"SPICE"
Can Help SmallSat Missions Compute Observation Geometry from Ancillary Data

12th Low-cost Planetary Missions Conference

Caltech

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Charles Acton

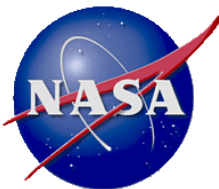**Jet Propulsion Laboratory, California Institute of Technology**
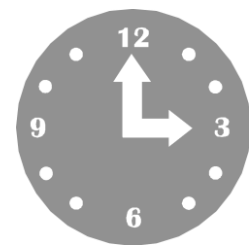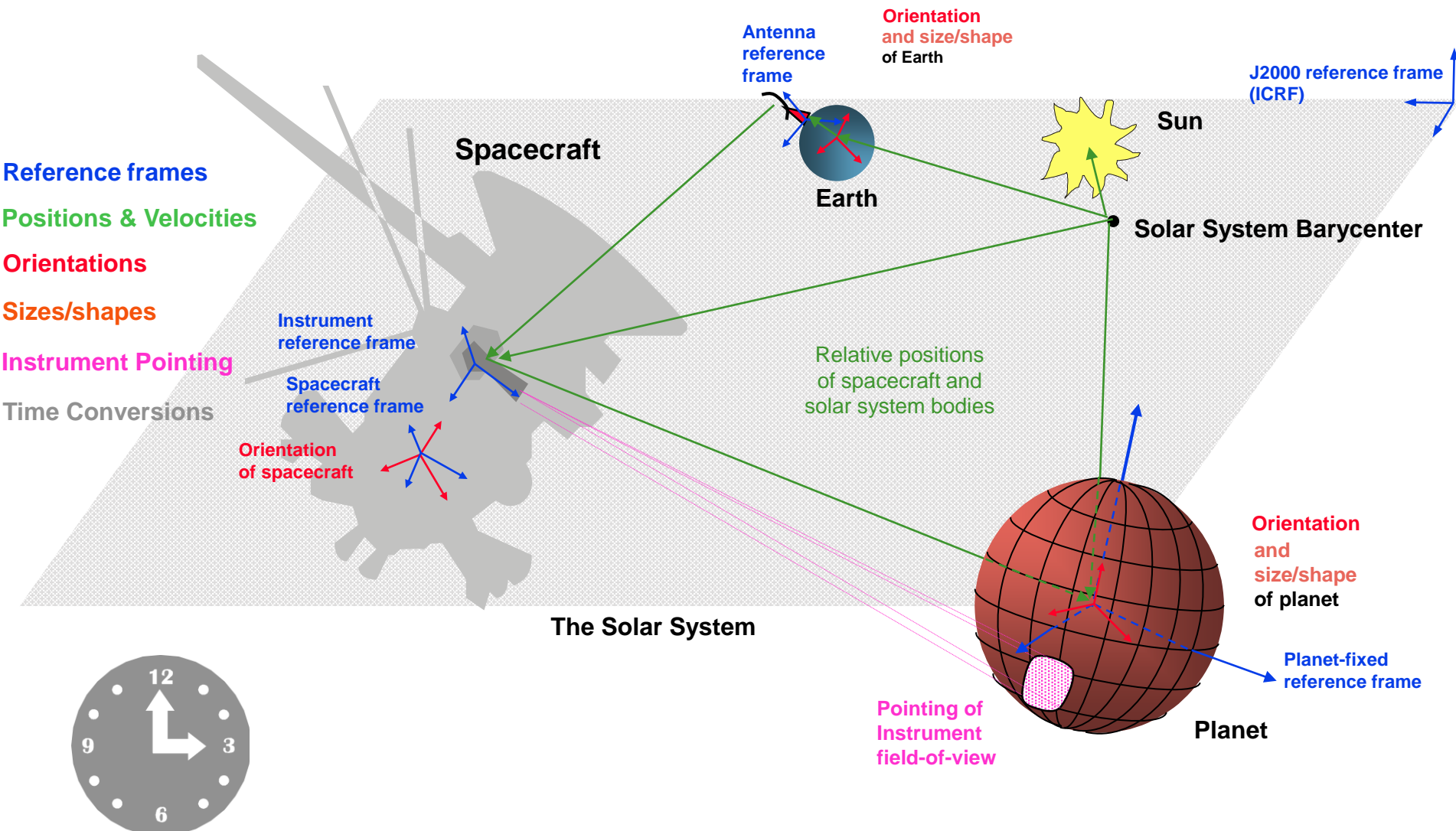
charles.acton (at) jpl.nasa.gov

Topics

- **What are "ancillary data?"**

- **Why are such 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

Antenna reference frame

Orientation and size/shape of Earth

Sun

J2000 reference frame (ICRF)

Spacecraft

Earth

Solar System Barycenter

Instrument reference frame

Spacecraft reference frame

Orientation of spacecraft

Relative positions of spacecraft and solar system bodies

Orientation and size/shape of planet

Planet-fixed reference frame

The Solar System

Pointing of Instrument field-of-view

Planet

Time Conversion Calculations

3

Examples of Using Ancillary Data

- **Help mission designers converge on a spacecraft orbit 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**
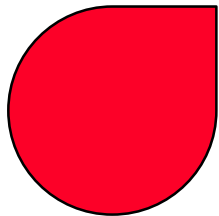 - **science data analysis**
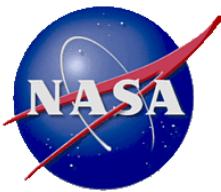
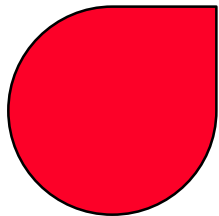# Contrast "Ancillary Data" and "Observation Geometry"

Ancillary Data
(Files)
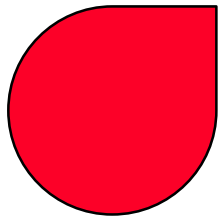
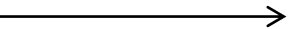Spacecraft trajectory

Spacecraft orientation
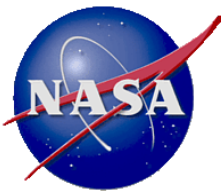
Spacecraft clock correlation

etc.

Some
Software
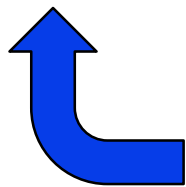
Observation Geometry
(Parameters)

- 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 maximu
- Phase angle is in the range of 24 to 28 degree
- etc.

