“SPICE”
Might Help CubeSat, SmallSat and Human Lunar Exploration Missions Compute Observation Geometry from Ancillary Data

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Topics

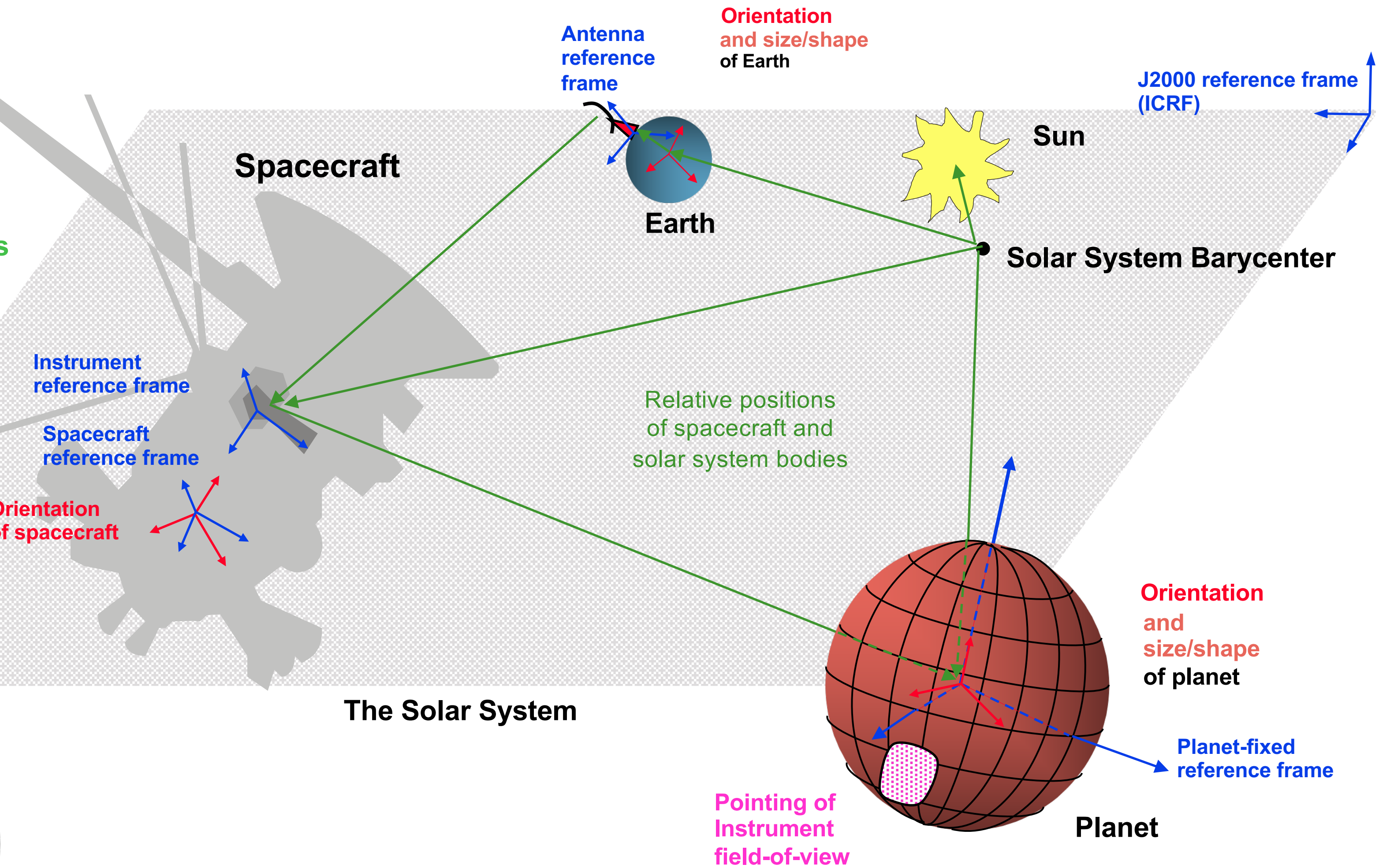
- What are “ancillary data?”

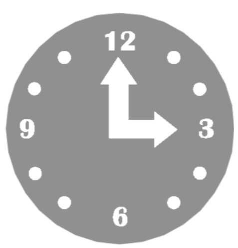
- Why are these data needed?

- Producing and using ancillary data using NASA’s “SPICE” system

A Pictorial of Ancillary Data

- Reference frames
- Positions & Velocities
- Orientations
- Sizes/shapes
- Instrument Pointing
- Time Conversions





