THE GROUND-BASED CALIBRATION OF SWS

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ABSTRACT

We present a summary of all ground based SWS instrument tests and calibrations together with a description of test equipment and environment. The contents and results of the SWS ground calibration are discussed and their value for the in-flight calibration of SWS is demonstrated.

Key words: ISO – Instrumentation: spectrographs – Space vehicles: instruments

1. INTRODUCTION

The Short Wavelength Spectrometer (SWS) (de Graauw et al. 1993, de Graauw et al. 1996) on-board the Infrared Space Observatory (ISO) (Kessler et al. 1996) has been subject to extensive laboratory testing and calibration prior to launch. The definition and design of the individual test steps and procedures has been carried out with great care, not only to verify proper instrument function and performance, but also to avoid from missing critical topics, which are not measurable in flight. For a short-lived mission like ISO, all observations had to be prepared already before launch and the actual routine phase of the mission was supposed to start earlier than 3 months after launch, leaving not much time for initial in-orbit calibration. Therefore, a strong requirement on the calibration efforts on ground was driven by the need of accurate estimates for instrument observing performance and exposure time. In the same context, Astronomical Observation Templates (AOT) and their underlying logic needed to be developed already during the laboratory tests. Besides minimising overheads, the calibration strategy on the internal infrared calibration stimuli had to be developed such that easy adjustments of AOT logic parameters were possible for adapting to the in-flight performance of the instrument, without a severe impact on the necessary observing time.

In order to optimise our efforts, we have chosen for a close correspondence of test and characterisation procedures on the ground to the envisaged in-orbit procedures. In this way, many of the data reduction and analysis techniques that had to be developed for the data acquired on ground could easily be propagated for the in-orbit calibration analysis.

More details on the initial ground-based calibration results have been presented by Beintema et al. 1993 and Valentijn et al. 1993. This paper intends to present the significant weight and contribution of ground-based work for the calibration of the SWS data in the ISO legacy archive.

2. INSTRUMENT MODELS AND TEST PHASES

The instrument development cycle for ISO SWS comprised 3 different models of the entire instrument, the Qualification Model (QM), Flight Model (FM) and Flight Spare Model (FS). The first one, more of prototype character but operationally almost fully representative, had to pass all environmental tests at qualification levels (e.g. cryogenic vibration), while the other two were exposed to acceptance levels only. Each model consisted of the Focal Plane Unit (FPU) and the warm electronic boxes. Since the QM has been almost fully operational, the first instrument level tests (Table 1) provided already valuable information on design improvements of the FPU, the basic detector behaviour and the performance of the cryogenic detector readout circuits. After the return of the QM from Integrated Module Tests (IMT), it has been refurbished and upgraded to the FS by replacement of mechanisms, detectors and various other parts.

In the course of the cryogenic tests on the different models a number of problems in design and performance of the instrument have been encountered, requiring fast corrections within the tight schedule of the ISO project and led to significant additional test efforts. The most important problems and the respective corrective actions were:

- Spectral ghosts in grating section → SWS “balcony”

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Table 1. Test phases of QM, FM and FS. ^{A} indicates that SWS AOT testing has been included in the test program. ILT = Instrument Level Test; IMT = Integrated Module Test; EMC = Conducted Emission and Susceptibility Test; DBT = Dark Background Test; (S)IST = (Short) Integrated System Test; TVC = Thermal Vacuum Cycling Test; EE = End-to-End Test; SVT = System Validation Test.

