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Observing with the ISO Short-Wavelength Spectrometer ⋆

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Abstract. The Short-Wavelength Spectrometer (SWS) is one of the four instruments on-board ESA's Infrared Space Observatory (ISO), launched on November 17, 1995. The spectrometer covers the wavelength range of 2.38 to 45.2 μm with a spectral resolution ranging from 1000 to 2000. By inserting Fabry-Perot filters the resolution can be enhanced by a factor 20 for the wavelength range from 11.4 to 44.5 μm. An overview is given of the instrument, its in-orbit calibration, performance, observing modes and off-line processing software.

Key words: Instrumentation : spectrographs – Methods: data analysis – Methods: observational – Techniques: Spectroscopic – Infrared: General

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1. Introduction

The SWS is one of the two spectrometers on-board ISO (see Kessler et al. 1996). Together with the Long Wavelength Spectrometer it provides ISO with unprecedented capabilities for moderate and high spectral resolution observations, from the near to the far infrared, over 6 octaves. The instrument has two grating sections covering the wavelength range from 2.38 to 45.2 μm with a spectral resolving power of the order of 1000 to 2000. With its Fabry-Perot (F-P) etalons located at the output of the long-wavelength (LW) section, the resolution can be increased to about 25,000 for the wavelength range from 11.4 to 44.5 μm.

The SWS instrument was developed, fabricated and space-qualified by the Space Research Organisation of the Netherlands (SRON) and the Max Planck Institut für Extraterrestrische Physik (MPE) with contributions by the Technical Physics Department (TNO/TPD) of the University of Delft. The detectors were procured from the Battelle Institut, Cincinnatti Electronics Corporation, Rockwell International, and Steward Observatory with contributions by AF Phillips Laboratory, Hanscom, USA.

The preparations of the operations of the SWS and its instrument-specific software were carried out by a team

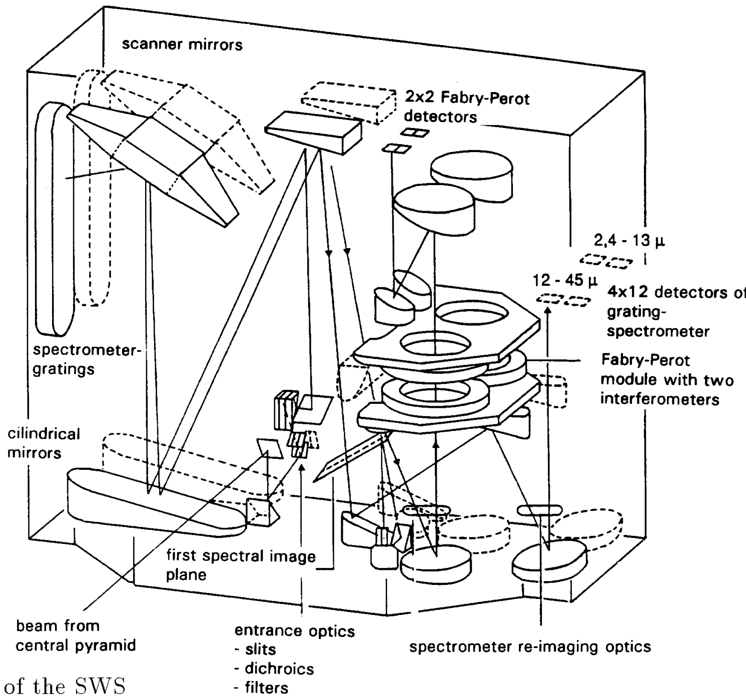

Fig. 1. Schematic of layout of the SWS

of SRON and MPE scientists and engineers. The team was enlarged through the participation of the University of Leuven (KUL). With the installation of the SWS Instrument Dedicated Team (SIDT) in 1994, ESA personnel were included as well.

