

Solar Orbiter: SPICE

Data Product Description Document

[SPICEFITS]

Issue 1.4

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CHANGE LOG

Date	Issue	Revision	Pages	Reason for change
28.06.2018	0	1	All	Document created based on SOL-SGS-OTH-0004-DPDDtemplate and [SPICELLFITS]
01.11.2018	0	9	All	Document rewritten and extended.
07.11.2018	0	91	All	Added comments based on IAS/UiO telecon.
07.11.2018	0	92		Fixed date, added READMODE in Section 4.7.1, removed an accidentally pasted random number
04.03.2019	0	93	All	<ul style="list-style-type: none"> – Updated sections that are copied from LLDAPD (from v1.7). Noticeable changes include a new paragraph on “Scanned Time Series” in Section 4.1, a new header example in Section 4.7.1 with some new LL01+ keywords, clarifications on the relationship between OBS_TYPE and the SPICE on-board Observation ID in Section 4.7.1.1.1, a new section 4.7.1.2.6 on keywords describing on-board processing steps, and a new table in Appendix B on the keywords that are derived from the value of STUDYFLG. See change log in LLDAPD for further details. – 3.3.3, 3.3.4.3, 4.6: the L2 data cubes will be corrected for geometric distortions, only S/C roll will be described by the PC_{i_j} matrix. – 3.3: some restructuring of the text, changed temporary placeholder names

				<p>of calibration routines to better match input from MPS.</p> <ul style="list-style-type: none"> – 4.7.1: added L1+ keywords UCD, OBS_ID, TIMEDER, TIMESYER, DATE-AVG, SOOPNAME, TELAPSE, LONPOLE, SPECSYS, VELOSYS, INFO_URL, and Solar ephemeris data keywords. Renamed SOOP_ID to SOOPTYE. – 4.7.1.1.1: added explanation of Solar Orbiter-wide keyword OBS_ID – 4.7.2: brief mention of L2+ keywords PRxxxxn, CRDERi, CSYERi, solar ephemeris data keywords. – 4.7.2.1: New section on keywords describing the calibration processing steps (L1 to L2) – 4.7.4: New section on keywords describing the processing steps when creating derived data products (L2 to L3) – Appendix C rewritten – Multiple minor changes, reformulations and fixing of typos
21.03.2019	0	94	All	<ul style="list-style-type: none"> – 4.7.1 and 4.7.3.1: corrected value of BUNIT – 3.2, 3.3.4.1, 3.3.4.3, 4.1, 4.2, 4.7.1.5, 4.7.3.2, and 4.7.4: Modified descriptions of intensity-windows to make it clear that such windows are not necessarily observed in line/background pairs. – 4.7.2.1: Added keyword PRPVERn giving the version of the processing function given by PRPROCn
03.05.2019	1	00	All	<ul style="list-style-type: none"> – Multiple clarifications, restructuring and moving of text, fixings of typos and minor modifications. – Updated sections that are copied from LLDAPDD (v1.8). Noticeable changes include new section 4.7.1.1.7 on FILE_RAW, and rewording on intensity-windows in 4.7.1.5 – Keywords TIMEXOBT and TIMEXUTC renamed TIMAQOBT and TIMAQUTC.
02.12.2019	1	1	All. 3.3.1, 4.3.1, 4.4.1.2, 4.4.1.3.1, 4.4.2, 4.4.3.1, 4.4.4.2	<ul style="list-style-type: none"> – Updated sections that are copied from LLDAPDD (v.1.10). Noticeable changes include new header example with new COMPRESS and COMP_RAT replacing COMPDESC. COMPPARA set to 0 for SHC and uncompressed data. New keyword SPIOBSID giving the SPICE Observation ID, no longer equal to OBS_MODE.

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				<p>Simplified sections by removing all examples of header differences between the example header and headers of HDUs with other window types and study types. Added new Section 4.4.4.2.</p> <ul style="list-style-type: none"> – All: Removed references in figures, tables and text to the non-existing study/window type combination sit-and-stare intensity-windows. – Removed old Section 4.4.1.4.2 on description of processing steps in L1 files – 3.3.1: Added additional processing steps and new sub-section 3.3.3.1 describing the handling of telemetry loss. – 4.3.1: Added description of representation of space craft roll and geometrical distortions. – 4.4.1.2: Brand new L1 FITS header example. – 4.4.1.3.1: Rewritten. – 4.4.2: Added description of L1 to L2 change of window size. – 4.4.3.1: Use SI units <p>All: Multiple minor corrections, additions, and deletions.</p>
17.12.2019	1	2	1.3, 4, 4.4.1.2, 4.4.1.3.4, 4.4.1.4, 4.4.2	<ul style="list-style-type: none"> – 1.3: Added [SPICELOST] to Reference Documents. – Updated sections that are copied from LLDPDD (v.1.11). Noticeable changes include added description of HDU layout for two-exposure mode (4.1), clarification of text and fixing of typo regarding the representation of lost telemetry in binary table extensions, and new Section 4.4.1.4 explaining the value of the <code>BLANK</code> keyword and the data type of the HDU's data arrays – 4.4.1.2: New header example – 4.4.2: New default behaviour of the calibration routines is to crop the windows to preserve the number of pixels instead of padding the windows to preserve the data

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01.09.2020	1	3	<p>1.3, 4.3, 4.4.1.2, 4.4.2, 4.4.1.3.3, 4.4.1.4.1, 4.4.4.3, 4.4.5, Appendix B, Appendix C</p>	<p>– Multiple sections: Updated paragraphs that are copied from LLDPDD (v1.13), see changelog therein. Important changes are found in paragraphs describing the scan direction of the slit: 4.3, 4.4.1.3.3, and Appendix B.</p> <p>– 1.3: Added [DISPERSION] to Reference Documents</p> <p>– 4.4.2: reverted to the previous way of treating windows, i.e. with padding to preserve the data. Added information on changes in plate scale when going from L1 to L2</p> <p>– 4.4.1.2, 4.4.1.4.1, 4.4.4.3, 4.4.5: Renamed some of the FITS keywords used for lost telemetry book keeping to make the syntax more similar to the syntax of the SOLARNET keyword NLOSTPIX:</p> <pre>NCHKLOST -> NLOSTCHK NCHKFAIL -> NFAILCHK NPLNAPRX -> NAPRXPLN NPLNLOST -> NLOSTPLN PKTLOST -> LOSTPKTS BINLOST -> LOSTBINS</pre> <p>– 4.4.1.2: New FITS keyword XSTART. Removed TIMSYER and TIMRDER for the time being, may be reintroduced in the future</p> <p>– Appendix C: New paragraphs on IORs and Study Sets, fixed errors in Study Set table.</p> <p>– Multiple sections: future simple -> simple present...</p>
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	1	4	<p>3.2, 3.3.3, 4, 4.1, 4.4.1.2, 4.4.1.3.7, 4.4.1.3.9, 4.4.1.4, 4.4.1.5, 4.4.1.6, 4.4.1.7, 4.4.2, 4.4.2.1, 4.4.3.1, 4.4.3.3, Appendix A, Appendix B, Appendix C</p>	<ul style="list-style-type: none"> – 3.2: Rewritten text, updated all figures, added new figures 3-6 and 3-7. Updated all tables and added new table 3-4. – 3.3.3: Corrected names of calibration subroutines, added intensity units – 4: Updated Table 4.2. Added info on sit-and-stare studies and repeated full detector studies, highlighted these changes in the text – 4.1: SPIOBSID-RASTERNO is a part of the filename. – 4.4.1.2: Updated L1 header example with new keywords extracted from IORs and Study Sets, data statistics keywords, and updated keywords on data processing. – 4.4.1.3.7: New section on FITS keywords describing data processing – 4.4.1.3.9: New section on FITS keywords describing linear fit to scan mirror position. – 4.4.1.4-7: Updated tables – 4.4.2: Added description of adjacent and near-adjacent windows. New value for UCD. – 4.4.2.1: Updated PRxxxxn keywords – Appendix A: Removed some descriptors that should not be there, e.g. [int] for sit-and-stare studies. – Appendix B: RASTNUM renamed to RASTERNO. – 4.4.3.1: New formatting of BUNIT values following recommendations given in the FITS standard – 4.4.3.3: Updated PRxxxxn keywords – Appendix C: Added new keywords extracted from the IORs: STP and WINSHIFT, and from the Study Sets: MISOSTUD, XSTART, and MISOWIN.
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1. INTRODUCTION

1.1 Purpose and Scope

This Data Product Definition Document describes the format and content of the SPICE Science data. It includes descriptions of the data products and associated metadata, including the data format, content, and generation pipeline. These products will be stored and distributed from the Solar Orbiter Science Archive (SOAR) of the SOC.

The specifications described in this document apply to all SPICE Science products submitted to ESA's Solar Orbiter SOC for further archival and exploitation. The specifications described in this document apply to all SPICE data products generated by the Science Data Pipeline running at the SPICE premises in Oslo. It does not address the Low Latency data (see [LLData]) delivered by the Low Latency Pipeline run at SOC, as these data products are described in [SPICELLFITS].

Sections in this document that are identical to sections in [SPICELLFITS] are coloured green.

1.2 Applicable Documents

APPL. DOC. SHORT	APPLICABLE DOCUMENT TITLE	DOCUMENT ID	ISSUE
[DPICD]	<i>Data Producer to archive ICD</i>	SOL-SGS-ICD-0002 ?	<i>Will be rewritten from scratch</i>

Table 1-1: Applicable Documents

1.3 Reference Documents

REF. DOC. SHORT	REFERENCE DOCUMENT TITLE	DOCUMENT ID	ISSUE
	Template for SoLO Data Product Description Document	SOL-SGS-OTH-0004-DPDDtemplate	
[ACRONYMS]	SPICE Acronym List	SPICE-RAL-LI-0001	1.0
[LLFITSICD]	Solar Orbiter Interface Control Document for Low Latency Data FITS Files	SOL-SGS-ICD-0005	1.4
[FITSpaper]	Definition of the Flexible Image Transport System (https://fits.gsfc.nasa.gov/standard40/fits_standard40aale.pdf)		4.0
[METADATA]	Metadata Definition for Solar Orbiter Science Data	SOL-SGS-TN-0009	2.4
[IOR ICD]	Solar Orbiter Instrument Operations Request ICD	SOL-SGS-ICD-0003	1.1
[SEGU]	SOC Engineering Guidelines for External Users	SOL-SGS-TN-0006	1.2
[SOAR]	Solar Orbiter Archive Plan	SOL-SGS-PL-0009	2.0
[MAN]	SPICE Instrument User Manual	SPICE-RAL-MAN-0001	13.0
[DATAICD]	SPICE Data Interface Control Document	SPICE-RAL-ICD-5003	10.0
[RAW]	SPICE FM Raw Science Data Handling Scheme	SPICE-RAL-TN-5202	1.0
[DECOMP]	SPICE Science Data Decompression Recipe	SwRI EM 17489-017	0
[SUNSPICE]	The SunSPICE Ephemeris Package for Solar Missions, William Thompson, 2018 (https://hesperia.gsfc.nasa.gov/ssw/packages/sunspice/doc/sunspice.pdf)		
[DISTORTIONS]	Simulated Image Distortions in SPICE Data, William Thompson, 2019 (https://spice-wiki.ias.u-psud.fr/lib/exe/fetch.php/documents:internal:simulate.pdf)		
[DISPERSION]	SPICE spectral dispersion function and detector geometry, Thompson and Young, 2020 (unpublished, under development)		
[LLdata]	Solar Orbiter Low-Latency Data: Concept and Implementation	SOL-SGS-TN-0003	1.2
[SPICELLFITS]	SPICE Low Latency Data Product Description Document	SPICE-UIO-DPDD-0001	1.14
[SPICELOST]	Solar Orbiter SPICE Reconstructing Data with Lost Telemetry Packets (https://spice-wiki.ias.u-psud.fr/lib/exe/fetch.php/documents:internal:spice-uio-dpdd-0003-0.2-reconstructing_data_with_missing_telemetry_compressed_images_hd.docx)	SPICE-UIO-DPDD-0003	0.2
[SOLARNET]	SOLARNET Metadata Recommendations for Solar Observations (https://arxiv.org/abs/2011.12139 , http://sdc.uio.no/open/solarnet/SOLARNET_Metadata_Recommendations_v1.4b-live.docx)		1.4b
[FITSCOORD]	Representation of spectral coordinates in FITS, Greisen & al., 2006, A&A, 446, 747-771 (https://www.aanda.org/articles/aa/pdf/2006/05/aa3818-05.pdf)		
[CFIT]	The Component Fitting System (CFIT) in IDL	CDS Software Note No. 47	2

Table 1-2: Reference Documents

 	Data Product Description Document	Ref: SPICE-UIO-DPDD-0002	Issue: 1.4
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1.4 Abbreviations and Definitions

FITS	Flexible Image Transport System
JPEG	Joint Photographic Experts Group; a lossy image format
MPEG	Moving Picture Experts Group; a lossy format for encoding and compressing video images.
LL01	Low Latency Level 1
LL02	Low Latency Level 2
L0	Level 0
L1	Level 1
L2	Level 2
L3	Level 3
SHC	Spectral Hybrid Compression
SOAR	Solar Orbiter Archive
SOOP	Solar Orbiter Observing Program
WCS	World Coordinate System

A complete list of all acronyms used in the SPICE project can be found in [ACRONYMS].

2. SPICE INSTRUMENT DESCRIPTION

SPICE is a high-resolution imaging spectrometer operating at ultraviolet wavelengths. It will address the key science goals of the Solar Orbiter mission, by providing quantitative knowledge of the physical state and composition of the plasmas in the solar atmosphere, in particular investigating the source regions of outflows and ejection processes which link the solar surface and corona to the heliosphere. [MAN]

2.1 Science Objectives

See Table 2 in Section 2.1 of [MAN].

2.2 Operational Modes

Data from the SPICE instrument is read out in wavelength regions, see [MAN] Section 2.2.2.2. Depending on the operational mode (study definition), the data from each of these readout windows may result in 1, 2 or 3 data arrays. It is also possible to make a full-frame read-out, resulting in one data array per detector array.

2.3 Calibration

2.3.1 On-ground Calibration

Description of the on-ground calibration performed on the instrument, and results. Include references to calibration performance reports.

2.3.2 In-flight Calibration

Description of the in-flight calibration, with references to existing document where applicable.

3. DATA GENERATION PROCESS AND ANALYSIS PROCESS

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The SPICE Science Data products are produced by the Science Data Pipeline delivered by the SPICE Instrument Team and running in Oslo. The data generation and analysis process are described in this section.

Science data received by the SOC from the SPICE team are made available to end users through the Solar Orbiter archive following the policies described in the Archiving Plan [SOAR]

3.1 Scientific Measurements

Top-level description of the data acquired by the instrument (RAL).

3.2 Data Flow Overview

The SPICE team in Oslo retrieves the telemetry data from IAS, passing it as input to the Science Data Pipeline running in Oslo. The Science Data Pipeline produces science data files of Level 1, 2 and 3¹. Level 1 and Level 2 files are in the FITS format (Sections 3.3.2 and 3.3.3). Level 3 files come in three flavours: Regular Level 3 FITS (L3 R, Section 3.3.4.1), Concatenated Level 3 FITS (L3 C, Section 3.3.4.2), and Quicklook Level 3 JPEG/MPEG (L3 QL, Section 3.3.4.3).

The SPICE detectors are read in wavelength regions, or windows. Each window is of a specific *window type*, see [Table 4-1](#). A study is of a given *study type* ([Table 4-2](#)) and may consist of multiple window types, and the study may be repeated. The dataflow differs for the multiple combinations of window types and study types, and for repeated vs non-repeated studies. See Section 4 for further information regarding window types, study types, and data products.

The dataflow inside the Science Data Pipeline is illustrated in the following Figures:

- Figure 3-1: Narrow-slit spectral-profile, repeated rasters
- Figure 3-2: Narrow-slit spectral-profile, special cases:
 - Column A: single raster, or single sit-and-stare
 - Column B: repeated sit-and-stare
- Figure 3-3: Intensity-window, repeated rasters
- Figure 3-4: Intensity-window, single raster
- Figure 3-5: Wide-slit and dumbbell:
 - Column A: repeated rasters or (repeated) sit-and-stare
 - Column B: single sit-and-stare
 - Column C: single raster
- Figure 3-6: Full detector, narrow slit
 - Column A: single full detector
 - Column B: repeated full detector
- Figure 3-7: Full detector, wide slit
 - Column A: single full detector
 - Column B: repeated full detector

¹ The production of L3 files is as of May 2021 not yet implemented. The calibration routines producing L2 files are under development.