	Test Phase	Date
QM	ILT 1	21 May 1990 - 30 May 1990
QM	Cryo-Vibration	18 Jun 1990 - 20 Jun 1990
QM	ILT 2	22 Jun 1990 - 16 Jul 1990
QM	IMT + EMC	29 Oct 1990 - 06 Nov 1990
QM	FP Check	24 Jan 1991 - 30 Jan 1991
FM	Pre-ILT 1	27 Mar 1991 - 10 Apr 1991
FM	Pre-ILT 2	24 Apr 1991 - 26 Apr 1991
FM	Pre-ILT 3	06 Aug 1991 - 09 Aug 1991
FM	Cryo-Vibration	27 Aug 1991 - 30 Aug 1991
FM	ILT 1 ^{A}	16 Sep 1991 - 07 Oct 1991
FM	ILT 2 ^{A}	22 Oct 1991 - 08 Jan 1992
FM	ILT 3 ^{A}	10 Feb 1992 - 15 Apr 1992
FM	ILT 4 ^{A}	22 Sep 1992 - 10 Nov 1992
FS	Cryo-Vibration	03 Feb 1993 - 05 Feb 1993
FS	ILT 1 ^{A}	10 Feb 1993 - 08 Apr 1993
FS	ILT 2	10 May 1993 - 27 May 1993
FM	ILT 5 ^{A}	29 Jun 1993 - 03 Aug 1993
FS	ILT 3 ^{A}	12 Oct 1993 - 29 Nov 1993
FM	IMT + DBT + EMC	5 days in Jan/Feb 1994
FS	ILT 4 ^{A}	23 Mar 1994 - 25 May 1994
FM	IST 1	01 Aug 1994 - 02 Aug 1994
FS	PV ILT ^{A}	07 Sep 1994 - 25 Nov 1994
FM	TVC 1 + SIST ^{A}	5 days in Oct/Nov 1994
FM	TVC 2	11 Dec 1994 - 12 Dec 1994
FS	Final Functional Test	9 Jan 1995 - 30 Jan 1995
EE	1 / SVT 1 ^{A}	4 days in Jan/Feb 1995
EE	2 / SVT 2 ^{A}	4 days in Apr 1995
FM	IST 2	02 May 1995 - 03 May 1995
FM	IST 3	20 Jul 1995 - 26 Jul 1995

- Detector exchanges due to poor performance: band 3: Si:P → Si:Sb → Si:As BIB; band 5: Si:P → Si:Sb
- Radioactive lenses (thorium bearing coating) in front of the short-wavelength grating detectors → lenses with different coating.
- The aluminium bolts for mounting of SWS onto the optical bench failed during cryogenic vibration → replaced by stainless steel bolts.
- Poor performance and failed channels triggered several manufacturing runs, improved processes for the cold readout electronics (IA16) and subsequent exchange within the instrument.
- The instrumental profile of the FS Fabry-Pérot (FP) has been double peaked. Despite extensive investigations the reason for this could not be clarified.
- The FM grating scanners end stop has been shifting during ILT, indicating that they have become loose → removed, fixed by an improved gluing procedure and remounted.
- An order sorting problem for the short-wavelength FP section has been resolved by an additional filter in the detector block.
- Upgrade of the detector block to suppress spurious reflections.
- The pre-filter of the Fabry-Pérot calibration source has been damaged during bake-out → replacement and improved processes.

However, there have been no remaining instrumental problems in the SWS FM after integration into the ISO satellite. Three different SWS models, the number of encountered problems and the requirement to fully calibrate both, FM and FS, finally added up to 638 days of cryogenic instrument tests, a remarkable number compared to the total of 874 ISO revolutions.

3. INSTRUMENT LEVEL TEST SET-UP

3.1. TEST CRYOSTAT

The thermal interfaces to SWS have been simulated during instrument level tests by a three baths cryostat. The LN_2 tank provides the required thermal shielding of the pumped LHe_{3K} and $LHe_{1.8K}$ reservoirs. The $3K$ stage represents the ISO optical bench temperature, while a cooling strap to the $1.8K$ stage simulated the required connection of the SWS Ge:Be detectors to the ISO main LHe tank. The cryostat was equipped with one window at $300K$ and a movable shutter/window at $77K$ to provide access to external infrared sources for calibration and alignment measurements (Fig. 1). The diameter of the circular optical bench has been 40 cm and the maximum operation time of the cryostat before the necessary refill of coolants has been $\sim$ 12 hours with a total consumption of $\sim$ 30 l/d of LHe and $\sim$ 15 l/d LN_2.