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When are Ancillary Data Used?

Mission concept development	**Mission design validation**	**Detailed science observation planning**	**Science archive preparation**	

Pre Phase A	Phases A - D	Phase E	Phase F

Launch

Mission End

Mission design

Mission operations support

Initial science data analysis

Science archive user support

Full Mission Lifecycle
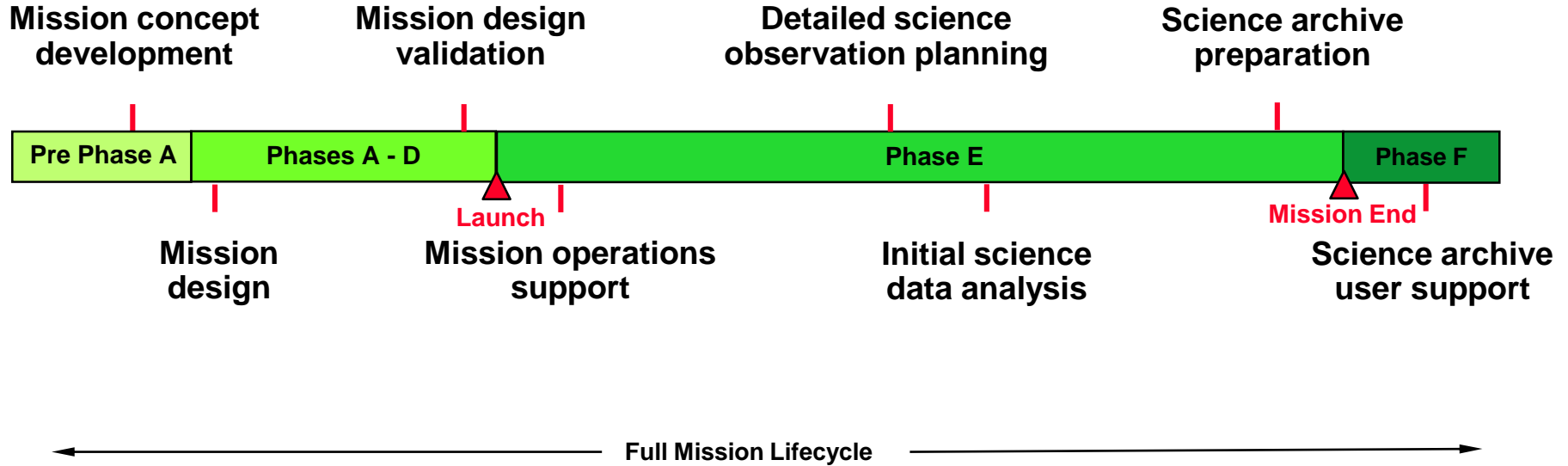
Projects typically begin using ancillary data quite early in the mission!
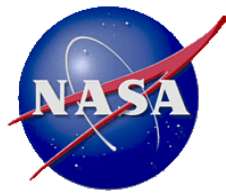
Examples of Challenges in Producing Planetary Ancillary Data

- **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**

The SPICE Methodology

for

Producing and Using Ancillary Data

SPICE System Components

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

Software (SPICE Toolkit) …………..

Documentation ……..

Tutorials ………………………………….

Programming lessons …………………………...

From Where do SPICE Ancillary Data Come?

- **From the spacecraft**
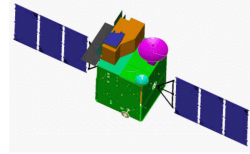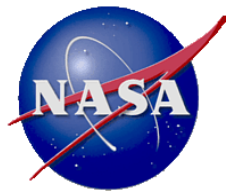
- **From the mission control center**

- **From the spacecraft and instrument builders**

- **From science organizations**

SPICE is used to organize and package these data in a collection of multi-mission 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
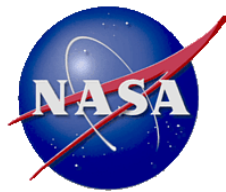- **FK** — Reference frame specifications
- **LSK** — Leapseconds tabulation
- **SCLK** — Spacecraft clock coefficients
- **DSK** — Digital shape models

* See the Backup section for details

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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**

