SOLAR SYSTEM GEOMETRY TOOLS WITH SPICE FOR ESA'S PLANETARY MISSIONS

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ABSTRACT

ESA has a number of science missions under development and in operation that are dedicated to the study of our Solar System (i.e. MEX, Rosetta, ExoMars, BepiColombo, Solar Orbiter and JUICE). The Science Operations Centres for these missions, located at the European Space Astronomy Centre (ESAC) in Spain, are responsible for all science operations planning, data processing and archiving tasks, being the essential interface between the science instruments and the spacecraft (S/C), 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.

SPICE is an information system that uses auxiliary data to provide Solar System geometry information to scientists and engineers for planetary missions in order to plan and analyze scientific observations from space-born instruments. SPICE was originally developed and maintained by the Navigation and Ancillary Information Facility (NAIF) team of the Jet Propulsion Laboratory (NASA).

This article outlines the different set of tools that are dedicated to geometry handling, visualization and analysis software using SPICE from mission concept development though the entire analysis of mission data for ESA planetary missions.

1. INTRODUCTION TO SPICE

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, often called kernels, and software -mostly subroutines. 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.

SPICE was developed and is maintained by the Navigation and Ancillary Information Facility (NAIF) team of the Jet Propulsion Laboratory, California Institute of Technology, under contract with the U.S. National Aeronautics and Space Administration (NASA). Export of SPICE data, software and expertise is not restricted under U.S. law. SPICE software is available in Fortran 77 (SPICELIB), C (CSPICE), IDL (icy) and Matlab (Mice).

This multi-mission capability has been used for more than 20 years now on many NASA missions. More recently, scientists who work with data from ESA's planetary missions: Mars Express (MEX), Venus Express (VEX), Rosetta, Smart-1 and Bepi Colombo) use SPICE to analyze their data. For what concerns ESA´s future planetary missions, SPICE is currently being developed for Exomars16, Exomars18, BepiColombo, Solar Orbiter and JUICE.

2. USING SPICE IN ESA MISSIONS

SPICE is used in ESA planetary missions in the whole mission lifecycle for ancillary data is used to support (see Figure 1):

- Mission concept development by the scientific community.
- Science Ground Segment (SGS) design.
- Science Observation planning.
- Quick look of science and data analysis.
- Science data archive preparation.
- Science data analysis.

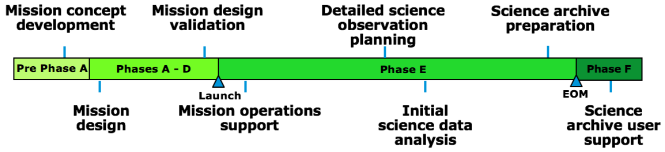


Figure 1 – Space Flight Project generic Timeline (Source: NAIF/JPL).

Most of the activities performed by SPICE for ESA planetary missions can be classified in the following:

- Evaluation of a planned trajectory (during a study phase or during nominal science phase mission operations)
- Mission engineering analyses
- Planning an instrument pointing profile
- Observation geometry visualization
- Science data archiving and analysis

Different tools and procedures for ESA missions covering these activities are described in Section 5. In order to use SPICE, a set of kernels has to be produced for each mission. The following section describes the required kernels.

3. SPICE KERNELS FOR ESA MISSIONS

ESA's planetary missions (and all SPICE supported projects in general) SPICE dataset consists of several SPICE kernels, organized as follows:

- CK kernels. This kernels contain information about orientation of the space vehicle or any articulating structure on it.
- FK kernels. Reference frame specifications. Definitions of, and specifications of, relationships between reference frames (coordinate systems). Among the frames kernels included, there are kernels that specify reference frames related to the earth and the spacecraft.
- IK kernels. Kernels that hold instrument information, such as field of view or internal timing.
- LSK kernel. This kernels hold a table with the leapseconds used to convert between ET and UTC.
- PCK kernels. These kernels provide information about Solar System bodies orientation and shape, and possibly parameters for gravitational, atmospheric or rings models.
- SCLK kernel. This kernel (spacecraft clock coefficients) allows for conversion between ET and spacecraft clock. If there are multiple LSK kernels in this dataset, the latest kernel supersedes he previous ones.
- SPK kernels. Kernels with information about ephemeris (position and velocity) of the spacecraft and solar system bodies. The dataset provides such information for the planets, the Sun, the Moon, the New Norcia tracking station, several DSN tracking stations, and the spacecraft.

