SCIAMACHY In-Orbit Mission Report

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Abbreviations and Acronyms

ADC	Analogue-to-Digital Converter
ANX	Ascending Node Crossing
AO	Announcement of Opportunity
AOI	Announcement of Opportunity Instrument
AOP	AO Instrument Provider
APSM	Aperture Stop Mechanism
ASM	Azimuth Scan Mechanism
ATC	Active Thermal Control
AZACM	Azimuth Aperture Cover Mechanism
BCPS	Broadcast Pulse Synchronisation
BOL	Begin-of-Life
BU	Binary Unit
CA	Corrective Action
C&C	Command & Control
CCA	Communication Area
CCW	CounterClockWise
CFI	Customer Furnished Item
CTI	Configurable Transfer Item
CW	Clockwise
DARA	Deutsche Agentur für Raumfahrtangelegenheiten
DBPM	Dead and Bad Pixel Mask
DBU	Digital Bus Unit
DFD	Deutsches Fernerkundungs-Datenzentrum
DHCM	Decontamination Heater Control Module
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DME	Detector Module Electronics
DMOP	Detailed Mission Operation Plan
D-PAC	German PAC
EA	Electronic Assembly
EEPROM	Electrical Erasable Programmable Read Only Memory
ELACM	Elevation Aperture Cover Mechanism
ENVISAT	Environmental Satellite
EOL	End-of-Life
ESA	European Space Agency
ESM	Elevation Scan Mechanism
ESOC	European Space Operation Centre
ESRIN	European Space Research Institute
ESTEC	European Space Research and Technology Centre
FOCC	Flight Operation Control Centre
FODP	Flight Operation and Data Plan
FOP	Flight Operations Procedures
FOS	Flight Operation Segment
FoV	Field of View
HK	Housekeeping
HSM	High Speed Multiplexer
HTR	Heater
ICU	Instrument Control Unit
ID	Identifier

IECF	Instrument Engineering and Calibration Facility
IFoV	Instantaneous Field of View
IMF	Institut für Methodik der Fernerkundung
IMIA	Instrument Mission Implementation Agreement
IOM	Instrument Operation Manual
IR	Infrared
IUP-IFE	Institut für Umweltphysik / Institut für Fernerkundung
KBS	Ka-band Subsystem
LEOP	Launch and Early Operation Phase
LLI	Life Limited Item
LoS	Line-of-Sight
LRAC	Low Rate Reference Archive Centre
MCMD	Macrocommand
MDI	Measurement Data Interface
MLI	Multilayer Insulation
MLST	Mean Local Solar Time
MO&C	Moon Occultation & Calibration
MPH	Main Product Header
MPS	Mission Planning System
NCW	Nadir Calibration Window
NCWM	Nadir Calibration Window Mechanism
NDF	Neutral Density Filter
NDFM	Neutral Density Filter Mechanism
NIR	Near Infrared
NIVR	Nederlands Instituut voor Vliegtuigontwikkeling en Ruimtevaart
NNDEC	Non-nominal Decontamination
NNTM	Non-Nominal Telemetry
NRT	Near-realtime
NSO	Netherlands Space Office
OA	Optical Assembly
OBM	Optical Bench Module
OBT	On-Board Time
OCM	Orbit Control Manoeuvre
OCR	Operation Change Request
OSDF	Orbit Sequence Definition File
OU	Optical Unit
PAC	Processing and Archiving Facility
PET	Pixel Exposure Time
PI	Principle Investigator
PMD	Polarisation Measurement Device
PMTC	Power Mechanism and Thermal Control Unit
RAD A	Radiator A
RF	Refuse
RGT	ROP Generation Tool
ROP	Reference Operation Plan
RRU	Radiant Reflector Unit
RTCS	Relative Time Command Sequence
R/W	Reset/Wait
SAA	South Atlantic Anomaly
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography

SCOOP	SCIAMACHY On-board Operation Plan
SDMOP	SCIAMACHY DMOP
SDPC	Science Data Processing Controller
SDPU	Science Data Processing Unit
SEU	Single Event Upset
SF	Sun Follower
SLS	Spectral Line Source
SO&C	Sun Occultation & Calibration
SODAP	Switch-on and Data Acquisition Phase
SOR	SCIAMACHY Operations Request
SOST	SCIAMACHY Operations Support Team
SPH	Secondary Product Header
SQWG	SCIAMACHY QWG
SRC	SCIAMACHY Radiant Cooler
SRON	SRON Netherlands Institute for Space Research
SSAG	SCIAMACHY Science Advisory Group
SSC	Subsolar Calibration
SSCO	Subsolar Calibration Opportunity
SWIR	Short-Wave Infrared
SYSM	Stellar Yaw Steering Mode
TC	Thermal Control
TCFoV	Total Clear Field of View
TN	Technical Note
TRUE	Tangent Height Retrieval by UV-B
UTC	Universal Time Coordinated
UV	Ultraviolet
VIS	Visible
WGS84	World Geodetic System 1984
WLS	White Light Source
YSM	Yaw Steering Mode

Applicable Documents

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AD [2] Optical and Radiant Cooler Assemblies Requirements and Constraints for In-Flight Operation and Instrument Calibration, TN-SCIA-1000FO/117, Issue 4, 22 March 2000
AD [3] SCIAMACHY Operations Concept – I. Mission Scenarios, PO-TN-DLR-SH-0001/1, Issue 3, Rev 0, 15 October 2001
AD [4] SCIAMACHY Operations Concept – II. Timelines: Generation, Planning & Execution Rules and Reference Timeliness, PO-TN-DLR-SH-0001/2, Issue 3, Rev. 0, 31 October 2001
AD [5] SCIAMACHY Operations Concept – III. Instrument States and Onboard Tables (PFM), PO-TN-DLR-SH-0001/3, issue 4, Rev. 4, 09 January 2002
AD [6] RGT – DLR Interface Control Document, GMV-RGT-ICD-04, Version 1.2, 08 February 2002
AD [7] FOCC – External User Generic Interface Control Document, PO-ID-ESA-GS-00400, Issue 1.7, 19 February 2001
AD [8] SCIAMACHY/ENVISAT-1 DLR/FOCC Interface Control Document, PO-ID-ESA-SH-00426, Issue 1.2, 08 February 2002

The content of AD [3], AD [4] and AD [5] was occasionally modified when required by Operation Change Requests (OCR). This has been documented via the SOST website RD [1].

Reference Documents

RD [1] SOST website (http://atmos.caf.dlr.de/projects/scops/)
RD [2] SCIAMACHY - Exploring the Changing Earth's Atmosphere, Manfred Gottwald, Heinrich Bovensmann (Eds.), ISBN 978-90-481-9895-5, DOI 10.1007/978-90-481-9896-2, Springer Dordrecht Heidelberg London New York
RD [3] Expected SCIAMACHY Instrument Performance in the Years 2010-2014, PO-TN-DLR-SCIA-SH-0018, Issue 1, Rev. 0, 7 December 2007
RD [4] SCIAMACHY Mission Extension Orbit Analysis, PO-TN-DLR-SCIA-SH-0021, Issue 2, Rev. 0, 23 September 2010
RD [5] The Impact of the ENVISAT Mission Extension on the Scanner Control System, TN-SCIA-0000DO/31, Issue C, 30 September 2010
RD [6] Operating SCIAMACHY Beyond 2013, PO-TN-DLR-SH-0031, Issue 1, Rev. 0, 15 September 2011
RD [7] SCIAMACHY Mission Extension Performance Verification, PO-TN-DLR-SH-0030, Issue 1, Rev. 0, 30 April 2011
RD [8] The Status of the SCIAMACHY Active Thermal Control (ATC), PO-TN-DLR-SH-0032, Issue 1, Rev. 0, 10 March 2012
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RD [11] SCIAMACHY Extra Misalignment Model, PO-TN-DLR-SH-0016, Issue 1, 07 March 2007
RD [12] SCIAMACHY Non-nominal Telemetry Monitoring, PO-TN-DLR-SH-0026, Issue 2, Rev. 0, 12 July 2011
RD [13] Reference Telemetry Parameters for SCIAMACHY Azimuth and Elevation Scanners, PO-TN-DLR-SH-0020, Issue 1, Rev. 0, 23 July 2008

RD [14] SCIA PFM Life Limited Item Status List, LI-SCIA-0000DO/03, Issue A, 01 December 2000

RD [15] Calculation of SCIAMACHY M-Factors, IFE-SCIA-TN-2007-01-CalcMFactor, Issue 1, draft 3, 1 April 2008

RD [16] SCIAMACHY Operations Information Long-term Archiving, PO-TN-SH-DLR-0035, Issue 1, Rev. 0, 15 December 2015

RD [17] SCIAMACHY Operations Change Request Catalogue 2002-2012, PO-TN-SH-DLR-0036, Issue 1, Rev. 0, 15 December 2015

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1. Scope and Purpose

This Technical Note (TN) describes the operational aspects of the in-orbit phase of the atmospheric science instrument SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Chartography) on-board the ESA ENVISAT mission. Following ENVISAT's fatal anomaly on April 8, 2012 and the unsuccessful recovery actions, the ENVISAT mission had been declared as ended by ESA on May 9, 2012.

Shortly after the end of the ENVISAT mission, ESA had requested from DLR to prepare a comprehensive summary of operational and performance aspects of SCIAMACHY's 10 years in-orbit lifetime as input to an overview of 10 years of ENVISAT operations. In response, the SCIAMACHY Operations Support Team (SOST) assembled the *SCIAMACHY Preliminary In-Orbit Mission Report* (PO-TN-DLR-SH-0033, Issue 1, Rev. 0, 31 July 2012). This document turned out to be rather detailed and complete. It already came close to the final version which was planned as one of the deliverables at the end of the SOST-DLR phase F activities.

This preliminary version of the operations report covered the instrument status in both the Commissioning Phase and routine operations phase. Commissioning Phase activities were only addressed when they impact the much longer routine operations phase. No details on certain Commissioning Phase activities such as e.g. functional check-outs, calibration and characterization or sub-system testing were given. Main emphasis of this report was put on the evolution of the instrument performance as long it was related to in-orbit operations and the record of the instrument availability.

With the SOST-DLR phase F coming to an end, the preliminary in-orbit mission report has been edited to yield the final version. Only minor changes were necessary. This included expanding the OCR section, adding a chapter on PMD temperature monitoring and editorial modifications, e.g. correcting typos. During phase F, as a result of analyses in the framework of the SCIAMACHY Quality Working Group (SQWG), the modelling and understanding of several aspects of instrument performance and in-orbit behaviour improved. Corresponding documentation is always provided as part of the SQWG reporting. We do not include these findings in the final in-orbit mission report. Instead, we always refer to the status as of mid-2012, i.e. the status at the end of the mission.[1]

2. Introduction

SCIAMACHY was an Announcement of Opportunity (AO) instrument on-board ENVISAT provided by DLR and NSO (then DARA and NIVR) with the Dutch part being supplemented by a Belgian contribution. Therefore certain contents of the ESA provided template for this report are not applicable, which mainly concern contractual aspects including deliverable items. For SCIAMACHY the share of responsibilities was defined in the Instrument Implementation Agreement (IMIA) in general and specified in the Flight Operation and Data Plan (FODP) in detail. In addition it had been agreed between the German and Dutch partners that the operational tasks on AO provider (AOP) side were covered by DLR. For this purpose a team had been established consisting of staff from DLR (then German Remote Sensing Data Center – DFD; now Remote Sensing Technology Institute – IMF) and the SCIAMACHY Principal Investigator's (PI) Institute of Environmental Physics / Institute of Remote Sensing (IUP-IFE) at the University of Bremen. This SCIAMACHY Operations Support Team (SOST) developed, in close cooperation

[1] The information provided in the final report complies with product version L1 V7. The SQWG phase F yielded improvements in certain calibration aspects, e.g. the new concept for degradation correction or updates on mispointing angles. They will be reflected in future later product versions (L1 V8 and L1 V9).

with ESA, the industrial prime contractors EADS-Astrium (former Dornier Satellitensysteme) and Dutch Space with subcontractors, the SCIAMACHY calibration experts and the SCIAMACHY Science Advisory Group (SSAG) the infrastructure and interfaces required for operating the instrument in space, particularly aiming at optimizing the execution of the in-flight measurements. It included

- mission planning
- instrument configuration control
- performance long-term monitoring

During the Commissioning Phase SOST formed an integrated team with industry. With the beginning of the routine operations phase the operational responsibility was transferred from industry to SOST. However industrial support persisted: EADS-Astrium retained responsibility for on-board s/w maintenance including the instrument's engineering settings and Dutch space for thermal subsystems related issues. ESA operated SCIAMACHY as the remaining ENVISAT payload instruments. However all specifications and inputs had to be provided by the AOP, via SOST, using dedicated interfaces as regulated in the FODP. A dedicated SCIAMACHY operation engineer at the Flight Operation Control Centre (FOCC) at ESOC was the prime operation point-of-contact for SOST. For mission planning purposes, the share of duties between facilities located at ESOC and ESRIN required establishing separate interfaces between SOST and both entities.

2.1 Instrument

Conceptually, SCIAMACHY was a passive imaging spectrometer for the UV via VIS and NIR to SWIR, comprising a scan mirror system, a telescope and a spectrometer, controlled by thermal and electronic subsystems (Fig. 1). Functionally it consists of three main blocks, the Optical Assembly (OA), the Radiant Cooler Assembly (SRC) and the Electronic Assembly (EA). The instrument was 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 pointed sideways into deep space away from any heat source. Interfaces with the ENVISAT platform existed for the provision of on-board resources. These included power and command interfaces from the platform to the instrument. In the other direction measurement data and housekeeping (HK) telemetry from SCIAMACHY were routed into the overall ENVISAT data stream for downlinking.

2.1.1 Optical Assembly

The Optical Assembly was the part of the instrument which collects solar radiation as input and generates the spectral information as output. It consisted of the Optical Unit (OU) and for maintaining the specified thermal conditions, the Radiator A and the Thermal Bus Unit. The Optical Unit was organised into two levels. Entrance optics, pre-disperser prism, calibration unit and channels 1 and 2 can be found in level 1 facing in flight direction (Fig. 2). Channels 3-8 are located in level 2 (Fig. 3). All components were mounted onto the Optical Bench Module (OBM) which served as the structural platform and maintained overall alignment between modules.