- **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

Spacecraft Builder

Instrument Builders

Navigation Team

Spacecraft Ops Team

Mission Control Team

Science Team

SPICE Operations People

Ancillary Data

SPK *

PCK

IK

CK

FK

SCLK

LSK

DSK

Inputs come from multiple sources

* See the Backup section for details

Your SPICE Server

13
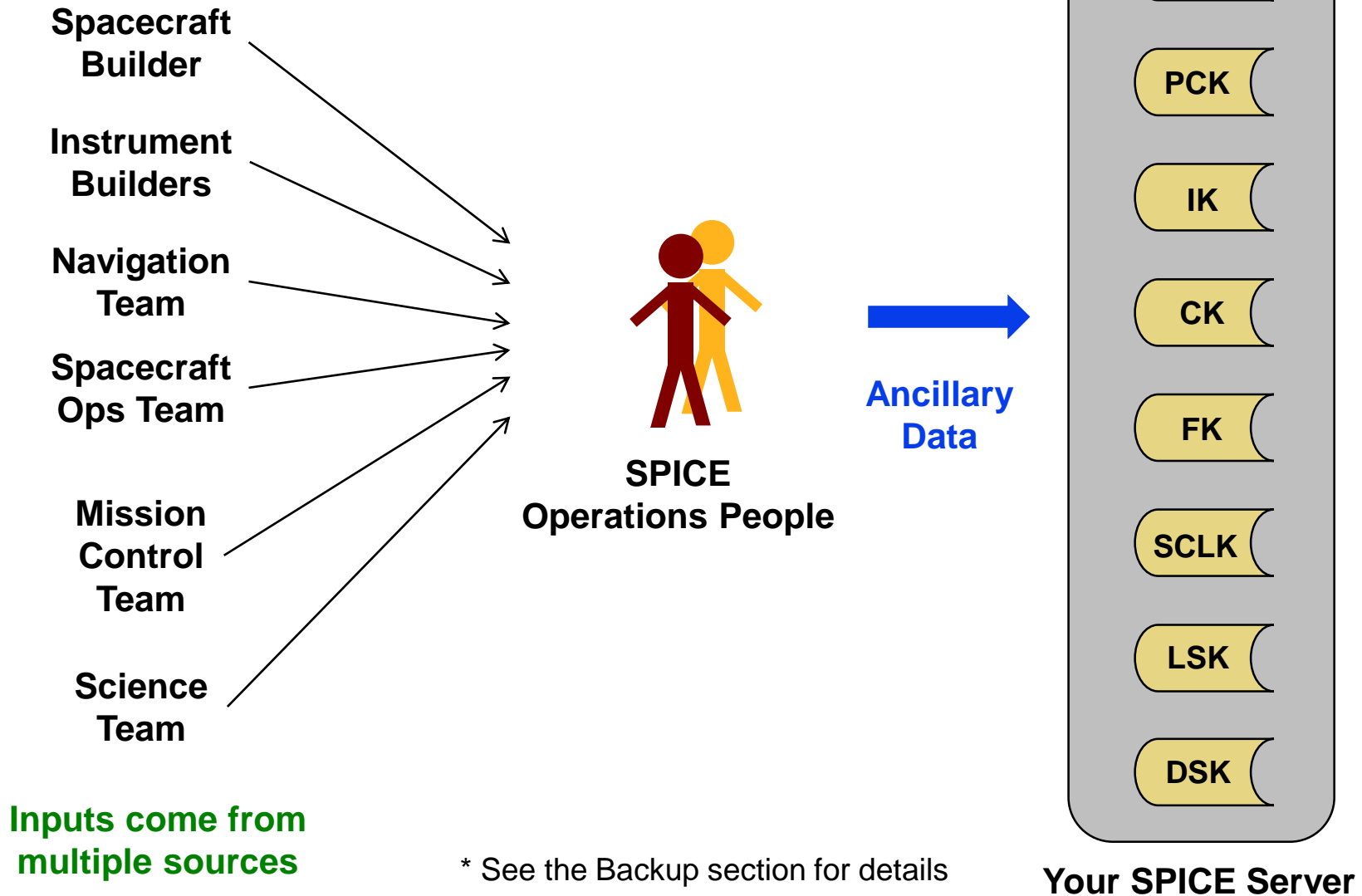
How Does One Use SPICE Ancillary data?
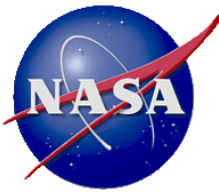
Using SPICE Ancillary Data

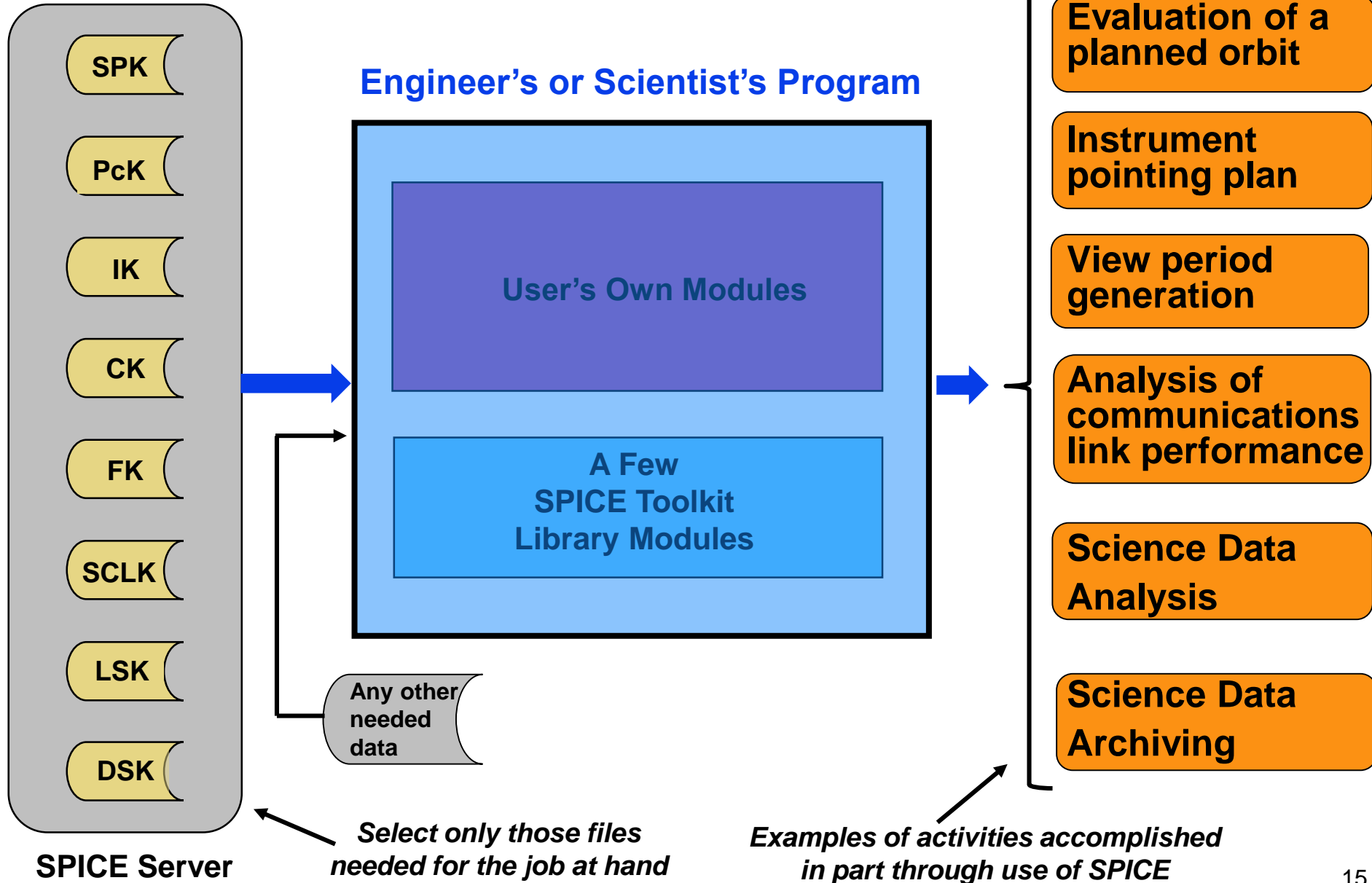**Observation geometry parameters used for …**