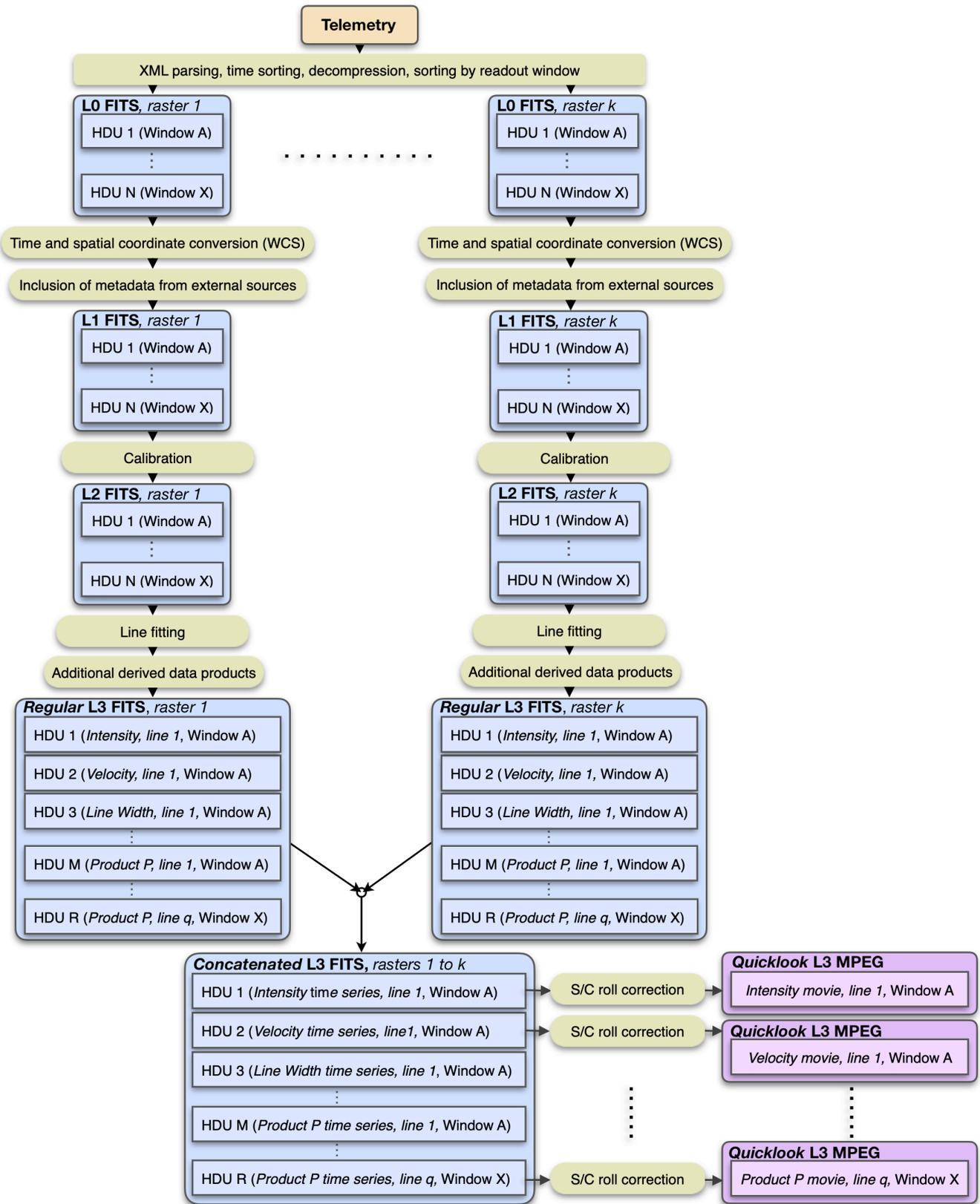


Figure 3-1 Pipeline dataflow: narrow-slit spectral-profile, repeated rasters. This dataflow also applies to studies labelled “Scanned Time Series” in the SPICE Study Generator tool. If the raster is not repeated the Quicklook L3 files will be JPEGs, see Figure 3-2, Column B.

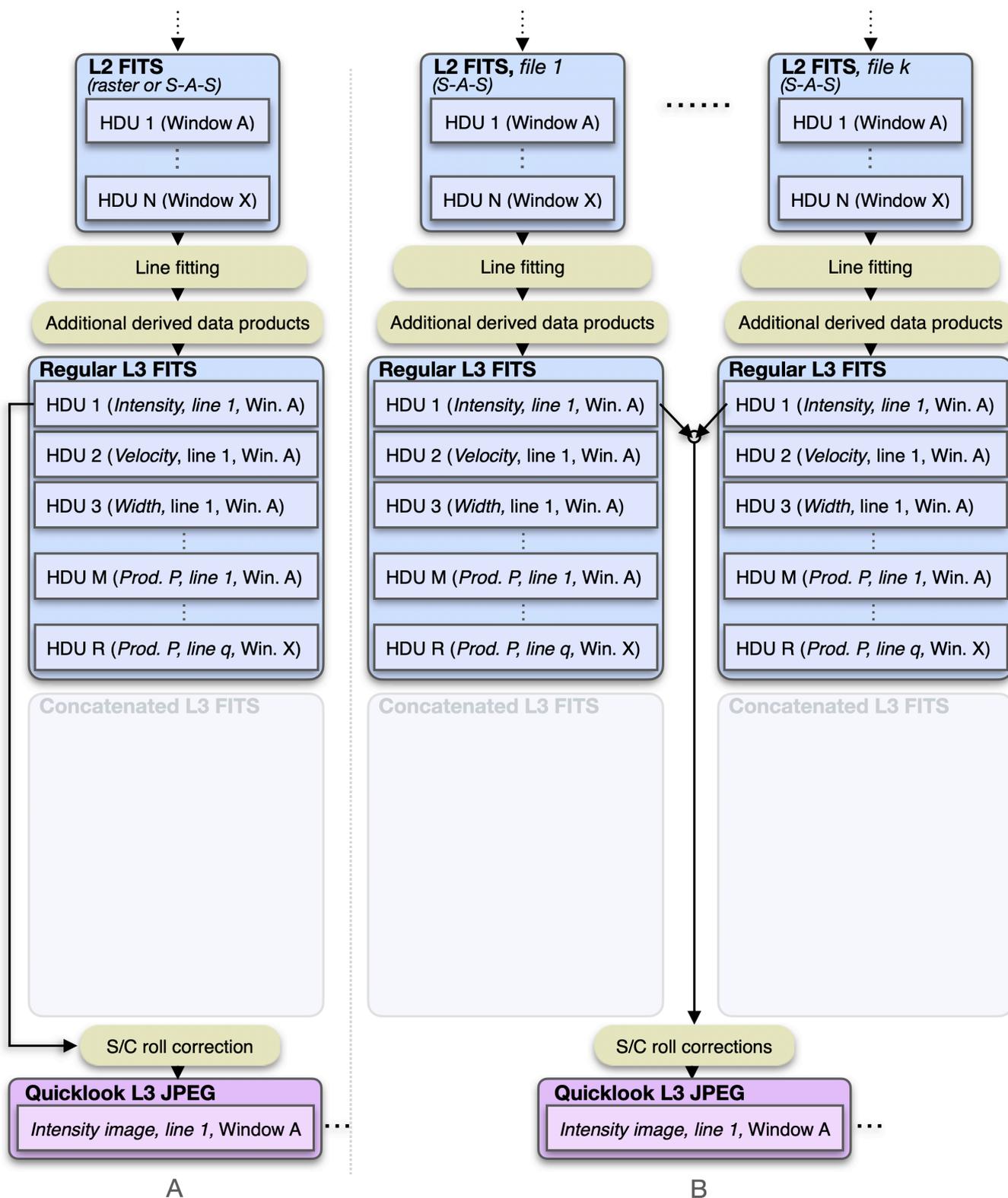


Figure 3-2 Pipeline dataflow (starting at L2): narrow-slit spectral-profile, special cases. Column A: single raster, or single sit-and-stare. Column B: Repeated sit-and-stare.

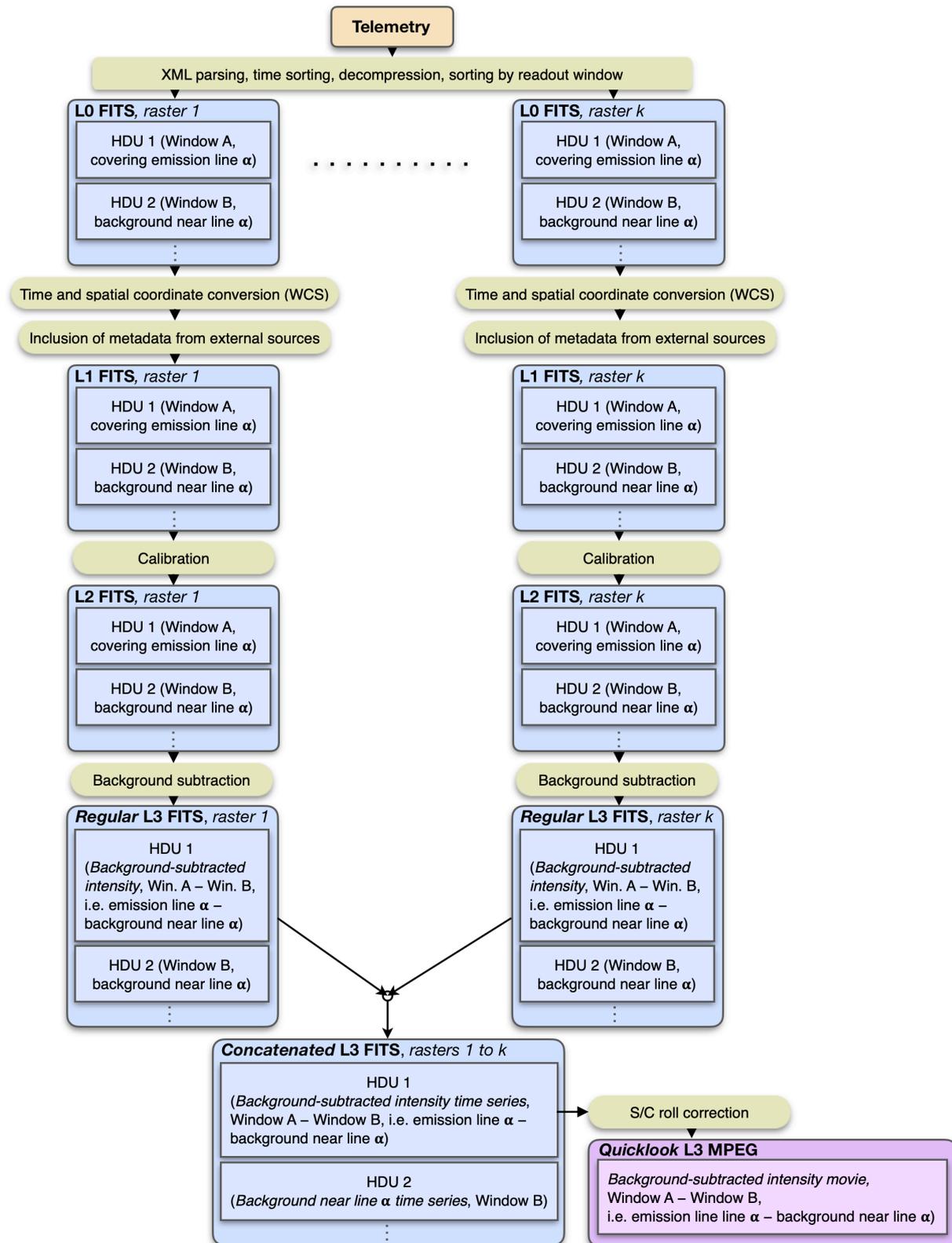


Figure 3-3: Intensity-window, repeated rasters. The spectral binning factor is equal to the window width. It is also possible to create a stand-alone intensity-window without an associated background (or line) window. In such cases no background subtraction is performed, and the L3 R and L2 data arrays will be identical.

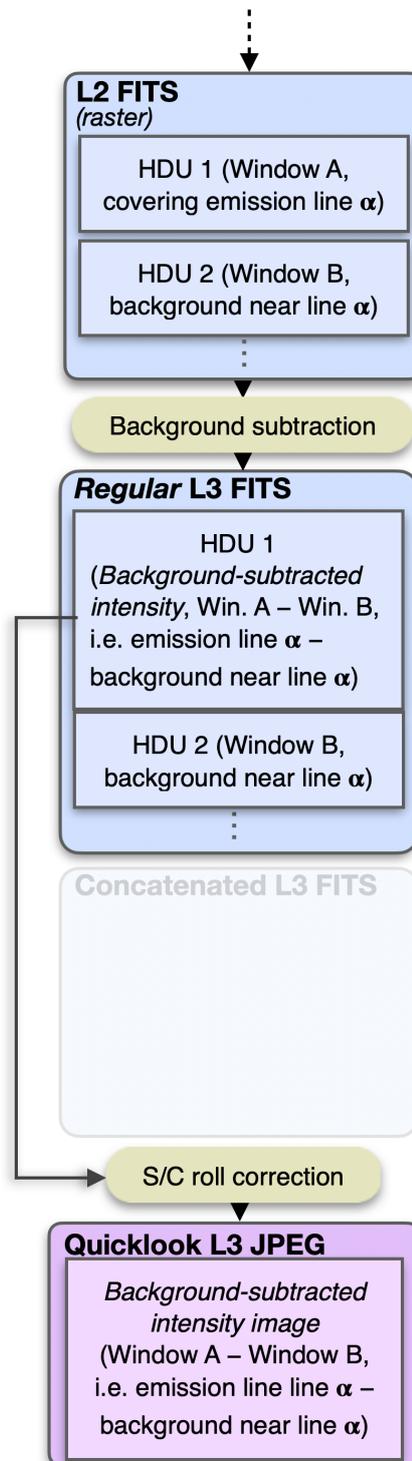


Figure 3-4: Intensity-window, single raster. The spectral binning factor is equal to the window width. It is also possible to create a stand-alone intensity-window without an associated background (or line) window. In such cases no background subtraction is performed, and the L3 R and L2 data arrays will be identical.

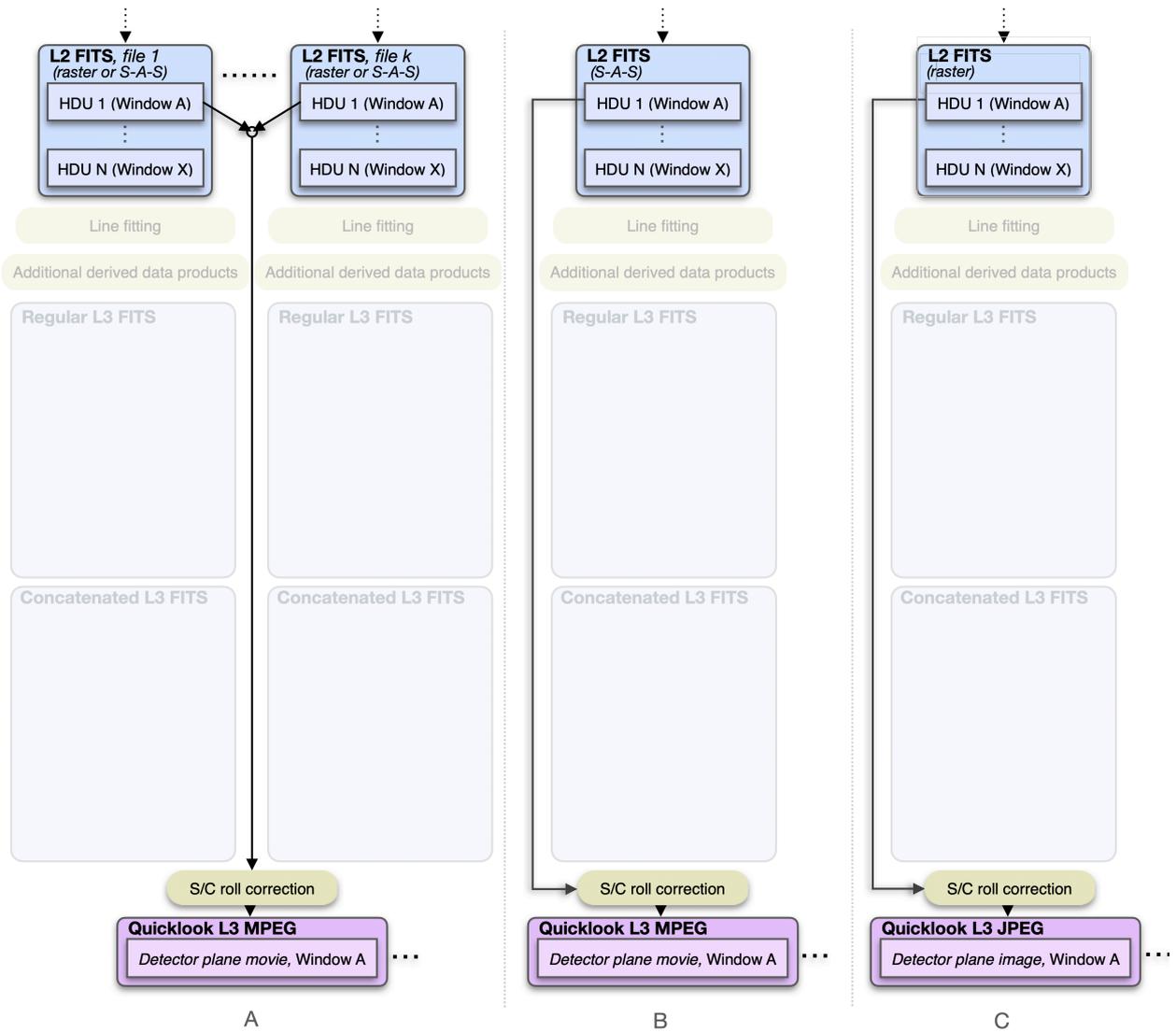


Figure 3-5 Pipeline dataflow (illustration starting at L2): wide-slit and dumbbell. Column A: repeated raster or repeated sit-and-stare. Column B: single sit-and-stare. Column C: single raster

