Planning and Processing Space Science Observations using NASA's SPICE System

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Solar system exploration is increasingly a joint venture, demanding close cooperation amongst those scientists and agencies participating in the planning, operations and data analysis phases. Cooperating agencies must employ an array of common practices, standards and tools to achieve technical success within available financial and schedule resources. Common business practices, use of the metric system for measurements, use of the English language for human-to-human communications and use of ASCII computer codes for exchange of electronic information are well established standards. There also exist a number of commonly accepted standards for scientific measurements. But there is room for more use of standards to advance common goals.

To facilitate cooperation on the design and execution of space science missions, and on the timely and correct interpretation of scientific data obtained from these missions, it seems advisable to establish data standards and develop tools for the exchange and use of ancillary or engineering data.

About fifteen years ago the U.S. space science community made a strong recommendation to NASA for the establishment of new information systems and their attendant standards to help make ready access to, and use of, archived scientific data more of an expectation and less of a dream. While most of the discussion focused on data obtained directly from instruments, included in this report was a recommendation for the establishment of standards and processes for obtaining and using the relevant ancillary/engineering data needed to help fully understand science instrument measurements, and to correlate results across instruments and missions. Out of this recommendation was born NASA's "SPICE" ancillary information system.

The primary SPICE data sets are often called "kernels." SPICE kernels are composed of navigation and other ancillary information that has been organized and formatted for easy access and correct use by the space science and engineering communities. SPICE kernel file contents are summarized below.

S- **S**pacecraft ephemeris, or more generally, location of an observer, given as a function of time.

P- **P**lanet, satellite, comet, or asteroid ephemerides, or more generally, location of a target body, given as a function of time.

The P kernel also logically includes certain physical, dynamical and cartographic constants for target bodies, such as size and shape specifications, and orientation of the spin axis and prime meridian..

I- **I**nstrument description kernel, containing descriptive and operational data peculiar to a particular scientific instrument, such as field-of-view model parameters and internal timing relative to the spacecraft clock.

C- Pointing kernel, containing a transformation traditionally called the **C**-matrix that provides time-tagged pointing (orientation) angles for a spacecraft structure upon which science instruments are mounted.

E- Events kernel, summarizing mission activities–both planned and unanticipated. Three distinct classes of events data are defined: Science Plans, Sequences, and Experiment Notes.

Perhaps the "SPICE" acronym should have been "SPICES," with the final "S" standing for **S**oftware. The SPICE system includes the SPICE Toolkit, a large collection of allied software available in both ANSI FORTRAN 77 and ANSI C. The principal component of this Toolkit is a library of portable routines used to write kernels, to read kernels, and to calculate many commonly used observation geometry parameters derived from data provided in the kernels. Customers integrate these SPICE Toolkit routines into their own application programs to compute observation geometry parameters and similar ancillary information.

Why Establish Ancillary Data Standards ?

Ancillary data standards help promote the exchange of good ideas for mission design and the validation of a selected design. They help distributed team members participate in constructing detailed observation sequence designs, or in simply understanding what the planned observations are. They help maximize the complete and precise interpretation of scientific data returned from those observations, including when cross correlation between datasets is attempted. They facilitate the access to such data by future scientists who might have improved data or methods for analyzing old data. And they can reduce local data system development costs, particularly as re-use comes into play.

What Vehicles Should Be Supported ?

The challenges of planning observations and providing ancillary data to help analyze the data returned from those observations are associated with every kind of robotic vehicle in use today and planned for the future exploration of the solar system–interplanetary spacecraft, orbiters, landers, rovers, balloons and airplanes. Vehicles examining the earth and the solar environment are equally good candidates for use of such standards.

Prime Components of an Ancillary Information System

Data are the fundamental component of an ancillary information system. Ancillary data provide vehicle position and velocity; target body size, shape and orientation; vehicle or instrument pointing; instrument aperture size, shape and orientation; and logs of observation plans, spacecraft and instrument commands, and notes detailing how things worked. Reference systems are another key component: coordinate systems and time systems are prime examples. Documents providing precise and complete definitions of the data and reference systems are a third component. Archives that provide easy and timely access to the data and other information system components are important and must exist for pre-flight, mission operations, and post-flight long-term data analysis phases.

Software that helps a scientist find, acquire and utilize ancillary data should also be considered a prime information system component. Adding software to this "mix" makes the job of building an ancillary information system much larger, but if done properly the payoff is well worth the extra investment. This software suite could include general application programs, utility programs and scripts, and subroutine libraries used by scientists in building their own applications.

Requirements on Ancillary Information System Components

A number of requirements are mandatory to ensure meeting expectations of the large and diverse customer community. Portable: data files and software must be useable on and easily moved between all popular computing platforms. Extensible: it must be easy to add or extend functionality. Correct: all components must be thoroughly tested and validated, including peer review where appropriate. Precise: generally all calculations must be done to meet the needs of the most demanding customer; the use of approximations must be carefully controlled. Documented: data and software must be clearly, fully documented. Convenient: all components must be freely available and easily obtained by all interested parties. Supported: professional help for customers must be available. It also seems that providing a fully open system–providing source code for software–invites extra confidence and participation of the user community.