Engineer's or Scientist's Program

SPK

PcK

IK

CK

FK

SCLK

LSK

DSK

User's Own Modules

A Few SPICE Toolkit Library Modules

Any other needed data

Evaluation of a planned orbit

Instrument pointing plan

View period generation

Analysis of communications link performance

Science Data Analysis

Science Data Archiving

SPICE Server

Select only those files needed for the job at hand

Examples of activities accomplished in part through use of SPICE

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Typical Uses of SPICE

Evaluation of a
planned trajectory
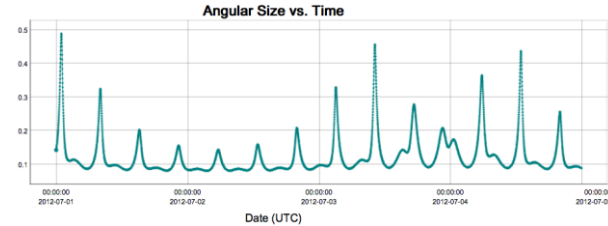
Angular size of Phobos as seen
from the Mars Express spacecraft

Spacecraft Visibility

Station #1
Station #2
Station #3

Time

Mission engineering
analyses
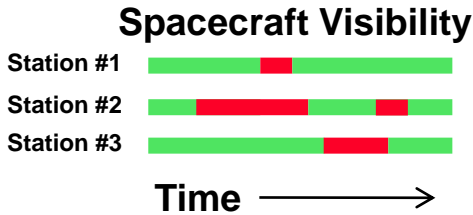
Planning an instrument
pointing profile
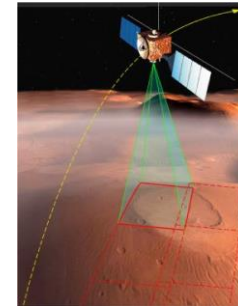
Observation geometry
visualization
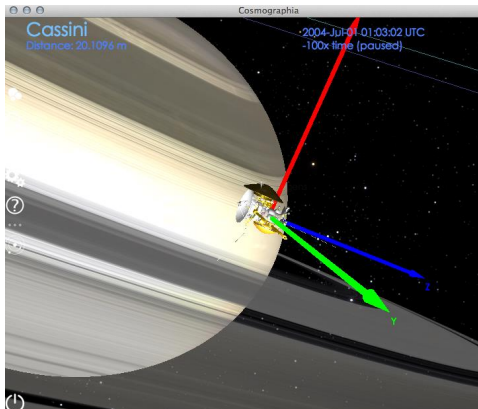
Science data archiving
and analysis

Elevation

-10   -2   -1 -0.5   0   0.5   1   2   10

Latitude

Longitude

16
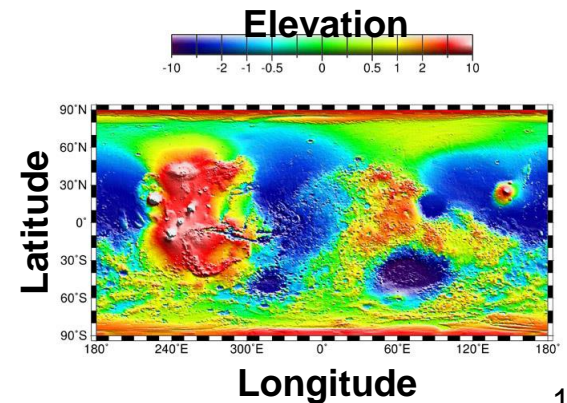
Kinds of Instruments Using SPICE

In Situ Instruments

- **Particle detectors**
- **Plasma detectors**
- **Magnetometers**
- **Mass spectrometers**

Remote Sensing Instruments

- **Framing cameras**
- **Line-scan cameras**
- **Polarimeters**
- **Photometers**
- **Spectrometers**
- **Radiometers**
- **Synthetic Aperture Radar**
- **Altimeters**
- **Radio science instrumentation**

What Can One Do With SPICE?

Compute many kinds of observation geometry 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
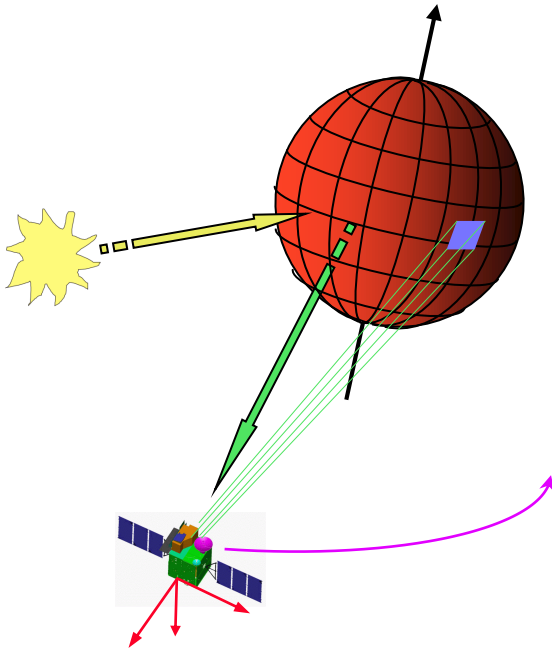
What Can One Do With SPICE?