Time Conversion
Calculations

Examples of Using Ancillary Data

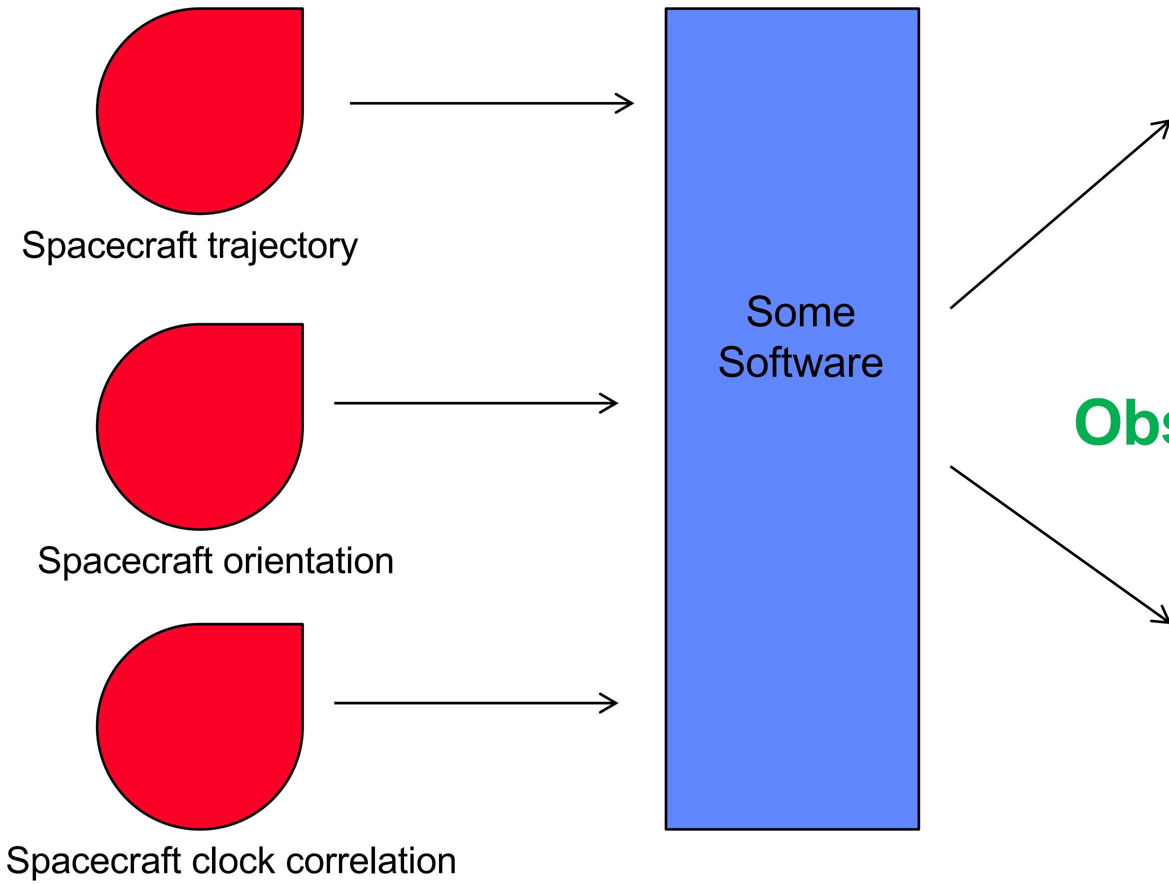
- **Help mission designers converge on a spacecraft trajectory design**

- **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 data analysis
  - science archive preparation

Contrast
"Ancillary Data" vs. "Observation Geometry"

Ancillary Data
(Files)



etc.

Observation Geometry
Derived parameters

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

Observation Geometry
Viewing Conditions

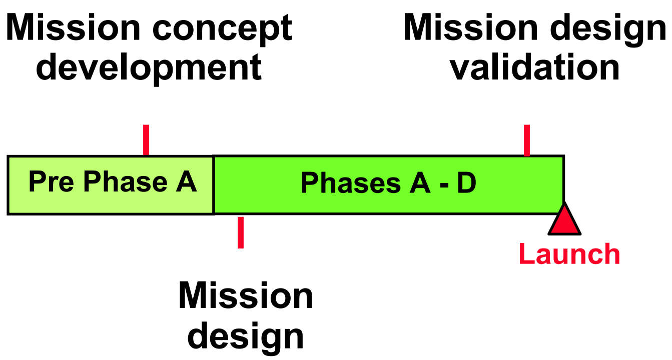
- Spacecraft is in occultation by Mars
- Altitude is at a global maximum
- Phase angle is in the range of 24 to 28 degrees
- etc.

When are Ancillary Data Used?

