Solar Orbiter: SPICE

SPICE Instrument User Manual Issue 7.0 DRAFT

<table>
<thead>
<tr>
<th>Name</th>
<th>Signature / Date</th>
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<tbody>
<tr>
<td>Prepared by</td>
<td>Martin Caldwell (editor)</td>
</tr>
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</table>
| Reviewed by               | Paul Eccleston (SPICE Engineering Manager)  
                          | Andrzej Fludra (Project Scientist) |
| Approved by               | Nigel Morris (SPICE Project Manager) |
| Approved by               | Jenny Davenne (SPICE PA Manager) |

STFC Rutherford Appleton Laboratory  
RAL Space  
Harwell Oxford  
Didcot  
Oxfordshire OX11 0QX  
United Kingdom
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<td>RID #111. Update to performance analysis RP-0002, consistency with Study definitions. A note is added to updated Study table 4 of this document to show the link.</td>
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<td>RID #126. Out-of-band stray-light, grating scatter. Separate tech note has been written SPICE-RAL-TN-0103. This is referred to in Science Performance doc, also updated for this RID.</td>
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<td>RID #127. Proposed studies, instrument performance. Column added to studies table 4 to confirm what line-SNR is reached in each case, and at what spatial resolution (binning). Note added to explain that advertised velocity resolution is at 1-sigma.</td>
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<td>Requested acronyms added and reference given to SPICE acronym list</td>
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<td>Sect 2.2.2: documents added to the ref. docs. Fig 2-18 ref removed. - References to figures and RD’s checked and corrected. Use of acronym DPM corrected.</td>
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<td>- 1) Repetition of calibration tasks in NECP and CP. Previous table 5 with list of tests, now split into separate tables per phase. Repeats of tests explicitly stated, and justifications given.</td>
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</table>
### Section 2.2.2.1 Image Readout

- 3) ‘encounter’ changed to ‘rs window’
- 4) NMP calibrations, clarified which tests recommended in which RS windows
- 6) out-of-field, generalised to cover any location on the solar limb

Some test durations now decreased thanks to use of ‘full-frame’ detector operation.

Calibration plan PL-0005 also updated.

RID #138 Added detail on definition of science packets and data overheads, with examples

Action 155-B, RID #155: Note added, for 2”, 4”, 6”, slit-length is less than 14’. Impact on science window size is now noted.

Inst-CDR action 99-A

RID #140, text added.

RID #150 text added to clarify detector HV operation

RID #117 updated text on data compression

RID #139 spacecraft communication rolls

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### Section 2.6.3.4 Data Management

RID #139 spacecraft communication rolls

### Section 2.6.3.3

RID #117 updated text on data compression

### Section 4.1

RID #150 text added to clarify detector HV operation

### Section 4.2.3

RID #139 spacecraft communication rolls

### Section 3.4

Identification of PIDs for commanding:

**Identification of PIDs for TM retrieval by OBC.** These now added to section 3.4 (S. Sidher)

### Section 4.4

SPICE Instrument Action #1702: Inserted sub-sections in the Autonomy section 4.4 to clarify usage of Services 20 and 22. (S. Sidher)

FDIR actions on spacecraft, list of OBCPs and title indicating function, added in section 4.5.1 (C. Howe)
<table>
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<td>09-01-14</td>
<td>SPICE</td>
<td>section 4.6 Operations Plan, section 4.6.3 NECP phase</td>
<td>Inst-CDR RID #134: Section updated to move details to separate document, i.e. re-instated commissioning plan. Updated table 7. (M Caldwell)&lt;br&gt;Updated Table 4.</td>
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<td>Following HLC to turn on, time delay before communication with the instrument becomes active via TM (C. Howe)</td>
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<td>RID #152 off-pointing constraint, description of variation with solar distance</td>
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<td>RID #36 monitoring parameters, what HK parameters SPICE wants. Answered in previous iss. 3.0, in section 3.4</td>
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<td>RID #134 to make separate detailed commissioning plan, answered in version 3.0, see above change note for that version</td>
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RID’s<br>#140<br>#150<br>#117<br>#139<br>-these are already done since issue 2.0
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<td>RID #117 (compression strategy) originally answered since version 2.0 (see change notes above). Note now added to section 4.6.5.1 NMP calibrations, to show priorities for data down-link. Ops Concept, also covered by RID #154 below.</td>
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<td>App.G</td>
<td>App. G Sun off-pointing constraint. Sub-section added, ‘effect of pointing errors’. In response to SOL-EST-MN-10334, AI #1</td>
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<td>Revision-marked edits by TWG, now included. Tables. 4 (data rate) and table 6 (low-latency data), updated for the new study durations. Section 4.5 FDIR, draft from 6th May now copied in, to be checked. Sect 4.5.2 newly-defined information on the RTHK packet flags and monitoring rates, from ASTR TN288 Section 5.8.2.1 – Monitors</td>
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1. INTRODUCTION

1.1 Scope
This document is the user manual for the SPICE instrument in accordance with the DRD SOL-EST-RS-4095.

1.2 Documentation

1.2.1 Applicable documents

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<td>Data Requirements Document for the Solar Orbiter Payload</td>
<td>SOL-EST-LI-2241</td>
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Table 1-1: Applicable Documents

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<td>ISS0.1 EM 14885-018</td>
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Table 1-2: Reference Documents

1.3 Acronyms

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Other acronyms are given in the SPICE Acronym List in #RD16.
2. SPICE INSTRUMENT DESCRIPTION

2.1 SPICE Scientific objectives

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 the 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.

SPICE is designed to study the structure, dynamics and composition of the corona by observing key emission lines on the solar disk over critical time scales. A key aspect of the SPICE observing capability is the ability to quantify the spatial and temporal signatures of temperature and density tracers to unravel the inter-relationship between the chromosphere, coronal structures, coronal mass ejections, the solar wind, and the low corona.

Careful selection of the two SPICE passbands provides:
1. Complete temperature coverage from the low chromosphere to the flaring corona,
2. A range of strong coronal (Li-like) resonance lines,
3. Detailed remote composition diagnostic capability of high and low FIP ion species as well as ions with different mass to charge (M/q) ratios to be compared with in-situ composition measurements on Solar Orbiter.

The two EUV wavelength bands, 70.0 – 79.2 nm and 97.0 – 105.3 nm, observed by SPICE are dominated by emission lines from a wide range of ionized atoms of H, C, O, N, Ne, S, Mg, Si, and Fe, formed in the Sun’s atmosphere at temperatures from 10,000 to 10 million K. A selection of representative lines over the entire temperature range is given in Table 1.

SPICE will measure plasma temperature, ‘emission measure’ EM=$\int N_e^2 dV$, flow velocities, the presence of plasma turbulence, plasma composition and the dependence of elemental abundances of the solar plasma on the First Ionization Potential. It will be observing, at all latitudes, the energetics, dynamics and fine-scale structure of the Sun’s magnetized atmosphere.

Table 1 – Selection of SPICE spectral lines.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Wavelength (Å)</th>
<th>Log T (K)</th>
<th>FIP (eV)</th>
<th>M/q</th>
</tr>
</thead>
<tbody>
<tr>
<td>H I</td>
<td>1025</td>
<td>4.0</td>
<td>13.6</td>
<td>---</td>
</tr>
<tr>
<td>C II</td>
<td>1036</td>
<td>4.3</td>
<td>11.3</td>
<td>12.0</td>
</tr>
<tr>
<td>C III</td>
<td>977</td>
<td>4.5</td>
<td>11.3</td>
<td>6.0</td>
</tr>
<tr>
<td>O IV</td>
<td>787.7</td>
<td>5.2</td>
<td>13.6</td>
<td>5.3</td>
</tr>
<tr>
<td>O V</td>
<td>760</td>
<td>5.4</td>
<td>13.6</td>
<td>4.0</td>
</tr>
<tr>
<td>O VI</td>
<td>1032</td>
<td>5.5</td>
<td>13.6</td>
<td>3.2</td>
</tr>
<tr>
<td>O VI</td>
<td>1037</td>
<td>5.5</td>
<td>13.6</td>
<td>3.2</td>
</tr>
<tr>
<td>S V</td>
<td>786.5</td>
<td>5.2</td>
<td>10.36</td>
<td>8.0</td>
</tr>
<tr>
<td>Ne VI</td>
<td>1005</td>
<td>5.5</td>
<td>21.6</td>
<td>4.0</td>
</tr>
<tr>
<td>Ne VII</td>
<td>973</td>
<td>5.6</td>
<td>21.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Ne VIII</td>
<td>770</td>
<td>5.8</td>
<td>21.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Mg VIII</td>
<td>772</td>
<td>5.9</td>
<td>7.7</td>
<td>3.4</td>
</tr>
<tr>
<td>Mg IX</td>
<td>706</td>
<td>6.0</td>
<td>7.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Mg XI</td>
<td>997</td>
<td>6.2</td>
<td>7.7</td>
<td>2.4</td>
</tr>
<tr>
<td>Si VII</td>
<td>1049</td>
<td>5.6</td>
<td>8.1</td>
<td>4.8</td>
</tr>
<tr>
<td>Si XII</td>
<td>521 (n)</td>
<td>6.5</td>
<td>8.1</td>
<td>2.6</td>
</tr>
<tr>
<td>Fe X</td>
<td>1028</td>
<td>6.0</td>
<td>7.9</td>
<td>6.2</td>
</tr>
</tbody>
</table>
Spacially resolved UV imaging spectroscopy is an essential tool to study Sun’s atmosphere. SPICE is the only instrument providing the plasma diagnostic capability for these studies. It will remotely determine plasma properties on the Sun and provide understanding of the linkage between in-situ measurements of solar wind streams using the suite of plasma instruments on Solar Orbiter and remote imaging of their source regions on and near the Sun.

