Chapter 3
The Instrument

M. Gottwald, R. Hoogeveen, C. Chlebek, H. Bovensmann, J. Carpay, G. Lichtenberg, E. Krieg,
P. Lützow-Wentzky, and T. Watts

Abstract The objective of the SCIAMACHY mission requires the instrument to be capable of determining concentrations of a large number of trace gas species over the full vertical extent of the atmosphere from the troposphere up to the mesosphere. In addition, aerosol properties as well as pressure and temperature shall be derived. Therefore SCIAMACHY was designed as a passive imaging spectrometer, comprising a scan mirror system, a telescope and a spectrometer, controlled by thermal and electronic subsystems. Scan mirrors, telescope and spectrometer together form the optical assembly. The scan mechanisms permit steering the line-of-sight according to the required viewing geometries. Solar radiance and irradiance are dispersed by the spectrometer into eight channels from the UV to the SWIR range. With signals gained from the calibration unit and the Polarisation Measurement Device, the spectral and radiometric calibration of the science channels can be maintained over the mission lifetime. Thermal stability is ensured via active and passive thermal control systems including the Radiant Cooler assembly. Those units which control the entire instrument and interface electrically with the ENVISAT platform are hosted by the Electronic Assembly. SCIAMACHY was developed in a combined effort of German, Dutch and Belgian space agencies, industry and scientists and ready for the ENVISAT launch in March 2002.

Keywords Imaging absorption spectrometer • Optical Assembly • Detector channels • Scanner • Radiant Cooler • Electronic Assembly

The scientific requirements define the overall concept of the instrument. They comprise detecting all species listed in Chapter 1. This can be achieved by continuously observing the wavelength ranges 214–1773, 1934–2044 and 2259–2386 nm. The retrieval of the amount of constituents depends on the ability to measure their absorptions precisely. Retrieving total column concentrations of minor trace gases with an accuracy of 1–5% – or 5–10% for their profiles – requires measuring intensity changes of 10^{-3}–10^{-4}. An instrument capable of acquiring data with a high signal-to-noise ratio and a good radiometric calibration can accomplish this task (SSAG 1998).

To fulfil the mission objectives with respect to spatial resolution and coverage, it is necessary to observe the scattered and reflected solar photons in nadir and limb direction as well as the light transmitted through the atmosphere in solar and lunar occultation geometry (Burrows and Chance 1991; Bovensmann et al. 1999). For calibration and monitoring purposes the solar and lunar irradiance above the atmosphere has to be determined. As total column amounts and height resolved profiles are required, the spectrometer must alternately observe the atmosphere in limb and nadir viewing. Combining both geometries of a single orbit for the same volume of air allows the study of tropospheric properties. Global coverage has to be obtained within 3 days in limb or nadir mode.

M. Gottwald (✉), G. Lichtenberg, and E. Krieg
Remote Sensing Technology Institute, German Aerospace Center
(DLR-IMF), Oberpfaffenhofen, 82234 Wessling, Germany
e-mail: manfred.gottwald@dlr.de

R. Hoogeveen
SRON, Netherlands Institute for Space Research, Sorbonnelaan 2,
3584 CA Utrecht, The Netherlands

C. Chlebek
German Aerospace Centre, Space Agency,
Königswinterer Straße 522-524, 53227 Bonn, Germany

H. Bovensmann
Institute of Environmental Physics/Institute of Remote Sensing
(IUP-IFE), University of Bremen, Otto-Hahn-Allee 1,
28359 Bremen, Germany

J. Carpay
Netherlands Space Office (NSO), Juliana van Stolberglaan 3,
2595 CA The Hague, The Netherlands

P. Lützow-Wentzky
EADS Astrium GmbH, Claude Dornier Straße, 88090 Immenstaad,
Germany

T. Watts
Dutch Space B.V., Newtonweg 1, 2333 CP Leiden, The Netherlands

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3.1 Instrument Concept

The requirements outlined above, together with the accommodation on the ENVISAT platform, were translated into an instrument concept for SCIAMACHY providing spectroscopic capabilities from the UV via VIS and NIR to SWIR with

- Moderately high spectral resolution
- High radiometric accuracy
- High spectral stability
- High dynamic range
- High signal-to-noise

Possible viewing geometries must include steering the line-of-sight (LoS) towards nadir, limb (in flight direction), sunrise and moonrise direction. Additional observability of the Sun around occurrence of the sub-solar point is needed. Maintaining thermal stability at all operating temperature levels is fundamental for achieving high radiometric and spectral accuracy. This is ensured by sophisticated thermal control systems. Finally, instrument control must be executed continuously in a highly autonomous manner with the ability to react to a wide variety of operations conditions. This includes not only measurement data relevant parameters as, e.g. line-of-sight, signal-to-noise levels and spectral sampling but also the tasks of overall instrument command and control. All SCIAMACHY instrument requirements were documented in the ‘SCIAMACHY Instrument Requirements Document’ (SIRD, DARA 1998).

Conceptually, SCIAMACHY is a passive imaging spectrometer, comprising a scan mirror system, a telescope and a spectrometer, controlled by thermal and electronic subsystems (Fig. 3.1 and Table 3.1). Functionally, three main blocks, the Optical Assembly (OA), the Radiant Cooler Assembly (SRC) and the Electronic Assembly (EA) can be identified (Fig. 3.2). The instrument is located on the upper right (i.e. starboard, referring to nominal flight direction) corner of the ENVISAT platform with the OA mounted onto the front and the EA mounted onto the top panel. The Radiant Reflectance Unit (RRU) of the SRC points sideways into deep space away from any heat source. Interfaces with the ENVISAT platform exist for the provision of on-board resources. These include power and command interfaces from the platform to the instrument. In the other direction measurement data and housekeeping (HK) telemetry from SCIAMACHY are routed into the overall ENVISAT data stream for downlinking.

Whilst a complex instrument such as SCIAMACHY cannot provide for full redundancy – particularly not for the optical path and the detectors – some essential hardware components do exist twice (Table 3.2). Nominally the instrument is operated using its primary chain of hardware, called *side A*. In case of a malfunction in side A, SCIAMACHY can be switched to *side B* which has identical

Table 3.1 SCIAMACHY instrument physical characteristics

Dimensions	
Optical Assembly	109 cm × 65 cm × 101 cm
Electronic Assembly	82 cm × 90 cm × 28 cm
Radiant Cooler Assembly	51 cm × 91 cm × 62 cm
Total mass	215 kg
Power consumption	140 W

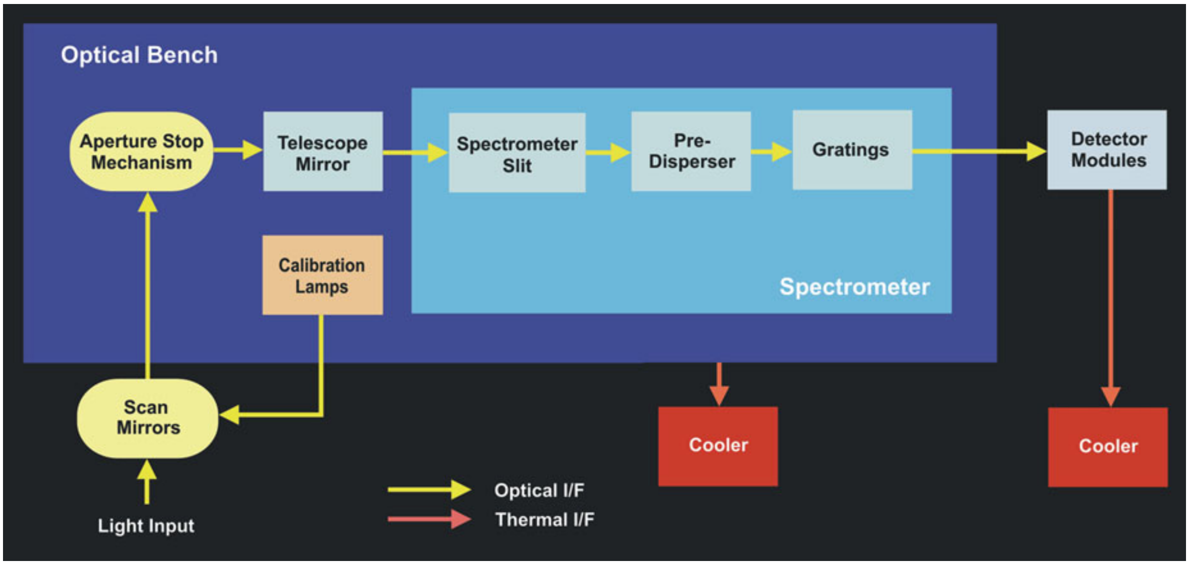

Fig. 3.1 General spectrometer layout illustrating SCIAMACHY’s main components (Courtesy: DLR-IMF).