This kernels, fundamental to use SPICE for a given mission are produced in a collaborative manner by different parties: NAIF, mission's SGS, and the Insturment Teams.

NAIF generates kernels that are mission independent. Some of them are used by ESA missions:

- Binary and text PCK and LSK kernels.
- Some SPK kernels with ephemeris of the solar system bodies.
- SPK kernels for ground stations.
- Frames kernels for ground stations.

NAIF also collaborates with the ESA SPICE Service and the Instrument Teams to create instrument and frames kernels for the different ESA Missions.

Orbit, clock and attitude kernels are by ESA's SPICE Service created from ESOC data. ESOC ancillary data are the main source of information required to create SPICE kernels for attitude (CK), orbit (SPK) and time (SCLK) information for the Spacecraft. Also, ESOC ephemeris data are used in the creation of SPK and CK kernels for some natural bodies –such as Phobos for MEX or 67P/Churyumov-Gerasimenko for Rosetta-.

Typically, S/C frame and instrument kernels are created by the SPICE Service in collaboration with the Mission's SGS and the instrument teams. This kernels are usually created during the mission's development phase and are then updated during mission's operations –correction of wrong data, alignment of boresights, etc.-. See Figure 2.

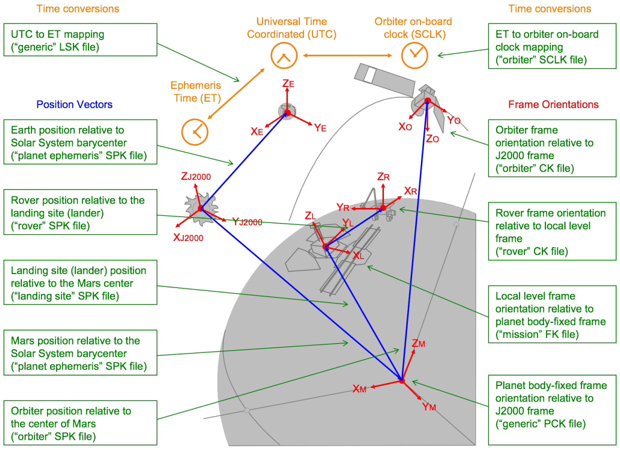


Figure 2 – Overview of geometric relationships for a mission given a set of kernels (Source: NAIF/JPL).

4. CREATION OF KERNELS FROM ESOC ANCILLARY DATA

Whilst instrument and frame kernels do not require further explanation on their generation, S/C trajectory, attitude and SC components orientation kernels do. The following sections outlines the typical ESA Planetary mission ephemeris data types and origin.

4.1. Orbit data

In terms of orbital data, the mission can be divided in two stages: pre-operations (or development) and operations. For each stage each mission has three different phases: cruise phase, nominal phase and extended phase.

For missions in pre-operations such as BepiColombo or JUICE, mission analysis provides study trajectories for the cruise phase and for an excerpt of the nominal (science) phase. Typically study trajectories are updated throughout mission concept development and the mission design phase. Because of this mission analysis might irregularly distribute to the SGS a new trajectory file. We refer to this files as Orbit Ephemeris Message (OEM), although for missions in operations this definition is not precise, it is used in this article.

For missions in operations –Rosetta, MEX-, Flight Dynamics (FD) routinely provides OEM files for the three before mentioned mission phases. In general FD provides two type of trajectory files:

1. Long Term Plan (LTP) predicted and reconstructed files (By reconstructed data what is meant is trajectory reconstructed with ground station ranging of the spacecraft).
2. Medium/Short/Very Short (MTP) predicted and reconstructed files.

Typically, LTP OEM files are large files that include long term predicted trajectory (up to five years in advance in some cases) resulting from a high level request from the missions Science Working Team (SWT) along with reconstructed data from the period that has already been flown.

MTP OEM files usually are a more detailed implementation of LTP OEMs for a given planning period (from 3 days in the case of Rosetta to one month in the case of MEX). Sometimes led by a request from the SGS. Because of that, MTP OEMs include predicted data for the mentioned periods and in general also reconstructed data for previous periods.