SPICE contributes to all four top-level science objectives of Solar Orbiter (Definition Study Report, ESA/SRE(2011)14):

1. How and where do the solar wind plasma and magnetic field originate in the corona?
2. How do solar transients drive heliospheric variability?
3. How do solar eruptions produce energetic particle radiation that fills the heliosphere?
4. How does the solar dynamo work and drive connections between the Sun and the heliosphere?

Detailed science goals, required observations and measurement objectives relating to each of these four questions are given in Table 2. Traceability of these science goals to instrument parameters is given in Appendix H.

Table 2: Traceability of SPICE Science goals and measurements. Further traceability to instrument parameters is given in Appendix H.

<table>
<thead>
<tr>
<th>Science Question</th>
<th>Required SPICE Observations</th>
<th>SPICE Measurement Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.1 What are source regions of the solar wind &amp; heliospheric magnetic field?</td>
<td>(a) Composition of solar wind source regions</td>
<td>Determine FIP and Q/M effect in solar wind source regions</td>
</tr>
<tr>
<td></td>
<td>(b) spectral images of chromosphere &amp; corona</td>
<td>Identify feature types that give rise to the solar wind by correlating Doppler shift to structure and composition</td>
</tr>
<tr>
<td>2.1.2 What mechanisms heat and accelerate the solar wind?</td>
<td>(a) High-res spectral images of loops &amp; evolving structures</td>
<td>Evolution of source regions on time scale of network evolution. Measure outflow (from Doppler shift) and correlate with structure type.</td>
</tr>
<tr>
<td></td>
<td>(b) Wave propagation and heating</td>
<td>Line width, Doppler shift, &amp; Intensity time series observations</td>
</tr>
<tr>
<td>2.1.3 What are the sources of solar wind turbulence and how does it evolve?</td>
<td>Images of source regions in Doppler-broadened lines</td>
<td>Identify jets, heating, and turbulence; correlate to network evolution</td>
</tr>
</tbody>
</table>
### 2.2.1 How do CMEs evolve through the corona and inner heliosphere?

| Map CME source location, expansion, rotation and composition | Identify areas of coronal dimming; Measure velocities in the erupting CME; Establish identity of plasma in visible parts of a proto-CME on-disk and connect (via compositional correlation) to higher altitudes and in situ measurements |

### 2.2.2 How do CMEs contribute to solar magnetic flux and helicity balance?

| Map source regions to in-situ properties magnetic connectivity, polarity, & helicity | Establish identity of plasma in visible parts of a proto-CME on-disk and connect (via compositional correlation) to higher altitudes and in situ measurements |

### 2.2.3 How and where do shocks form in the corona?

| High-resolution coronal and chromospheric images | Identify and characterize small-scale shocks in the low corona from spicules and other excitation sources. Establish identity of plasma in different parts of a proto-CME and connect (via compositional correlation) to higher altitudes and in situ measurements. |

### 2.3.1 How and where are energetic particles accelerated at the Sun?

| (a) UV & X-ray imaging of loops, jets, flares, and CMEs | Identify jets and reconnection sites that give rise to SEPs |
| (b) Images of longitudinal extent of CMEs in visible, UV, and hard X-rays | Image structure & longitudinal extent of CMEs in UV |

### 2.3.2 How are energetic particles released from their sources and distributed in space and time?

| Timing, location and intensity profiles of VUV emissions in relation to energetic particle intensities at a wide range of energies | Provide thermodynamic characteristics of plasmas in the SEP sources. Establish identity of plasma supplying SEPs and connect (via compositional correlation) to higher altitudes and in situ measurements |

### 2.4.1 How is magnetic flux transported to and re-processed at high solar latitudes?

| High-resolution images of small-scale magnetic features at the poles | Determine evolution of magnetized regions on the time scale of network evolution, by observing evolution of the structure seen in the EUV emission and associated flows. Provide constraints on meridional circulation at high latitudes. Reveal the pattern of differential rotation in the chromospheric and transition region emission. |

### 2.4.2 What are the properties of the magnetic field at high solar latitudes?

| Line-of-sight plasma flows, spatial distributions of intensities of chromospheric and transition region lines, and temperatures of polar regions | Identify feature types that give rise to the solar wind by correlating Doppler shift to structure and composition. Contribute to the investigation of the 3D structure of the inner heliosphere – study the links between the polar regions and the in-situ properties of the solar wind and the IMF. Study the response in the EUV emission to the magnetic field cancellation process during the polarity reversal. |
2.1.1 Performance Characteristics

SPICE performance characteristics are given in Table 3.

SPICE design features:

- Telescope type: Single-mirror off-axis paraboloid operating at near normal incidence
- Mirror characteristics: 43x43 mm² aperture area (physical mirror size 103x103 mm²), 622 mm focal length, λ/20 rms figure, <2 Å rms micro-roughness, B₄C coating
- Low-expansion mirror substrate (fused silica)
- Entrance aperture at the front
- Deflector plates: Two plates with static HV supply
- Baffles
- Heat rejection pre-slit mirror in front of the slit
- Precision manufactured CFRP structure
- Single toroidal variable line space (TVLS) grating, ruling density = 2400 lines/mm
- Slit assembly: linear translation, 4 slits: 2", 4", 6", 30" width
- ±0.5 mm focus adjustment along telescope chief ray
- Detector assembly with conductive cooling, 2 intensified APS detectors, 1024×1024 arrays
- KBr coated microchannel plates

Particular features of the instrument needed due to proximity to the Sun include: use of dichroic coating on the mirror to reject the majority of the solar spectrum by transmitting it through the instrument and back into space, particle-deflector to protect the optics from the solar wind, and use of data compression due to telemetry limitations.

Referring to optical layout in the figure below. The single-mirror telescope is an off-axis paraboloid design. The mirror has a di-chroic coating such that the wanted EUV light is reflected, but the bulk of the solar energy in visible and IR is transmitted. The mirror and baffles are sized such that for all SO pointing positions on the solar disc, the direct solar light is passed by the mirror. This transmitted beam is then folded by the Heat Rejection Mirror to a direction where it can leave the spacecraft, via the instrument exit aperture.

**Table 3 - SPICE performance characteristics**

<table>
<thead>
<tr>
<th>Plate scale</th>
<th>1.1 arcsec/pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSF size</td>
<td>~3 arcsec (FWHM)</td>
</tr>
<tr>
<td>FOV sizes</td>
<td>14 arcmin slit length for 30&quot; slit incl. 30&quot;x30&quot; dumbbell at each end</td>
</tr>
<tr>
<td></td>
<td>11 arcmin slit length for 2&quot;, 4&quot; and 6&quot; slits</td>
</tr>
<tr>
<td></td>
<td>16 arcmin raster-fov</td>
</tr>
<tr>
<td>APS usable pixels</td>
<td>968 x2 bands spectral pixels, 800 spatial pixels</td>
</tr>
<tr>
<td>Slit widths</td>
<td>2, 4, 6 and 30 arcsec</td>
</tr>
</tbody>
</table>
### Spectral Coverage

<table>
<thead>
<tr>
<th></th>
<th>SW: 70.387 - 79.019 nm (1st order)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LW: 97.254 - 104.925 nm (1st order)</td>
</tr>
<tr>
<td></td>
<td>48 - 53 nm (2nd order)</td>
</tr>
</tbody>
</table>

### Dispersion Plate Scale

<table>
<thead>
<tr>
<th></th>
<th>~ 0.0095 nm/pixel (SW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>~ 0.0083 nm/pixel (LW)</td>
</tr>
<tr>
<td>(</td>
<td>~ 40 km/sec per pixel</td>
</tr>
</tbody>
</table>

### Resolution at 2” Slit Width

<table>
<thead>
<tr>
<th></th>
<th>~3500 SW (3.6 pixel FWHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>~5000 LW (4 pixel FWHM)</td>
</tr>
</tbody>
</table>

### Out-of-band Background

~ 1 photon/s per pixel

### Line Centroid Accuracy

14 km/sec for 100 photons in line, 2 arcsec spatial bin.  
4 km/sec for 1000 photons

### Effective Area, BOL

<table>
<thead>
<tr>
<th></th>
<th>SW: 5 mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LW: 11 mm²</td>
</tr>
</tbody>
</table>

### Temporal Resolution (Raster Cadence)

Exposure time >1s, typically 4s for dynamics studies  
(cadence 2 min/arcmin)

### Data Compression

between 18:1 and 26:1 for spectral data, 10:1 for imaging data

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### 2.2 SPICE Measurement Principle

The SPICE Instrument is an imaging spectrograph which records high resolution EUV spectra of the Sun. The optical path is shown in the figure below. The solar light is collected by a single-mirror telescope. The instrument entrance aperture is at the front of the SPICE optics box, it is sized at ~4x4cm, and has a sliding door. Before reaching this aperture the solar beam is restricted by the heat-shield feed-through baffle, which extends to approx. 30cm ahead of SPICE, and this restricts the angular range of illumination and so also the solar heat load onto the SPICE aperture and door.
Figure 2-1 SPICE optical chain

In the reflected light the mirror forms an EUV image of the solar disc, on the SPICE slit.