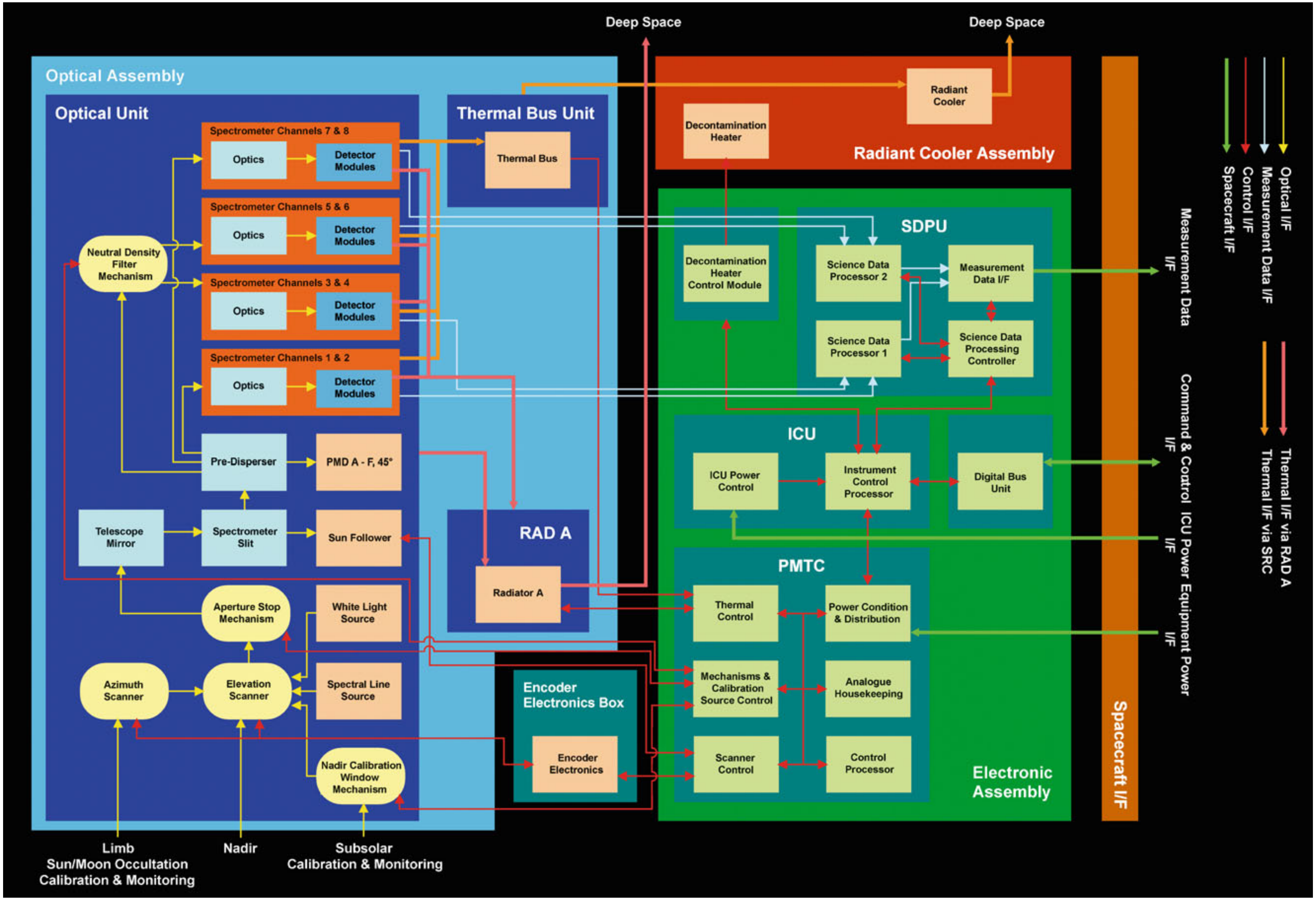

Fig. 3.2 SCIAMACHY functional block diagram with simplified interfaces between assemblies and modules (Courtesy: DLR-IMF; adapted from EADS Astrium 2004).

functions. However, since several modules are shared by both chains, a loss of one of these non-redundant components would result in degraded instrument performance.

3.2 Optical Assembly

The Optical Assembly is the part of the instrument which collects solar radiation as input and generates the spectral information as output. This occurs in the Optical Unit (OU). To maintain the specified thermal conditions, the OA includes Radiator A and the Thermal Bus Unit. The Optical Unit is organised into two levels. Entrance optics, predisperser prism, calibration unit and channels 1 and 2 can be found in level 1 facing in flight direction (Fig. 3.3). Channels 3–8 are located in level 2 (Fig. 3.4). All components are mounted onto the Optical Bench Module (OBM) which serves as the structural platform and maintains overall alignment between modules. By combining the optical-components described below, various optical paths (‘trains’) from external and internal light sources to detectors can be established (Fig. 3.5).

Scan Mechanisms and Baffles

Scanning is required in order to steer the line-of-sight both for executing particular observation geometries and for collecting light not only from the limited size of the ground projection of the Instantaneous Field of View (IFoV, see below) but from a wider ground scene. During nominal measurements light enters the instrument via the azimuth (ASM) or elevation (ESM) scan mechanisms. Both are

Table 3.2 SCIAMACHY redundant components for nominal operations

Component	Redundant hardware
Interfaces	Equipment power (incl. converter), ICU power, DBU (command and control), measurement data
Electronic Assembly	ICU, PMTC mechanisms and calibration source control, PMTC control processor, PMTC ESM scanner control, SDPU
Encoder Electronics Box	ESM and ASM encoder electronics
Optical Assembly	ESM/ASM encoders, ESM motor, redundant equipment can be powered by redundant chain

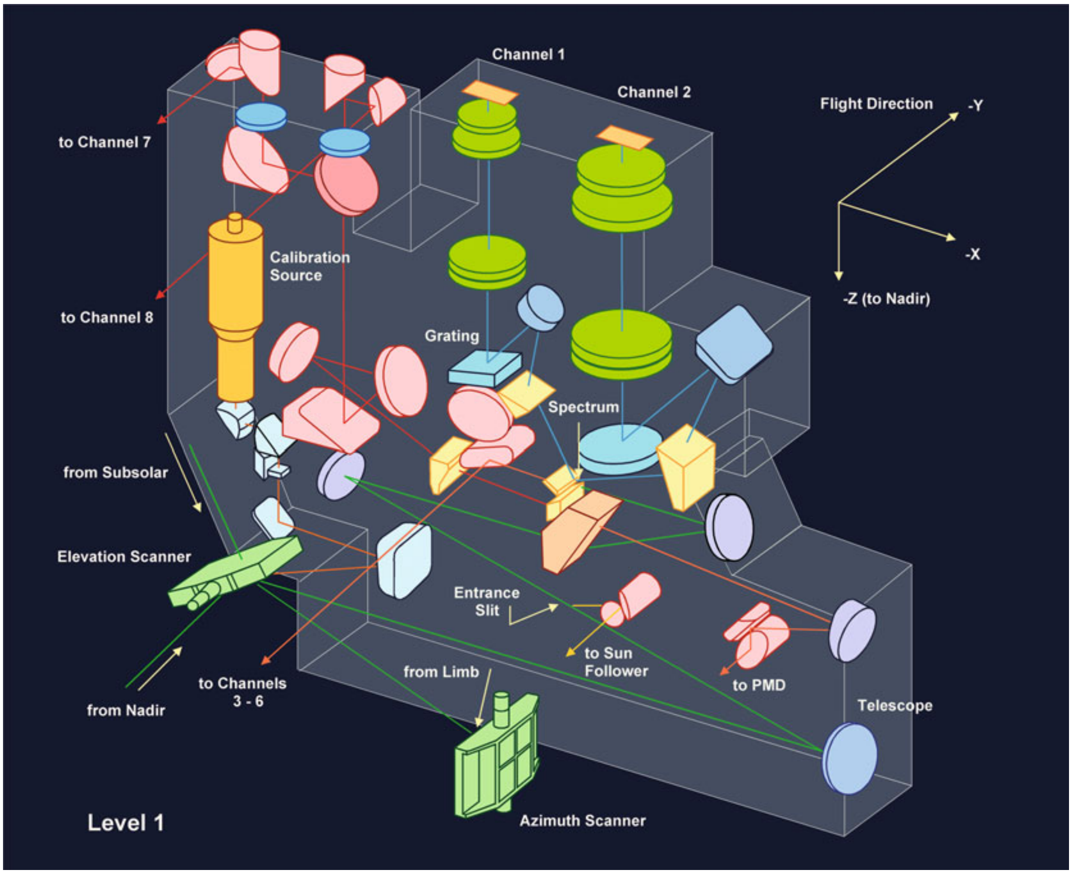

Fig. 3.3 Optical configuration level 1 (Courtesy: DLR-IMF; adapted from SJT 1996).

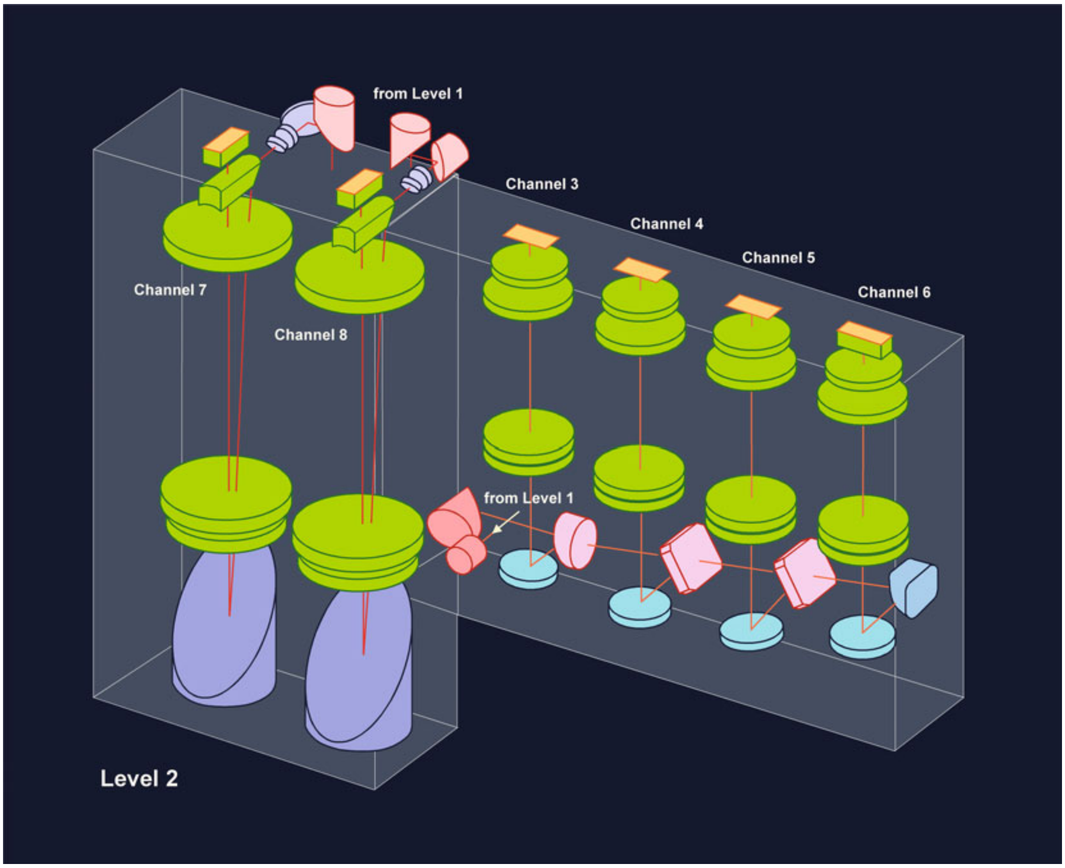

Fig. 3.4 Optical configuration level 2 (Courtesy: DLR-IMF; adapted from SJT 1996).

located below the lower part of level 1 of the OU. Mechanically, each scanner comprises a mirror block, bearings, a drive motor and encoders (Fig. 3.6). Bearings use a special lubrication allowing quasi-continuous in-orbit operation without life-time limitations. The scanning mirrors have uncoated, polished aluminium surfaces with a size of 90 mm × 60 mm for the ESM and 125 mm × 110 mm for the ASM. Whilst the ASM captures radiation coming from regions ahead of the spacecraft, the ESM either views the ASM or the region directly underneath the spacecraft. In limb observations light from the ASM mirror is directed via the ESM mirror into the spectrometer. In nadir observations, only the ESM mirror is used. Both scanners shall ideally be mounted such that their axes are parallel to the platform coordinate system. Because placing the scanners actually resulted in small alignment errors, their pitch, roll and yaw mispointings had been measured on-ground during instrument integration. The corresponding values are stored on-board and are used in scanner control to compensate these misalignments. The LoS pointing knowledge is of particular importance for limb observations where even a small pitch mispointing of, e.g. only 10 mdeg would translate into an altitude error of 570 m thus degrading the scientific value of the information in limb profiles.