After the launch on November 17, 1995, there was a three week period of spacecraft- and instrument check-out (SCP) followed by 8 weeks of performance verification (PV) and calibration observations. Analysis of the data obtained during the SCP and PV phases resulted in the in-orbit instrument calibration. Details of the flux calibration, the determination of the in-orbit Relative Spectral Response Function (RSRF) and beam profile are described by Schaeidt et al. (1996). The in-orbit wavelength calibration, the spectral resolution and instrumental profile is described by Valentijn et al. (1996). The SCP and PV observations resulted in adjustments of some of the instrument settings and in updates of the up-link calibration tables. The experience with the behaviour of SWS gained during SCP and PV also led to a number of small changes in the SWS astronomical observing templates (AOT, see also section 3). In parallel with these adjustments to the instrument settings and observing procedures the SWS off-line processing software (SWS Interactive Analysis, IA, see also section 4) was adapted to allow proper analysis of the observations. Furthermore IA was considerably rearranged and expanded to cope e.g. with the effects of particle hits on the detectors.

We will give here a description of the instrument, its in-orbit performance, AOT's and SWS IA software from a user's point of view, to support the description of the SWS observations of the letters in this A&A issue. More details on the design of the SWS can be found in de Graauw et al. 1989, in the ISO-SWS observer's manual and in a forthcoming paper by de Graauw et al. (1996).

2. Instrument Description

The SWS instrument consists of two nearly independent grating spectrometers plus a set of two scanning Fabry-Perot filters (see Fig. 1). The short wavelength section (SW) uses a 100 lines/mm grating in the first four orders, covering 2.4-13 μm. The long wavelength (LW) section has a 30 lines/mm grating used in the first two orders, covering 11-45 μm. The two FP's are at the output of the LW section and in this mode the third order of the LW grating is used as well.

The SWS has three apertures. A shutter subsystem allows use of only one of them while keeping the other two closed. For observations, the spacecraft pointing has to be adjusted to have the astronomical object imaged onto the selected aperture. The shutter can also be used to close SWS, permitting directl determination of the signal from the instrument when it is not illuminated. Each aperture is used for two wavelength ranges, one for the SW section and one for the LW section. This is achieved by using Reststrahlen crystal filters as dichroic beamsplitters behind the apertures. The transmitted beams enter the SW section, the reflected beams enter the LW section. The actual spectrometer slits are located behind the beamsplitting crystals. Interference filters or crystal filters take care of further order sorting. Each grating has its own scanning device, allowing the use of both grating sections of the SWS at the same time, albeit through the

Table 1. Definition of the SWS AOT bands

	Band	λ_{key} (μm)	Grating order	Aperture nr.	Aperture area ($''$)	Detector type	Detector area (pixels)	Wavelength range (μm)	Sensitivity ratio $\frac{\text{in-orbit}}{\text{ground}}$
SW section	1A	2.5	SW 4	1	14 × 20	InSb	1 × 12	2.38 - 2.60	0.6
	1B	2.9	SW 3	1	14 × 20	InSb	1 × 12	2.60 - 3.02	0.6
	1D	3.1	SW 3	2	14 × 20	InSb	1 × 12	3.02 - 3.52	1.1
	1E	3.8	SW 2	2	14 × 20	InSb	1 × 12	3.52 - 4.08	1.1
	2A	4.5	SW 2	2	14 × 20	Si:Ga	1 × 12	4.08 - 5.30	4.5
	2B	5.9	SW 1	2	14 × 20	Si:Ga	1 × 12	5.30 - 7.00	4.5
	2C	7.7	SW 1	3	14 × 20	Si:Ga	1 × 12	7.00 - 12.0	4.5
LW section	3A	14.0	LW 2	1	14 × 27	Si:As	1 × 12	12.0 - 16.5	6.5
	3C	17.0	LW 2	2	14 × 27	Si:As	1 × 12	16.5 - 19.5	6.5
	3D	24.0	LW 1	2	14 × 27	Si:As	1 × 12	19.5 - 27.5	6.5
	3E	28.5	LW 1	3	20 × 27	Si:As	1 × 12	27.5 - 29.0	6.5
	4	32.0	LW 1	3	20 × 33	Ge:Be	1 × 12	29.0 - 45.2	5.5
FP	5A	11.8	LW 3	1	10 × 39	Si:Sb	1 × 2	11.4 - 12.2	5.5
	5B	14.0	LW 2	1	10 × 39	Si:Sb	1 × 2	12.2 - 16.0	1.7
	5C	17.0	LW 2	2	10 × 39	Si:Sb	1 × 2	16.0 - 19.0	1.7
	5D	24.0	LW 1	2	10 × 39	Si:Sb	1 × 2	19.0 - 26.0	2.0
	6	27.0	LW 1	3	17 × 40	Ge:Be	1 × 2	26.0 - 44.5	2.1