The telescope mirror mount includes a focussing mechanism. This is needed to cope with the T-range of the operating environment, and thermal deformations of the mirror. The mount also has an angle-scan function. This is to generate the raster-FOV. The slit is also on a mechanism, to allow changes between slits of 4 different widths.

The slit is the entrance-slit to the SPICE spectrometer, which is a single-element system using a focussing (concave) grating, to image the slit onto the detector. The magnification of this imaging is approx. x5. In order to control the aberrations (mainly astigmatism) the grating has to be toroidal in form, and has to have a variable line-spacing, a so called ‘chirp’ of linear variation with position. For the SPICE bands the detector consists of two arrays (for SW and LW), positioned at the appropriate locations in the grating focal plane. Each detector consists of a photocathode coated microchannel plate image intensifier, coupled to active-pixel-sensor (APS).

The measurement chain following the optics is summarised in the figure below.
Figure 2-2  SPICE measurement chain (summary)
2.2.1 Optical Images

An optical image in instantaneous-FOV is recorded for each commanded exposure, on the detector which consists of two arrays (short-wave SW and long-wave LW).

The FEE reads out the detector as one array, and rows and columns are labelled in spectral dimension (wavelength $\lambda$) and spatial dimension (Y) (see next section).

Y is the along-slit direction of the spectrometer slit, i.e. instantaneous-FOV direction (SPICE z-axis), approximately north-south on the sun. The two detectors cover different wavelength ranges and similar spatial IFOV ranges, values are as given in the figure below.

![SPICE 'camera plane' geometry](image)

The array-size of the APS detector (HAS type) is 1024x1024 pixels. However not all of these are used optically. The maximum extent of the optically used field of the detector (i.e. image size) is in Y equal to 800 pixels, this being to the nearest multiple of 32, which is a read-out constraint (see next section). It is described in RP-0002 section 8.1 FOV, how the instantaneous-FOV of +/-7arcmins, is contained within this Y extent. This image size in Y in terms of arc-minutes differs slightly between SW and LW due to magnification effect, as shown in the above figure:

- **SW, y-direction:** $(18\text{micron/pixel})/(16.34\text{micron/arcsec}) = 1.1\text{ arcsec/pixel}$
- **LW, y-direction:** $(18\text{micron/pixel})/(17.0\text{micron/arcsec}) = 1.06\text{ arcsec/pixel}$
Examples of images (for each slit type) are shown below.

For each of the slits, the dumbbell areas are located at the ends of the +/- Y range as indicated in the figure, and these are each a square region of nominal size 30 x30 arcsec. For the 30” slit these dumbbells become part of the slit as they have the same width as the slit. For 2”, 4” and 6” slits, the physical slit length is smaller than the gap between the dumb-bells. This is gives the following I-FOV’s (slit lengths)

30” slit: length = +/- 7 arcmin
2”, 4”, 6” slits: length = +/- 5.52 arcmin

![Image showing example images and I-FOV's for slits]

Figure 2-4 Example images. The given sizes are for optical parameters at the mid-band positions of SW and LW

For the narrower slits the image is a spectral image (Y times lambda) for each solar emission line, as for example shown below. The spectral-resolution (in full-width-half-maximum of the line) is given by combination of the slit width and other instrument resolution effects.
Figure 2-5  Example line-spectral image (slice in lambda) for typical line-SNR=10 (150 detected-photons), 2” slit
time 2” y-bin. Solid line=pixel signal level, dashed-line=Gaussian fit

In these images, the conversion of pixel scale to lambda scale is given by dispersion values (RP-0002, section 8.1.1) giving mid-band values, as stated in the above table 3.

For the wide slit, and for the dumb-bells, the image for a given isolated spectral line, is a geometric image i.e. 2-D spatial, with resolution in the lambda-direction given by the spatial resolution. In this case the conversion of lambda scale to spatial scale (known as X’) is given by the across-slit magnification (RP-0002, table 2) and the pixel size, giving (mid-band values):
- SW, X’ direction = (18micron/pixel)/(18.39micron/arcsec) = 0.98 arcsec/pixel
- LW, X’ direction = (18micron/pixel)/(20.83micron/arcsec) = 0.86 arcsec/pixel

An example of such a spatial image (a dumb-bell) is shown below.

Figure 2-6  Example of dumbbell image, case of SW mid-band. Simulation from SDO image, binned to SPICE pixel size

For the images of dumbbell pairs at +/-y (alignment windows) there is a readout restriction that only one such pair can be obtained per exposure (study, see next section). There are cases where two such pairs are needed at the same time (in different spectral lines), and in that case they have to be made using separate
exposures (studies). This is in particular where alignment windows are needed, and have to be well-separated in wavelength across SW and LW, to determine roll errors in the alignment.

Also, in these cases the different y-magnification with wavelength (e.g. between SW and LW as in the figure above), means that the dumbbells are offset in Y (from the figure, this is by an amount (793-765)/2 ~ 14 pixels for SW/LW). Therefore in order to capture the full dumbbell in different windows at the same y-range read-out settings, the dumbbell y-range would have to be increased from 32 to 64 pixels.

2.2.2 Image readout: data-cubes and SPICE ‘Study’ format

The optical image from each exposure, as above, is referred to as one ‘camera plane’.

In science observations the instrument takes multiple exposures, for a given selected slit in the spectrometer, at EITHER fixed view position on the sun, OR at a range of spatial scan positions X across a region of the sun. The latter is the case of scanning over SPICE’s raster-FOV, approximately east-west on the sun. The label used to designate this raster-FOV spatial scan position is X, and so here X co-ordinate can indicate the raster-scan position number, or in the case of fixed view, the exposure number.

Each such series of exposures thus produces a data cube, dimensions (Y * Lambda * X), as shown in the figures below.

Each such series of exposures is termed a Study. A Study is the basic building-block for commanding observations, and any observing timeline is built from a series of Studies. Important features are:

- The execution of each study produces one data-cube
- The SEB processes the data-cube from one study, before proceeding to start the next study in the list
- It is possible to request multiple repeats of most study types with a single command. Each repeat will produce data with an identical format and quantity.

Studies are implemented via a combination of the SPICE Electronics Box (SEB), and the detector Front End Electronics (FEE). The SEB contains an Image Processing FPGA (IPF) to perform all of the computation-heavy steps, such as binning and data compression. The two units communicate via a Spacewire link, with the SEB acting as the master unit. The flight software in the SEB is responsible for coordinating the study process, and passes the necessary read-out settings to the FEE for image acquisition. The basic process involves moving the scan mirror to each spatial position (X), and acquiring an image from the FEE at each one. This process is designed to allow the study to run efficiently, taking account of the times needed to operate each device. The key components of a study are described in the following section.

2.2.2.1 FEE operation: Exposure Times

The FEE is responsible for collecting each individual image (exposure) and passing the raw data back to the SEB. It does not perform any internal processing on the data. The FEE operation for each exposure proceeds as follows (known as ‘destructive read-out’):

- Reset all required pixels for the exposure
- Wait for the user-specified exposure time to elapse
- Read-out and digitise all pixels (14-bit resolution) and transmit to SEB

The FEE is in control of the exposure time, i.e. the amount of time for which the pixels are sensitive to light (or the time between resetting and reading-out the pixels). There is a finite time required to reset the pixels in the array. The following rules apply to the user-specified exposure time and overheads:

- User-specified exposure time:
  - Between 0.1s and 204.7s, with 0.1s resolution
  - Between 205.0 and 1023.5s with 0.5s resolution
Overheads must be added for resetting the detector pixels. These scale with the number of different wavelength pixels required in the study:

- Overhead = \( \frac{\text{Number of pixels}}{2048} \times 0.42\text{s} \)
- e.g. for a typical dynamics study (272 pixels), overhead = 0.0558s

The total exposure time is the user time + overhead.

The FEE always reads-out the full Y dimension of the array (1024 pixels), although this may be reduced by further processing in the SEB. The choice of Y dimension for the study (see later section) therefore has no effect on the overheads.

### 2.2.2.2 Wavelength Regions and “Windows”

The FEE and SEB work together to offer a choice of modes to the user for defining the wavelength range to be included in a study. SPICE may read out all or part of the camera plane, either:

- **a)** A full-frame read-out, in so-called Calibration Mode (1024 x 2048 pixels)
- **b)** A ‘windowed’ read-out

In the Calibration Mode case, there is a restriction on the possible repeat time (in X), because in this mode the data has extra processing steps, in connection with the ‘calibration’ usage of the data, such as keeping a copy of it for dark-map update.

In the windowed readout the Detector is read in wavelength ‘Regions’ each of specified lambda-range, and from these ‘windows’ are made of 3 types;

1. ‘spectral-profile without dumb-bell’
2. ‘spectral-profile with dumb-bell’
3. ‘intensity’.

Examples of each are shown schematically in the figure below. For spectral-profile with dumb-bell, the dumb-bell part is also known as an ‘alignment window’.
In a spectral-profile window, one Region is used, and all of the columns are included in the resulting window.

