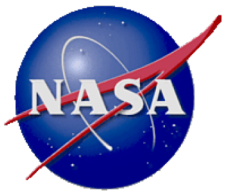

Navigation and Ancillary Information Facility (NAIF)

"SPICE"
Might Help Cubesat and SmallSat Missions Compute Observation Geometry from Ancillary Data

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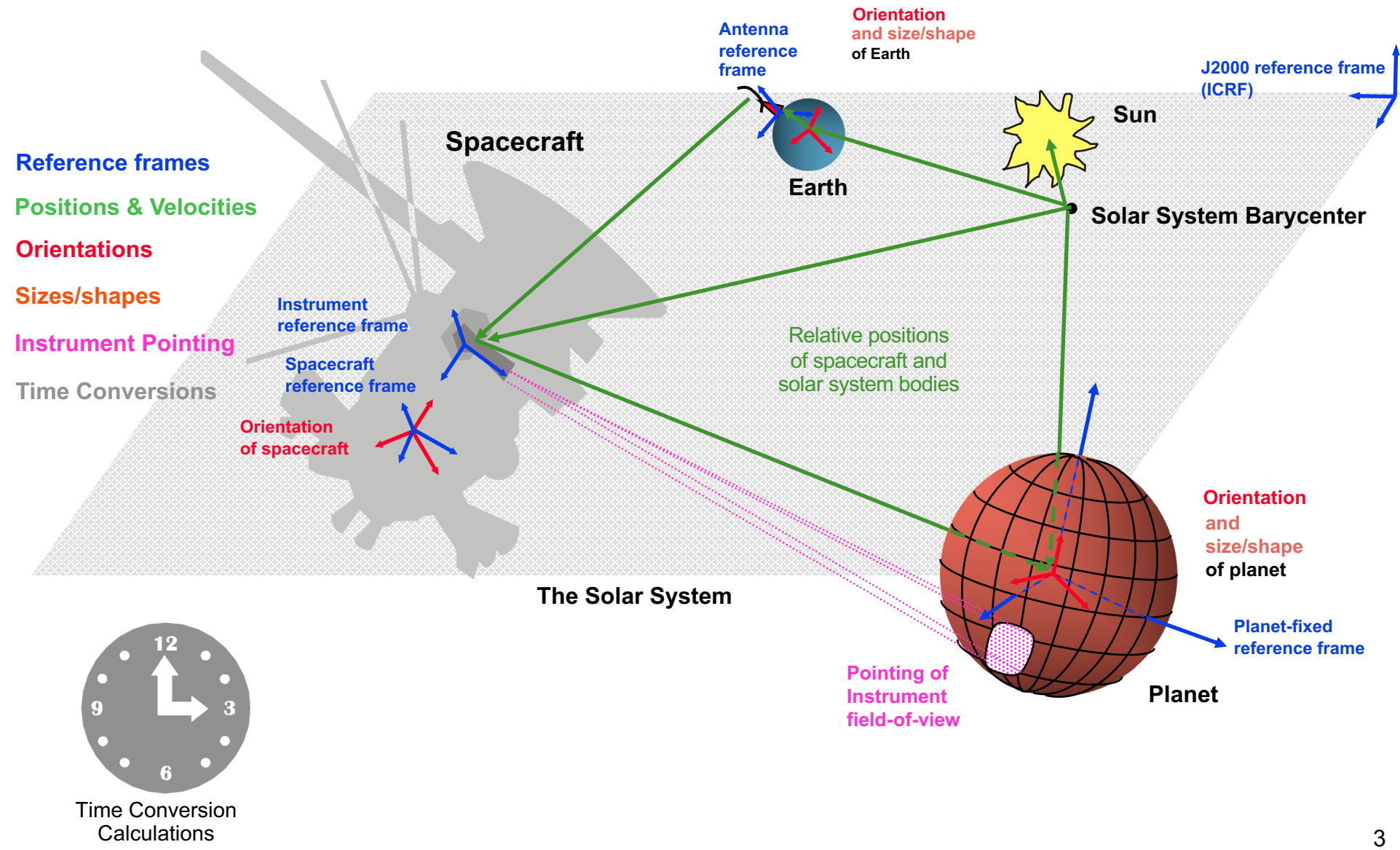
The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

Topics

- What are “ancillary data?”
- Why are these data needed?
- Producing and using ancillary data using NASA’s “SPICE” system

A Pictorial of Ancillary Data



Examples of Using Ancillary Data

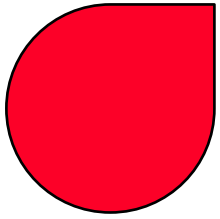
- **Help mission designers converge on a spacecraft trajectory design**

- **Compute observation geometry parameters needed by engineers for…**
  - **communications station view period calculations**
  - **antenna pointing**
  - **thermal and telecom analyses**

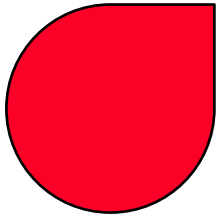
- **Compute observation geometry parameters needed by scientists for…**
  - **science observation planning**
  - **science archive preparation**
  - **science data analysis**

Contrast
"Ancillary Data" vs. "Observation Geometry"

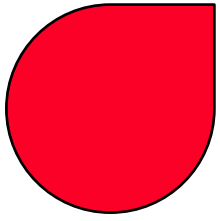
Ancillary Data
(Files)



Spacecraft trajectory



Spacecraft orientation



Spacecraft clock correlation

etc.

Observation Geometry
(Derived parameters)

- Altitude = xxx km.
- Latitude = xxx deg.
- Longitude = xxx deg.
- Phase angle = xxx deg.
- etc.

Observation Geometry
(Conditions)

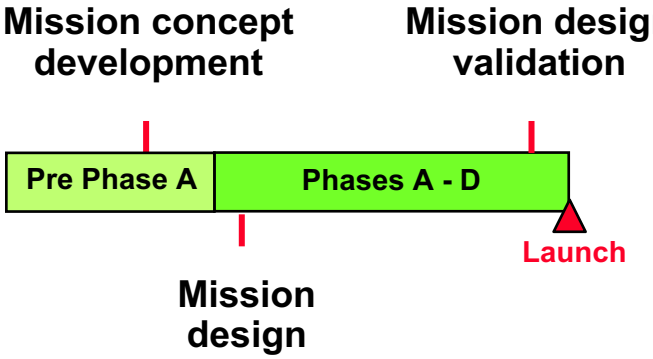
- Spacecraft is in occultation by Mars
- Altitude is at a global maximum
- Phase angle is in the range of 24 to 28 degrees
- etc.

When are Ancillary Data Used?