The Optical Unit was formed by several subsystems including

Scan Mechanisms and Baffles

Scanning was required in order to steer the line-of-sight (LoS) 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. Two scanners were housed on-board, the azimuth (ASM) and the elevation (ESM) scan mechanism. Whilst the ASM captured radiation coming from regions ahead of the spacecraft, the ESM either viewed the ASM or the region directly underneath the spacecraft. In limb observations, light from the ASM mirror was directed via the ESM mirror into the spectrometer. In nadir observations, only the ESM mirror was used. Both scanners shall ideally be mounted such that their axes are parallel to the platform coordinate system.

Baffles limited the scanner's effective field of view. This resulted in the observation mode dependent Total Clear Field of View (TCFoV – Fig. 4). For the limb and occultation LoS, the baffles provided a symmetric range on either side of the flight direction (azimuth = ± 44° from flight direction) while vertically they restricted viewing from slightly below the horizon to an altitude of about 380 km (elevation 27.5°-19.5°). The nadir LoS was limited to an area of about ± 32° across track. For a special type of measurement, the rectangular shaped Nadir Calibration Window (NCW) could be opened temporarily allowing sunlight from above to enter the instrument via the ESM mirror. Its elongated TCFoV of 1.7° × 14.8° was designed to view the Sun at high elevation when the spacecraft crosses the orbital sub-solar point.

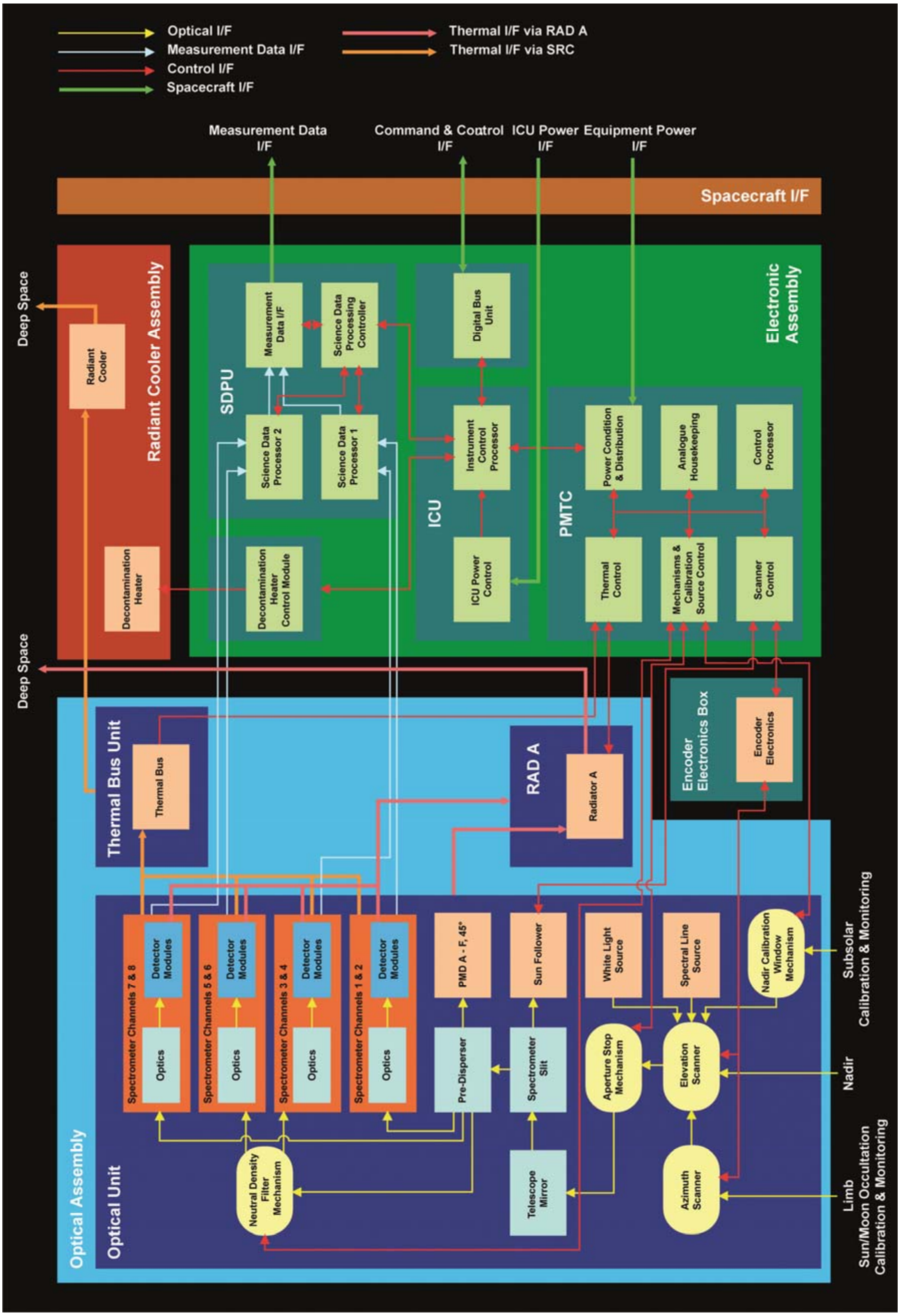


Fig. 1: SCIAMACHY functional block diagram with simplified interfaces between assemblies and modules. (from RD [2])

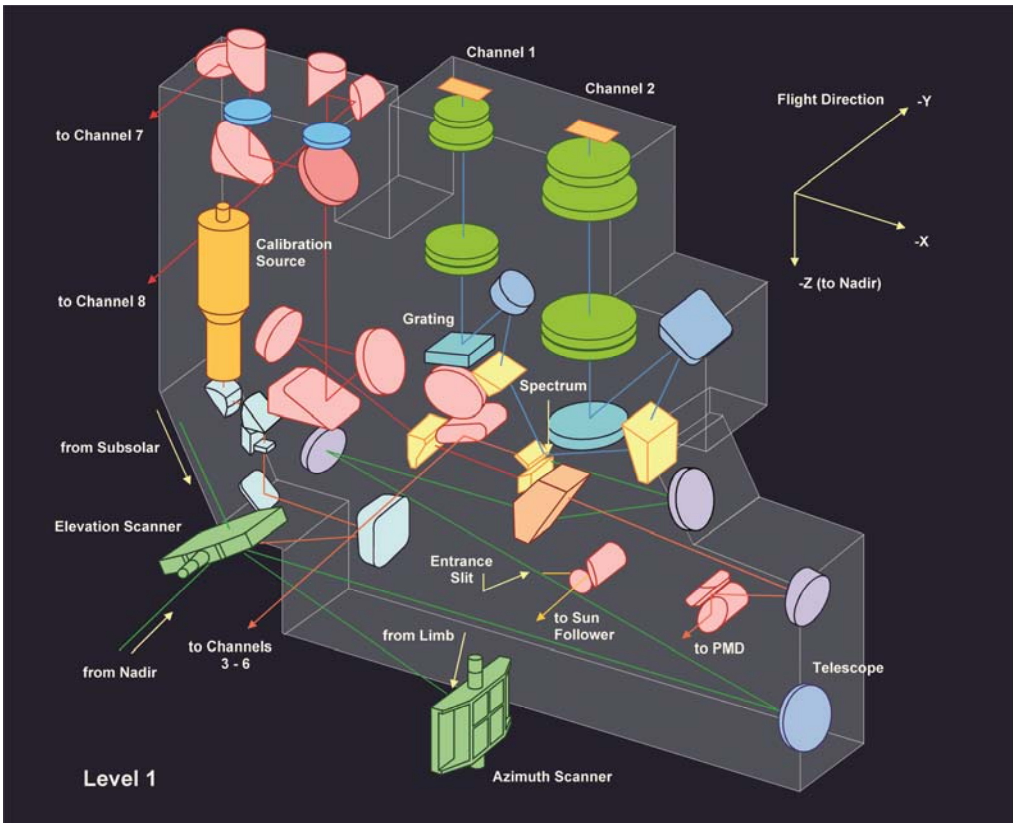


Fig. 2: Optical configuration level 1. (from RD [2])

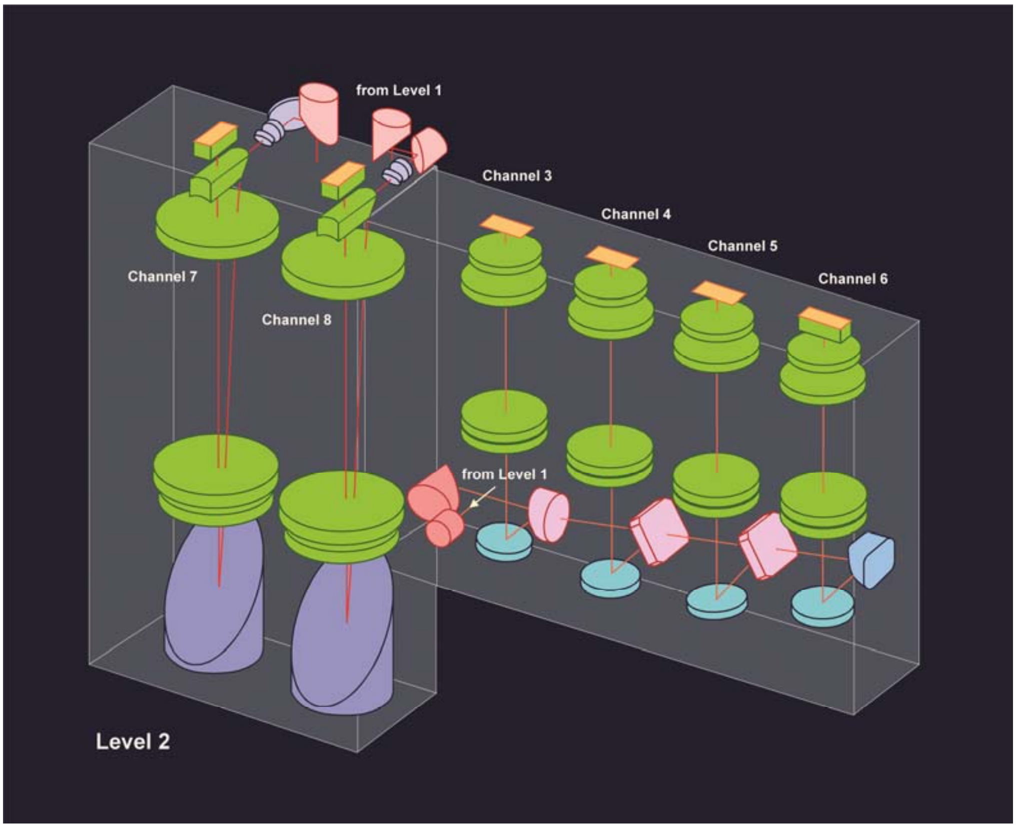


Fig. 3: Optical configuration level 2. (from RD [2])

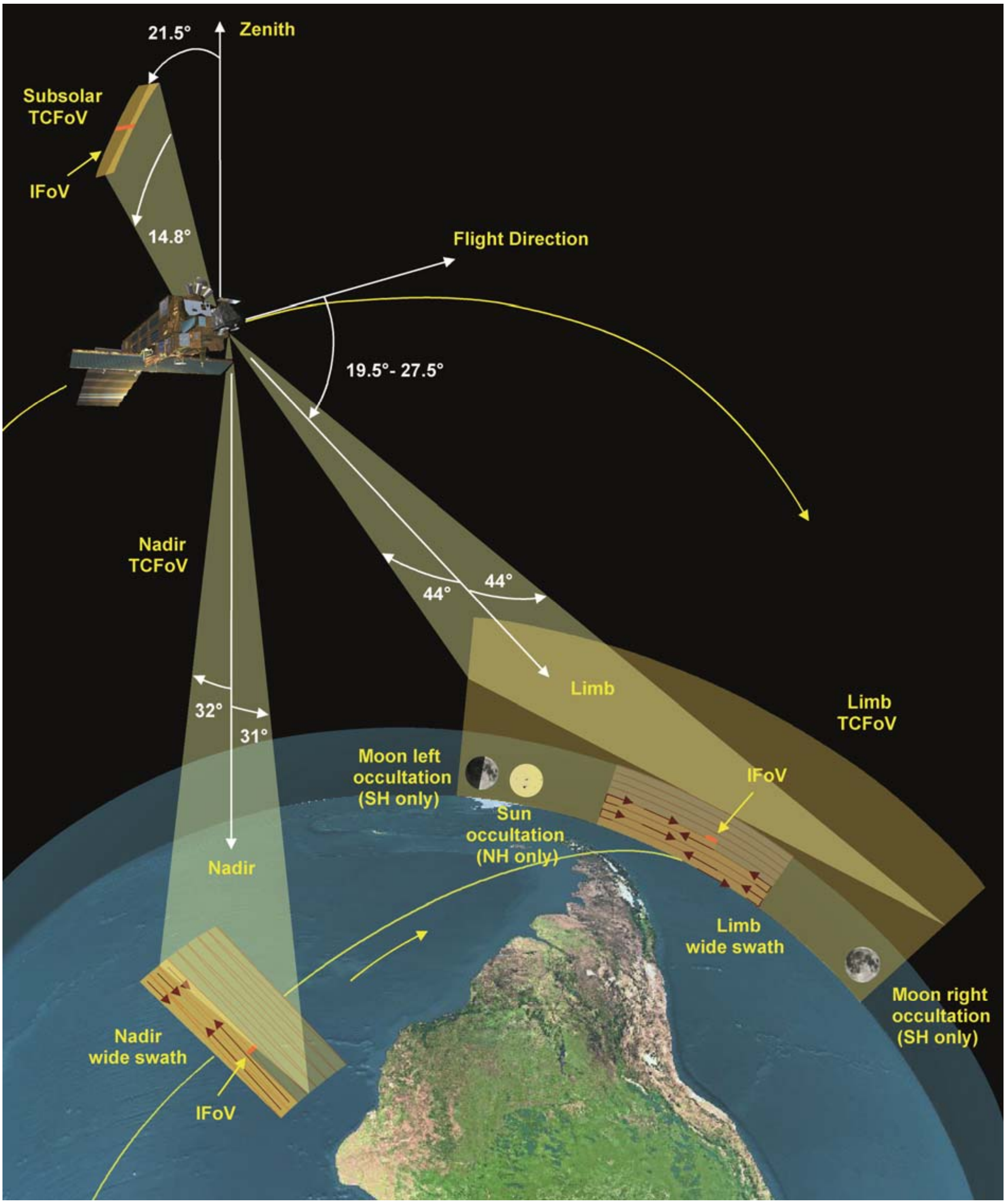


Fig. 4: Sketch of SCIAMACHY's TCFoV and observation geometries. (from RD [2])

Each scanner was operated separately in feedback control using measurements of the rotation angle by an incremental optical encoder. Angular scan trajectories were 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 depend on various scanner internal or external parameters, the selected trajectory could be corrected correspondingly. In limb measurements, the horizontal scans through the atmosphere maintained a constant altitude by applying a correction which took into account the varying curvature of the Earth (WGS84 model) along the orbit. Further corrections provided 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 required the LoS to be centred onto the target. Therefore, information derived from the readout of the four quadrants of the the Sun Follower (SF) was fed into the control loop for steering the scanner motors such that the mirrors – either the ASM or the ESM or both – locked onto the central part of the intensity distribution and followed the trajectory of Sun or Moon after successful acquisition. The SF received light which was reflected from the polished blades of the spectrometer entrance slit.