In an intensity window, 2 adjacent lambda Regions are used, and the pixel data from these is then reduced to just 2 values per y-value. These are intended to represent 1) the overall intensity of the spectral line (such as that in the figure above), and 2) the background level in the neighbourhood of the line. In algorithm terms, the two numbers returned (per Y bin), are:

1. The sum of the pixel signals over certain width (lambda-pixels) covering the spectral line
2. The sum of the pixel signals over the width (lambda-pixels) of the adjacent Region, of width 4 or 8 pixels

In the set-up of a Study, there are rules on the number, size, type and recording rate of windows. These rules (for window mode) are listed below.

1. Detector is read as a set of wavelength Regions, which cannot overlap (but can be adjacent)
2. One Region is needed for Spectral-profile, two regions needed for Intensity
3. Total number of Regions allowed is <= 32

This leads to total number of windows allowable being $N_{SP} + 2.N_{Int} < 32$

(in each Study the planned numbers of window of each type, are given in the table in the later section 2.6 (re. data-volume calculation))

4. Each region has a width of 4, 8, 16 or 32 lambda-pixels
5. Max. total number of lambda pixels (sum over all Regions) allowable is 256. This applies after the pixels in the intensity regions are summed, and so each intensity window contributes only 2 lambda pixels towards this total.

6. Spectral-profile window typical width is 32, so allowable $N_{\text{SP}} = 256/32 = 8$, if $N_{\text{int}} = 0$.

7. For spectral-profile with dumb-bell, only 1 window is allowed. This is required to be 32 pixels wide. It can be transmitted as the dumb-bell part (alignment window) only. I.e. the slit part can be thrown away.

8. Each dumb-bells is always 64 Y pixels * 32 lambda pixels in size.

9. The Y-start and Y-range values must be the same for all windows in the Study.

10. The Y-range values (pixel row numbers) must be multiples of 32, but the Y start value can be any number.

11. The Y-start value for each dumb-bell can be selected. It can be adjacent to the slit region, or it can be separated by a chosen number of pixels.

### 2.2.2.3 Study Design

The most important choice in designing a study is to select one of the following operating schemes:

1. **Full Spectrum** (also known as ‘Calibration Mode’)
   - A full spectrum is acquired at a single scan position
   - Conventional (efficient) scanning is not available, but a limited scan with higher overheads can be performed.
   - Used for ‘Spectral Atlas’ studies, and calibration activities including acquiring a dark map

2. **Spatial Scan (X)**
   - A spatial scan is performed while collecting data for a list of spectral lines
   - Used for studies such as ‘Dynamics’ and ‘Composition Mapping’

3. **Time Series**
   - A single spatial location is observed while collecting data for a list of lines
   - Used for temporal studies such as ‘30” Movie’ and ‘Waves’

Each operating scheme has various different options available to the user. There are also some common features for all three schemes.

#### Common Study Options

- **Slit Selection**: 2", 4", 6" or 30". Overhead of ~60s required to select slit (if different from last study).
- **Automatic Focus**: the telescope focus can be automatically set to a value in a LUT at the start of the study. This is enabled by default, but can be disabled if required (to avoid activating motors in EMC-quiet periods, or to reduce overheads).
- **Exposure Time**: As defined in 2.2.3.1.
- **Dark map subtraction**: Automatic subtraction of detector dark maps. This is to avoid saturation, and has the potential to improve the quality of compressed science data by removing detector artefacts (e.g. hot pixels). The best use of this option will be determined during in-flight calibration.

#### Full Spectrum

- Wavelength options: none – all wavelengths are recorded
- Y spatial options: none – the full area is recorded, covering the slit, dumb-bells and dark regions of the detector
- Binning options: none – pixels cannot be summed in the Y or $\lambda$ directions
- Compression options:
   - **Uncompressed**: all data is downlinked with no loss of information
   - **Lossy compression**: all data is processed with a compression ratio of up to 10:1. The same compression ratio is applied to all pixels.
Both: a special option to downlink the data with both of the above formats. This is intended for use in calibration and early in-orbit testing, to prove that the compression is working properly.

- Scanning options:
  - Conventional scanning is not available, since the data volume per exposure is large and there is insufficient memory in the SEB to buffer the data.
  - Limited scans may be specified using the SPICE on-board ‘macro’ functions. Scans can contain up to 30 positions (equivalent to 30 studies) with any step size or resolution, e.g. 1’ at 2” resolution.
  - A large time overhead of approximately 45 seconds is required per scan position, to allow for the data to be processed and transmitted.

- Overheads:
  - Additional Exposure Time: 0.42s per exposure, to be added to the user-specified exposure time
  - Time per Scan Position: ~45s

- Special Features:
  - A dark map may be recorded by taking a single exposure, then writing the contents to the on-board flash memory.

Spatial Scan

- Wavelength options: A list of spectral lines may be specified. This will be converted into a set of wavelength regions, as defined in 2.2.3.2.
- Y spatial options: The Y dimension for the study is a global parameter that applies to all wavelength regions, as defined in 2.2.3.2.
- Binning options: Each wavelength region may be configured individually, subject to some restrictions:
  - Summing in the λ direction is used to create intensity windows, by summing over all wavelength pixels in the region. The instrument supports more options than this, by allowing groups of 2, 4, 8 or 16 pixels to be summed up to the size of the region (i.e. a region of 8 pixels wide can be summed over every 2, 4, or 8 pixels). Also summing over a neighbouring region to give a background value (as described earlier).
  - Summing in the λ direction is only available for regions that are uncompressed or formatted with ‘spatial lossy’ compression.
  - Summing in the Y direction can be done for any region. Groups of 2, 4, 8, 16 or 32 pixels are allowed, but the Y dimension after summing must be a multiple of 8 pixels (e.g. 640/16=40 is okay, 640/32=20 is not allowed). If the size after summing is less than a multiple of 64, there are further restrictions in the allowed compression ratio.

- Compression options: Each wavelength region may be configured individually, subject to some restrictions:
  - Uncompressed: data is downlinked with no loss of information. Any valid region size and binning may be used.
  - ‘Spatial’ Lossy compression: data is formatted as a series of Y-X plane compressed images, with a compression ratio of up to 10:1. Any valid region size and λ binning may be used. Y binning must result in an image size divisible by 64 in order to access the full range of compression ratios. If the image size is divisible by 32, 16 or 8, the maximum ratio of 10:1 is still available, but the choice of intermediate ratios is progressively reduced.
  - ‘Spectral Hybrid Compression (SHC)’: This compression type requires a region of 32 wavelength pixels with no λ summing. Summing in the Y direction must result in an image size by 64. Up to 8 different SHC ‘recipes’ may be in use on SPICE for each encounter, which allow different levels of compression and hence different levels of data quality. This recipe to be used may be selected on a per-region basis. The details of the recipes will be determined during instrument calibration.

- Scanning options:
  - Conventional mirror scanning is supported to allow a series of exposures at different X position across the sun. The SPICE scan mirror range is +8’ to -8’, with 2” resolution.
  - Scans must contain a multiple of 32 mirror positions, in order to be compatible with the SHC and Spatial Lossy compression schemes.
- The maximum number of scan positions is 480 (covering all 16’ at 2” resolution).

- Overheads:
  - Study set-up time: ~20s (before first scan position only)
  - Additional Exposure Time: Variable, depending on the number of wavelength pixels included in the study. See section 2.2.3.1 for details. Typically ~0.05s.
  - Time to move mirror before first scan: ~10s
  - Time to move mirror for each subsequent scan position: ~0.25s

- Special Features:
  - A “number of repeats” may be specified when commanding the study to run, which allows the whole scan to be repeated more than once. This is useful when preparing a timeline, as a single study definition can be used for different observing durations.

**Time Series**

- Wavelength options: A list of spectral lines may be specified. This will be converted into a set of wavelength regions, as defined in 2.2.3.2.
  - For this scheme, all regions must contain 32 wavelength pixels.

- Y spatial options: The Y dimension for the study is a global parameter that applies to all wavelength regions, as defined in 2.2.3.2.

- Binning options: Each wavelength region may be configured individually, subject to some restrictions:
  - Summing in the \( \lambda \) direction is not available.
  - Summing in the Y direction can be done for any region. Groups of 2, 4, 8, 16 or 32 pixels are allowed, but the Y dimension after summing must be a multiple of 8 pixels (e.g. 640/16=40 is okay, 640/32=20 is not allowed). If the size after summing is less than a multiple of 64, there are further restrictions in the allowed compression ratio.

- Compression options: Each wavelength region may be configured individually, subject to some restrictions:
  - Uncompressed: data is downlinked with no loss of information. Any valid region size and binning may be used.
  - 'Focal' Lossy compression: data is formatted as a series of Y-\( \lambda \) plane compressed images, with a compression ratio of up to 10:1. Regions must contain 32 wavelength pixels. Y binning must result in an image size divisible by 64 in order to access the full choice of compression ratios. If the image size is divisible by 32, 16 or 8, the maximum ratio of 10:1 is still available, but the choice of intermediate ratios is progressively reduced.

