run.**
  - **Thus a specific body-fixed frame name would rarely be needed as an input to modules dealing with body-fixed frames**
  - **Instead, SPICE could use the body-fixed frame associated with a given body simply by knowing the body name or ID**
    - » **For most bodies SPICE associates the body with a body-fixed frame named** `IAU_<body name>` **(example:** `IAU_MOON`**)**
    - » **This is known as the default body-fixed frame**
- **This was a bad assumption… at least for the Earth and the Moon!**
  - **Multiple body-fixed frames exist for the Moon and Earth**
  - **The default body-fixed frames for the Moon and the Earth, for which the defining data are provided in a generic text PCK (taken from an IAU report) are very inaccurate representations of the actual orientations of these bodies**

Better Choice for the Default

- For the Earth and the Moon there are other choices for body-fixed frame that are almost certainly better than the default body-fixed frame conjured up by SPICE

Body	SPICE Default Body-fixed Frame	Better choice
Earth	IAU_Earth	ITRF93 ITRFxx (in the future)
Moon	IAU_Moon	Moon_PA or Moon_ME

The Problem

- The SPICE modules that make use of the default body-fixed reference frame are these
  - LSPCN, ET2LST, ILLUM, SRFXPT, SUBPT, SUBSOL (and their C, Icy and Mice equivalents)
  - Your code might overtly call one of these, or it could call one indirectly through use of a parameterized dynamic frame

Still available, but better to use those noted below

- NAIF rules regarding stability of our software offerings prevent us from changing the designs of those modules
  - So we must provide you means to change the default body-fixed frame associated with any solar system body of interest to you. See the next several pages.
- However, starting with the version N62 Toolkits, a new set of modules is available for those calculations where precision body orientation is important.
  - These modules require the user to name the desired body-fixed frame, rather than using a default body-fixed frame
  - The new N62 modules are these
    - » ILUMIN, SINCPT, SUBPNT, SUBSLR

New: safer to use, and offer improved accuracy in some cases

Changing the Default Body-Fixed Frame Name

- **All bodies for which a body-fixed frame is defined by the IAU, and where the defining data are found in a SPICE text PCK file, have an associated <u>default</u> body-fixed frame name within SPICE:**
  - **The name pattern is:** `IAU_<body name>`
  - **Examples:** `IAU_MARS, IAU_MOON, IAU_EARTH`
- **A different default body-fixed frame name can be assigned within a program by placing the following assignment in any text kernel that is loaded into the program:**

```
OBJECT_<body name>_FRAME = '<new default frame name>'
```

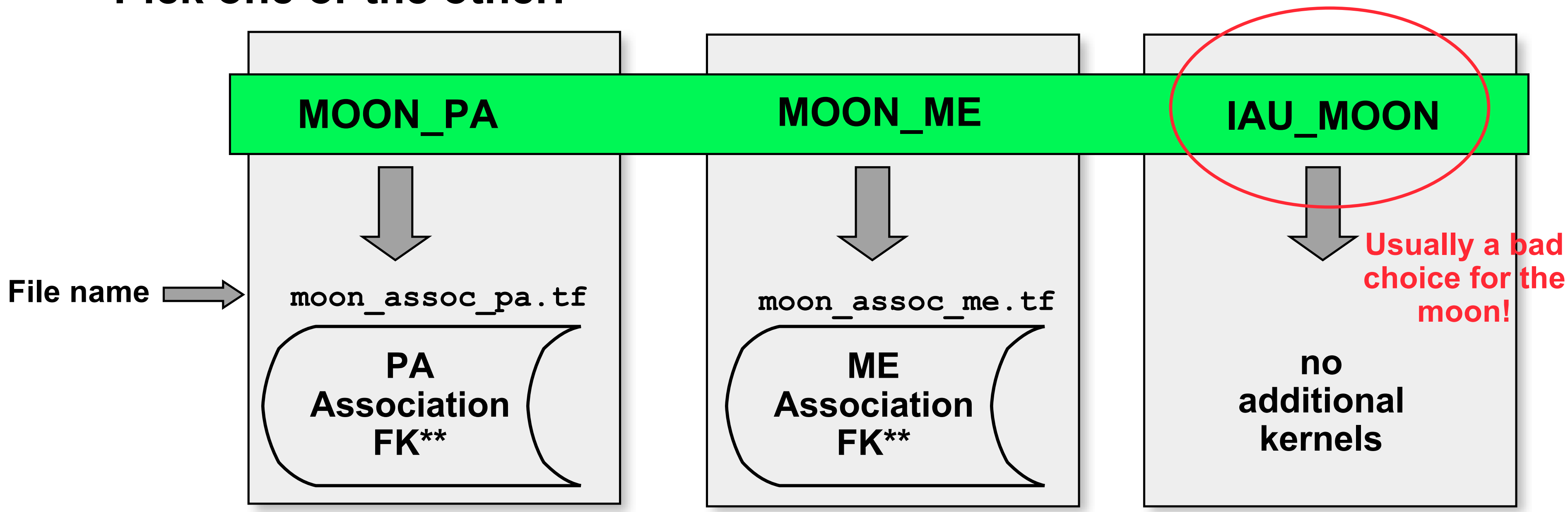
  - **Example:** `OBJECT_MOON_FRAME = 'MOON_ME'`
- **NAIF offers three "association FKs" to accomplish this.**
  - **See next page.**

Using Association FKs to Change the Default

- For the Earth and the Moon, changing the default body-fixed frame name as described on the previous page can be accomplished by loading the appropriate "association" frame kernel provided by NAIF. The association kernels available are shown below
  - For the Earth:
    - earth_assoc_itrf93.tf
  - For the Moon: (pick one or the other–not both)
    - moon_assoc_me.tf
    - moon_assoc_pa.tf
- These kernels are available on the NAIF server
  - For the Earth:
    - ftp://naif.jpl.nasa.gov/pub/naif/generic_kernels/fk/planets/
  - For the Moon:
    - ftp://naif.jpl.nasa.gov/pub/naif/generic_kernels/fk/satellites/

Lunar FK/PCK/Association FK Usage

Which additional kernel is needed to use the indicated frame in those (older) SPICE APIs* that use a default (assumed) frame? Pick one or the other.



*** ET2LST, ILLUM, SRFXPT, SUBPT, SUBSOL (and their C, Icy and Mice equivalents)**

But best to use the N62 replacements for these four, which don't use a default body-fixed frame:
- ILUMIN
- SINCPT
- SUBPNT
- SUBSLR

****Any version of one or the other of these kernels is good indefinitely; you do not need to use the latest instance offered on the NAIF server.**