Although both scan devices can be rotated by 360°, baffles limit the effective field of view. This results in the Total Clear Field of View (TCFoV) which depends on the observation mode as listed in Table 3.3 and sketched in Fig. 3.7. For the limb and occultation LoS, the baffles provide a symmetric range on either side of the flight direction while vertically they restrict viewing from slightly below the horizon to an altitude of about 380 km, i.e. well above the top of the atmosphere at 100 km. The nadir LoS is limited to an area of about ±32° across track. For a special type of measurement, the rectangular shaped Nadir Calibration Window (NCW) can be opened temporarily allowing sunlight from above to enter the instrument via the ESM mirror. Its elongated TCFoV of 1.7° × 14.8° is designed to view the Sun at high elevation when the spacecraft crosses the orbital subsolar point. In almost all measurements the scanners execute oscillating movements (forward/backward scans) or follow a certain trajectory which is a segment of a circle. Each type of

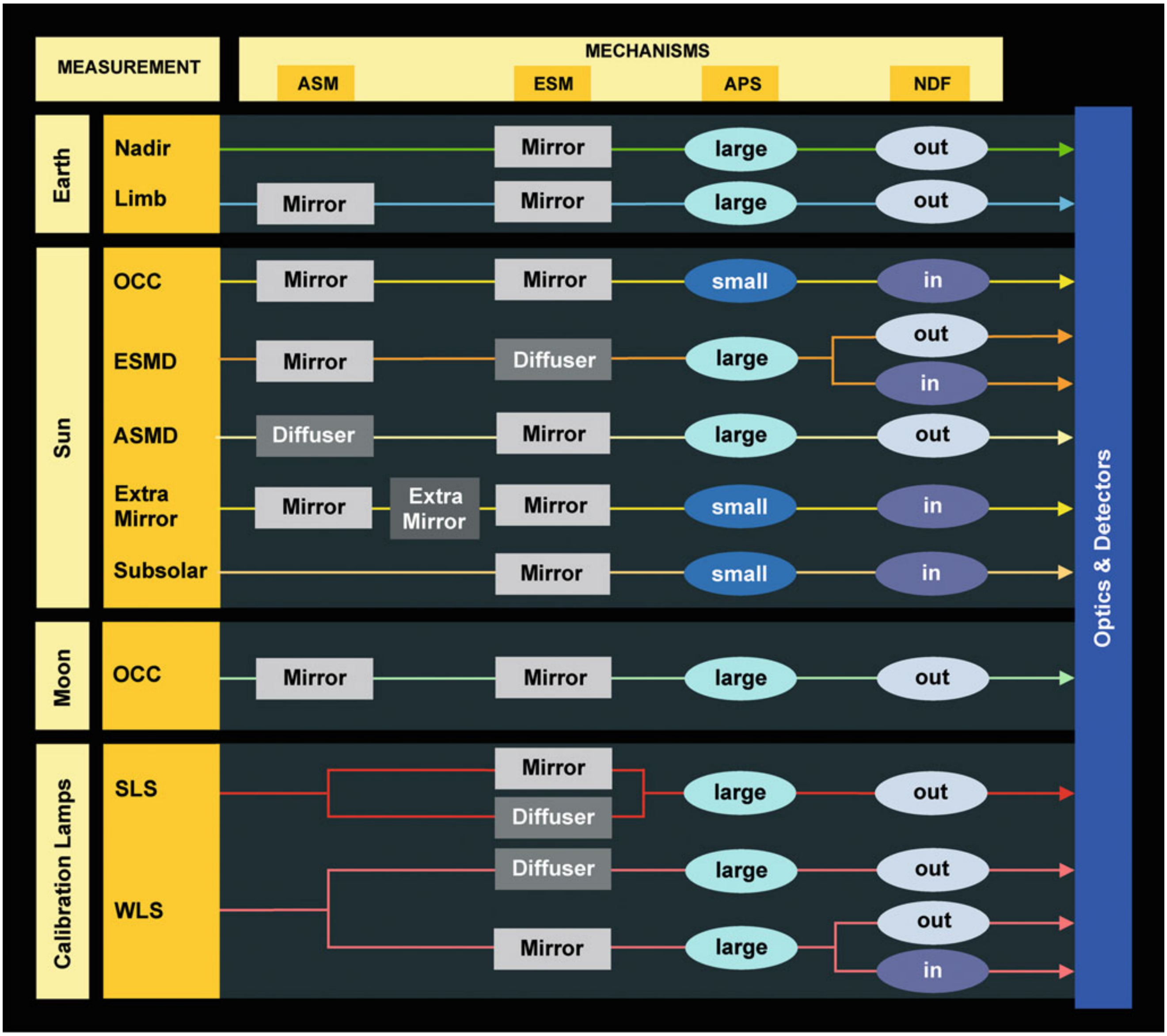

Fig. 3.5 SCIAMACHY optical 'trains'. Each 'train' defines a path for the measured light through the instrument to the detectors. Light sources can be external or internal (Courtesy: DLR-IMF/SRON).

measurement has its specified scanner start positions and scan ranges. These are defined by the orientation of the normal of the ASM and ESM scan mirror (Figs. 3.8 and 3.9).

Executing various LoS trajectories and pointing to the Sun or Moon requires sophisticated scanner control functions, particularly when the movement of both mechanisms has to be synchronised. The scanner control tasks are programmed in on-board software with supporting information being generated by the Sun Follower (SF) in the case of solar and lunar observations. Nominally, each scanner is operated separately in feedback control using measurements of the rotation angle by an incremental optical encoder. Angular scan trajectories are assembled from preprogrammed basic and relative scan profiles for offset and motion generation. Since precise LoS steering to the Earth's limb or celestial targets depends on various scanner internal or external parameters, the selected trajectory can be corrected correspondingly. In limb measurements the horizontal scans through the atmosphere maintain a constant altitude by applying a correction which takes into account the varying curvature of the Earth (WGS84 model) along the orbit. Further corrections provide for the yaw steering attitude mode of the ENVISAT platform and the known misalignment of the instrument reference frame relative to the spacecraft frame. Sun and Moon observations

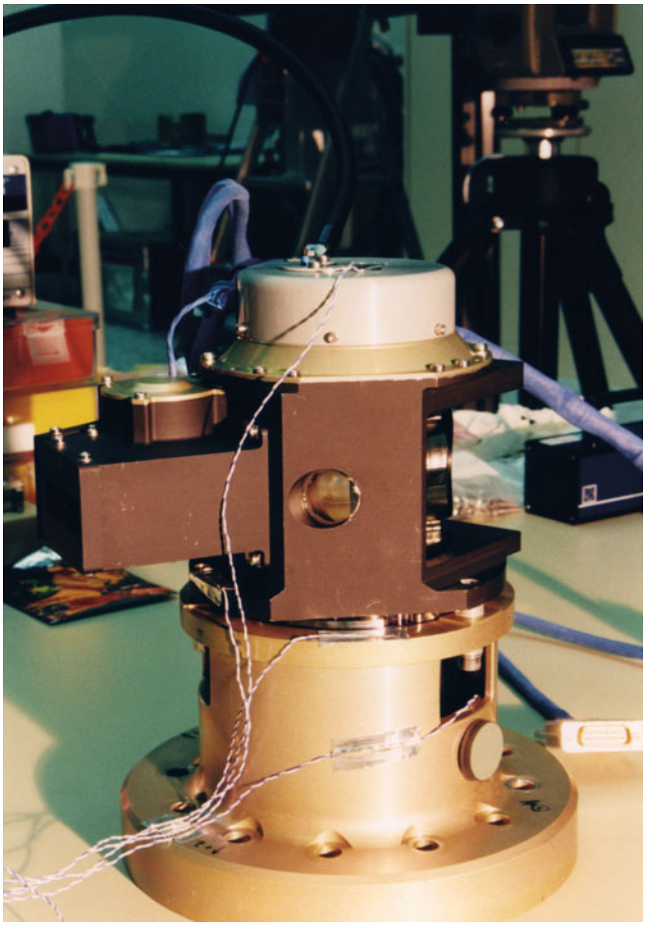

Fig. 3.6 ESM on vibration test adaptor. The leftmost rectangular opening is the Nadir Calibration Window (Photo: EADS Astrium).

Table 3.3 SCIAMACHY Total Clear Field of View

Observing geometry	Total Clear Field of View (TCFoV)
Nadir	32°/31° (ESM, across-track left/right)
Limb, occultation	88° (ASM, azimuth 316°–44°) × 8° (ESM, elevation 19.5°–27.5° from X-Y plane downwards)
Sub-solar	1.7° (azimuth) × 14.8° (ESM, elevation 53.7°–68.5° from X–Y plane upwards)

require the LoS to be centred onto the target. Analytical control algorithms cannot always ensure this. Therefore, information derived from the readout of the four quadrants of the SF is fed into the control loop to steer the scanner motors such that the mirrors – either the ASM or the ESM or both – lock onto the central part of the intensity distribution and follow the trajectory of Sun or Moon after successful acquisition. The SF receives light which is reflected from the polished blades of the spectrometer entrance slit. It is able to detect the Sun or Moon in a 2.2° × 2.2° wide field.

For obtaining the solar irradiance, the Sun has to be measured via a diffuser. Two aluminium diffusers are mounted on SCIAMACHY: one on the backside of the ESM mirror, the other on the backside of the ASM mirror. Originally the ESM diffuser was the only one in the instrument. During calibration it had turned out that this type of diffuser exhibits spectral features which would have jeopardised successful retrieval of some trace gas species. Thus very late in the development of phase C/D an ASM fitted with an additional diffuser was integrated. Its surface was ground in a different way to yield optimised diffuser properties.