- Scanning options:
  - Mirror scanning is disabled. The mirror will be moved to a fixed location in field of view before starting to acquire exposures.
  - The study may contain any of the following numbers of exposures:
    - 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 (maximum value)

- Overheads:
  - Study set-up time: ~20s (before first exposure only)
  - Additional Exposure Time: Variable, depending on the number of wavelength pixels included in the study. See section 2.2.3.1 for details. Typically ~0.05s.
  - Time to move mirror before first scan: ~10s
  - Data handling overhead between each exposure: up to 0.1s
  - Extra time added between study repeats: minimum of 0.15s

- Special Features:
  - A “number of repeats” may be specified when commanding the study to run, which allows a longer time series to be collected.
  - When > 1 repeat is selected, the time before starting the second repeat can be specified. This allows the cadence of the time series to be maintained.

**Special Modes**
The following features may be used with some of the schemes above:
• ‘Two-Exposure’ Mode:
  o A mixture of bright and faint lines can be specified,
  o Exposures of all wavelength regions are collected in a single study, with both a short and long exposure time
  o The detectors are set to non-destructive read-out mode, to allow charge to continue to be accumulated after the first exposure
  o Additional restrictions apply due to the extra data volume and more complex processing
  o A maximum of 16 wavelength regions and 128 wavelength pixels are supported (half the usual number).
  o Dumb-bell regions are supported, but data will only be available for the shorter of the two exposure times.
  o Time series and spatial scanning schemes are available,
  o Data overheads are relatively high, since some regions will be saturated and others will contain faint images (approximately twice as much data is transmitted as will be useful).

• Scanned Time-Series:
  o It is possible to combine certain features of a spatial scan and time series. This is used in the proposed ‘90” Movie’ study definition.
  o Most rules follow the ‘Time Series’ scheme.
  o A limited mirror scan could be defined, with the number of scan positions restricted as per the number of exposures in the Time Series scheme.
  o Overheads would follow the ‘Spatial Scan’ scheme, due to the movement of the mirror. This would most likely result in a reduced observing efficiency (e.g. ~60% efficiency for the 90” Movie definition used in this user manual).

2.2.3 Data processing in SEB

This is defined in Flight software design in SPICE-SWRI-RS-5005 #RD17, and described in science data-flow in SPICE-RAL-DD-5001, section 3.8, #RD18.

The acquired window data (previous figure) is placed in a scan memory buffer, forming a 3-D data cube (2 detector dimensions, times 1 exposure or X position dimension).

The SEB takes data from the buffer and processes it separately for each window in the image processing FPGA. This processing includes possible steps as described above:
  • Dark map subtraction
  • Subtraction of multiple exposures (TBD)
  • Extracting and processing the dumb-bell data
  • Data-reduction, such as for intensity windows
  • Data compression

In addition to this data processing, the SEB combines windows of consecutive exposures/scan positions, into data-cube sets called raster-segments. Each of these is an X- series of one window, forming a data-cube of dimensions (X,Y,λ), and the number of exposures/scan-positions per raster segment has to have X<=64, due to the size limits of data buffers in the SEB (note: the appropriate raster segment size for each study is determined automatically by the flight software).

The 3 types of raster segment are shown in the figure below.
Note that:
- The intensity-window raster-segment has 2 elements in the $\lambda$-dimension
- In the dumb-bell stack, since the slit width is large (30arcsec) and an isolated bright line is used (monochromatic image), the $\lambda$-dimension is equivalent to spatial dimension X, and is denoted as X’
- For calibration mode, the spectral format is used, but the X dimension has a size of 1, i.e. the data is formatted as a single Y-$\lambda$ image.

### 2.2.3.1 Data compression

The science data compression is applied to each raster segment as described above. It is specified separately for each observation, by means of parameters in the Study definition. This is done on a per-window basis, i.e. within one study each window may have its own compression type and level applied.

The possible options are:

- ‘Focal lossy’: compression of Y-lambda planes
- ‘Spatial lossy’: compression of X-Y planes
- ‘SHC lossy’: (spectral hybrid compression): compression of y-lambda-x segments

For the focal and spatial lossy cases there is also a ‘lossless’ option, i.e. to pass the data without compressing.
These compressions are applied in the Image Processing FPGA (the IPF) within the SEB, as described in SPICE-SWRI-TN-5013 (EM 17489-013). The focal-plane and spatial plane compressions are of 2-d data planes, and use an algorithm known as discrete wavelet transform (DWT), which is similar to JPEG compression. In this case the compression level for the window is specified in the study.

The SHC compression uses 2 steps; firstly a fast-fourier transform in the lambda dimension, resulting in a series of complex fourier components, with one x-y plane per component, and secondly a compression of each component plane (2-d data), again using the DWT algorithm. In this case the DWT compression level is specified per fourier component (with the method that the compression level becomes progressively more severe with increasing fourier order, so-called 'bit-starving' scheme). These details, and the recipes for using these data compressions, are given in SPICE-SWRI-TN-5017 (EM 17489-017) “decompression recipe”.

2.2.3.2 Science packet

In the operation of SPICE, the instrument executes a Study, which is one particular exposure/raster scan, recording a particular set of windows. This is described in the operations concept document SPICE-RAL-PL-0002.

Each raster-segment is transmitted as one group of science packets, a set of CCSDS packets for transmission over spacewire link to the spacecraft. The group consists of 1 header packet, N data packets and one checksum packet. The size N thus depends on the size of the raster segment (i.e. size of window in y * lambda, size in number of X positions), and the compression ratio used. The compression takes place before packetsation.

The number of pixels in the science packet is the product of the size of the raster-segment, which has maximum X=64, and the window size (lambda times Y). The maximum possible value is for the case of spectral (French-fry) raster segment of maximum size (lambda, Y, X) of 32 times 1024 times 64.

A more typical example is that of a spectral window (French fry) of 32 wavelength pixels * 800 Y spatial pixels * 32 raster positions, with a compression of 20:1 being used, the standard SHC-compression level, and no spectral or spatial binning being used.

The number N of CCSDS packets is given in this example as:

Total science pixels: 32 * 800 * 32 = 819200
Raw science data volume = 819200 * 2 (bytes/pixel) = 1638400 bytes
Compressed science data volume: 819200 * 0.05 = 81920 bytes
Number of science data packets (max CCSDS size 4096 bytes of data): 81920 / 4096 = 20
Science data packet header overhead: 16 bytes per packet
Size of each science packet: 4096 + 16 = 4112 bytes (maximum size allowed in CCSDS TM packets for SO mission)
Size of science metadata (header) packet: 1086 bytes
Size of checksum packet: 18 bytes

The total data volume per raster-segment of this type: (4112 * 20) + 1086 + 18 = 83344 bytes
The CCSDS Packetisation Overhead (16 bytes per packet) = 22*16 = 352 bytes
⇒ CCSDS Overhead: 0.42%
⇒ Non-science pixel overhead (counting metadata and packet headers as overhead): 1.72%

The CCSDS packetisation process uses only the number of data packets required for the raster segment dataset. The number of science data packets (20 in the above case) could be anything between 1 and 1024, depending on the window dimensions, compression, binning and number of mirror positions. The total number of packets can vary between 2 and 1026, as the checksum data is included in the final science packet if there is enough space.
CCSDS packetisation overheads are always 16 bytes per packet, so the efficiency is fairly constant except for the case of a very small science dataset, where data volumes are already low. Therefore the packetisation overheads are not significant.

Metadata overheads will vary with the size of the science pixel dataset and the number of mirror positions. Values of approximately 1% are typical for compressed data, but can be much smaller for uncompressed cases (0.1% or less).

2.2.4 Data processing on ground

In the ground processing the sequence is:
   a) science packets are re-assembled into each raster-segment
   b) each raster-segment is de-compressed
   c) the Raster-segments re-assembled into a single X-series, to produce one data cube per window for the whole study, as shown in the figure below.

![Diagram of data processing]

**Figure 2-9** Final set of data-cubes for one SPICE Study (1 example each type)

A Study may be repeated multiple times to produce an Observation.
2.3 SPICE Instrument Overview

The SPICE optical design is based on the comprehensive work carried out during the earlier phases of the project. As shown in Figure 2-10, the light enters the instrument through the entrance aperture then an image is formed at the slit by the off-axis parabola. The slit defines the portion of the solar image that is allowed to pass onto a concave Toroidal Variable Line Space (TVLS) grating, which disperses, magnifies, and re-images incident radiation onto two detectors. The two wavebands cover the same one-dimensional spatial field, and are recorded simultaneously.

The instrument contains four mechanisms:

- The SPICE Door Mechanism (SDM) which can be actuated to provide a quasi-contamination tight seal of the entrance aperture during non-operational periods (both during ground handling and non-operational periods in flight) and to protect the primary mirror coating from the solar wind when the SPICE particle deflector system is not active (when the instrument is off).

- The telescope mirror is mounted to a two-axis mechanism (tilt and focus), the scan focus mechanism (SFM), that is used to direct different portions of the solar image onto the selected entrance slit and to focus the telescope relative to the entrance slit.
- The image of the Sun is repeatedly scanned across the entrance slit. During each scan the image of the Sun is stepped across the entrance slit such that the region of interest is sampled.

- A slit change mechanism (SCM) provides four interchangeable slits of different widths, one of which can be selected depending upon the science activities to be conducted. In the nominal design these slits have a 2", 4", 6" and 30" width on the external field of view.