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?
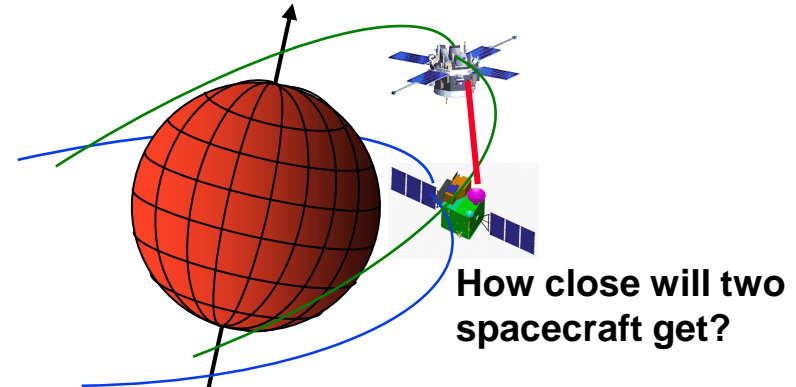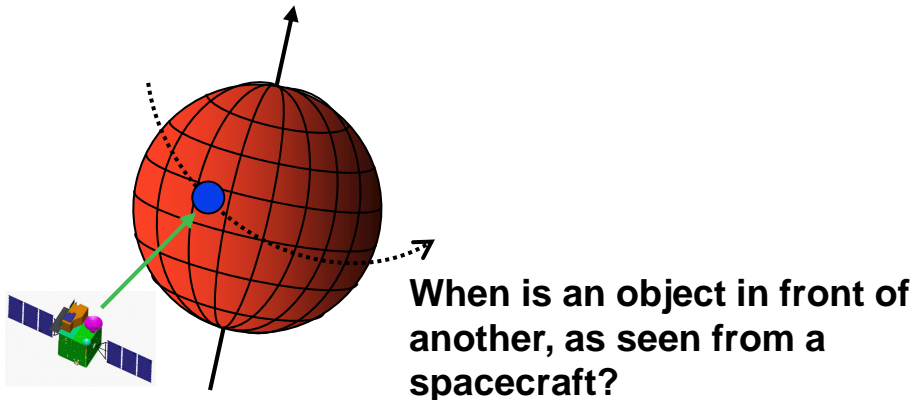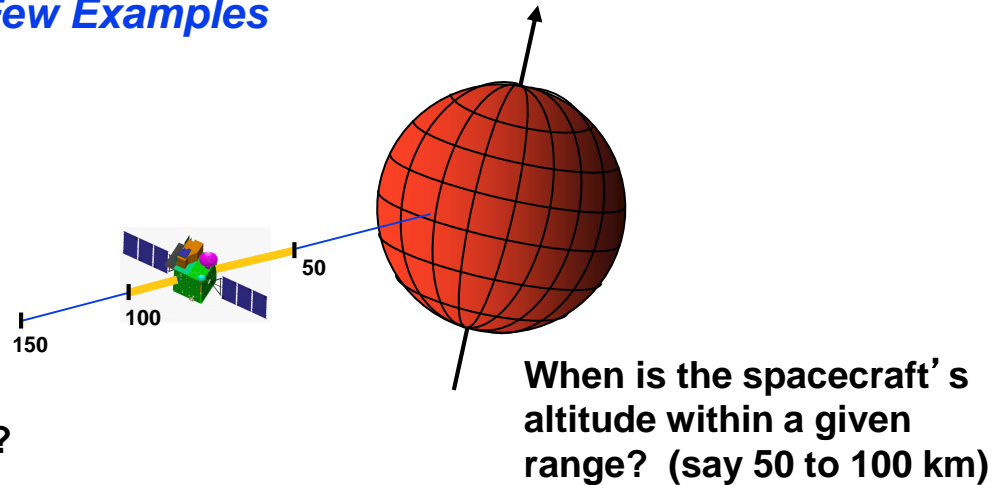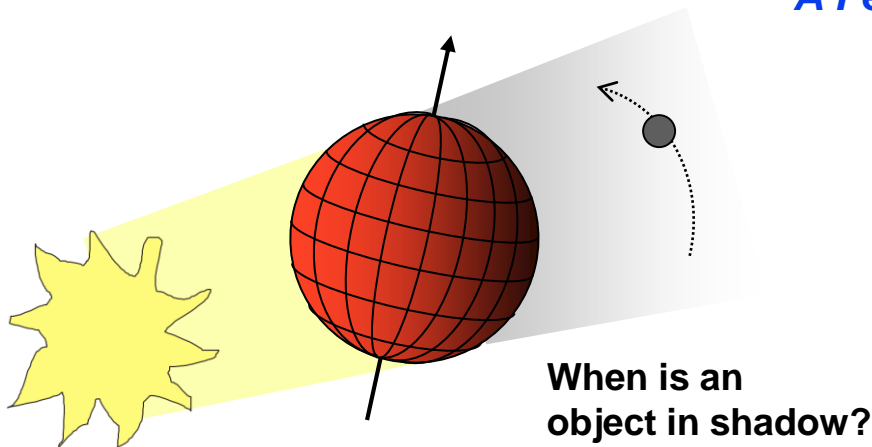
What Can One Do With SPICE?

Produce 3D Mission Visualizations
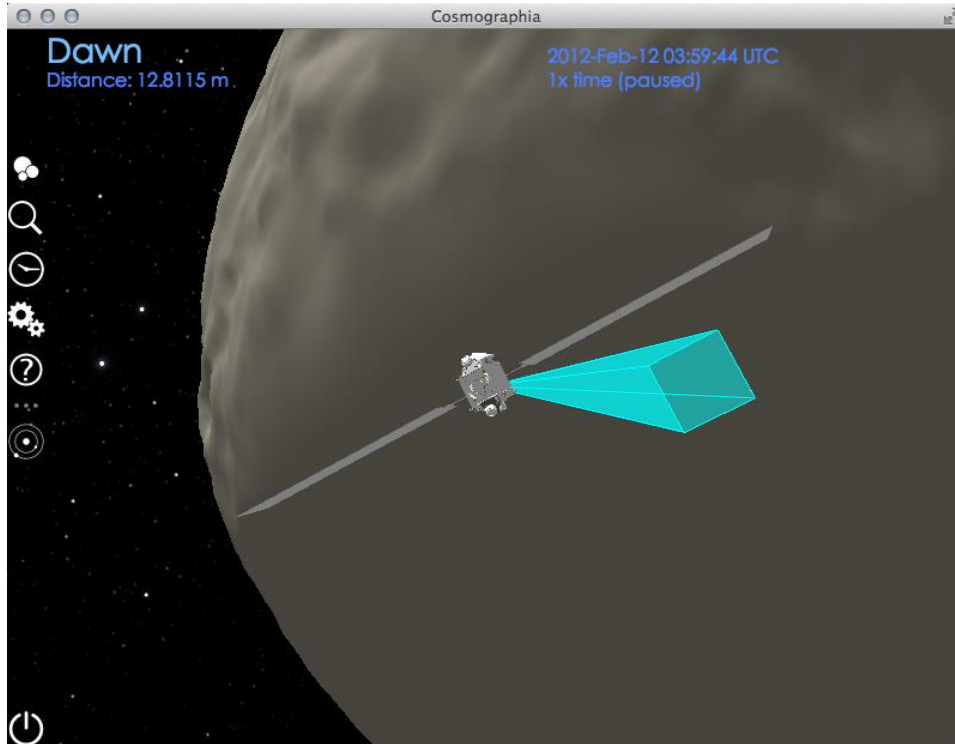
Cosmographia* visualization of DAWN's framing Camera photographing Vesta

