An Update on NAIF's Package of "SPICE" Astrodynamics Tools

Charles Acton, Nathaniel Bachman, Boris Semenov, Edward Wright

Jet Propulsion Laboratory/California Institute of Technology

ABSTRACT

"SPICE"[1] is an information system, comprising both data and software, providing engineers and scientists with the geometry data needed to help design robotic solar system missions, conduct mission engineering operations, plan observations from instruments, and analyze the data returned from those observations. The SPICE system has been used on the majority of worldwide planetary exploration missions since the time of NASA's Magellan mission to Venus, and it appears to be the ancillary information system of choice for most future solar system exploration missions. Along with its "free" price tag, portability and the absence of licensing and export restrictions, its stable, enduring qualities and substantial user support in terms of training and consultation help make it a popular choice among scientists and engineers. The SPICE system is implemented and maintained by NASA's Navigation and Ancillary Information Facility (NAIF) located at the Jet Propulsion Laboratory in Pasadena, California: http://naif.jpl.nasa.gov

1. INTRODUCTION

From pre-Phase A to many years after the conclusion of a robotic space science mission engineers and scientists need access to a variety of mission "geometry" used for designing the mission, planning instrument observations, analyzing the data returned from the instruments and archiving the science data. "Geometry" information is also needed within a space agency's infrastructure, supporting activities such as communications, spacecraft navigation and spacecraft engineering analysis.

The SPICE information system, initiated in 1989 in association with NASA's Magellan mission to Venus, is designed to satisfy the objectives noted above. Over the years it has slowly grown in worldwide acceptance to the point where it has become a *de facto* standard in the planetary science community, and beyond.

A description of SPICE was presented at the original ICATT symposium in July 2001. This presentation will bring attendees up-to-date on the current capabilities of SPICE and plans for its further evolution.

[1] **S**pacecraft, **P**lanet, **I**nstrument, **C**amera-matrix, **E**vents

2. SPICE OVERVIEW

As shown in Figure 1 the SPICE system comprises ancillary data, known as "kernels," and SPICE Toolkit software used to produce those kernels and to read those kernels and compute derived geometry quantities such as sub-spacecraft LAT/LON, positions and velocities, lighting angles, etc. Also part of the system is extensive user-focused documentation, tutorials, programming lessons, training classes and user consultation.

Figure 2 provides a graphical depiction of the kinds of ancillary data used within the SPICE system. These data come from multiple sources, including flight dynamics teams, spacecraft and instrument builders, and science standards entities. Some of the kernels use binary formats to allow rapid access to data while others are in a text format to allow for human readability and easy editing.

While originally focused on aiding science data analysis and archiving, the use of SPICE has grown to cover the entire mission lifecycle, finding use in mission engineering applications as well as in all aspects of conducting a science investigation. Figure 3 provides a graphical peek at some of these uses. Other uses include antenna scheduling and pointing, tuning of ground station transmitters and receivers, telecommunications and spacecraft thermal analyses, telescope pointing for terrestrial observations, and support for public outreach.

3. SPICE SYSTEM CHARACTERISTICS

A number of SPICE system characteristics have helped make SPICE a popular choice in the worldwide planetary science community.

- Software and data formats are very stable
- Computations are of high accuracy and precision
- SPICE Toolkit software is available in many popular languages and on most popular platforms and operating systems
- Code is thoroughly tested before being released

- Well documented source code is provided, including working examples
- Software includes built-in exception handling that captures and explains most user errors

In addition, all SPICE components are free of cost and are not subject to licensing or export restrictions; SPICE may be used by everyone.

4. WHO IS USING SPICE?

SPICE saw its first use with NASA planetary missions managed at the Jet Propulsion Laboratory. The Magellan mission was a test-bed. The Mars Observer (failed at Mars) and Galileo missions were the first to officially adopt use of SPICE. It has been used on almost every NASA planetary mission since then, and has been used on most non-NASA planetary missions as well. Use of SPICE has also extended outside of the planetary domain, finding use worldwide in heliophysics, astrophysics and earth science missions. Figure 4 provides a summary of many of the past and current SPICE users. This is significant in that it helps indicate a high level of quality and the likelihood SPICE will endure well into the future.

5. RECENT ADDITIONS TO SPICE

While SPICE has been around for quite some time, it continues to grow to support the evolving field of space science.