- A vacuum door mechanism on the Detector Assembly (DA Door). The micro-channel plate and image intensifier used to translate the incident EUV photons into visible light photons which can be detected by the detectors must be maintained either at vacuum or in zero humidity during ground handling. Therefore the detector assembly contains a door mechanism which is only opened during vacuum testing on ground, and opened finally once on-orbit.

The instrument structure consists of a Carbon Fibre reinforced plastic and Aluminium honeycomb baseplate with side walls and lids also made from Carbon fibre panels. It is isostatically mounted to the spacecraft panel. The structure is designed to have approximately zero CTE, therefore maintaining instrument alignment throughout the wide operating temperature range. The instrument optics unit (SOU) mechanical design and layout are shown in Figure 2-11 and Figure 2-9 below.

![Figure 2-11: SPICE Optics Unit with light beams shown](image-url)
The instrument control function will be provided by a dedicated electronics box, the SPICE Electronics Box (SEB). This provides the drive and monitoring for all mechanisms, the acquisition and processing of all housekeeping telemetry and the processing and packetisation of the science data. It controls and communicates with the detector front end electronics (FEE) via a SpaceWire link. The SEB also contains the SPICE flight software (FSW) which is responsible for all control and monitoring of the instrument, plus the processing and compression of the science data to allow the data rate and volume requirements to be achieved. A functional block diagram of the SEB is shown below.
A full description of the SPICE Instrument design is given in [RD10] and its reference documents.

2.4 Instrument Unit Detailed Descriptions

Detailed descriptions of the design of the subsystems of the SPICE instrument are given in [RD10] and its reference documents. A summary for each of the major subsystems is given in the section below as an introduction and background for the reader of the user manual.

2.4.1 SPICE Door Mechanism (SDM)

The SPICE door mechanism provides a quasi-contamination tight seal at the entrance aperture to the instrument and protects the primary mirror coating during flight when the PDS is switched off (i.e. the SEB is unpowered). The design of the door mechanism is detailed further in [RD10] and its reference documents, the design overview is shown in Figure 2-14 below.
2.4.2 Scan Focus Mechanism (SFM)

The scan focus mechanism provides the rotational degree of freedom on the primary mirror that allows the instrument to raster the slit image across the field of view. The mechanism also provides for focus adjust to compensate for the CTE of the SOU Optics Bench and the change in mirror focal length with temperature. The design of the Scan Focus Mechanism is detailed further in [RD10] and its reference documents, the design overview is shown in Figure 2-15 below.
Figure 2-15: SFM Design Overview

Figure 2-16: SFM Drive System Components
The SFM Scan degree of freedom is controlled in closed loop control by the SEB using the feedback from an LVDT. The closed loop control system is described in detail in [RD11].

### 2.4.2.1 Primary Mirror

The primary mirror is a 105mm off-axis parabolic mirror, the front face is coated with B4C for maximum reflectivity in the EUV, the rear face is anti-reflection coating to minimise absorbed solar radiation. The mirror is mounted by being bonded into a Titanium mount which includes flexures and bond pads sized to limit the mechanical stresses in the mirror due to the high incident heat load and temperature changes. The design of the mirror and mount is detailed further in [RD10] and its reference documents, the design overview is shown in figure 2-14 below.

The mirror mount also includes a snubber pin at the top of the mirror that limits the displacements of the top of the mirror with respect to the instrument structure during vibration. This protects the flexures of the SFM from over-stress during the vibration. The clearance on the snubber is sized to allow full range of motion needed by the focus stage during operating (including suitable clearance margins).

![Figure 2-17: Primary Mirror Mount within SPICE Optical Bench](image)

### 2.4.3 Slit Change Mechanism (SCM)

The Slit Change Mechanism allows one of four different width slits to be selected and placed at the instrument focus. This slit is tailored for the observation requested and can be a nominal 2” (6 micron), 4” (12 micron), 6” (18 micron) or 30” (90 micron) width. The design of the slit change mechanism is detailed further in [RD10] and its reference documents, the design overview is shown in section in Figure 2-18 below.
2.4.4 Grating Assembly (GA)

The Grating Assembly is composed of a Toroidal Variable Line Spacing (TVLS) grating on a silica substrate, and a 5 degree of freedom adjustable mechanical mount to allow for instrument level alignment activities. The design of the GA is detailed further in [RD10] and its reference documents, the design overview is shown in Figure 2-19 below.

![Grating Assembly Diagram](image)
2.4.5 Detector Assembly

This assembly includes:

1. The two VUV image-intensified array detectors, each of which is in a fixed precise alignment to the spectrometer focal planes (i.e. for the short-wave and long-wave bands).
2. The front-end electronics (FEE), described in the next sub-section
3. The sealed housing to provide a protected environment to the detectors. This is a sealed box, with a mechanised door at the front-aperture, and purge gas supply. This system has to be used at all times that SPICE is in an ambient-air environment, to protect the detectors from humidity, and molecular and particulate contamination, which would otherwise degrade the responsivity (of the VUV-sensitive photo-cathode of the detector). In flight the door is opened during commissioning and then remains open.
4. Internal harnesses, thermal link, and bellows arrangement, mating to interface flange at the SOU rear wall. This design includes measures to vent any out-gassing products, out of the SOU enclosure.
5. Mechanical mount, interfacing to the SOU base-plate, and including an alignment-shim.

2.4.5.1 Front End Electronics

The Front End Electronics (FEE) is housed within the DA and includes two HAS2 APS detector chips and the necessary support and communication electronics. The flex circuits provide the clocking and control of the detectors, the readout and the translation of the data to SpaceWire packets for communication to the SEB. The design of the FEE is detailed further in [RD10] and its reference documents, the EM FEE is shown in Figure 2-20 below (still in the flat configuration).
2.4.6 **SPICE Electronics Box (SEB)**

The SPICE Electronics Box provides the instrument command and telemetry functions, in addition to control of the mechanisms and the front end electronics. It is also responsible for the compression and packetisation of the spectro-heliograms produced by the instrument in order for the data rate to remain compliant with the tight budget.

The design of the SEB is detailed further in [RD10] and its reference documents, a block diagram of the functions of the SEB is shown in Figure 2-13 above.

2.5 **Instrument on-board software**

2.5.1 **Status for CDR**

The instrument on-board software is described in detail in #RD3 and #RD17. This section will contain a summary of the high-level information that is directly relevant to the instrument user, while the lower-level details will remain in the reference.

2.5.2 **Overview of Software Concept**

The SPICE flight software resides in the Digital Processing Module (DPM) of the SPICE Electronics Box (SEB). This contains a CPU FPGA which runs an emulation of an 8051 microprocessor, which is used to run the flight software. The software is split into two principle components:

- **Boot Code Image:**
  - Stored in a 32KB PROM
  - Responsible for managing the initial operations of the SEB at power-on, maintenance of the science software image (e.g. patching, memory loads/dumps), integrity tests of the stored software images, and start-up of science code image execution.
  - Communicates with the spacecraft via a 10Mbps Spacewire link.

- **Science Code Image:**
- Stored in a 256KB EEPROM (multiple copies may be stored)
- Copied to SRAM for execution
- Communicates with the spacecraft via a 10Mbps Spacewire link i.e. receives telecommands and sends instrument telemetry.
- Manages all engineering and science functions of the instrument
- Provides instrument safety protection as defined in the FDIR (see section 4.5).

### 2.5.3 Software Architecture and Design

This is described in sections 4 and 5 of RD4, which provide information on:

- Software static architecture and interfaces
- Data structures, including hardware registers
- Software task loop algorithm, timing and interrupts
- Interfaces between software elements and the SEB hardware
- Memory and CPU utilisation
- TM/TC interface with the Spacecraft
- Software table structures
- Specific design details for each software module, including operational algorithms and timing

A summary of this information will be added to the next issue of the user manual.

### 2.5.4 Software Operations

This is described in several sections of RD4. The following topics will be summarised in the next issue of the user manual:

- Software start-up
- Maintenance of the code images and tables
- Software interfaces and operation of the spacecraft interface

Further information on instrument operations is contained in section 4 of this manual.

### 2.5.5 SpW link heartbeat monitor limits

For the SPICE heartbeat counter increments, the limits above which a fault is indicated, for detection by spacecraft FDIR, are the following:

- HK interval (max duration between HK packets): 4 seconds
- HB counter limit: 12 seconds TBC

### 2.6 Payload Data Definition

Reference Data ICD #RD1

The instrument modes are described in later section xxx. At power up, the FSW in start-up mode.

#### 2.6.1 Standby mode

After making checks FSW transfers instrument to standby mode which is the stable and safe configuration. From this point HK data is generated.

#### 2.6.2 Engineering Mode
Transition to engineering mode from either standby or operating modes is made with a command. This mode includes setting the HVPS outputs to engineering voltage levels.

### 2.6.3 Operate Mode

In this mode science image acquisition, data processing and science data TM are made. In each encounter there is a planned time-line of observations.

A science "observation" is a series of "studies". The study types are tailored to the different science areas, and the current list is:
- Spectral Atlas
- Composition Mapping
- Dynamics
- Limb
- CME Watch
- movie
- Waves (Sit & stare)

These are listed in the operational concepts document PL-0002, section 3, and in table 3 of this User Manual. The studies are controlled as per other on-board commands, i.e., by the macros in the FSW.