3.2. EGSE

The Electrical Ground Support Equipment (EGSE) is illustrated in Fig. 1. It simulates the spacecraft interface to the warm electronic boxes, provides the necessary power supplies and drive electronics for the test optics and external calibration sources and allows for real time analysis of the instrument house keeping data and quick look analysis of the detector data. The Real Time Unit (RTU) simulator in connection with the PDP11/73 computer handled the telecommand and telemetry stream from/to the instrument station (VAX Station 3100-48). The advantage of this rather sophisticated system has been that from the very first ILT onwards, the telemetry data has been already in a format which is almost identical to the in-flight data, such that all SWS software packages (even the post-mission versions) could easily read in and process these data in the nominal way.

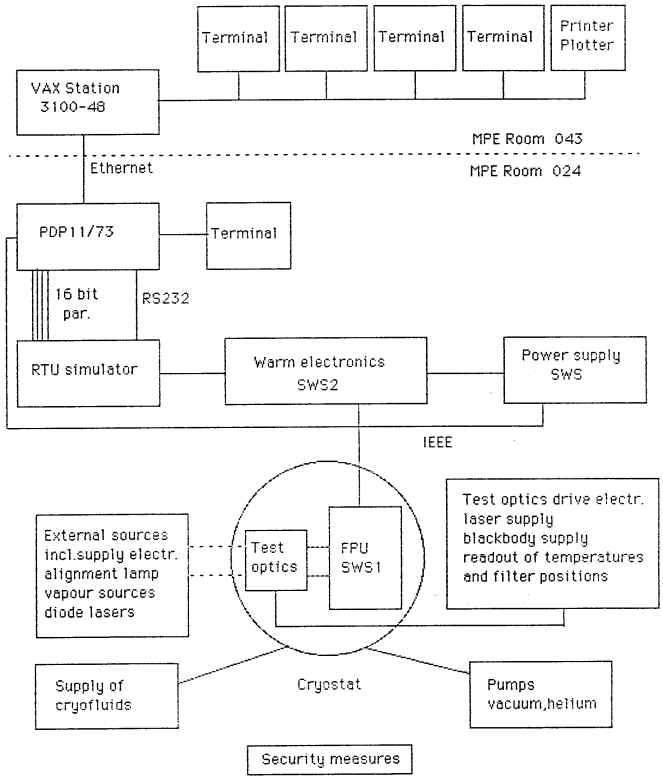

Figure 1. Block diagram of the test set-up for SWS instrument level testing.

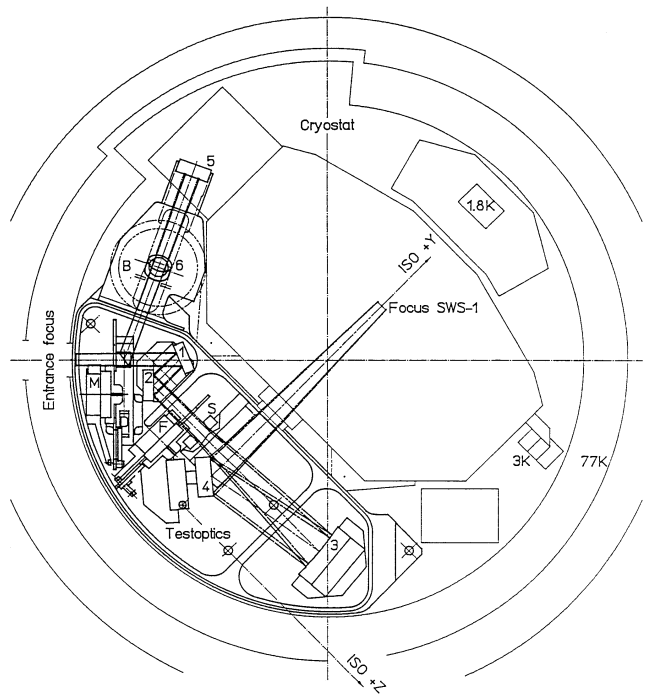

Figure 2. Cryogenic test optics mounted inside the cryostat: Numbers 1-6 denote mirrors; B = black body source; D = diode laser source; M = mirror wheel; F = filter wheel; S = movable aperture stop; SWS is represented as the large empty box in the centre of the drawing, with the balcony for the grating section to the upper left (mirror 5 lies below).

