

**“SPICE”**

**Might Help CubeSat and SmallSat Missions  
Compute Observation Geometry  
from Ancillary Data**

**Charles Acton**

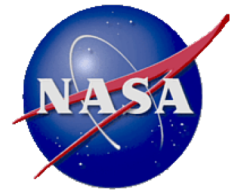
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**<https://naif.jpl.nasa.gov>**

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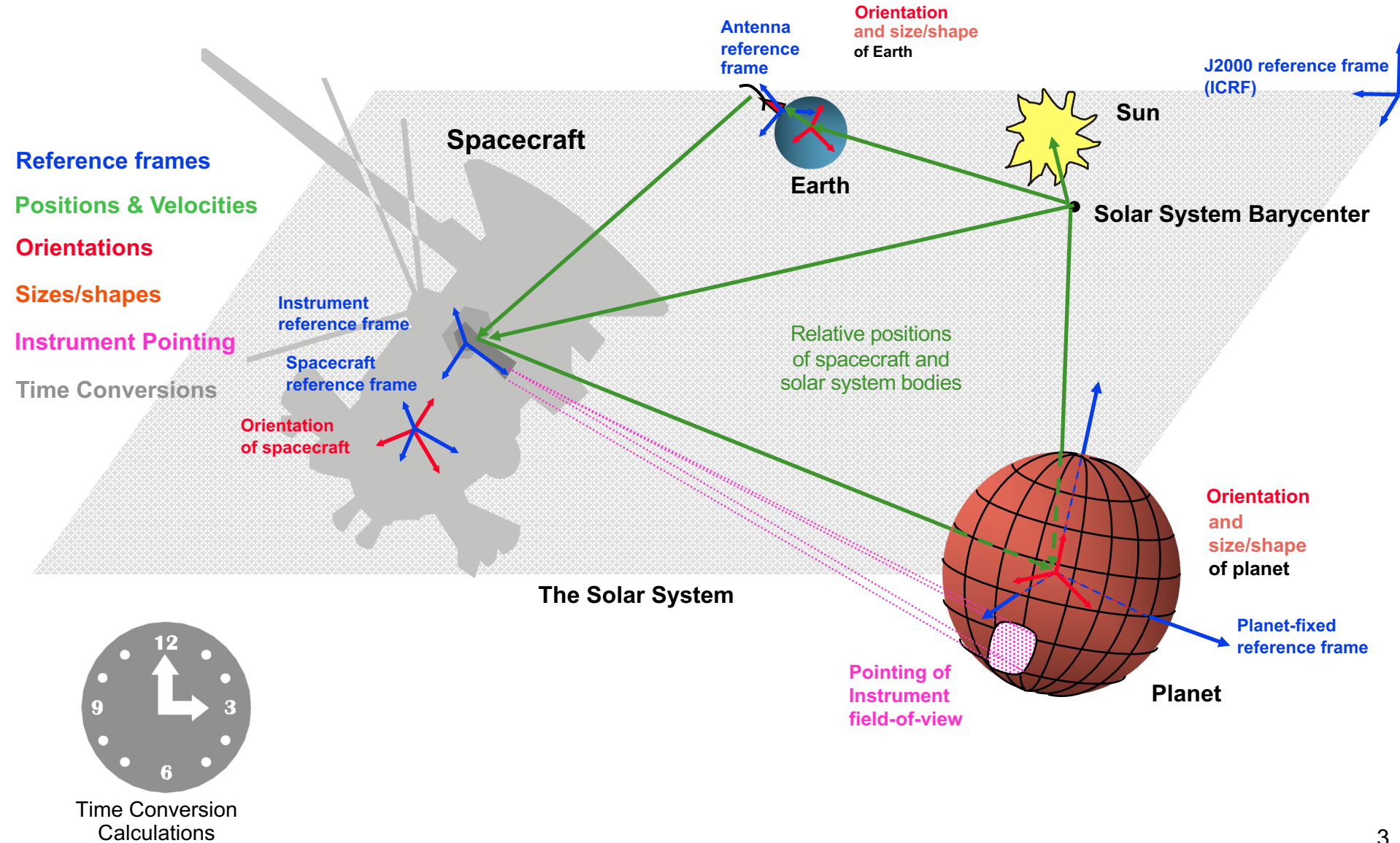


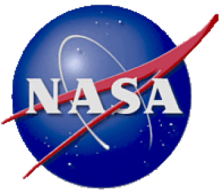
# Topics

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



# A Pictorial of Ancillary Data





# Examples of Using Ancillary Data

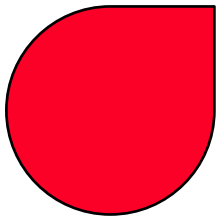
- **Help mission designers converge on a spacecraft trajectory design**
- **Compute observation geometry parameters needed by engineers for...**
  - communications station view period calculations
  - antenna pointing
  - thermal and telecom analyses
- **Compute observation geometry parameters needed by scientists for...**
  - science observation planning
  - science archive preparation
  - science data analysis



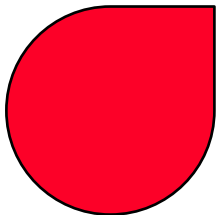
# Contrast “Ancillary Data” vs. “Observation Geometry”

## Ancillary Data

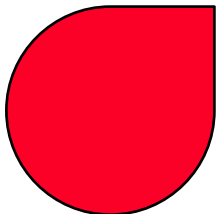
Files



Spacecraft trajectory



Spacecraft orientation



Spacecraft clock correlation

etc.

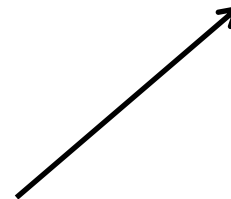


Some  
Software

## Observation Geometry

Derived parameters

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

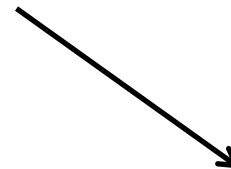


## Observation Geometry

Derived Conditions

Within a defined time span:

- the spacecraft is occulted by Mars
- the altitude is at a global maximum
- the phase angle is in the range of 24 to 28 degrees
- etc.





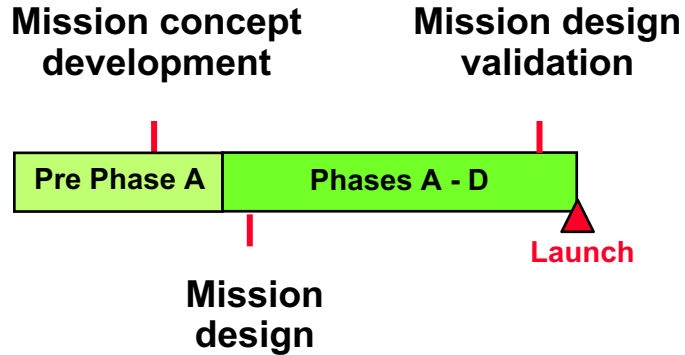
# When are Ancillary Data Used?

