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DOCUMENT

SOC-Provided Ancillary Data for Solar Orbiter

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1 INTRODUCTION

Ancillary data products are those products that are not strictly science data, but are still helpful in scientific analysis or the preparation of higher-level science data products, for example an orbit file containing the position and velocity of the spacecraft. For Solar Orbiter, the Science Operations Centre (SOC), based at ESAC near Madrid has the responsibility of producing those ancillary data products that are not relevant to only a single instrument, and that are not based on instrument telemetry, but rather platform telemetry (e.g. AOCS parameters in housekeeping) or other data available on ground. This is not only to reduce duplication of effort, but also to ensure consistency in the ephemerides etc. that are used in producing the higher-level science data products on the ground, and therefore make multi-instrument data analysis as simple as possible.

The purpose of this document is to describe the content and format of the various ancillary data products that will be produced by the Solar Orbiter SOC, and explain how they will be distributed to the rest of the Science Ground Segment (SGS) and the broader scientific community.

1.1 Applicable Documents

AD1	SOL-SGS-TN-0009	Metadata Definition For Solar Orbiter Science Data	Iss 2. Rev 2.

1.2 Reference Documents

RD1	SPICE Toolkit user guide (https://naif.jpl.nasa.gov/naif/documentation.html)		N65
RD2	SOL-SGS-ICD-0004	Solar Orbiter Interface Control Document for Low Latency Data CDF Files	Iss 1. Rev 2.
RD3	SOL-SGS-ICD-0002	Solar Orbiter Data Producer to Archive ICD	Iss 0. Rev 2.
RD4	SOL.S.ASTR.TN.00079	Solar Orbiter TM-TC and Packet Structure ICD	Iss 7.
RD5	CDF Documentation (http://cdf.gsfc.nasa.gov/html/cdf_docs.html)		3.6.3
RD6	SOL-SGS-ICD-0009	File Transfer SOC – Instrument Teams ICD	Iss 0. Rev 3.
RD7	SOL-SGS-ICD-0005	Solar Orbiter Interface Control Document for Low Latency Data FITS Files	Iss 1. Rev 2.
RD8	SOL-SGS-TN-0015	The Effect of Solar Orbiter Spacecraft Attitude on EPD and SWA Science Return	Iss 1. Rev 0.

1.3 List of Acronyms and Abbreviations

AOCS	Attitude and Orbit Control System
CDF	Common Data Format
DDS	Data Distribution System
ESA	European Space Agency
ESAC	European Space Astronomy Centre
ESOC	European Space Operations Centre
FECS	Flight Events and Communications Skeleton
GAM	Gravity Assist Manoeuvre
GFTS	Generic File Transfer Service
LL	Low Latency (Data)
LL02	Low Latency Level 2
MOC	Mission Operations Centre
NAIF	Navigation and Ancillary Information Facility
NASA	National Aeronautics and Space Administration
OBT	On Board Time (used interchangeably with SCET)
OEM	Orbit Ephemeris Message
PTR	Pointing Request
SCET	Spacecraft Elapsed Time (used interchangeably with OBT)
SFTP	Secure File Transfer Protocol
SGS	Science Ground Segment (SOC + Instrument Teams)
SOAR	Solar Orbiter Archive
SOC	Science Operations Centre
UTC	Coordinated Universal Time

2 SUMMARY OF ANCILLARY DATA PRODUCTS

SOC will primarily produce ancillary data products for and using the SPICE toolkit, provided by NAIF. The SPICE toolkit and associated data files ('kernels') have been successfully used on many ESA and NASA solar system science missions in the past. Detailed documentation [RD1] for the SPICE software can be found on the NAIF Website[1] and is also accessible via the ESAC SPICE Service[2]. SOC will produce SPICE kernels that will provide the following:

- The position and orbital velocity of the Solar Orbiter spacecraft.
- Spacecraft attitude.
- The conversion between SCET and UTC.
- A frames kernel that will allow for the transformation of data between spacecraft coordinates, instrument coordinates and various heliophysical coordinate systems.
- Operational misalignments for the remote sensing instruments.
- Instrument kernels that define fields of view.