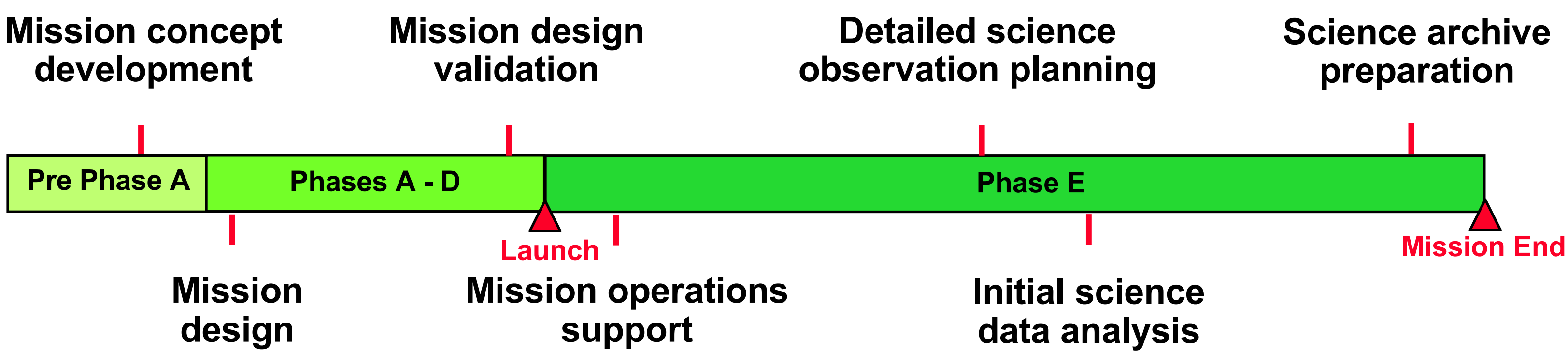
Mission concept development

Pre Phase A

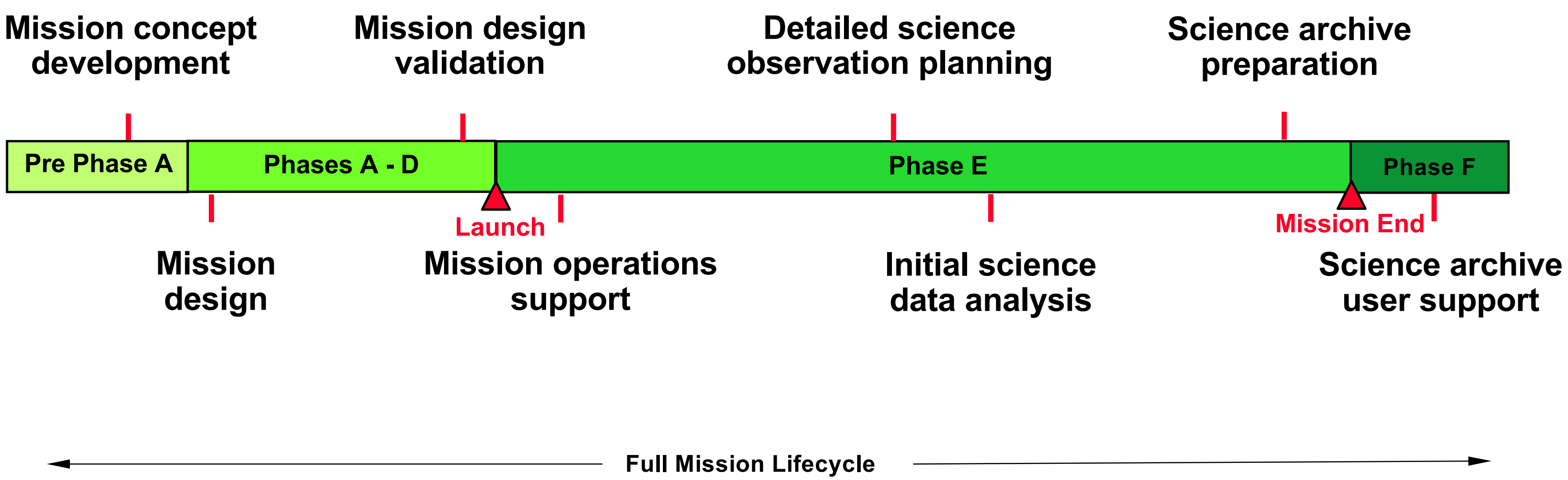
When are Ancillary Data Used?



When are Ancillary Data Used?



When are Ancillary Data Used?



Challenges in Producing and Using 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 after initial computation**

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, SmallSat and lunar exploration projects might find useful.

- Even if your mission exists outside of NASA sponsorship, you still might find SPICE useful.

NAIF and SPICE

- **NAIF: Navigation and Ancillary Information Facility**
  - Formed in 1983 at NASA's Jet Propulsion Laboratory
  - It's primary job is to develop the SPICE system
  - For JPL missions, it also deploys and operates the SPICE system
  - It serves as the SPICE archive node of the Planetary Data System
  - More information: https://naif.jpl.nasa.gov/naif/about.html

- **SPICE: stands for Spacecraft, Planet, Instrument, Camera-matrix, Events**
  - The SPICE concept was defined by a group of planetary scientists as one result of a 1983 NASA-mandated Planetary Data Workshop
  - More information: https://naif.jpl.nasa.gov/naif/aboutspice.html

SPICE System Components

Ancillary data files ("kernels")……...……………

1100
1010
0101

Software (SPICE Toolkit) …………..

Documentation …………....

Tutorials …………......

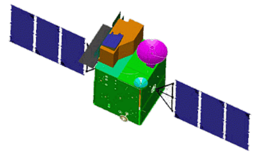
Programming lessons …..

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

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

SPICE Data Overview

Logical Components	Kernels	Contents*
S Spacecraft	SPK	Spacecraft and target body ephemerides
P Planet	PCK	Target body size, shape and orientation
I Instrument	IK	Instrument field-of-view size, shape and orientation
C Camera-matrix	CK	Orientation of spacecraft and any articulating structure on it
E Events	~~EK ESP ESQ ENB~~ Rarely used	Events information: - Science Plan (ESP) - Sequence of events (ESQ) - Experimenter's Notebook (ENB)
	Others: FK	Reference frame specifications
	Others: LSK	Leap seconds tabulation
	Others: SCLK	Spacecraft clock coefficients
	Others: DSK	Digital shape models

* See the "Details" section for more info

SPICE Software Overview
(The SPICE Toolkit)
https://naif.jpl.nasa.gov/naif/toolkit.html

Contents

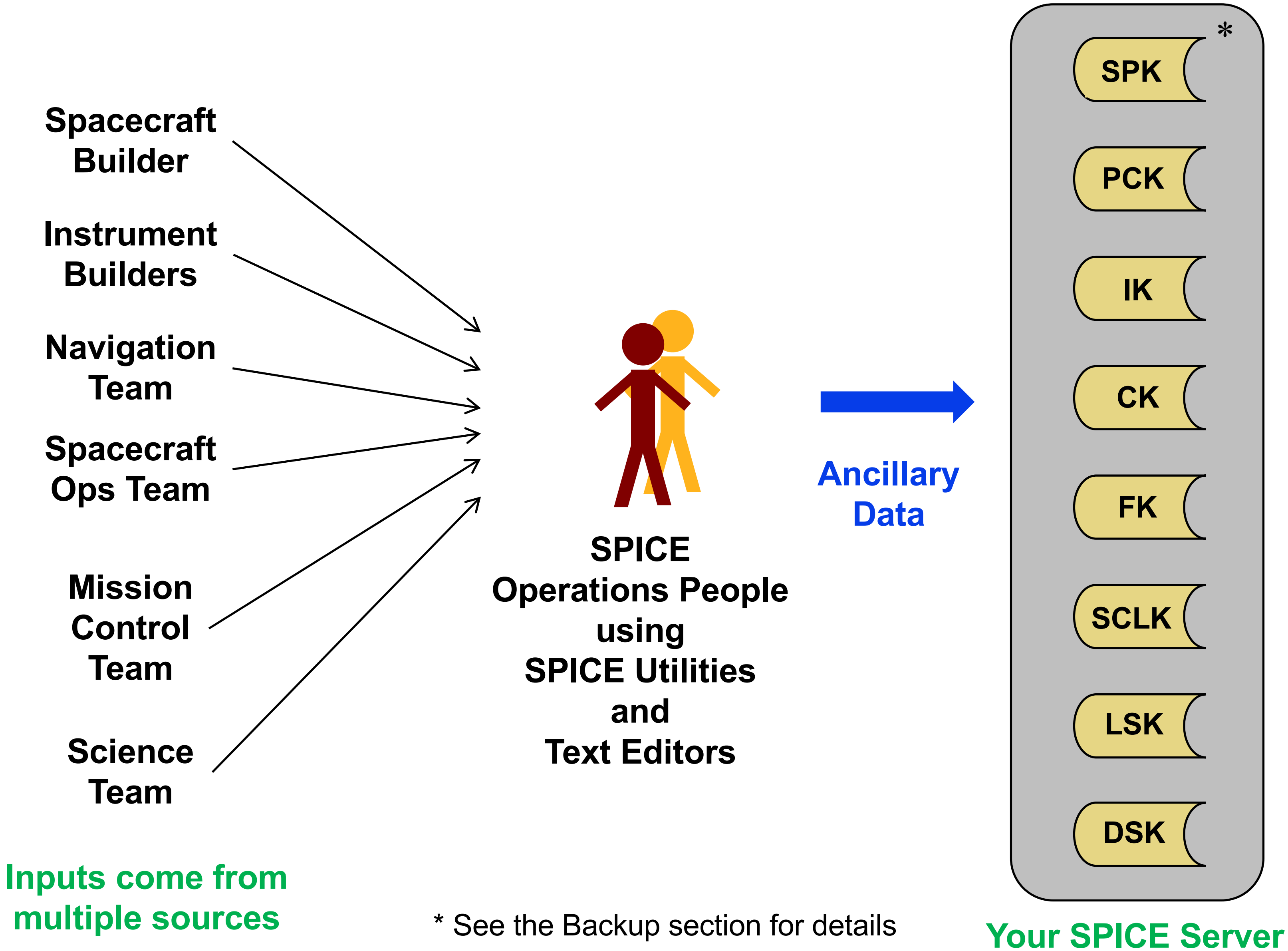
- **Library of subroutines**
  - Typically just a few are used within a customer's program to compute observation geometry quantities derived from SPICE kernels
- **Utility Programs**
  - SPICE data production
  - SPICE data management
- **Documentation**
  - Highly annotated source code
  - Technical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