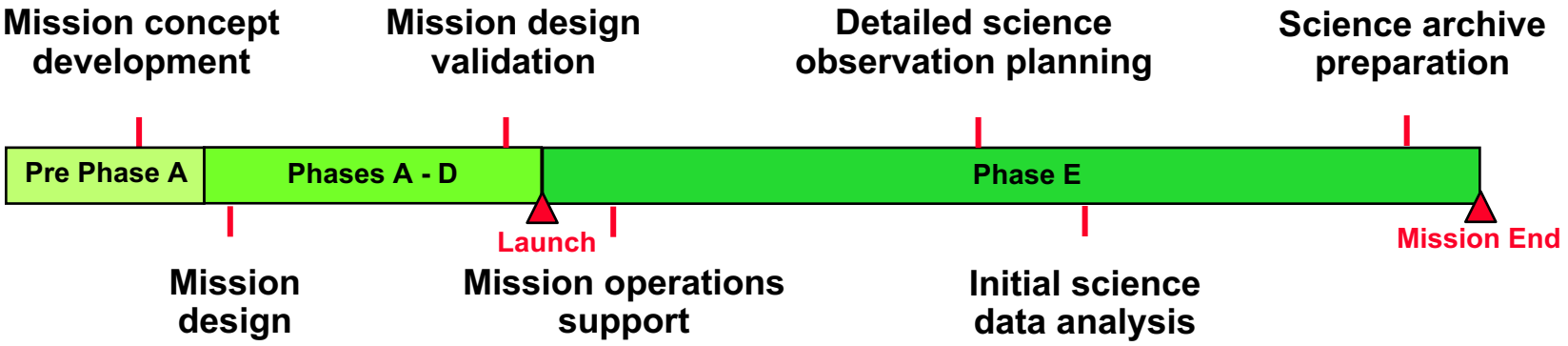
Mission concept development

Pre Phase A

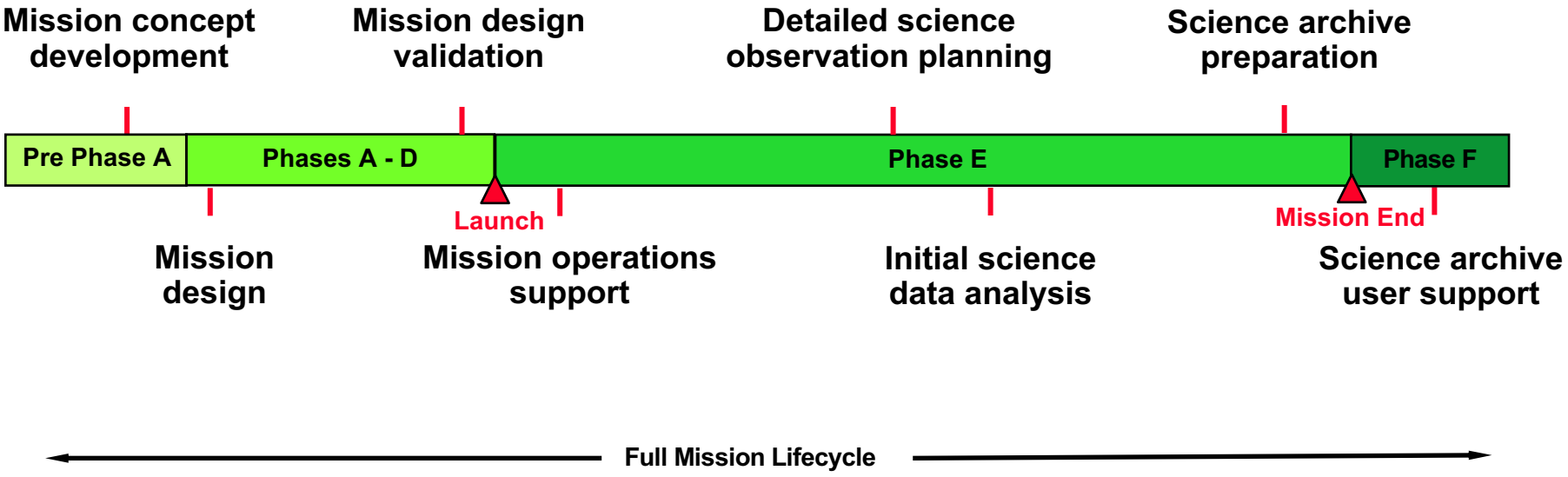
When are Ancillary Data Used?



When are Ancillary Data Used?



When are Ancillary Data Used?



Examples of Challenges in Producing Planetary Ancillary Data

- Almost everything is moving and/or rotating
- Multiple reference frames, coordinate systems and time systems are used
- Size and shape estimates for target bodies are constantly evolving
- Improvements in spacecraft trajectory and orientation often occur

It's Your Choice

- **Within NASA, how your mission will deal with producing and using ancillary data is your choice–there are no NASA mandates.**
  - **Not within the Planetary Science Division (PSD)**
  - **Probably not within other divisions as well**

- **The rest of this presentation describes one substantial offering, named SPICE, that NASA/PSD-funded CubeSat or SmallSat projects might find useful.**

SPICE System Components

Ancillary data files ("kernels")……

Software (SPICE Toolkit) ……

Documentation ……

Tutorials ……

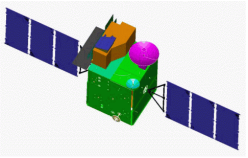
Programming lessons …..

Training classes ……

User consultation ……

From Where do SPICE Ancillary Data Come?

- From the spacecraft



- From the mission control center

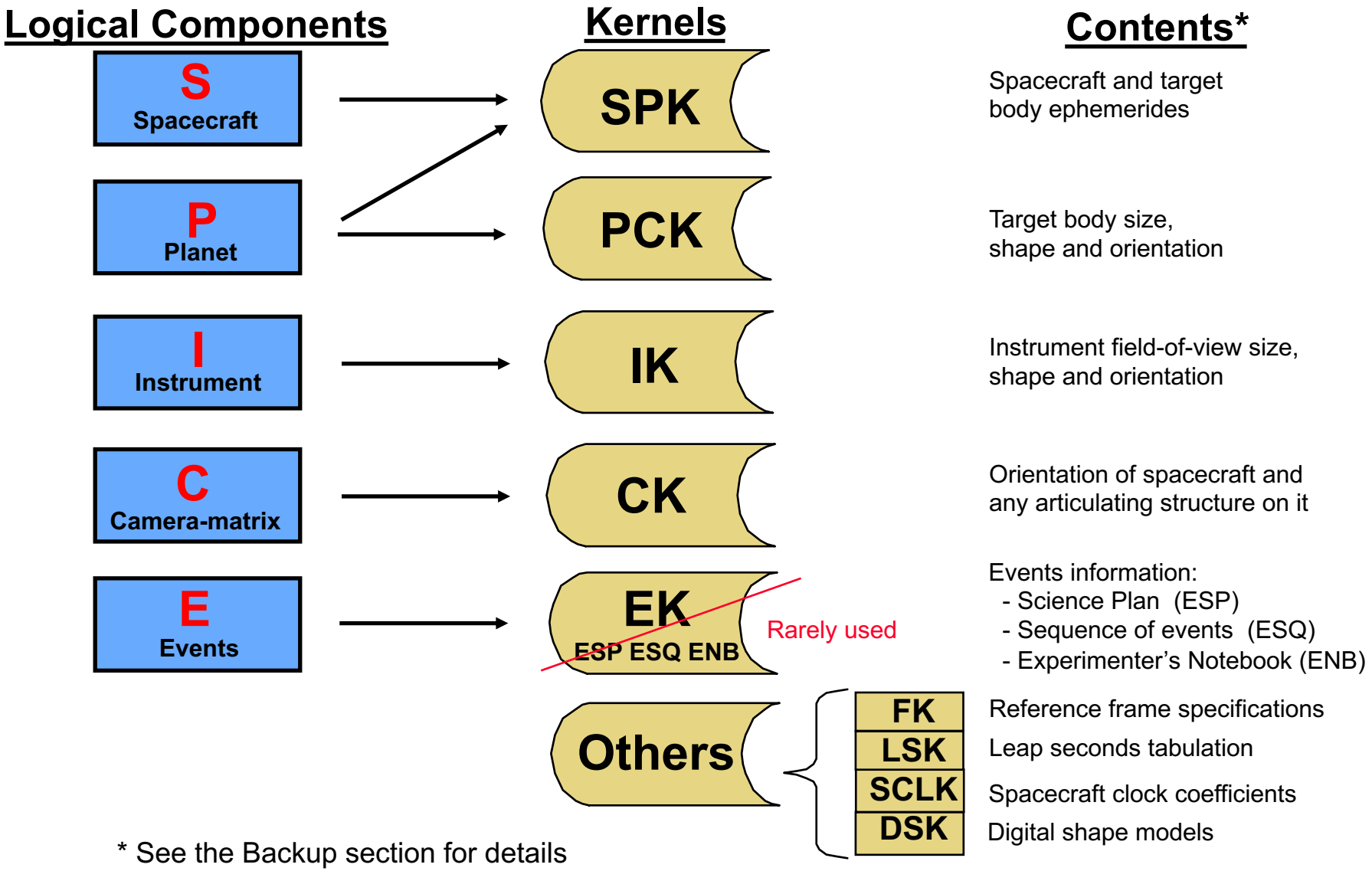
- From the spacecraft and instrument builders

- From science organizations

IAU

SPICE is used to organize and package these data in a collection of multi-mission data files, called "kernels."