For obtaining the solar irradiance, the Sun had to be measured via a diffuser. Two aluminium diffusers were mounted on SCIAMACHY: one on the backside of the ESM mirror, the other on the backside of the ASM mirror.

Telescope and Spectrometer

The ESM reflected light towards the telescope mirror, which had 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 defined an Instantaneous Field of View (IFoV) of 1.8° × 0.045°. For solar observations, the IFoV could be reduced to 0.72° × 0.045° by the Aperture Stop Mechanism (APSM), which was located between the ESM and telescope mirror. The APSM reduced the aperture area and thus the intensity level in the channels. In the light path routed to channels 3-6, the Neutral Density Filter Mechanism (NDFM) could move a filter into the beam. With a filter transmission of 25% it was used, in conjunction with the APSM, to even further reduce light levels during solar measurements.

Detector Modules

Spectral information was generated in 8 science channels (Table 1) employing two types of detectors. Channels 1-5 cover the UV-VIS-NIR range using standard Silicon photodiodes with 1024 pixels. The SWIR channels 6-8 used Indium Gallium Arsenide detectors, again 1024 pixels wide. In order to be sensitive to wavelengths beyond 1700 nm, the detector material in the upper part of channel 6 above pixel number 794 ('channel 6+') and channels 7 and 8 had been grown with higher amounts of Indium and thus displayed different detector behaviour. All channels had to be cooled to achieve the specified signal-to-noise performance (Table 1).

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

Table 1: SCIAMACHY science channels (1 & 2 = UV, 3 & 4 = VIS, 5 = NIR, 6-8 = SWIR).

Calibration Unit

Maintaining high spectral stability and high relative radiometric accuracy over the mission's lifetime was ensured via an on-board calibration unit. It consisted of two calibration lamps, the White Light Source (WLS) and the Spectral Line Source (SLS). While the WLS served the verification of the pixel-to-pixel signal stability and the monitoring of the etalon effect, the SLS allowed the determination of the pixel-to-wavelength relation. The calibration unit was located close to the ESM such that by rotating the ESM mirror into specific positions, it became possible to reflect light from the WLS respectively the SLS via the telescope mirror onto the entrance slit. An extra calibration mirror near the ESM could be used for an additional reflection of the incoming light onto the ESM mirror. Because of its protected position well within the instrument it was assumed that this extra mirror will not degrade throughout the mission, i.e. it could be used as a further means for monitoring the optical performance.

Polarisation Measurement Device

The sensitivity of the spectrometer depended on the polarisation state of the incoming light. Therefore, SCIAMACHY was equipped with a Polarisation Measurement Device. Six of its channels (PMD A-F) measured light polarised perpendicularly to the SCIAMACHY optical plane. The spectral bands were quite broad and overlapped with spectral regions of channels 2-6 and 8. The PMD and the light path to the array detectors, including the detectors, had different polarisation responses. Thus an appropriate combination of PMD data, array detector data and on-ground polarisation calibration data permitted determination of the polarisation of the incoming light from the nadir measurements. Atmospheric limb measurements required measurements of additional polarisation information of the incoming light. A seventh PMD channel measured the 45° component of the light extracted from the channels 3-6 light path. All PMD channels were read out every 1/40 sec. They observed the same atmospheric volume as the science channels.

Radiator A and Active Thermal Control

The OBM needed to be operated in orbit at a constant temperature for preserving the validity and accuracy of the on-ground calibration and characterisation. Additionally, a low temperature level was required for keeping the thermal radiation of the instrument itself at a minimum in order not to enhance the signal background in the SWIR channels 7 and 8. A dedicated radiator, RAD A, was 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 avoided direct solar illumination. While the RAD A provided cooling capacity, thermal stability of the OBM had to be established via a closed loop Active Thermal Control (ATC) system. It consisted of three control loops with heater circuits and thermistors. The heating was controlled by the Power Mechanism & Thermal Control Unit (PMTC) based on measurements by the thermistors. Once ATC settings had been selected, the system maintained the OBM temperature to high precision at the specified level. When heater control reached a limit of the specified power range, the OBM temperature could no longer be kept stable over the whole orbit. By commanding appropriately modified ATC parameters, the required ATC performance could then be re-established.

Thermal Bus

In-orbit operating temperatures of the detectors were specified below ambient, i.e. the detectors had to be cooled. This occurred via the Radiant Reflector Unit (RRU) of the Radiant Cooler (SRC) Assembly. The Thermal Bus connected thermally the detector modules with the reflector. Heat from detectors 1-6 was transported via an aluminium thermal conductor, from detectors 7 and 8 via two methane filled cryogenic heat pipes. Since the cooling efficiency of the Radiant Cooler was designed to provide sufficient cooling capacity until the end of the mission, a Thermal Control (TC) system was part of the Thermal Bus. It prevented the detector modules from becoming too cold by counter heating using three trim heaters. The TC system used open loop heater control. Whenever drifting temperatures of the detectors reached their limits, the power settings of the trim heaters were adjusted by ground command bringing the temperatures back into the specified range.

2.1.2 Radiant Cooler Assembly

SCIAMACHY's Radiant Cooler dissipated 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 were connected via the Thermal Bus of the OA. As for RAD A, the RRU pointed in the -X direction away from the Sun. Earthshine and sunshine was blocked from the radiating surface of the SRC to gain maximum cooling efficiency. Because of its low temperature, the RRU surface was expected to attract contaminants from the in-orbit environment, particularly from ENVISAT itself. This would have degraded the performance of the Radiant Cooler leading to reduced cooling efficiency. In order to clean the Radiant Cooler, the cold stage and the reflector had been equipped with decontamination heaters which, when turned 'on', would have raised the temperatures of the RRU, thus removing contaminating substances and re-establishing the cooling performance.

2.1.3 Electronic Assembly

The Electronic Assembly (EA) provided the control of the instrument and 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 housed all electrical and software functions required for autonomous operation of the whole instrument. It consisted of the primary processor called Instrument Control Unit (ICU) and the secondary processors, the PMTC and the Science Data Processing Unit (SDPU). The EA was 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 was the task of the ICU. It ensured

- reception, verification and execution of macrocommands (MCMD) and potential software updates
- 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

All time information was derived from the ICU on-board clock providing the SCIAMACHY On-Board Time (OBT). OBT and ENVISAT's PMC master clock were synchronised. The internal clocks of the secondary processors were not synchronised with the ICU clock. Datation of the scanners and detectors relied on an internal 16 Hz Broadcast Pulse (BCPS) which was generated in the ICU. For command execution a finer time resolution with a rate of 256 Hz (1 Count = 3.9 msec) was used to synchronise instrument internal control functions. Scanner control operations were driven by a dedicated PMTC internal 1 kHz clock.

Secondary Processors

The SDPU controlled and acquired 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 occurred prior to formatting and transfer to ENVISAT's High Speed Multiplexer (HSM) via the measurement data interface. The PMTC received power from the platform and supplied the various modules in the OA. Additionally, it controlled the thermal status of the OA and detectors as well as the operations of mechanisms, including scanners and calibration sources.

Modes

The operational instrument configurations were called 'modes' with *Measurement* and *Decontamination* being those where SCIAMACHY could fulfil its measurement objectives. The *Measurement* mode may have been either *Timeline* or *Idle*. Various support modes existed to achieve or maintain full operational conditions. Some of them were the response to an ICU or platform detected anomaly. Up to 255 HK parameters could be monitored by the ICU simultaneously. As long as the monitoring function did not report any anomaly, the instrument continued operations. Each anomaly detected triggered a Corrective Action (CA). Some anomalies resulted in a CA which did not interrupt operations but was just recorded in the ICU's history area which was regularly downloaded via telemetry for inspection. More severe errors caused an immediate stop of ongoing measurements and the transition of the instrument into a safe configuration = mode lower than *Measurement*. After careful analysis of the anomaly and eliminating its cause, the instrument could be commanded from safe configuration back to nominal operations.

2.2 Operations

Because of the characteristics of a polar orbiting platform with short telemetry coverage at the high latitude station Kiruna or via the Ka-band Artemis link, SCIAMACHY operations were largely autonomous. This comprised not only on-board anomaly detection and initiation of corrective actions as part of the instrument control but also the ability for configuring the instrument status and to execute measurements without direct manual intervention from ground.

Scientific requirements included viewing geometries for atmospheric measurements of nadir, limb, Sun occultation and Moon occultation. In addition, external (dark current, Sun reference) and internal (calibration lamps) calibration and characterisation observations supplemented the measurement schedule. One of SCIAMACHY's main objectives was to measure the same atmospheric volume both in nadir and limb within one orbit, i.e. achieving limb/nadir matching of the geolocation of limb states with associated nadir states. This was a unique feature and allowed collecting scientific information for the same volume of air from two different measurement modes.

2.2.1 Mission Scenarios

A typical SCIAMACHY reference mission scenario defined an orbit which consisted of (AD [3]):

- alternating limb/nadir measurements in the illuminated part of the orbit
- a swath width of ± 480 km relative to ground track in nadir and limb scans for global coverage within 6 days (taking the alternating limb/nadir measurements into account)
- Sun occultation measurements each orbit
- Moon occultation measurements whenever possible (moonrise on nightside of Earth)
- mesosphere/lower thermosphere measurements in eclipse each orbit, intermittent with calibration and monitoring measurements
- the equivalent of 2 days per month with mesosphere/lower thermosphere measurements in the illuminated part of the orbit (this requirement was added in the mission)
- calibration and monitoring measurements on a daily (every 14^{th} orbit), weekly (every 100^{th} orbit) and monthly basis

For a typical orbital mission scenario, 92% of the orbital period was covered by measurements. The remaining 8% were idle gaps required for potential command and control activities or were caused by the fact that the smallest possible time slice in a timeline was the duration of a state. Therefore, the continuous seasonal changes of solar and lunar constellations could not always be perfectly matched and caused gaps up to the duration of a state.

Measurements started above the northern hemisphere with an observation of the rising Sun. In order to acquire light also from the sparsely illuminated atmosphere at the limb in the direction of the rising Sun, a sequence of limb measurements preceded each Sun occultation measurement. Once the Sun had risen, it was tracked by the ESM for the complete pass through the SO&C window. After about 175 sec the Sun left the limb TCFoV at the upper edge. In order to fully exploit the high spatial resolution during occultation, measurement data readout with a high rate (1.8 Mbit/sec) was required in the SO&C window. Until the passage of the sub-solar point, a series of matching limb/nadir observations was executed. At the sub-solar point the Sun, generally close to descending node crossing, had reached its highest elevation relative to ENVISAT. A sub-solar measurement was only executed when a sub-solar calibration opportunity had been assigned by ENVISAT. Because the Ka-band antenna in its operational position vignetted the sub-solar TCFoV, only 3 orbits per day with sub-solar opportunities were possible. Again, a sequence of matching limb/nadir measurements followed. Above the southern hemisphere, the Moon became visible during the monthly lunar visibility period, otherwise matching limb/nadir observations continued. The rising Moon was observed similarly to the rising Sun from bottom to top of the limb TCFoV. A series of limb/nadir observations concluded the illuminated part of the SCIAMACHY orbit. Because the instrument was still viewing sunlight while the projected ground-track in the flight direction already had seen sunset, the final measurements in this phase were only of the nadir type. When ENVISAT entered the eclipsed part of the orbit, dedicated eclipse observations could be executed until SCIAMACHY moved towards another sunrise and the orbit sequence started again (Fig. 5). The reference orbit was entirely based on the *Sun/Moon fixed* concept. While *Sun fixed* events showed a relatively stable temporal behaviour over a year, orbital segments related to Moon occultation measurements did not. They exhibited strong variability both within a monthly lunar observation period and over a year.