5.1. New Calculations

Many new or improved calculations have been added to the SPICE Toolkit over the years. This includes an entire class of new calculation types, referred to as the "geometry finder" (GF) or "event finder" subsystem. Traditional SPICE calculations performed with SPICE involve calculating quantities of interest such as distances, vectors, angles, or orientations for specified times. The GF subsystem solves the inverse problem: it finds times when specified geometric conditions are met. Examples:

- Within a user-specified time bounds, find all the time intervals when Saturn occults Titan as seen by the Cassini spacecraft.
- Within a user-specified time bounds, find the time(s) when the angular separation between comet C-G and the sun, as seen by the Rosetta spacecraft, is at a global or local maximum.
- Within a user-specified time bounds, find the time intervals when the Akatsuki spacecraft's altitude above Venus is between 400 and 450 km.

5.2. New Interfaces

For some years SPICE has been offered in four languages: Fortran 77, C, IDL and MATLAB. (The MATLAB version reportedly works under OCTAVE as well.) NAIF has been working towards the addition of a Java Native Interface (JNISpice), currently in alpha-test status but available to interested persons as it's been pretty well tested.

Realizing that not everyone has the skills or time to write their own SPICE-based geometry calculator, NAIF recently implemented a geometry engine with a Graphical User Interface accessed through a user's browser. This WebGeocalc (WGC) tool uses simple menus and GUI widgets to allow a user to select a computation to be made and the SPICE kernels to be used. The WGC server performs the computations needed and returns numeric and optional graphical results to the customer's browser. An ability to perform chaining using outputs from one computation as inputs to a subsequent computation make WGC quite powerful. A demonstration of WebGeocalc will be provided at the 6th ICATT meeting. Interested persons may access the WebGeocalc tool at this location: http://naif.jpl.nasa.gov/naif/webgeocalc.html

5.3. New Models for Solar System Bodies

For many years the only means within SPICE for modeling a planet, satellite, comet or asteroid has been to use a tri-axial ellipsoid or oblate spheroid. This has become a severe limitation as target bodies have ever more physical diversity–think of the Rosetta mission's primary target, comet 67P/Churyumov–Gerasimenko, as modern missions fly closer to those target bodies, and as modern instruments achieve ever higher resolution.

To address this shortcoming NAIF is currently adding to the SPICE system two new shape model containers, both falling under the name Digital Shape Kernel (DSK). One of those containers is designed to hold a set of tessellated triangular plates, a popular shape model representation for small, irregularly shaped objects. The second container is designed to hold traditional digital elevation model (DEM) representations of large bodies with measureable terrain.

As for the other kinds of SPICE data, NAIF is not a fundamental producer of shape data; rather, NAIF provides container mechanisms for the shape data produced by the science/engineering community. Why do this? Software that is part of the DSK subsystem not only packages tessellated plate data or digital elevation data, but it also provides means to compute an assortment of observation geometry parameters relative to these bodies–quantities such as altitude, LAT/LON and lighting angles that are important to scientific investigations and mission engineering applications. Thus a scientist or engineer who has elected to use SPICE for other kinds of space geometry computations will not have to exit the SPICE domain in order to make computations involving tessellated plate or DEM data.

Alpha-test SPICE Toolkits that handle the tessellated plate model have been in use for some time, and this portion of the DSK subsystem will be officially added to SPICE Toolkits by Spring 2016. An early-stage version of the DEM style of DSK has been successfully deployed in support of the Soil Moisture Active-Passive (SMAP) earth science mission. Official integration into SPICE Toolkits of this part of the DSK subsystem will come at a future date. In parallel NAIF plans to prepare DSKs using the best publically available DEM data sets for the moon, Mercury and Mars. But any DSK user will be able to make her/his own DSKs for any body for which there are tessellated plate data or DEM data available.

5.4. Mission Visualization Tool

SPICE has always been in the numbers game, used to calculate numeric quantities used in downstream applications, in user-made graphing or visualization tools, or in publications. Some SPICE users have indeed implemented their own visualization tools that use some or much of SPICE, and some of these are available to the community. But over the years SPICE users asked NAIF if it could provide a generic, fully SPICE-enabled visualization tool having characteristics similar to the SPICE Toolkits: portable, easy to use, free and not export limited.