SPICE Data Overview



* See the Backup section for details

SPICE Toolkit Software

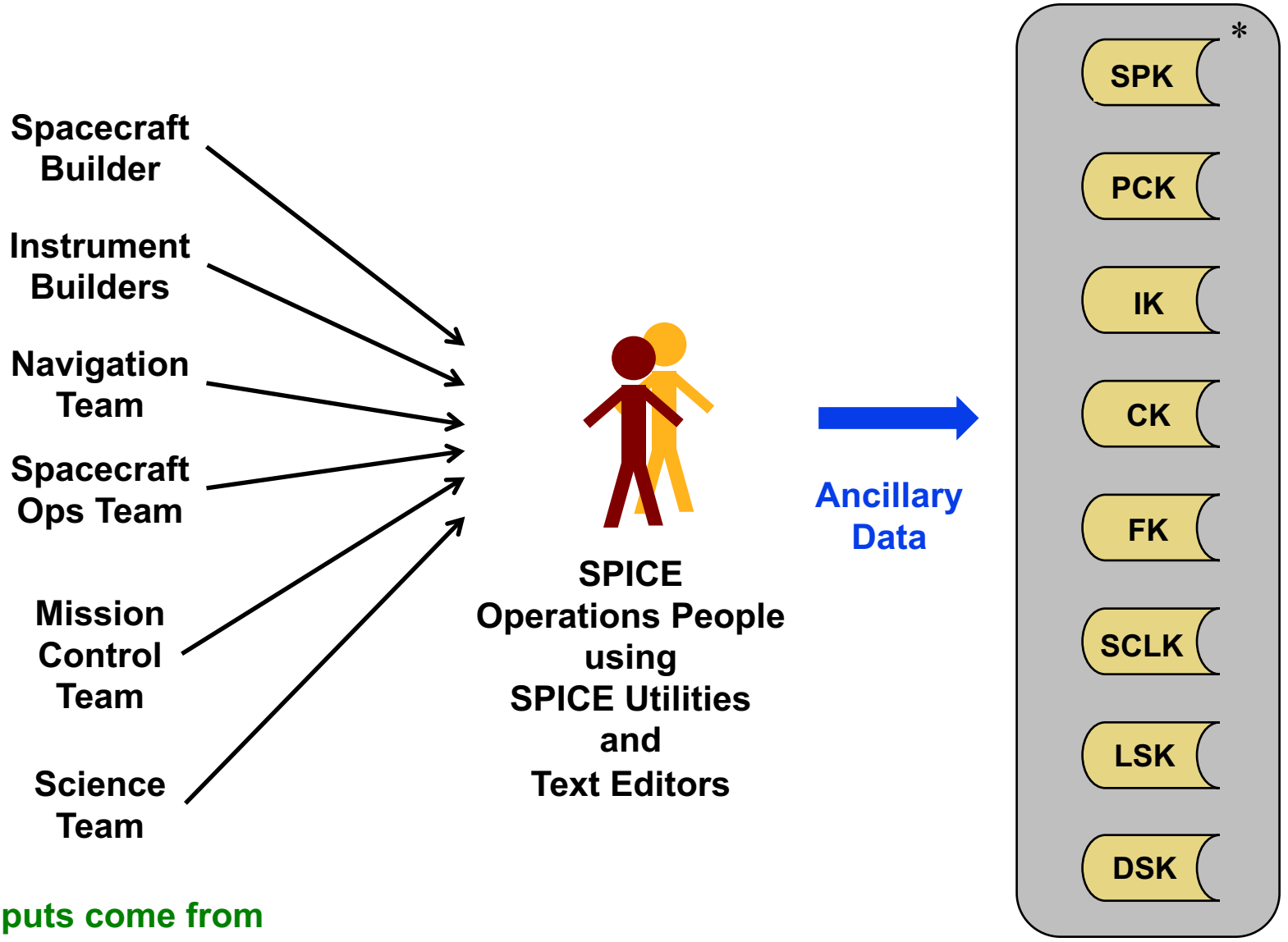
Contents

- **Library of subroutines**
  - Typically just a few used within a customer's program to compute observation geometry quantities derived from SPICE kernels
- **Utiity Programs**
  - SPICE data production
  - SPICE data management
- **Documentation**
  - Highly annotated source code
  - Technical Reference Manuals
  - User Guides

Versions

- **Six languages**
  - Fortran
  - C
  - IDL
  - MATLAB
  - Java Native Interface (JNI)
  - Python
- **Six platforms**
  - PC/Linux
  - PC/Windows
  - PC/CYGWIN
  - Sun/SPARC/Solaris
  - Sun/Intel
  - Mac/Intel/OSX
- **Several compilers**
  - For the Fortran and C Toolkits