**Mission concept  
development**

Pre Phase A

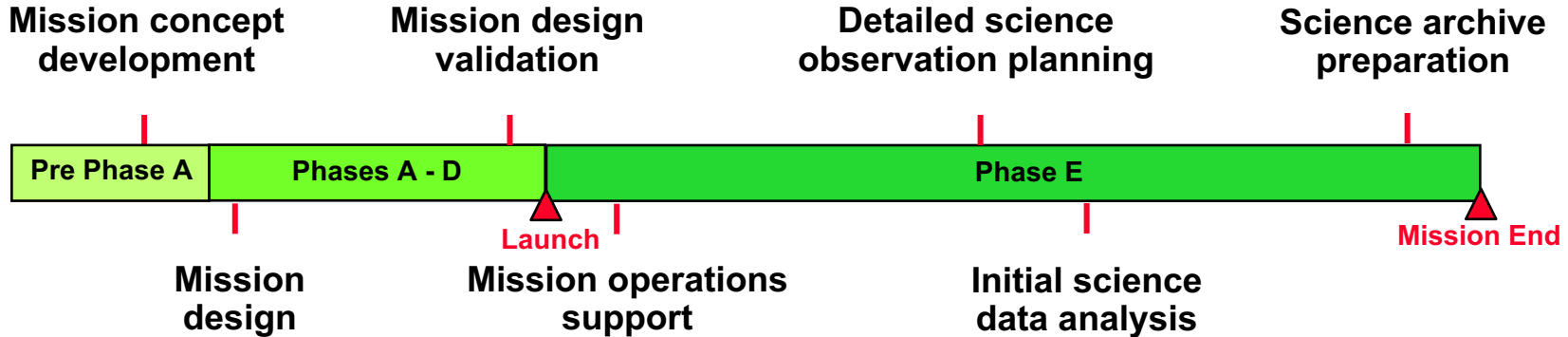


# When are Ancillary Data Used?





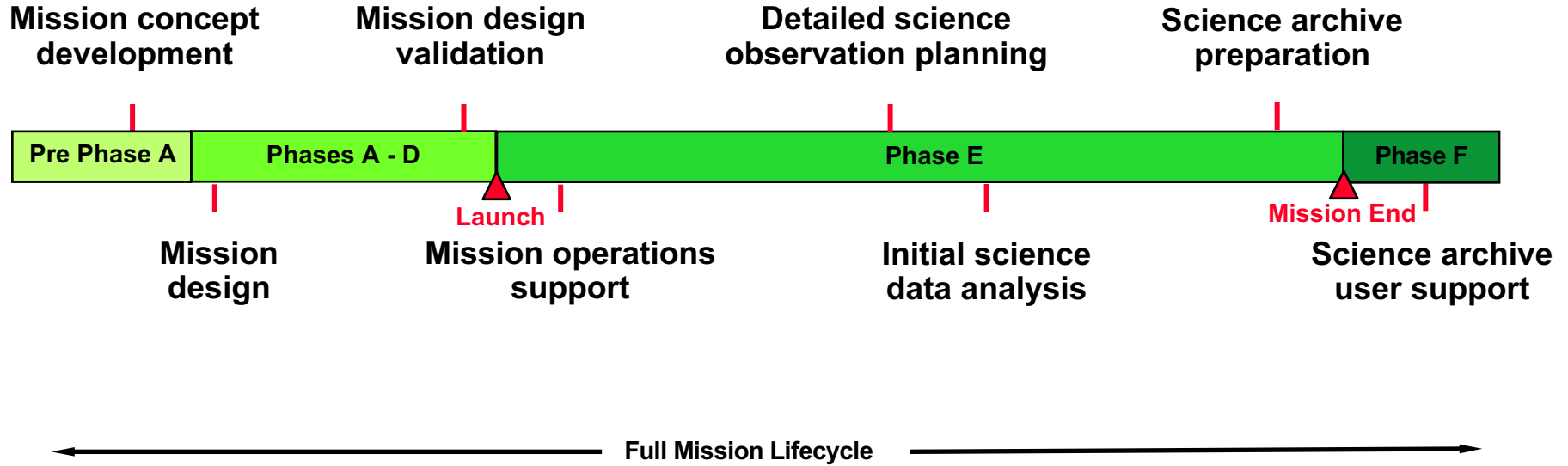
# When are Ancillary Data Used?

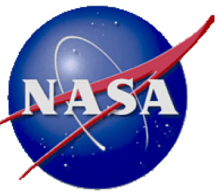






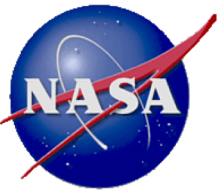
# When are Ancillary Data Used?





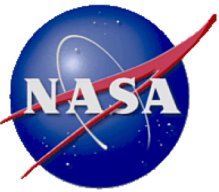
## Challenges in Producing and Using Planetary Ancillary Data

- **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 during the mission**



## 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 re SPICE.**
  - Not within the Planetary Science Division (PSD)
  - Probably not within other NASA divisions as well
- **If your mission exists outside of NASA sponsorship, you still might find SPICE useful.**
- **The rest of this presentation describes SPICE in more detail.**

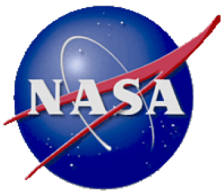


# SPICE and NAIF

- **SPICE: stands for **S**pacecraft, **P**lanet, **I**nstrument, **C**amera-matrix, **E**vents**

  - The SPICE concept was defined by a group of planetary scientists as one result of a 1983 NASA-mandated Planetary Data Workshop
  - SPICE is a system for providing scientists and engineers a wide assortment of space mission geometry
  - The SPICE system is implemented by the NAIF group at JPL

- **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 NASA's Planetary Data System



# SPICE System Components

Ancillary data files (“kernels”).....

1100  
1010  
0101

Software (SPICE Toolkit) .....



Documentation .....



Tutorials .....



Programming lessons .....



Training classes .....



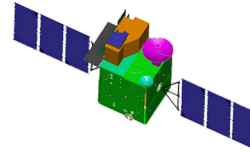
User consultation .....