Cosmographia* visualization of Cassini in Orbit at Saturn, showing spacecraft axes
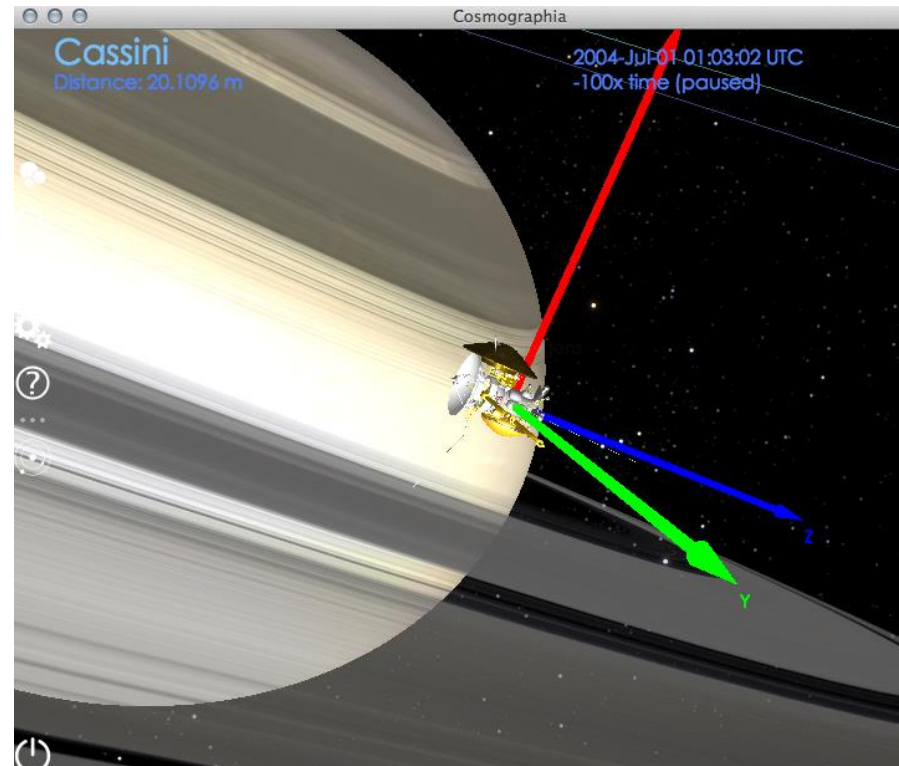
* Cosmographia is part of the SPICE tools suite

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
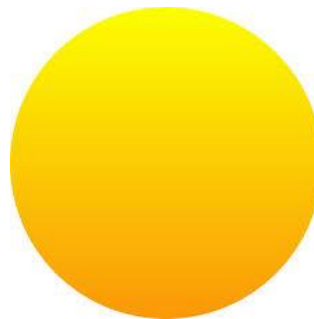
Heliophysics

Earth Science
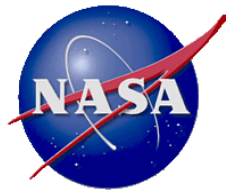
Advantages of Using SPICE

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

- **SPICE products are free to all**
- **If contracted to a project, NAIF services are inexpensive**

Disadvantages of Using SPICE

- **Requires use of 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**

- **Projects should provide SPICE-aware problem solving and user consultation services throughout the life of the mission**

Questions?

- **Stop by the NAIF "booth," a table set up near the posters.**

- **Also, we can provide you a more detailed version of this presentation.**

—————— Finis ——————

Backup Charts Follow

What Can NAIF Provide 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**

- **For NASA's planetary missions**
  - **SPICE archive guide and tools; peer review; post-mission consultation on use of the archive**

- **About once every year and a half, a three day SPICE users training class**
  - **The next one will be November 7–9, 2017, in a hotel near Pasadena**

*PDS = NASA's **P**lanetary **D**ata **S**ystem

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**

What Could NAIF Provide if Funded to Do So?

- **Many flight projects at JPL and 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
- **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 for which NAIF has a substantial 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

Graphics Depicting SPICE Data

Global SPICE Geometry

Time conversions

UTC to ET mapping ("generic" LSK file)

Universal Time Coordinated (UTC)

Orbiter on-board clock (SCLK)

Time conversions

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

Ephemeris Time (ET)