SOC will distribute the operational misalignments for the remote sensing primarily as a record of the misalignments used in the production of LL02 data [RD7] and generation of PTRs. In situ instrument alignments are expected to be stable enough relative to the angular resolution of the data such that fixed rotation matrices, included in the LL data files themselves [RD2] will be used and a separate product will not be necessary.

SOC will not produce products that will allow for the transformation of data between instrument coordinates and spacecraft coordinates to a level of accuracy suitable for scientific analysis for the simple reason that we will not have the expertise to produce them. Furthermore, unlike for some other solar system missions, instrument teams are expected to provide Level 2 science data products to the SOAR that are already in either spacecraft or heliophysical coordinate systems, as appropriate, and that have the necessary metadata such that they are suitable for scientific analysis without reference to SPICE kernels [RD3, AD1]. Our SPICE-based ancillary products are primarily designed to aid in the production of L2 and higher-level science data by the instrument teams.

In addition to the ancillary data products in SPICE format, SOC will produce a more limited set of ancillary data in CDF format. These products will provide a summary or digest of the spacecraft orbit and roll angle, and are intended for use as a quick reference by the SGS during planning, and also for basic situational awareness as a complement to the low latency data.

[1] https://naif.jpl.nasa.gov

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

3 SPICE-BASED ANCILLARY DATA PRODUCTS

The primary format in which SOC will distribute ancillary data is the SPICE format. SPICE is a comprehensive toolkit and set of data files specifically designed for common tasks involving ancillary data for solar system missions [RD1]. The following describes the SPICE-based ancillary products produced by SOC. We do not attempt here to discuss the full capabilities of SPICE and the comprehensive uses of each type of SPICE data file (kernel), which are well documented elsewhere, but rather focus on the specific SPICE kernels that we will produce. It is recommended that for any operational software that requires SOC ancillary data, the SPICE kernels rather than the CDF products are used.

Note that SOC will not distribute other SPICE kernels that are necessary for the use of our ancillary products, for example leap second kernels and planetary ephemerides. These are readily available from NAIF and the ESA SPICE Service. It is up to instrument teams to determine which additional kernels are necessary for their applications and keep these up to date. SOC will maintain a recommended list for consistency in data processing (details TBC).

3.1 Time Conversion Products

While a UTC packet time is available in the SCOS2000 headers of packets retrieved from the DDS, this information is not available for any acquisition times (for example) held within the data field of the packet. In the case of some instrument teams these acquisition times may be significantly different from the time at which the packet was created and as such the conversion between UTC and OBT for the data within the packet may not be the same as that in the packet header. As such SOC will provide a means of conversion between SCET and UTC for use by all instrument teams in the production of their data: the time correlation. This will ensure conversion to UTC is applied consistently across all data and will aid in multi-instrument data analysis. SOC will provide this time correlation as a SPICE kernel.

In SPICE, the conversion between onboard time (SCET/OBT) and UTC is carried out via a spacecraft clock kernel (sclk). These kernels as produced for Solar Orbiter essentially contain pairs of correlated SCET and UTC times and the time conversion is linearly interpolated between these pairs. SOC will provide two spacecraft clock kernels, a so-called 'fictional' clock kernel for use before launch and the operational clock kernel, which will be based on empirical time correlation data determined at MOC. A reference implementation in Python explaining the use of the spacecraft clock kernel can be found in APPENDIX A.

3.1.1 Fictional Spacecraft Clock Kernel

In order for many of the SPICE APIs to function properly a spacecraft clock kernel needs to be loaded and available, even if a real time correlation is not available. The fictional spacecraft clock kernel fulfils this need and simply contains a 1:1 correlation between on-board coarse time ticks and UTC seconds, with zero seconds defined as 00:00:00 UTC on 1

January 2000 [RD4]. The fictional spacecraft clock kernel will be produced once and has the filename

```
solo_ANC_soc-sclk-fict_20000101_V01.tsc (TBC)
```