Telescope and Spectrometer

The ESM reflects light towards the telescope mirror, which has a diameter of 32 mm. From the telescope mirror the light path continues to the spectrometer entrance slit. With linear dimensions of 7.7 mm × 0.19 mm (cross-dispersion × dispersion) the entrance slit defines an Instantaneous Field of View (IFoV) of 1.8° × 0.045°. This corresponds to a ground pixel size of 25 km × 0.6 km at the sub-satellite point (nadir) and of 103 km × 2.6 km at the Earth's horizon (limb). For solar observations, the IFoV can be reduced to 0.72° × 0.045° by the Aperture Stop Mechanism (APSM), which is located between the ESM and telescope mirror. The APSM reduces the aperture area and thus the intensity level. Channel dependent effects lead to a reduction by a factor of about 11000 for channels 1 and 2, 5000 for channels 3–5 and 2500 for channels 6–8.

The overall spectrometer design is based on a two stage dispersion concept: The pre-disperser prism, located behind the entrance slit, serves two purposes. It weakly disperses the light and directs fully polarised light for further processing to the Polarisation Measurement Device (PMD). Small pick-off prisms and subsequent di-chroic mirrors direct the intermediate spectrum to the 8 science channels where the light is further dispersed by individual gratings. The selected approach has the advantage of reducing stray light in the channels with low light levels in the UV and NIR-SWIR part of the spectrum. It also effectively prevents the various spectral orders from one grating overlapping with the other parts of the spectrum (Goede et al. 1991). In the light path routed to channels 3–6 the Neutral Density Filter Mechanism (NDFM) can move a filter into the beam. With a filter transmission of 25% it can be used, in conjunction with the APSM, to even further reduce light levels during solar measurements.

Detector Modules

The full resolution spectral information is generated in 8 science channels (Fig. 3.10 and Table 3.4). These employ two types of detectors (Fig. 3.11). For the UV-VIS-NIR range covered by channels 1–5, standard Silicon photodiodes (RL

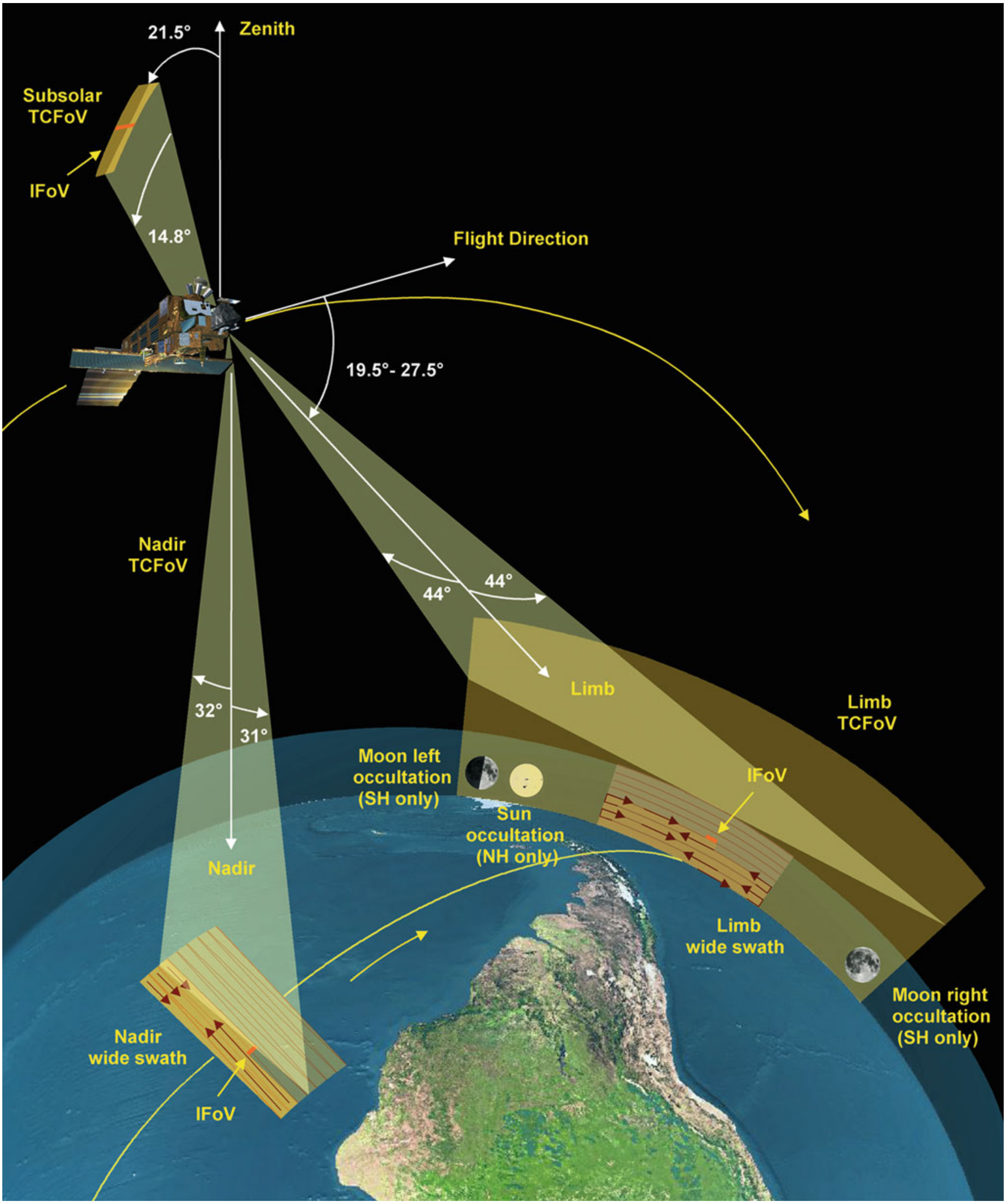

Fig. 3.7 Sketch of SCIAMACHY's TCFoV and observation geometries (Courtesy: DLR-IMF).

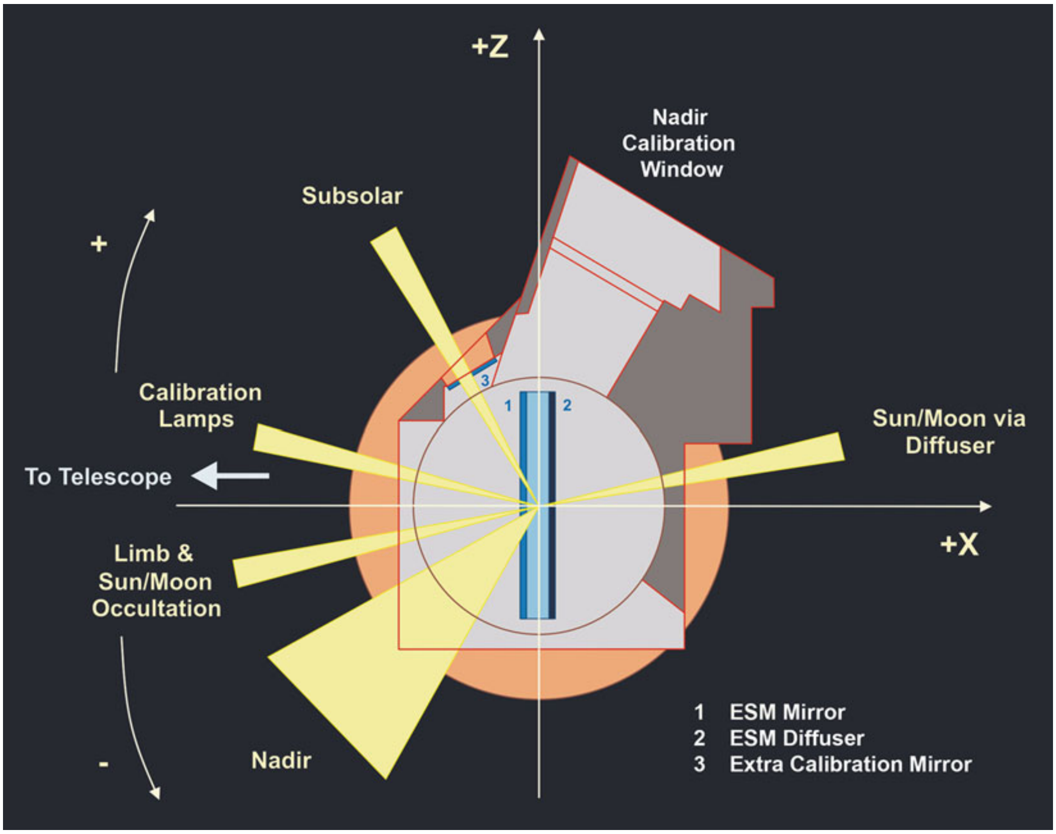

Fig. 3.8 ESM mirror's normal during specified observing geometries (Courtesy: DLR-IMF).

1024 SR, EG&G RETICON, California) with 1024 pixels are used which are sequentially read out. Additionally, UV channels 1 and 2 are electronically divided into two virtual bands 1a/1b and 2a/2b, which can be configured separately. The SWIR channels 6–8 use Indium Gallium Arsenide detectors (InGaAs by EPITAXX, New Jersey) specifically developed and qualified for SCIAMACHY (Hoogeveen et al. 2001). In the SWIR channels all pixels are read out in parallel. In order to be sensitive to wavelengths beyond 1700 nm, the detector material in the upper part of channel 6 above pixel number 794 (named 'channel 6+') and channels 7 and 8 were grown with higher amounts of Indium. All channels have to be cooled to achieve the specified signal-to-noise performance. The operational temperature range is channel dependent and lowest for the SWIR channels 7 and 8.

The pixel readout sequence in channel 2 is reversed in wavelength to avoid spatial aliasing in the overlap region of channels 1 and 2 and channels 2 and 3. Spatial aliasing occurs due to the fact that for channels 1–5 the detector pixels are read out sequentially with a time delay between the first and the last pixel of about 28.75 ms. Therefore pixels that are read out at a different time see a somewhat different ground scene because during the sequential readout the platform and the scan mirrors continue to move. The size of the wavelength dependent spectral bias depends on the variability of the ground scene. Reversing the readout of channel 2 ensures that the channel overlaps observe the same ground scene.

In the UV-VIS channels the minimum Pixel Exposure Time (PET) amounts to 31.25 ms. In order to avoid saturation in the SWIR channels, exposures in channels 6–8 can be set as short as 28 μs. Since the movement of the scanners and the readout of the detectors are synchronised by pulses of 62.5 ms, the maximum data transfer rate is 16 Hz. Therefore, for readouts with exposure times shorter than 62.5 ms the readout is taken only once for the specified PET duration within the 62.5 ms interval and transmitted to ground. However, such cases occur only for calibration and monitoring measurements and not when executing nadir or limb observations.