The SPICE implementation strives to address the suggested requirements outlined above. Key elements of SPICE are depicted in the figure below.

SPK

- Spacecraft 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"

IK

- Instrument information such as:
  - Mounting alignment
  - Field-Of-View specifications
  - Internal timing

(Separate IK file for each instrument)

CK

- Instrument platform attitude
- More generally, the time varying orientation of something relative to a specified reference frame

EK

- Observation plan
- Spacecraft & instrument commands
- Scientists' "notebooks" and ground data system logs

Others

- Frames file (FK)
  - Shows interrelationship of coordinate systems
- Spacecraft clock coefficients file (SCLK)
- Leapseconds file (LSK)
- Others:
  - Star catalog, shape model, etc.

Figure 1 Key Elements of SPICE

Also key to the SPICE system is the SPICE Toolkit, a large suite of software consisting of:

- SPICELIB subroutine library, used to
  - write SPICE files
  - read SPICE files
  - compute quantities derived from SPICE data

- Utility programs
  - Used to summarize and manage SPICE data files

- Cookbook programs
  - Provide basic examples of using SPICE Toolkit software and with SPICE data

- Documentation
  - Extensive tutorials, user guides and references

The various elements of SPICE are used at JPL and numerous other institutions in mission design, observation planning, mission operations (including visualization), and science data analysis. The SPICE Toolkit is available in both FORTRAN 77 and C, and is supported on most popular platforms.

The ephemeris component of SPICE is now the standard for customer's of NASA's Deep Space Network. It is used for long and short term scheduling of DSN antennas and for pointing these antennas and tuning transmitters and receivers during tracking passes.

The SPICE system has been in constant development for over eight years. Recent major new developments include a plate model applicable to small, irregularly shaped bodies and a high precision earth orientation capability. Currently under development are a generic sky catalog, new tools for creating SPICE ephemeris (SPK) files, a method for providing high performance access to high precision comet and asteroid ephemerides, and new software to improve the portability of binary-format SPICE files.

Lots of work remains to be done. Examples of possible extensions to SPICE include:

- integration of digital shape models
- design and implementation of a tightly coupled surface features database
- design and implementation of a more robust instrument model
- design and implementation of routines to search for specified geometric conditions
- design and implementation of means to incorporate and properly utilize trajectory/orbit accuracy information

Examples of possible application programs to be added to the SPICE family include:

- a highly evolved orbit characterization program
- tools to facilitate cooperative mission/observation planning in a distributed environment
- tools to facilitate planning for relay links
- visualization tools

Examples of possible new data management capabilities include:

- implementation of a means for aggregating a collection of files into an information "library"
- implementation of a web-based SPICE products SPICE products selection and distribution mechanism
- establishment and operation of mirror sites

Development of tutorial materials–possibly in multiple languages–would also be of benefit to the growing user community, as would devising methods of applying these fundamental data to education and public outreach.

The SPICE system is in use on a large assortment of space science missions as indicated in the Table 1 below. While the principle use of SPICE has been in the planetary science discipline, astrophysics, space physics and Earth science projects are also using this technology.

Restorations	Past	Current	Pending
Apollo 15 [P]	Voyagers [P]	Galileo	Muses-CN (ISAS)
Mariner 9 [P]	Magellan [P]	NEAR	Mars Express (ESA)
Mariner 10 [P]	Clementine (NRL)	Mar Global Surveyor	
Viking Orbiters [P]	Mars Observer	Space VLBI [P]	
Pioner 10/11 [P]	Mars 96 (Russia)	Stardust	**Future Possibilities**
Haley armada [P]	Hubble Telescope [S]	Cassini	
Phobos 2 [P] (Russia)	ISO [S]	Deep Space 1	Space Technology
Ulysses [P]	MSTI-3 (by ACT)	Mars Climate Orbiter	Planet - B (Japan)
	OTD (by MSFC)	Mars Polar Lander	Contour
	Mars Pathfinder	DSN Metric Predicts	EOS - MISR [P]
		Mars 01	EOS - TES
		SIRTF [S]	Messenger
		Genesis	Deep Impact
		Mars 03	Rosetta (ESA)
		Mars 05	Selene (Japan)
		SIM [P]	

[P] = partial use of SPICE [S] = special SPICE-based products

Table 1 SPICE Applications

The NAIF Team believes there is a lot of room for new applications of these standards in support of space science endeavors and solicits suggestions from the community for such.

The author wishes to thank the NAIF development staff at JPL–those men and women who have designed, assembled, tested and deployed the many capabilities that exist today. Thanks are also due to the managers at JPL and NASA who have believed in this idea and provided the funding and opportunities for using SPICE. Finally, thanks are due to the hundreds of scientists and engineers around the world who have taken the chance on

SPICE–investing precious time to learn how to use it and then supporting and guiding its further development; without such customers are endeavors would be pointless.

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