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SPICE for ESA Planetary Missions: geometry and visualization support to studies, operations and data analysis

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Abstract

SPICE is an information system that provides the geometry needed to plan scientific observations and to analyze the obtained. The ESA SPICE Service generates the SPICE Kernel datasets for missions in all the active ESA Planetary Missions. This contribution describes the current status of the datasets, the extended services and the SPICE support provided to the ESA Planetary Missions (Mars Express, ExoMars2016, ExoMars2020, Solar Orbiter, BepiColombo, JUICE, Rosetta, Venus Express and SMART-1) for the benefit of the science community.

1. Introduction

SPICE is an information system the purpose of which is to provide scientists the observation geometry needed to plan scientific observations and to analyze the data returned from those observations. SPICE is comprised of a suite of data files, usually called kernels, and software -mostly subroutines [1]. A customer incorporates a few of the subroutines into his/her own program that is built to read SPICE data and compute needed geometry parameters for whatever task is at hand. Examples of the geometry parameters typically computed are range or altitude, latitude and longitude, phase, incidence and emission angles, instrument pointing calculations, and reference frame and coordinate system conversions. SPICE is also very adept at time conversions.

2. SPICE for ESA Missions

ESA has a number of science missions under development and in operations dedicated to the study of our Solar System (Mars Express, Rosetta, ExoMars, BepiColombo, Solar Orbiter and JUICE). The Science Operations Centers for these missions, located at the European Space Astronomy Centre (ESAC) in Spain, are responsible for all science operations planning, and archiving tasks, being the essential interface between the science instruments who process these data, and the spacecraft via the Mission Operations Center located at the European Space Operations Center (ESOC) in Germany, and with the scientific community. From the concept study phase to the day-to-day science operations, these missions produce and use auxiliary data (spacecraft orbital state information, attitude, event information and relevant spacecraft housekeeping data) to assist science planning, data processing, analysis and archiving. Auxiliary data are those that help scientists and engineers to determine the location and orientation of the spacecraft, when and how an instrument was acquiring scientific data. These data also help to determine what other relevant events were occurring on the spacecraft or ground that might affect the interpretation of the scientific observation or the S/C systems performance. Software applications are required to know what were the location, size, shape and orientation of the observed target in addition to these auxiliary data. All ESA planetary missions have embraced the use of the SPICE system for ancillary data archiving and for science data analysis. Although the Flight Dynamics Division provides software to read the position and orientation files of the orbiters, most of the Principal Investigators have pointed out their interest in having all the auxiliary data distributed in SPICE format.

3. The ESA SPICE Service

The ESA SPICE Service (ESS)[1] located at ESAC leads the SPICE operations for ESA missions. The group generates the SKDs for missions in operations (EM16, MEX) missions in development (SOLO, BepiC, JUICE and ExoMars 2020) and legacy missions (ROS, VEX, SMART-1, Huygens and Giotto). The generation of these datasets includes the operational software pipelines to convert orbit,

[1] http://spice.esac.esa.int

attitude, telemetry and spacecraft clock correlation data into the corresponding SPICE format. ESS also provides consultancy and support to the Science Ground Segments of the planetary missions, the Instrument Teams and the science community. ESS works in partnership with NAIF and with the SPICE support for IKI/ROSCOSMOS. Finally, ESS periodically organizes training classes and workshops.

The current status of the SKDs for the before mentioned missions –most of which are publicly available- and the resources available to use that data and exploit are described in the following sections. The ESS reviews the legacy and operational datasets and develops the ones for the future missions, -the MEX and VEX SKDs are currently under review whereas the EM16, ROS, BepiC, Solar Orbiter and JUICE SKDs are in an optimal state according to their applicability. ESS is also responsible for generation of PDS3 and PDS4 formatted SPICE Archives that are published by the Planetary Science Archive of the European Space Agency (PSA) [2]. ESS, in close collaboration with NAIF peer-reviews the operational kernels for the PSA to publish being compliant with the Planetary Data System (PDS) standards and uses them in the processes that require geometry computations.

4. SPICE Kernel Datasets

The main purpose of the ESS is to provide a complete, consistent, high-quality, validated and up-to-date SKDs for the mission it supports in order to be able to use SPICE in an operations environment and for data analysis. A SKD consists on a complete set of SPICE Kernels that cover the whole mission lifespan including predicted long term, operational and reconstructed and or "measured" trajectory and orientation information. Kernels in a SKD can be classified in two main types:

Setup Kernels (STK) they are typically text files and they are developed by ESS and are reviewed and iterated with the SGS and with the Instrument Teams when need be during the whole duration of the mission. The STKs include the following information:

- Set of Reference Frames of interest for geometry computations.
- FoV and boresight modeling for science payload.
- Study trajectory default orientation for S/C.
- Physical models for natural bodies of the mission.
- Digital shape models for S/C elements.