Trace gas features are distributed non-uniformly over the spectrum. The limited total data rate would therefore

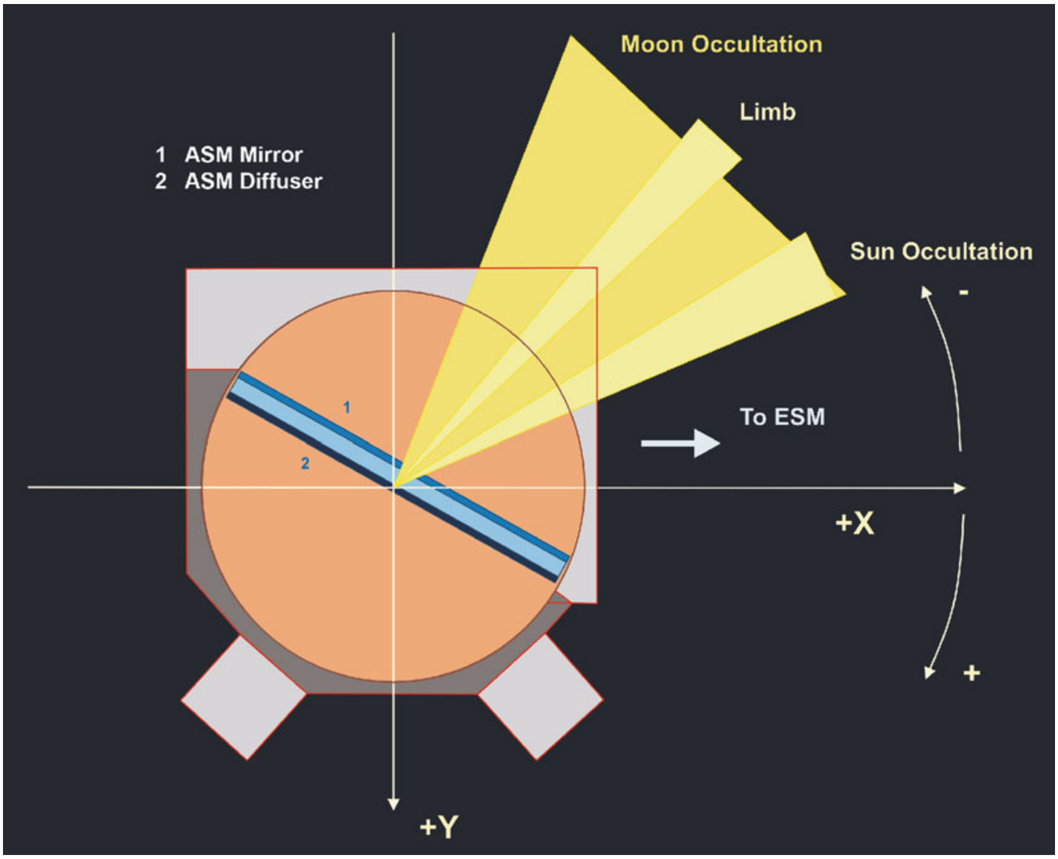

Fig. 3.9 Same as Fig. 3.8 but for the ASM (Courtesy: DLR-IMF).

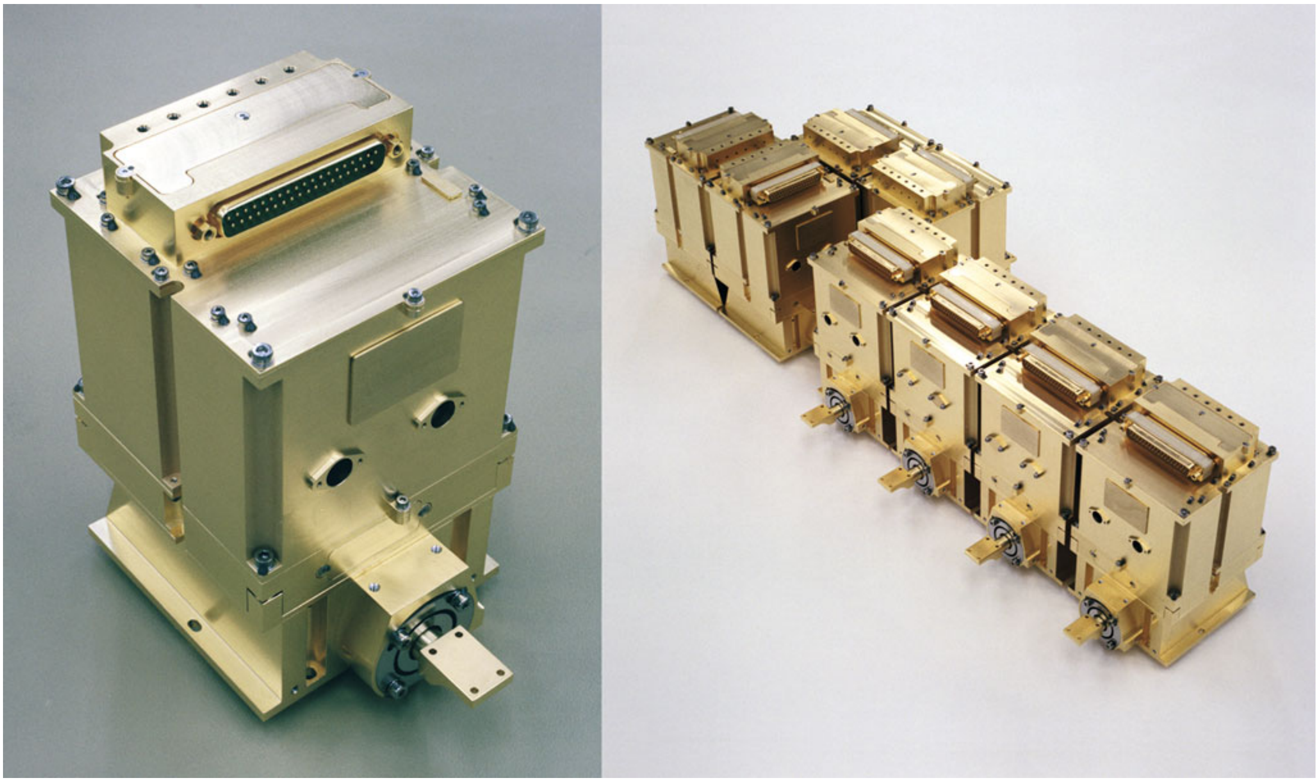

Fig. 3.10 Single SCIAMACHY detector module (*left*) and the full complement of 8 detector modules (*right*) (Photo: SRON).

Table 3.4 SCIAMACHY science channels (1 and 2 = UV, 3 and 4 = VIS, 5 = NIR, 6–8 = SWIR)

Channel	Spectral range (nm)	Resolution (nm)	Stability (nm/ 100 min)	Temperature range (K)
1	214–334	0.24	0.003	204.5–210.5
2	300–412	0.26	0.003	204.0–210.0
3	383–628	0.44	0.004	221.8–227.8
4	595–812	0.48	0.005	222.9–224.3
5	773–1063	0.54	0.005	221.4–222.4
6	971–1773	1.48	0.015	197.0–203.8
7	1934–2044	0.22	0.003	145.9–155.9
8	2259–2386	0.26	0.003	143.5–150.0

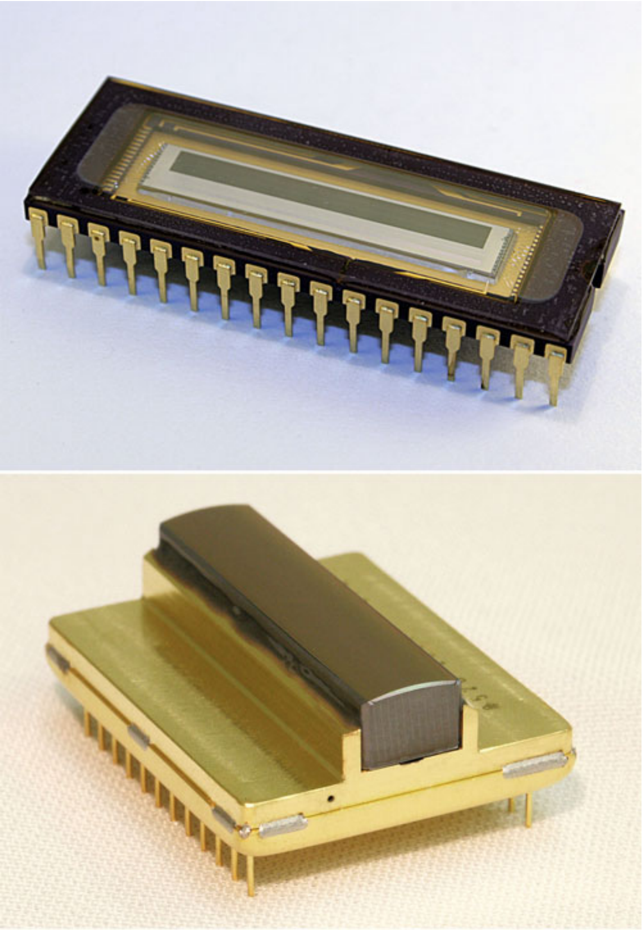

Fig. 3.11 The RETICON (*top*) and EPITAXX (*bottom*) linear detector arrays (Photo: SRON).

prohibit the detailed sampling of those ranges of interest if the full spectrum had to be downlinked as one block. SCIAMACHY avoids this situation by using spectral clusters and co-adding. The 1024 pixels per channel can be subdivided into a number of *clusters* identifying regions where trace gas retrieval will take place. Each cluster can be sampled by on-board data processing applying *co-adding* factors f_{coadd} to the readout of the pixels of this cluster. This results in an integration time (IT)

$$IT = PET \times f_{coadd}$$

which defines how many subsequent readouts of each pixel of a cluster are added to generate one measurement data readout. By appropriately setting the integration time, high or low temporal resolution – equivalent to high or low spatial resolution – can be selected. Thus, depending on the executed measurement states, variable ground pixel sizes as a function of spectral region, i.e. trace gas features, are achieved. Efficient setting of co-adding factors is also required to ensure that the volume of the generated data does not violate the assigned nominal data rate limit of 400 kbit/s. The measurement data stream finally consists of cluster sequences representing different wavelength regions read out at different rates.

Overall the detector performance is characterised by low noise and high instrument throughput. This allows measuring the incoming light with the required very high signal-to-noise ratio (Fig. 3.12), a prerequisite for the retrieval of the targeted geophysical parameters.