Position Vectors

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

Frame Orientations

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

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

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

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

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

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

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

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

XSC YSC ZSC YC ZC XC XA ZA YA XAG YAG YSG ZSG XSG ZAG XM YM ZM

31
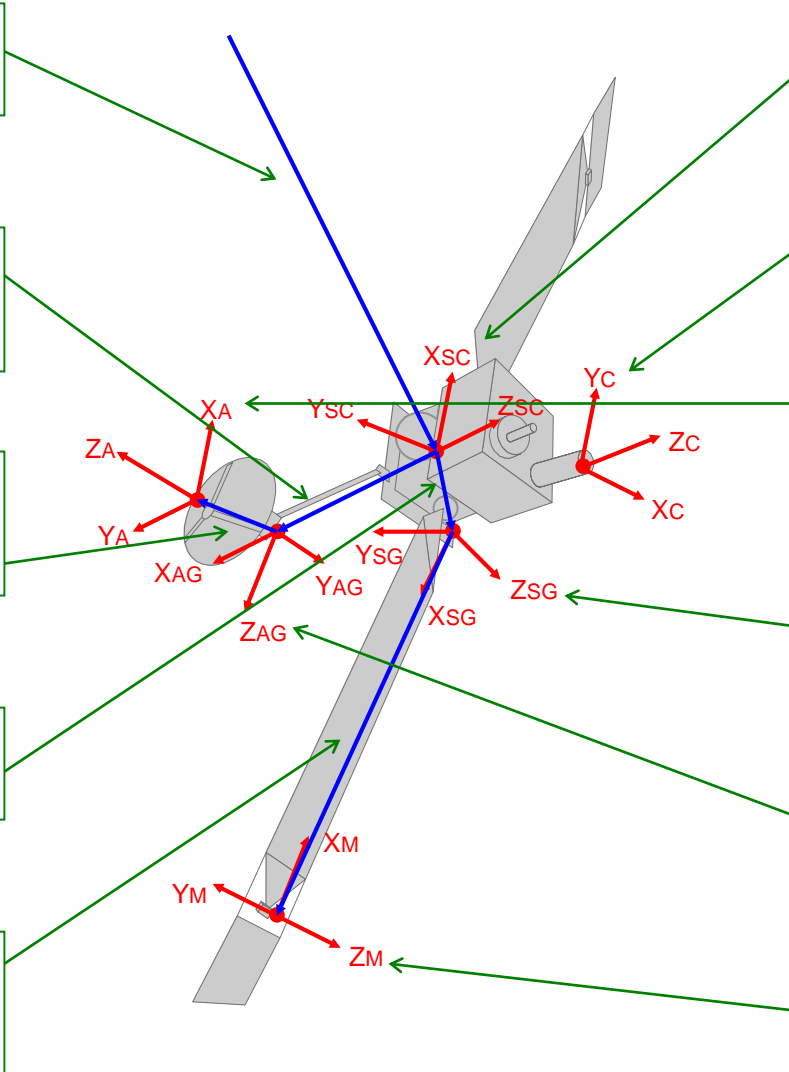
Digital Shape Kernel

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 PCK.
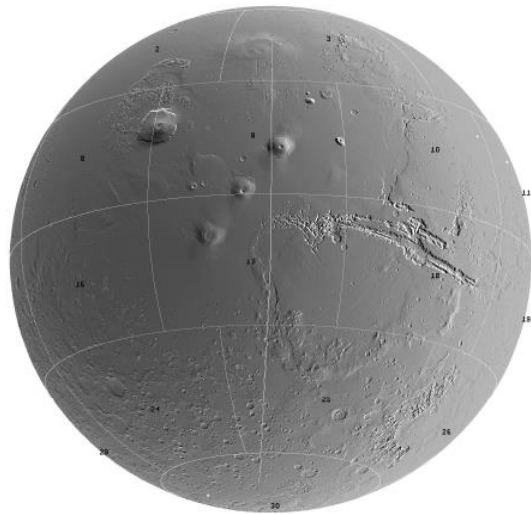
Digital elevation model

For large, regular bodies such as Earth, Moon and Mars
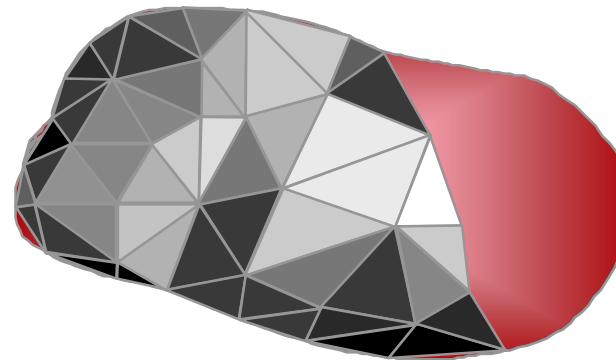
Tessellated plate model

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**
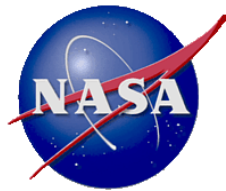
SPICE Data Details- 2

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)**

  Under development now

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

Ancillary Data Production Challenges
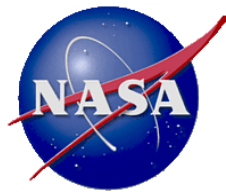
Ancillary Data Production and Usage Challenges

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; how distinguish between these?
  - Need you combine both reconstructed and predicted data in one file?
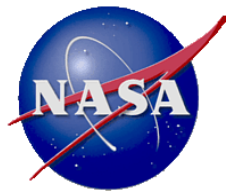 - How to manage the many files needed?
- **Need to reduce or eliminate gaps in coverage**
- **How avoid "jumps" between adjacent trajectory solutions?**
- **How to handle improved trajectory solutions:**
  - resulting from long arc fits
  - resulting from use of better gravity model
- **How to notify 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?

- How accurate are reconstructed attitude data time tags?

- 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 does one name and document attitude data files so as to meet end user needs?

Examples of Ancillary Data Production & Usage Challenges
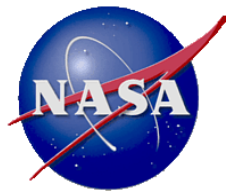
Spacecraft Clock Calibration

- **Often 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 or ?**

  - **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
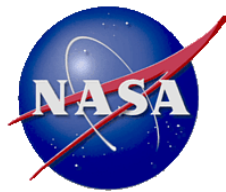
Reference Frames and Coordinate Systems

- **Planetary missions tend to 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
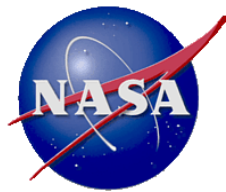
Instrument Geometry

- **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
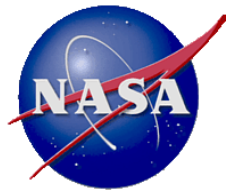
Target Body Shape Data

- **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
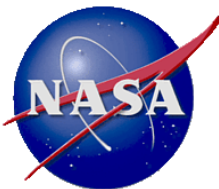   - » lack of standard software for using models