3.1.2 Spacecraft Clock Kernel

The 'real' spacecraft clock kernel will be produced at SOC whenever a new time correlation is published by MOC. Each kernel will cover the entirety of the mission to date (see below). A new time correlation will be published when the instantaneous SCET-UTC conversion drifts by more than 5ms (TBC) from the currently published correlation. MOC time correlations are essentially straight-line segments (UTC = m * SCET + c) that have an earliest valid time and are considered to be valid until the next segment starts. This means that the MOC time correlation is discontinuous, which is not allowed by SPICE. As such, when producing the SPICE kernel, SOC will insert an extra segment, joining two MOC segments together. This is illustrated in Figure 3.1. Adopting this approach, made necessary by using SPICE, means that for short periods near the start of a new MOC time correlation (~60 s) SGS and MOC time correlations will be slightly different. The same

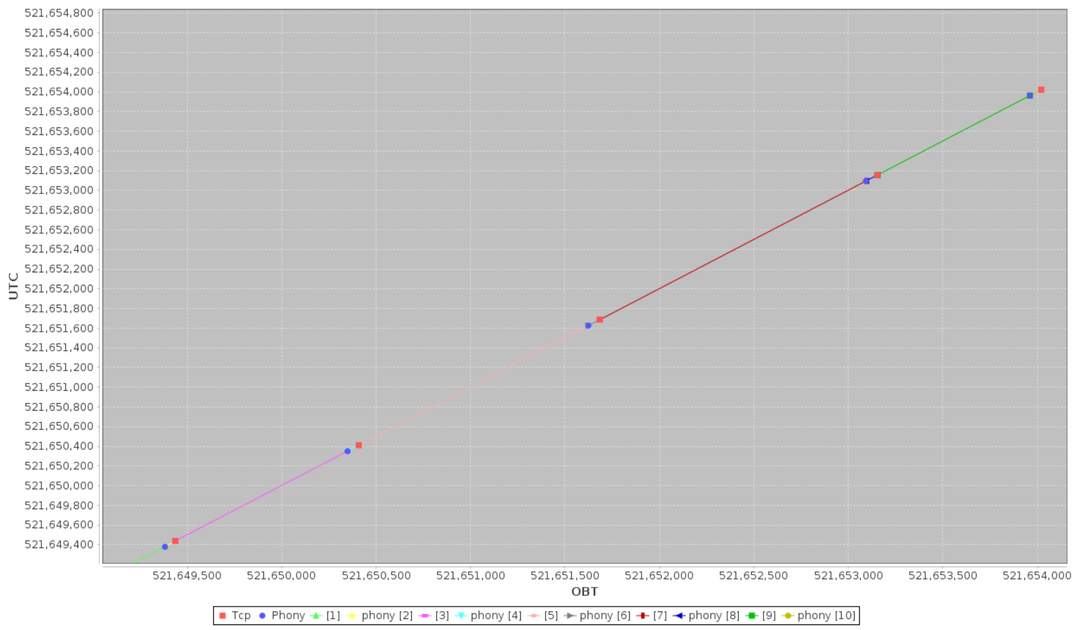

Figure 3.1 An example time correlation. Red squares indicate MOC time correlation pairs, blue circles the pairs inserted by SOC to create a continuous correlation. The 'phony' straight-line segments linking a SOC pair to a MOC pair will have a slightly different gradient to the segment linking the previous MOC pair to the SOC pair.

The spacecraft clock kernel will be named according to [AD1] as follows:

```
solo_ANC_soc-sclk_YYYYMMDD-YYYYMMDD_V01.tsc
```

Here YYYYMMDD-YYYYMMDD represents the earliest validity of the kernel (i.e. the UTC associated with 0 SCET) and the UTC of the most recent time correlation pair in the file. This is currently expected to be 2000-01-01T00:00:00 UTC.

While SCET-UTC conversions for times after the most recent time correlation pair in the file are possible, for planning purposes these ought to be avoided. The relationship between SCET and UTC can change with new information (a new leap second kernel or new time-correlation data). Thus only historical conversions are stable. There should be no planning need to predict the relationship of OBT to UTC into the future, so the fictional clock kernel can be used when SPICE requires a sclk. It is recommended that any science data be reprocessed once a stable time correlation for their acquisition time is available.