# 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 "**kerrels.**"



# SPICE-style Ancillary Data

## Logical Components

**S**  
Spacecraft

**P**  
Planet

**I**  
Instrument

**C**  
Camera-matrix

**E**  
Events

## Kernels

**SPK**

**PCK**

**IK**

**CK**

**EK**  
ESP ESQ ENB

**Others**

Rarely used

- FK**
- LSK**
- SCLK**
- DSK**

## Contents\*

Spacecraft and target body ephemerides

Target body size, shape and orientation

Instrument field-of-view size, shape and orientation

Orientation of spacecraft and any articulating structure on it

Events information:  
- Science Plan (ESP)  
- Sequence of events (ESQ)  
- Experimenter's Notebook (ENB)

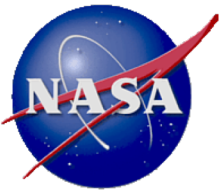
Reference frame specifications

Leap seconds tabulation

Spacecraft clock coefficients

Digital shape models

\* See the Backup section for details



# SPICE Software (The SPICE Toolkit)

<https://naif.jpl.nasa.gov/naif/toolkit.html>

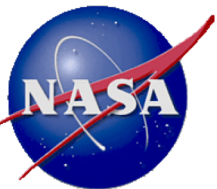
## Contents

- **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

- **Nine languages**
  - Fortran
  - C
  - IDL
  - MATLAB
  - Java Native Interface (JNI)
  - Python, Ruby, Swift, Julia  
(provided by 3<sup>rd</sup> 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