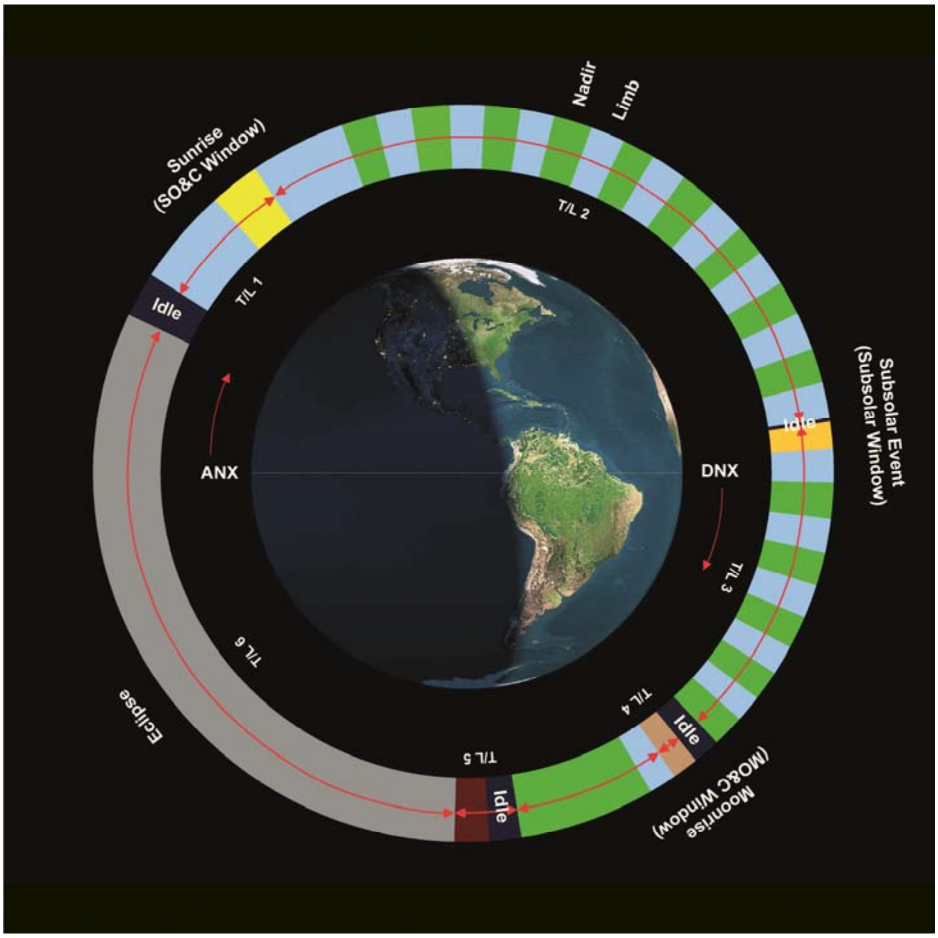


Fig. 5: SCIAMACHY reference orbit with Sun/Moon fixed events along the orbit. The events define orbital segments which are filled with timelines. State duration is not to scale. (from RD [2])

2.2.2 Parameter Tables

The high degree of flexibility in the instrument design was accomplished through parameterisation of on-board operations. Changing the instrument status could occur either via software patching or changing parameter settings via commanding. Those sets of parameters which were associated with basic instrument properties, e.g. scanner, thermal and mechanism control definitions, were termed *engineering* parameters. More than 4600 engineering parameters existed (Table 2). Most of them had been defined prior to launch and were verified during the Commissioning Phase. During routine operations, engineering parameters were subject to modifications only at a very low rate. Parameters relating to the configuration of the spectrometer while acquiring data, the *measurement* parameters, had also been defined prior to launch (Table 3). However, changing scientific requirements or adapting to platform or instrument needs (e.g. orbit change, degradation) made it necessary to update measurement parameters occasionally. More than 25000 measurement parameters were needed to execute all the required measurements.

Type	Table	Purpose
Monitoring	Monitoring Enable Monitoring Inhibit Monitoring	on-board monitoring of 255 HK parameters
Corrective Action	CA_Mask Enable Autonomous Switching Inhibit Autonomous Switching CA_Matrix	on-board fault handling including Corrective Actions
Engineering	Scanner Constants Scanner Control Parameters Thermal Control Parameters Mechanism Control Parameters	control of scanner algorithms, scanner position, thermal subsystems and mechanisms
Command	RTCS RTCS Waits Reset Index Mode_Mode_Matrix AUX_MCMD_Mode_Matrix	commanding of timing sequences and associated conditions

Table 2: Engineering parameter tables.

Type	Table	Number of specified parameters
State	Scanner State Pixel Exposure Time Hot Mode State Index State Duration Co-Adding Detector Cmd Words DME Enable State RTCS Index	10080 1400 420 280 420 4480 35 8 140
Common	Basic Scan Profile Relative Scan Profile Cluster per Channel Cluster Definition	60 8652 40 464

Table 3: Measurement parameter tables.

2.2.3 Measurement States

The different configurations of the individual functions to operate SCIAMACHY in measurement modes were defined as *states* (AD [5]). A state controlled a sequence of activities to execute a particular measurement task, e.g. nadir observations with certain pixel exposure times, Sun occultation with a certain scan geometry, etc. A total of 70 states were defined on-board (Table 7 in chapter 4.2.2). 35 states implemented scientific observation requirements, 26 had the purpose of in-flight calibration, 4 for in-flight monitoring and the data from 5 states could be used for scientific and calibration analyses. The high number of calibration and monitoring states was the result of the thorough and complex in-flight calibration and monitoring concept.

Throughout the mission all except one (state 55) state retained their definition from the beginning of the routine operations phase. This state originally should have executed a moon occultation through the troposphere but as it had turned out could never be accomplished due to limitations in lunar viewing in the lower part of the Earth atmosphere. However, although the functionality did not change, occasional updates to individual state parameters occurred for responding to scientific or calibration and monitoring requirements (see chapter 4).

2.2.4 Timelines

Individual states formed sequences called *timelines* (AD [4]). A total of 63 timelines could be stored on-board and started via a single MCMD.

Based on the mission scenarios and the occurrence of Sun and Moon fixed events along the orbit, timelines were generated from the set of 70 states. Each timeline corresponded to an orbit interval with start/stop being related to a Sun or Moon fixed event. Timelines could be assigned to the following orbit intervals:

- SO&C window
- MO&C window
- start to end of eclipse
- end of SO&C window to start of eclipse
- end of SO&C window to start of sub-solar window
- end of sub-solar window to start of eclipse
- end of SO&C window to start of MO&C window
- end of sub-solar window to start of MO&C window
- end of MO&C window to start of eclipse

A complete orbital mission scenario was implemented by assembling a sequence of timelines which covered the full orbit. The most frequent scenario executed 4 timelines only – a SO&C timeline, followed by a long limb/nadir sequence and two calibration timelines in eclipse.
All timelines starting or ending with the MO&C window had to accommodate the strong temporal variability of lunar events within a monthly visibility period. Therefore, several versions of Moon related timelines with different lengths existed for the same segment. Triggered by mission planning, they were exchanged on-board whenever required by lunar position. This was different from timelines allocated to Sun related orbit segments which required only single instances due to the moderate seasonal changes.

Other than in the case of timelines, the original final flight timeline set was not maintained throughout the mission. Instead, several uploads of new timeline sets had to occur (see chapter 4).

3. Mission Operations Phases

On 1 March 2002 at 1:07 UTC, SCIAMACHY was lifted into space from Kourou as part of the ENVISAT mission. At about 02:53:51 UTC, ENVISAT crossed the Earth's equator on the night side for the first time corresponding to the start of absolute orbit no. 1. Since then, until the end of the mission on April 8, 2012, 52868 orbits were accumulated in total with SCIAMACHY having executed only slightly less owing to its first switch-on about 10 days into the mission (see below). SCIAMACHY mission phases consisted of the launch and early operation phase (LEOP), the switch-on and data acquisition phase (SODAP), the main validation phase with quasi-routine operations and finally, the routine operations phase (Table 4).

Phase	Instrument Activity	Date	Orbit
LEOP	OFF-Leo mode	1/7 Mar 2002	
SODAP	first switch-on	11 Mar 2002	147
	first MPS driven operations	17 Mar 2002	238
	first decontamination	18 Mar 2002	253
	AZACM cover released	3 Apr 2002	477
	SRC released	15 Apr 2002	653
	final ATC/TC settings loaded	10 Jun 2002	1454
	ELACM cover released	20 Jun 2002	1594
	β states loaded	17 Jul 2002	1982
	timelines with β states loaded	18 Jul 2002	1990
	end SODAP (remaining SODAP measurements inserted as *Δ SODAP* in validation phase)	2 Aug 2002	2204
Validation	start validation	2 Aug 2002	2204
	end Δ SODAP measurements	14 Dec 2002	4127
	final flight states loaded	15 Dec 2002	4143
	timelines with final flight states loaded	16 Dec 2002	4151
	first non-nominal decontamination started	19 Dec 2002	4204
Routine Operations	nominal measurement programme – start	6 Jan 2003	4457
	ENVISAT orbit change	24 Oct 2010	45222
	nominal measurement programme – end	8 Apr 2012	52868

Table 4: Main SCIAMACHY activities from launch to end of mission (for details see text).

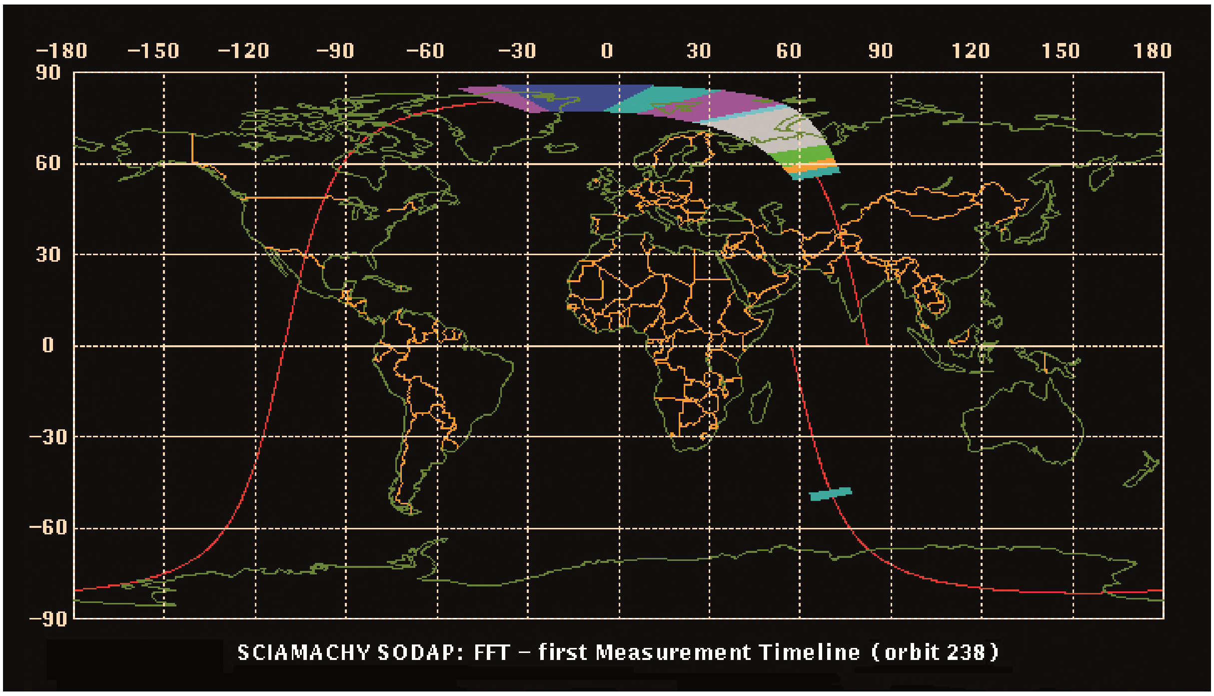


Fig. 6: A historical planning document – SCIAMACHY's first timeline in orbit 238 on March 17, 2002 when the first states and the first timeline were executed for the *Full Functional Test*. The different segments covering the orbit from Central Asia to northern Greenland depict the different states.

Fig. 7: Participants of the SODAP review in April 2002 at ESOC. At this meeting the successful first weeks of ENVISAT operations were confirmed thus marking the start of a successful 10 years in-orbit mission lifetime.

3.1 Commissioning Phase

SCIAMACHY's initial operational programme had the goal reaching routine operations as soon as possible but also to perform a thorough in-orbit functional check-out and verification of the instrument. Establishing the instrument activities in the Commissioning Phase, particularly SODAP, required assembling a plan that included engineering and specific measurement tasks. This plan had to provide a continuous, conflict-free schedule at instrument, as well as on ENVISAT level, which finally permitted the declaration that SCIAMACHY was ready for routine operations. The approach was to start with separate planning of engineering and measurement tasks, to integrate both in order to obtain a complete SCIAMACHY flow, and to insert this flow into the overall ENVISAT SODAP plan.

3.1.1 The Switch-on and Data Acquisition Phase (SODAP)

Engineering Tasks

Instrument operations on command and control level were described in the Instrument Operation Manual (IOM). The IOM provided the ENVISAT Flight Operation Control Center (FOCC) with all information necessary to properly operate and maintain the instrument. During SODAP, the instrument capabilities, which later should be used on a routine basis, had to be functionally tested and verified, both in nominal and non-nominal situations. In addition, engineering settings for dedicated subsystems had to be derived. The engineering SODAP tasks comprised:

- mode transitions with associated parameters
- thermal operations including decontamination
- flight procedures
- routine monitoring
- processor patch and dump

These were supplemented by dedicated operations that occurred only once during SODAP. Major activities included the release of the azimuth and elevation aperture cover mechanisms and the opening of the SCIAMACHY Radiant Cooler (SRC) door. Thermal operations were executed for the first time under in-orbit conditions. Therefore, emphasis was put on a thorough verification of the thermal subsystems Active Thermal Control (ATC), Thermal Control (TC) and Radiant Cooler. The goal was characterising the subsystems well enough in order to be able to routinely select the correct parameter settings suitable to maintain the temperatures of the Optical Bench Module (OBM) and detector within specified limits after the end of SODAP.

Measurement Tasks

The flexibility of the instrument required verification of many different functionalities and characterisation of a large set of instrument parameters. This occurred via executing specific SODAP states. Each new state corresponded to a new instrument on-board configuration that had to be commanded via the upload of measurement parameter CTI (Configurable Transfer Item) tables. Individual states, new ones and those already existing, were assembled to generate specific timelines. Execution of the states was triggered via the start of such SODAP specific timelines scheduled via the ENVISAT Mission Planning System (MPS). Since some commissioning objectives required particular instrument configurations – e.g. aperture covers released, a certain thermal status – or needed the output of other SODAP measurements as a precondition, it was impossible to generate a full SCIAMACHY SODAP measurement plan. Instead, engineering and measurement tasks were sequentially integrated as SODAP progressed. On planning level the result was the SCIAMACHY On-Board Operation Plan (SCOOP), an Excel based database of the complete SODAP period. It split this period into engineering and measurement windows. In an engineering window, SCIAMACHY operation was procedure driven, while in a measurement window, the instrument operations were timeline driven and controlled by the ENVISAT MPS.