Versions

- **Seven languages**
  - Fortran
  - C
  - IDL
  - MATLAB
  - Java Native Interface (JNI)
  - Python and Ruby (provided by 3rd parties)
- **Six platforms**
  - PC/Linux
  - PC/Windows
  - PC/CYGWIN
  - Sun/SPARC/Solaris
  - Sun/Intel
  - Mac/Intel/OSX
- **Several compilers**
  - For the Fortran and C Toolkits

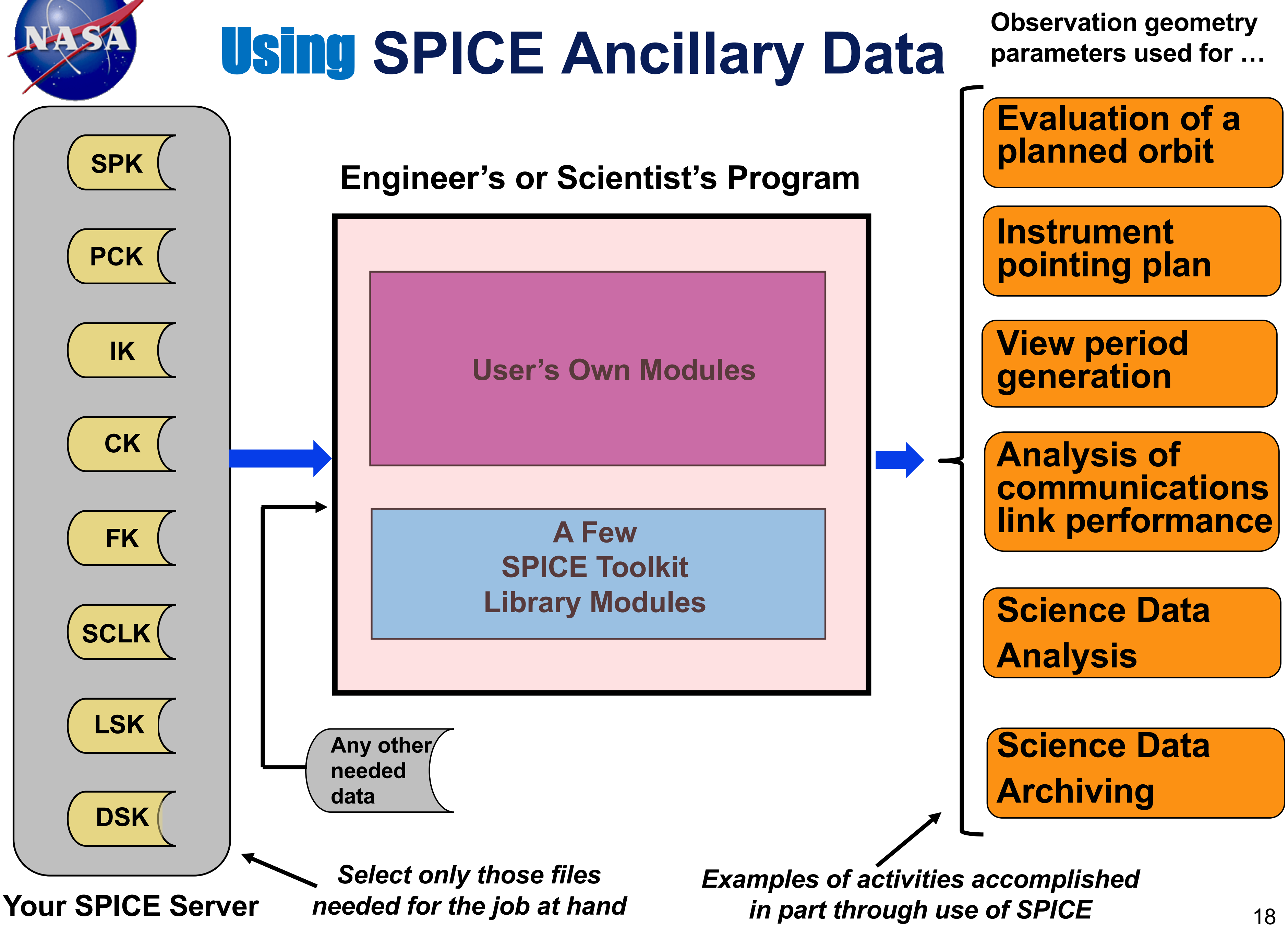
All combinations provided by NAIF are fully built and individually tested before being made available to customers