Calibration Unit

The requirement to maintain high spectral stability and high relative radiometric accuracy over the mission's lifetime is ensured via an on-board calibration unit. It consists of two calibration lamps, one for white light and one for spectral lines. The White Light Source (WLS) is a 5 W UV-optimised Tungsten–Halogen lamp with an equivalent blackbody temperature of about 3000 K. Its signal is used to verify the pixel-to-pixel signal stability and to monitor the etalon effect (see section "Operational Level 0-1b Processing" of Chapter 8). The Spectral Line Source (SLS) is a Neon filled hollow Pt/Cr cathode lamp. Its operation allows the determination of the pixel-to-wavelength relation. The calibration unit is located close to the ESM. By rotating the ESM mirror into specific positions it is possible to reflect light from the WLS respectively the SLS towards the telescope mirror and thus onto the entrance slit.

An extra calibration mirror near the ESM can be used for an additional reflection of the incoming light onto the ESM mirror. Due to its protected position well within the instrument it is assumed that this extra mirror will not degrade throughout the mission. Thus it can be used as a further means for monitoring optical performance (see section "Optical Performance Monitoring"of Chapter 5).

Polarisation Measurement Device

The sensitivity of the spectrometer depends on the polarisation state of the incoming light. Therefore SCIAMACHY is equipped with a Polarisation Measurement Device. Six of its

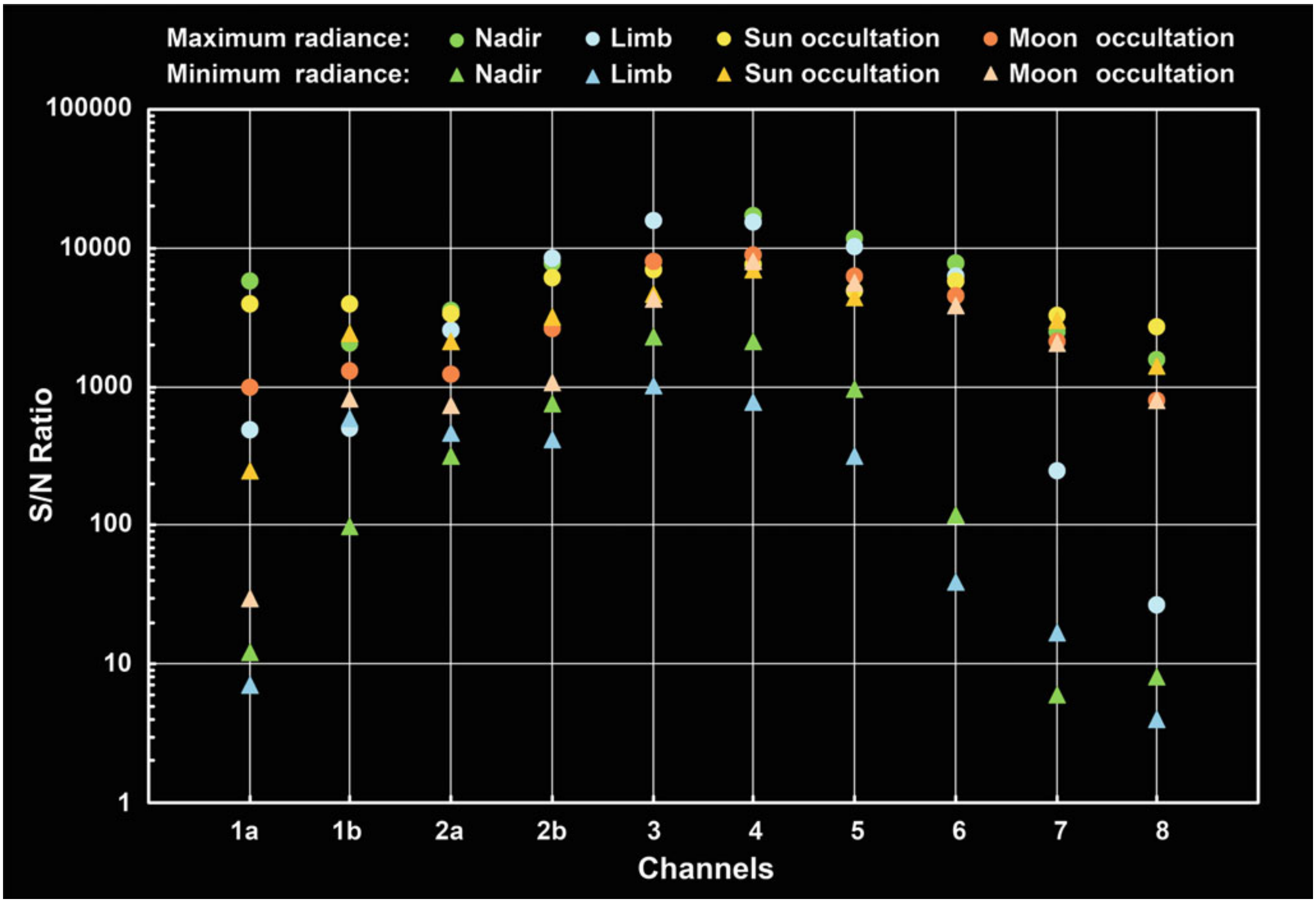

Fig. 3.12 The signal-to-noise ratios for all channels as obtained during OPTEC-5 tests. The ratios were determined for minimum and maximum radiance signals (Courtesy: DLR-IMF).

Table 3.5 SCIAMACHY PMD. The wavelength ranges are defined to contain 80% of the total signal in the respective PMD channel

Channel	Spectral range (nm)	Detector Temperature (°C)
A	310–365	−18
B	455–515	−18
C	610–690	−18
D	800–900	−18
E	1500–1635	−18
F	2280–2400	−18
45°	800–900	−18

channels (PMD A-F) measure light polarised perpendicular to the SCIAMACHY optical plane, generated by a Brewster angle reflection at the second face of the pre-dispersing prism. This polarised beam is split into six different spectral bands (Table 3.5). The spectral bands are quite broad and overlap with spectral regions of channels 2–6 and 8. The PMD and the light path to the array detectors, including the detectors, have different polarisation responses. Consequently, with the appropriate combination of PMD data, array detector data and on-ground polarisation calibration data the polarisation of the incoming light from the nadir measurements can be determined. For atmospheric limb measurements, where both mirrors are used, the light is outside the optical plane of the spectrometer. This requires measurements of additional polarisation information of the incoming light. A seventh PMD channel measures the 45° component of the light extracted from the channels 3–6 light path. All PMD channels are non-integrating and are read out every 1/40 s. They observe the same atmospheric volume as science channels 1–8.

Radiator A and Active Thermal Control

The OBM needs to be operated in orbit at a constant temperature to preserve the validity and accuracy of the on-ground calibration and characterisation. Additionally, a low temperature level is required to keep the thermal radiation of the instrument itself at a minimum in order not to enhance the background in the SWIR channels 7 and 8. Therefore a dedicated radiator, RAD A, is used to cool the OBM and the detector module electronics to between −17.6 and −18.2°C. Its location on the -X side of the instrument avoids direct solar illumination. Heat pipes are used to transfer heat from the OBM and the detector module electronics to the radiator (Fig. 3.13).

While the RAD A provides cooling capacity, thermal stability of the OBM needs to be established via a closed loop Active Thermal Control (ATC) system. It consists of three control loops with heater circuits and thermistors. The heating is controlled by the Power Mechanism & Thermal Control Unit (PMTC) based on measurements by the thermistors. Once ATC settings have been selected, the system maintains the OBM temperature to high precision at the specified level (see section "Thermal Performance" of Chapter 6). When heater control reaches a limit of the specified power range, e.g. due to in-orbit thermal degradation, the OBM temperature can no longer be kept stable over the whole orbit. By commanding appropriately modified ATC parameters the required ATC performance can then be re-established.

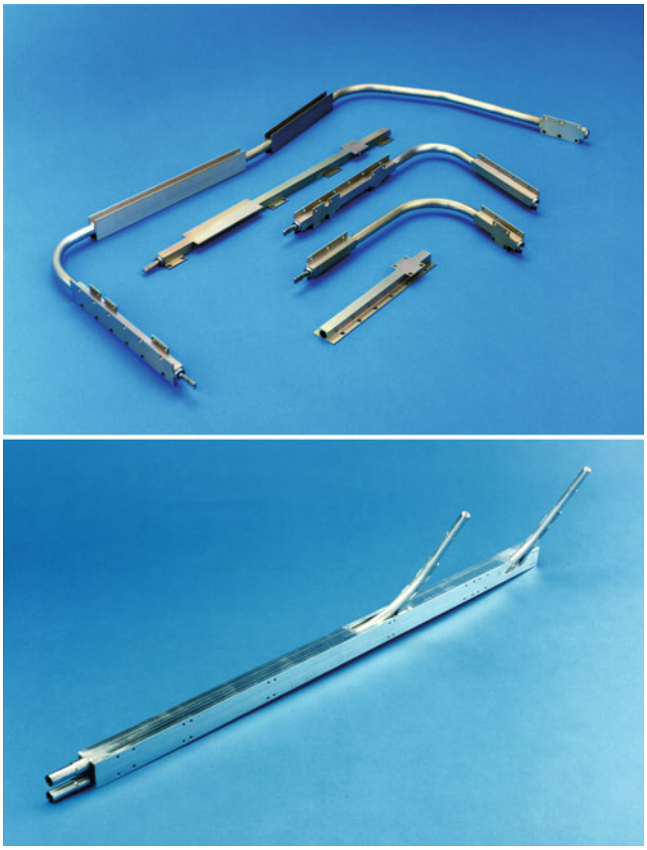

Fig. 3.13 Heat pipes from the optical bench to RAD A (*top*) and cryogenic heat pipes from detector modules 7 and 8 to the SRC (*bottom*) (Photo: EADS Astrium).

Thermal Bus

In-orbit operating temperatures of the detectors are well below ambient. The detectors are cooled via the Radiant Reflector Unit (RRU) of the Radiant Cooler (SRC) Assembly. The Thermal Bus connects the detector modules thermally with the reflector. Heat from detectors 1–6 is transported via an aluminium thermal conductor, from detectors 7 and 8 via two methane filled cryogenic heat pipes (Fig. 3.13). The heat pipes provide an efficient heat transfer in the temperature range 100–160 K.

Since the cooling efficiency of the Radiant Cooler is designed to provide sufficient cooling capacity until the end of the mission, a Thermal Control (TC) system is part of the Thermal Bus. It prevents the detector modules from becoming too cold by counter heating using three trim heaters. The TC system uses open loop heater control. Whenever drifting temperatures of the detectors reach their limits, the power settings of the trim heaters are adjusted by ground command bringing the temperatures back into the specified range.