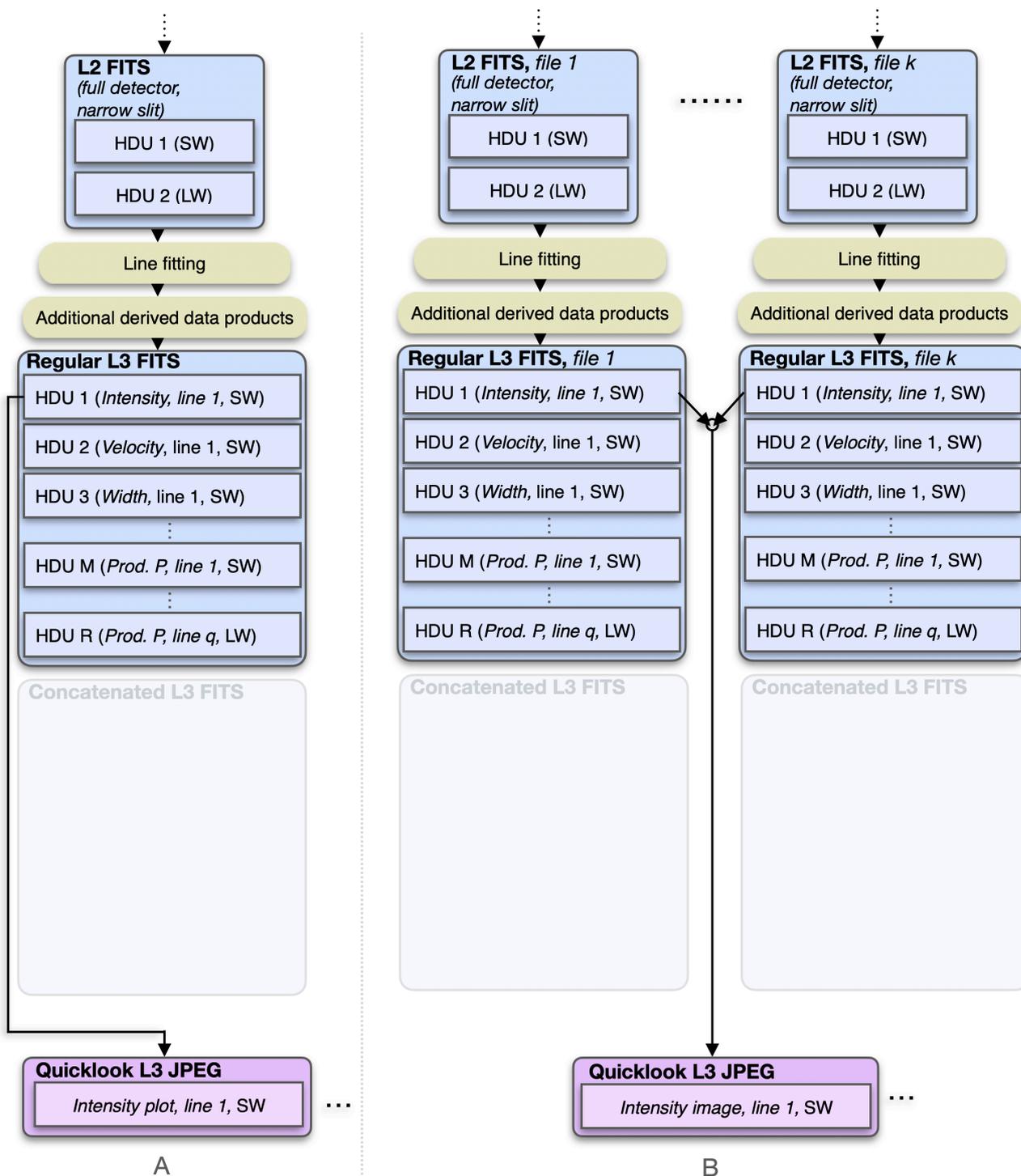


Figure 3-6 Pipeline dataflow (illustration starting at L2): Full detector, narrow slit. Column A: single full detector. Column B: Repeated full detector.

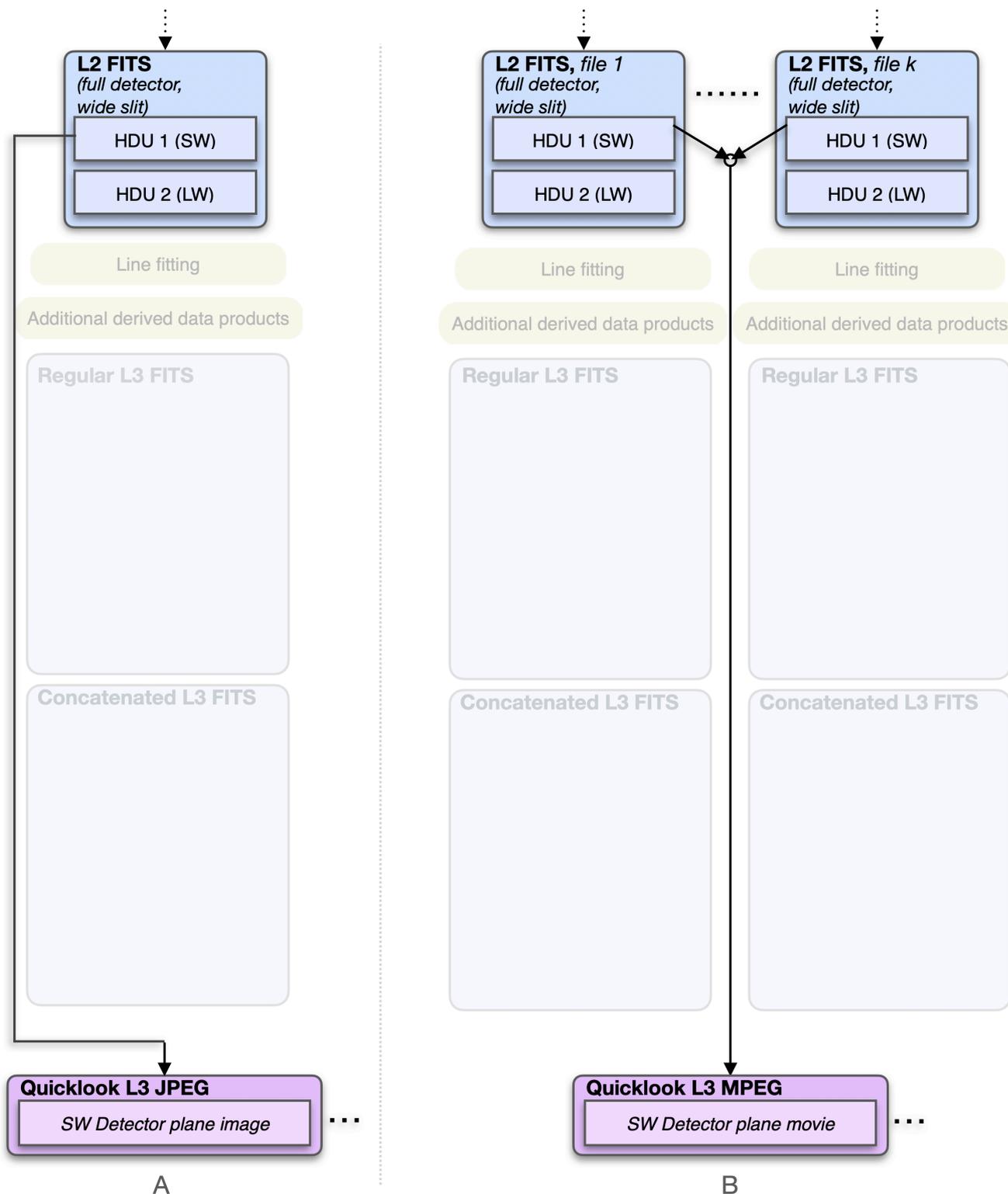


Figure 3-7 Pipeline dataflow (illustration starting at L2): Full detector, wide slit. Column A: single full detector. Column B: Repeated full detector.

The tables below summarise Figure 3-1 to Figure 3-7, and lists the formats of the files that the Science Data Pipeline produces, depending on window type, study type, and repetition status:

	Narrow-slit spectral-profile			
	Repeated rasters (Figure 3-1)	Single raster (Figure 3-2, Column A)	Single sit-and-stare (Figure 3-2, Column A)	Repeated sit-and-stare (Figure 3-2, Column B)
L1	FITS	FITS	FITS	FITS
L2	FITS	FITS	FITS	FITS
L3 R	FITS	FITS	FITS	FITS
L3 C	FITS	–	–	–
L3 QL	MPEG	JPEG	JPEG	JPEG

Table 3-1 Narrow-slit spectral-profile file formats. Only repeated studies result in data arrays in L3 C FITS files.

	Intensity-window			
	Repeated rasters (Figure 3-3)	Single raster (Figure 3-4)	Single sit-and-stare	Repeated sit-and-stare
L1	FITS	FITS	–	–
L2	FITS	FITS	–	–
L3 R	FITS	FITS	–	–
L3 C	FITS	–	–	–
L3 QL	MPEG	JPEG	–	–

Table 3-2 Intensity-window file formats. Only repeated studies result in data arrays in L3 C FITS files. Intensity-windows are not possible for sit-and-stare observations.

	Wide-slit and dumbbell			
	Repeated rasters (Figure 3-5, Column A)	Single raster (Figure 3-5, Column C)	Single sit-and-stare (Figure 3-5, Column B)	Repeated sit-and-stare (Figure 3-5, Column A)
L1	FITS	FITS	FITS	FITS
L2	FITS	FITS	FITS	FITS
L3 R	–	–	–	–
L3 C	–	–	–	–
L3 QL	MPEG	JPEG	MPEG	MPEG

Table 3-3 Wide-slit and dumbbell file formats. Neither wide-slit nor dumbbells result in data arrays in L3 R or L3 C files.

	Full detector			
	Single narrow-slit (Figure 3-6, Column A)	Repeated narrow-slit (Figure 3-6, Column B)	Single wide-slit (Figure 3-7, Column A)	Repeated wide-slit (Figure 3-7, Column B)
L1	FITS	FITS	FITS	FITS
L2	FITS	FITS	FITS	FITS
L3 R	FITS	FITS	–	–
L3 C	–	–	–	–
L3 QL	JPEG	JPEG	JPEG	MPEG

Table 3-4 Full Detector file formats. Full detector observations don't result in L3 C files. Wide slit full detector observations result in neither L3 R nor L3 C files.

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3.3 Data Generation

The Science Data Pipeline takes XML telemetry as input, and produces files of all file levels described in Sections 3.3.1 to 3.3.4 sequentially. The pipeline is written in IDL, with the use of java objects and C executables.

3.3.1 Level 0 – Raw Data

Level 0 FITS files (L0) are used as temporary files within the Science Data Pipeline and will normally not be made available to the scientific community². L0 files contain uncalibrated data expressed in engineering units (counts). The Science Data Pipeline up to (and including) the generation of L0 files is identical to the Low Latency Pipeline running at SOC. L0 files are indistinguishable from Low Latency Level 01 FITS files (LL01), with the exception of the values of a few descriptive FITS keywords (e.g. `FILENAME`, `LEVEL`, `CREATOR`, etc.).

The processing steps performed by the Science Data Pipeline to create an L0 file:

1. The Science Data Pipeline regularly checks its input directory for processing requests.
2. If a request is found, the XML contents of the request is read, and the telemetry data is extracted.
3. The telemetry packets are sorted by time of packet creation.
4. A processing request may contain telemetry from multiple observations. The following steps are repeated for each observation found in the sorted telemetry stream:
5. Each telemetry packet is inspected, and the data and metadata of a packet is extracted according to Sections 4.2.6.1 to 4.2.6.3 of [DATAICD]. Data and metadata in telemetry packets are accumulated into collections called raster segments. The data array of a raster segment is a 1-dimensional 8-bit array.
6. When a raster segment is complete, or there are no packets left in the telemetry that belongs to the segment, it is decompressed according to [RAW] and [DECOMP]. Special care must be taken when telemetry packets are lost, see Section 3.3.1.1.
7. The decompressed raster segment data array is translated into a 3-dimensional 16-bit data cube with dimensions (`exposure`, `y`, `dispersion`), according to [RAW]. If the telemetry was compressed using Spectral Hybrid Compression (SHC), this translation also involves an inverse Fourier transform as described in [DECOMP].
8. The decompressed raster segment data cubes are assembled into window data cubes. Window data cubes may consist of multiple raster segments, but each data cube only contains data stemming from a single readout window.
9. When all window data cubes of the observation are complete, or there are no more packets left in the telemetry, the data from each window data cube is reformatted into (`x`, `y`, `dispersion`, `time`) data cubes, with a singular `x` dimension for sit-and-stare observations and singular `time` dimension for raster scans.
10. A temporary L0 FITS file is created, with the data for each window stored in separate Header/Data Units (HDUs). The data from the first readout window are stored in the primary HDU, data from additional readout windows are stored in image extension HDUs.
11. If the telemetry contains data stemming from dumbbells, the data cubes are stored in the two last image extension HDUs (or in the last image extension HDU if only one dumbbell was recorded and/or received).
12. Each L0 HDU that contains data from readout windows also contains all relevant metadata present in the telemetry packets, see Appendix B. Such HDUs also contain metadata that have been derived from the telemetry, in some cases using formulas and conversion tables stored in the virtual machine.

² L0 files were made available to the SPICE consortium during the commissioning phase.

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13. In the case of multi-exposure observations, the L0 file also contains a binary header extension storing the individual values of keywords that vary with exposure number, see Section 4.4.4.1.
14. In the case of multi-segment observations, the binary header extension mentioned in bullet 13 will also store the individual values of keywords that vary with segment number, see Section 4.4.4.2.
15. If telemetry packets are lost, the lost packet indices are stored in a binary table extension. If SHC compression was applied to the data, this binary table extension also stores the lost FFT Bin indices, see Section 4.4.4.3.
16. If telemetry packets are lost, JPEG or SHC compression was applied to the data, and one or more image planes have approximated values, the indices of these image planes are stored in a binary table extension, see Section 4.4.5.
17. GOTO 5

3.3.1.1 Reconstructing data with lost telemetry packets

The implications of lost telemetry are discussed in [SPICELOST]. Missing telemetry packets affect the reconstructed data cube depending on the type of compression applied to the data:

- **No compression:** pixel columns in the dispersion-Y plane are lost, i.e. they have the BLANK value.
- **JPEG compression:** entire X-Y or dispersion-Y image planes are affected. All pixels in affected planes have *either*:
 - the BLANK value if the missing packets contained JPEG header information, or
 - approximated values if the missing packets did *not* contain JPEG header information
- **SHC compression:** all pixels stemming from the segment that the lost packets belonged to have approximated values. The degree of approximation depends on which FFT Bins are lost, see discussion in [SPICELOST].

Detailed information about lost telemetry is stored in binary table extensions and in FITS header keywords of the observational HDUs, see Sections 4.4.4.3. and 4.4.5.

3.3.2 Level 1 – Engineering Data (uncalibrated)

Level 1 FITS files (L1) contain uncalibrated data expressed in engineering units (counts). The FITS headers include additional keywords giving times converted from on-board time (OBT) to UTC, and the spatial coordinates are converted from being given relative to the spacecraft boresight to coordinates relative to the Solar disc. In this respect L1 files are identical to the Low Latency Level 02 files generated by SOC. However, L1 files also include additional metadata gathered from the Study Set files and the IORs. These additional metadata describe all available information about:

- a) the study definition (e.g. name of the study, name of the readout windows, name of the author of the study, etc.), and
- b) this particular instance of the study (e.g. the Solar Orbiter-wide ID of the observation, name of the SOOP, etc)

The L1 FITS files also include all metadata needed by the calibration routines in order to convert the file from L1 to L2, including Solar ephemeris data. L1+ FITS files will be stored in the SOAR.

The processing steps performed by the Science Data Pipeline to create an L1 file:

1. An L0 file is given as input to the Level 1 FITS file generator.

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2. The on-board time is converted to UTC using the SunSPICE IDL implementation of the SPICE³ toolkit, see [SUNSPICE]. Additional FITS standard keywords `DATE-BEG`, `DATE-END` and `DATEREFP` given in UTC are added to the L1 file.
3. Solar ephemeris data keywords are added using the SPICE toolkit.
4. IAS produces XML files with metadata that describe the specific studies and the specific instances of each study, i.e. the study definitions and the IORs. Oslo hosts a local database storing all this metadata. Based on this database and the FITS keywords in the input L0 file, additional metadata are added to the L1 file.
5. The keywords describing the pointing and FOV are converted from being relative to the spacecraft boresight to being relative to the solar disc (helioprojective) using SPICE toolkit routines and the XML metadata files obtained from IAS.
6. The spacecraft roll is calculated using the SPICE toolkit. The `PCi_j` transformation matrix explained in Section 4.3 is updated in order to describe the resulting rotation of the field-of-view.
7. The L1 file inherits any binary table extensions present in the L0 file. An additional binary table column storing the acquisition time converted to UTC is added to the binary table extension. See Section 4.4.4 and 4.4.5 for details.

3.3.3 Level 2 – Science Data (calibrated)

Level 2 FITS files (L2) are calibrated L1 files that are ready for scientific analysis:

- The data are corrected for dark current (only if a dark frame hasn't already been subtracted on-board).
- The data are corrected for flat-field.
- The data are corrected for spatial and spectral distortions. Corrections for slit tilts, spectral slant, detector misalignments, non-uniform dispersion, and other geometric distortions are applied to the data cubes by interpolation onto a linear grid.
- The data are calibrated to physical units: $\text{W/m}^2/\text{sr}/\text{nm}$, i.e. spectral radiance.

The rotation of the field-of-view due to spacecraft roll is not corrected for, instead the rotation of the field-of-view is described by the `PCi_j` transformation matrix.