Producing SPICE Ancillary Data



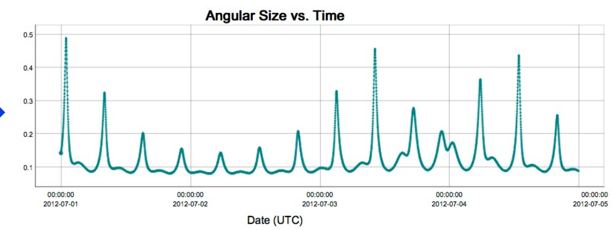
* See the Backup section for details

Using SPICE Ancillary Data

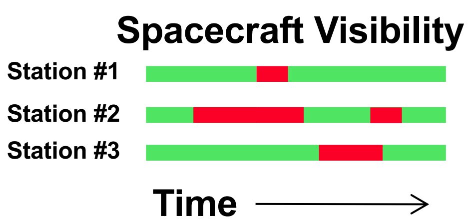


Typical Uses of SPICE

Evaluation of a planned trajectory

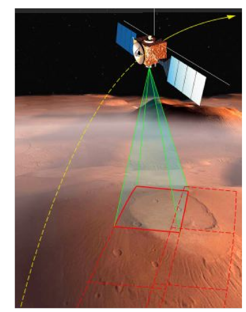


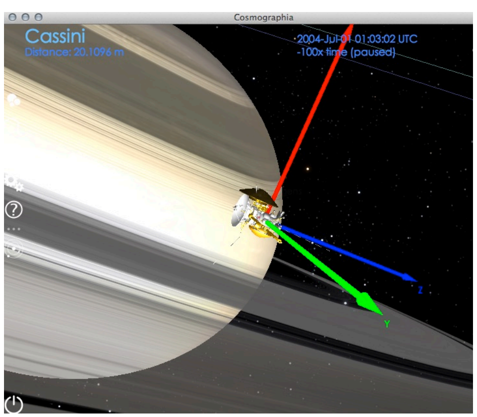
Angular size of Phobos as seen from the Mars Express spacecraft



Mission engineering analyses

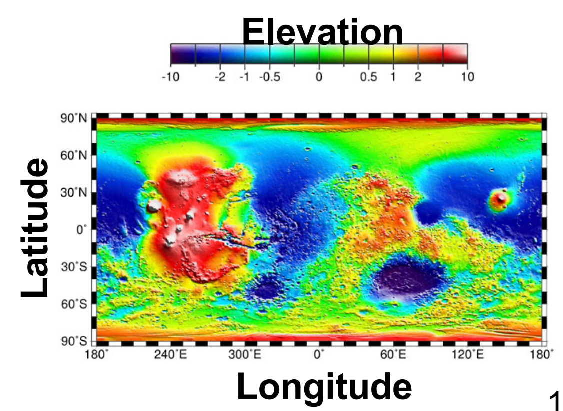
Planning an instrument timing and pointing profile





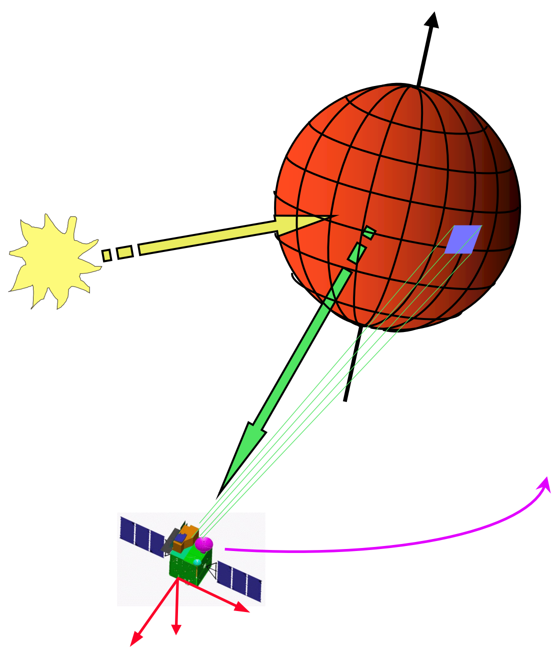
Observation geometry visualization

Science data archiving and analysis



What One Can Do Using SPICE - 1

Compute many kinds of derived parameters at selected times



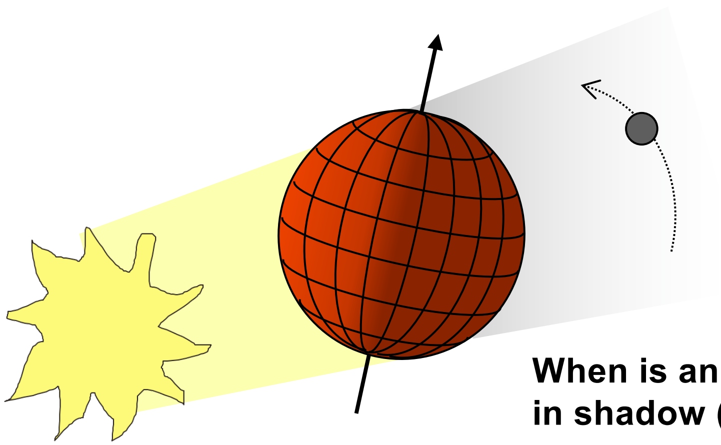
A Few Examples

- **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 footprint on a planet’s surface or atmosphere**