3.3. Test Optics

The number and complexity of ILT calibration and test requirements, forced the design of a highly sophisticated test optics (Fig. 2). Its key purpose has been to simulate the ISO telescope (f/15 beam) and to provide cryogenic infrared sources for absolute flux calibration, spectral resolution and wavelength calibration measurements. In the final design it consisted of the optics, 3 cryogenic mechanisms, a black body source and an infrared diode laser:

- Attenuation filters on wheel F: $1, 2 \times 10^{-2}, 1 \times 10^{-3}$, 1×10^{-6}
- Narrow band filters on wheel F: 11.9 μm, $16 - 28$ μm, 23 μm
- Attenuation filters on wheel M: $1, 1 \times 10^{-1}, 1 \times 10^{-4}$
- Narrow band filters on wheel M: 2.6 μm, 5.7 μm
- Mirrors to feed in the black body source and the diode laser on wheel M
- Calibrated cryogenic black bode source: range = 30-300 K; accuracy = ± 1 K; typical heat dissipation $\sim$100 mW; spatially extended
- Cryogenic diode laser: exchangeable only at ambient temperature; mostly 28 μm used; spatially extended
- Movable aperture stop for validation of optical alignment.

The selection of sources and filters is made by rotating the respective wheel into the beam. Apart from above “internal” sources mounted inside the test cryostat, it has been possible to measure “external” sources through the cryostat window and the wheels’ hole positions. Narrow emission lines have been available from several infrared lead salt lasers (3.1, 4.3, 11, 16, 25, 28.3, 32 μm) and a 2.4 μm $He - Ne$ laser reflected by a scatter plate. A water vapour absorption cell (path = $36cm$; p$\sim$23 mbar; $\rightarrow$ column density $\sim 2 \times 10^{19}cm^{-2}$) provided well known spectral signatures at sufficient strength to calibrate most of the SWS wavelength range. Spectral regions with poor coverage were calibrated with additional NH_3 and HCl vapour absorption set-ups. Alignment measurements and locations of the detector arrays within the SWS apertures have been facilitated by using a movable (dispersion direction) hot wire source and a movable stop (cross dispersion direction) with broadband background illumination.

4. TEST CONTENTS

The nature of instrument level tests can be divided into 3 different groups: Tests of more functional character, characterisation of instrument behaviour and calibration in the sense of converting an instrument specific signal into physical units. An additional separation for some functional and characterisation tests has been introduced for those tests which had to be carried out also during ISTs.

4.1. Functional Tests

Prerequisite for every ILT has been to verify the health and correct function of all the SWS sub-units before and during their integration. Electrical continuity tests on the warm electronic boxes and the FPU and the alignment of the test optics with the FPU preceded every cool down for an ILT.

The functional tests started with a well defined check-out program of the warm electronics (Start-up procedures, RAM tests, microprocessor tests, redundancy checks, low telemetry bit rate test, etc.). Initial function of all mechanisms and internal stimulators has been proven by short checks, followed by quick detector and electronics noise tests, verification of detector signal quality and the SWS overall thermal behaviour. A course verification of the grating spectral resolution has been achieved by a short scan of the internal grating calibrator source. After alignment checks of the SWS optical axis with respect to its dedicated alignment device and of the influence of the scanner on the positions of the arrays in the slits, the functional test sequence concluded with one iteration of the FP parallel adjustment procedure. Specifically for the IST, an ISO cryostat background check measurement procedure has been defined to provide information on the infrared background illumination on spacecraft level.

The described functional test sequence has been carried out during every ILT and IST and the generated data served as a unique monitor of the instrument health, possible changes and proper function.

4.2. Characterisation

Characterisation in the sense of assessment of instrumental behaviour, like linearity and temperature effects, reproducibility, sampling, etc., represent the major fraction of SWS ILTs. Large parameter spaces needed to be covered by systematic adjustments of detector heaters, biases, illumination levels, reset intervals, source position in apertures, etc., to find optimum values and in order to properly characterise the instrument for the expected in-flight conditions. The following major measurement sequences have been carried out:

- Detector signal quality and thermal self-emission
- Stabilisation time for signals of internal stimulators
- Non-linearity and effective noise as a function of illumination level and reset intervals
- Detector response transients (for large flux changes)
- Detector memory effects as a function of flux changes, flux history and background flux
- Response to very low signal (minimum NEP as a function of reset intervals)
- Reproducibility of grating calibrator scans
- Verification of Fabry-Pérot spectral reproducibility
- FP straylight suppression
- Temperature dependence of band 3 Si:As dark currents
- Semi-automatic on-board FP parallelisation.