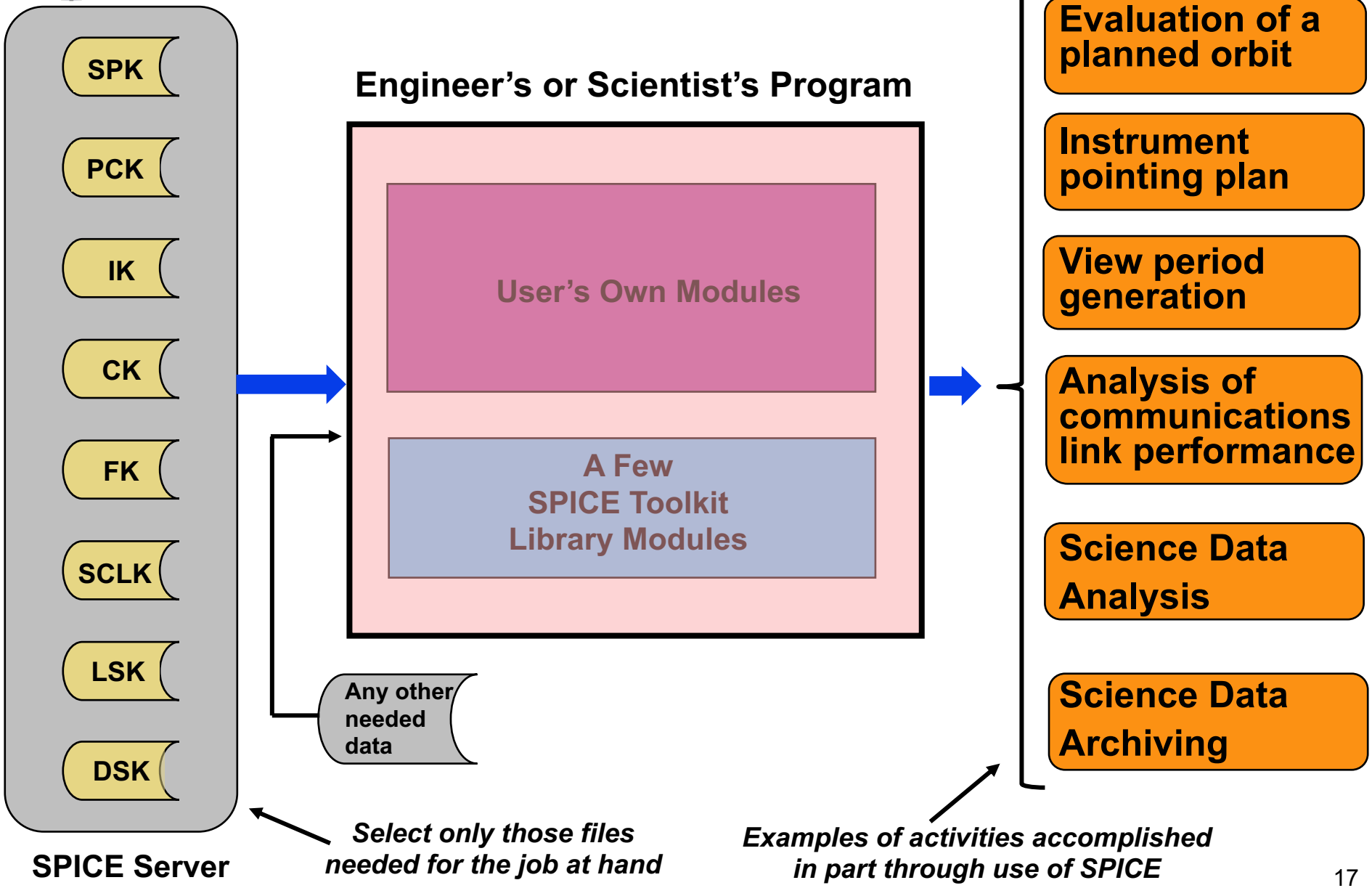
Producing SPICE Ancillary Data



Inputs come from multiple sources

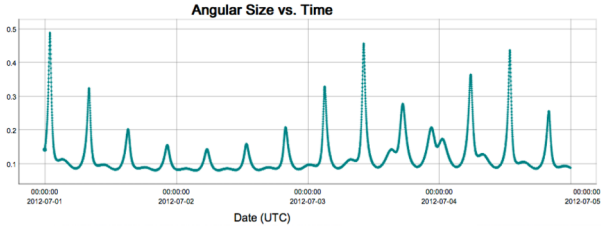
* See the Backup section for details

Using SPICE Ancillary Data



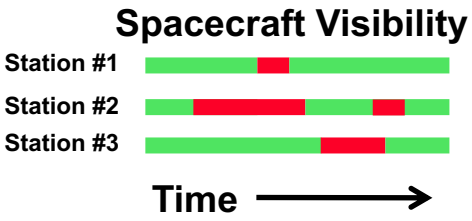
Typical Uses of SPICE

Evaluation of a planned trajectory

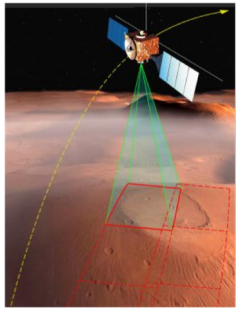


Angular size of Phobos as seen from the Mars Express spacecraft

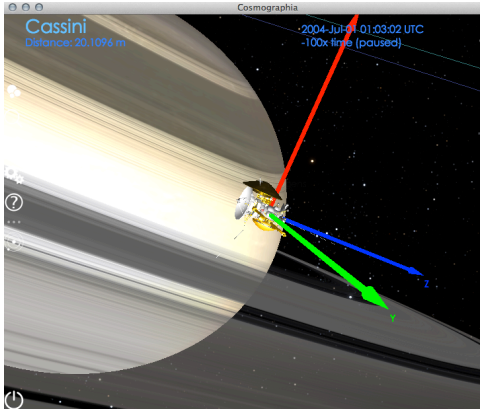
Mission engineering analyses



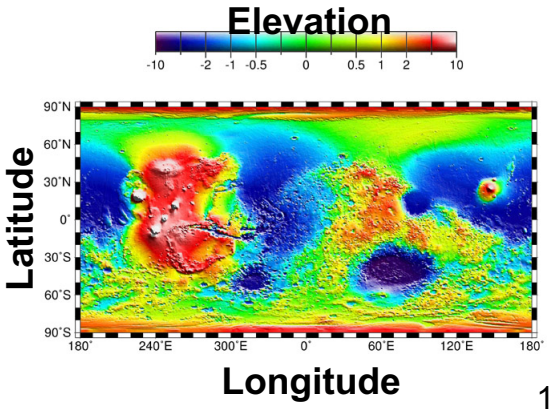
Planning an instrument pointing profile



Observation geometry visualization

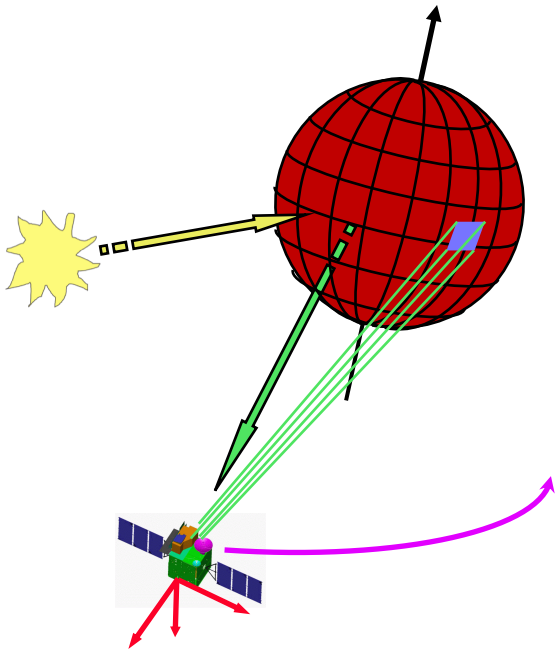


Science data archiving and analysis



What Can One Do With SPICE?

Compute many kinds of derived parameters at selected times



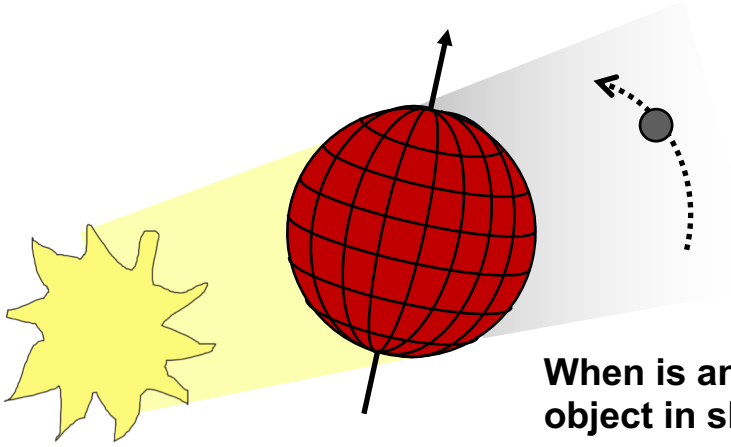
A Few Examples

- **Positions and velocities of planets, satellites, comets, asteroids and spacecraft**
- **Size, shape and orientation of planets, satellites, comets and asteroids**
- **Orientation of a spacecraft and its various moving structures**
- **Instrument field-of-view location on a planet's surface or atmosphere**

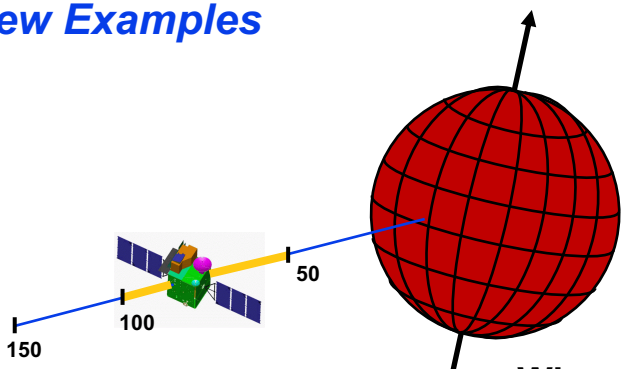
What Can One Do With SPICE?