3.2 Spacecraft Orbit Products

SOC will produce a single orbit SPICE kernel (spk) from ESOC-provided OEM files for the entire mission, unless the required time resolution makes this unmanageable. This will be updated whenever ESOC produces a new OEM file. Since Solar Orbiter's trajectory is essentially ballistic it is expected that this will be after launch and subsequently after each GAM. The spacecraft state vector (position and velocity) can be obtained from the spk at an arbitrary time resolution in any coordinate system known to SPICE.

The spk will be named as follows:

```
solo_ANC_soc-orbit_YYYYMMDD-YYYYMMDD_V01.bsp
```

Here YYYYMMDD-YYYYMMDD refers to the start and end validity of the file.

3.3 Spacecraft Attitude Products

SOC will provide three different spacecraft attitude products, two as-planned attitude kernels and one as-flown kernel. An attitude SPICE kernel is known as a 'ck'.

3.3.1 As-Planned Attitude Kernels

The two predicted attitude kernels produced by SOC assume that the spacecraft will be pointed at the centre of the solar disk.

The first as-planned attitude kernel will cover the entire length of the mission and will also assume that the spacecraft will have its default roll-angle. This kernel will have 1-hour resolution and will be updated with the same frequency as the orbit kernel. It will be named as follows:

```
solo_ANC_soc-default-att_YYYYMMDD-YYYYMMDD_V01.bc
```

Here YYYYMMDD-YYYYMMDD represents the start and end validity of the file and will be the same as for the orbit kernel.

The second as-planned attitude kernel will assume disk-centre pointing but will also include spacecraft rolls for communications or calibration purposes. There will be one file for each six month planning period, based on the FECS issued by MOC. They will be distributed approximately 6 months in advance of the start of that planning period. They will also be updated whenever the orbit kernel is updated. These kernels will have 5-minute time resolution and will be named as follows

```
solo_ANC_soc-pred-roll_YYYYMMDD-YYYYMMDD_V01.bc
```

Here YYYYMMDD-YYYYMMDD indicates the valid date range of the file.

3.3.2 As-Flown Attitude Kernel

Contrary to some other missions, for Solar Orbiter predicted spacecraft attitude is not made available by flight dynamics at ESOC. This is because spacecraft pointing is decided comparatively late. As such the complete, detailed attitude (not just roll angle) information made available by SOC will be based on quaternions returned in housekeeping data from the AOCS. SOC will produce the as-flown attitude kernel from these quaternions and will have their native time resolution, 60 s (Details TBC). The as-flown attitude kernel will be produced daily and will have the following file name:

```
solo_ANC_soc-flown-att_YYYYMMDD_V01.bc
```

Here YYYYMMDD represents the date for which the file is valid.

3.4 Coordinate System and Reference Frame Products

SOC will produce two SPICE kernels with coordinate system and reference frame information. The first will contain spacecraft and instrument coordinate systems (details TBW). The second will contain those scientific coordinate systems on the following list that are not internal to SPICE (NAIF are in the process of defining a 'standard' scientific frames kernel):

HCI
HEE
HAE
GAE
GSE
HEEQ This is the same as Stonyhurst
IAU_Sun
Carrington
RTN
Spacecraft Centric Mirror Helioprojective

Details TBW

SOC will also produce simple instrument kernels containing field of view information only. It is expected that these remain will fixed throughout the mission based on information provided by Instrument Teams Details TBW

4 CDF ANCILLARY DATA PRODUCTS

The following describes the ancillary data products that SOC will provide in CDF format. Following the Solar Orbiter Metadata standard [AD1], CDF products will be of CDF version > 3.6 [RD5].

4.1 Spacecraft Orbit Digest

SOC will produce a single 'orbit digest' file for the entire mission from the Solar Orbiter SPK, which in turn will be based on the OEM orbit file produced by the Solar Orbiter MOC at ESOC. Since, between GAMs, Solar Orbiter's orbit is essentially ballistic, it is anticipated that this file will not need to be updated with high cadence, and as such a new version will be nominally be issued after launch and after each GAM.