Time-Varying Kernels (TVK) [SPK, CK, SCLK, MK] are either text or binary files and are generated with an auxiliary data processing pipeline and the source auxiliary data is provided by the Flight Dynamics team (FDy). TVKs include the following information:

- Predicted attitude and predicted/reconstructed trajectory.
- OBT to UTC/CAL time conversion.
- Reconstructed trajectory and measured orientation for S/C.
- Orientation of Solar Arrays, HGA, MGA or any other moving element of the S/C.
- Position of scans or turn-tables or articulations of payload.
- Digital Shape models for local terrain or extended bodies shapes

In addition to the two types of kernels included the SKD, SKDs can be classified in one of the following states depending on the mission phase they are:

Studies or pre-operational (JUICE, BepiC, SOLO and ExoMars 2020): These kernel datasets are characterized for being highly dynamic with changes in Instrument and S/C frames definitions. Usually different study cases for different consolidated trajectories provided by Mission Analysis (MAn) and with default and or study S/C Orientations are generated by the ESS.

Operational (MEX, EM16): These kernel datasets are updated with kernels generated from the periodical trajectory and orientation updates and from the relevant information obtained from housekeeping telemetry. Some updates on Instrument and S/C models might occur responding to operational demands (e.g.: after commissioning, after the start of the science phase, due to some particular event, etc.)

Legacy or post-operational (ROS, VEX): These ought to be final peer-reviewed and consolidated datasets. This process is currently on-going for both missions. The generation of the SKDs for Giotto and Huygens has not begun yet.

SKDs are released in a regular basis with STKs-lead updates, for missions in operations this also includes periodical updates to ensure that the latest data is available with the automatic generation of TVKs. SKDs are properly documented with general descriptions, status reports, “readme” files per kernel type and release notes.

4.1 Kernels Generation an Update

Whilst the generation of STKs does not require further explanation on their generation, TVK kernels; S/C trajectory, attitude and SC components orientation kernels do. Typically, a SKD will contain the following pieces of information:

1. Set of Reference Frames of interest for geometry computations (FK).
2. FoV and boresight modeling for remote and in situ sensors -at least- (IK)
3. Predicted trajectory and as-planned or default orientation for the S/C (SPK, CK)
4. OBT to UTC/CAL time conversion (SCLK)
5. Reconstructed trajectory and orientation and on-board measured orientation for S/C
6. Orientation of S/C parts (CK from HK Telemetry)
7. Position of scans or turn-tables or articulations of payload (CK from HK Telemetry)

Both 1. and 2. kernels will be ready already for the study phase and will be generated by ESS, whilst 3. will be hardly updated during the study phase but will be periodically generated during the science phase. From 3. to 7., those kernels will be generated by an operational pipeline. The particular order in which they have been described indicates how important are they for users and which implementation priority they do have. For instance, although all of them are implemented for MEX.

4.2 Kernel Dataset Distribution

Most of the SKDs for ESA Missions are publicly available[2] (hence the “at your glance” part of the title of this contribution) and all the relevant information on how to obtain and use the available SDKs can be found in the home page for SPICE at ESA[3]. Public SKDs are distributed to the users by three different means:

File Transfer Protocol (FTP): The FTP[4] contains all the kernels that have been generated for any mission and it also contains the operational MK that specifies which are the latest applicable kernels. This might not be the best solution for users to obtain a SKD for they need third party applications to manage the SKD or they need to obtain the kernels manually. This FTP is mirrored by NAIF for most of the missions.

Zipped directory. There is a permanent link to the latest SKD, containing only a subset of the kernels present in the latest operational meta-kernel. This solution is recommended for a user that need to make quick usage of the latest SKD.

Git repository. Distribution of SPICE Kernel Dataset via Git is available in BitBucket[5] and the latest version of a subset of the SKD for a given meta-kernel will is available via a Git Pull. Large files (SPKs and CKs mainly) are available without overloading the repository with GIT-lfs (GIT large file system). This is considered to be the best solution to work with SPICE Kernels.

Please note that as already indicated the SPICE FTP contains all the kernels that have ever been generated and published for a given mission; a user can always reproduce a given mission scenario for any mission period.

5. Using SPICE for ESA Planetary Missions

The ESS offers other services beyond the SPICE Kernels datasets, such as configuration and instances for WebGeocalc and Cosmographia for the ESA Missions [3].