Find times when a selected "geometric event" occurs, or when a selected "geometric condition" exists

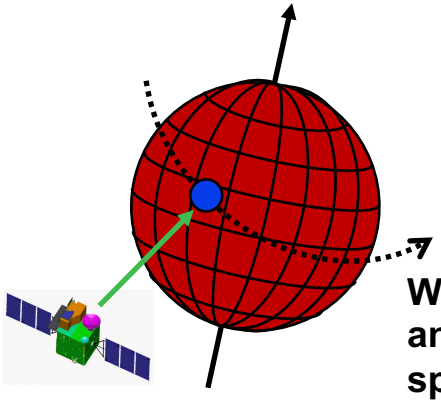
A Few Examples



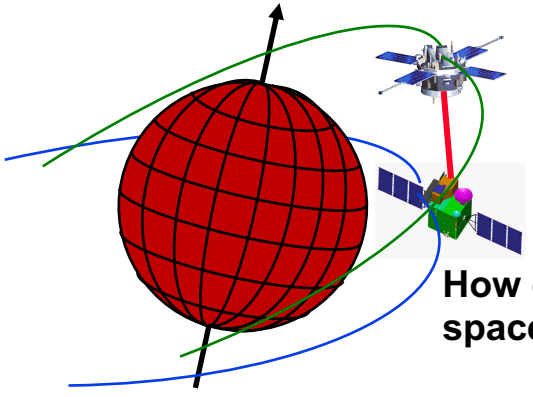
When is an object in shadow?



When is the spacecraft's altitude within a given range? (say 50 to 100 km)



When is an object in front of another, as seen from a spacecraft?

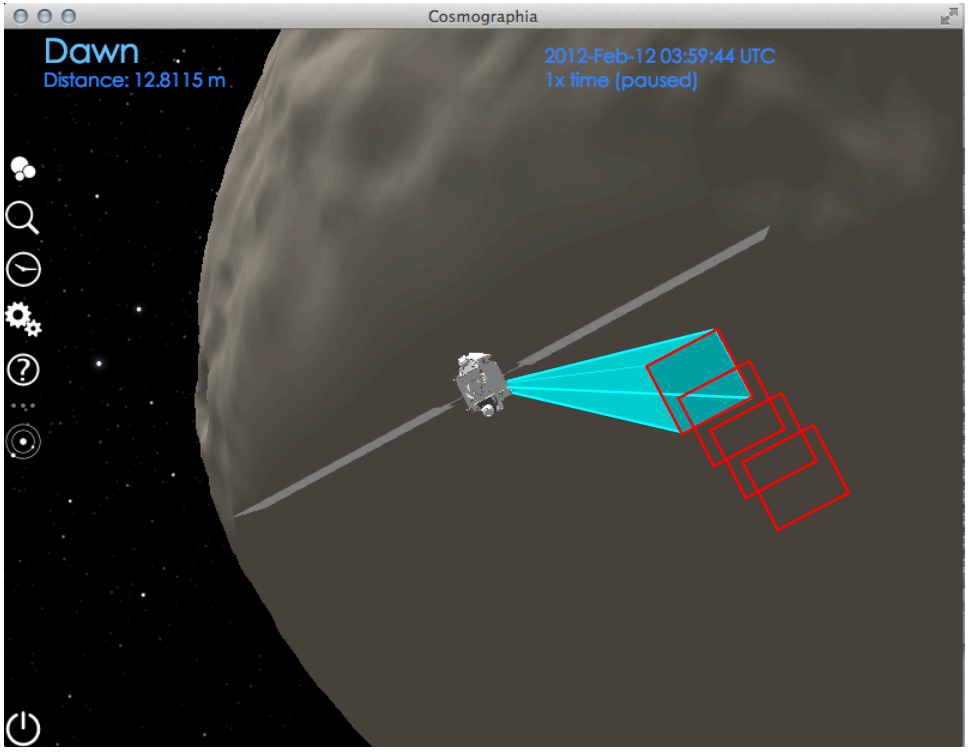


How close will two spacecraft get?

Navigation and Ancillary Information Facility (NAIF)

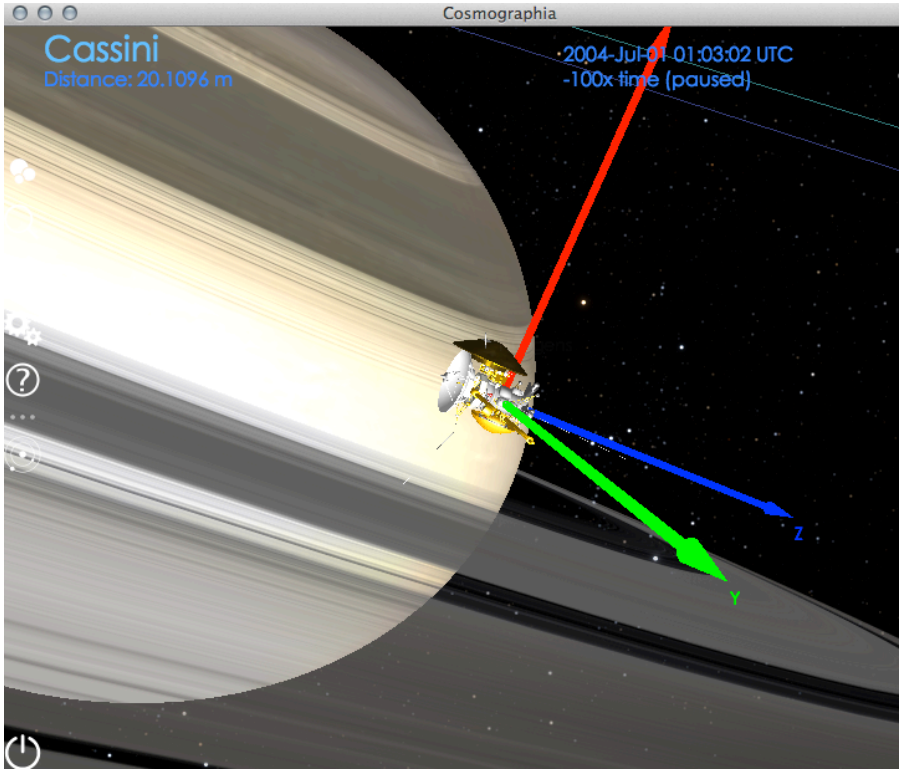
What Can One Do With SPICE?

Produce 3D Mission Visualizations



Cosmographia* visualization of DAWN's framing Camera photographing Vesta

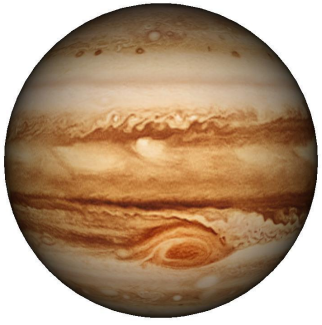
Cosmographia* visualization of Cassini in Orbit at Saturn, showing spacecraft axes



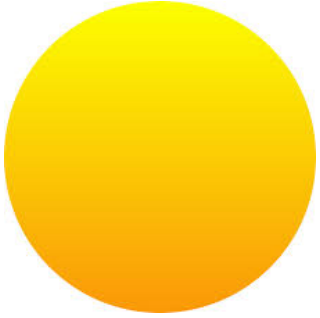
* SPICE-Enhanced Cosmographia is part of the SPICE tools suite