The processing steps performed by the Science Data Pipeline to create an L2 file:

1. An L1 file is given as input to L2 FITS file generator, and it is sent to the calibration wrapper routine `spice_prep.pro`
2. `spice_prep.pro` calls the following calibration subroutines:
 - o `spice_prep_dark_offset_correction.pro` (dark current subtraction)
 - o `spice_prep_flat_field_correction.pro` (flatfield correction)
 - o `spice_prep_distortion_correction` (correct for geometrical distortions)
 - o `spice_radiometric_calibration.pro` (ADU to physical units)
3. Image planes that contain approximated values in the L1 file are set to `NaN` in the L2 file, see Sections 4.4.4.3 and 4.4.5.
4. The output from `spice_prep.pro` is a calibrated L2 FITS file.
5. The L2 file inherits any binary table extensions present in the L1 file.

3.3.4 Level 3 – Higher Level Data

Level 3 files (L3) contain higher-level data products. L3 can be either FITS files (Sections 3.3.4.1 and 3.3.4.2), or JPEG images or MPEG movies (Section 3.3.4.3).

³ NASA's Observation Geometry System for Space Science Missions.

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3.3.4.1 Regular Level 3 FITS (L3 R)

Regular Level 3 FITS files (L3 R) contain derived data products. An L3 R FITS file will consist of HDUs stemming from narrow-slit spectral-profile window types (windowed or full detector readout), or intensity-windows, see tables and figures on pages 12 to 19.

Intensity-windows result in a single type of derived data product in a single L3 R HDU: background-subtracted intensity⁴.

Narrow-slit spectral-profile windows result in multiple derived data products:

- Parameters of gaussian fits to all emission lines in the readout window, i.e. peak intensity, line shift, and line width
- Parameters derived from the gaussian fit parameters

Each spectral-profile HDU of an L2 file will result in multiple HDUs in the corresponding L3 R file, one HDU per derived data product.

Note that line fitting is sensitive to the initial values of the Gaussian parameters and in some cases the derived data products produced by the pipeline may therefore be less trustworthy than if the line fitting had been performed with human supervision. Also, the algorithm that automatically detects emission lines may fail, and it may report false positives or miss some weaker emission lines. For scientific purposes, we therefore strongly encourage users to perform the line fitting manually starting with L2 files.

The processing steps performed by the Science Data Pipeline to create an L3 R file:

1. An L2 file is given as input to the L3 FITS file generator and is passed to a gaussian line fitting routine.
2. This routine selects HDUs with data stemming from narrow-slit spectral-profile windows, or a single detector in the case of full detector readouts, and attempts to automatically detect and identify up to 10 emission lines in each readout window.
3. An initial guess of the amplitude, position, and width of each line is given as input to the line fitting routine `cfits.pro` (see [CFIT]), which returns the fitted gaussian line parameters peak intensity, line shift and line width.
4. Based on the fitted gaussian line parameters, secondary derived parameters are estimated:
 - Abundances
 - FIP bias
 - Density
 - Temperature
5. A Regular Level 3 FITS file is created with a single derived data product stored in each HDU. For each detected emission line 4 HDUs will be created: three containing the gaussian fit parameters, and one containing the residuals of the fit (TBD). Finally, there is one HDU for each of the secondary derived data products in the bullet list above.
6. The L3 FITS file generator then selects all HDUs with data stemming from intensity-window pairs: one window covering an emission line, and a corresponding nearby window covering a region without any strong emission lines. For each window pair the intensity from the background window is subtracted from the intensity of the line window, and a difference image is stored in an HDU in the L3 file. The background window is also stored in a

⁴ The data stemming from the intensity-window covering the background will also be stored in a separate HDU in the L3 R file. For the special case of stand-alone intensity-windows, i.e. intensity-windows without an associated window, no background subtraction is performed. For such HDUs the L3 R and L2 data arrays are identical, and there is no separate HDU storing a background.

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separate HDU, making it easy for the user to reconstruct the original intensities in the line window if needed. No background subtraction is performed for stand-alone intensity-windows that do not have an associated window. For such HDUs the L2 and L3 R data arrays are identical, and there is no separate HDU storing a background.

7. If present in the L2 file, the L3 R file inherits the L2 binary header extension storing the individual values of keywords that vary with exposure number.

3.3.4.2 Concatenated Level 3 FITS (L3 C)

Concatenated Level 3 FITS files (L3 C) consists of time series of derived data products from multiple Regular L3 files. Only narrow-slit spectral-profile windows and intensity-windows in studies that are repeated will result in HDUs in L3 C files.

The processing steps performed by the Science Data Pipeline to create an L3 C file:

1. All L3 R files from a repeated study are identified
2. The data cubes of these files are concatenated in the time dimension.
3. A Concatenated L3 FITS file is created, each HDU containing a concatenated data cube.
4. The coordinates of an L3 C data cube may need to be specified using table lookup (see Section 6 of [FITSCoord]), and some of the FITS keywords may need to be stored using the variable-keyword mechanism (Appendix I of [SOLARNET]).

3.3.4.3 Quicklook Level 3 MPEG and JPEG (L3 QL)

Quicklook Level 3 files (L3 QL) will be either MPEG movies or JPEG images. L3 QL files are not suitable for scientific analysis, as they are not in an appropriate scientific file format, they are highly compressed, and they do not contain the necessary metadata required for a thorough analysis. They may, however, provide useful context information, and they can be used as a tool to find interesting observations that should be investigated further.

L3 QL files contain either an image/movie of a single derived data product (narrow-slit observations), or an image/movie showing a part of the detector (wide-slit/dumbbell observations):

- An L3 QL MPEG file is either
 - a movie of a derived data product based on narrow-slit spectral-profile observations (Figure 3-1)
 - a movie of the background-subtracted integrated intensity of an intensity-window (Figure 3-3). For stand-alone intensity-windows no background subtraction is performed.
 - a movie of wide-slit/dumbbell multi-exposure observations (Figure 3-5, Column A and B).
- An L3 QL JPEG file is either
 - an image of a derived data product based on narrow-slit observations (Figure 3-2, Column B and C)
 - an image of the (background-subtracted) integrated intensity of an intensity-window (Figure 3-4, Column B and C)
 - a wide-slit/dumbbell image (Figure 3-5, Column C).
 - In the special case of a single-exposure narrow-slit observation, an L3 QL JPEG is either
 - a plot of a derived data product as a function of position along the slit (Figure 3-2, Column A).
 - a plot of the (background-subtracted) integrated intensity of an intensity-window as a function of the position along the slit (Figure 3-4, Column A)

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The processing steps performed by the Science Data Pipeline to create an L3 QL file:

1. An L2, L3 R or L3 C file is given as input to the L3 quicklook jpeg/mpeg file generator.
2. The spacecraft roll is adjusted for before the data cube is written to a movie/image file (in L2, L3 R and L3 C files rotation of the FOV is described by the `PCi_j` transformation matrix).
3. Movies are created using the `IDLffVideoWrite` object using the mpeg4 codec (TBD)
4. Images are created using the `write_jpeg.pro` procedure with `QUALITY` set to 75 (TBD).

3.3.5 CAL - Calibration data

Input from MPS needed. The calibration routines and the necessary calibration data will be made available in SolarSoft (SSW) and in the SolarSoft Data Base (SSWDB).

3.3.6 HK - Housekeeping data

(In SOL-SGS-OTH-0004-DPDDtemplate this section is named "ANC – Ancillary data".)

3.4 Validation

(TBD)

3.4.1 Instrument Team Validation

Compare data products with output from RAL's cube builder (L0). Need input from SPICE team scientists for validating derived data products.

3.4.2 SOC Validation

SOC will check the data types that the SPICE team intends to archive. The SOC might also perform spot checks on contents of the files. The exact procedure in which this routine check will take place is still TBD.

4. DATA PRODUCT DESCRIPTIONS

SPICE data products stored in FITS files are formatted in accordance with the rules outlined in [METADATA]. This section provides details on the formats, metadata, and filenames for each of the products included in the SPICE data.

A SPICE FITS file contains a primary Header/Data Unit (HDU), and it may contain one or more image extensions. All primary and image extension HDUs are “observational HDUs” that contain observational data with a full header as described in [METADATA] – i.e. there is no distinction between primary HDUs and image extensions other than those required by [FITSpaper]. Each HDU is regarded as a data product.

In addition, the file may contain binary table extensions used for storing auxiliary data that have individual values for each exposure of the observation, or descriptions of lost telemetry, see Sections 4.4.4 and 4.4.5.

The SPICE detector is read in wavelength regions, or windows, of a specified wavelength range. The data array of an observational HDU stem from one of the following **6 window types**, described in the `WIN_TYPE` FITS keyword:

	Window type description	WIN_TYPE
1	Narrow-slit spectral-profile (2", 4", and 6" slits)	'Narrow-slit Spectral'
2	Dumbbell stack	'Dumbbell (lower)' or 'Dumbbell (upper)'
3	Wide-slit (30" slit)	'Wide-slit'
4	Intensity-window (2", 4", and 6" slits)	'Intensity-window'
5	Full detector read-out (2", 4", and 6" slits)	'Full Detector Narrow-slit'
6	Full detector read-out (30" slit)	'Full Detector Wide-slit'

Table 4-1: All available window types and corresponding values of `WIN_TYPE`

The window types may be of one the following **3 study types**, described in the `STUDYTYP` FITS keyword:

	Study type	Possible window types	STUDYTYP	X	t
1	Sit-and-stare	1, 2, 3	'Sit-and-stare'	1	>1
2	Raster	1, 2, 3, 4	'Raster '	>1	1
3	Single exposure	5, 6	'Single Exposure'	1	1

Table 4-2: All available study types and corresponding values of `STUDYTYP`

Window type 4 (Intensity-window) may not be of study type 1 (Sit-and-stare). Window types 5 and 6 (full-detector read-out) may only be of study type 3 (single exposure). However, it is possible to repeat full detector observations, with or without moving the scan mirror, thereby enabling the construction of L3 rasters and sit-and-stare observations also for full detector observations (see Section 3.2)

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Note that a full-frame read-out results in a FITS file with two HDUs, one for each detector array⁵.

Also note that for double exposure studies the FITS file contains two HDUs per window, one for each exposure time. For a study with N windows the first N HDUs of the FITS file contain data recorded with the short exposure time, and the next N HDUs contain data acquired using the long, accumulated exposure time.

Considering all possible combinations of window types and study types, SPICE FITS files may contain 9 distinct types of data products or HDUs. The data product description is stored in the keyword `DATAPROD`, which is simply the concatenation of `WIN_TYPE` and `STUDYTYP`, e.g. 'Narrow-slit Spectral Raster'. See also Table 4-8.

Note that in other SPICE documents and applications, e.g. [MAN] and in the SPICE Study Generator tool, the nomenclature is a bit different from what has been outlined above. As an example, instead of differentiating between study types and window types, the Study Generator only uses the concept of study type, which may have one of the following values: "Full Spectrum", "Spatial Scan", "Time Series" and "Scanned Time Series". In the pipeline a "Scanned Time Series" is treated identical to a series of repeated "Spatial Scans":

- in both cases the series of spatial scans are stored in multiple L1, L2 and L3 R FITS files – each file contains a single spatial scan per readout window
- In both cases all spatial scan repetitions will be gathered in a single L3 C file

4.1 Filename, L1, L2, L3 R, and L3 C

Following the specifications in [METADATA], the SPICE FITS file names have the following format:

```
solo_[level]_spice[-concat][-slit][-type][-db][-int]_[time]_V[version]_SPIOBSID-RASTERNO.fits
```

- [level] is L1, L2, or L3.
- [-concat] is `-concat` for Concatenated L3 files, otherwise empty.
- [-slit] is either `w` or `n`, for "wide" (30") or "narrow" (2"/4"/6") respectively.
- [-type] is either `-ras` (for "raster"), `-sit` (for "sit-and-stare") or `-exp` (for "single exposure").
- [-db] is `-db` for files that include dumbbells, otherwise empty.
- [-int] is `-int` for files that include intensity-windows, otherwise empty.
- [time] is the UTC time at the beginning of the study. For Concatenated L3 files it is the start time of the first observation in the concatenated file.
- [version] is an incremental number padded with '0' to two characters.
- The combination of `SPIOBSID` (SPICE Observation ID) and `RASTERNO` uniquely identifies a single observation. If a study is repeated all files in the series will have the same `SPIOBSID` but different `RASTERNO`.

4.2 Filename, L3 QL

Quicklook L3 files contain an image or a movie of a single data product or a single detector plane readout window extracted from an L2, L3 R or L3 C FITS file. Based on the names of these files, the L3 QL files will have the following format:

⁵ SPICE is capable of transmitting full-frame data in both compressed and uncompressed format. In this case the LL01 file contains *four* HDUs, *two* for each detector array, one with decompressed data and one with the uncompressed data.

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solo_L3-spice[-concat]-q1-[line] [-product] [-slit] [-type] [-db] [-int]_[time]_V[version]_SPIOBSID_RASTERNO.[ext]

- [-concat] is -concat for files stemming from L3 C files or from multiple L2 files (Figure 3-5, Column A), otherwise empty.
- [-line] contains a string identifying the emission line.
- [-product] contains the name of the derived data product for narrow-slit observations, otherwise empty. The list of possible names is TBD.
- [-slit] is either w or n, for "wide" (30") or "narrow" (2"/4"/6") respectively.
- [-type] is either -ras (for "raster"), -sit (for "sit-and-stare") or -exp (for "single exposure").
- [-db] is -db for dumbbell images/movies, otherwise empty
- [-int] is -int for intensity-windows images/movies, otherwise empty.
- [time] is the UTC time at the beginning of the study. For files stemming from L3 C files it is the start time of the first observation in the concatenated file.
- [version] is an incremental number padded with '0' to two characters.
- [ext] is either mpeg or jpeg.

4.3 The PC_{i_j} transformation matrix of FITS files

In general, the WCS coordinate c_i of a pixel with pixel indices $p_j=(p_1,p_2,p_3,\dots,p_N)$ is expressed by:

$$c_i(p_1,p_2,p_3,\dots,p_N) = CRVAL_i + CDELTA_i \sum_{j=1}^N PC_{i_j}(p_j - CRPIX_j)$$

Thus, for a four dimensional data cube, the WCS coordinate c_i of a pixel with indices $p_j=(p_1,p_2,p_3,p_4)$ is expressed by:

$$c_i(p_1,p_2,p_3,p_4) = CRVAL_i + CDELTA_i * (PC_{i_1} * (p_1 - CRPIX_1) + PC_{i_2} * (p_2 - CRPIX_2) + PC_{i_3} * (p_3 - CRPIX_3) + PC_{i_4} * (p_4 - CRPIX_4))$$

For HDUs where each coordinate is coupled only to "its own" dimension (i.e. coordinate $i=1$ is coupled to data cube dimension $j=1$ only, coordinate $i=2$ is coupled to dimension $j=2$ only, etc), the PC_{i_j} matrix has only diagonal entries and all off-diagonal entries have the default value of 0. This represents cases with no shear, rotation, mirroring, or transposition. In L1+ FITS files the rotation of the field-of-view is described by four PC_{i_j} matrix elements: for a non-zero roll angle PC_{1_1} and PC_{2_2} do not have the default value of 1, and PC_{1_2} and PC_{2_1} do not have the default value of 0. The space craft counter-clockwise roll angle relative to Solar north is given in the CROTA keyword. In L2 FITS files all geometrical distortions other than the rotation of the FOV are corrected for by linear interpolation of the data, and these distortions are therefore not described by FITS keywords. However, the L1 to L2 calibration routine (`spice_prep.pro`) will be made publicly available and the users will be able to turn off the data interpolation if desirable. In such cases the geometrical distortions will be described by FITS keywords, see [DISTORTIONS] and [DISPERSION].

For both Low Latency FITS files and L1+ FITS files, the j th dimension of the data cube may contribute to the i th coordinate for raster scans and wide-slit/dumbbell observations. In these cases, the off-diagonal entries of the PC_{i_j} matrix are not 0:

- For raster observations, time increases for each new slit position. Since the scan direction of the scan mirror is from Solar West to Solar East this means that the time coordinate t decreases in the x dimension ($j=1$) of the data cube. Therefore, the $PC4_1$ element of the transformation matrix is less than zero, coupling the t coordinate to the x dimension of the data cube.
- For all wide-slit (30”) and dumbbell HDUs, the x coordinate increases in the dispersion dimension ($j=3$), and the headers have a non-zero $PC1_3$ matrix element. The value of $PC1_3$ is given by the spatial pixel size in the dispersion dimension divided by $CDELTA1$.

L1, L2, and L3 R files do not contain multiple repetitions of raster scans; therefore, the time dimension of raster scan data cubes is degenerate and there is no natural value for $CDELTA4$. On the other hand, $CDELTA4$ cannot be zero, since the product $CDELTA4*PC4_1$ must be equal to the time between two consecutive exposures within a raster scan. We therefore let $CDELTA4$ have the default value of 1, and $PC4_1$ is thereby equal to the time between exposures.

For the HDUs of L3 R and L3 C files the dispersion coordinate is singular, and $CDELTA3$ therefore has the default value of 1.

For sit-and-stare observations the t coordinate is only dependent on the fourth dimension ($j=4$), and $PC4_1$ in the equation above is 0. The time between two consecutive exposures is $CDELTA4$ for sit-and-stare observations.

Note that the time coordinate t is the centre time of an exposure relative to the start time of the observation as a whole, i.e. the relative start time of the exposure + $XPOSURE/2$. Thus, the t coordinate of the first exposure of an observation is $XPOSURE/2$, the t coordinate of the exposure that corresponds to the reference pixel is $CRVAL4$, and t of the last exposure is the end time of the observation $-XPOSURE/2$.