4.2. Attitude data

Attitude data for the S/C are provided by FD for all mission phases except for safe modes, for the past and the near future. The attitude is provided in several records, called segments, each covering a specific time span. These segments have no overlap, but there may be gaps between the segments, and even gaps in the segments. This files are called Attitude Ephemeris Message (AEM) files.

For missions in pre-operations it is rare to have predicted Attitude data although sometimes is provided for Cruise phase. For missions in operations FD will provide predicted MTP AEM files.

MTP AEM files usually are a response from an Attitude timeline provided by the mission's SGS for a given planning period (from 3 days in the case of Rosetta to one month in the case of MEX). Because of that, MTP OEMs include predicted data for the mentioned.

But what about measured attitude? Measured data is obtained form the housekeeping data of the S/C telemetry when is made available by the Mission Operations Center (MOC) to SGS. It is important to understand though that measured data might not be as accurate as predicted data: there might be intervals where due to issues with star trackers (not tracking enough starts), attitude is then determined by the S/C gyros which might not be enough accurate for certain pointing types. In order to solve this issue there is a third type of attitude kernel which can be created: the reconstructed type. Reconstructed attitude will then feature the most precise combination of measured and predicted attitude.

4.3. Time correlation data

Time Correlation is one of the most critical pieces of information needed for the use of the SPICE system within the planetary missions. This information allows the conversion between S/C Clock time and UTC time. ESOC delivers time correlation data which are the source for the SCLK kernel.

4.4. Other components' orientation data

Other S/C's moving components such as the Solar Arrays, Payload moveable platforms and steerable High Gain Antenna's are produced by using S/C housekeeping telemetry in the same fashion as the measured attitude data.

4.5. Ephemeris kernel generation

In order to generate SPK and CK kernels from OEM, AEM delivered files and Housekeeping data from the telemetry an automatic pipeline is setup at ESAC.

This automated pipeline is called ADCS (Automatic Data Conversion System) and it is responsible for the generation of CK, SPK and SCLK kernels from the before mentioned

ESOC flight dynamics data. ADCS detects when a new product was generated or a new time correlation packet is available, and run a series of processes in order to create the corresponding kernels.

ADCS then publishes the newly created kernels into a mission specific FTP directory on a dedicated SPICE server at ESAC (note that all kernels are publicly available [1]).

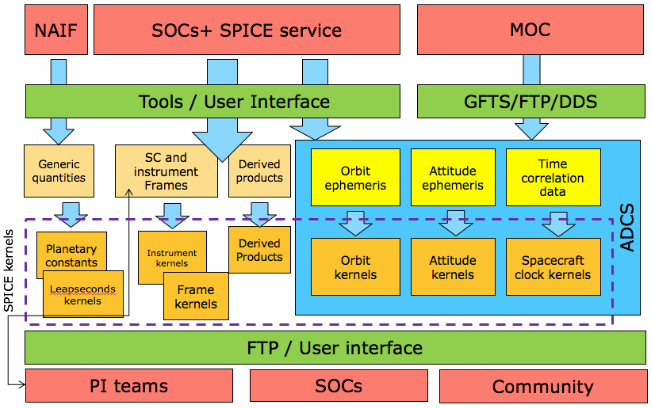


Figure 3 – Scheme of ESA Planetary missions kernel generation process.

Figure 3 depicts the overall kernel generation process for an ESA planetary mission –this excerpt is based on Exomars16-. The red boxes indicate users/clients, the orange blocks depict kernels, the yellow boxes are ESOC files whilst the light orange boxes indicate products/information that are translated to kernels. Finally, green boxes indicate interface tools and processes. The ADCS system is depicted as an inclusive blue box. Starting from the top, NAIF, SGS and the SPICE Service –along with PI teams for "SC and instrument frames" generate the set of text kernels: Planetary Constants (PCK), Leapseconds kernels (LSK), Instrument Kernels (IK) and Frame Kernels (FK). This kernels are then distributed to the PI teams, the science community and to other SGSs via FTP. The rest of the kernels: Orbit kernels (SPK), Attitude kernels for S/C, Solar Arrays, Steering platforms… (CK) and S/C clock kernels (SCLK) are produced by the ADCS pipeline.

5. SPICE TOOLS

So far it has been described that:

- SPICE provides users a large suite of SW used to read SPICE ancillary data files to compute observation geometry.
- SPICE is used to organize and package these data in a collection of files called kernels.
- SPICE includes SW for writing, reading kernels and computing observation geometry from kernels.