4.3. Calibration

For a spectrometer like SWS, three distinct top level parts, spatial, spectral and photometric calibration had to be covered by the laboratory measurements. The spatial calibration without the real ISO telescope obviously is restricted to basic determinations of the relative location of the entrance apertures with respect to the telescope axis and the position of the detectors within the slits. The actual focal plane geometry, i.e. the position of the SWS slits in the ISO focal plane could only be measured in orbit.

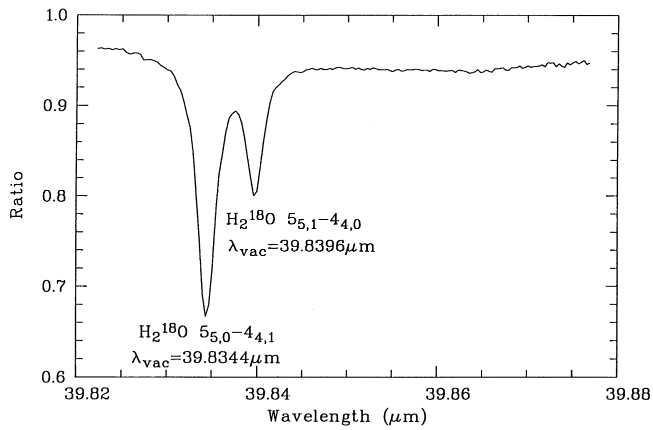

Figure 3. Fabry-Pérot measurement of water absorption lines for wavelength calibration.

Spectral calibration comprises a wavelength calibration over the full SWS wavelength range in both, the grating and FP sections, determination of the instrumental profile, FWHM and a validation of the spectral purity (ghosts, etc.). The vapour absorption cells of the test set-up provided narrow spectral molecular absorption lines for both, the FP section (Fig. 3) and the grating section (Fig. 4). For the scanning FP, the initial gap width has been determined based on the internal FP calibration source. The gap width then has been tied to the vapour measurements, characterising also the wavelength dependence of the gap width.

Subsequently, the grating wavelength scale has then been tied to the internal grating calibrator source. The generated fringe pattern (Fig. 5) allowed to monitor the stability of the calibration relying exclusively on this internal source. Analysis of the various laser measurements (ex. Fig. 6 and Fig. 7) provided the instrumental profile, the accurate angular offsets between individual detector pixels, different detector bands and the entrance apertures and verified the spectral purity.

The photometric calibration was derived from full grating and FP scans (at smallest scanner step sizes) of the cryogenic black body source at adequate temperature settings for the respective AOT bands. Fig. 7 shows an example for band 2. The accurate wavelength scale available from the previous step and the calibration of the black body source establish the relation

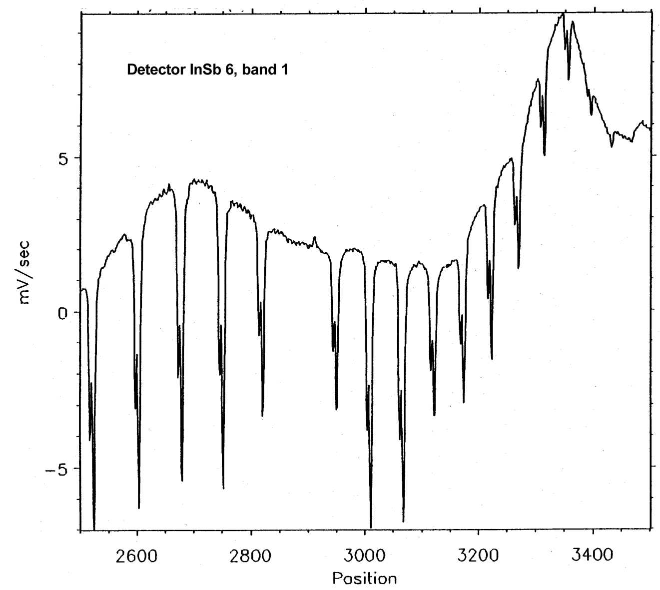

Figure 4. HCl absorption lines on an arbitrary continuum, measured on the band 1 grating array. The scanner position range from left to right corresponds to $\sim 2.7048\ \mu m$ *to* $\sim 2.4755\ \mu m$.