Examples of Ancillary Data Production & Usage Challenges
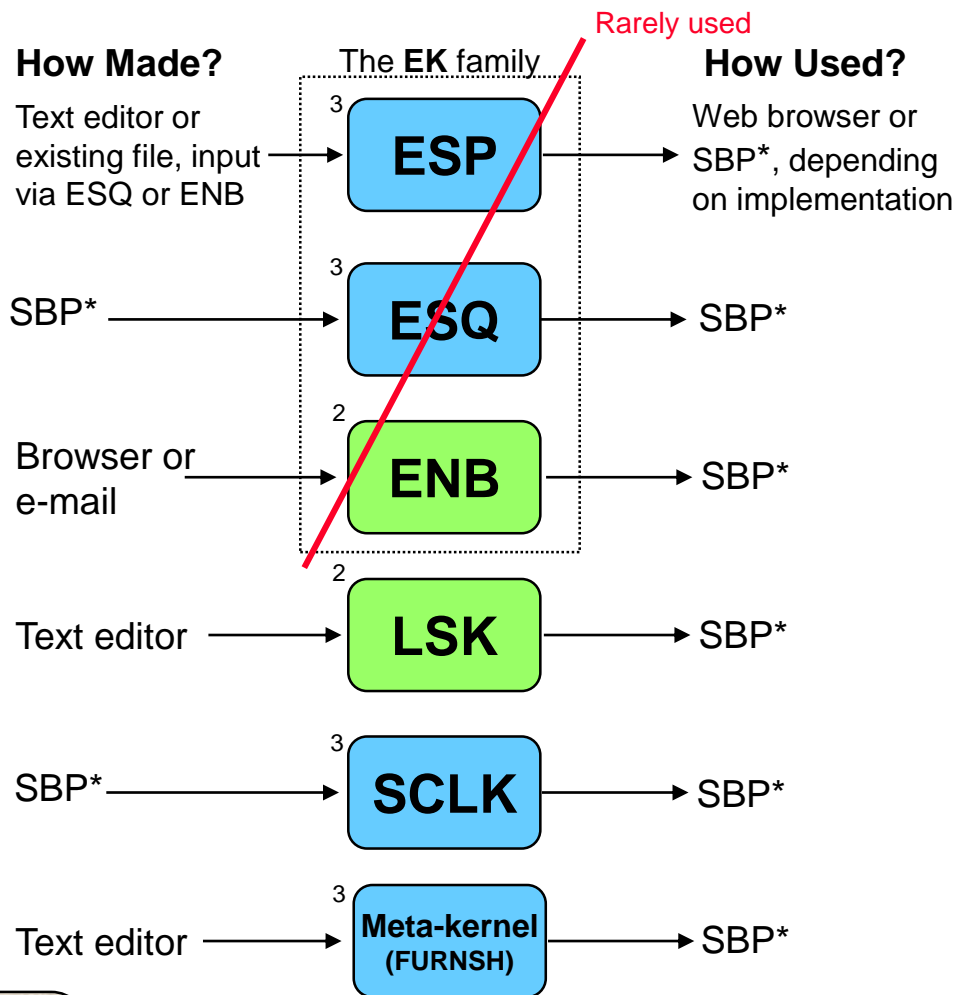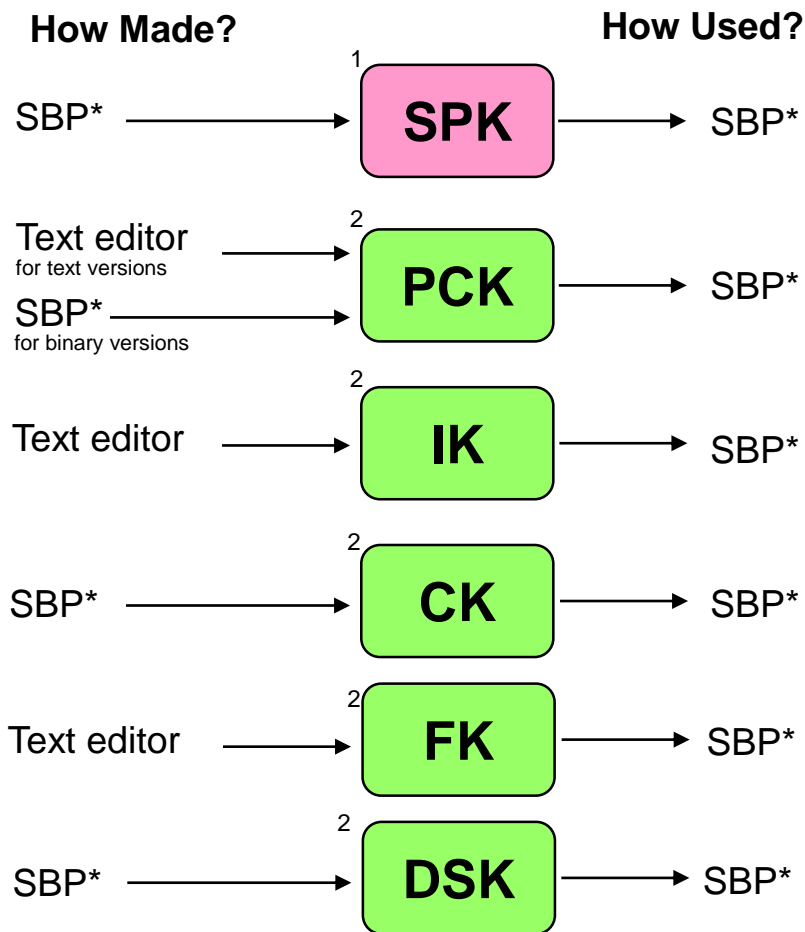
Data Availability Notification

- **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

How Made?

How Used?

SBP* ⟶ **SPK** [1] ⟶ SBP*

Text editor
for text versions ⟶
SBP*
for binary versions ⟶ **PCK** [2] ⟶ SBP*

Text editor ⟶ **IK** [2] ⟶ SBP*

SBP* ⟶ **CK** [2] ⟶ SBP*

Text editor ⟶ **FK** [2] ⟶ SBP*

SBP* ⟶ **DSK** [2] ⟶ SBP*

How Made?

The **EK** family

Rarely used

How Used?

Text editor or existing file, input via ESQ or ENB ⟶ **ESP** [3] ⟶ Web browser or SBP*, depending on implementation

SBP* ⟶ **ESQ** [3] ⟶ SBP*

Browser or e-mail ⟶ **ENB** [2] ⟶ SBP*

Text editor ⟶ **LSK** [2] ⟶ SBP*

SBP* ⟶ **SCLK** [3] ⟶ SBP*

Text editor ⟶ **Meta-kernel (FURNSH)** [3] ⟶ 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.
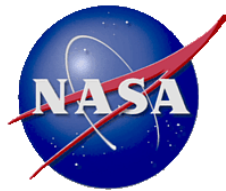
Why & How Kernels are "Modified" - 1

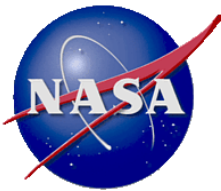| File Type	Why Modified	How Modified
SPK	-To add comments -To merge files or subset a file -To correct/revise an object ID	- COMMNT, SPACIT or SPICELIB module - SPKMERGE - BSPIDMOD
PCK **Text version**	-To revise data values -To add additional data items and values	- Text editor - Text editor
IK	-To 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		
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 leapsecond	- Text editor
SCLK	- To add comments	- Text editor
Meta-kernel (FURNSH)	- To revise contents in any way	- Text editor

Rarely used