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[2] ROS, MEX, VEX, SMART-1, Chandrayaan-1, EM16, BepiC and JUICE are publicly available for ultimately ESS is responsible for these data. For SOLO the SGS is responsible for its distribution and although ultimately they will be made public, the current study SKD is not. ExoMars 2020 is a special case for ESS collaborates and provides consultancy to the ExoMars 2020 Rover and Surface Platform Operations Centers but is not ultimately responsible for the SPICE data.

[3] https://www.cosmos.esa.int/web/spice/data

[4] ftp://spiftp.esac.esa.int/data/SPICE

[5] https://repos.cosmos.esa.int/socci/projects/SPICE_KERNELS

5.1 SPICE-Enhanced Cosmographia

SPICE-enhanced Cosmographia (COSMO) [4] is an interactive tool used to produce 3D visualizations of planet ephemerides, sizes and shapes; spacecraft trajectories and orientations; and instrument field-of-views (FoV) and footprints. COSMO is provided by NAIF and is based on the well-known 3D visualization tool Celestia. It can also be used to display simple geometrical quantities such as angles of separation in between given directions and distances. These characteristics make Cosmographia an ideal complementary tool for planning an instrument pointing profile, observation geometry visualization and evaluation of a planned trajectory (it is also very useful for PR purposes).

COSMO needs the generation of a set of input files – JSON configuration files- which are generated by ESS and are publicly available for most of the ESA Planetary missions[6].

5.2 WebGeocalc

The main drawback of using SPICE is that it usually requires a user which has moderate programming skills along with a reasonable experience with the data and geometry of the mission that she/he is going to work on. An excellent workaround for this drawback is WebGeocalc (WGC) [4]. WGC provides a web-based graphical user interface to many of the observation geometry computations available from SPICE. A WGC user can perform SPICE computations without the need to write a program; the user needs to have only a computer with a standard web browser. WGC can support ESA's planetary projects and planetary data research in several ways:

- It opens up much of the SPICE computational capability to those unable to write programs.
- It offers a mechanism that scientists and engineers may use to help verify their own SPICE-based code.
- It provides a quick and easy means for peer reviewers of science data archives to spot check many of the observation geometry computations included in the archive.
- It opens the possibility to obtain a quick answer to a geometry question arising during a meeting.

WGC makes the job of computing many kinds of observation geometry quicker and somewhat easier than if one has to write a program to do so. With this characteristics WGC is ideal both for missions in operations in order to quickly assess the feasibility of observations in terms of derived quantities and –specially- for missions in development. A WGC instance for ESA Planetary missions is available[7]. This instance includes operational, archived, study, test and SPICE lessons scenarios and complements the NASA instance which is available in the NAIF server.

5.3 An example use case for data analysis

Let's take it from the data analysis perspective. Say that we are working with Mars-Express data, more concretely we are performing surface studies of Phobos, the Martian moon. First of all, we can access the PSA web-based user interface [2][8] and retrieve the list of Phobos observations by the High Resolution Stereo Camera (HRSC) on board of MEX. We would like to somehow constrain our search by only looking for those who provide us a good resolution, namely; those which were acquired at a distance closer than 1.000 km. How can we constrain our search? One option would be to check the PDS3 labels of all the images and look for that geometrical information, which will definitively be an arduous task, or, we could use SPICE. Say that, on top of this we want to know the illumination of a given set of surface areas and we also want to know the intersection of the instantaneous FOV (iFOV) of a given pixel of the HRSC sensor. We will certainly not find that geometry information anywhere in the archive: SPICE is the solution.

But, in all those SPICE use cases mentioned in the paragraph before, how could we proceed? Well to begin with we could immediately use an Application Programming Interface (API) of the the Geometry Finder (GF) subsystem available with WGC that allows us to find time windows for which a given geometry condition is met (the inverse problem of calculating a given quantity of interest), see Fig.1. That would give us a list of time windows with the periods in which MEX was less than 1.000 km from Phobos and then we could use those time windows in the PSA UI to constrain the Phobos image search

[6] https://www.cosmos.esa.int/web/spice/cosmographia

[7] http://spice.esac.esa.int/webgeocalc/

[8] https://archives.esac.esa.int/psa

(see Fig.2). Say we decide to go with the image in Fig.3). What we could do next in order to better understand the observation geometry is to run the COSMO scenario with the MEX kernels, with that we could obtain the context depicted in Fig.4 and Fig.5, and as can be seen in Fig.6, we could also use the HRSC boresight and FoV and obtain a simulation of the image itself. The geometry seems alright and there is a very good match with the real data. Now, in order to obtain the illumination of a given surface location on Phobos, we could write a SPICE-based script/function in one of the languages that SPICE is available for (C, FORTRAN, Matlab, IDL or Python).