Kinds of Projects Using SPICE

- **Cruise/Flyby**
  - Remote sensing
  - In-situ measurement
  - Instrument calibration
- **Orbiters**
  - Remote sensing
  - In-situ measurement
  - Communications relay
- **Landers**
  - Remote sensing
  - In-situ measurements
  - Rover or balloon relay
- **Rovers**
  - Remote sensing
  - In-situ sensing
  - Local terrain characterization



Planetary Science



Heliophysics

Earth Science

Advantages of Using SPICE

- Provides lots of geometry computational capability
- Software is well tested and always backwards compatible
- SPICE is familiar to many scientists and engineers
- SPICE is the NASA/PSD-preferred ancillary data archive format
- No U.S. ITAR restrictions, no licensing

- SPICE components and generic data are free to all 
  - You can go it yourself in learning to deploy and operate a SPICE system
  - You can contract with NAIF at quite modest cost to help with training and/or operations

Perhaps SPICE is not for Everyone

- Requires use of NASA/NAIF's SPICE software
  - Maybe your project doesn't wish to count on "outside" software?
- Learning to correctly *produce* SPICE data requires effort and at least some domain knowledge
- Learning to correctly *use* SPICE data and software also requires effort
  - Some scientists and engineers don't wish to take the time to do so
- SPICE doesn't specifically handle instrument geometric calibration
- Projects should provide SPICE-aware problem solving and user consultation services throughout the life of the mission
- Unknown possibilities for NAIF support for missions funded outside of NASA's Planetary Science Division

Moving Ahead

- Whether you choose SPICE or another means for computing observation geometry, you should begin implementing your choice sooner rather than later

- NAIF encourages the LCPM community to band together to lobby for institutional (NASA and otherwise) support; this could help you achieve the best and most timely results for the least expense

What is Available for Free?

- The SPICE Toolkit, available at the NAIF website
  - Includes several SPICE kernel production utilities
- Access to all generic SPICE data available at the NAIF website
  - Some may be useful–even required–for your project
- A collection of SPICE tutorials and "open book" SPICE programming lessons, also available at the NAIF website
- About once every year and a half, a three day SPICE users training class

What You'll Need to Provide if You Go It Alone

- Capable personnel who have learned how to produce and validate SPICE kernels
- A data production infrastructure for producing and distributing SPICE kernels
- Careful oversight of the SPICE production process
  - Analysis and correction of problems encountered in SPICE production
  - Often requires good knowledge of your spacecraft and/or its ground data system
- Any needed training for your scientists and engineers intending to consume your SPICE data
  - If the timing works out, perhaps they can attend the SPICE training class mentioned on the previous page
- Consultation for your project's SPICE consumers
- Any SPICE data archiving required by your sponsor

What Could NAIF Provide if Funded to Do So?

- Many flight projects at JPL and some elsewhere within NASA elect to fund NAIF to do some or all of:
  - SPICE data production
  - training and consultation for project SPICE users
  - archive production and archive server
- NAIF could provide training for others on data production or archive production
- What's the cost for such support?
  - There's not a simple answer, but for recent projects in which NAIF has a role, NAIF ops support has ranged from about $30K to $70K per year, usually spanning from Phase C into Phase F
  - The yearly cost typically varies quite a bit depending on what effort is needed, how much of the mission is quiescent, and how long the mission will last

Backup Charts Follow

Graphics Depicting SPICE Data

Global SPICE Geometry

Time conversions

UTC to ET mapping
("generic" LSK file)

Position Vectors

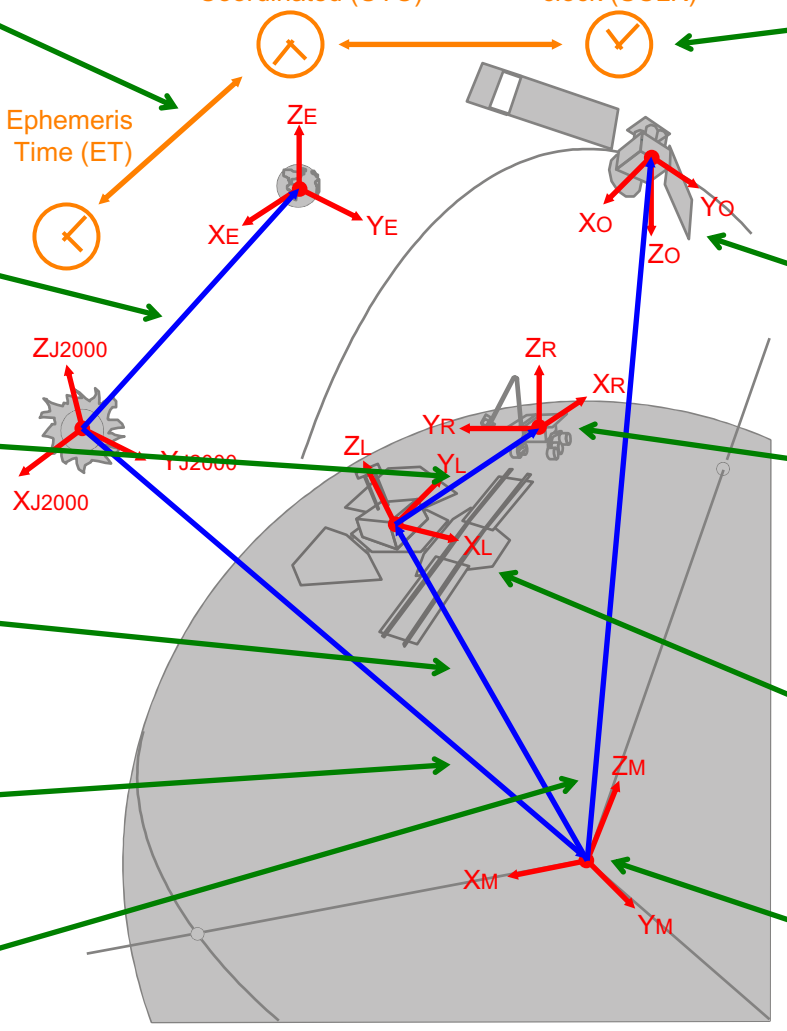
Earth position relative to
Solar System barycenter
("planet ephemeris" SPK file)

Rover position relative to the
landing site (lander)
("rover" SPK file)

Landing site (lander) position
relative to the Mars center
("landing site" SPK file)

Mars position relative to the
Solar System barycenter
("planet ephemeris" SPK file)

Orbiter position relative to
the center of Mars
("orbiter" SPK file)



Time conversions

ET to orbiter on-board
clock mapping
("orbiter" SCLK file)

Frame Orientations

Orbiter frame
orientation relative to
J2000 frame
("orbiter" CK file)

Rover frame orientation
relative to local level
frame
("rover" CK file)

Local level frame
orientation relative to
planet body-fixed frame
("mission" FK file)

Planet body-fixed frame
orientation relative to
J2000 frame
("generic" PCK file)

Orbiter Geometry

Position Vectors

Spacecraft position relative to planet center ("spacecraft" SPK file)

High gain antenna gimbal position relative to spacecraft ("structures" SPK file)

High gain antenna phase center location relative to high gain antenna gimbal ("structures" SPK file)

Solar array gimbal position relative to spacecraft center ("structures" SPK file)

Magnetometer position relative to solar array gimbal ("structures" SPK file)

Frame Orientations

Spacecraft frame orientation relative to inertial frame ("spacecraft" CK file)