# Producing SPICE Ancillary Data

Spacecraft  
Builder

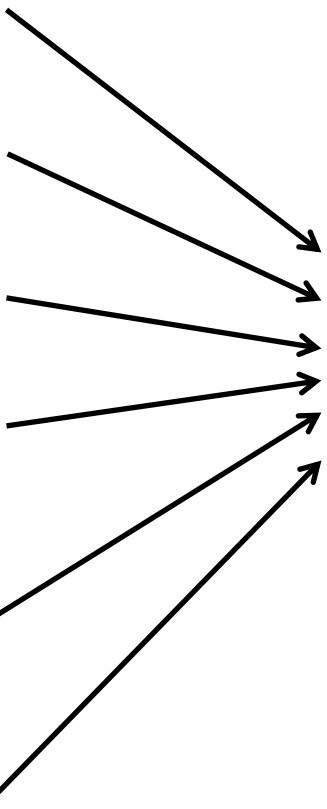
Instrument  
Builders

Navigation  
Team

Spacecraft  
Ops Team

Mission  
Control  
Team

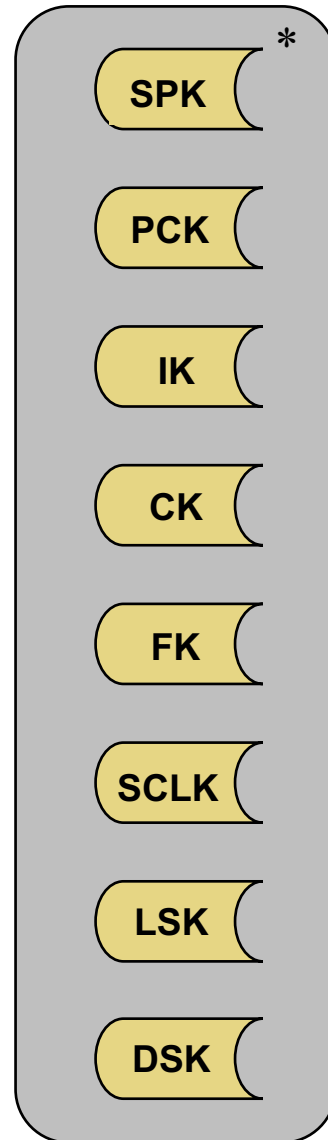
Science  
Team



**SPICE  
Operations People  
using  
SPICE Software  
and  
Text Editors**



**Ancillary  
Data**



**Inputs come from  
multiple sources**

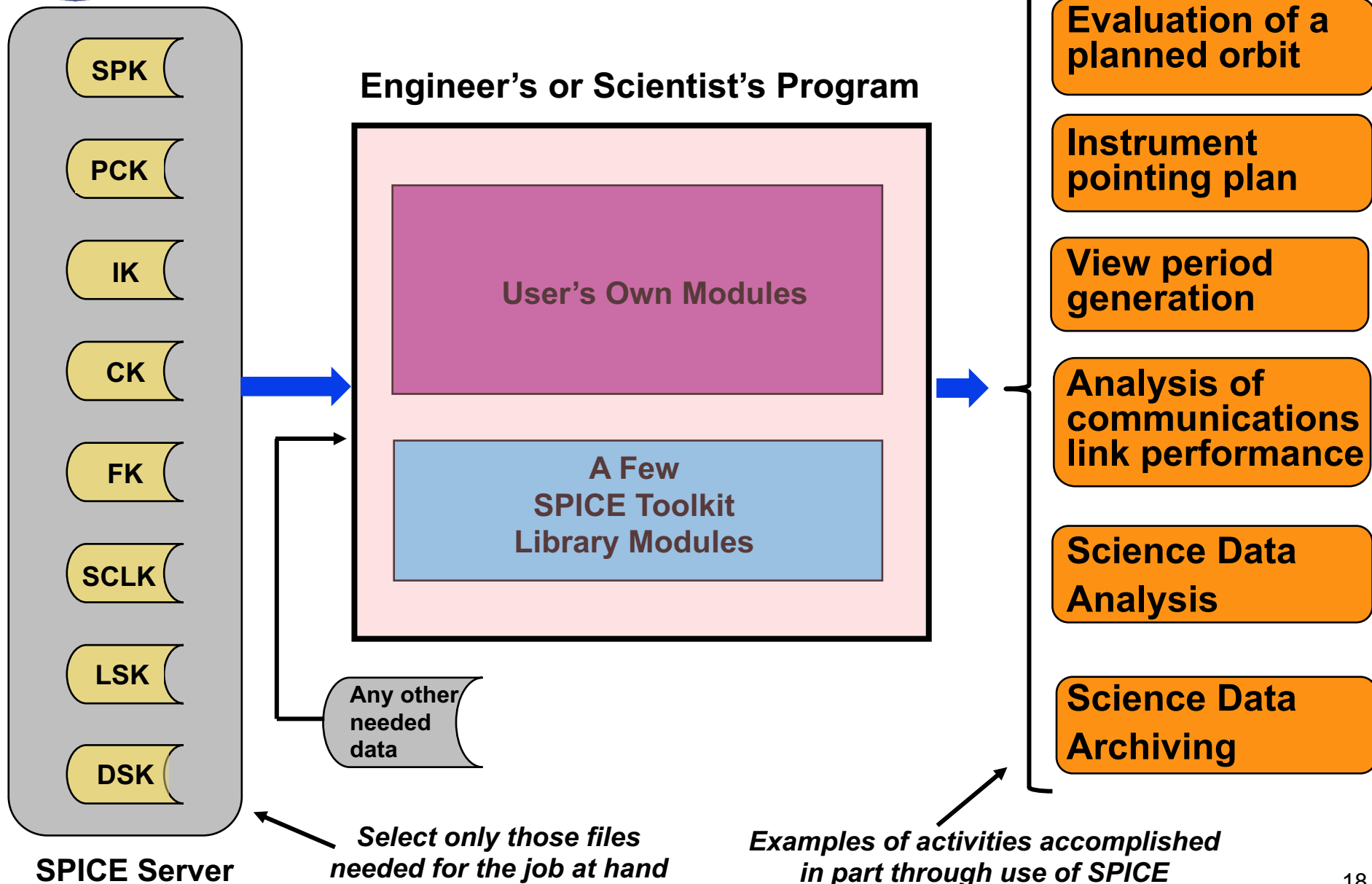
\* See the Backup section for details

**Your SPICE Server**



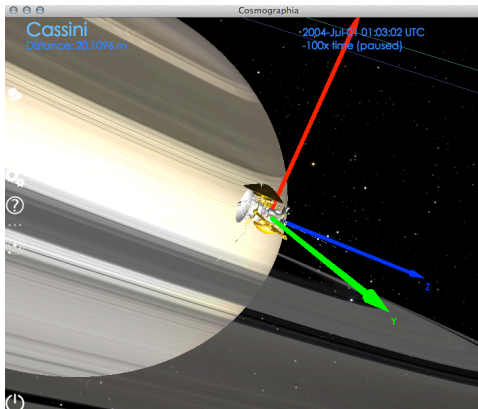
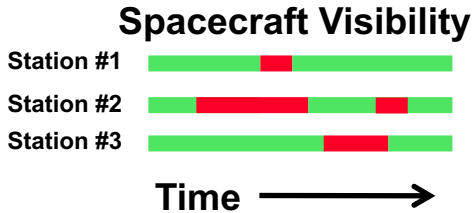
# Using SPICE Ancillary Data

Observation geometry parameters used for ...

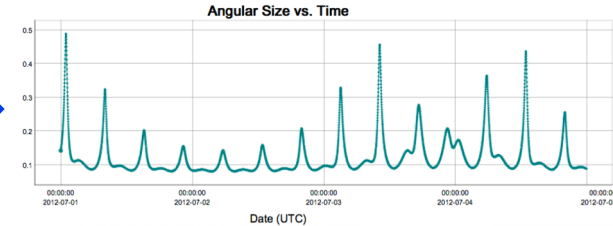




# Typical Uses of SPICE



Evaluation of a planned trajectory

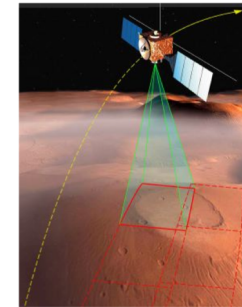


Angular size of Phobos as seen from the Mars Express spacecraft

Mission engineering analyses



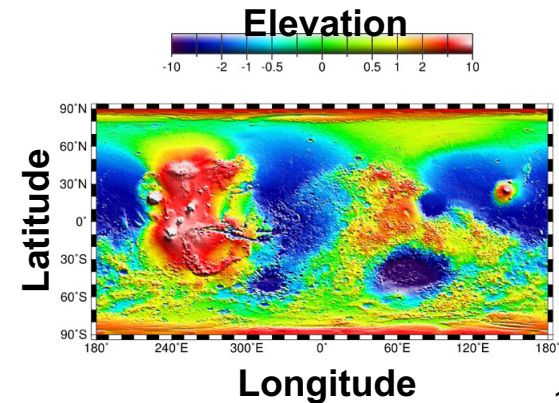
Planning an instrument timing and pointing profile