same aperture. The scanning device consists of a flat mirror mechanism mounted on a rotation mechanism, located close to the grating. For further details see Wildeman et al. (1987) and Aalders et al. (1989). The spectral image at the output of each of the two grating sections is reimaged onto two small (1×12) detector arrays. Altogether the SWS has 4 arrays for the grating sections.

Using the different possible combinations of grating order, aperture and detector array, for the grating sections a total of 12 different, partly overlapping, spectral bands are obtained, the so-called AOT bands. Table 1 gives an overview of the properties of these various AOT bands. Clearly although the 12 grating AOT bands together make a full SWS spectrum, none of the 12 bands has exactly the same optical path. As a result discontinuities can be present in an observed spectrum which can in principle be eliminated if a correction for the spectral responsivity of the instrument is applied. The quality of this correction depends on an accurate determination of the Relative Spectral Response Function (RSRF, see Schaeidt et al., 1996).

The scanning mechanism is also used to select one of the two scanning FP's and the wavelength range to be observed, as the FP input mirrors are located near the exit of the LW section. The FP's are mounted on a single pair of parallel plates whose separation can be varied by changing the currents in three coils, thus scanning the wavelength. Each FP has its own calibrated scan current table. Each FP has also its own detector pair. There are 5 FP AOT bands (see table 1).

3. SWS Observing Modes and AOT's

There are two main SWS observing modes: in one mode the two SWS grating sections operate in parallel, in the other mode the FP operates in parallel with the SW grating section.

In the grating observations arrays of 1×12 detectors are used and as a result the spectral range covered instantaneously is of the order of 8 resolution elements. The grating is scanned in steps with different scan schemes depending on the AOT used. See also table 2 for details.

In all AOT's the basic strategy is to take dark current measurements at regular intervals, and at least one before *and* after each measurement. This allows dark current values to be interpolated for any given time during the observation. A measurement of the internal calibrator sources to monitor possible long term responsivity variations is done at the end of the AOT's.

There are no SWS spatial raster AOT's. Mapping has to be achieved by defining a grid of positions on the sky, to be observed in a concatenated repetition of the AOT's.

3.1. AOT S01, a scan of the full SWS wavelength range

AOT S01 observes the full SWS wavelength range: from 2.38 to 45.2 μm. There are 4 scan speeds, to be specified by the observer. The scan speed determines the spectral resolution and the sensitivity. Duration is about 1/4, 1/2, 1 and 2 hours. The resolving powers are 1/8, 1/8, 1/4, 1/2 respectively of the full SWS resolution. Dark currents are recorded around each aperture change and at the start and end of the observation.

Table 2. Properties of SWS AOTs

AOT	Band							Notes
S01	1-4	t_r	1	2	2	2		
		L_s	32	32	16	8		*a*
		n_{scan}	2	2	2	2		*b*
		n_{int}	24	24	24	24		
		Resol.	R/8	R/8	R/4	R/2		*c*
S02	1,2,3[f]	t_r	1	2	4			
		L_s	1	1	1			
		n_{scan}	2	2	2			*d*
		n_{int}	110	110	110			
S02	4	t_r	1	2				
		L_s	2	2				
		n_{scan}	2	2				*d*
		n_{int}	90	90				
S07 F-P	5,6	t_r	1	2				
		L_s	$\frac{\Delta\lambda}{4}$					
		n_{scan}	3	3				*e*
S06 & SW section in S07	1,2,3[f,g]	t_r	1	2	2	4	4	
		L_s	4	4	2	2	1	
		n_{scan}	2	2	2	2	2	*d*
		n_{int}	27	27	55	55	110	
S06	4	t_r	1	2	2	2	2	
		L_s	6	6	3	2	1	
		n_{scan}	2	2	2	2	2	*d*
		n_{int}	30	30	60	90	180	