The orbit digest will follow the Solar Orbiter metadata standard and its filename will have the format:

```
solo_ANC_soc-orbit_YYYYMMDD-YYYYMMDD_V01.cdf
```

Where YYYYMMDD-YYYYMMDD represents the start date and end date of the coverage of the file.

The orbit digest will contain the following parameters at 1-hour resolution:

- HCI Position, XYZ, km.
- HCI Velocity, XYZ, km/s.
- HEE Position XYZ, km.
- Spacecraft Heliocentric distance.
- Spacecraft Heliographic latitude.
- Spacecraft HCI longitude.
- Spacecraft Carrington Heliographic longitude.
- Angle between Sun-spacecraft line and its projection on the ecliptic plane.
- Angle between projection of Sun-spacecraft line on the ecliptic plane and the Sun-Earth line.

The ecliptic of J2000 will be used in defining the orbit digest file. See APPENDIX B for the definition of the HCI, HEE and Carrington Heliographic coordinate systems.

4.1.1 Orbit Digest CDF Variables and Attributes

TBW

4.2 Spacecraft Attitude Products

SOC will produce two attitude products in CDF format. These are intended to provide simple information about the predicted and as-flown spacecraft roll angle. Here rolls are around spacecraft X and roll angle is defined as the angle between the spacecraft Z-axis and the zero roll reference. The zero roll reference is currently spacecraft Z parallel to the normal of the spacecraft orbital plane. If the spacecraft baseline attitude is not changed such that the spacecraft XY plane is held parallel to the ecliptic or solar equatorial plane [RD8] we will add the projection of solar north on the spacecraft YZ plane to the roll digest files (TBC). Rolls are defined as positive around spacecraft +X. Spacecraft coordinates are defined in APPENDIX B. Spacecraft offpoints will not be included in the CDF attitude products since these will nominally be less than 1 degree, and LL02 data and L2 science data should have taken already these into account. For applications that require detailed pointing information, the SPICE kernels should be used. If possible, a quality flag showing periods of non-nominal pointing (i.e. contingency cases) will be included in the as-flown roll angle file (TBC).

4.2.1 Predicted Roll Angle File

The predicted roll angle file will be issued per medium term planning period (~6 months: Jan-Jun, Jul-Dec), approximately 6 months in advance of the beginning of that planning period. It will contain the expected spacecraft roll angle that results from the long-term planning process. It will be produced based on the predicted roll angle CK, which is itself produced from the FECS issued by the Solar Orbiter MOC at ESOC. It will have 5-minute resolution.

The predicted roll angle file will follow the Solar Orbiter metadata standard and will be named as follows:

```
solo_ANC_soc-pred-roll_YYYYMMDD-YYYYMMDD_V01.cdf
```

Where YYYYMMDD-YYYYMMDD represents the start date and end date of the coverage of the file. This is equivalent to the predicted roll SPICE kernel.

4.2.1.1 Predicted Roll Angle CDF Variables and Attributes

TBW

4.2.2 As-Flown Roll Angle File

One as-flown roll angle file will be issued per calendar day, and will be produced a few hours after the end of each communications pass. It will contain the actual spacecraft roll angle that was flown. It will be produced based on the flown-attitude CK, which is itself produced from spacecraft housekeeping. It will have the native resolution of the housekeeping data from which it is derived, 60-seconds (TBC).

The as-flown roll angle file will follow the Solar Orbiter metadata standard and will be named as follows:

```
solo_ANC_soc-flown-roll_YYYYMMDD_V01.cdf
```

Where YYYYMMDD represents the date of the coverage of the file.

4.2.2.1 As-Flown Roll Angle CDF Variables and Attributes

TBW

5 DISTRIBUTION OF ANCILLARY DATA PRODUCTS

The primary distribution channel of SOC ancillary products to the instrument teams will be via GFTS [RD6], whereby as files are produced they will be pushed from SOC to the GFTS nodes located at instrument team premises. The files will be distributed via GFTS first and the most recent files will always be available via this mechanism. As such, any operational workflows that require SOC ancillary data should be designed with this in mind.