Observation geometry visualization



Science data archiving and analysis



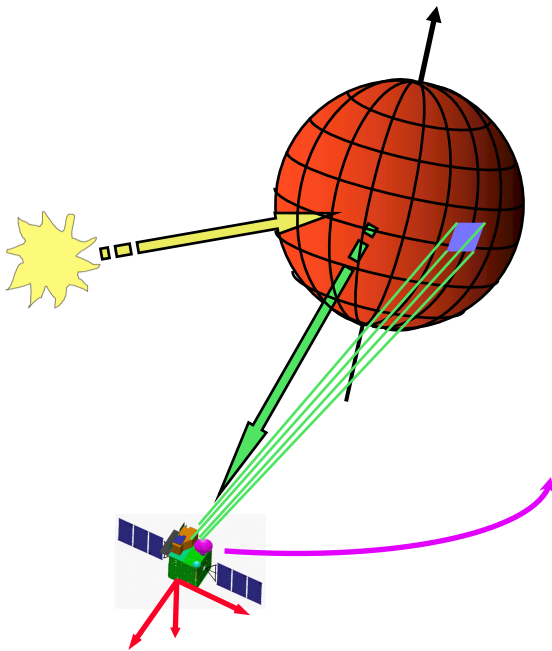


# Observation Geometry Computed Using SPICE - 1

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

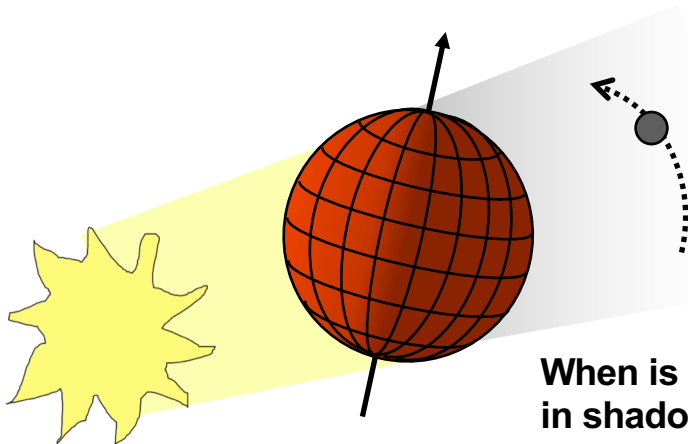




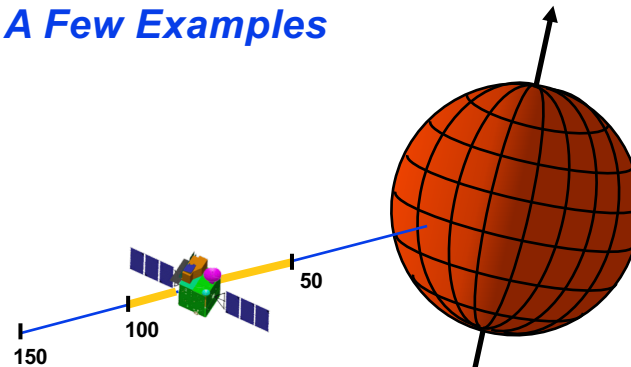
# What One Can Do With SPICE

Find times when a specified “geometric event” occurs

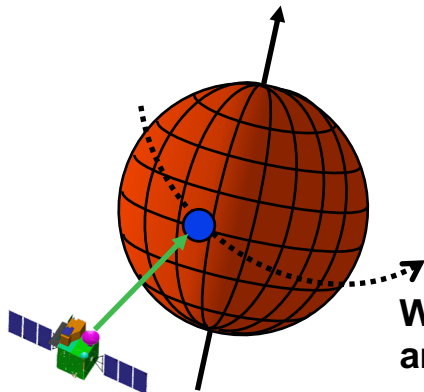
## A Few Examples



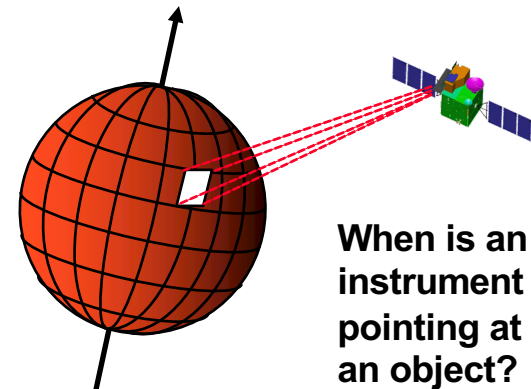
When is an object in shadow (occultation) ?



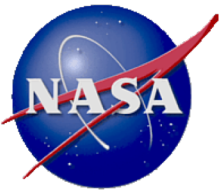
When is the spacecraft's altitude within a given range (say 50 to 100 km)?



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



When is an instrument pointing at an object?

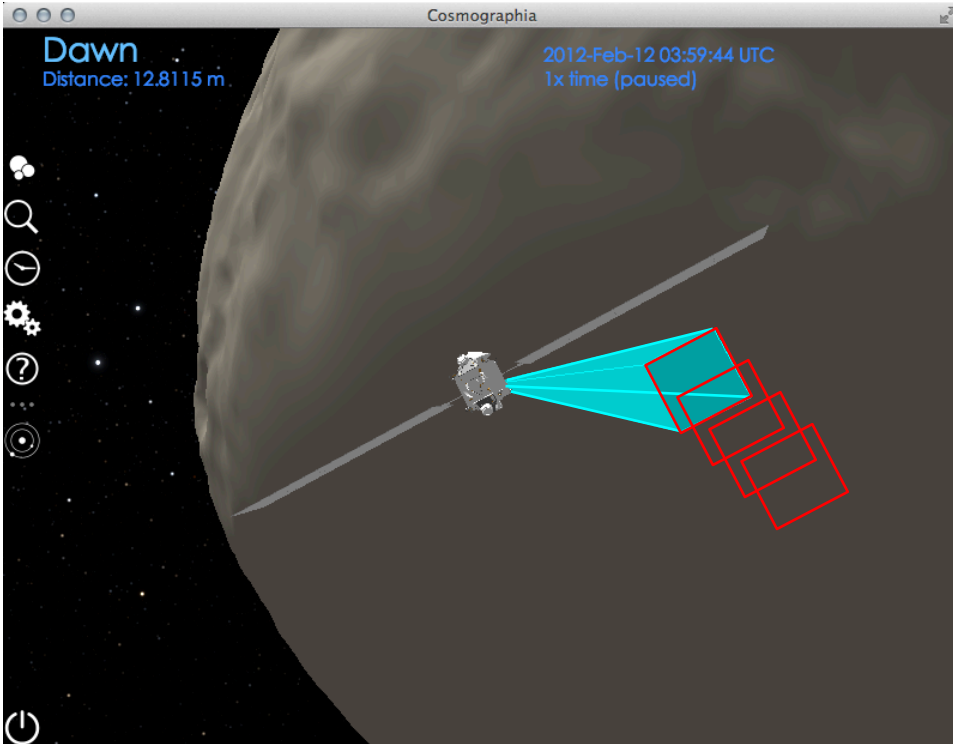


# What Else Can One Do With SPICE?

## Produce 3D Mission Visualizations

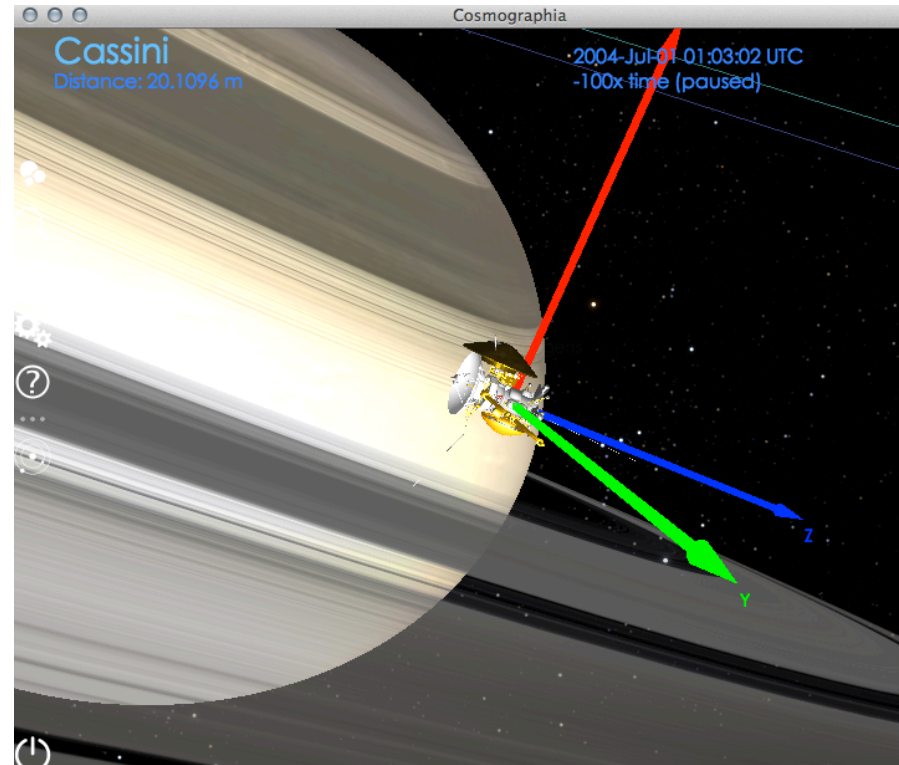
(Below we show only screen shots)