SODAP Sequence

At the time of launch, the SODAP specific planning information – SCOOP, states and timelines – was available and ready for activation. The ENVISAT SODAP plan had scheduled SCIAMACHY's first switch-on for orbit 147 (March 11, 2002), eleven days after launch. Six days later (March 17, 2002), the instrument was controlled for the first time by the ENVISAT MPS when the first timeline was executed, which ran successfully the so-called *Full Functional Test*. Because all aperture covers were still closed, no external light was collected and only light from the internal calibration sources was used. The sequence of engineering and measurement activities continued until April 3, 2002. That day, the first aperture cover, the azimuth aperture cover mechanism (AZACM), was released and the light path via the limb port opened, permitting limb and occultation observations. The time delay between launch and the first appendage release was required to avoid possible contamination of the instrument due to outgassing from the platform. Another important milestone was reached on April 15, 2002 with the opening of the SRC. This event started the passive cooling of the detectors to their nominal temperatures, i.e. from this release on, detectors could be operated under in-flight thermal conditions. Furthermore, thermal tests aimed to find the final settings for the instrument were now possible. End of April the first lunar measurement window occurred and was successfully providing moon occultation observations. In June, SODAP had progressed so far that the final flight settings for the ATC and TC could be uploaded. OBM and detectors were now under continuous thermal control with modifications only being triggered by seasonal effects or the status of the SRC. On June 20, 2002 the third and final cover, the elevation aperture cover mechanism (ELACM), was removed from the light paths. It permitted light to enter SCIAMACHY via the nadir port. From then on the engineering and measurement programme focused on finalising SODAP with the goal to begin the validation part of the Commissioning Phase in early August. With the set of β *states*, originating from the evaluation of earlier measurements, and with the associated timelines, a configuration was specified and uploaded mid July which already came very close to the envisaged final flight definitions. SODAP ended on August 2, 2002 but leaving a few measurements still to be done. This was mainly due to the occurrence of anomalies (see chapter 6). Also some of the measurements required seasonally dependent observing conditions, available only in the second half of the year.

3.1.2 The Validation Phase

From an instrument point of view, SCIAMACHY was operated during the validation phase in a quasi-routine fashion. Only some inserted Δ *SODAP* measurements interrupted the nominal measurement plan. SCIAMACHY executed a continuous measurement programme which reflected the mission scenarios for routine operations. The end of the validation phase corresponded to the end of the Commissioning Phase. Therefore, the definition and upload of the final flight states and timelines was accomplished mid December 2002. After a decontamination the instrument was prepared and ready for the start of the routine operations phase (see Table 4).

3.2 Routine Operations Phase

In January 2003, SCIAMACHY commissioning had ended and transfer to the routine operations phase was initiated. At the start of routine operations operational responsibilities on the instrument provider side were transferred from EADS Astrium to the SCIAMACHY Operations Support Team (SOST).

Routine operations were characterised by maintaining the baseline measurement programme. Only when required for specific test cases (temporary change) or driven by modified science/calibration needs (mostly permanent changes) a change in the instrument configuration had to occur. From an instrument performance point of view the routine operations phase, together with the validation phase when quasi nominal measurements had been executed, forms the basis for the operations performance analysis and results presented in the chapter 7. Only in this period the instrument was maintained in a stable configuration for a sufficiently long time such that meaningful conclusions could be drawn.

4. Instrument Configurations

4.1 Commissioning Phase

When SCIAMACHY was switched-on on March 11, 2002 it occurred using the primary chain of hardware, called *side A*. In case of a malfunction in side A, SCIAMACHY could have been switched to *side B* which had identical functions. However, the instrument stayed on side A for the entire in-orbit mission lifetime. No need arose to activate any of the redundant hardware components (Table 5).

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

Table 5: SCIAMACHY redundant components for nominal operations.

Throughout the Commissioning Phase the instrument underwent many configuration changes as required by the scheduled engineering and measurement tasks. Listing individual activities would be beyond the scope of this document (for the thermal status in the Commissioning Phase see chapter 7). In summary, at the end of the Commissioning Phase SCIAMACHY had successfully

- executed more than 21200 MCMDs,
- started almost 5500 timelines, which had
- triggered more than 78000 individual states, which had required
- upload of 5700 parameter tables and
- upload of 560 timelines.

Each parameter table was equivalent to reconfiguring one functionality or characteristic of the instrument. SODAP proved that the operational concept and the flight operations ground segment interfaces were well developed to handle the complex mission.

4.1.1 On-board S/W Maintenance

The Commissioning Phase was the only period when patching of on-board s/w, executed under the responsibility of EADS Astrium, was required. It occurred twice.

ICU patch

An ICU patch (one word only) was uploaded in orbit 3399 (October 24, 2002) for repairing the MCMD Transfer CCA Check Error (see chapter 6) which was several times during SODAP responsible for suspending SCIAMACHY operations. The patch was not a full remedy – complete repair would have required a more extended patch – but reduced the average rate of the check error to an acceptable low level of about 1/year.

PMTC patch

A sign error in the scanner control software for limb states was corrected via patching the PMTC s/w in orbit 3784 (November 20, 2002). This error had caused an erroneous across-track shift of the limb ground pixels. After the patch the geolocation of nadir and limb pixels displayed the required across-track matching.

4.2 Routine Phase

In the routine operations phase changing the instrument configuration was required in response to

- platform operations modifications
- instrument degradation
- instrument anomalies
- science requirements updates
- calibration and characterisation requirements updates

Implementation occurred via changes in engineering parameters, measurement parameters or mission scenarios, i.e. rules, how individual measurements had to be arranged along the orbit.

4.2.1 Engineering Parameter Updates

Updates of engineering parameters usually required the execution of flight operation procedures (FOP) at FOCC. The content of the FOP was specified by SOST according to rules and requirements outlined in the corresponding applicable documents, particularly the IOM (AD [1]). Transfer of this information occurred using the SCIAMACHY Operations Request (SOR) interface. This was a text file listing all relevant information (dependent on SOR content) such as parameters to be modified, updated values and time window for updates. Feedback about SOR implementation came via the ENVISAT Special Operations Request (ENVISAT SOR). This was again a text file listing the exact execution times and the new uploaded parameter values. Table 6 lists all SORs which caused a permanent change of the instrument configuration.

As obvious from Table 6, most of the engineering parameter related configuration changes dealt with adjustments of the Thermal Control (TC) system for maintaining detector temperatures. It happened mainly in the first part of the mission. Later, calibration and characterisation had progressed such that detector temperatures outside the assigned limits were found acceptable (for further details see chapter 7). The entries labelled 'ERCORMS update' were related to permanent changes of measurement parameters (see below). SOR no. 24 responded to a repeated occurrence of the SDPU / PMTC Tx Buffer Overflow anomaly. This failure was not so well explored in early 2006. It was hoped that modifying the Min/Max reporting within the SCIAMACHY Report Format fixed area could help to identify the cause of the anomaly. Because the Min/Max reporting capacity was already fully exploited some parameters had to be removed from the reporting prior to adding the new parameters dedicated to the anomaly investigation.

Overall, the SOR interface proved to be rather efficient. It was operated only via manual interaction (word textfiles, e-mail exchange between SOST and the SCIAMACHY engineer at FOCC) without the need of automatic processing of information. Therefore even short-notice SORs could be implemented successfully.

SOR	Purpose	Date	Orbit
02	TC adjustment	16 April 2003	5887
03	TC adjustment	15 May 2003	6301
05	ERCORMS update	21 July 2003	7265
06	ERCORMS update	21 July 2003	7267
08	TC adjustment	01 August 2003	7417
09	ERCORMS update	15 October 2003	8489
10	TC adjustment	22 October 2003	8591
12	TC adjustment	05 December 2003	9227
13	TC adjustment	30 January 2004	10023
14	TC adjustment	16 March 2004	10681
15	TC adjustment	01 April 2004	10909
16	TC adjustment	03 May 2004	11368
18	ERCORMS update	06 September 2004	13172
20	TC adjustment	17 December 2004	14630
21	TC adjustment	05 April 2005	16191
22	TC adjustment	06 January 2006	20142
23	TC adjustment	24 March 2006	21245
24	modification of REPORT definition	06 October 2006	24050
25	TC adjustment	23 January 2007	25611
26	TC adjustment	22 March 2007	26441
27	TC adjustment	02 May 2007	27027
28	TC adjustment	03 January 2008	30550
29	TC adjustment	11 April 2008	31967
31	ATC adjustment	15 October 2008	34642
32	ERCORMS update	08 November 2008	34992
35	operate SCIAMACHY in YSM after OCM	07 December 2009	various*
36	ERCORMS update	16 June 2010	43362
38	ERCORMS update	10 August 2010	44151
39	update engineering parameters for/in mission extension	24 October 2010	various*
40	ERCORMS update	27 October 2010	45262
41	ERCORMS update	10 January 2011	46340
44	stop update engineering parameters in mission extension	19 April 2012	various*

* when implementation of this SOR had occurred in various orbits, the date listed specifies the first instance

Table 6: SCIAMACHY Operations Requests resulting in permanent changes of on-board configuration (details see text).

4.2.2 Measurement Configuration Updates

With the start of routine operations the final flight status of the measurement configuration had to be established. It consisted of the applicable

- mission scenarios
- 70 states
- timeline set (63 timelines stored on-board, > 63 timelines specified on-ground and exchanged as specified in mission planning)

Based on the findings of the Commissioning Phase the first final flight configuration was uploaded on December 15, 2002. The set of states was as listed in Table 7. Since then, until April 8, 2012, the state definitions underwent 11 modifications (Table 8). Only one of these changes altered the functionality of the state. It concerned state 55, which should have observed the Moon in occultation through the troposphere. Due to cloud coverage and illumination conditions this was never achieved. Therefore, state 55 was later (November 3, 2008) changed to execute limb scans from the lower thermosphere down to the mesosphere.

The first final flight timeline set was assigned no. 25. Until the end of the mission 6 more timeline sets were required together with rare additions of individual timelines (Table 9). Usually the different timeline sets contained the timelines for the same orbit phases. However, because of the handling of timelines in the SCIAMACHY-FOCC interface (AD [8]), existing timeline IDs and sub-IDs (AD [4]) could not be overwritten such that only new timeline sets avoided excessive timeline exchange activities while maintaining a clear structure in the on-board timeline store.

Contrary to engineering parameters, measurement parameters and timelines were always updated via MCMD. Whenever needed, parameter tables with modified parameter settings or new timelines were translated by SOST to the CTI table format and submitted to FOCC via the ssh interface for inclusion into the corresponding command databases or further transfer to ESRIN (AD [7],[8]). Each submission was supplemented by a *ROP_checklist* file which was used for administration of the CTIs on FOCC side.

State ID	State	Type	Remark
1 - 7	nadir 960 km swath	S	all orbital positions
8, 26, 46, 63, 67	dark current	C	pointing at 250 km
9 - 15	nadir 120 km swath	S	all orbital positions
16	NDF monitoring, NDF out	M	
17 - 21	sun ASM diffuser	C	Sun above atmosphere
22	sun ASM diffuser atmosphere	M	various azimuth angles
23 - 25, 42 - 45	nadir pointing	S	all orbital positions
27	limb mesosphere	S	scanning 150 - 80 km
28 - 33	limb 960 km swath	S	all orbital positions
34 - 37, 40, 41	limb no swath	S	all orbital positions
38	nadir pointing left	M	
39	dark current Hot Mode	C	
47	SO&C scanning/pointing	S, C	Sun through / above atmosphere
48	NDF monitoring, NDF in	M	
49	SO&C nominal scanning, long duration	S, C	Sun through / above atmosphere
50	SO&C fast sweep scanning	C	
51	SO&C pointing	S, C	Sun through / above atmosphere
52	sun ESM diffuser, NDF out	C	Sun above atmosphere
53	sub-solar pointing	C	
54	moon nominal scanning	C	Moon above atmosphere
55	Moon pointing troposphere	S, C	Moon through atmosphere
	limb_mesosphere_lower_thermosphere*	S*	scanning 150 - 60 km
56	moon pointing	S, C	Moon through atmosphere
57	moon pointing, long duration	S, C	Moon through / above atmosphere
58	sub-solar pointing/nominal scanning	C	
59	SLS	C	
60	sub-solar fast sweep scanning	C	
61	WLS	C	
62	sun ESM diffuser, NDF in	C	Sun above atmosphere
64	sun extra mirror pointing	C	Sun above atmosphere
65	ADC, scanner maintenance	C	
66	sun extra mirror nominal scanning	C	Sun above atmosphere
68	sun extra mirror fast sweep scanning	C	Sun above atmosphere
69	SLS ESM diffuser	C	
70	WLS ESM diffuser	C	

* functionality at mission end

Table 7: Measurement state definition at start of routine phase of mission (S = science, C = calibration, M = monitoring). The functionality of state 55 was changed during the mission (details see text).

Date	Operation Change Request	Affected Tables
15 Dec 2002	n.a. (start routine operations)	all new
10 Mar 2003	reduce moon occultation PET (OCR_01)	Pixel Exposure Time (PET)
08 Apr 2003	change nadir scan (OCR_02)	Basic Scan Profile, Relative Scan Profile
26 May 2003	change limb dark tangent height (OCR_08)	Scanner State, Basic Scan Profile
21 Jul 2003	revise calibration dark states (OCR_07)	PET, Co-adding, Hot Mode
15 Oct 2003	improve limb/nadir matching (OCR_11)	Scanner State, State Duration
06 Sep 2004	increase signal at high latitudes (OCR_17)	Scanner State, State Duration, Co-adding, PET
03 Nov 2008	implement mesosphere / lower thermosphere (OCR_36)	Scanner State, State Duration, State Index, PET, Basic Scan Profile
16 Jun 2010	improve dark current PET / co-adding (OCR_43)	PET, Co-adding
10 Aug 2010	change channel 3 cluster 16/18 integration times (OCR_47)	Co-adding
27 Oct 2010	Configure SCIAMACHY for mission extension orbit (OCR_48)	Scanner State, State Duration, Basic Scan Profile, Relative Scan Profile
10 Jan 2011	Adjust tangent heights for mission extension orbits (OCR_50)	Basic Scan Profile

Table 8: Permanent modifications of the state final flight configuration and associated Operation Change Requests.