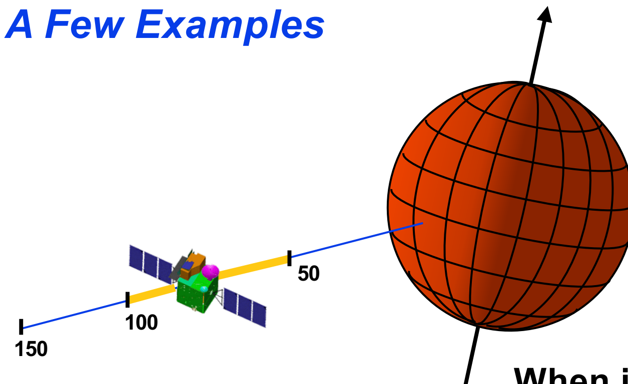
What One Can Do Using SPICE - 2

Find times when a specified “geometric event” occurs

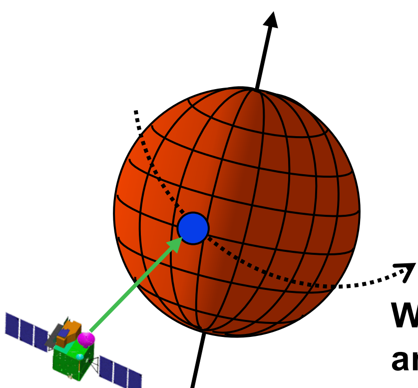
A Few Examples



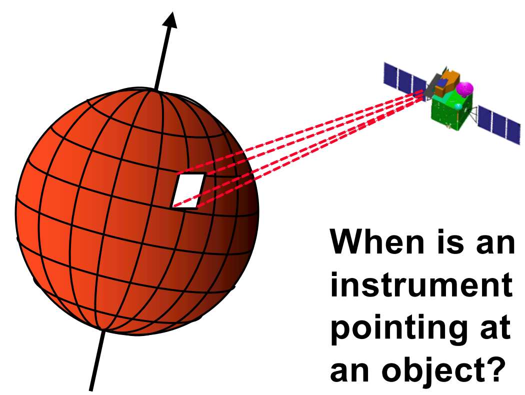
When is an object in shadow (occultation) ?



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



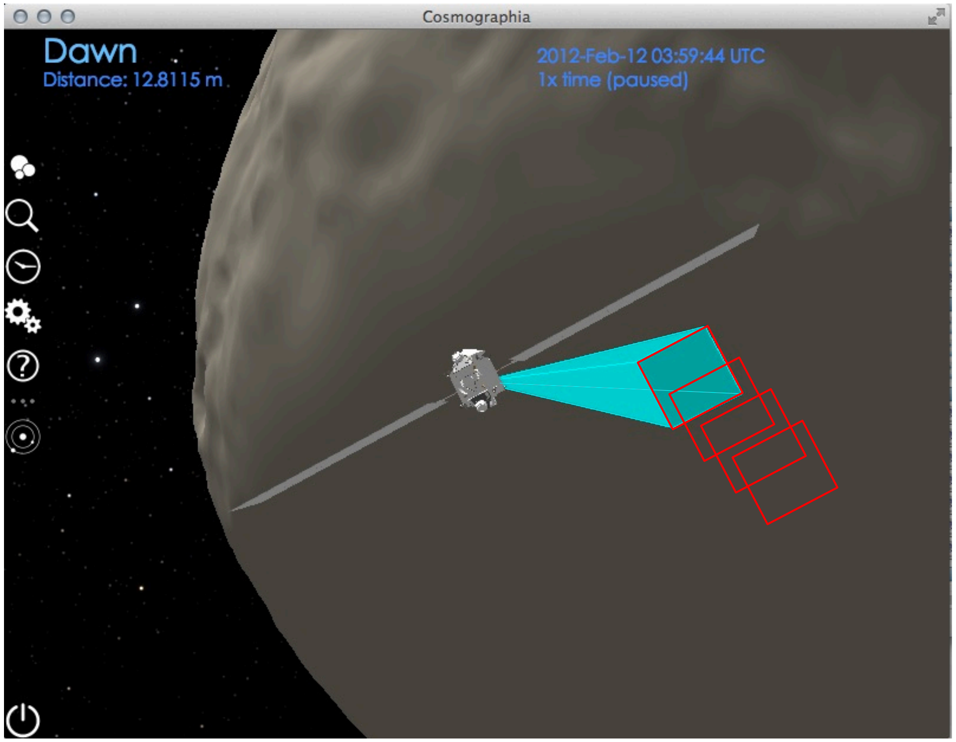
When is an object in front of another, as seen from a spacecraft (transit)?



When is an instrument pointing at an object?

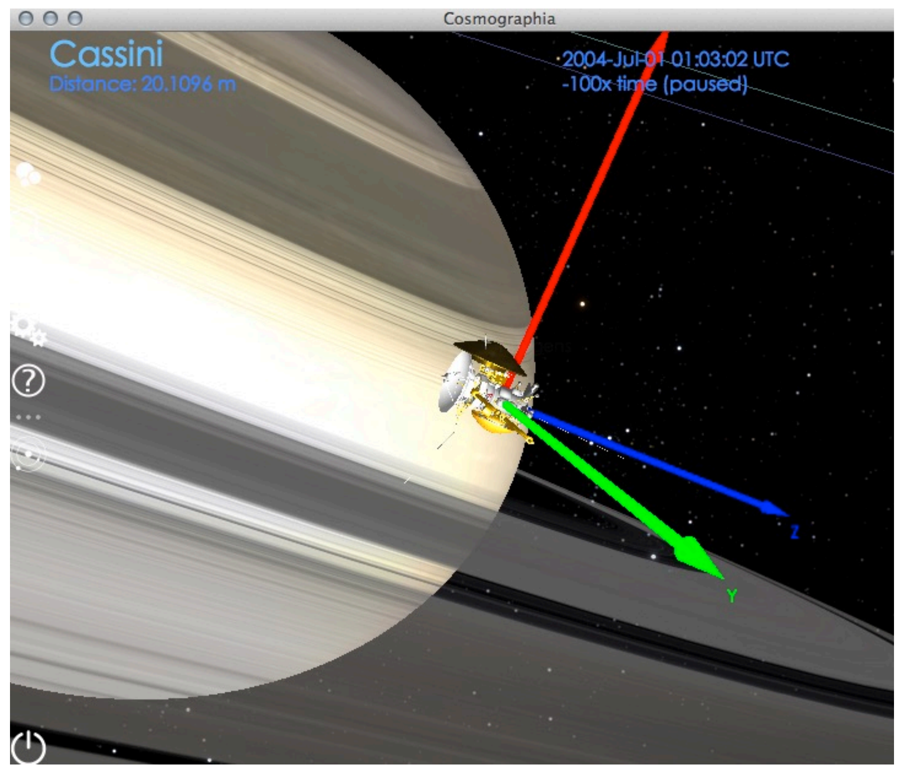
What One Can Do Using SPICE - 3

Produce 3D Mission Animations



Cosmographia* visualization of DAWN's framing Camera photographing Vesta, including display of image footprints