The NAIF Group had been experimenting with an open source tool named Celestia, then learned of a new tool named Cosmographia by the same author. It appeared Cosmographia could be the basis for a NAIF-supported visualization tool. After successful discussions with Cosmographia's author, NAIF embarked on making modifications to the tool to enhance its SPICE compatibility, to add more functionality, and to provide a variety of user-focused tutorial materials.

A demonstration of the SPICE-enhanced version of Cosmographia will be provided during the 6th ICATT meeting. More information about Cosmographia and access to the download page is available here: http://naif.jpl.nasa.gov/naif/cosmographia.html

5.5. Performance Enhancements

The SPICE software was architected to provide correct, high-precision results and broad flexibility while also alerting users to erroneous inputs wherever possible: high speed was not a consideration. Nevertheless some customers asked if performance could be improved. The NAIF Team looked into this question and found several areas where modest changes could be implemented in SPICE software that would improve run-time performance in some situations while not altering functionality or user interface. The very latest SPICE Toolkit–version N66–contains these improvements, and the next Toolkit will benefit from some additional performance enhancements.

5.6. A Running Summary of Changes

Each SPICE Toolkit includes a simple text file named "whats.new" that summarizes all of the changes in each new Toolkit release. This same file, named "What's New in SPICE," is available under each Toolkit language page on the NAIF website–for example here for the C Toolkits: http://naif.jpl.nasa.gov/pub/naif/toolkit_docs/C/index.html

6. LOOKING AHEAD: PLANNED ADDITIONS

The NAIF Group has a long list of ideas for further improving the SPICE system. Here we list a number of them. Which of these and others will actually be addressed depends on user feedback.

- Complete the in-progress Java Native Interface suite of Toolkits.
- Add a suite of Python Toolkits.
- Change from Fortran 77 to a new base development language, one that offers the possibility for building thread-safe and possibly object-oriented toolkits. (But we must not abandon any of the current languages.)
- Add new reference frames (sometimes called coordinate systems). Most would be dynamic frames.
- Provide means to generate script-based dynamic frames.
- Implement a smart reference frame creation and validation tool.
- Add rings model(s).
- Add troposphere, magnetosphere or plasma models.
- Add a star catalog.

- Provide new/better means to select "the right" kernel(s) out of a collection of kernels.
- Provide more SPICE-based web services.
- Implement run-time SPK (ephemeris) and CK (orientation) functionality.
- Add functionality to the prediCkt orientation tool, used to produce predicted (planned) spacecraft orientation based on pointing rule sets.
- Prepare and teach advanced SPICE training classes.

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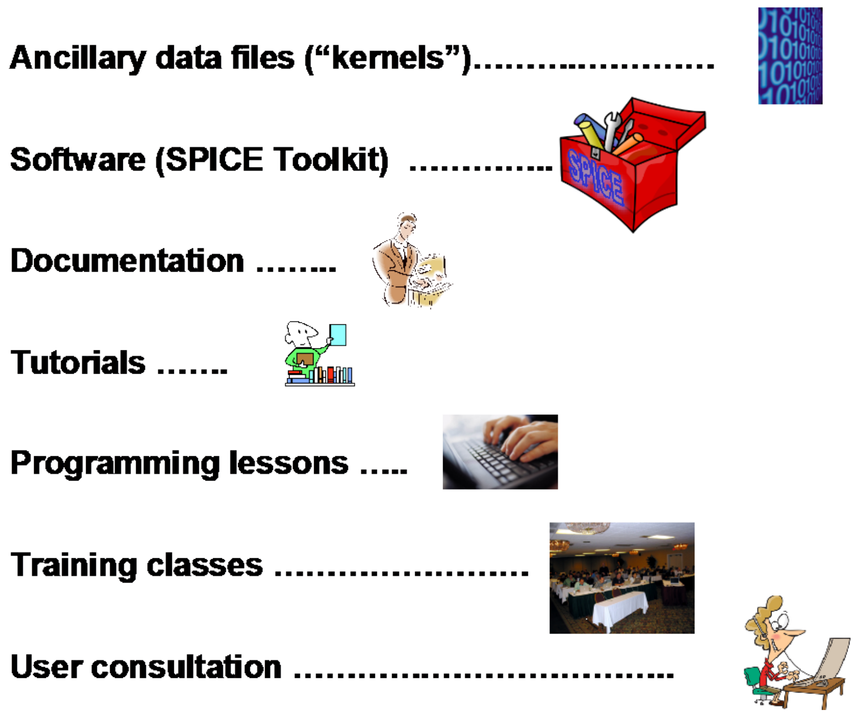