Date	Operation Change Request	Affected Timelines
15 Dec 2002	n.a. (start routine operations)	all new (set 25)
04 Apr 2003	harmonise monthly dark signal calibration orbits (OCR_05) & increase number of dark current blocks in eclipse	44, 53, 54, 58, 59, 60, 61, 62
13 Jul 2003	perform WLS over diffuser in eclipse only (OCR_10)	60, 61, 62
15 Oct 2003	improve limb/nadir matching (OCR_11)	all (set 31)
22 May 2004	improving limb/nadir matching (OCR_12)	all (set 32)
06 Sep 2004	increase signal at high latitudes (OCR_17) & replace eclipse_nadir by limb_mesosphere measurements (OCR_19)	all (set 33)
01 Oct 2006	Increase rate of subsolar pointing measurements (OCR_29)	all (set 34)
03 Nov 2008	Implement mesosphere / lower thermosphere (OCR_36)	all (set 35)
27 Oct 2010	Configure SCIAMACHY for mission extension orbit (OCR_48)	all (set 36)
12 Jan 2012	Increase rate of monitoring measurements (OCR_52)	61, 62

Table 9: Permanent modifications of the timeline final flight configuration and associated Operation Change Requests.

Operation Change Requests

Since SOST kept final flight configurations under strict configuration control, the formal process of an *Operation Change Request (OCR)* was necessary whenever changes to either the mission scenario, state or timeline final flight configuration had to be made. This applied to both temporary and permanent changes. OCR implementation was a sequential process between the author of the OCR, the SSAG approving/disapproving the OCR from a science point of view, SOST analysing and finally implementing the OCR and the AOP agency giving the formal approval. During the mission the OCR mechanism had proven successful. It permitted the handling of rather different requests – from changing only a single measurement parameter to achieve better retrieval results to complex modifications such as adapting SCIAMACHY to measurements from a lower ENVISAT orbit or even observing an extraterrestrial target such as planet Venus.

From January 2003 to April 2012 50 OCRs had been successfully implemented in total (Fig. 8 and Table 10). Two more OCRs had been prepared for being executed in May and June 2012 but could not be scheduled anymore. On average about 5-6 OCRs had to be processed each year.

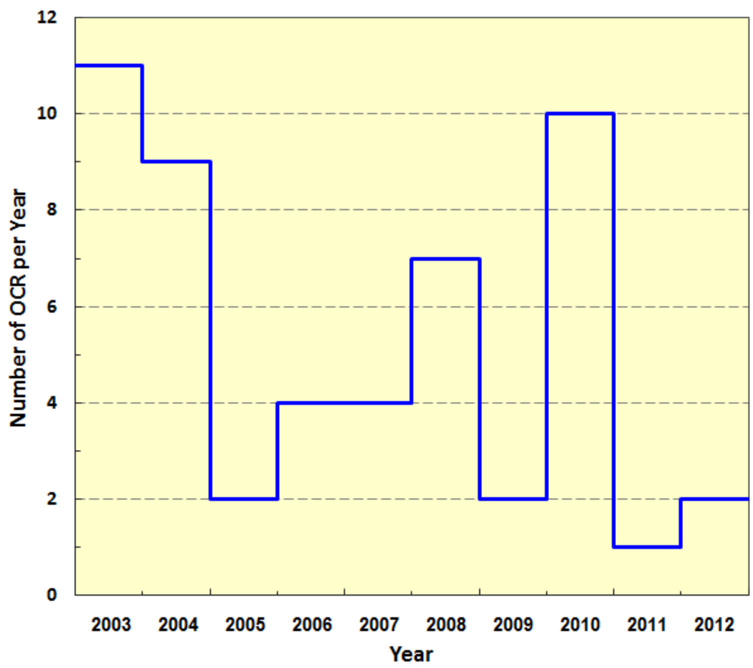


Fig. 8: OCRs submitted between 2003 and 2012.

OCR_ID	Date Start	Date Stop	Orbit Start	Orbit Stop	OCR_Type
OCR_01	10-03-2003	n.a.	5358	n.a.	permanent
OCR_02 test	31-03-2003	08-04-2003	5656	5770	temporary
OCR_02	08-04-2003	n.a.	5771	n.a.	permanent
OCR_03	30-04-2003	01-05-2003	6091	6109	temporary
OCR_05	04-04-2003	n.a.	5711	n.a.	permanent
OCR_06	04-04-2003	n.a.	5711	n.a.	permanent
OCR_07	21-07-2003	n.a.	7267	n.a.	permanent
OCR_08 part 1	26-05-2003	n.a.	6456	n.a.	permanent
OCR_08 part 2	21-07-2003	n.a.	7265	n.a.	permanent
OCR_09*	17-06-2003	17-06-2003	6778	6779	temporary
OCR_09	16-07-2003	16-07-2003	7193	7194	temporary
OCR_10	13-07-2003	13-07-2003	7153	7154	temporary
OCR_11 test*	16-08-2003	18-08-2003	7633	7660	temporary
OCR_11 test*	01-09-2003	03-09-2003	7862	7889	temporary
OCR_11	15-10-2003	n.a.	8489	n.a.	permanent
OCR_12 test	15-04-2004	16-04-2004	11108	11135	temporary
OCR_12	22-05-2004	n.a.	11638	n.a.	permanent
OCR_13 part 1	10-08-2004	10-08-2004	12782	12795	temporary
OCR_13 part 2	12-01-2005	12-01-2005	15002	15015	temporary
OCR_14 part 1	22-03-2004	22-03-2004	10767	10783	temporary
OCR_14 part 2	24-03-2004	24-03-2004	10797	10810	temporary
OCR_16 test	19-04-2004	19-04-2004	11168	11172	temporary
OCR_16	08-06-2004	08-06-2004	11880	11889	temporary
OCR_17 test	23-07-2004	24-07-2004	12525	12552	temporary
OCR_17	06-09-2004	n.a.	13172	n.a.	permanent
OCR_18	14-09-2004	n.a.	13291	n.a.	permanent

* OCR execution failed

Table 10: OCRs issued and implemented 2003-2012.

OCR_ID	Date Start	Date Stop	Orbit Start	Orbit Stop	OCR_Type
OCR_19	06-09-2004	n.a.	13172	n.a.	permanent
OCR_20	02-08-2004	09-08-2004	12672	12772	temporary
OCR_21	15-01-2005	n.a.	15054	n.a.	permanent
OCR_22	29-01-2005	23-02-2005	15244	15602	temporary
OCR_23	08-05-2005	30-06-2005	16667	17425	temporary
OCR_24	19-03-2006	15-04-2006	21175	21567	temporary
OCR_25 part 1	06-07-2006	12-07-2006	22734	22821	temporary
OCR_25 part 2	04-08-2006	10-08-2006	23158	23236	temporary
OCR_25 part 3	03-09-2006	08-09-2006	23575	23655	temporary
OCR_25 part 4	02-10-2006	08-10-2006	23994	24076	temporary
OCR_25 part 5	01-11-2006	05-11-2006	24420	24481	temporary
OCR_26	01-10-2006	n.a.	23978	n.a.	permanent
OCR_27	10-10-2006	n.a.	23978	n.a.	permanent
OCR_28	01-09-2006	27-09-2006	23552	23924	temporary
OCR_29	17-04-2007	18-04-2007	26812	26833	temporary
OCR_30*	30-07-2007	31-07-2007	28304	28325	temporary
OCR_30	08-08-2007	09-08-2007	28433	28454	temporary
OCR_31 part 1	11-09-2007	11-09-2007	28917	28920	temporary
OCR_31 part 2	23-01-2008	24-01-2008	30836	30849	temporary
OCR_32	04-11-2007	25-11-2007	29687	29987	temporary
OCR_33	30-06-2008	14-07-2008	33108	33309	temporary
OCR_34	13-05-2008	30-06-2008	32428	33115	temporary
OCR_35	20-04-2008	17-05-2008	32092	32492	temporary
OCR_36 test 1	26-07-2008	26-07-2008	33481	33494	temporary
OCR_36 test 2	24-09-2008	24-09-2008	34339	34353	temporary
OCR_36 test 3	24-10-2008	25-10-2008	34769	34783	temporary
OCR_36	03-11-2008	n.a.	34922	n.a.	permanent

* OCR execution failed

Table 10 (continued): OCRs issued and implemented 2003-2012.

OCR_ID	Date Start	Date Stop	Orbit Start	Orbit Stop	OCR_Type
OCR_37 test	20-03-2009	20-03-2009	36873	36876	temporary
OCR_37	25-06-2009	25-06-2009	38261	38266	temporary
OCR_38	14-12-2008	14-12-2008	35499	35505	temporary
OCR_39	04-11-2008	03-12-2008	34940	35341	temporary
OCR_40	09-06-2009	18-07-2009	38038	38596	temporary
OCR_41	01-10-2009	31-10-2009	39664	40106	temporary
OCR_42	01-04-2010	15-05-2010	42269	42913	temporary
OCR_43	16-06-2010	n.a.	43362	n.a.	permanent
OCR_44 part 1	06-08-2010	06-08-2010	44091	44093	temporary
OCR_44 part 2*	09-08-2010	09-08-2010	44134	44136*	temporary
OCR_44 part 2	10-08-2010	10-08-2010	44149	44150	temporary
OCR_45 part 1	19-08-2010	23-08-2010	44275	44339	temporary
OCR_45 part 2	25-08-2010	25-08-2010	44360	44368	temporary
OCR_46	12-06-2010	31-07-2010	43306	44015	temporary
OCR_47	10-08-2010	n.a.	44151	n.a.	permanent
OCR_48	27-10-2010	n.a.	45261	n.a.	permanent
OCR_49	08-12-2010	08-12-2010	45865	45868	temporary
OCR_50	10-01-2011	n.a.	46340	n.a.	permanent
OCR_51 part 1	05-05-2011	05-05-2011	47994	47999	temporary
OCR_51 part 2	10-05-2011	10-05-2011	48069	48074	temporary
OCR_52 part 1	01-01-2012	n.a.	51463	n.a.	permanent
OCR_52 part 2	09-01-2012	n.a.	51578	n.a.	permanent

* OCR execution failed

Table 10 (continued): OCRs issued and implemented 2003-2012.

4.2.3 ENVISAT Mission Extension with Orbit Change

Since April 4, 2002 (orbit 486) the ENVISAT orbit had remained unchanged with mean orbital parameters as listed in Table 10 (second column). These parameters were applicable in the specified mission 5 years mission lifetime and the first phase of the mission extension lasting well into 2010. For extending the mission up to 2013 ESA had selected an approach which required lowering the orbit and introducing drifting parameters from end of October 2010 on (Table 11 third column).

SCIAMACHY as an instrument with multi-viewing capabilities was strongly dependent on the status of the Line-of-Sight (LoS) during measurements. Additionally, instrument operations were always driven by sun- and moon-fixed events along the orbit. Therefore the modification of the ENVISAT orbit had major impacts on SCIAMACHY operations. Owing to the share of responsibilities, SOST and EADS Astrium prepared the instrument for the extension phase with a modified orbit (RD [3]-[6]). This included

- analysis of the viewing conditions in the modified orbit (Sun, Moon)
- impact on state timeline definitions
- impact on timeline definitions
- impact on engineering parameters in Scanner Constants table (Kepler elements and parameters for Earth model correction)
- impact on on-board s/w (instrument yaw steering correction table and potential hard s/w limits)

	Nominal Orbit	Mission Extension Orbit (October 2010)	Remark (Mission Extension Orbit)
Semi-major Axis	7159.496 km	7142.146 km	Drifting with a rate of -64 m/year
Orbital Period	6035.928 sec	6014.036 sec	Drifting with a rate of -0.087 sec/year
Inclination	98.549°	98.537°	Drifting with a rate of -0.46 mdeg/year
Repeat Cycle	35 days / 501 orbits	30 days / 431 orbits	n.a.
MLST	22:00:00	21:59:39	Drifting (max: 22:07, min 21:55)

Table 11: ENVISAT orbit parameters in the nominal and the mission extension orbit (as originally planned).

Scanner Control

Changing the ENVISAT orbit parameters altered the SCIAMACHY scan trajectories of the Instantaneous Field of View (IFoV). Therefore it affected the control system of both scanners. The corresponding engineering parameters to be updated were

- semi-major axis a_0
- inclination i_0
- number of orbits per day N_{ref}
- mean tangent length $l_{t,obs}$ (from spacecraft to Earth's horizon)

- mean elevation angle $\varphi_{t,obs}$ (of Earth's horizon)

The first three parameters referred to the mean Kepler elements of the ENVISAT orbit, i.e. the reference orbit with a 35 day / 501 orbits repeat cycle in the nominal phase and the slowly drifting orbit in the mission extension phase from October 2010 onwards. The final two elements were used in the framework of the Earth model correction for computing the polar and equatorial radius of the observation reference ellipsoid, which describes the observation altitude above the reference Earth model (Table 12).

Since semi-major axis and inclination were specified with rather tight orbital tolerances of ± 68 m and ± 0.009°, the larger drifts in both parameters over the mission extension period necessitated to update them on-board at regular intervals over the entire planned mission extension phase. For the semi-major axis 2 additional updates were required separated by 475 days while for the inclination this even had to occur every 59 days. In order to ensure that the remaining 3 parameters match the regularly updated semi-major axis, these were modified as well with the same rate of 475 days.

	Nominal Orbit	**Start Extension (October 2010)**
Tangent length $l_{t,obs}$ (km)	3290.000	3252.940
Elevation angle $\varphi_{t,obs}$ (rad)	4.239098	4.241683
Elevation angle $\varphi_{t,obs}$ (°)	242.882	243.031

Table 12: Mean tangent length and elevation angle of nominal ENVISAT orbit together with modified orbit at start of mission extension phase.

Measurement Parameters

The modifications of azimuth/elevation angles due to the change in orbit altitude affected only the Basic Scan Profile table. Of the 15 basic profiles 5 addressing constant altitudes required adapting the elevation angles. All other measurement parameter updates resulted from maintaining the quality of the limb/nadir matching.