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

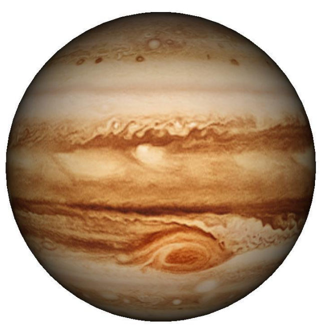


* SPICE-Enhanced Cosmographia is part of the SPICE tools suite

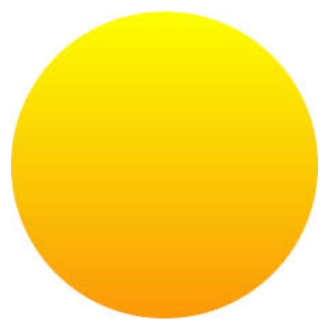
Kinds of Projects Using SPICE

- **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
- **Space Technology Demos**

  - e.g. optical communications



Planetary Science



Heliophysics

A bit of Earth Science

Advantages of Using SPICE

- Provides lots of geometry computational capability
- Software is well tested, works in many computing environments, and is always 100% backwards compatible
- Data formats are un-changing
- SPICE is familiar to many scientists and engineers
- SPICE is the NASA/PSD- and PDS-preferred ancillary data archive format
- There are no U.S. ITAR/EAR restrictions, and no licensing

- SPICE components and generic data are free to all
  - You could go it yourself in learning to deploy and operate a SPICE system
  - You could contract with NAIF at quite modest cost to help with consultation and training
  - In special circumstances it might be possible for you to contract with NAIF at quite modest cost to conduct SPICE kernel production

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 and domain knowledge
- 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

- Of course most of the issues mentioned above could apply to any other approach taken

Moving Forward

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

- **NAIF encourages the CubeSat and lunar exploration communities to lobby for institutional (NASA or otherwise) support; this could help you achieve the most timely and correct results, with the least risk and for the least expense**

What is Available from NAIF 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
  - "Generic" kernels are data that are independent of any particular mission, such as planetary ephemerides
  - 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 Using SPICE

- 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
    - » No matter how hard you try, there will ALWAYS be problems encountered
  - This often requires good knowledge of your spacecraft and its ground data system
- Any needed training for your scientists and engineers intending to use your SPICE data for planning observations and/or for analyzing the returned science 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 users (scientists and engineers)
- Any SPICE data archiving required by your sponsor

What Could NAIF Provide if Funded to Do So?

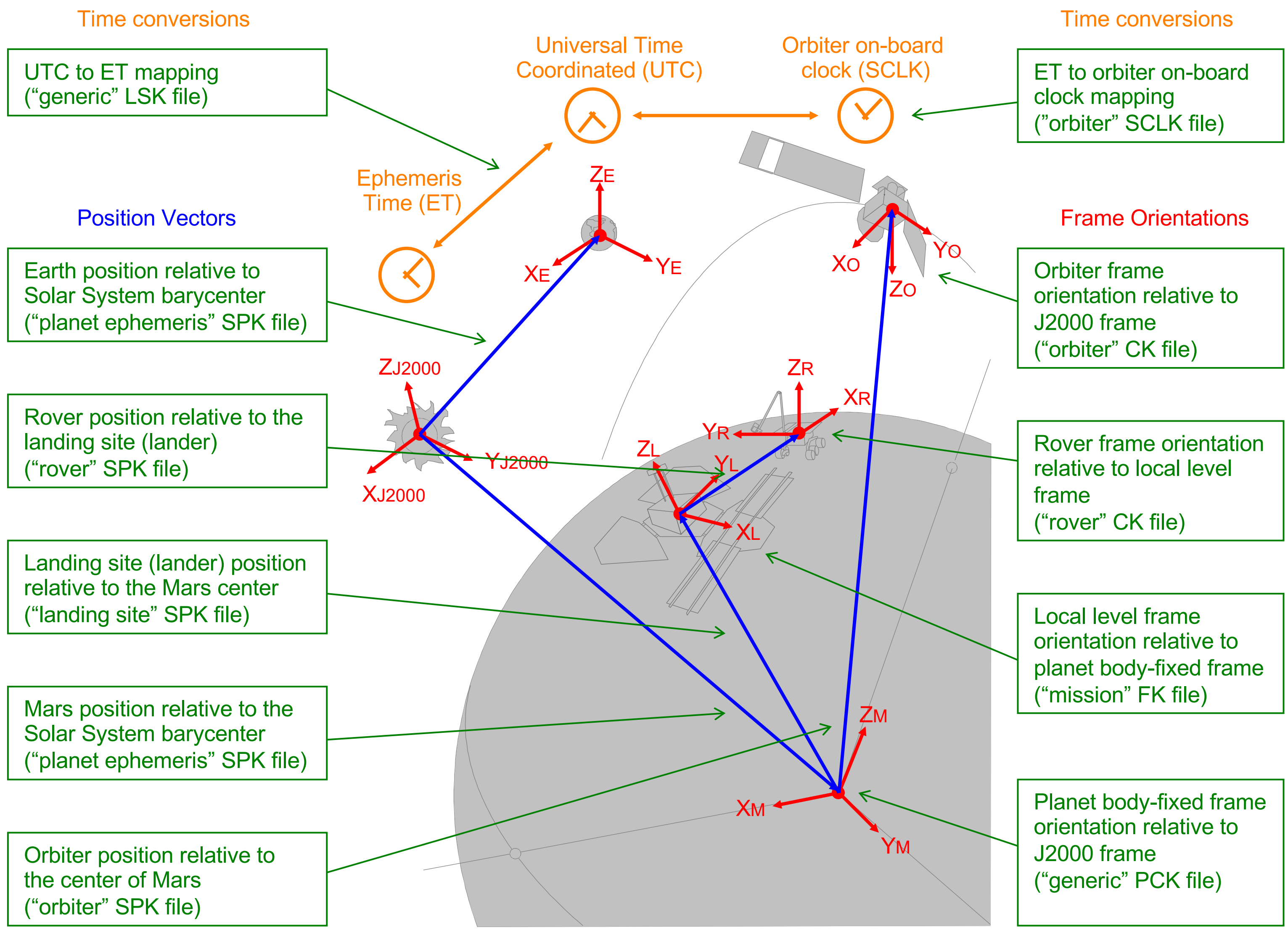
- Flight projects at JPL and sometimes elsewhere within NASA elect to fund NAIF to do some or all of:
  - SPICE data production
  - training and consultation for project SPICE users
  - SPICE archive production and delivery to NASA's PDS
- If funded to do so, NAIF could provide training for others on SPICE data production, SPICE data use, or SPICE archive production
- What's the cost for such support?
  - There's no simple answer, but NAIF costs are typically small.