Input Values

Calculation type	Distance Event Finder
Target	PHOBOS
Observer	MARS EXPRESS
Light propagation	No correction
Time system	UTC
Time format	Calendar date and time
Time range	2010-01-01 to 2010-12-01, step 6 hours
Event condition	is less than 1000
Output time unit	seconds
Complement result window	no
Result interval adjustment	No adjustment
Result interval filtering	No filtering

Tabular Results

Click a value to save it for a subsequent calculation.

Save All Intervals

	Start Time	Stop Time	Duration (secs)
1	2010-02-28 16:18:07.102645 UTC	2010-02-28 16:29:03.406319 UTC	656.30367434
2	2010-08-24 08:22:05.025171 UTC	2010-08-24 08:32:29.283596 UTC	624.25842512
3	2010-08-27 20:28:51.926715 UTC	2010-08-27 20:34:53.806208 UTC	361.87949306

Figure 1: Result window of WebGeocalc.

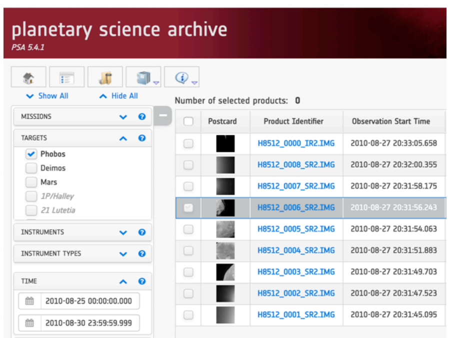

Figure 2: PSA web UI with a search for Phobos.

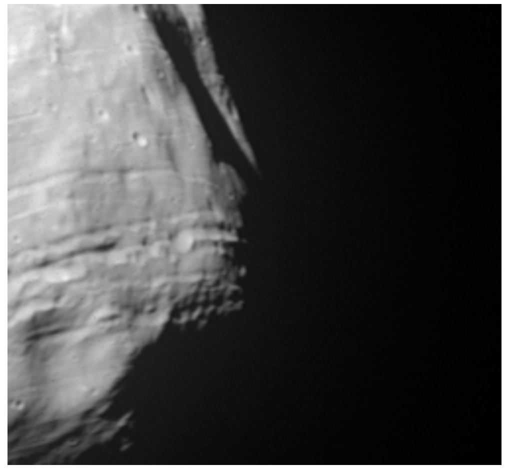

Figure 3: HRSC image of Phobos

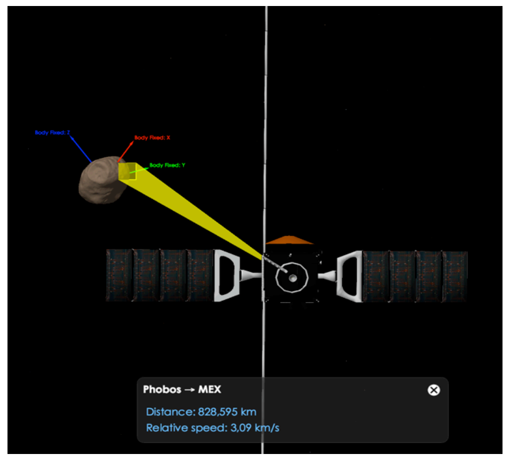

Figure 4: SPICE-enhanced Cosmographia with MEX HRSC Phobos observation.

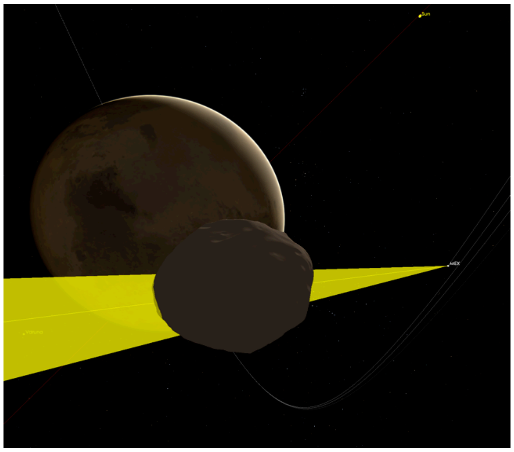

Figure 5: SPICE-enhanced Cosmographia MEX HRSC Phobos observation context.

Figure 5: SPICE-enhanced Cosmographia MEX HRSC Phobos observation FOV view.

References

[1] Acton C., Ancillary data services of NASA's Navigation and Ancillary Information Facility (1996), Planet. And Space Sci., 44, 65-70.

[2] Bessel, S. et al., ESA's Planetary Science Archive: Preserve and Present Reliable Scientific Datasets (2018) Planet. And Space Sci., 150, 131-140.

[3] Acton, C. et al., A Look Towards the Future in the Handling of Space Science Mission Geometry (2018) Planet. And Space Sci., 150, 9-12.