Limb/Nadir Matching

The matching of the geolocation of limb states with associated nadir states was a major scientific requirement for SCIAMACHY operations. It had an across-track and an along-track aspect, both being orbit dependent. Across-track matching was ensured in the scanner control by applying the instrument yaw steering correction table, which was available on-board as a look-up table with 1° orbital increments. This procedure corrected for the angular shift resulting from ENVISAT's Stellar Yaw Steering Mode (SYSM), which compensated for the Earth velocity vector at the subsatellite point, and the fact that the limb LoS intersected the Earth's atmosphere 3290 km ahead of the subsatellite point. Since the platform yaw steering model of the nominal mission phase was maintained in the mission extension orbit, the instrument yaw steering correction table for the nominal orbit turned out to be also applicable in the mission extension orbit. However adaption of the limb across-track extent due to the smaller swath width of 933 km (954 km in the nominal orbit) for an orbit with a reduced mean altitude of 782.4 km had to be implemented. It occurred via updating the Relative Scan Profile table.

For the along-track limb/nadir matching the lower orbit caused the limb tangent LoS to be shorter by about 35-40 km, i.e. the limb tangent points would have fallen no longer into the centre but in the first phase of the corresponding nadir pixel. By shortening the limb measurements by one horizontal scan (1.6875 sec) a perfect central matching could be achieved again. In order to maintain the final scan altitude at 93 km, it had been additionally decided to raise the first horizontal limb scan from -3 km to 0 km. All these modifications required changing the Scanner State and State Duration tables. Because all limb states had thus been altered, a new timeline set needed to be generated and uploaded.

Operations Performance in Modified Orbit

All inputs for ENVISAT flight operations – CTI parameter tables according to OCR_48, timeline set 36, SOR_39 – were transferred to FOCC using the operational interfaces as outlined above. Once uploaded, SCIAMACHY was finally ready to continue measurements on October 27, 2010 (orbit 45262). Up to November 2, 2012 the platform operated in Yaw Steering Mode (YSM) instead of the more precise Stellar Yaw Steering Mode (SYSM), i.e. in that period the LoS performance of SCIAMACHY was slightly reduced.

A direct impact of the orbit lowering on instrument performance was found only for the LoS tangent heights in limb states. The start/stop altitudes as specified could not be fully accomplished. What caused these small deviations was not fully understood. We suspected that they were related to a correction function in a particular scanner control algorithm (Fig. 9-11). However applying small Δ-elevation angles – equivalent to the required Δ-altitudes – to the corresponding entries in the Basic Scan Profile table solved the issue (OCR_49, OCR_50).

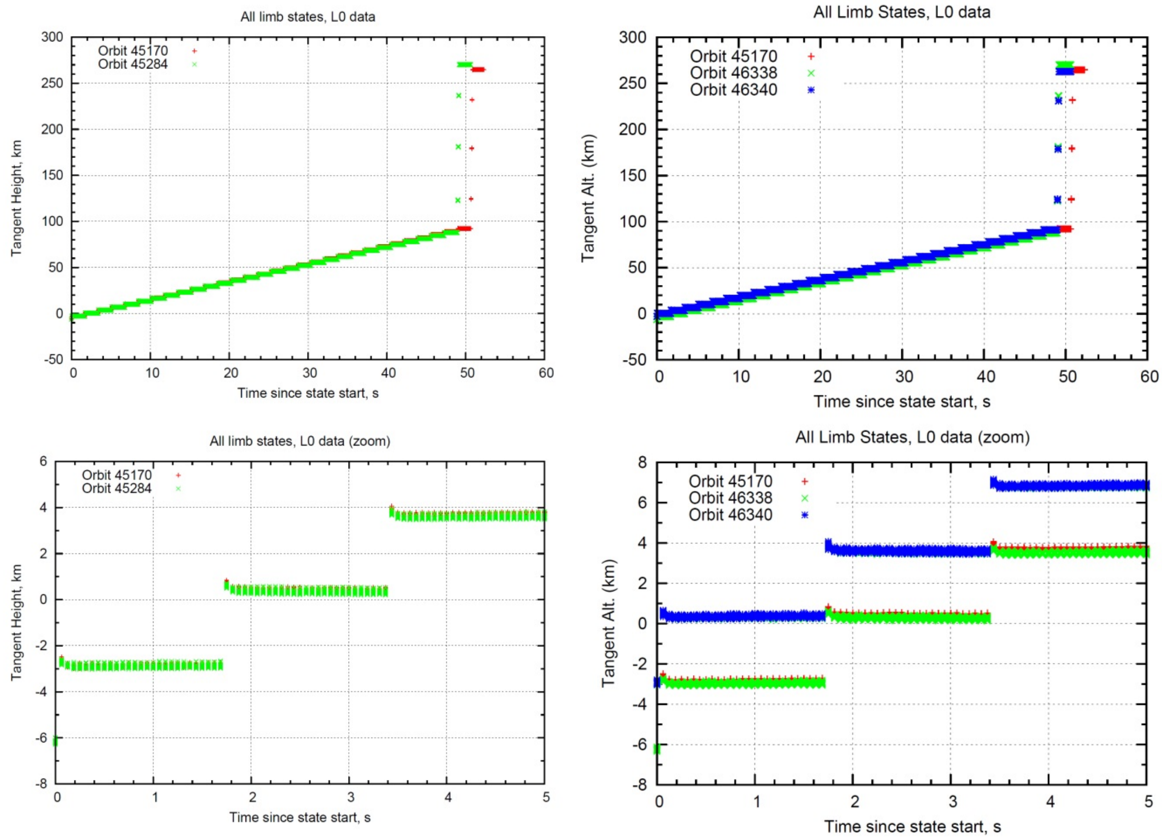


Fig. 9: Tangent heights for all limb states in an orbit from the nominal mission phase (orbit 45170) and the mission extension phase (orbit 45284) using the Basic Scan Profile settings as loaded with OCR_48 (left panels). The right panels show the tangent heights after the Basic Scan Profile table adjustment in January 2011 (OCR_50). The blue data points (orbit 46340) correspond to the accepted final flight configuration for the mission extension phase and indicate that the first horizontal scan achieved an altitude of 0 km instead of -3 km. Two orbits before the adjustment (orbit 46338) the still incorrect scan altitudes were still obvious.

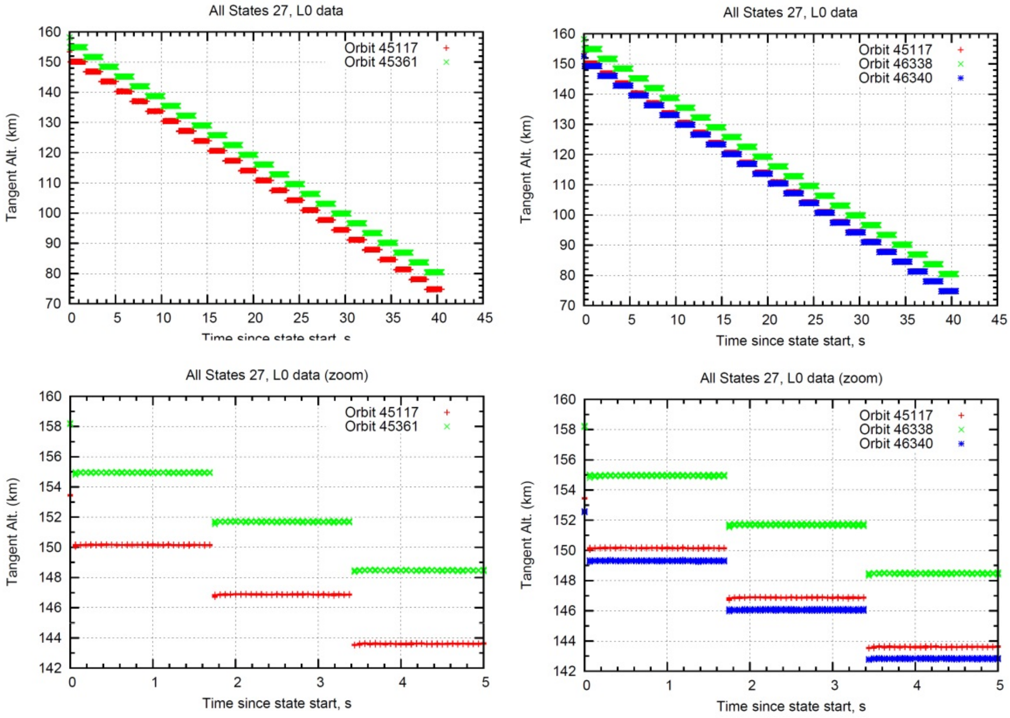


Fig. 10: Same as Fig. 9 but for the limb_mesosphere state executing a downward sequence of horizontal scans with a final dark current pointing. The blue data points demonstrate that state 27 executed horizontal scans with a starting altitude in agreement with the nominal orbit.

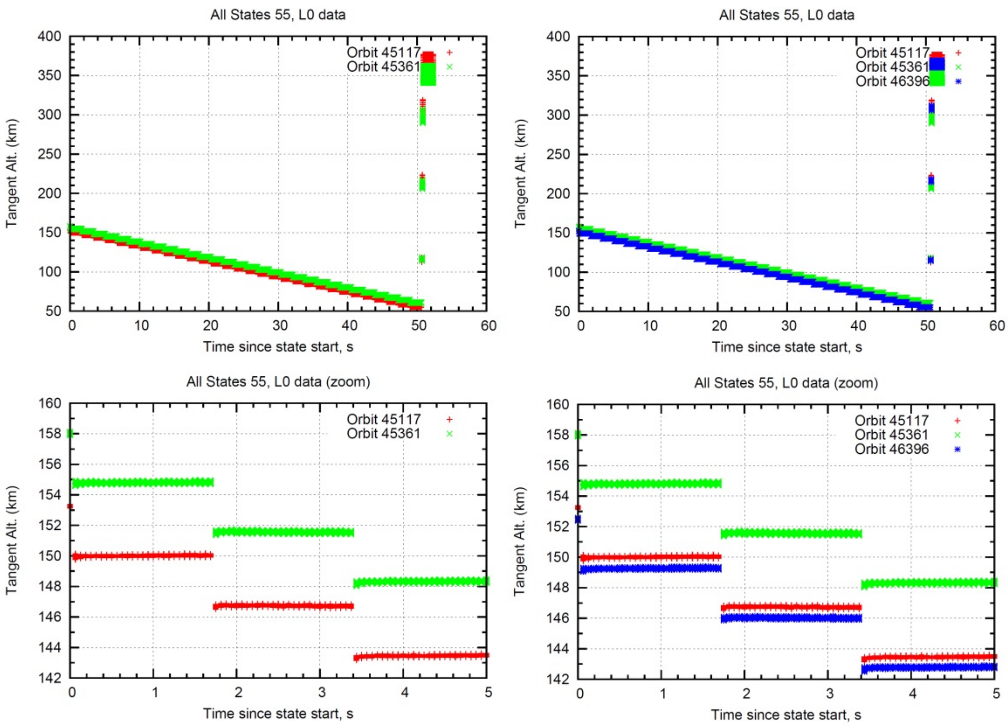


Fig. 11: Same as Fig. 9 but for the limb_mesosphere_thermosphere state. Again, the blue data points show that state 55 executes horizontal scans identical to the measurements in the nominal orbit.

Verification of the limb nadir matching occurred by analyzing the geolocation (longitude/latitude) of the corner points of limb and nadir ground pixels in an orbit. For the nadir state the length of a ground pixel was defined by the start/stop times of state execution (along-track) and the width by the left/right positions of the ESM scanner motion (across-track). Similarly the limb ground pixel width corresponded to the left/right position of the horizontal ASM scanner motion (across-track) while the length of the pixel was defined by the geolocation of the LoS tangent heights at the start and stop of the state. It could be verified that the shortening of the limb states by one horizontal scan maintained the limb/nadir along-track performance as expected. Also the across-track coverage had remained unchanged (Fig. 12).

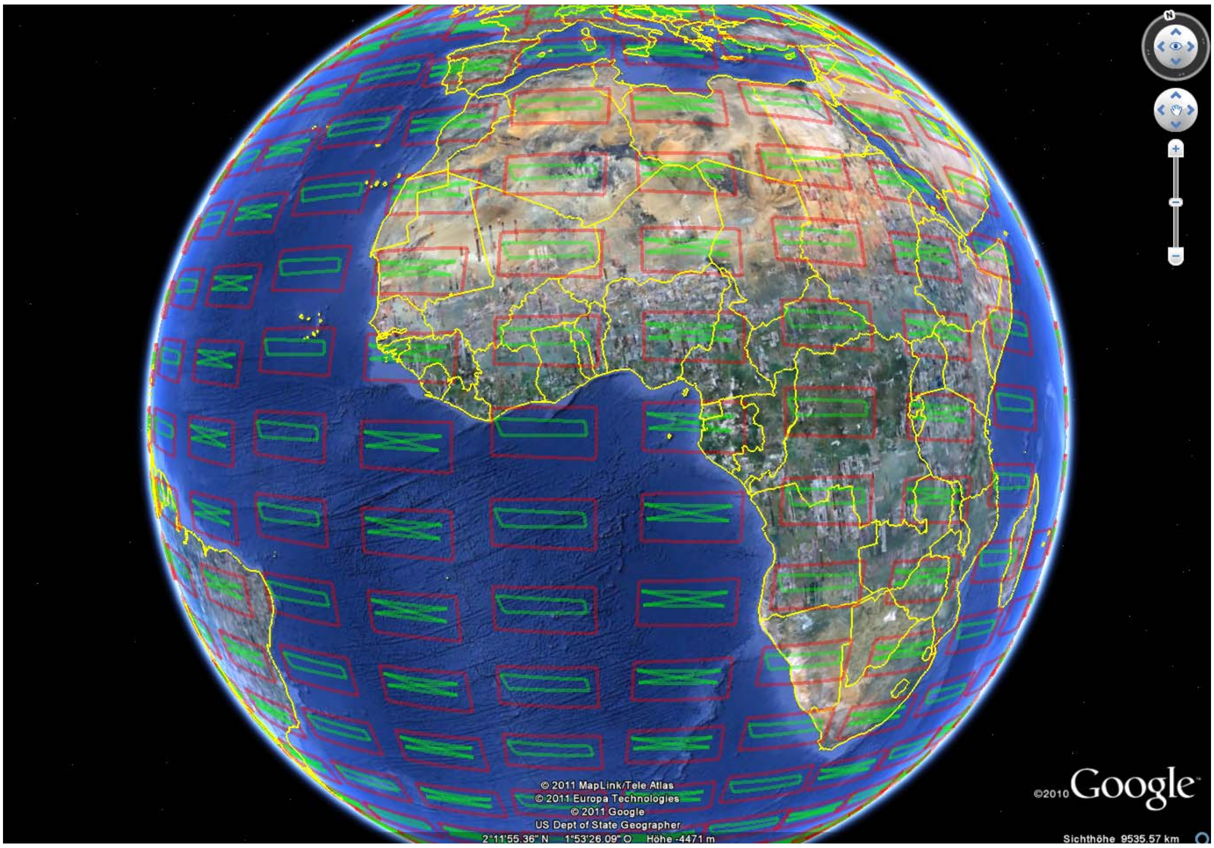


Fig. 12: Matching of limb (green symbols) and nadir (red boxes) before and after the ENVISAT orbit manoeuvre. The green boxes are from October 10, 2010, the hourglass shaped symbols from October 27, 2010.