t_r - reset interval in seconds
L_s - number of scan steps per reset interval
n_{scan} - minimum number of scans per observation
n_{int} - number of integrations per resolution element. This is the product of n_{scan}, the number of detectors in an array (12), and the ratio between resolution and stepsize.
a) effectively, actually 8 steps are made per second
b) 1 scan up and 1 scan down
c) effective spectral resolution, R is the full grating resolution
d) a series of up and down scan pairs, total number depending on required sensitivity
e) unidirectional, minimum 3 scans
f) t_r=4 not used for bands 2 and 3
g) band 3 not with S07

3.2. AOT S02, SWS line scans

AOT S02 permits observing spectral lines and a small range of surrounding continuum to an extent of about 1500 km/sec, with the full spectral resolution. The AOT logic will optimise the observing programme for simultaneous execution of scans in both SW and LW sections. Dark currents are recorded at regular intervals, interspersed between different line scans.

3.3. AOT S06, scans over large wavelength ranges

AOT S06 is designed for longer wavelength scans with full resolution. Like S02 this AOT will also simultaneously execute SW and LW observations. Dark currents are recorded at the start and the end of each measurement. During the scans at regular intervals a short reference scan is made at a user selected wavelength. These data can be used to monitor possible responsivity and dark current drifts.

3.4. AOT S07, high resolution Fabry-Perot observations

For the FP observations (AOT S07), the LW grating section is used as order sorter with the maximum of the grating transmission tuned to the desired wavelength. Also the gap of the scanning FP unit is tuned to match one of its transmission peaks. When scanning the FP, grating tracking to obtain optimum grating transmission is needed to keep the contribution of unwanted FP orders as low as possible.

Parallel to the FP scans the SW section can be used for grating spectral range observations. However it has been necessary to define a fourth SWS aperture, replacing aperture 3 for the LW-FP in operating in AOT band 6, to correct for a misalignment. Thus in AOT band 6 parallel FP and SW observations are not possible.

3.5. Changes in AOTs

The in-orbit performance verification measurements resulted in some minor changes to the AOT logic. These changes were directly or indirectly linked to minimise the effects from transients and particle radiation on the detectors. One of the consequences of particle radiation is more detector noise than measured during the laboratory tests. This effect has led to adjustment of the detector noise parameter tables and to reduction of the reset intervals to 1 and 2 seconds, except for band 1 where a reset interval of 4 seconds is still used.

Secondly dark-current measurements got more emphasis, resulting in longer duration measurements and at a higher frequency in some of the AOT's.

Finally the use of the photometric checks, mainly to check the responsivity of the detectors against an internal source has been reduced to minimise the unwanted after-effects on dark measurements and low flux level observations.

4. Calibration and analysis of SWS data

To support the calibration of SWS the development of SWS Interactive Analysis (IA) was started in the early 1990's (see also Roelfsema et al. 1993). During the Instrument Level Tests (ILT's), the preparations for ISO operations, SCP, PV and routine ISO operations IA was constantly adapted to reflect the increased understanding of the instrument. The design and implementation of IA was carried out by a team spread over several different instititutes. To allow development of IA with a geographically split up group and to safeguard against unwanted, hastily implemented changes in IA a rigorous configuration control system has been, and will be used throughout the development and operations phase (see Huygen and Vandenbussche, 1996).

It was recognised early on that as part of SWS calibration full data reduction capabilities are needed in IA. For this purpose the Standard Product Generation 'Pipeline' software for SWS has been fully integrated with IA (see Roelfsema et al, 1993). As result IA has become a good environment for reducing SWS science data as well as calibration data, while at the same time it is the ideal environment for further development of the pipeline software. Apart from these standard reduction programs, also manipulation routines varying from basic arithmatic to advanced noise reduction and fitting algorithms have been implemented. For detailed inspection of SWS data in IA a suite of display and print routines are available.