3.3 Radiant Cooler Assembly

SCIAMACHY's Radiant Cooler dissipates heat generated in the detector modules to deep space to permit cooling of the detector arrays to in-orbit operating temperatures. The reflecting unit and the detectors are connected via the Thermal Bus of the OA. As for RAD A, the RRU points in the -X direction away from the Sun. Earthshine and sunshine are blocked from the radiating surface of the SRC to gain maximum cooling efficiency. Cold temperatures are obtained using a two stage process. An intermediate stage in the Radiator Unit lowers temperatures of detectors 1–6, while the cold stage, fitted with a parabolic reflector, yields temperatures around 150 K for detectors 7 and 8.

Due to its low temperature, the RRU surface is expected to attract contaminants from the in-orbit environment, particularly from ENVISAT itself. This would degrade the performance of the Radiant Cooler leading to reduced cooling efficiency. In order to clean the Radiant Cooler, the cold stage and the reflector are equipped with decontamination heaters. Turning the decontamination heaters 'on' raises the temperatures of the RRU, contaminating substances are removed through evaporation and the cooling performance is re-established. Whether contaminants begin to degrade the SRC performance can be determined from the power settings of the TC trim heaters. Degraded cooling efficiency is equivalent to higher radiator temperatures, i.e. higher detector temperatures. Consequently the trim heaters require less power when the SRC efficiency degrades because of contamination.

3.4 Electronic Assembly

SCIAMACHY's 'brain' resides in the Electronic Assembly. It provides the processing and formatting link of the detectors generating the primary science data with the spacecraft platform transmitting the digitised science data to ground. In addition, the EA houses all electrical and software functions required for autonomous operation of the whole instrument.

Functionally the EA consists of the primary processor called Instrument Control Unit (ICU) and the secondary processors, the PMTC and the Science Data Processing Unit (SDPU) as illustrated in Fig. 3.14. Serial data lines for the transmission of commands and data connect these three units. The EA is supplemented by the Decontamination Heater Control Module (DHCM) for operating the decontamination heaters on the SRC and the Digital Bus Unit (DBU) providing the instrument's command and control communication front-end interface to the ENVISAT platform.

Instrument Control Unit

Central control of all SCIAMACHY equipment in response to commands from ground and autonomous in-orbit operations of the instrument is the task of the ICU. It ensures

- Reception, verification and execution of macrocommands (MCMD) – and potential software updates – relayed by ENVISAT's Payload Management Computer (PMC)
- Autonomous instrument control as required by instrument mode, instrument states and parameters
- Monitoring of instrument HK telemetry data to verify instrument health
- Detection of anomalies and execution of autonomous corrective actions
- Acquisition and formatting of HK telemetry data from the secondary processors and the ICU itself for transmission to the PMC
- Maintaining a History Area to record significant instrument events

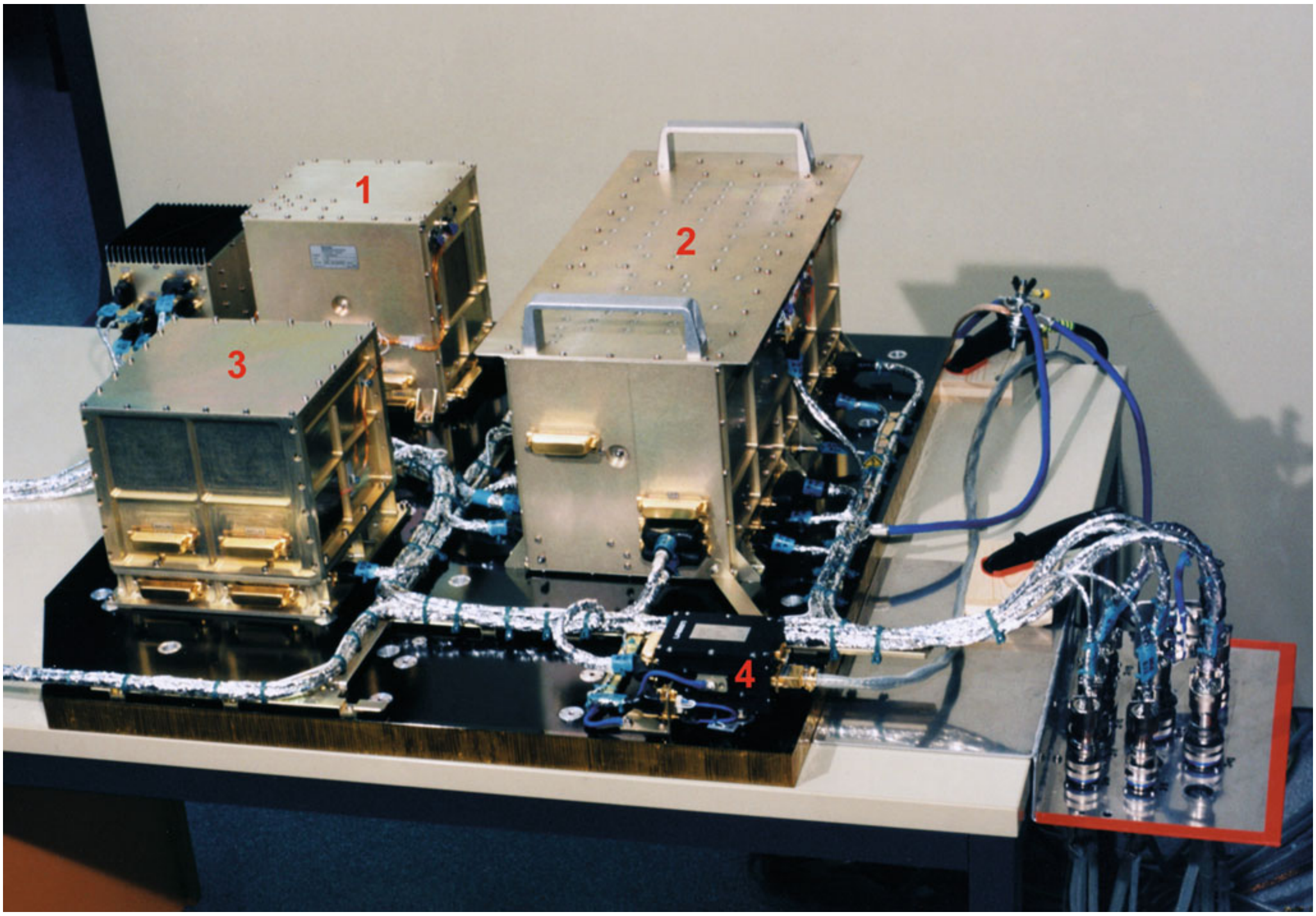

Fig. 3.14 The Simplified Engineering Model of the EA with ICU (1), PMTC (2), SDPU (3) and DBU (4) (Photo: EADS Astrium).

All time information is derived from the ICU on-board clock providing the SCIAMACHY On-Board Time (OBT). OBT and ENVISAT's PMC master clock are synchronised. The internal clocks of the secondary processors are not synchronised with the ICU clock. Datation of the scanners and detectors relies on an internal 16 Hz Broadcast Pulse (BCPS) which is generated in the ICU. For many aspects of command execution however, a time resolution of 62.5 ms is too low. Therefore another rate of 256 Hz defines the time unit *Count* – equivalent to 3.9 ms – to synchronise instrument internal control functions. Scanner control operations are driven by a dedicated PMTC internal 1 kHz clock.

The ICU's control logic implements the operations concept. This is not only true for the scientifically oriented (see Chapter 4) but also for engineering related activities. Tables configure ICU functions with the content of the tables being interpreted by ICU software. Operations modifications can thus be implemented by changes of table parameters, loadable via MCMD. Engineering tasks particularly concern the monitoring of the instrument health and safety and autonomous handling of anomalies. Up to 255 HK parameters can be monitored simultaneously. As long as the monitoring function does not report any anomaly, the instrument continues operations. Each anomaly detected triggers a Corrective Action (CA). The relation between anomalies and CA is again defined in tables. Some anomalies result in a CA which does not interrupt operations but is just recorded in the ICU's history area. This area is regularly downloaded via telemetry for inspection. More severe errors cause an immediate stop of ongoing measurements and the transition of the instrument into a safe configuration. After careful analysis of the anomaly and eliminating its cause, the instrument can be commanded from safe configuration back to nominal operations.

Secondary Processors

The SDPU controls and acquires science data from all 8 detector modules and auxiliary information from the PMD, the Sun Follower and the PMTC. On-board data preprocessing in this unit occurs prior to formatting and transfer to ENVISAT's High Speed Multiplexer (HSM) via the measurement data interface. The PMTC receives power from the platform and supplies the various modules in the OA. Additionally it controls the thermal status of the OA and detectors as well as the operations of mechanisms, including scanners and calibration sources.

Modes

Various operational instrument configurations, called 'modes', exist. They are divided into support modes and operations modes. The latter are those where SCIAMACHY can fulfil its measurement objectives. Two operations modes are defined: *Measurement* (see Chapter 4) and *Decontamination*. The *Measurement* mode may either be *Timeline* or *Idle*. *Measurement* corresponds to periods when the instrument collects science data. Once in *Idle*, the instrument has finished a particular measurement and waits until the next measurement will be started. The purpose of support modes is to achieve or maintain full operational conditions. Some of them are the response to an ICU or platform detected anomaly. Depending on the severity of the anomaly the instrument equipment and EA processors may be transferred to restricted activity levels. Other modes represent intermediate steps in the sequence from a lower mode up to *Measurement* mode. Predefined procedures transfer the instrument from one mode to another, both for nominal operations and anomaly cases.

3.5 The Making of SCIAMACHY

Following the selection of SCIAMACHY as an AO instrument aboard ENVISAT in 1989, the space agencies of Germany and The Netherlands initiated the development of the instrument aiming at an ENVISAT launch date before the end of the last century (for details about the early phase of the SCIAMACHY programme see section "SCIAMACHY's Past and Beyond its Future" of Chapter 1). Between 1990 and 1992 conceptual studies were carried out and predevelopment of innovative technology occurred at EADS Astrium (former Dornier Satellitensysteme) in collaboration with TNO-TPD and SRON in The Netherlands. This Phase B ended with a Baseline Design Review in November 1992. Phase C/D work started then in 1993 as a bilateral programme between Germany and The Netherlands and ended with the final delivery of the instrument to ESA in March 2000. DLR and NIVR agreed to a 'Memorandum of Understanding' which outlined the commitments of both partners. Finally Belgium joined the programme by funding the Polarisation Measurement Device, originally part of the Dutch contribution. For the management of the industrial contracts, DLR and NIVR set up DNPM, the common project management entity acting as the interface to the selected industrial contractors. To ensure continuous scientific oversight during instrument development and successive operations, participating institutes formed the SCIAMACHY Science Advisory Group (SSAG), chaired by the Principal Investigator (PI), under the auspices of DLR, NIVR and ESA. This group not only gave advice in scientific data product matters but also hosted the calibration and the validation subgroups with the lead assigned to the Netherlands Institute for Space Research (SRON) and the Royal Dutch Meteorological Institute (KNMI), respectively.