When a study starts, the FSW reads the corresponding science LUTs which hold the parameters to configure the SPICE instrument for the study.

The LUTs contain:

Per study:
- slit choice;
- exposure time;
- scan mirror start, stop and increment information;
- camera-plane:
  - window position, size, binning and compression parameters.

The FSW then commands the mechanisms, communicates with the FEE, sets up the image processing FPGA for acquisition, configures the DWT and BPE ASICs for compression (if any), and coordinates the science data product packetization process.

#### 2.6.3.1 Data Contents

The science packet contains image header information in the first packet, followed by image data in the continuation and last packets. A checksum of the image header and data is appended and stored in the last packet. This is described in full in the SPICE Data ICD #RD1.

#### 2.6.3.2 Data rate/volume

For the purpose of describing the output data volume and rate for each observation type, a spreadsheet model is used.

The main required parameters of the observation are those listed in the table below, where baseline values are given, for each observation:
Table 4: Input parameters for each observation type, and resulting data sizes

<table>
<thead>
<tr>
<th>Observing Mode (Study)</th>
<th>Line List, Window Parameters</th>
<th>Study Parameters</th>
<th>No of repeats</th>
<th>Duration in hours (inc. 15sec per repeat)</th>
<th>Science data compression</th>
<th>Header Data Vol, Mbytes</th>
<th>Net Data Vol, Mbytes</th>
<th>Net Data rate, kbit/s</th>
<th>Spectral-line performance (line-SNR and spatial resolution combinations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Atlas</td>
<td>Full spectrum, calibration (32 spectra x 64 pixels wide)</td>
<td>4” slit, 60 s exposure, readout=45s, processing=0.1sec step, X-range=10 times 4” step</td>
<td>2</td>
<td>0.67</td>
<td>Profiles 10.1 (note 1)</td>
<td>0.07</td>
<td>8.484</td>
<td>28.26</td>
<td>line-SNR&gt;10 at 4”x2” in C-III, O-VI, Ne-VIII, and Mg-IX-AR</td>
</tr>
<tr>
<td>Composition Mapping</td>
<td>15 total, 2 Spectral, 12 Intensity, 32 pixels wide</td>
<td>4” slit, 20+10s set-up, 180 s exp X=64 times 4” step</td>
<td>1</td>
<td>3.21</td>
<td>Profile SHC 20.1 Intensity 10.1</td>
<td>0.01</td>
<td>0.606</td>
<td>0.42</td>
<td>line-SNR&gt;10 at 4”x2” in C-III, O-VI, Ne-VIII, and Mg-IX-AR</td>
</tr>
<tr>
<td>Dynamics</td>
<td>4 Spectral (H I, C III, O VI, Ne VIII), 32 pixels wide</td>
<td>2” slit, 30+10s setup, 5 s exposure X=128 times 2” step</td>
<td>10</td>
<td>1.97</td>
<td>Profile SHC 20.1 Intensity 10.1</td>
<td>0.16</td>
<td>15.756</td>
<td>17.79</td>
<td>line-SNR&gt;10 at 2”x2” in C-III, O-VI, in Ne-VIII-AR, and 5”x5” in Ne-VIII-CH, QS</td>
</tr>
<tr>
<td>Limb (low corona above limb)</td>
<td>3 Spectral (C III, O VI, Ne VIII), 3 Intensity (coronal line)</td>
<td>4” slit, 20+10s setup, 60 s exp X=224 times 4” step</td>
<td>1</td>
<td>3.76</td>
<td>Profile SHC 20.1 Intensity 10.1</td>
<td>0.05</td>
<td>4.545</td>
<td>2.69</td>
<td>line-SNR&gt;10 at 4”x2” in C-III, O-VI, Ne-VIII, and Mg-IX-AR</td>
</tr>
<tr>
<td>CME Watch</td>
<td>5 Spectral, 10 Intensity</td>
<td>4” slit, 20+10s setup, 30 s exp X=96 times 4” step</td>
<td>30</td>
<td>24.49</td>
<td>Profile SHC 20.1 Intensity 10.1</td>
<td>0.45</td>
<td>45.45</td>
<td>4.12</td>
<td>line-SNR&gt;10 at 4”x2” in C-III, O-VI, Ne-VIII, and 4”x4” in Mg-IX-AR</td>
</tr>
<tr>
<td>30” wide movie (slit &amp; star)</td>
<td>1 or 2 Spectral, 32 pixels per window (extract the full slit width)</td>
<td>30” slit, 20+10s setup, 5 s exp X=128 times 0” step</td>
<td>1</td>
<td>0.17</td>
<td>Profiles 10.1 (note 3)</td>
<td>0.03</td>
<td>2.626</td>
<td>34.44</td>
<td>NA</td>
</tr>
<tr>
<td>90” wide movie</td>
<td>1 or 2 Spectral, 32 pixels per window (extract the full slit width)</td>
<td>30” slit, 5 s exp X=3 times 28” step</td>
<td>40</td>
<td>0.51</td>
<td>Profiles 10.1 (note 3)</td>
<td>0.03</td>
<td>2.626</td>
<td>11.44</td>
<td>NA</td>
</tr>
<tr>
<td>Waves (slit &amp; stare)</td>
<td>3 Spectral (C III, O VI, Ne VIII)</td>
<td>4” slit, 20+10s setup, 5 s exp X=480 times 0” step</td>
<td>5</td>
<td>3.38</td>
<td>Profiles 10.1 (note 2)</td>
<td>1.13</td>
<td>114.13</td>
<td>75.15</td>
<td>line-SNR&gt;10 at 4”x2” in C-III, O-VI, Ne-VIII-AR, and at 4”x8” in Ne-VIII-CH, QS</td>
</tr>
<tr>
<td>Two-exposure</td>
<td>2 Spectral, Combination of bright and faint lines, Use spectra to monitor saturation</td>
<td>4” slit, 20+10s, 5s + 55 s exp X=64 times 4” step</td>
<td>5</td>
<td>5.40</td>
<td>Profiles 10.1 (note 2)</td>
<td>0.06</td>
<td>6.646</td>
<td>2.66</td>
<td>line-SNR&gt;10 at 4”x2” in C-III, O-VI, Ne-VIII, and Mg-IX-AR</td>
</tr>
</tbody>
</table>

Notes:
1. For Cal-mode, SHC cannot be used so compression is focal plane (JPEG) only. Also the readout pipeline is slower than other modes.
2. For spatial X=64 the profiles compression is JPEG as series of (lambda,Y) images (SEB-0080).
3. Limited ratio, JPEG not SHC as x-dimension is pseudo-spatial.
Note that:
1) for some of the weaker observed lines in some of these studies, the nominal required line-SNR=10 is reached by using increased spatial binning of pixels in these cases. This is as indicated in the final column, and the analysis of this is in the science performance document (RP-0002). (The criterion of line-SNR=10 corresponds to the required resolution in the Doppler-velocity data product, of 5 km/sec, at the 1-sigma uncertainty level.)
2) for the stronger observed lines, the detector dynamic range (pixel saturation) effect means that some of the exposures will have to be divided into 2 parts; a short exposure for these lines, plus remaining exposure for the other lines. The saturation criterion is given in RP-0002, section 8.7.11.

As regards the functionality provided in the instrument on-board SW (as described in #RD3), this covers the above observing needs. In particular for (1) The binning required will be done on ground, and so does not affect on-board SW, or the data values in the above table. For (2) it is noted that the on-board SW does not allow for different exposure times for different lines; the whole of the study data cube has to be measured at the same exposure time. This is why the exposure has to be split into 2 parts for such cases.

**DOES THIS MEAN NONDESTRUCTIVE READOUT WILL NOT BE USED?**

From the above observation parameters, and the key parameters of FEE and data compression in SEB, the **total data volume is calculated as shown in the table below.**
<table>
<thead>
<tr>
<th>Item #</th>
<th>Parameter name</th>
<th>description</th>
<th>Value</th>
<th>Units</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FEE properties</td>
<td>Detector size, row length, 798 rounded up</td>
<td>1024</td>
<td>pixels</td>
<td>LI-0002</td>
</tr>
<tr>
<td>2</td>
<td>pixel signal digitisation</td>
<td></td>
<td>16</td>
<td>bits/pix</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Observing parameters</td>
<td>number of line spectra</td>
<td>32</td>
<td>lines</td>
<td>PL-0002, table 3.2.2, Obs=Dynamics/Compositions</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>width of line spectrum</td>
<td>64</td>
<td>rows</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>spectral region total size</td>
<td>(lines * width * row_length)</td>
<td>2097152</td>
<td>pixels</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>number of intensity lines</td>
<td>0</td>
<td>lines</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>intensity region total size</td>
<td>(lines * row_length)</td>
<td>0</td>
<td>pixels</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>alignment windows total size</td>
<td>0.5x0.5 arcmin = 32x32pix, x2</td>
<td>4096</td>
<td>pixels</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>spectral region bits/expr</td>
<td>total size x pixel-bits</td>
<td>33554432</td>
<td>bits</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>intensity region bits/expr</td>
<td>total size x2 numbers x pixel-bits</td>
<td>0</td>
<td>bits</td>
<td>2 numbers/line</td>
</tr>
<tr>
<td>11</td>
<td>alignment window bits/expr</td>
<td>total size x pixel-bits</td>
<td>65536</td>
<td>bits</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>total bits/expr泄漏 (region_sizes)*bits</td>
<td>(region_sizes)*bits</td>
<td>33619968</td>
<td>bits</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>number of exposures (X or t)</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>number of study repeats</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>total data volume generated</td>
<td>window data * X * repeats</td>
<td>672399360</td>
<td>bits</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>time taken</td>
<td>X * repeats * step period</td>
<td>1322</td>
<td>sec</td>
<td>60s+5s readout+0.1s step time +10 sec per repeat</td>
</tr>
<tr>
<td>17</td>
<td>SEB parameters</td>
<td>Spectral SHC compression ratio (up to 20:1 IRD-603)</td>
<td>10</td>
<td>limited ratio as x-dimension is too small for SHC</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>spectral win, compressed total</td>
<td>(total_bits)/SHC-comp-ratio</td>
<td>8388608</td>
<td>bytes</td>
<td>includes un-padding of 16 bits to 14</td>
</tr>
<tr>
<td>19</td>
<td>intensity &amp; align window compression</td>
<td>wavelet compression</td>
<td>10</td>
<td>JPEG</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>intensity win, compressed total</td>
<td>0 bytes</td>
<td></td>
<td>bytes</td>
<td>includes un-padding of 16 bits to 14</td>
</tr>
<tr>
<td>21</td>
<td>align window compressed total</td>
<td>16384 bytes</td>
<td></td>
<td>bytes</td>
<td>includes un-padding of 16 bits to 14</td>
</tr>
</tbody>
</table>