This said, when all the necessary kernels for a given mission are made available the possibilities for a given mission SGS –or the ESA SPICE Service- to produce tools based on SPICE are almost endless. In this section we will some which are –or will be- available for all missions as long as some mission specific examples.

5.1. 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 he is going to work on. An excellent workaround for this drawback is WebGeoCalc (WGC).

WGC [2] 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:

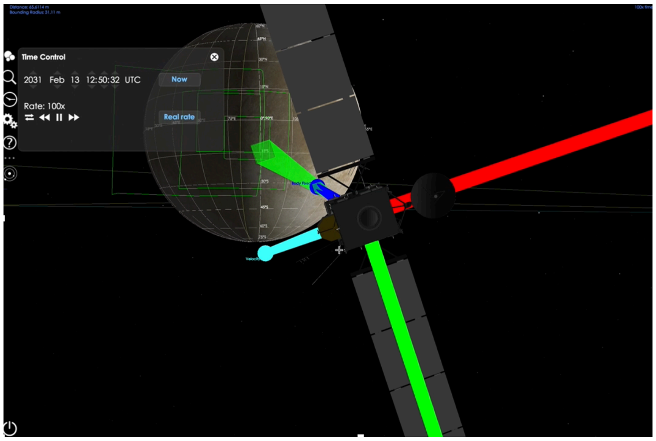
- It opens up much of the SPICE computational capability to those unable to write programs
- It offers a mechanism that scientists and engineers may use to help verify their own SPICE-based code
- It provides a quick and easy means for peer reviewers of science data archives to spot check many of the 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. JUICE, ExoMars16 and BepiColombo are the ESA missions which currently have a WebGeoCalc instance. In the near future MEX, VEX, Rosetta and Solar Orbiter will be added.

5.2. Cosmographia

Cosmographia [3] 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. 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). See Figure 4.


Distance: 65.6114 m
Bounding Radius: 31.11 m

2031 Feb 13 12:50:32 UTC

Rate: 100x

Figure 4 - Cosmographia displaying an example of an Europa fly-by of the JUICE mission.

Cosmographia needs the generation of a set of input files – JSON configuration files- which are generated by the SPICE Service. The creation of a pipeline to automatically generate Cosmographia's input files from SGS planning products and for Archive datasets is currently being considered. Additionally, Cosmographia will be made available for all ESA Planetary missions in the near future.

5.3. SOLab

The Solar System Science Laboratory (SOLab) provides a variety of science quantity plots, geometrical events and visual displays that help to assess the feasibility of science observations and science campaigns [4].

SOLab was extensively used in VEX for designing the Venus Monitoring Camera (VMC) observations and to assist the Attitude timeline generation of MEX. It was also used in early stages of the JUICE study phase to determine the characterisation of the Europa Fly-bys by the SGS. Figure 5 depicts a comparison in between a simulated VEX pointing as seen from the VMC FoV and the actual acquired image.

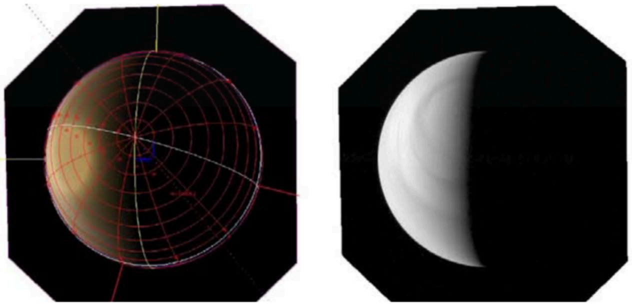


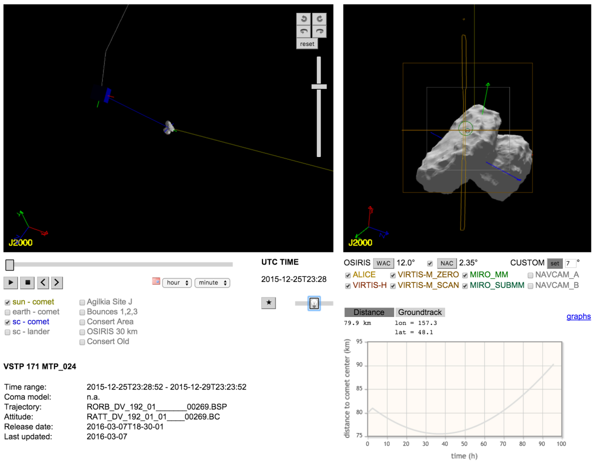
Figure 5 – Left: SOLab simulation of a VMC observation. Right: Actual image acquired by VMC.