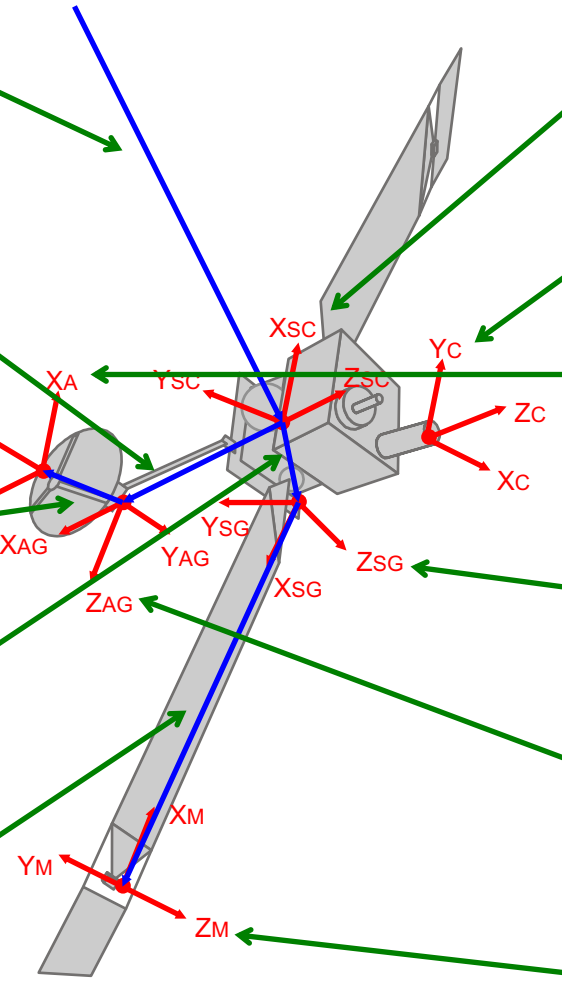
Camera frame orientation relative to spacecraft frame ("mission" FK file)

High gain antenna frame orientation relative to high gain antenna gimbal frame ("mission" FK file)

Solar array gimbal frame orientation relative to spacecraft frame ("solar array" CK file)

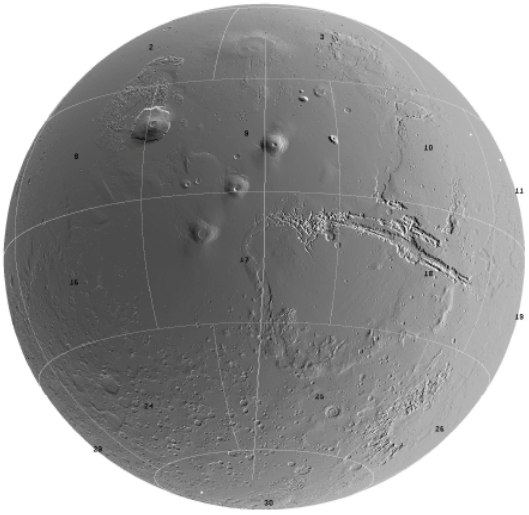
High gain antenna gimbal frame orientation relative to spacecraft frame ("antenna" CK file)

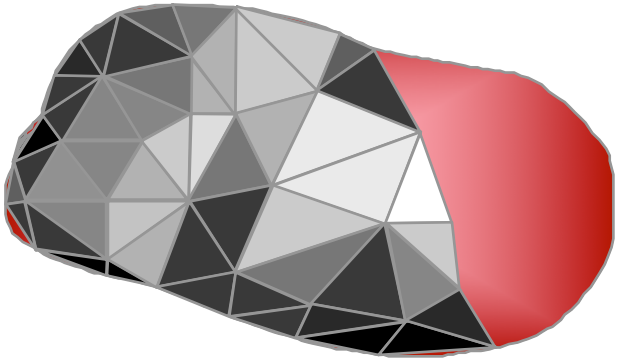
Magnetometer frame orientation relative to solar array gimbal frame ("mission" FK file)



Digital Shape Kernel

The two DSK types shown here are used to provide high fidelity shape models needed by modern experiments. Would be used instead of, or in addition to, the spherical, spheroidal and ellipsoidal models available in a SPICE PCK.





Digital elevation model

For large, regular bodies such as Earth, Moon and Mars

Tessellated plate model

For small, irregular bodies such as asteroids and small satellites

Contents of SPICE Kernels

SPICE Data Details- 1

SPK

- Space vehicle ephemeris (trajectory)
- Planet, satellite, comet and asteroid ephemerides
- More generally, position of something relative to something else

PCK

- Planet, satellite, comet and asteroid orientations, sizes, shapes
- Possibly other similar “constants” such as parameters for gravitational model, atmospheric model or rings model

IK

- Instrument field-of-view size, shape, orientation
- Possibly additional information, such as internal timing

SPICE Data Details- 2

CK

- Instrument platform (e.g. spacecraft) attitude
- More generally, orientation of something relative to a specified reference frame

EK

3 components

- "Events," broken into three components:
  - ESP: Science observation plans
  - ESQ: Spacecraft & instrument commands
  - ENB: Experiment "notebooks" and ground data system logs

EK is not much used

SPICE Data Details - 3

FK

- **Frames**
  - Definitions of and specification of relationships between reference frames (coordinate systems)
    - Both “fixed” and “dynamic” frames are available

LSK

- **Leap seconds Tabulation**
  - Used for UTC <--> TDB (ET) time conversions

SCLK

- **Spacecraft Clock Coefficients**
  - Used for SCLK <--> TDB (ET) time conversions

DSK

- **Shape models (digital elevation model and tessellated plate model) (DSK)**

Partially implemented

UTC = Coordinated Universal Time TDB = Barycentric Dynamical Time SCLK = Spacecraft Clock Time

Ancillary Data Production Challenges

Ancillary Data Production and Usage Challenges

Introduction

- No matter what approach is selected for providing engineers and scientists (and an archive) with ancillary data, real effort is needed to provide an effective system, and to detect and resolve the inevitable problems that arise
- Even when good ancillary data are made available, end users often have trouble using these data

- The next several charts provide some examples

Examples of Ancillary Data Production & Usage Challenges

Spacecraft Trajectory

- Will users need both predicted as well as reconstructed ("definitive") trajectory data?
  - Often both types need be available
  - Need you combine both reconstructed and predicted data in one file?
  - How to manage the many files needed?
- Need to eliminate gaps in coverage
- How avoid "jumps" between adjacent trajectory solutions?
- How to handle improved trajectory solutions:
  - resulting from long arc fits
  - resulting from use of a new, better gravity model
- How to notify end users when new data are available, and for what purpose?
- Will the time system used be a problem for end users?
- Any special requirements placed by tracking stations?
- Any issues resulting from a changing time step size?
- Need you provide end users an evaluation/interpolation algorithm?

Examples of Ancillary Data Production & Usage Challenges

Spacecraft Attitude (Orientation)

- Are predicted attitude data needed in addition to reconstructed data? (Perhaps for observation planning purposes.) With what fidelity, and how achieve that fidelity?
- Are the accuracy and frequency of downlinked (reconstructed) attitude data sufficient for all users?
- Are the time tags attached to reconstructed attitude data sufficiently accurate?
- How does the attitude file producer deal with gaps in downlinked (reconstructed) attitude telemetry?
- How will end users know about and deal with gaps in reconstructed attitude data? (Encountering such gaps is inevitable!)
- Must end users deal with simultaneous use of predicted and reconstructed attitude data?
- Is the volume of attitude data too excessive for end users?
- How can you name and document attitude data files so as to meet end user's needs?