4.4 Data arrays and FITS headers

All FITS keywords in LL01 files (see [SPICELLFITS]) are present in L1+ FITS files⁶, but their values may differ. L1+ files also have additional FITS keywords. As an example, the start time of the observation measured in onboard time is given in the keyword OBT_BEG , and L1+ files also contain $DATE-BEG$, which gives the start time converted into UTC. In addition, the WCS coordinate keywords of L1+ FITS files are calculated based on the values of the LL01 WCS keywords and external input.

4.4.1 Data arrays and FITS headers: L1

4.4.1.1 General format of L1 data arrays

The dimensions of the L1 data arrays are (X, Y, D, t) for all 6 window types in Table 4-1.

The x dimension of a data array always denotes the number of slit positions during the observation, and y is the height along the slit, in pixels⁷.

⁶ Except for modifications required by [FITSpaper], e.g. the $BLANK$ keyword can only be present in integer valued HDUs (e.g. LL01) but not in floating point HDUs (e.g. L2).

⁷ When referring to pixels along detector Y (height along the slit) or pixels along the dispersion direction (λ/X'), these might represent *binned* pixels, depending on the study.

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The third dimension, D , always represents a position along the dispersion direction of the detector. For type 1, this dimension unambiguously corresponds to wavelength (λ). For dumbbell stacks and wide-slit (30"), however, this dimension corresponds to both spatial x and wavelength. Thus for any given x and t , the (Y, D) plane shows a transposed spatial image. However, the x position (relative to the centre of the solar disc) of every pixel in such an image is still given by the first WCS coordinate ($CTYPE1='HPLN-TAN'$). This means that there is an off-diagonal value in the PCi_j matrix to couple the x and D dimensions of the data cube, see Section 4.3

Dimension four, t , always represents the number of exposures per slit position. I.e. for sit-and-stare observations, t is the number of exposures and x is 1. For raster observations, where the slit is moved between each exposure, t is 1. For such observations, there is an off-diagonal element in the PCi_j matrix to couple time and the x position of the slit, see Section 4.3. In L3 data products, data cubes may represent repeated rasters, i.e. raster movies, and both x and t may be greater than 1.

A window of type 4, Intensity-window, is binned in the dispersion dimension with a binning factor equal to the width of the window. The size of the resulting data cube is $(x, y, 1, t)$, i.e. it has no spectral resolution. The wavelength coordinate is such that the value reflects the central wavelength (i.e. the midpoint between the central two pixels) of the readout window. Intensity-windows are normally observed in pairs: one window covers an emission line, and a nearby window covers a region with no strong emission lines. The data from the latter window may be used as an estimate of the background level of the window covering the emission line. Such a background intensity-window may be used as a background estimate for multiple intensity-windows covering emission lines. The Science Data Pipeline uses line/background intensity-window pairs to create background-subtracted intensity data products, see Figure 3-3, Figure 3-4, and Section 4.4.3.2. The link between an HDU storing the emission line data and the corresponding HDU storing the background data is established with FITS keywords, see Section 4.4.1.7.

For all study types, the maximum number of exposures is 480, i.e. x and t are always less than 480.

4.4.1.2 L1 FITS Header Example

Below is an example header of an L1 observational HDU including all keywords required by [METADATA].

The header describes a 2" narrow-slit, spectral-profile, raster observation obtained during cruise phase. Sections 4.4.1.4 to 4.4.1.8 describe the data arrays resulting from all available window types and study types.

A selection of the FITS keywords is further described in Section 4.4.1.3. The correspondence between the metadata parameter names used in [DATAICD] and the FITS keywords of the L1 HDUs is explained in Appendix B. The correspondence between the Study Generator fields and FITS keywords is outlined in Appendix C.

Note that although the example is for a primary HDU and thus contain $SIMPLE=T$ and $EXTEND=T$, it might just as well have been an image extension HDU, with modifications as required by [FITSpaper].

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```

SIMPLE = T / Written by IDL: Thu May 6 23:15:40 2021
BITPIX = 16 / Integer*2 (short integer)
NAXIS = 4 / Number of dimensions
NAXIS1 = 160 / Number of slit positions (x)
NAXIS2 = 192 / Number of pixels along slit (y)
NAXIS3 = 32 / Number of pixels in dispersion dimension
NAXIS4 = 1 / Number of exposures per slit position (time)
EXTEND = T / FITS dataset may contain extensions
DATE = '2021-05-06T23:15:40' / Date and time of FITS file creation

```

```

EXTNAME = '[STP122] O III 703 / Mg IX 706 - SH' / Extension name
FILENAME= 'solo_L1_spice-n-ras_20201122T021113_V03_33554618-000.fits' / FI

```

Study parameters valid for all Obs-HDUs in this file

```

STUDYTYP= 'Raster' / Sit-and-stare, Raster or Single Exposure
STUDYDES= 'SPROUT, 4"' / Study description
STUDY = 'SCI_SPROUT-TEST_SC_SL04_60.0S_FF' / SPICE Study name
OBS_MODE= 'SCI_SPROUT-TEST_SC_SL04_60.0S_FF' / = STUDY
OBS_TYPE= 'o36n' / Unique code for OBS_MODE
AUTHOR = 'Miho Janvier' / Author of study
STP = 122 / SoLO Short-Term Plan number
OBS_ID = 'SSPI_021A_RF4_111_o36n_116' / SOC Observation ID
SPIOBSID= 33554618 / SPICE Observation ID (hex 20000ba)
OBS_DESC= 'SPROUT test (data to normal PS)' / Observation description
PURPOSE = 'Science' / Purpose of study (Science/Calibration/Checkout)
READMODE= 'Destructive' / Destructive or non-destructive
TRIGGERD= 'None' / Event that triggered observation
TARGET = 'None' / Planned type of target
SOOPNAME= 'R_FULL_LRES_LCAD_Out-of-RSW-synoptics' / SOOP Campaign name(s)
SOOPTYPE= 'RF4' / SOOP Campaign name code(s)
APID = 1404 / Application Process ID
NRASTERS= 1 / Number of planned rasters for this SPIOBSID
RASTERNO= 0 / Raster number (starting at 0)
STUDY_ID= 12 / On-board Study ID slot (0-63)
MISOSTUD= 1870 / Ground study ID used in MISO planning tool
XSTART = 320 / [arcsec] Slit instr. x rel. to instr. boresight
XPOSURE = 60.0000 / [s] Total effective exposure time
FOCUSPOS= 11943 / Focus position
NSEGMENT= 5 / Number of segments per window
NWIN = 5 / Total number of windows (incl. db and int win)
NWIN_PRF= 5 / Number of windows not dumbbell or Intensity
NWIN_DUM= 0 / Number of dumbbell windows
NWIN_INT= 0 / Number of Intensity-windows

```

Other keywords valid for all Obs-HDUs in this file

```

TIMESYS = 'UTC' / TIMESYS included for readability
DATeref = '2020-11-22T02:11:13.751' / [UTC] Zero point of time coordinate
DATE-BEG= '2020-11-22T02:11:13.751' / [UTC] Beginning of data acquisition
DATE-OBS= '2020-11-22T02:11:13.751' / [UTC] Equals DATE-BEG
DATE-AVG= '2020-11-22T03:31:33.757' / [UTC] Data acquisition midpoint
DATE-END= '2020-11-22T04:51:53.516' / [UTC] End of data acquisition

```

```

SEQ_BEG = '2020-11-22T02:10:43' / [UTC] Approximated start of observation series
TELAPSE =          9639.76500010 / [s] Elapsed time between beg. and end of acqu.
OBT_BEG =          659326233.051 / Start acquisition time in OBT
LEVEL = 'L1' / Data processing level
CREATOR = 'SDP-SPICE' / Name of pipeline
ORIGIN = 'University of Oslo' / Name of institution
VERS_SW = '2841' / UiO SVN revision number of L1 pipeline
VERSION = '03' / Incremental file version number
COMPLETE= 'C' / Complete data set
OBSRVTRY= 'Solar Orbiter' / Observatory Name
INSTRUME= 'SPICE' / Instrument name
CROTA =          3.38931412991 / [deg] S/C counter-clockwise roll rel to Solar N

```

STUDYFLG and its derived keywords

```

STUDYFLG=          0 / Study flags
NOSPECTR=          0 / Applies only to dumbbells
CALMODE =          0 / Applies only to full frame readouts
DBLEXP =          0 / If set, double exposure is enabled
DBLEXPNO=          0 / Applies only when DBLEXP=1
DARKMAP =          0 / If set, a dark map was subtracted on-board
BLACKLEV=          0 / If set, a bias frame was subtracted on-board

```

Keywords valid for this HDU (WINDOW0_70.35)

```

WIN_TYPE= 'Narrow-slit Spectral' / Description of window type
DATAPROD= 'Narrow-slit Spectral Raster' / WIN_TYPE+STUDYTYP
TELESCOP= 'SOLO/SPICE/SW' / Telescope/Sensor name/Detector array name
DETECTOR= 'SW' / Detector array name
WINNO =          0 / Window number (starting at 0) within this study
WINTABID=          53 / Index in on-board window data table (0-255)
MISOWIN =          2739 / Ground window ID used in MISO planning tool
WINSHIFT=          0 / [pixel] Win redshift rel to win 2739 base pos.
SLIT_ID =          2 / Slit ID (0-3)
SLIT_WID=          4 / [arcsec] Slit width
DUMBBELL=          0 / 0/1/2: not a dumbbell/lower dumbbell/upper dumbbell

WAVEUNIT=          -9 / Power of 10 by which the metre is multiplied
WAVEMIN =          70.1997 / [nm] Left edge of first read detector pixel
WAVEMAX =          70.5055 / [nm] Right edge of last read detector pixel
WINWIDTH=          0.305816 / [nm] Window width

BTYPE = 'Intensity' / Type of data
UCD = 'phot.count;em.line' / Unified Content Descriptors v1.23
BUNIT = 'adu' / Units of uncalibrated data
BSCALE =          1.00000 / Data value = BZERO + BSCALE*FITS array value
BZERO =          0 / Default value for unsigned integers
BLANK =          65535 / Value of undefined and lost pixels
NTOTPIX =          983040 / Number of potentially usable pixels =all for L1
NSATPIX =          0 / Number of fully saturated pixels
NDATAPIX=          983040 / Number of usable pixels excl. saturated & BLANK
DATAMIN =          2309.00 / [adu] Minimum data value
DATAMAX =          31768.0 / [adu] Maximum data value

```

```

DATAMEAN=          3618.51 / [adu] Mean      data value
DATAMEDN=          3270.00 / [adu] Median  data value
DATAP01 =          2631.00 / [adu] 1st    percentile of data values
DATAP10 =          2791.00 / [adu] 10th   percentile of data values
DATAP25 =          2951.00 / [adu] 25th   percentile of data values
DATAP75 =          3820.00 / [adu] 75th   percentile of data values
DATAP90 =          4753.00 / [adu] 90th   percentile of data values
DATAP95 =          5675.00 / [adu] 95th   percentile of data values
DATAP98 =          7345.00 / [adu] 98th   percentile of data values
DATAP99 =          8698.00 / [adu] 99th   percentile of data values
DATARMS =          1186.57 / [adu] RMS dev: sqrt(sum((data-DATAMEAN)^2)/N)
DATANRMS=          0.327917 / Normalised RMS dev: DATARMS/DATAMEAN
DATAMAD =          731.414 / [adu] Mean abs dev: sum(abs(data-DATAMEAN))/N
DATASKEW=          4.04225 / Data skewness
DATAKURT=          29.4972 / Data kurtosis
PXOFFSET=          200 / Pixel level offset

NPACKETS=          50 / Number of packets with observational data
LOSTPKTS=          0 / Number of lost packets w/data, variable keyword
NLOSTCHK=          0 / Number of lost Final Packets, w/checksum+data
NFAILCHK=          0 / Number of checksums failed
NLOSTPIX=          0 / Number of lost pixels
NAPRXPLN=          0 / Number of approximated X-Y planes
NLOSTPLN=          0 / Number of lost X-Y planes
LOSTBINS=          0 / Applies only to SHC-compressed data

PCT_DATA=          100.000 / NDATAPIX/NTOTPIX*100
PCT_LOST=          0.00000 / NLOSTPIX/NTOTPIX*100
PCT_SATP=          0.00000 / NSATPIX/ NTOTPIX*100

PXBEG1 =          160 / [pixel] First read-out pixel in X dimension
PXEND1 =           1 / [pixel] Last  read-out pixel in X dimension
PXBEG2 =          101 / [pixel] First read-out pixel in Y dimension
PXEND2 =          868 / [pixel] Last  read-out pixel in Y dimension
PXBEG3 =           55 / [pixel] First read-out pixel in dispersion dim.
PXEND3 =           86 / [pixel] Last  read-out pixel in dispersion dim.
PXBEG4 =           1 / [pixel] First read-out pixel in time dimension
PXEND4 =           1 / [pixel] Last  read-out pixel in time dimension

NBIN1 =           1 / Binning factor in X dimension
NBIN2 =           4 / Binning factor in Y dimension
NBIN3 =           1 / Binning factor in dispersion dimension
NBIN4 =           1 / Binning factor in time dimension
NBIN =           4 / Total binning factor

COMPRESS= 'Spatial Lossy' / JPEG Compression description
COMP_RAT=          9.84615 / Compression ratio decompressed/compressed
COMPTYPE=          6 / Compression type (0-7)
COMPPARA=          26 / Compression amount parameter (0-255)
SHCFFTID=          0 / Applies only to SHC-compressed data

```

World Coordinate System (WCS) keywords

```

WCSNAME = 'Helioprojective-cartesian' / Name of coordinate system
LONPOLE =          180.000 / [deg] Native longitude of celestial pole

```

```

SPECSYS = 'TOPOCENT' / Spectral coord. not corrected for S/C velocity
VELOSYS = 0.00000 / [m/s] Default for SPECSYS='TOPOCENT'

CTYPE1 = 'HPLN-TAN' / Type of 1st coordinate
CNAME1 = 'Helioprojective longitude (Solar X), increases towards Solar West' /
CUNIT1 = 'arcsec' / Units for 1st coordinate (for CRVAL1, CDELT1)
CRVAL1 = -76.9686748509 / [arcsec] 1st coordinate of reference point
CDELT1 = 4 / [arcsec] Increment of 1st coord at ref point
CRPIX1 = 80.5000 / [pixel] 1st pixel index of reference point
PC1_1 = 0.998250871416 / Non-default value due to CROTA degrees S/C roll
PC1_2 = -0.0649311213911 / Contribution of dim 2 to coord 1 due to roll

CTYPE2 = 'HPLT-TAN' / Type of 2nd coordinate
CNAME2 = 'Helioprojective latitude (Solar Y), increases towards Solar North' /
CUNIT2 = 'arcsec' / Units for 2nd coordinate (for CRVAL2, CDELT2)
CRVAL2 = -74.7709759889 / [arcsec] 2nd coordinate of reference point
CDELT2 = 4.39316 / [arcsec] Increment of 2nd coord at ref point
CRPIX2 = 96.5000 / [pixel] 2nd pixel index of reference point
PC2_1 = 0.0538293139403 / Contribution of dim 1 to coord 2 due to roll
PC2_2 = 0.998250871416 / Non-default value due to CROTA degrees S/C roll

CTYPE3 = 'WAVE' / Type of 3rd coordinate
CNAME3 = 'Wavelength' / Description of 3rd coordinate
CUNIT3 = 'nm' / Units for 3rd coordinate (for CRVAL3, CDELT3)
CRVAL3 = 70.3526 / [nm] 3rd coordinate of reference point
CDELT3 = 0.00955676 / [nm] Increment of 3rd coord at ref point
CRPIX3 = 16.5000 / [pixel] 3rd pixel index of reference point
PC3_3 = 1.00000 / Default value, no rotation

CTYPE4 = 'UTC' / Type of 4th coordinate
CNAME4 = 'Time (Degenerate Dimension)' / Description of 4th coordinate
CUNIT4 = 's' / Units for 4th coordinate (for CRVAL4, CDELT4)
CRVAL4 = 4819.87500000 / [s] 4th coord of ref point, relative to DATEREFF
CDELT4 = 1.000000000000 / [UTC] Degenerate dimension; default value
CRPIX4 = 1.00000 / [pixel] 4th pixel index of reference point
PC4_4 = 1.00000 / Default value, no rotation
PC4_1 = -60.2500000000 / Contribution of dimension 1 to coordinate 4

```

Auxiliary data and reference to bintab with variable keywords