5.3. Tools used by Rosetta's SGS

The Rosetta SGS has intensively used SPICE based tools in their system. More concretely it has been mostly used in the Long Term Plan (LTP) planning cycle [5].

LTP mainly features interaction in between the liaison scientists and the instrument teams in order to produce a skeleton plan for the Medium Term Planning (MTP) periods which have a duration of 28 days.

In order to assist the LTP processes several tools have been developed. The earliest one which was used long before Rosetta entered its nominal face was the so called "3dtool", this was a web-based tool used to analyze the feasibility of the early skeleton trajectories that SGS was designing during the Rosetta Escort phase [6] and to obtain a general overview and geometric characteristics of the pre-landing phase trajectories. This tool was also able to produce a given set of basic plots (altitude, longitude and latitude of Sub S/C point, nadir coverage, etc.). See Figure 6


UTC TIME
2015-12-25T23:28

☑ sun - comet
☐ earth - comet
☑ sc - comet
☐ sc - lander

☐ Agilkia Site J
☐ Bounces 1,2,3
☐ Consert Area
☐ OSIRIS 30 km
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VSTP 171 MTP_024

Time range: 2015-12-25T23:28:52 - 2015-12-29T23:23:52
Coma model: n.a.
Trajectory: RORB_DV_192_01_______00269.BSP
Attitude: RATT_DV_192_01_01____00269.BC
Release date: 2016-03-07T18-30-01
Last updated: 2016-03-07

OSIRIS WAC 12.0° ☑ NAC 2.35° CUSTOM set 7 °
☑ ALICE ☑ VIRTIS-M_ZERO ☑ MIRO_MM ☐ NAVCAM_A
☑ VIRTIS-H ☑ VIRTIS-M_SCAN ☑ MIRO_SUBMM ☐ NAVCAM_B

79.9 km
lon = 157.3
lat = 48.1

Figure 6 – Snapshot of the 3dtool for Rosetta. On the left we see the general context of the S/C and the comet. On the right we see the FoV of several instruments.

Another tool used by during the LTP process which was distributed to the instrument teams is the “flying potato”. This JAVA based tool helped the instrument teams operations engineers to generate pointing snippets for observations that were used to build up the Pointing Timeline requests for FD which would then result in Rosetta’s attitude timeline. The tool gave the users the possibility of choosing amongst the different allowed pointing types along with their parameters and would show the results interactively. In addition, it would query a FD webtool which would determine the feasibility of the pointings in term of attitude and illumination constraints.

Another SPICE based tool which was used by Rosetta’s SGS was ASPEN. ASPEN is an automated and semi-automated scheduling software [7] that was implemented in Rosetta as RSSC in collaboration with JPL. RSSC was implemented using an adaptation of the ASPEN scheduling framework. The purpose of ASPEN in Rosetta was to bridge the LTP and the MTP planning processes by automatically generating an MTP baseline attitude and commanding timeline provided a series of high-level inputs in which S/C attitude and illumination constraints along with S/C resources such as downlink, SSMM filling and power were taken into account. The output of ASPEN would then be a complete Attitude and commanding timeline ready to be processed by operations engineer’s in the MTP planning process.

Finally, another tool that is being used by the Rosetta SGS’s during the LTP and MTP planning processes is the Cost function tool. This tool quantifies the total amount of nadir available for a consolidated Attitude timeline proving the necessary information to the In-Situ instrument teams whether if the given Attitude timeline matches their science objectives.

6. CONCLUSION

This article outlines the importance of SPICE as the basis of a series of tools used to assist the science planning during all the mission stages for ESA Planetary missions. In order to do so, SPICE is introduced along with its usage, the necessary products to use SPICE based applications are explained in detail along with their generation and finally a series of tools based on SPICE are described.

The aim of the authors is to make the reader aware of the need for SPICE for ESA Planetary missions and to make her/him aware of the processes to generate the required inputs along with the fundamental added value that SPICE based tools provide to the overall quality of the data acquired by the missions.

7. REFERENCES

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