Examples of Ancillary Data Production & Usage Challenges

Spacecraft Clock Calibration

- **Usually the science data and the spacecraft attitude data returned from a spacecraft have time tags determined by an on-board clock**
- **If this is the case, the ground system must be able to convert such time tags to another time system, such as UTC or TAI**
  - **Requires the flight system generate and downlink time correlation "packets," and that these be used to calibrate the spacecraft clock to the accuracy required by the project**
  - **Doing this sort of calibration well can be quite difficult**
  - **Calibration can be complicated by inadequate frequency of returned calibration packets, clock temperature changes, unplanned clock resets, and planned clock "jumping"**

Examples of Ancillary Data Production & Usage Challenges

Reference Frames and Coordinate Systems

- Planetary missions generally make use of multiple reference frames and coordinate systems
- In many cases the definition of the frame or coordinate system is not a true standard
  - For some reference frames the defining data are not well documented, and/or are disputed, and/or are evolving over time
  - For some coordinate systems what is meant by a name can be uncertain or totally left up to the creator
- Some end users do not know how to write code to convert between frames or between coordinate systems
- The above can result in confusion, inconsistencies and outright errors in geometry parameter computations

Examples of Ancillary Data Production & Usage Challenges

Instrument Geometry

- Geometry pertaining to "instruments" is important to understanding the science data acquired
  - Where the instrument is mounted, and with what orientation
    - » Could involve multiple "view ports"
  - If applicable, also need to know the instrument's field-of-view size and shape
- Such data are often built-in to an instrument's ground software, and thus hidden from other flight team members and users of the instrument archive
- A good ancillary information system makes these data readily available and clearly documented
  - Must be checked using real flight observations, since errors of 90 or 180 degrees often crop up
- The same info is often needed, or useful, for antennas, solar arrays, star trackers, etc.

Examples of Ancillary Data Production & Usage Challenges

Target Body Shape Data

- **Gone are the days when every target body was modeled as a sphere, spheroid or tri-axial ellipsoid**
  - **Either tessellated plate models for small, irregular objects, or digital elevation models, for large bodies are becoming the norm**
- **Estimating such shapes is generally in the purview of instrument experiments**
  - **But making such shapes readily available to other scientists, and to project engineers, is increasingly important. This is complicated due to:**
    - » **multiple methods used for modeling**
    - » **rapidly evolving model data**
    - » **lack of standard software for using models**

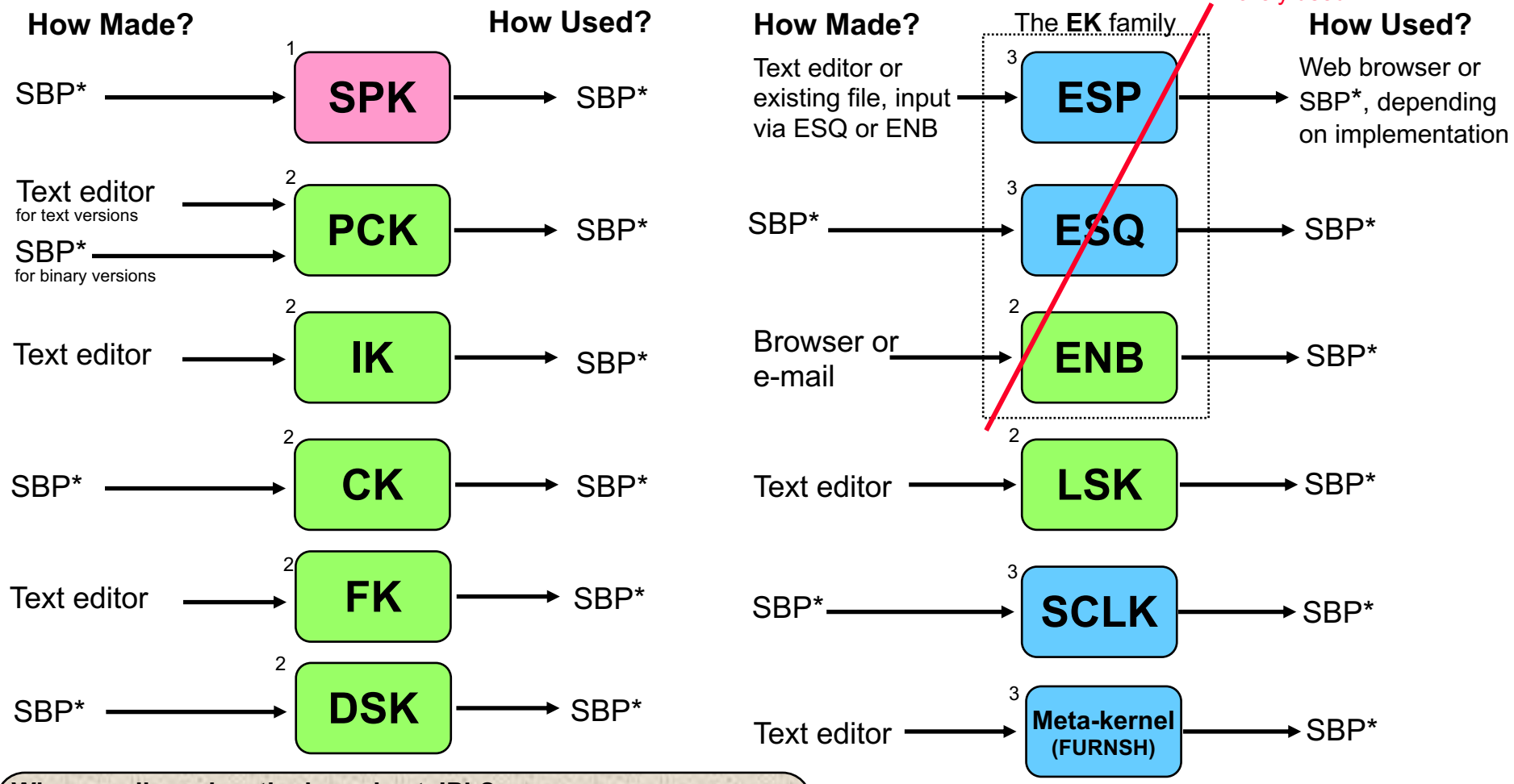
Examples of Ancillary Data Production & Usage Challenges

Data Availability Notification

- What method will be used to notify data users when each newly produced ancillary data file becomes available?
- How will the project handle notifications of errors and replacement files?

Graphics Depicting How SPICE Kernels are Made and Modified

How Kernels are Made and Used at JPL



Who usually makes the kernels at JPL?

1 NAV and NAIF
2 NAIF
3 NAIF or other

This represents current practice for most JPL missions, but is by no means a requirement. Anyone can make SPICE files.

***SBP** = SPICE-based program that uses modules from the SPICE Toolkit. In some cases the Toolkit contains such a program already built. In some cases NAIF may have such a ready-built program that is not in the SPICE Toolkit.

Why & How Kernels are "Modified" - 1

File Type	Why Modified	How Modified
SPK	-To add comments -To merge files or subset a file -To correct/revise an object ID	- COMMNT, SPACIT or SPICELIB module - SPKMERGE - BSPIDMOD
PCK Text version	-To revise data values -To add additional data items and values	- Text editor - Text editor
IK	-To revise data values -To add additional data items and values	- Text editor - Text editor
CK	-To add comments -To merge files -To revise the interpolation interval -To subset a file	- COMMNT, SPACIT, or SPICELIB module - DAFCAT, CKSMRG - CKSPANIT, CKSMRG - CKSLICER
FK	-To revise data values -To add additional data items and values	- Text editor - Text editor
DSK	-To add comments -To merge files or subset a file	- COMMNT, SPACIT or SPICELIB module - DSKMERGE

Why & How Kernels are "Modified" - 2

File Type	Why Modified	How Modified
The **EK** family (Rarely used)		
ESP	-To add, revise or delete "data" -To add comments	- (Depends on implementation) - (Depends on implementation)
ESQ	-To add additional data -To revise data -To delete data -To add comments -To merge files	- Toolkit modules - Toolkit modules - Toolkit modules - COMMNT, SPACIT or SPICELIB module - (under development)
ENB	-To change entry status (public <--> private) -To delete an entry	- WWW - WWW
LSK	- To add a new leap second	- Text editor
SCLK	- To add comments	- Text editor
Meta-kernel (FURNSH)	- To revise contents in any way	- Text editor