```

LONGSTRN= 'OGIP 1.0' / The OGIP long string convention may be used.
COMMENT This FITS file may contain long string keyword values that are
COMMENT continued over multiple keywords. This convention uses the '&'
COMMENT character at the end of a string which is then continued
COMMENT on subsequent keywords whose name = 'CONTINUE'.
VAR_KEYS= 'VARIABLE KEYWORDS;TIMAQOBT,MIRRPOS,TN_FOCUS,TN_GRAT,TN_SW,TN_LW,T_F&'
CONTINUE 'OCUS,T_GRAT,T_SW,T_LW,VN_MCPSW,VN_MCPLW,VN_GAPSW,VN_GAPLW,V_MCPSW,V&'
CONTINUE 'MCPLW,V_GAPSW,V_GAPLW,TIMAQUTC &'
CONTINUE ' / Variable keywords
TIMAQOBT= 659331022.926 / [OBT] Average Start time of data acquisition
MIRRPOS = 39581.1 / [adu] Average Scan mirror position
TN_FOCUS= 2398.64 / [adu] Average SFM focus temperature
TN_GRAT = 2688.30 / [adu] Average SFM grating temperature
TN_SW = 2804.17 / [adu] Average HAS SW temperature
TN_LW = 2803.73 / [adu] Average HAS LW temperature

```

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T_FOCUS = 2.56188 / [Celsius] Average SFM focus temperature
T_GRAT = -5.22909 / [Celsius] Average SFM grating temperature
T_SW = -20.6691 / [Celsius] Average HAS SW temperature
T_LW = -20.6575 / [Celsius] Average HAS LW temperature
VN_MCPSW= 2704 / [adu] Average MCP SW voltage
VN_MCPLW= 2586 / [adu] Average MCP LW voltage
VN_GAPSW= 2941 / [adu] Average GAP SW voltage
VN_GAPLW= 2932 / [adu] Average GAP LW voltage
V_MCPSW = 897 / [V] Average MCP SW voltage
V_MCPLW = 849 / [V] Average MCP LW voltage
V_GAPSW = 2800 / [V] Average GAP SW voltage
V_GAPLW = 2789 / [V] Average GAP LW voltage
TIMAUTC= '2020-11-22T03:31:03.633' / [UTC] Average Start t. of data acquisition

Keywords describing processing steps

PRSTEP1 = 'Y-BINNING' / Type of processing, step 1
PRPROC1 = 'Y Binning (On-board)' / Name of procedure, step 1

PRSTEP2 = 'COMPRESSION' / Type of processing, step 2
PRPROC2 = 'JPEG Compression (On-board)' / Name of procedure, step 2

PRSTEP3 = 'TELEMETRY-PARSING' / XML decoding, decompression if applicable, etc
PRPROC3 = 'spice_process_telemetry.pro' / Name of procedure, step 3
PRPVER3 = '02.01.01' / Version of procedure, step 3
PRLIB3A = 'uio_spice_pipeline' / Software library containing PRPROC3

Hardware and software processing environment

LONGSTRN= 'OGIP 1.0' / The OGIP long string convention may be used.
COMMENT This FITS file may contain long string keyword values that are
COMMENT continued over multiple keywords. This convention uses the '&
COMMENT character at the end of a string which is then continued
COMMENT on subsequent keywords whose name = 'CONTINUE'.
PRENV3 = ' Kernel: Darwin &
CONTINUE ' Kernel release number: 18.7.0 &
CONTINUE ' Architecture: x86_64 &
CONTINUE ' Host name: black.uio.no &
CONTINUE ' OS: Mac OS X 10.14.6 build 18G9216 &
CONTINUE ' CPU: Intel(R) Xeon(R) CPU E5-1650 v2 @ 3.50GHz &
CONTINUE ' IDL 8.5 (Jul 7 2015), memory bits: 64, file offset bits: 64 &
CONTINUE '' / Hardware and software

SOLARNET keywords, and additional keywords

SOLARNET= 0.500000 / Fully/Partially/No SOLARNET compliant (1/0.5/-1
OBS_HDU = 1 / HDU contains observational data (1) or not (0)
PARENT = 'solo_L0_spice-n-ras_0659326233_V202105062313C_33554618-000.fits' / L0
FILE_RAW= 'sc_2020_11_21.xml;sc_2020_11_22.xml' / Telemetry file
INFO_URL= 'https://spice.ias.u-psud.fr/' / URL to additional information
MIRRDILT= 168.484 / Slope of linear fit to MIRRPOS

SMIRRDEL= 4.12052 / Sigma of slope of linear fit to MIRRPOS

Solar Ephemeris Keywords

DSUN_OBS= 136212323845. / [m] S/C distance from Sun
 DSUN_AU = 0.910523187036 / [AU] S/C distance from Sun
 RSUN_ARC= 1053.48153019 / [arcsec] Apparent photospheric Solar radius
 RSUN_REF= 6.95700E+08 / [m] Assumed photospheric Solar radius
 SOLAR_B0= -5.76287386873 / [deg] Tilt angle of Solar North toward S/C
 SOLAR_P0= -25.4591466531 / [deg] S/C Celestial North to Solar North angle
 SOLAR_EP= -2.03494592249 / [deg] S/C Ecliptic North to Solar North angle
 CAR_ROT = 2237 / Carrington rotation number
 HGLT_OBS= -5.76287386873 / [deg] S/C Heliographic latitude (B0 angle)
 HGLN_OBS= 121.972982547 / [deg] S/C Heliographic longitude
 CRLT_OBS= -5.76287386873 / [deg] S/C Carrington latitude (B0 angle)
 CRLN_OBS= 207.099625683 / [deg] S/C Carrington longitude (L0 angle)
 HEE_X_OBS= -72188775962.4 / [m] S/C Heliocentric Earth Ecliptic X
 HEE_Y_OBS= 115474958929. / [m] S/C Heliocentric Earth Ecliptic Y
 HEE_Z_OBS= 2848096309.52 / [m] S/C Heliocentric Earth Ecliptic Z
 HCI_X_OBS= -38115459677.7 / [m] S/C Heliocentric Inertial X
 HCI_Y_OBS= 130053605728. / [m] S/C Heliocentric Inertial Y
 HCI_Z_OBS= -13677300094.0 / [m] S/C Heliocentric Inertial Z
 HCI_X_VOB= -23992.3392822 / [m/s] S/C Heliocentric Inertial X Velocity
 HCI_Y_VOB= -13737.8974062 / [m/s] S/C Heliocentric Inertial Y Velocity
 HCI_Z_VOB= 2249.89467691 / [m/s] S/C Heliocentric Inertial Z Velocity
 HAE_X_OBS= 7585.52410237 / [m] S/C Heliocentric Aries Ecliptic X
 HAE_Y_OBS= -26676.5109359 / [m] S/C Heliocentric Aries Ecliptic Y
 HAE_Z_OBS= 497.778878831 / [m] S/C Heliocentric Aries Ecliptic Z
 HEQ_X_OBS= -71762524787.5 / [m] S/C Heliocentric Earth Equatorial X
 HEQ_Y_OBS= 114964640936. / [m] S/C Heliocentric Earth Equatorial Y
 HEQ_Z_OBS= -13677300094.0 / [m] S/C Heliocentric Earth Equatorial Z
 GSE_X_OBS= 219938721054. / [m] S/C Geocentric Solar Ecliptic X
 GSE_Y_OBS= -115474958929. / [m] S/C Geocentric Solar Ecliptic Y
 GSE_Z_OBS= 2848096309.52 / [m] S/C Geocentric Solar Ecliptic Z
 OBS_VR = -6629.03654019 / [m/s] Radial velocity of S/C away from the Sun
 EAR_TDEL= 38.4853619193 / [s] Time(Sun to Earth)-Time(Sun to S/C)
 SUN_TIME= 454.355405581 / [s] Time(Sun centre to S/C)
 DATE_EAR= '2020-11-22T02:11:52.236' / [UTC] DATE-BEG + EAR_TDEL
 DATE_SUN= '2020-11-22T02:03:39.396' / [UTC] DATE-BEG - SUN_TIME

HISTORY and checksums

HISTORY process_request.pro
 HISTORY spice_process_telemetry.pro
 HISTORY spice_l0_to_l1.pro
 DATASUM = '4217305804' / data unit checksum created 2021-05-06T21:15:44
 CHECKSUM = '9jOMCjOJ9jOJCjOJ' / HDU checksum created 2021-05-06T21:15:44
 O_BLANK = 32767 / Original BLANK value
 O_BZERO = 32768.0 / Original BZERO Value
 END

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4.4.1.3 Brief description of some selected FITS keywords

4.4.1.3.1 Keywords identifying the study

The keyword `OBS_TYPE` is a 3-character alphanumeric string that uniquely identifies the `OBS_MODE`, which contains the name of the SPICE study. The value of the Solar Orbiter-wide `OBS_MODE` is repeated in the SPICE-specific keyword `STUDY`.

The keyword `OBS_ID` contains the SOC Observation ID. The `OBS_ID` is built up of parameters that together uniquely identify the observation in a Solar Orbiter-wide context. The format of the SOC Observation ID is:

AAAA_PPvV_SSS_III_0000_JJJ

The components of this string are:

AAAA: 4-character instrument ID, is always “SSPI” for SPICE

PPvV: 4-character string, Long-Term Planning plan ID

SSS: 3-digit alphanumeric SOOP Type, equals FITS keyword `SOOPTYPE`

III: 3-digit (base-58) SOOP Instance

0000: 4-character (base-58) Observation Type, equals FITS keyword `OBS_TYPE`

JJJ: 3-digit (base-58) Observation Instance

An observation may belong to multiple SOOPs. In such cases, the SOC Observation ID contains multiple strings as described above, each sub-string being separated by a semicolon. See [IOR-ICD] for details.

Note that the SPICE Observation ID is given in the keyword `SPIOBSID`. This keyword uniquely identifies the observation in a SPICE context. The `SPIOBSID` is a 32-bit on-board monotonically increasing observation counter.

4.4.1.3.2 Keywords derived from the value of `STUDYFLG`

The 8-bit value of the `STUDYFLG` keyword stems from the Science Header Packets, and the 6 keywords following `STUDYFLG` in the header example are set based on this value, in accordance with Section 4.2.6.1. of [DATAICD].

4.4.1.3.3 Keywords describing the size of the readout windows

The window start column on the detector and the window width are both given in pixel coordinates in the telemetry, see Table 4-10. The values of `WAVEMIN` and `WINWIDTH` are derived from these pixel values, using the conversion from pixel indices to nm given in [DISPERSION] and [MAN]. `WAVEMIN` is the wavelength of the leftmost edge of the first detector pixel column of the readout window, ignoring any binning, and `WINWIDTH` is the edge-to-edge window width. `WAVEMAX` is the wavelength corresponding to the rightmost edge of the window’s last pixel column. For narrow-slit observations the pixel value of the window start column (starting at 1 for the leftmost pixel column on the SW detector, 1025 for the leftmost column on the LW detector) can be found in the Solar Orbiter mandatory keyword `PXBEG3`, and the pixel value of the last column is stored in `PXEND3`. The edge-to-edge pixel width of the window is therefore `PXEND3 - PXBEG3 + 1`.

Due to the optics of the instrument wide-slit and dumbbell images are reversed in the East-West direction when they are projected onto the detector, i.e. Solar East is increasing towards higher dispersion pixel numbers. In the FITS files, however, the images are stored according to the regular convention with Solar West increasing towards higher pixel indices. Therefore, for such

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observations the window start column extracted from the telemetry is stored in `PXEND3`. `PXBEG3` is a higher number than `PXEND3`, and the edge-to-edge pixel width of the window is `PXBEG3 - PXEND3 + 1`. Note that this does not apply to full-detector readouts: for such observations `PXBEG3` and `PXEND3` are 1 and 1024 for the SW detector, and 1025 and 2048 for the LW detector, regardless of the slit used.

The window start *row*, starting at 1 for the lowermost⁸ pixels on the detector, is also given in the telemetry and is stored in the FITS files as `PXBEG2`. The window end row is stored in `PXEND2`.

The scan direction of the scan mirror is from Solar West to Solar East. This is indicated by always having `PXEND1 = 1`. For raster observations `PXBEG1 > 1`, for other study types `PXBEG1 = PXEND1 = 1`.

`PXBEG4 = 1` for all observation types. For sit-and-stare observations `PXEND4 > 1`, for other study types `PXEND4 = PXBEG4 = 1`.

4.4.1.3.4 The *BLANK* keyword

The data type of an HDU's data array is normally 16-bit *unsigned* integer. However, when reconstructing SHC-compressed data some pixel values may end up being negative, and the data type for SHC-compressed data is therefore always 16-bit *signed* integer. Due to this difference the value of undefined pixels (*BLANK*) is set to `-1` for unsigned integer array HDUs and `-1` for signed integer array HDUs.

4.4.1.3.5 Keywords describing telemetry and telemetry loss and consequences thereof

`NPACKETS` gives the total number of packets *with observational data* that were prepared on-board for downlink. I.e. this number includes the total number of Data Packets of all the window's *n* segments, plus *n* if the *n* Final Packets contained observational data.

The total number of lost packets with observational data is given in `LOSTPKTS`, and the number of lost Final Packets (with or without observational data) is given in `NLOSTCHK`. If a packet with observational data is lost:

- a number of pixels may be lost: `NLOSTPIX`
- a number of image planes (or FFT coefficient planes for SHC data) may be lost: `NLOSTPLN`
- a number of image planes may have approximated values: `NAPRXPLN`
- a number of FFT bins may be lost (in the case of SHC data): `LOSTBINS`

Sections 4.4.4.3 and 4.4.5 describe how the indices of lost telemetry packets, lost FFT coefficient planes, approximated image planes, and lost FFT bins are stored in binary table extensions. Lost pixels (and lost image planes) can easily be identified by selecting pixels having the *BLANK* value and therefore the indices of such pixels and image planes are not stored in binary table extensions.

4.4.1.3.6 Variable keywords

The use of the `VAR_KEYS` keyword is described in Section 4.4.4, and the `SOLARNET` keyword is described in `[SOLARNET]`.

4.4.1.3.7 Keywords describing the processing steps

The individual processing steps that have been applied to the data are described by the `PRxxxxn` keywords. The type of processing performed (`PRSTEPn`) and the name of the procedure performing

⁸ i.e. the southernmost detector pixel row in the case of no spacecraft roll

the processing are given by `PRSTEPn` and `PRPROCn`. For onboard data processing, i.e. binning, dark subtraction and/or compression, these are the only `PRxxxxn` keywords that are defined.

Processing performed on-ground are described with additional `PRxxxxn` keywords giving the version number of the processing routine (`PRPVERn`) and the name of the library that contains the processing routine (`PRLIBnA`). Finally, the keyword `PRENVn` describes the hardware and software environment of the on-ground processing. `PRENVn` is valid for all processing steps starting at step `n`, until a new `PRENVn` keyword is defined. However, for SPICE FITS files created by the pipeline, the processing environment is normally the same for all processing steps, and therefore only a single `PRENVn` keyword that is valid for all processing steps performed on ground will normally be defined.

For L0 and L1 files the only on-ground processing that is described is the XML telemetry parsing itself, which includes XML decoding and decompression.

4.4.1.3.8 Keyword giving the name(s) of the telemetry file(s)

The name of the source telemetry file is given in the keyword `FILE_RAW`. If also a telemetry file from the preceding day is given as input to the pipeline, the value of `FILE_RAW` is the names of the telemetry files of the preceding day and the current day, separated by a semicolon.

4.4.1.3.9 Keywords used to determine the study type: sit-and-stare or raster

Due to readout noise the scan mirror position of a sit-and-stare observation reported in the telemetry is not constant during the observation. The readout noise is in fact so large that the reported mirror positions of a raster observation do not necessarily have to be monotonically increasing. Therefore, a linear fit is made to the scan mirror position values in order to determine if the observation is a sit-and-stare or a raster. For pipeline debugging purposes the parameters of the fit are included in the headers: `MIRRDELTA` gives the slope of fit and `SMIRRDEL` gives the 1-sigma uncertainty estimate of the fit. These keywords can safely be ignored by all users other than the pipeline developer.

4.4.1.4 L1 HDUs with narrow-slit spectral-profile data (window type 1)

Data arrays:

SPICE narrow-slit (2", 4" or 6") spectral-profile data arrays have dimensions according to Table 4-3 below. Readout windows have a width in the dispersion direction of $D = 4, 8, 16$ or 32 pixels.

Study type	Dimensions
Sit-and-stare	(1, Y, D, t)
Raster	(X, Y, D, 1)
Single exposure	Not applicable

Table 4-3: Dimensions of narrow-slit spectral-profile data arrays

4.4.1.5 L1 HDUs with dumbbell stack data (window type 2)

At each end of the slit in the Y direction there is an area of nominal size 30" x 30" used for making small context images, so called dumbbell or alignment windows. It is possible to downlink one or both dumbbells, but only for a single window per study. The dumbbells may be downloaded in addition to, or instead of, the spectral-profile data cube, and are included in the same FITS file as the spectral-profile data, in separate HDUs.

Data arrays:

SPICE dumbbell stack data arrays have dimensions according to Table 4-4 below.

Study type	Dimensions
Sit-and-stare	(1, 32, 64, t)
Raster	(X, 32, 64, 1)
Single exposure	<i>Not applicable</i>

Table 4-4: Dimensions of dumbbell stack data arrays

4.4.1.6 L1 HDUs with wide-slit data (window type 3)

Data array:

SPICE wide-slit (30") data arrays have dimensions according to Table 4-5 below. Readout windows have in most cases a width in the dispersion direction of $D = 32$ pixels.

Study type	Dimensions
Sit-and-stare	(1, Y, D, t)
Raster	(X, Y, D, 1)
Single exposure	<i>Not applicable</i>

Table 4-5: Dimensions of wide-slit data arrays

4.4.1.7 L1 HDUs with intensity-window data (window type 4)

An intensity-window is binned in the dispersion dimension with a binning factor equal to the width of the window. Intensity-windows are normally observed in pairs, with one window covering a spectral line, and a nearby window covering a part of the spectrum without any strong emission lines. The intensity-window data cubes are saved in separate HDUs. The value of the wavelength coordinate is the central wavelength (i.e. the midpoint between the central two pixels before binning) of the readout window.

Data array:

SPICE intensity-window data arrays have dimensions according to Table 4-6 below.

Study type	Dimensions
Sit-and-stare	<i>Not applicable</i>
Raster	(X, Y, 1, 1)
Single exposure	<i>Not applicable</i>

Table 4-6: Dimensions of intensity-window data arrays

If the HDU stems from an intensity-window that was defined as either a line window or a background window, the HDU has two of the following three keywords that are not present in the HDUs of any other window type: `IWINTYPE`, and either `IWINBKG` or `IWINLINE`. HDUs storing stand-alone intensity-windows do not include any of these three keywords.

The value of `IWINTYPE` tells if the data of the HDU stems from a window covering an emission line (`IWINTYPE = 'LINE'`), or from a window that doesn't cover any strong emission lines (`IWINTYPE = 'BACKGROUND'`). In the former case an additional keyword `IWINBKG` gives the `EXTNAME` of the HDU storing the data from the background window, and in the latter case `IWINLINE` gives the `EXTNAME` of the HDU storing the data from the emission line window.

As an example, the following keywords may be present in an HDU stemming from a window covering the emission line Ne VIII 770 A:

```
EXTNAME = 'Ne VIII 770 A' / Extension name
IWINTYPE = 'LINE' / This intensity-window covers an emission line
IWINBKG = 'Red wing of Ne VIII 770 A' / EXTNAME of HDU storing background
```

The following keywords may be present in the corresponding HDU with data to be used for background-subtraction from the Ne VIII 770 A line:

```
EXTNAME = 'Red wing of Ne VIII 770 A' / Extension name
IWINTYPE = 'BACKGROUND' / This intensity-window considered as background
IWINLINE = 'Ne VIII 770 A' / EXTNAME of HDU storing emission line
```

4.4.1.8 L1 HDUs with full-detector read-out data (window types 5 and 6)

It is possible to make a full-frame read-out where the full areas of both detector arrays are recorded. A full-frame read-out always consists of a single exposure – sit-and-stare or raster observations are not possible. Data from each detector array are stored in separate HDUs⁹. Both the three narrow slits and the wide slit may be used, in the latter case the PC1_3 transformation matrix element has a non-zero value.

Data array:

SPICE full-detector read-out data arrays have dimensions according to Table 4-7 below.

Study type	Dimensions
Sit-and-stare	Not applicable
Raster	Not applicable
Single exposure	(1,1024,1024,1)

Table 4-7: Dimensions of full-detector read-out data arrays

4.4.2 Data arrays and FITS headers: L2

An L2 observational HDU contains data from the same readout window as the L1 HDU with the same HDU number. However, in order to include data from all pixels present in the L1 data array, the geometrically corrected L2 data arrays are a few pixels larger in the dispersion dimension compared to the L1 data arrays described in Section 4.4.1. The values of padded pixels are set to NaN.

In order to ensure that an emission line is completely covered, or to catch multiple closely spaced lines, two or more adjacent windows may be downlinked. A L2 window is normally padded in the dispersion dimension on both the red and blue side of the window. However, for adjacent windows the adjoining edge is not padded, i.e. there is no overlap between two adjacent L2 windows. Due to the geometrical correction of L2 files, pixels close to the adjoining edge of one L2 window have contributions from pixels originally a part of the adjacent window. In a future update of the calibration routines adjacent windows will be merged into to a single window.

Two windows may be close but not adjacent. In such cases the end result may be the same as for adjacent windows: pixels originally belonging to one window will end up in the other L2 window. A

⁹ SPICE is capable of transmitting full-frame data in both compressed and uncompressed format. In this case the L1 file contains *four* HDUs, *two* for each detector array, one with decompressed data and one with the uncompressed data.

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future update of the calibration routines will ensure that pixels are only present in their original window.

In L2 files the spatial plate scale along the slit is the same on the two detector arrays, and a given pixel along the slit on the SW or LW detector correspond the same location on the Sun. The plate scale in the dispersion dimension is adjusted in order to get the same spatial plate scale in the dispersion and y dimensions for dumbbells and the wide-slit observations.

Note that if telemetry is lost for compressed observations, entire image planes or even full data cubes may be missing (i.e. have the value NaN) in L2 files, see Sections 4.4.4.3 and 4.4.5.

L2 HDUs contain all of the keywords of the L1 header example in Section 4.4.1 (except for modifications required by [FITSpaper]), but with additional keywords:

- Keywords that describe the calibration. This includes the Solar Orbiter-wide keyword `VERS_CAL`, which gives the version of the calibration software, and `PRxxxxn` keywords describing the geometric corrections that have been applied on the data cube, see Section 4.4.2.1.
- Keywords that describe random and systematic errors (`CRDERi` and `CSYERi` respectively, see Table 3-8 of [METADATA])
- The keyword `UCD` giving the Unified Content Descriptors, e.g.:
`UCD = 'phot.radiance; em.line'` ; for narrow-slit observations
`UCD = 'phot.radiance; em.UV'` ; for wide-slit/dumbbell observations
The intensity unit of SPICE L2 files, given by `BUNIT`, is $W/m^2/sr/nm$, i.e. spectral radiance.

Finally, some of the L2 keyword values may differ from the L1 keyword values, e.g.:

The values of the WCS keywords:

- `PCi_j`
- `CDELTi`
- `CRVALi`
- `CRPIXj`

The values of keywords describing the data array:

- `NAXIS2`
- `NAXIS3`
- `WAVEMIN`
- `WAVEMAX`
- `WINWIDTH`
- `DATAMIN`
- `DATAMAX`

And the values of other descriptive keywords:

- `DATE`
- `FILENAME`
- `LEVEL`
- `EXTNAME`
- `VERSION`
- `BUNIT`
- `HISTORY`

In addition, the DATASUM and CHECKSUM keywords differ.

4.4.2.1 Keywords describing the individual L1 to L2 calibration steps

The individual L1 to L2 processing steps are described by the PRxxxxn keywords:

```

PRSTEP4 = 'DARK-SUBTRACTION' / Type of processing, step 4
PRPROC4 = 'spice_prep_dark_offset_correction.pro' / Name of procedure, step 4
PRPVER4 = '1.2' / Version of procedure, step 4
PRPARA4 = 'dark_spiobsid=33554603' / Parameters for PRPROC4
PRLIB4A = 'uio-spice-pipeline' / Software library containing PRPROC4

PRSTEP5 = 'FLATFIELDING' / Type of processing, step 5
PRPROC5 = 'spice_prep_flat_field_correction.pro' / Name of procedure, step 5
PRPVER5 = '1.2' / Version of procedure, step 5
PRPARA5 = 'ground-calibration flat field' / Parameters for PRPROC5
PRLIB5A = 'uio-spice-pipeline' / Software library containing PRPROC5

PRSTEP6 = 'SPATIAL-SPECTRAL-DISTORTION-CORRECTION' / Type of processing, step 6
PRPROC6 = 'spice_prep_distortion_correction.pro' / Name of procedure, step 6
PRPVER6 = '2.1' / Version of procedure, step 6
PRPARA6 = 'distortion correction matrix version: 2021-04-12' / Parameters for PR
PRLIB6A = 'uio-spice-pipeline' / Software library containing PRPROC6

PRSTEP7 = 'RADIOMETRIC-CALIBRATION' / Type of processing, step 7
PRPROC7 = 'spice_prep_radiometric_calibration.pro' / Name of procedure, step 7
PRPVER7 = '1.2' / Version of procedure, step 7
PRPARA7 = 'based on comparison to QS SUMER spectrum' / Parameters for PRPROC7
PRLIB7A = 'uio-spice-pipeline' / Software library containing

```

4.4.3 Data arrays and FITS headers: L3 R and L3 C

Each L2 HDU is the source for multiple L3 HDUs. Each L3 HDU will contain a derived data product based on L2 data containing derived data products. Therefore, both the data arrays and the header keyword values of the two file levels will differ significantly.

The data arrays of both L3 R and L3 C HDUs will always have a singular dispersion (third) dimension. In all other respects, the dimensionality will be similar to the dimensionality of L1 and L2 HDUs as described in Sections 4.4.1 and 4.4.2.

4.4.3.1 HDUs with narrow-slit spectral-profile or full detector readout data (window type 1 or 5)

Each HDU stemming from a window of type 1 or 5 contains a data array storing a single derived data product, derived from a single emission line. L3 R and L3 C HDUs contain the same keywords as the L1 and L2 HDUs described in Sections 4.4.1 and 4.4.2 but the values of keywords that describe the content of the data arrays will differ.

As an example, the BUNIT keyword will vary according to the type of derived data product:

L3 R/C Data Product	BUNIT
Peak Intensity	'W/m ² /sr/nm'
Velocity	'km/s'
Line Width	'nm'
Residuals	'W/m/sr/nm'

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```
PRPVER12=          0.1 / Version of procedure PRPROC12
PRPROC12= 'spice_temperatures.pro' / Name of procedure performing PRSTEP12
```

For intensity-window observations of a line/background window pair, the processing step leading to an HDU with background-subtracted intensity is described by the FITS keywords:

```
PRSTEP8 = 'BACKGROUND-SUBTRACTION' / Name of processing step 8
PRPVER8 =          3 / Version of procedure PRPROC8
PRPROC8 = 'spice_bkg_subtraction.pro' / Name of procedure performing PRSTEP8
```

4.4.4 Storing variable keyword values in binary table extensions

Some SPICE FITS keywords may have multiple values. Such keywords have:

- one value per exposure: acquisition times, mirror positions, and temperatures, see Section 4.4.4.1, or
- one value per segment: voltages, see Section 4.4.4.2, or
- values that are not directly linked to individual exposures or other dimensions of the data cube: lost telemetry packet indices and lost FFT Bin indices, see Section 4.4.4.3.

In all cases we use the *variable-keyword mechanism* outlined in Appendix I of [SOLARNET] (see <http://sdc.uio.no/open/solarnet/> for the latest version) to store the individual values of variable keywords in binary table extensions.

4.4.4.1 Variable keywords with one value per exposure: times, mirror positions, and temperatures

The acquisition time (OBT), scan mirror position and 4 instrument temperatures are recorded for each exposure of a SPICE observation. For single exposure observations, the values of these measurements are stored in the FITS keywords `TIMAQOBT`, `MIRRPOS`, `TN_FOCUS`, `TN_MIRR`, `TN_SW`, and `TN_LW`, and the temperatures converted from data numbers to degrees Celsius in `T_FOCUS`, `T_MIRR`, `T_SW`, and `T_LW`. In L1+ FITS files, `TIMAQUTC` stores the acquisition time converted to UTC. For multi exposure observations, these keywords hold the *average* values, and the *individual values* of each keyword, i.e. one value per exposure, are stored in a binary table extension using the variable-keyword mechanism.

In the header of a SPICE observational HDU that uses the variable-keyword mechanism, the `VAR_KEYS` keyword always have the following value:

```
VAR_KEYS= 'VARIABLE_KEYWORDS;TIMAQOBT,MIRRPOS,TN_FOCUS,TN_MIRR,TN_SW,TN_LW', &'
CONTINUE 'T_FOCUS, T_MIRR, T_SW, T_LW, TIMAQUTC' / Variable keywords
```

This means that in the binary table extension `VARIABLE_KEYWORDS`, the individual values of the keywords `TIMAQOBT`, `MIRRPOS`, `TN_XXXXX`, `T_XXXXX`, and `TIMAQUTC` are stored in columns with `TTYPEn` equal to the keyword names. Following Appendix I-d of [SOLARNET], the binary table columns and the referring HDU are to be associated pixel-by-pixel, since the `WCSDn` keywords are set to 'PIXEL-TO-PIXEL'. The dimensions of the value columns, given by `TDIMn`, are (1, 1, 1, NAXIS4), the singular dimensions signalling that there is one value per exposure that is valid for all (x, y, d) pixels for that exposure.

Below is an excerpt of such a binary table extension header, including column specific keywords that define the columns storing the individual `TIMAQOBT` and `TN_FOCUS` values.

```
XTENSION= 'BINTABLE'          / Written by IDL: Mon Sep 25 12:03:41 2017
:
```

```

EXTNAME = 'VARIABLE_KEYWORDS' / Extension name
:
WCSN1   = 'PIXEL-TO-PIXEL'    / Value column/referring HDU association type
TFORM1  = '64D'               / Real*8 (double precision)
TTYPER1 = 'TIMAQOBT'          / [OBT] Start time of data acquisition
TDIM1   = '(1,1,1,64)'        / Array dimensions for column 1
TUNIT1  = ' '                 / Units of column 1
TDMIN1  = 481295089.350       / Minimum value in column 1
TDMAX1  = 481295146.051       / Maximum value in column 1
TDESC1  = 'Variable values for TIMAQOBT' / Axis labels for column 1
:
WCSN3   = 'PIXEL-TO-PIXEL'    / Value column/referring HDU association type
TFORM3  = '64I'               / Unsigned Integer*2 (short integer)
TTYPER3 = 'TN_FOCUS'          / [adu] SFM focus adu temperature
TDIM3   = '(1,1,1,64)'        / Array dimensions for column 3
TUNIT1  = ' '                 / Units of column 3
TSCAL3  = 1 / Scale parameter for column 3
TZERO3  = 32768 / Zero offset for column 3
TDMIN3  = 846 / Minimum value in column 3
TDMAX3  = 871 / Maximum value in column 3
TDESC3  = 'Variable values for TN_FOCUS' / Axis labels for column 3

```

4.4.4.2 Variable keywords with one value per segment: voltages

4 instrument voltages per segment are downlinked in the science telemetry. For single-segment observations the raw values of these measurements are stored in the FITS keywords `VN_MCPSW`, `VN_MCPLW`, `VN_GAPSW`, and `VN_GAPLW`, and the voltages converted from data numbers to Volt in `V_MCPSW`, `V_MCPLW`, `V_GAPSW`, and `V_GAPLW`. For multi-segment observations these keywords hold the *average* values, and the *individual* values for each keyword, i.e. one value per segment, are stored in the same binary table extension described in the previous Section.

In the header of a SPICE observational HDU stemming from a multi-segment observation, the `VAR_KEYS` keyword have the following value:

```

VAR_KEYS= 'VARIABLE_KEYWORDS;TIMAQOBT,MIRRPOS,TN_FOCUS,TN_GRAT,TN_SW,TN_LW,T_F&'
CONTINUE 'OCUS,T_GRAT,T_SW,T_LW,VN_MCPSW,VN_MCPLW,VN_GAPSW,VN_GAPLW,V_MCPSW,V&'
CONTINUE '_MCPLW,V_GAPSW,V_GAPLW,TIMAQUTC' / Variable keywords

```

Below is an excerpt of the header of the 'VARIABLE_KEYWORDS' binary table extension, including column specific keywords that define the column storing the individual `VN_MCPSW` values, one value for each segment.

```

XTENSION= 'BINTABLE'          / Written by IDL:  Fri Oct 25 13:47:08 2019
:
EXTNAME = 'VARIABLE_KEYWORDS' / Extension name
:
-----
| Column 12 specific keywords |
-----
WCSN12  = 'PIXEL-TO-PIXEL'    / Value column/referring HDU association type
TFORM12 = '4I'                / Unsigned Integer*2 (short integer)
TTYPER12 = 'VN_MCPLW'         / [adu] MCP LW voltage
TDIM12  = '(1,1,1,4)'         / Array dimensions for column 12
TUNIT12 = ' '                 / Units of column 12
TSCAL12 = 1 / Scale parameter for column 12
TZERO12 = 32768 / Zero offset for column 12

```

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```
TDMIN12 = 553 / Minimum value in column 12
TDMAX12 = 553 / Maximum value in column 12
TDESC12 = 'Variable values for VN_MCPLW' / Axis labels for column 12
```

4.4.4.3 Variable keywords describing lost telemetry packets and lost FFT Bins

If telemetry packets containing observational data are lost the packet indices (starting at 0 for the first data packet) are stored in the binary table extension with name 'LOST_TELEMETRY' in L1, L2 and L3 FITS files. The name of the binary table column storing the indices of the lost packets is 'LOSTPKTS', followed by a tag giving the EXTNAME of the observational HDU that uses the variable-keyword mechanism (the referring HDU). The lost packet indices are stored primarily for pipeline debugging purposes.

Below is an excerpt of the header of a 'LOST_TELEMETRY' binary table extension, including keywords that define the column storing the individual lost packet indices:

```
XTENSION= 'BINTABLE' / Written by IDL: Mon Sep 9 11:08:01 2019
:
EXTNAME = 'LOST_TELEMETRY' / Extension name
:
TFORM1 = '3J' / Integer*4 (long integer)
TTYPE1 = 'LOSTPKTS[WINDOW0_724.05A]' / Lost packets w/data, variable keyword
TUNIT1 = ' ' / Units of column 1
TDMIN1 = 1 / Minimum value in column 1
TDMAX1 = 28 / Maximum value in column 1
TDESC1 = 'Indices of lost packets containing observational data' / Axis labels
```

The value of the VAR_KEYS keyword of the referring HDU contains the binary table extension name and the column name:

```
VAR_KEYS= 'VARIABLE_KEYWORDS;TIMAQOBT,MIRRPOS,TN_FOCUS,TN_GRAT,TN_SW,TN_LW,T_F&'
CONTINUE 'OCUS,T_GRAT,T_SW,T_LW,TIMAQUTC, &'
CONTINUE 'LOST_TELEMETRY;LOSTPKTS[WINDOW0_724.05A]' / Variable keywords
```

As described in [SPICELOST] the implications of lost telemetry packets in the case of SHC data highly depends on how many and which FFT Bins are lost. This information is therefore stored in the FITS files in order to help the advanced user to determine the degree of degradation of the approximated data cube. An additional binary table column storing the lost FFT Bin indices is added to the 'LOST_TELEMETRY' binary table extension. The name of this column is 'LOSTBINS' plus a tag with the EXTNAME of the referring HDU.

L1 files may contain data cubes that are reconstructed from incomplete SHC telemetry, but in the L2 and L3 files produced by the Science Data Pipeline all pixels in such cubes have the value NaN. However, the user may choose to keep incomplete data cubes when running the L1 to L2 calibration routines manually and use the information in the LOSTBINS column when interpreting the data.

Below is an excerpt of the header of a 'LOST_TELEMETRY' binary table extension, including keywords that define the column storing the individual lost FFT Bin indices:

```
XTENSION= 'BINTABLE' / Written by IDL: Mon Sep 9 11:08:01 2019
:
EXTNAME = 'LOST_TELEMETRY' / Extension name
```

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```

:
TFORM2 = '8I          ' / Integer*2 (short integer)
TTYPE2 = 'LOSTBINS[WINDOW0_724.05A]' / Lost FFT bins, variable keyword
TUNIT2 = '          ' / Units of column 2
TDMIN2 =          0 / Minimum value in column 2
TDMAX2 =          31 / Maximum value in column 2
TDESC2 = 'Indices of lost FFT Bins' / Axis labels for column 2

```

The VAR_KEYS keyword of the referring HDU contains the binary table extension name and the column name:

```

VAR_KEYS= 'VARIABLE_KEYWORDS;TIMAQOBT,MIRRPOS,TN_FOCUS,TN_GRAT,TN_SW,TN_LW,T_F&'
CONTINUE 'OCUS,T_GRAT,T_SW,T_LW,TIMAQUTC,          &'
CONTINUE 'LOST_TELEMETRY;LOSTPKTS[WINDOW0_724.05A],LOSTBINS[WINDOW0_724.05A]&'
/
CONTINUE '' / Variable keywords

```

The referring HDU contains representative scalar values of variable keyword (see Appendix I of [SOLARNET]). The representative scalar values of LOSTPKTS and LOSTBINS are the number of lost telemetry packets and the number of lost FFT Bins respectively:

```

LOSTPKTS =          3 / Number of lost packets w/data, variable
keyword
LOSTBINS =          8 / Number of lost FFT bins, variable keyword

```

4.4.5 Flagging image planes with approximated values using binary table pixel list

As described in [SPICELOST] it is possible to reconstruct a data cube in the case of lost telemetry, even if the data is compressed. However, one or more planes of the data cube may in such cases have approximated values, depending on which kind of compression was applied and how many telemetry packets were lost. We use the pixel list mechanism described in Appendix II-a of [SOLARNET] to flag image planes that have approximated values.