For analysis of calibration observations a special set of reduction programs (Calibration Analysis Procedures, or CAP's) has been implemented in IA. Where possible these CAP's use the standard pipeline modules in IA. The CAP's are executed on specific calibration observations to generate specific calibration parameters. After careful scrutiny these calibration parameters are stored in the SWS calibration database and, when appropriate, forwarded to the Science Operations Center (SOC) for use in the operational system. Trends in these calibration parameters are also evaluated within IA. This may eventually lead to implementation of different instrument settings or observing strategies.

The standard processing of SWS data, the pipeline process (current version OLP V5.0), consists of a number of different parts (see also Fig. 2). The processing starts with the raw data in the form of an Edited Raw Data (ERD) product. Here the data consist of 24 digital readouts per second per detector corresponding to the digitised output of the detector and amplifier chain. In the first part of the pipeline these digital readouts are corrected for crosstalk between neighbouring detectors, flagged for saturation anywhere in the detection chain, corrected for effects of the reset pulse at the beginning of each reset interval, linearised and converted to analog voltages. Also in this stage an inventory is made of 'glitches' resulting from particle hits. In future pipeline versions it is envisaged that this glitch list will be used to remove the (long term) after-effects of the glitches. Currently, data affected by glitches are discarded. Subsequently a slope is fitted to the linearised readout ramps for each reset interval. These slopes are a direct measure for the flux incident on the detectors.

In the second stage of the pipeline, wavelengths are assigned to the data for each reset interval. The wavelengths are calculated from the grating positions and FP gap sizes by applying the grating equation with constants derived in the process of the SWS wavelength calibration (see Valentijn et al., 1996). The resulting dataset, the socalled Standard Processed Data (SPD), has for each detector for each reset interval a slope in μV/sec and a wavelength in μm, as well as ancillary information about timing, instrument settings used, data quality etc.

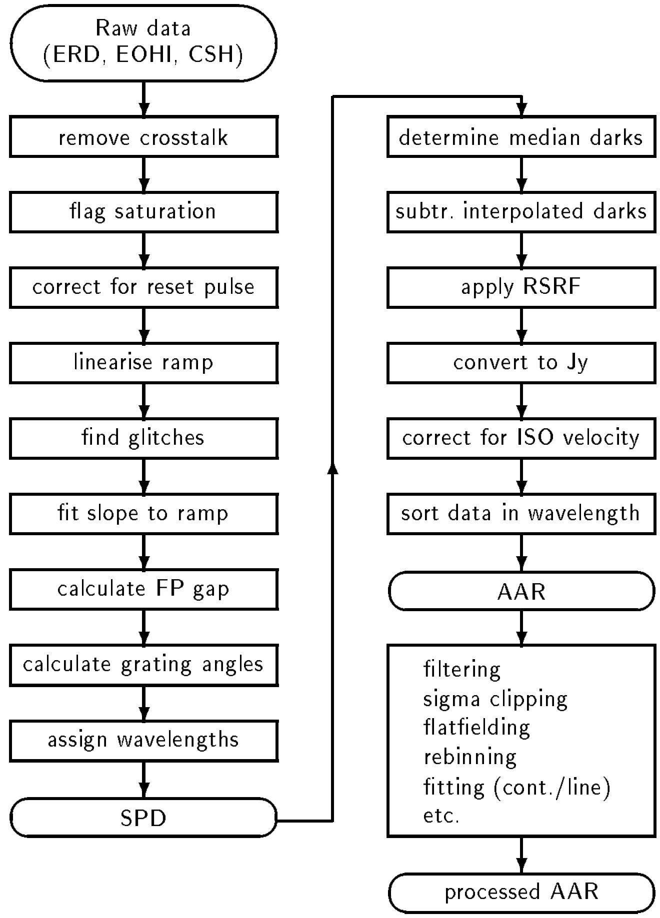

Fig. 2. Flow diagram of the SWS standard data processing

Following the SPD generation, the dark current signal has to be determined from the observation. In all AOT's executed after revolution 191 there is at least one dark measurement before and after each science measurement. For each detector the median dark current is determined in each of these dark measurements, and a dark value is interpolated and subtracted from each science data point. Clearly this process is quite sensitive to strong transients in the dark current data. For weak signals, i.e. signals a few times the dark current, even small errors in the dark currents may lead to large errors in the final spectrum.