| SEB science data total observation     | 8.40 mega-bytes |
| header overhead                        | 0.08 mega-bytes |
| Equivalent data rate (average over observ'n) | 51371 bits/sec |
Table 5 Science Data volume and rate calculation; example for ‘spectral atlas’

The resulting estimated science data volumes and rates for all observations are given in the table above.

2.6.3.3 On-board processing: Data compression

To fit within available resources for data down-link, the SPICE science data is compressed on-board. It is then un-compressed after down-link.

The methods used are:
- Intensity windows: wavelet image compression, in (x,y)
- Spectral windows (wide-slit) images, alignment-stacks: wavelet image compression in (x’,y)
- Spectral windows, in cases where SHC is not possible, wavelet image compression of x-series of images (lambda,y)
- Spectral-window (narrow-slit) spectro-heliograms, in (lambda,x,y) : spectral-hybrid compression (SHC). This consists of fourier-transform of the spectra (i.e in lambda dimension), followed by wavelet compression (CCSDS 122.0-B-1 ) of each fourier-coefficient, in (x,y), with different compression level for each coefficient. This requires lambda=32 pixels, and x>64.

For the wavelet image compression the typical compression ratio is 10:1.

The SHC method and its performance for SPICE is described in SHC Tech note, #RD2. The typical case uses is ‘case#5’, compression obtained is ~20:1.

The image data formats and constraints on data compression are included in the SEB specification, #RD3 section ‘Science data processing’.

2.6.3.4 Data management

Concept (including storage and transfer), both at instrument and platform (SSMM) level.

The following points outline the current concept:
- The SPICE instrument will be compliant with the permitted data link rate and data volume allocation during operations.
- All SPICE data will be transmitted to the SSMM. There is no internal data buffering capability within the SEB.
- Science data is temporarily stored in the SEB before being packetised and transmitted to the SSMM. This temporary storage is for on-board compression of science data. The compressed data will arrive later than uncompressed data and that packet generation times will not correspond to the data acquisition time. The exact delay is TBD but will depend on the study parameters.
- Most of the science data will be stored in a non-circular buffer in the SSMM.
- Use of a small circular buffer is possible for selective downlink of science data (TBC). Its implementation is being considered by the Science Team.
- Low latency science data will be used for certain studies, which are being considered by the Science Team.
- Buffer selection in the SSMM will be PID based.

2.6.3.5 On-ground data processing

- a reference to the data processing algorithms necessary to interpret the payload telemetry on-ground (referenced documents provided separately);
• for each data type (at packet level) the susceptibility to loss of single packets shall be stated, in terms of the impact on data quality.

### 2.6.3.6 Tele-command requirements

A budgetary estimate of the required number of TC’s is made, for each of the Studies given in the above Studies list in table 4.

The list of required commands to execute each study is below.

<table>
<thead>
<tr>
<th>COMMAND</th>
<th>COMMAND COUNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upload Study parameters</td>
<td>3</td>
</tr>
<tr>
<td>Transition to ENGINEERING</td>
<td>4</td>
</tr>
<tr>
<td>Transition to OPERATE</td>
<td>5</td>
</tr>
<tr>
<td>Run Study, times N repeats</td>
<td>5+N</td>
</tr>
<tr>
<td>Transition to STANDBY</td>
<td>5+N+1</td>
</tr>
</tbody>
</table>

This gives the following estimated number of commands for each study:

<table>
<thead>
<tr>
<th>Study</th>
<th>N (study repeats)</th>
<th>Commands budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Atlas</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Composition Mapping</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Dynamics</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>Limb</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>CME Watch</td>
<td>30</td>
<td>36</td>
</tr>
<tr>
<td>30° movie</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>90° movie</td>
<td>40</td>
<td>46</td>
</tr>
<tr>
<td>Waves</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Two-exposure</td>
<td>5</td>
<td>11</td>
</tr>
</tbody>
</table>
2.6.4 Low-latency science data

SPICE will make use of the system functionality to provide low-latency data down-link with **1MB data volume allocation per instrument per day**. The next issue of the SPICE Data ICD (#RD1, iss. 4) will contain detailed TM definitions of low-latency science data. The FSW will accept a command to switch the APID from normal science to low latency science and vice versa.

SPICE will make special low-latency science studies during the low-latency data periods, and these are data-reduced versions of the normal observation science studies list above in table 4. The main driver in deriving these low-latency versions is to be able to quickly assess the instrument performance and science data quality of each study, and make a planning update if necessary. The rules for devising the low-latency version are as follows:

- The following parameters remain the same as in the standard study: exposure time, spectral line selection, spectral window width and binning, spatial binning.

- The following parameters have reduced values to ensure that the total data volume of each LL study is below 0.1 MB: extent along the slit ('window height'), number of scan positions, number of study repeats. There is flexibility in choosing which of these parameters should be reduced most. The scan step size will be kept at same value as the nominal study, leading to reduced X-size of FOV, rather than making ‘sparse’ scan at wider FOV.

We envisage that in the observing timeline each science study will also be preceded by its special low-latency version.

Examples of the low-latency versions of each of the science studies are given in the table below, with the estimated reduced data volumes and rates.
### Table 6 Low-latency science study list and parameters (see Table 4 for study definitions)

<table>
<thead>
<tr>
<th>OBSERVING MODE (STUDY)</th>
<th>STUDY PARAMETERS REDUCED SIZES</th>
<th>Reduced No of repeats</th>
<th>Duration in hours</th>
<th>Net Data Vol, Mbytes</th>
<th>Net Data rate Kbit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Atlas</td>
<td>raster-fov positions 10 -&gt; 1</td>
<td>2 -&gt; 1</td>
<td>0.67 -&gt; 0.07</td>
<td>0.42</td>
<td>13.99</td>
</tr>
<tr>
<td>Composition Mapping</td>
<td>Window height 640 -&gt; 448</td>
<td>1</td>
<td>3.2 -&gt; 0.8</td>
<td>0.2121</td>
<td>0.58</td>
</tr>
<tr>
<td>Dynamics</td>
<td>Window height 640 -&gt; 448</td>
<td>10 -&gt; 1</td>
<td>1.97 -&gt; 0.32</td>
<td>0.1</td>
<td>0.70</td>
</tr>
<tr>
<td>Limb (low corona above limb)</td>
<td>Window height 640 -&gt; 128</td>
<td>1</td>
<td>3.76 -&gt; 1.1</td>
<td>0.1</td>
<td>0.21</td>
</tr>
<tr>
<td>CME Watch</td>
<td>Window height 640 -&gt; 128</td>
<td>30 -&gt; 1</td>
<td>24.5 -&gt; 0.27</td>
<td>0.2</td>
<td>1.63</td>
</tr>
<tr>
<td>30°-wide movie (sit &amp; stare)</td>
<td>Window height 800 -&gt; 224</td>
<td>1</td>
<td>0.17 -&gt; 0.04</td>
<td>0.1</td>
<td>5.23</td>
</tr>
<tr>
<td>90°-wide movie</td>
<td>Window height 800 -&gt; 448</td>
<td>40 -&gt; 6</td>
<td>0.51 -&gt; 0.08</td>
<td>0.1</td>
<td>2.90</td>
</tr>
<tr>
<td>Waves (Sit &amp; stare)</td>
<td>Window height 640 -&gt; 800</td>
<td>5 -&gt; 1</td>
<td>3.38 -&gt; 0.007</td>
<td>0.077</td>
<td>24.30</td>
</tr>
<tr>
<td>Two-exposure</td>
<td>Window height 640 -&gt; 448</td>
<td>5 -&gt; 1</td>
<td>5.4 -&gt; 0.54</td>
<td>0.1</td>
<td>0.41</td>
</tr>
</tbody>
</table>