The Phase C/D contractors EADS Astrium and Dutch Space (former Fokker Space) were jointly responsible for the instrument development up to delivery to and acceptance by the agencies at the ENVISAT Launch Readiness Review. EADS Astrium and Dutch Space concluded an agreement between both companies and became co-prime contractors on an equal level. In order to establish a counterpart to the DNPM, the co-primes created the Integrated System Team (IST) acting as the entity to ensure a coherent and harmonised industrial programme. Having two co-primes meant establishing joint plans for many aspects of project development, including Project Management Plan, Product Assurance Plan and Design, Development and Verification Plan.

Each of the two co-prime contractors led an industrial consortium with a well defined share of tasks between the German and Dutch partners (Table 3.6). The German consortium consisted of

- EADS Astrium, Friedrichshafen (lead)
- Jena Optronik, Jena
- OHB System, Bremen
- Carl Zeiss, Oberkochen
- Kayser Threde, München
- SGI, Altenstadt
- EADS Astrium (former Matra Marconi Space), Toulouse
- Austrian Aerospace (former ORS), Wien
- Kongsberg, Oslo
- Turbinegarden, Kopenhagen

Members of the Dutch consortium were

- Dutch Space, Leiden (lead)
- SRON, Utrecht
- TNO-TPD, Delft
- Delft Sensor Systems (OIP), Oudenaarde/Belgium

Dutch Space, SRON and TNO-TPD formed the SCIAMACHY Joint Team (SJT), with its key personnel co-located at TNO-TPD premises in Delft. Development of the OA, with a few exceptions, and the SRC was attributed to the Dutch consortium. German responsibility included EA, Encoder Electronics and instrument harness.

For ground verification and testing, a joint approach was pursued, since final performance verification occurred in many cases at instrument level. The thermal balance/thermal vacuum (TB/TV) and electromagnetic compatibility (EMC RE/RS) instrument tests were performed in the IABG facilities at Ottobrunn near Munich. Instrument level tests included five 'cold' campaigns with the OA being cooled inside the vacuum chamber of the Optical Test Facility (OPTEC) at the Dutch Space Amsterdam/Schiphol premises, designated OPTEC-1 through OPTEC-5. Each OPTEC campaign comprised a sequence of qualification, verification, functional, performance and calibration tests with the Proto Flight Model (PFM) and included also in total three PI Periods. The latter were time slots assigned to scientific measurements to collect representative spectra of trace gases with the instrument. The PI Periods also provided very valuable additional information on the performance of SCIAMACHY.

Table 3.6 Instrument development responsibilities (D = Germany, NL = The Netherlands, B = Belgium)

Item	Responsibility
Optical Assembly	NL
Optical Unit/Optical Bench	NL
Detector modules	NL
PMD and Sun Follower	B
Scan mechanisms (ASM, ESM)	D
Calibration lamps	NL
OA heat pipes	D
Mounting Support Structure	D
Radiator A	NL
Multilayer Insulation (MLI)	NL
Electronic Assembly	D
PMTC	D
ICU	D
SDPU	D
DBU	Customer furnished item
DHCM	D
Base Plate	D
MLI	D
Radiant Cooler Assembly	NL
Radiant Reflector Unit	NL
Thermal Bus Unit	NL
Cryogenic heat pipe	D
Mechanical and thermal accessories	NL
Encoder Electronics	D
Instrument Harness	D

In the course of the development several models were built in support of the instrument and ENVISAT integration, verification and testing requirements. The model finally delivered to ESA for integration onto the ENVISAT platform is referred to as the PFM. Prior to PFM the Simplified Engineering Model (SEM) was required to functionally represent SCIAMACHY in the ENVISAT Engineering Model programme. The SEM consisted of the EA and Instrument Harness while the OA and SRC were represented by electrical dummy loads. Structural Models (STM) were built for the OA and SRC and were used for mechanical testing of the ENVISAT structure (Fig. 3.15).

Further frameworks for the successful development of the SCIAMACHY mission consisted of the 'Instrument Mission Implementation Agreement' (IMIA) and the 'Flight Operation and Data Plan' (FODP), which specified the responsibility split between DLR/NIVR on instrument and ESA on ENVISAT mission provider side. Based on these definitions, DLR created in 1996 the national SCIAMACHY Operations Support Team (SOST) with personnel from DLR at DFD (later at the Remote Sensing Technology Institute – IMF) and at the Institute of Environmental Physics/Institute of

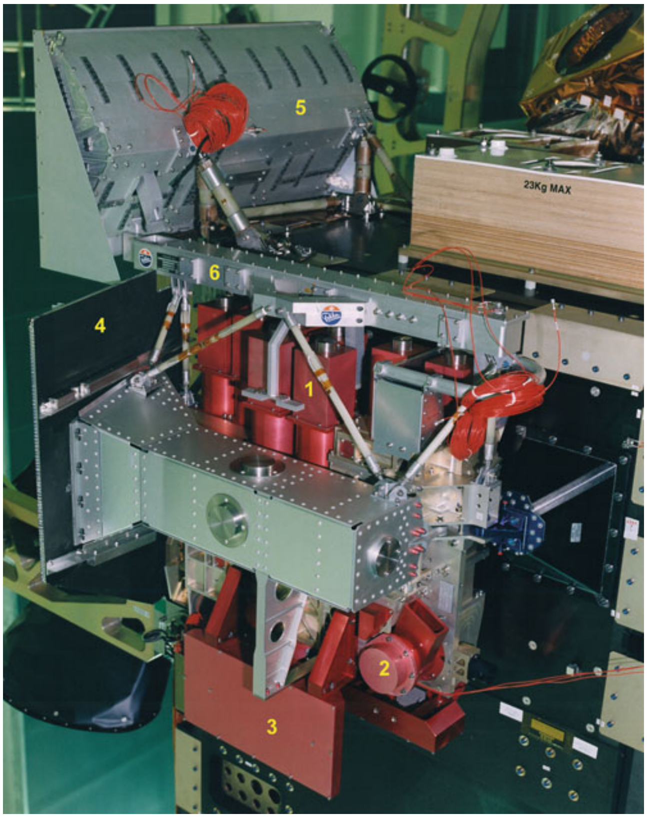

Fig. 3.15 Structural Model of the OA showing the SCIAMACHY design with detector modules (1), ESM with Nadir Calibration Window (2), limb baffle with cover (3), RAD A (4), SRC (5) and Thermal Bus (6) (Photo: ESA).

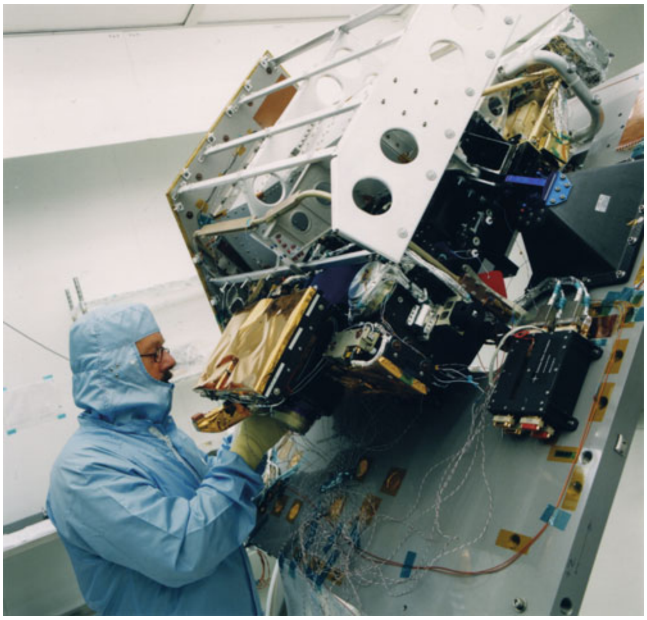

Fig. 3.16 Integration of the OA (Photo: Dutch Space).

Fig. 3.17 ENVISAT integration on the ESTEC Hydra vibration test facility. The instruments are covered with MLI. SCIAMACHY is the only instrument located on the front panel (*top right corner*) (Photo: ESA).

Remote Sensing (IUP-IFE), University of Bremen. Its objective was to develop the infrastructure and interfaces required for the execution of the in-flight measurements. In addition, SOST supported both industry and agencies in all other aspects of scientific instrument operations. Algorithm and processor development for operational measurement data analysis was performed as part of the implementation of the ENVISAT ground segment. Since the ground segment concept assigned tasks of operational SCIAMACHY product generation to the German Processing and Archiving Centre (D-PAC) located at DLR-Oberpfaffenhofen, a large fraction of the required algorithm and processor development work was put under the responsibility of the data processing group at DFD and IMF.

As not uncommon in the development of complex satellite hard- and software, unexpected difficulties both at management and technical levels introduced delays which had to be accommodated. This also occurred in the SCIAMACHY programme. Fortunately the targeted ENVISAT launch in the late 1990s had to slip as well so that finally the instrument could be delivered on time (Figs. 3.16 and 3.17).

The EA PFM passed its Consent-to-Ship Board successfully in February 1999 when it was handed over to ENVISAT. The OA PFM required investigation of a few deficiencies discovered in late characterisation and calibration data before being accepted by ENVISAT in March 2000. When the flight hardware had been integrated onto the platform, the ESM diffuser was found not to be best suited for the envisaged in-flight calibration strategy. In an extra effort, an additional diffuser was manufactured, tested and mounted on the back side of the spare ASM mirror. ESA accepted the replacement of the current ASM with the modified and retested spare ASM. This exchange operation at spacecraft level took place in March 2001. Only 2 months later, ENVISAT was shipped to the launch site in Kourou where it arrived 15 May on-board an Antonov-124 heavy lifter aircraft. Further months of testing and waiting for the finalisation of the ARIANE-5 requalification programme passed until ENVISAT could finally be launched into orbit on 1 March 2002. This completed SCIAMACHY's on-ground phase and started its in-orbit life.

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