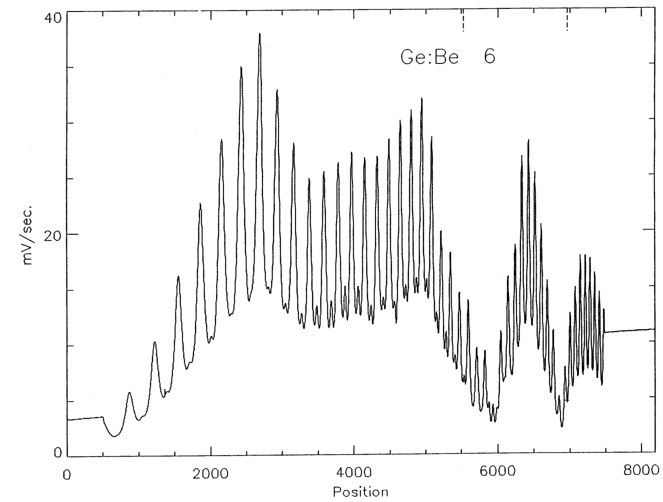

Figure 5. Full scan of the grating calibrator fringe pattern as seen from grating array detector Ge:Be 6.

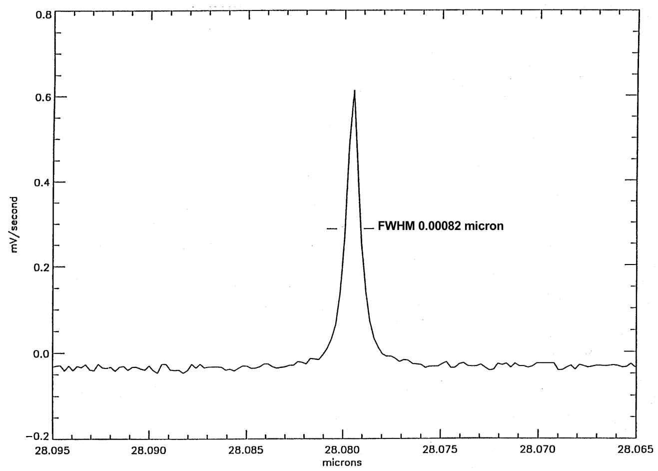

Figure 6. Fabry-Pérot measurement of the cryogenic $28\mu m$ *laser for characterisation of the spectral resolution.*

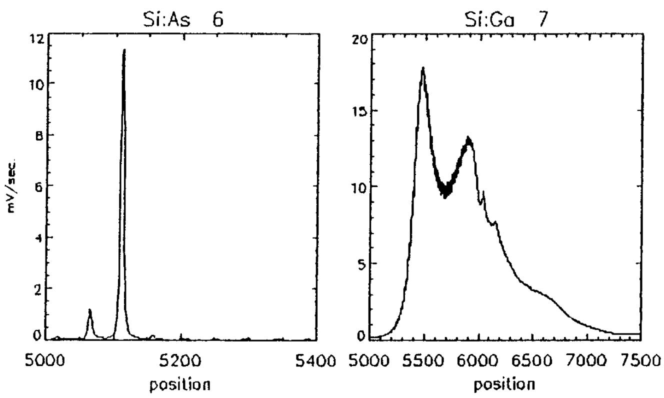

Figure 7. Left: Cyogenic diode laser measurement on a grating band 3 detector (several laser modes detected). Right: Measurement of the cryogenic black body source on a band 2 detector.

between output signal, flux and wavelength to obtain the detailed spectral response calibration.