(See <https://naif.jpl.nasa.gov/naif/cosmographia.html> for details)

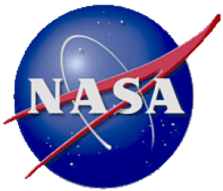


Cosmographia\* visualization of DAWN's framing Camera photographing Vesta, including display of **image footprints**

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

- **Landers**

- Remote sensing
- In-situ measurements
- Rover or balloon relay

- **Orbiters**

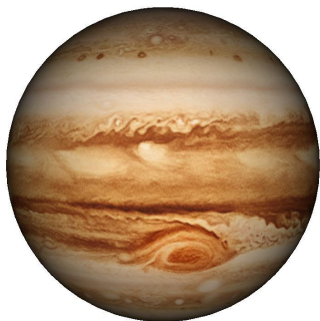
- Remote sensing
- In-situ measurement
- Communications relay

- **Rovers**

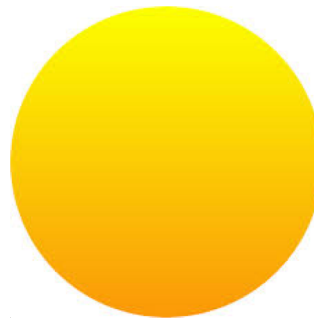
- Remote sensing
- In-situ sensing
- Local terrain characterization

- **Space Technology Demos**

- e.g. optical communications



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 preferred ancillary data archive format:
  - for NASA's Planetary Science Division
  - for NASA's Planetary Data System
- No U.S. ITAR/EAR restrictions
- No licensing
- SPICE components and generic data are free to all

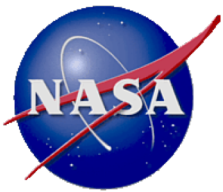






# Perhaps SPICE is not for Everyone

- **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**



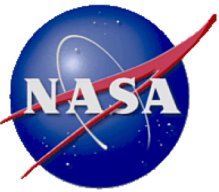
# Moving Forward

- **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 community to band together 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**
  - The next one is very soon – June 4-6, 2019
  - See [https://naif.jpl.nasa.gov/naif/WS2019\\_announcement.html](https://naif.jpl.nasa.gov/naif/WS2019_announcement.html) to register



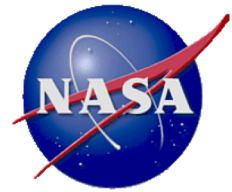
# What You'll Need to Provide if You Go It Alone Using SPICE

- 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
- Any needed training for your scientists and engineers intending to **consume** your SPICE data
  - If the timing works out, perhaps they can attend the free 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?

- **If funded to do so, NAIF could provide some or all of:**
  - **SPICE data production**
  - **training and consultation for project SPICE users**
  - **archive production**
  - **training for others on SPICE data production or SPICE archive production**
- **What's the cost for such support?**
  - **There's not a simple answer, but for recent projects in which NAIF has a major 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 depending on what effort is needed, how much of the mission is quiescent, and how long the mission will last**



# Backup Charts Follow

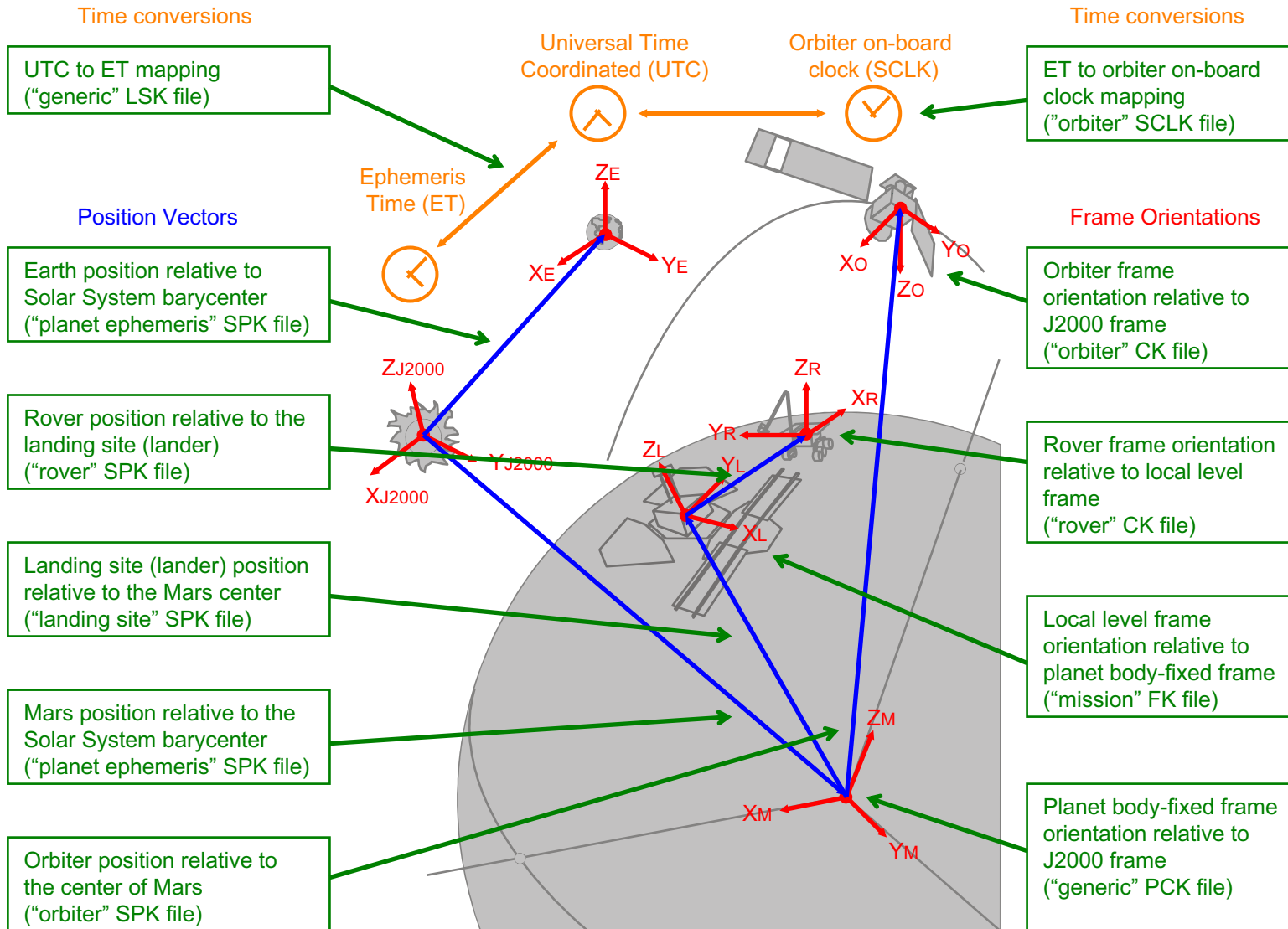
These charts contain some important issues to be considered no matter what approach you take for providing ancillary data and observation geometry calculations