The CDF orbit digest and as-flown roll angle files will also be available via the public and private instances of the SOC low latency display tool/website, as will visualisations of a subset of their parameters (details TBD).

Solar Orbiter SPICE kernels will also be made available to the broader scientific community via the ESA SPICE Service SFTP server, although not necessarily immediately after their production, and will be usable via the ESAC WebGeoCalc instance (TBC).

All SOC ancillary data products will also be archived and publicly available in the SOAR.

APPENDIX A

The code sample provided here is a reference implementation for the use of the spacecraft clock kernel written in Python - specifically, Python 2.7. The most recent version of this reference implementation can be found at https://issues.cosmos.esa.int/solarorbiterwiki/x/bwXz. NAIF does not provide an official Python API for the toolkit, so here we make use of the *spiceypy* library. This library can be found at https://pypi.python.org/pypi/spiceypy.

We recommend the use of Anaconda data science platform (https://www.continuum.io/downloads), which will allow you to easily create a Python 2.7 environment with the needed libraries (*spiceypy* in this case).

To perform the time translation two SPICE kernels are needed:

- Leap seconds kernel: currently *naif0012.tls*, which can be found here.

  The file is provided by NAIF via the ESA SPICE service: ftp://spiftp.esac.esa.int/data/SPICE/SOLAR-ORBITER/kernels/lsk and will be occasionally updated when new leap seconds are known.

- Spacecraft clock kernel: solo_ANC_soc-sclk_20000101_20160712_V01.tsc

  This is file is provided by the Solar Orbiter SOC and it will be frequently updated. The version linked above is the one used currently for SOC testing

For both the above kernels, it is instrument team responsibility to ensure provision of the up-to-date kernels to the software.

Python Code

```python
import spiceypy

# Provided by Solar Orbiter SOC
# Version: 1.0
# Date: 09-Aug-2016
class SpiceManager:

    # SOLAR ORBITER naif identifier
    solar_orbiter_naif_id = -144

    def __init__(self, tls_filename, sclk_filename):
       spiceypy.furnsh(tls_filename)
       spiceypy.furnsh(sclk_filename)

    def obt2utc(self, obt_string):
        # Obt to Ephemeris time (seconds past J2000)
        ephemeris_time = spiceypy.scs2e(self.solar_orbiter_naif_id, obt_string)
        # Ephemeris time to Utc
        # Format of output epoch: ISOC (ISO Calendar format, UTC)
        # Digits of precision in fractional seconds: 3
        return spiceypy.et2utc(ephemeris_time, "ISOC", 3)

    def utc2obt(self, utc_string):
        # Utc to Ephemeris time (seconds past J2000)
        ephemeris_time = spiceypy.utc2et(utc_string)
        # Ephemeris time to Obt
        return spiceypy.sce2s(self.solar_orbiter_naif_id,ephemeris_time)
```

Examples Using the Above Code

```python
# Load spice kernels files
tls_filename = "<<your_path>>\naif0012.tls"
sclk_filename = "<<your_path>>\solo_ANC_soc-sclk_20000101_20160712_V01.tsc"

# Initialise class
spicemanager = SpiceManager(tls_filename, sclk_filename)

# Execute conversions

obt = "0"
utc = "2000-01-01T00:00:00.000"
print "OBT {0} -> UTC {1}".format(obt, spicemanager.obt2utc(obt))
# Returns OBT 0 -> UTC 2000-01-01T00:00:00.000
print "UTC {0} -> OBT {1}".format(utc, spicemanager.utc2obt(utc))
# Returns UTC 2000-01-01T00:00:00.000 -> OBT 1/0000000000:00000

obt = "521651623:37539"
utc = "2016-194T15:13:46.381"
print "OBT {0} -> UTC {1}".format(obt, spicemanager.obt2utc(obt))
# Returns: OBT 521651623:37539 -> UTC 2016-07-12T15:13:46.381
print "UTC {0} -> OBT {1}".format(utc, spicemanager.utc2obt(utc))
# Returns: UTC 2016-194T15:13:46.381 -> OBT 1/0521651623:37539
```

APPENDIX B

Coordinate system definitions. TBW