5. AOT DEVELOPMENT

The development of Astronomical Observation Templates (AOTs) has been started already well before the FM ILT phase. First measurements have been obtained during FM ILT 1 and the development and optimisation of the various AOTs (Table 2) has been continued throughout the further test periods (Table 1) until into the SVT close to launch. A set of initially 9 different types of AOTs has been defined and exercised during the early phases of the tests (Table 2). In order to minimise operational complexities, calibration efforts and overheads, only 4 AOTs have been released to the observers. Celestial raster capabilities, originally implemented in AOT04 and AOT05 have been replaced by the possibility to schedule independent observations at different sky positions using the other AOTs. AOT08 and AOT09 have been used only during ILT and IST, to simplify the logic development and to allow for testing of all the AOT features within a short time.

Since multiple instrument operations during single revolutions has been the baseline mission profile for ISO, any ISO AOT needed to be designed in a self-contained way with respect to its calibration. Therefore two types of internal calibration measurements have been included in the SWS AOT logic, dark current measurements and relative photometric checks on the internal grating calibrator source. The major effort of ground-based AOT development has been obviously the design and testing of the related logic and commands, however both, the duration and the interval parameters of the internal calibrations have been optimised to their final values only in orbit. The ex-

*Table 2. List of SWS AOTs: Only AOTs marked with * have been released to the observers.*

AOT SWS01*	Low-Resolution Full Grating Scan
AOT SWS02*	Grating Line Profile Scan
AOT SWS03	FP Line Scan
AOT SWS04	Grating Line Profile Scan in a Celestial Raster
AOT SWS05	FP Line Scan in a Celestial Raster
AOT SWS06*	Grating Scan
AOT SWS07*	FP combined with SW Grating Scan
AOT SWS08	Scan Scenarios (different versions during ILT development)
AOT SWS09	"Tutti Frutti" (only for system level exercises)

cellent stability of the InSb band 1 detectors allowed to remove the photometric check dedicated for this band, saving some overheads in the AOT logic.

6. THE LEGACY OF GROUND-BASED CALIBRATION

The results of the ground-based calibration have been collected and inserted into calibration files for the different data processing systems of SWS (Wieprecht et al. 2003). Table 3 lists all SWS calibration files used in the ISO pipeline OLP10 together with the extent of ground-based work still contained in them. For a detailed description of the purpose and contents of the different calibration files see Leech et al. 2002.

It is quite obvious that the files containing properties of the SWS warm electronics only (SC02, SC04, SC05), have been mostly derived on ground, while the actual absolute flux calibration of the instrument is contained in calibration files with almost no contributions from ground based-work. However in general the share from ground calibration in Table 3 is major. The most precious calibration file for a spectrometer like SWS is probably the relative spectral response calibration of the various AOT bands (SC25_X). Although quite some refinements have been implemented (mainly extended source to point source corrections), these files are still strongly based on the cryogenic black body measurements from the ILTs. The knowledge how to make use of these calibration files however, has been continuously improved throughout the mission and post-mission and is reflected in the SWS pipeline and interactive analysis codes and algorithms.

Table 3. Calibration files in SWS pipeline OLP 10. The third column represents the contributions from ground-based work: a: none; b: partly; c: mostly; d: only.

Cal. file	Purpose	Legacy
SC01	Electrical Crosstalk matrix	c
SC02	RC time constants	c
SC02A	The zero Volt point in bit range	a
SC03	Reset cut-out length	c
SC04	Amplifier limits	d
SC05	Switchable gain values	d
SC06	Glitch reject levels	c
SC12	Position gap relation of scanning FPs	a
SC13	Key wavelengths and passbands	a
SC16A	Aperture offsets	c
SC16B	Detector element offsets	d
SC16C	Grating constant	d
SC16ET	Grating polynomial coefficients from FM ILT 4 to post-He	b
SC18	Wavelength dependence of FP gaps	d
SC19	FWHM values for each AOT band	a
SC23	Wavelength limits of detector bands	c
SC24	Wavelength limits of SWS apertures	c
SC25_X	Relative spectral response calibration of AOT band X	c
SC41	Average photometric check for error estimation	a
SC42	Signal to flux conversion for each AOT band	a a
SC43	Flat-fielding parameters for each AOT band	a

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