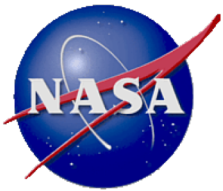
# Graphics Depicting SPICE Data



# 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)

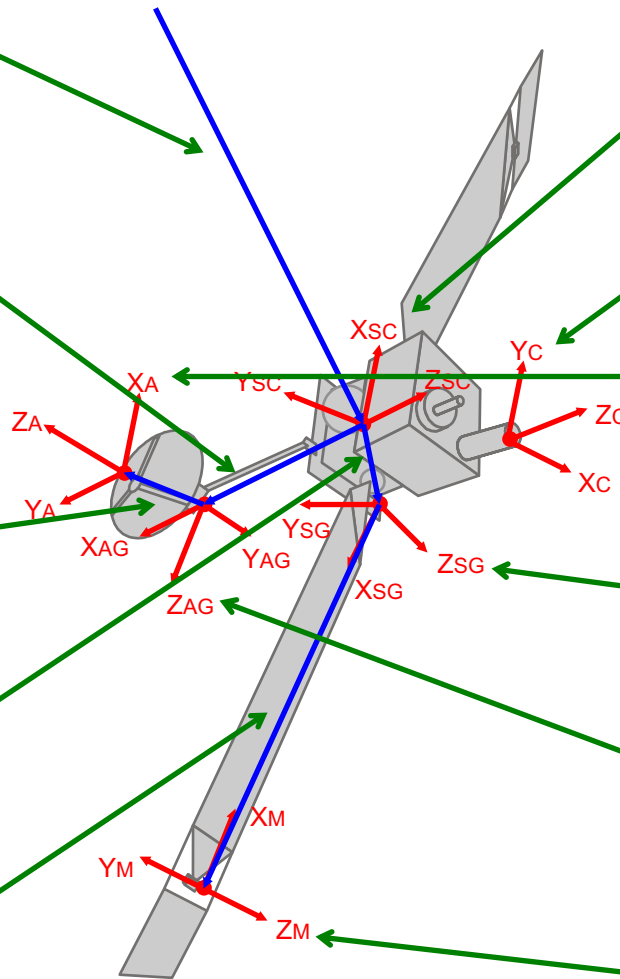
Camera frame orientation relative to spacecraft frame ("mission" FK file)

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)

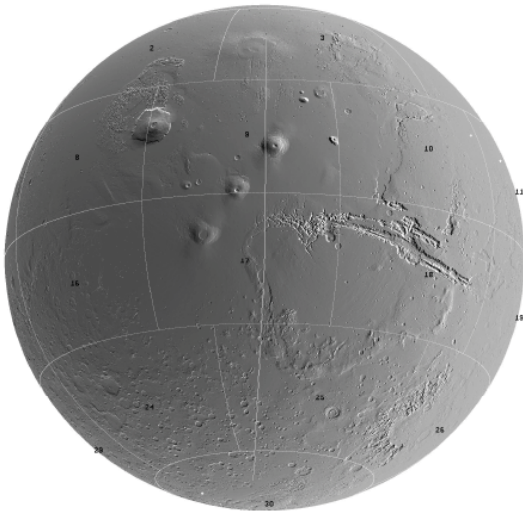
Magnetometer frame orientation relative to solar array gimbal frame ("mission" FK file)





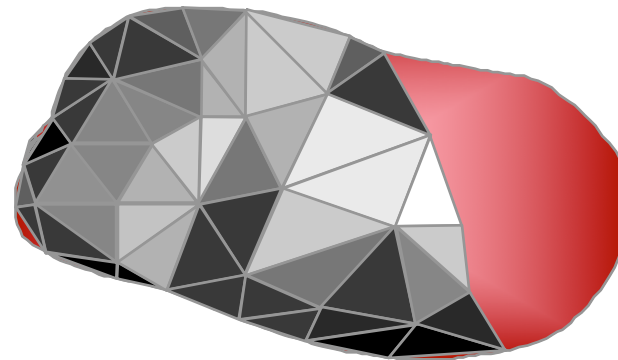
# Digital Shape Kernel (DSK)

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**

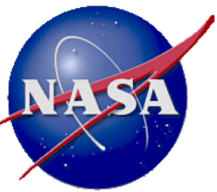
- Instrument platform (e.g. spacecraft) attitude
- More generally, orientation of something relative to a specified reference frame

**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



# 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**

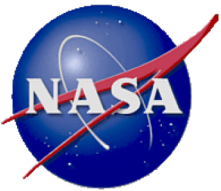




## Examples of Ancillary Data Production & Usage Challenges

### 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 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)

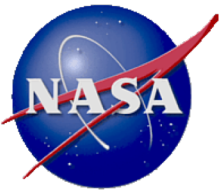
- **Are predicted attitude data needed in addition to reconstructed data? (Perhaps for observation planning purposes.) With what fidelity, and how achieve that fidelity?**
- **Are the accuracy and frequency of downlinked (reconstructed) attitude data sufficient for all users?**
- **Are the time tags 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?**



## 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 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

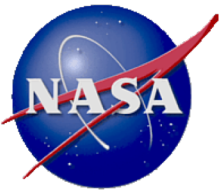
- **Planetary missions generally make use of multiple reference frames and multiple coordinate systems**
- **In many cases the definition of the frame or coordinate system is not a true standard**
  - For some reference frames the defining data are not well documented, and/or are disputed, and/or are 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 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 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.**