Some Details and Issues

These charts contain some important details and issues to be considered no matter what approach you take for providing ancillary data and observation geometry calculations

Graphics Depicting SPICE Data

Global SPICE Geometry



Orbiter Geometry

Position Vectors

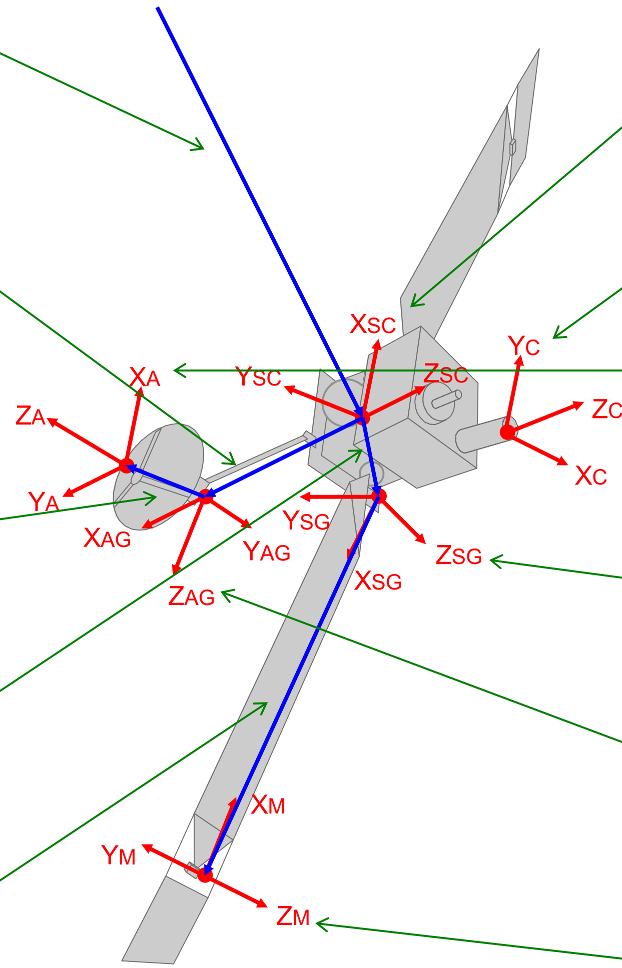
Spacecraft position relative to planet center (“spacecraft” SPK file)

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)

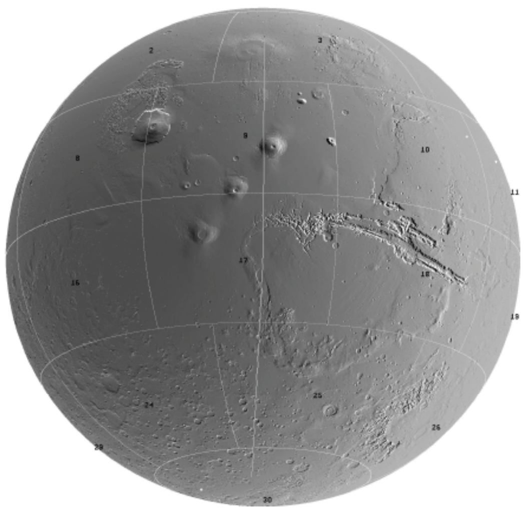
Solar array gimbal frame orientation relative to spacecraft frame (“solar array” CK file)

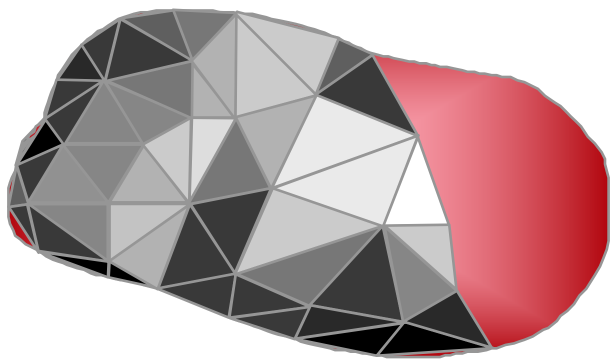
High gain antenna gimbal frame orientation relative to spacecraft frame (“antenna” CK file)

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

Digital Shape Kernel (DSK)

The two DSK types shown here are used to provide high fidelity shape models needed by modern experiments. One of these 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 (Also see DSK)
- 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
    - 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 produced, end users may have trouble understanding how to use those 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 will you 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(s) 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?**

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 TDB
  - 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 multiple 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 observation geometry parameter computations**

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 scientists 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.**

Target Body Shape Data

- Target body size/shape data are often evolving and may be in dispute
- Today not every target bodies is 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 common
- Estimating such shapes is generally in the purview of a mission's science team
  - 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

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

How Made?	Kernel	How Used?
SBP*	[1] SPK	SBP*
Text editor (for text versions); SBP* (for binary versions)	[2] PCK	SBP*
Text editor	[2] IK	SBP*
SBP*	[2] CK	SBP*
Text editor	[2] FK	SBP*
SBP*	[2] DSK	SBP*

The EK family — Rarely used

How Made?	Kernel	How Used?
Text editor or existing file, input via ESQ or ENB	[3] ~~ESP~~	Web browser or SBP*, depending on implementation
SBP*	[3] ~~ESQ~~	SBP*
Browser or e-mail	[2] ~~ENB~~	SBP*
Text editor	[2] LSK	SBP*
SBP*	[3] SCLK	SBP*
Text editor	[3] Meta-kernel (FURNSH)	SBP*

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.