Fig.1 SPICE System Components

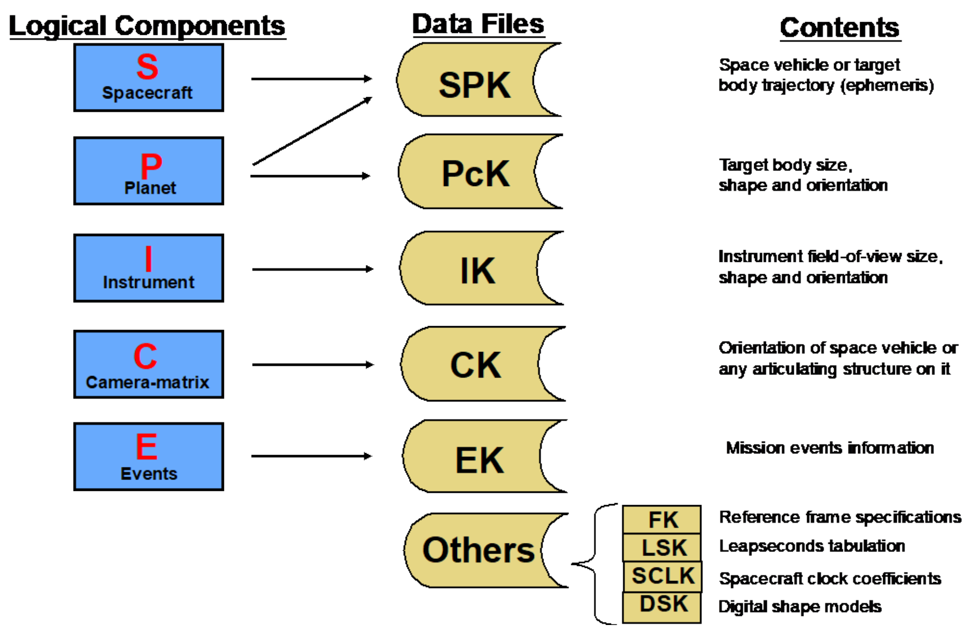

Fig.2 SPICE Data Overview

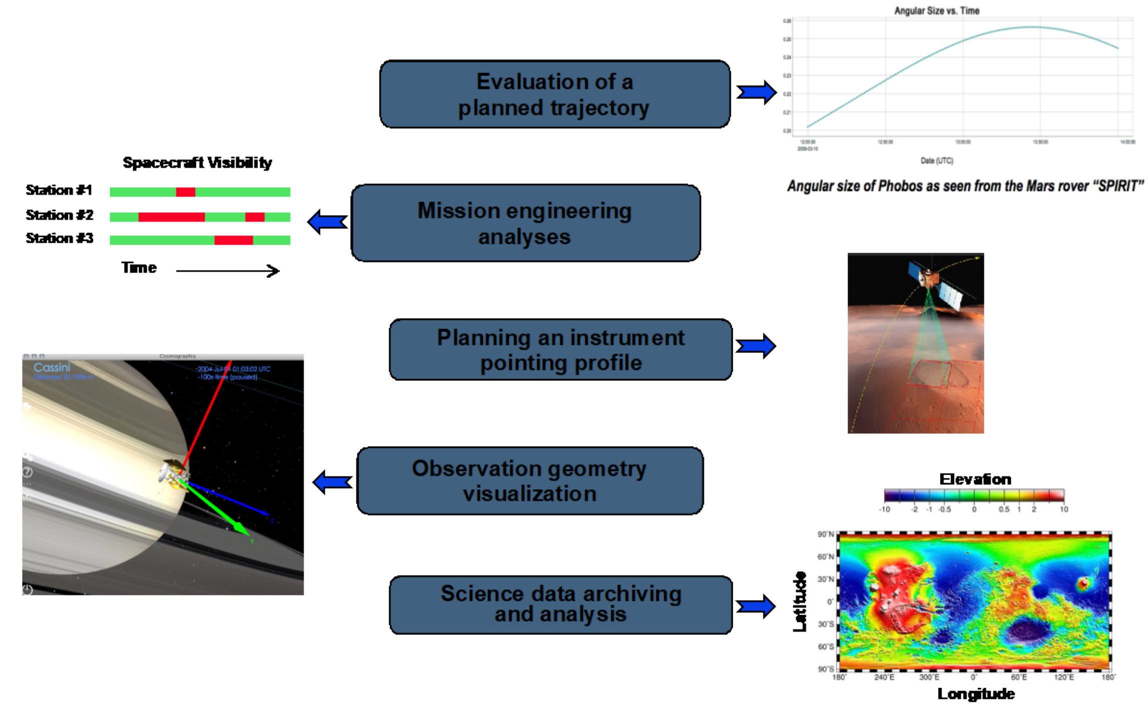

Fig. 3 Examples of how SPICE is used

Data Restorations	*Selected Past Users*	*Current/Pending Users*	*Possible Future Users*
Apollo 15, 16 [L]	Magellan [L]	Cassini Orbiter	NASA Discovery Program
Mariner 2 [L]	Clementine (NRL)	Mars Odyssey	NASA New Frontiers Program
Mariner 9 [L]	Mars 96 (RSA) [F]	Mars Exploration Rover	ExoMars 2018 (ESA, RSA)
Mariner 10 [L]	Mars Pathfinder	Mars Reconnaissance Orbiter	ARM (HEOMD)
Viking Orbiters [L]	NEAR	DAWN	*Examples of External Users*
Viking Landers [L]	Deep Space 1	Mars Science Lab	Emmirates Mars Mission (UAE via LASP)
Pioneer 10/11/12 [L]	Galileo	Juno	Bevo-2 CubeSat (U.T. Austin, Texas A&M)
Haley armada [L]	Genesis	MAVEN	Space Launch Systems (HEOMD)
Phobos 2 [L] (RSA)	Deep Impact	SMAP (Earth Science)	Proba-3 (ESA)
Ulysses [L]	Huygens Probe (ESA) [L]	OSIRIS REx	Solar Probe Plus
Voyagers [L]	Stardust/NExT	InSight	EUMETSAT GEO satellites [L]
Lunar Orbiter [L]	Mars Global Surveyor	Mars 2020	MOM (ISRO)
Helios 1,2 [L]	Phoenix	Europa Clipper	BepiColombo (ESA, JAXA)
	EPOXI	NISAR (NASA/ISRO; Earth Science)	JUICE (ESA)
	GRAIL	Lunar Reconnaissance Orbiter	Solar Orbiter (ESA)
	Messenger	New Horizons	Chang'e 3 ? (CNSA)
	Phobos Sample Return (RSA) [F]	Mars Express (ESA)	Van Allen Probes [L]
	Venus Express (ESA)	Rosetta (ESA)	STEREO [L]