## Examples of Ancillary Data Production & Usage Challenges

### Target Body Shape Data

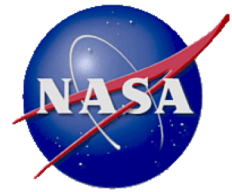
- **Today not every target bodies is modeled as a sphere, spheroid or tri-axial ellipsoid**
  - Either tessellated plate models for small, irregular objects, or digital elevation models, for large bodies, are becoming common
- **Estimating such shapes is generally in the purview of instrument teams**
  - 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

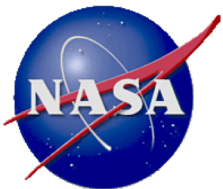
### Data Availability Notification

- **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?**

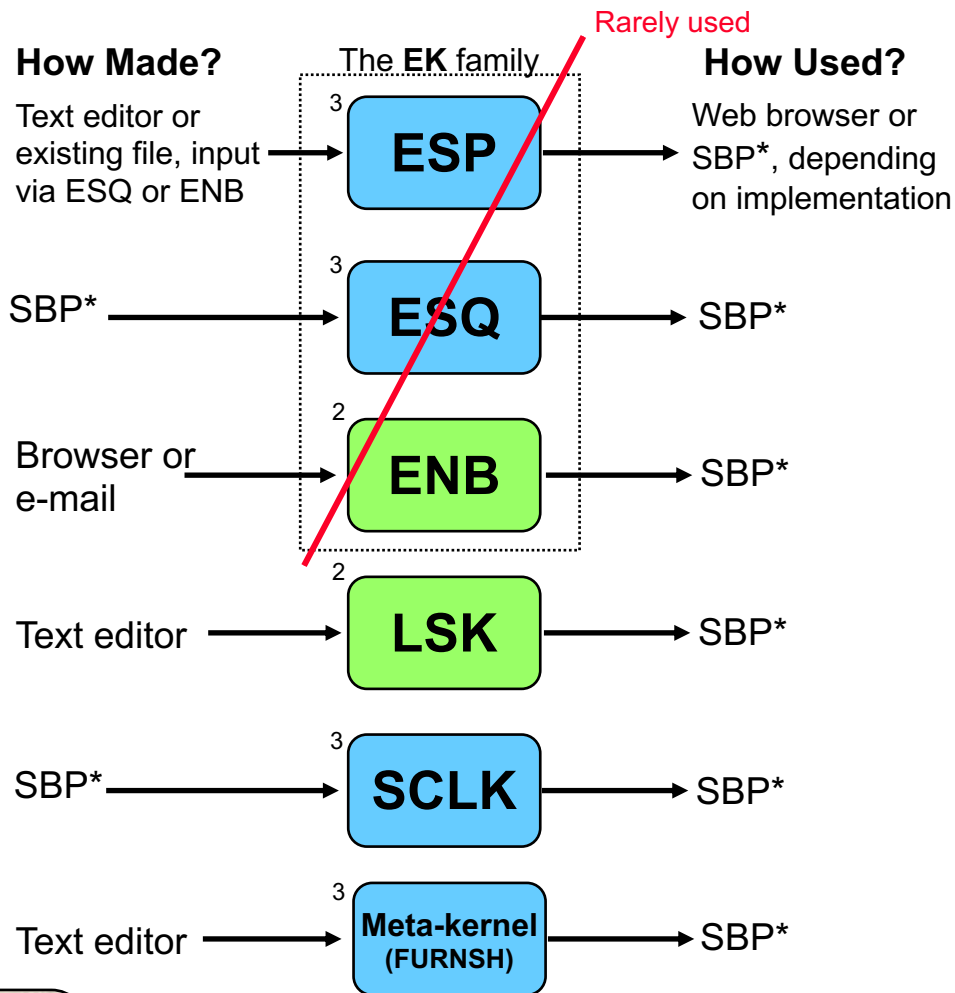
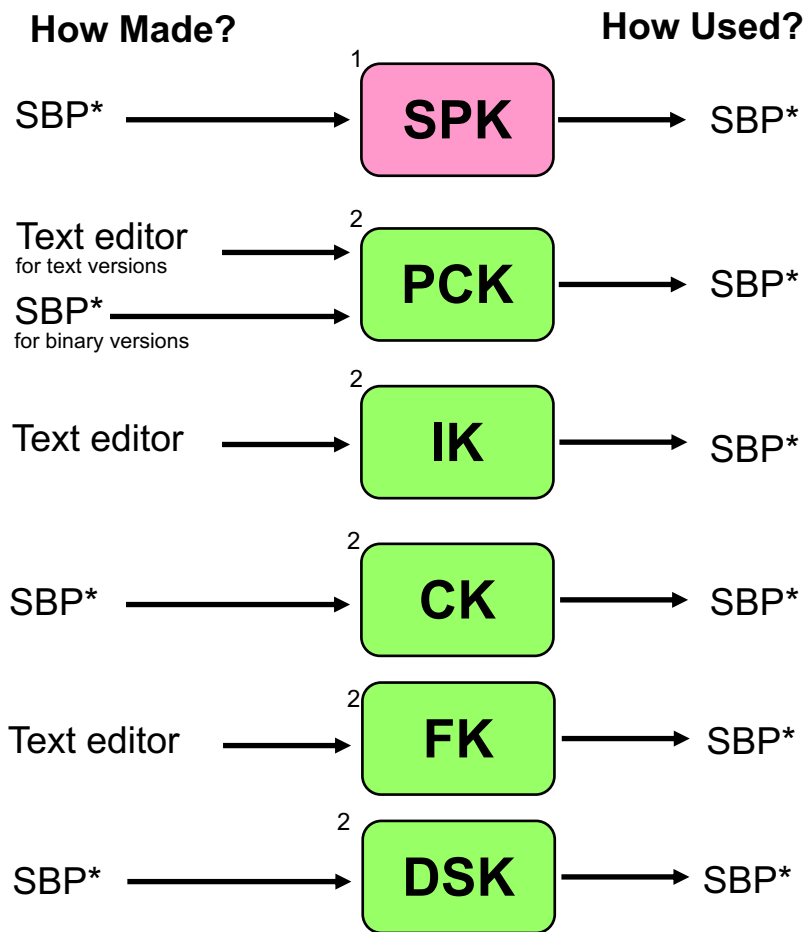


# Graphics Depicting How SPICE Kernels are Made and Modified





# 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**

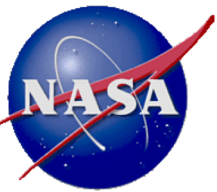
- To revise data values
- To add additional data items and values

- 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  
(FURNH)**

- To revise contents in any way

- Text editor