The data cubes of L1 files may contain approximated image planes, but in L2 and L3 files produced by the Science Data Pipeline all pixels in such image planes have the value NaN. However, the user may choose to keep approximated image planes when running the L1 to L2 calibration routines manually.

For every observational HDU that uses the pixel list mechanism there is a corresponding binary table extension containing a single pixel list where the image plane indices of approximated image planes are stored. The name of this binary table extension is 'PLNAPRXPIXLIST' plus a tag with the EXTNAME of the referring HDU.

As an example we consider a raster observation (i.e. the data cube has dimensions (X,Y,D,1)) where each X-Y image plane is JPEG compressed on-board. If telemetry packet 7 of the referring HDU WINDOW6_974.79A is lost, an excerpt of the 'PLNAPRXPIXLIST' binary table extension header may look like this:

```

XTENSION= 'BINTABLE' / Written by IDL: Mon Sep 9 14:20:48 2019
:
EXTNAME = 'PLNAPRXPIXLIST[WINDOW6_974.79A]' / Extension name
:
TFORM1 = '1I          ' / Integer*2 (short integer)

```

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```

TTYPE1 = 'DIMENSION3'           / Image plane indices
TCTYP1 = 'PIXEL '              / Indicates that column 1 is a pixel index
TPC1_1 =                        1 / Indicates that column 1 is a pixel index
TUNIT1 = ' '                   / Units of column 1
TDMIN1 =                        7 / Minimum value in column 1
TDMAX1 =                        7 / Maximum value in column 1
TDESC1 = 'X-Y image plane indices approximated b/c telemetry loss' / Axis label

```

The value of TTYPE1 means that the values stored in column 1 is an index into dimension 3 of the data cube, i.e. $(X, Y, D, t) = (*, *, 7, 1)$ is flagged as approximated.

In the header of the referring HDU the name of the pixel list binary table extension is given by PIXLISTS, and NAPRXPLN gives the number of approximated image planes:

```

PIXLISTS= 'PLNAPRXPIXLIST[WINDOW6_974.79A];' / List of approximated X-Y planes
NAPRXPLN= 1 / Number of approximated X-Y planes

```

Note that for SHC data *all* image planes stemming from a single segment are approximated if telemetry packets are lost. The amount of approximation may be estimated using the variable keyword LOSTBINS described in Section 4.4.4.3

APPENDIX A SPICE DATA PRODUCTS MATRIX

A FITS file may contain different types of HDUs/data products. Each HDU type may occur in files with a number of different combinations of descriptor elements.

L1 and L2:

In Table 4-8 we have listed all possible L1 and L2 data products, and the file descriptors that a FITS file containing such a product may have.

Data Product (HDU type)	Description	Descriptors	Avg cadence	Expected Daily Vol
Narrow-slit spectral-profile raster		n-ras[-db][-int]		
Narrow-slit intensity-window raster		n-ras[-db]-int		
Wide-slit raster		w-ras		
Dumbbell raster		n-ras-db[-int]		
Narrow-slit spectral-profile sit-and-stare		n-sit[-db]		
Wide-slit sit-and-stare		w-sit		
Dumbbell sit-and-stare		n-sit-db		
Narrow-slit full detector single exposure		n-exp		
Wide-slit full detector single exposure		w-exp		

L3 R and L3 C:

In Table 4-9 we have listed all possible L3 R and L3 C data products, and the file descriptors that a FITS file containing such a product may have.

Table 4-8: SPICE L1 and L2 Data Products Matrix

Data Product (HDU type)	Description	Descriptors	Avg cadence	Expected Daily Vol
Narrow-slit spectral-profile raster		n-ras[-db][-int]		
Narrow-slit spectral-profile sit-and-stare		n-sit[-db]		
Narrow-slit full detector single exposure		n-exp		

Table 4-9: SPICE L3 R and L3 C Data Products Matrix

APPENDIX B RELEATIONSHIP BETWEEN SCIENCE HEADER PACKET PARAMETERS AND FITS KEYWORDS

Section 4.2.6.1 of [DATAICD] lists the Science Header Packet parameters that describe the collection of Science Data Packets that builds up a raster segment. These parameters may apply to all windows of an observation, a single window, a single raster segment, or the parameters may have one value per exposure. The values of these parameters are stored as FITS keywords, see Table 4-10. Note that the “StudyFlags” parameter is an 8-bit integer with the value of each bit indicating different instrument settings, see Table 4-11. Both the primary HDU and all image extensions store all the FITS keywords described in the table. The shaded table rows indicate parameters/keywords with one value for each exposure. The mean values of these keywords are stored in the primary HDU and all image extensions, and the individual values for each exposure is stored in a binary table extension, see Section 4.4.4.

Science Header Packet Parameters	FITS keywords
Total number of CCSDS packets for this window	NPACKETS -1 or -2 (NPACKETS is the number of packets with observational data, excluding the Header Packet and the Final Packet if the latter only contains a checksum)
Observation ID	SPIOBSID
Focus position	FOCUSPOS
Slit position	SLIT_ID
Exposure time	XPOSURE * 10
Study ID	STUDY_ID
StudyFlags	STUDYFLG
Total Raster Segments per Window	NSEGMENT
ObsRasterNumber	RASTERNO
Raster Segment Number	-
Window Total Number	NWIN
Window Number	WINNO
Window Data Table ID	WINTABID
Window Start Column	PXBEG3 (PXEND3 for wide-slit and dumbbells)
Window Width	PXEND3 - PXBEG3 + 1 (PXBEG3 - PXEND3 + 1 for wide-slit and dumbbells)
Wavelength Binning Factor	NBIN3
Window Starting Row	PXBEG2
Window Height	PXEND2 - PXBEG2 + 1
Y Binning Factor	NBIN2
Compression Type	COMPTYPE
Compression Amount Parameter	COMPPARA
SHC FFT ID	SHCFFTID
Pixel Level Offset	PIXELOFF
Alignment Window Status	DUMBELL

Science Header Packet Parameters	FITS keywords
MCP SW Monitor Voltage	VN_MCPSW (and V_MCPSW)
MCP LW Monitor Voltage	VN_MCPLW (and V_MCPLW)
Gap SW Monitor Voltage	VN_GAPSW (and V_GAPSW)
Gap LW Monitor Voltage	VN_GAPLW (and V_GAPLW)
Segment X Size	-
Acquisition Time when initiating black level reset after arriving at X	TIMAQOBT
Scan Mirror Position	MIRRPOS
Temperature 1	TN_FOCUS (and T_FOCUS)
Temperature 2	TN_GRAT (and T_GRAT)
Temperature 3	TN_SW (and T_SW)
Temperature 4	TN_LW (and T_LW)

Table 4-10: Telemetry Science Header Packet Parameters and their keyword equivalents. Note that the two parameters that describe a single raster segment do not have FITS keyword equivalents. Keywords in red are Solar Orbiter-wide FITS keywords. The values of the individual bits of STUDYFLG determine the values of the 6 derived keywords in Table 4-11. The voltages and temperatures are given in engineering units in the VN_XXXXX and TN_XXXXX keywords, and are converted to Volt and Celsius in the V_XXXXX and T_XXXXX keywords. Orange shading indicates parameters with one value per segment, blue shading indicates parameters with one value per exposure. In L1+ FITS files the onboard time TIMAQOBT is converted to UTC and given in TIMAUTC (this keyword is not present LL01 FITS files).

Bit	Study Flag Description	FITS Keywords
0 -1	Spare	-
2	AlignExcludeSpectral - 0 = Do not exclude spectral window data - 1 = Exclude spectral window data	NOSPECTR
3	Cal Mode Config - 0 = 1 Data Plane - 1 = 2 Data Planes	CALMODE
4	Double Exposure Number - 0 = First Exposure - 1 = Second Exposure	DBLEXPNO
5	Double Exposure Enabled - 0 = False - 1 = True	DBLEXP
6	Dark Map Subtraction Used? - 0 = False - 1 = True	DARKMAP
7	Black Level Subtraction Used - 0 = False - 1 = True	BLACKLEV

Table 4-11: FITS keywords derived from the value of STUDYFLG. All FITS keywords have values 0 or 1.

APPENDIX C RELEATIONSHIP BETWEEN STUDY SETS, IORS AND FITS KEYWORDS

IAS provide Study Set files containing the definitions of all on-board studies, and IORs¹⁰ containing the commanded parameters of each observation (i.e. each instance of a study). These files are used by the Science Data Pipeline in order to populate L1+ FITS keywords.

For each observation the SPICE Observation ID found in the telemetry (`SPIOBSID`, see Appendix B) is used to find the IOR containing the information about that specific observation. The IOR contains information about which Study Set was used by the planning tool in creating the IOR (the Study Set `<version>`). Having found the correct Study Set file, the `STUDY_ID` of the telemetry is then used to find the Study Set's definition of the study in question.

If a parameter found in the IOR or Study Set is also found in the telemetry, the telemetry value is the one used as a FITS keyword value. This is to ensure that the metadata describe the actual contents of file, and not what was commanded.

The following FITS keywords are set based on XML tags, parameters values and XML comments in the IORs:

- STP – Solar Orbiter Short-Term Plan number
- WINSHIFT – The number of pixels the window is shifted towards the red on the detector relative to the base position of windows with the current `MISOID`
- OBS_ID – SOC Observation ID (not to be confused with the SPICE Observation ID, `SPIOBSID`)
- OBS_TYPE – Unique code for `OBS_MODE/STUDY`, derived from `OBSID`
- SOOPTYPE – Unique code for `SOOPNAME`, derived from `OBSID`
- SOOPNAME – The name of the SOOP (given in XML comments in the IORs)
- NRASTERS – The number of planned rasters for a given `SPIOBSID`
- DARKSPID – The `SPIOBID` of the dark that has been subtracted on-board. Set to -1 if no on-board dark subtraction

Table 4-12 below summarises the Study Set XML tags describing a study and their translation into FITS keywords.

XML tags	XML tag data type and values	FITS keywords	FITS keyword data type and values	In TLM
<code><studyInfo></code>				
<code><groundId></code>	$0 \leq \text{int} \leq ?$	MISOSTUD	Same as XML tag	No
<code><name></code>	String, free text	STUDY and <code>OBS_MODE</code>	Same as XML tag	No
<code><purpose></code>	String, {"Calibration", "Science", "Engineering"}	PURPOSE	Same as XML tag	No
<code><description></code>	String, free text	STUDYDES	Same as XML tag	No
<code><author></code>	String, free text	AUTHOR	Same as XML tag	No
<code></studyInfo></code>				
<code><onboardInfo></code>				
<code><onboardID></code>	$0 \leq \text{int} \leq 63$	STUDY_ID	Same as XML tag	Yes

¹⁰ Instrument Operation Requests

XML tags	XML tag data type and values	FITS keywords	FITS keyword data type and values	In TLM
</onboardInfo>				
<type>	String, {"Full Spectrum", "Spatial Scan", "Time Series", "Scanned Time Series"}	A mix of STUDYTYP and WIN_TYPE. These two keywords are populated using information in the telemetry.	STUDYTYP, {"Sit-and-stare", "Raster", "Single Exposure"} WIN_TYPE, {"Narrow-slit Spectral", "Dumbbell (lower)", "Dumbbell (upper)", "Wide-slit", "Intensity-window", "Full Detector Narrow-slit", "Full Detector Wide-Slit"}	Yes, implicitly
<slit>	$1 \leq \text{int} \leq 4$	SLIT_ID	Same as XML tag	Yes
<exposures>	$1 \leq \text{int} \leq 480$ ¹¹	CDELTA1 or CDELTA4 (when <exposures> eq actual number of exposures)	Same as XML tag (when <exposures> eq actual number of exposures)	Yes
<expTime>	$0.1 \leq \text{float} \leq 1023.5$ ¹²	XPOSURE	Same as XML tag	Yes
<totalExpTime>		XPOSURE for double exposure	Same as XML tag	No
<xStart>	float, default 0	XSTART. Also used when calculating CRVAL1	Same as XML tag	No
<stepSize>	float, default ?	CDELTA1	Same as XML tag	No
<delayTime>	float, default ?	None	–	No
<alignmentWindowConfig>				
<excludeSpectral>	boolean, default false	NOSPECTR	Int, {0,1}	Yes
<compressionUpper>				
<type>	String, {"Spatial Lossy", "Focal Lossy",	COMPRESS	Same as XML tag	Yes, implicitly

¹¹ Any number from 1 to 64, multiples of 2 between 66 and 128, multiples of 4 between 132 and 256, multiples of 8 between 264 and 480

¹² Overheads for resetting detector pixels are added to these numbers. The overhead scales with the number of pixels in the dispersion dimension. Resolution of expTime is 0.1 s between 0.1 s and 204.7 s, 0.5 s between 205 s and 1023.5 s.

XML tags	XML tag data type and values	FITS keywords	FITS keyword data type and values	In TLM
	"Spatial Uncompressed", "Focal Uncompressed", "SHC Low", "SHC High"			
<rawFactor>	$1 \leq \text{Int} \leq 256?$	COMP_RAT = raw data volume/compressed volume. Applies to all observations (not only JPEG compressed)	Int, {1,128}	Yes, implicitly
<shcCoef>	$0 \leq \text{Int} \leq 7$	SSHCFEFTID	Same as XML tag	Yes
</compressionUpper>				
<compressionLower>				
		See <compressionUpper>		
</compressionLower>				
</alignmentWindowConfig>				
<options>				
<readoutMode>	string, {"Destructive", "Non Destructive"}	READMODE	Same as XML tag	No
<calMode>	string, {"Uncompressed", "Compressed", "Both"}	CALMODE	Int, {0,1} (0 = one data plane (compressed or uncompressed), 1 = two data planes (compressed <i>and</i> uncompressed))	Yes
<focusCal>		None	–	No
<macroSteps>		None	–	No
<macroDelay>		None	–	No
<darkMap>	boolean	DARKMAP	Int, {0,1}	Yes
</options>				
<window>				
<windowInfo>				
<description>	string	EXTNAME. For dumbbells, either "DUMBBELL_UPPER_" or "DUMBBELL_LOWER_" is prepended to the description string.	Same as XML tag	No

XML tags	XML tag data type and values	FITS keywords	FITS keyword data type and values	In TLM
<wavelength>		None (keywords describing wavelength, e.g. WAVEMIN, WAVEMAX) are calculated from telemetry parameters)	-	Yes. implicitly
<onboardID>	$0 \leq \text{int} \leq 255$	WINTABID	Same as XML tag	Yes
<groundID>	$0 \leq \text{int} \leq ?$	MISOWIN	Same as XML tag	No
<iwin_type>	String, {"", "Background", "Line"}	IWIN_TYPE	Same as XML tag	
<background_number>	$0 \leq \text{int} \leq 255$	Used to determine IWINBKG	EXTNAME of extension storing background intensity-window	
<line_number>	$0 \leq \text{int} \leq 255$	Used to determine IWINLINE	(Comma-separated list of) EXTNAME(s) of extension(s) storing line intensity-window	
</windowInfo>				
<axis axisName="lambda">				
<start>		PXBEG3		Yes
<size>		PXEND3 - PXBEG3 + 1		Yes
<binFactor>		NBIN3		Yes
</axis>				
<axis axisName="Y">				
<start>		PXBEG2		Yes
<size>		PXEND2 - PXBEG2 + 1		Yes
<binFactor>		NBIN2		Yes
</axis>				
<compression>				
		See <compressionUpper>		
</compression>				
<alignmentWindow>		DUMBBEXT Not implemented yet	(Comma-separated list of) EXTNAME(s) of the extension(s) containing dumb-bell data for this window	No
</window>				

Table 4-12: Relationship between Study Generator XML tags and FITS keywords.

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