	Chandrayaan-1 (ISRO)	ExoMars 2016 (ESA, RSA)	Spitzer Space Telescope [L]
	Hayabusa (JAXA)	Akatsuki (JAXA)	Kepler [L]
[L] = limited use	Kaguya (JAXA)	Hayabusa-2 (JAXA)	Hubble Space Telescope [S][L]
[S] = special services	LADEE		Radioastron (RSA) [L]
[F] = mission failed	ISO [S] (ESA)		IBEX [L]
	CONTOUR [F]	Planetary Data System	James Webb Space Telescope [S][L]
	Space VLBI [L] (multinational)	Planetary Science Archive (ESA)	JPL's Solar System Dynamics Group [S][L]
Last updated: 12/3/15	Smart-1 (ESA)	NASA Deep Space Network [S]	International Astronomical Union [L]

- (blue) NAIF has or had project-supplied funding to support mission operations, consultation for flight team members, and SPICE data archive preparation. NAIF also has PDS funding to help scientists and students with using SPICE data that have been officially archived at the NAIF Node of the PDS.
- (pink) NAIF has or had NASA funding to support a foreign partner in SPICE deployment and archive review, and to consult with flight team SPICE users.
- (green) NAIF has token funding to consult with kernel producers at APL. APL provides support to science teams.
- (yellow) NAIF has or had modest PDS-supplied funding to consult on assembly of a SPICE archive.
- (purple) NAIF has PDS funding to help NASA funded scientists using SPICE data that have been officially archived at the NAIF Node of the PDS.

Fig. 4 Examples of past, current and future flight project users of SPICE