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

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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

The Solar System

- Spacecraft
- Sun
- Earth
- Solar System Barycenter

- Antenna reference frame
- Orientation and size/shape of Earth
- J2000 reference frame (ICRF)
- Relative positions of spacecraft and solar system bodies
- Instrument reference frame
- Planet reference frame
- Orientation and size/shape of planet
- Pointing of Instrument field-of-view

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)
- 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
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?

Mission concept development

Mission design validation

Pre Phase A  Phases A - D

Mission design

Launch
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

Mission design  Mission operations support  Initial science data analysis

Launch

Mission End
When are Ancillary Data Used?

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

Pre Phase A: Mission design
Phases A - D: Mission operations support
Phase E: Initial science data analysis
Phase F: Mission End

Launch
Science archive user support

Full Mission Lifecycle
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**: 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 **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 System Components

Ancillary data files ("kernels")
Software (SPICE Toolkit)
Documentation
Tutorials
Programming lessons
Training classes
User consultation
From Where do SPICE Ancillary Data Come?

- From the spacecraft
- From the mission control center
- From the spacecraft and instrument builders
- From science organizations

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

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<thead>
<tr>
<th>Component</th>
<th>Description</th>
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<td>P</td>
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## Kernels

<table>
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<td></td>
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<td>FK</td>
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<td>Spacecraft clock coefficients</td>
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<td>DSK</td>
<td>Digital shape models</td>
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</table>

* 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

Inputs come from multiple sources

* See the Backup section for details

Your SPICE Server
Using SPICE Ancillary Data

Your SPICE Server

- SPK
- PCK
- IK
- CK
- FK
- SCLK
- LSK
- DSK

User’s Own Modules

A Few SPICE Toolkit Library Modules

Select only those files needed for the job at hand

Any other needed data

Examples of activities accomplished in part through use of SPICE

Observation geometry parameters used for...

- Evaluation of a planned orbit
- Instrument pointing plan
- View period generation
- Analysis of communications link performance
- Science Data Analysis
- Science Data Archiving

Engineer’s or Scientist’s Program
Typical Uses of SPICE

- **Evaluation of a planned trajectory**
- **Mission engineering analyses**
- **Planning an instrument timing and pointing profile**
- **Observation geometry visualization**
- **Science data archiving and analysis**

**Spacecraft Visibility**
- Station #1
- Station #2
- Station #3

**Time**

**Angular size of Phobos as seen from the Mars Express spacecraft**
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 an object in front of another, as seen from a spacecraft (transit)?

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

When is an instrument pointing at an object?
What One Can Do Using SPICE - 3

Produce 3D Mission Animations

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

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

* 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

- **Time conversions**
  - UTC to ET mapping ("generic" LSK file)
  - ET to orbiter on-board clock mapping ("orbiter" SCLK file)

- **Position Vectors**
  - Earth position relative to Solar System barycenter ("planet ephemeris" SPK file)
  - Rover position relative to the landing site (lander) ("rover" SPK file)
  - Landing site (lander) position relative to the Mars center ("landing site" SPK file)
  - Mars position relative to the Solar System barycenter ("planet ephemeris" SPK file)
  - Orbiter position relative to the center of Mars ("orbiter" SPK file)

- **Frame Orientations**
  - Orbiter frame orientation relative to J2000 frame ("orbiter" CK file)
  - Rover frame orientation relative to local level frame ("rover" CK file)
  - Local level frame orientation relative to planet body-fixed frame ("mission" FK file)
  - Planet body-fixed frame orientation relative to J2000 frame ("generic" PCK file)
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

- **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

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

CK

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

EK

3 components

EK is not much used

EK is not much used
SPICE Data Details - 3

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

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

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

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

UTC = Coordinated Universal Time   TDB = Barycentric Dynamical Time   SCLK = Spacecraft Clock Time
Ancillary Data Production 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?
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 observation 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

• 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
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.