Next the data have to be corrected for the spectral responsivity of the instrument. To accomplish this for each reset interval, for each detector a correction factor is derived from the normalised RSRF (see Schaeidt et al., 1996) interpolated to the observed wavelength grid. If needed the RSRF is smoothed to the proper resolution in the process. These wavelength dependent correction factors are subsequently applied to the detector data. Following this the data of a each detector are scaled by a single flux conversion factor per AOT band. To convert the fluxes from instrument units to astronomical units (normally Jy). The value of this scale factor corresponds to the responsivity of SWS at the RSRF normalisation wavelength (the socalled key wavelength λ_{key}, see Schaeidt et al., 1996) The thus-obtained flux calibrated data are subsequently sorted in wavelength order and stored in the final pipeline product, the Auto Analysis Result (AAR). Again ancillary data are added for information.

Post AAR analysis normally involves discarding data points affected by transients, 'flat-fielding' the different detectors and resampling and averaging data from different detectors to a grid corresponding to the nominal resolution. What follows after this depends on the astronomy being done, but generally involves fitting of continuum levels and line shapes, determining fluxes, etcetera.

5. In-orbit Performance

In orbit, the check-out measurements and the performance verification and calibration observations showed all SWS mechanisms operating sucessfully. The grating- and FP scanners and the aperture shutters worked well, as on the ground. The launch and zero gravity condition had also no effect on the optical alignment and spectral resolution. In orbit it was for the first time that the spectrometer performance was measured with point-like sources. The spectral resolution is very close to calculated values, the instrumental profile is very clean and has a gaussian shape at least down to a level of 10%.

The main deviation from the ground tests is the detector performance. The detector dark current and dark noise are dominated by effects due to hits by cosmic particles. Indicative numbers for the resulting degradation in sensitivity are given in Table 3. Part of the degradation in sensitivity (some 20%) is due to the fact that the in-orbit values are derived from observations of point sources, while the ground calibration was done with sources which fully filled the entrance slits. Although there is considerable loss in sensitivity the achieved overall performance of SWS is well within the specifications given at the time of proposal submission.

6. Conclusions

The in-orbit performance and calibration measurements of the SWS demonstrate its scientific capabilities predicted from ground tests. The prepared observing modes, instantiated in four AOT's, allow to observe successfully a wide range of astronomical objects. This is demonstrated by the large number of publications based on SWS data in this issue.

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References

Aalders, J.W.G. et al., Cryogenics (1989) 550-552

de Graauw, Th., Beintema, D.A., Boonstra, A-J. et al. 1989, ESA SP-290, 549-551

de Graauw, Th., Haser, L.N., Beintema, D.A. et al. 1996, in prep.

Huygen, R. & Vandenbussche, B., 1996 in prep.

Hucht van der K. A., Lutz D., 1994, *ISO Short Wavelength Spectrometer Observer's Manual*, issue 2.0, ESA

Kessler, M.F.K. et al. 1996, this issue of A&A

Roelfsema, P.R., Kester, D.J.M., Wesselius, P.R., Leech, K., in *Astronomical Data Analysis Software and Systems II*, pp 254, eds. D.M. Worrall, C. Biemesdorfer, J. Barnes, 1993, Astronomical Society of the Pacific conference series, San Francisco

Schaeidt, S., Morris, P.W., Salama, A. et al. 1996, this issue of A&A

Valentijn, E.A., Feuchtgruber, H., Kester, D.J.M. et al. 1996, this issue of A&A

Wildeman, K.J. et al., 1987, Cryogenics 27 68-72

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