In the other areas of SCIAMACHY operations and instrument performance, i.e. thermal subsystem status including ATC and TC, scanners and optical properties including optical throughput, dark current and Dead and Bad Pixel Mask (DBPM), no impact of the orbit lowering on instrument performance had been found. It was another promising proof of the flexible SCIAMACHY operations concept, particularly when considering the – then – planned yearlong mission extension.

5. Mission Planning

Mission planning was a joint undertaking with SOST preparing the measurement plan (Orbit Sequence Definition File – OSDF) while ESRIN verified and integrated this plan into the overall ENVISAT plan (Reference Operations Plan using the ROP Generation Tool – RGT) and finally FOCC generated the ENVISAT schedule (Detailed Mission Operations Plan – DMOP). It included all platform and payload activities which were executed via MCMD. SOST then extracted from the ENVISAT schedule the SCIAMACHY specific part (SCIAMACHY DMOP – SDMOP). All planning on SOST side was based on ENVISAT reference orbit and relied on the current versions of the ESA provided ENVISAT CFIs (Customer Furnished Item) for e.g. orbit propagation and target visibility and the orbit definition as specified in the ESA provided Reference_Orbit_Event file (*MPL_ORB_EVVRGT*). The reference orbit differed from the predicted and finally executed orbit (restituted). Although the accuracy of the Mean Local Solar Time (MLST) range was specified with ± 5 min, the actually achieved time difference was much smaller. SOST monitored the difference between reference ANX time and predicted ANX time, which came very close to the restituted ANX time (Fig. 13). Over the entire mission, the times differed only between -10 sec to +15 sec. Of that order were also the time shifts for events along the orbit, e.g. sunrise, moonrise, subsolar event. This was uncritical for SCIAMACHY operations since the length of orbital segments, which defined the duration of timelines, remained unaffected and the on-board execution of sun- or moon-fixed timelines always used the actual times.

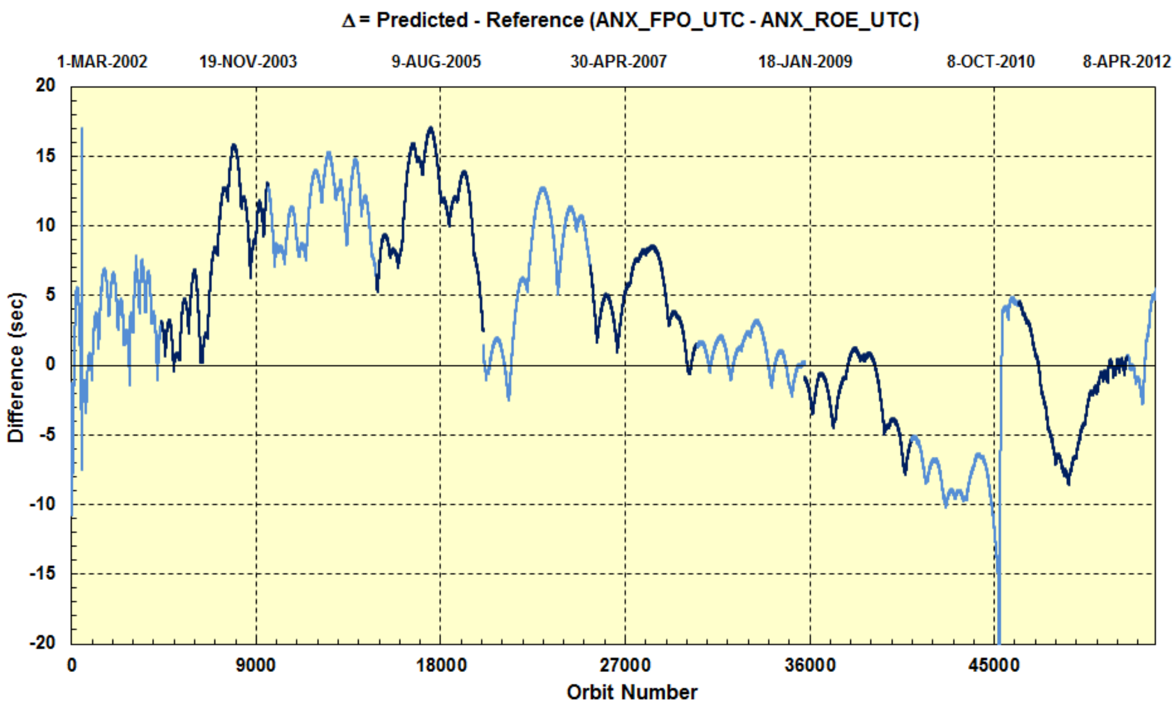


Fig. 13: ANX time difference between reference orbit and predicted orbit. At each discontinuity an orbit manoeuvre occurred for orbit maintenance. The value at about orbit 45000 goes off-scale and relates to the orbit change manoeuvre in October 2010.

5.1 Subsolar Calibration Opportunities

In subolar measurements, the NCWM opened the 'subsolar window' for the duration of the measurement providing a left-upward (relative to flight direction) looking viewing geometry for observations of the Sun when it had reached highest elevation each orbit. The 'subsolar window' was adjacent to the Ka-band antenna which ensured ground links via the Artemis relay satellite. Deploying the antenna dish in operating position caused vignetting of SCIAMACHY's sub-solar window (Fig. 14). In order to avoid conflicts, three orbits per day were reserved for subsolar observations. In each of those, a 950 sec long segment around the equator allowed scheduling the execution of a subsolar state because the Ka-band antenna was stowed in a dedicated parking position for this period. The three orbits, always crossing the eastern to central Pacific Ocean (Fig. 15), had been selected because Artemis was out-of-view for ENVISAT for the specified time. The subsolar calibration opportunities had been regularly derived by RGT and submitted to SOST via the Subsolar Calibration Opportunity file (*SSC_SHVRGT*).

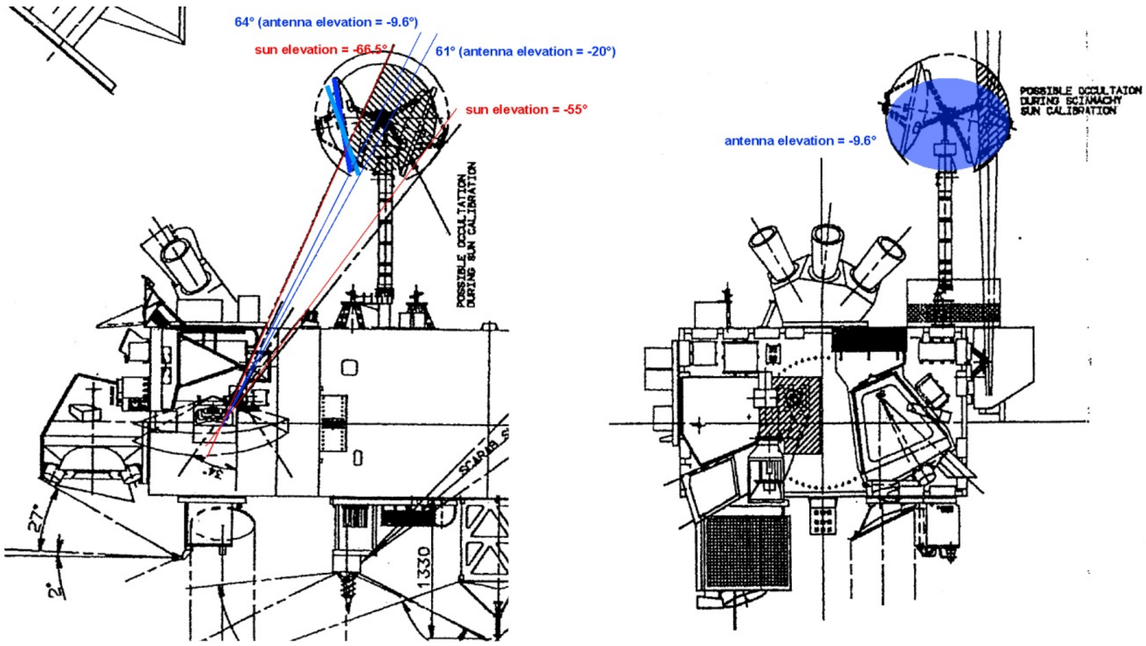


Fig. 14: Sketch of SCIAMACHY's view through the subsolar port (red lines) and the location of the Ka-band antenna. When rotating the dish (blue), the SCIAMACHY LoS can become vignetted.

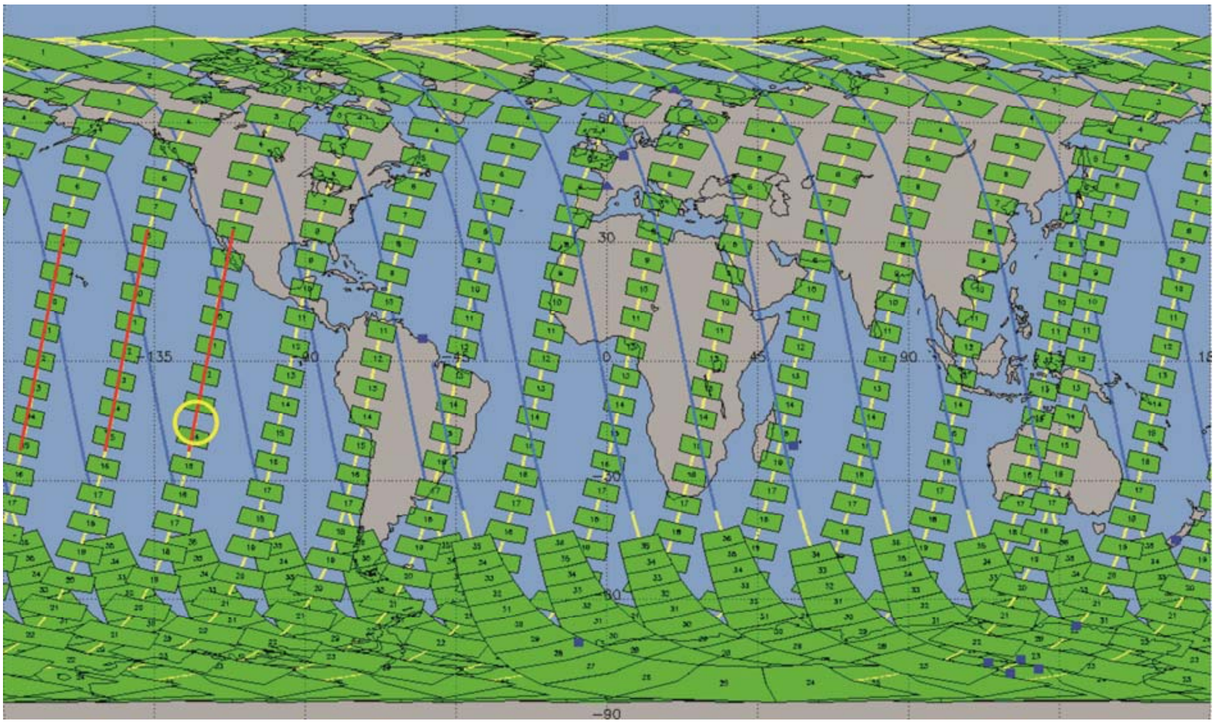


Fig. 15: One day of SCIAMACHY nadir measurements on January 17, 2012. The three orbits with subsolar calibration opportunities (orbit 51693, 51694, 51695) are indicated on the left with the slightly longer gap between two adjacent states in the first opportunity (yellow circle) indicating the execution of the 28 sec long subsolar state. The red bars display the orbital segment assigned for potential subsolar observations.

The SSCO mission planning interface worked as expected. Only in the cases listed below the Ka-band antenna blocked subsolar measurements. The first occasions happened early in the Commissioning Phase and routine operations phase and were due to not yet fully established operational procedures. Another period with blocking of the subsolar port occurred from May 30, 2007 (orbit 27436) to June 19, 2007 (orbit 27722). The cause could be tracked down to an earlier anomaly of the Antenna Pointing Controller (APC) in September 2006. After this event a new parking position for improving the solar illumination had been required. Over a year the Sun moves about 12° in elevation through the subsolar TCFoV. In May 2007, at its highest elevation (= smallest zenith distance around May/June) it had disappeared behind the Ka-band antenna dish in the new parking position. Since then, each year SOST informed FOCC about when obscuration can be expected. In that period, for the time of the subsolar measurement, the Ka-band antenna was specifically stowed to avoid vignetting. Only two Ka-band antenna blocking events had occurred after implementing this procedure. The first time occurred on October 27, 2010 when ENVISAT had returned to nominal operations after the orbit lowering manoeuvre (antenna was not parked due to MPS problem) and the second time in 2011 when for the two final orbits of the window the original parking position had been selected.

5.2 Orbit Sequence Definition File

The OSDF was SCIAMACHY's central planning document. It listed for a specified period, in routine operations usually 1-2 months, the sequence of timelines to be executed each orbit together with the timeline on-board configuration applicable for the start of the OSDF. In addition, timeline exchange records provided ENVISAT's mission planning system (MPS) with information when to exchange which timeline on-board. The on-board timeline table was limited to 63 entries while on-ground a timeline set consisted of about 100 timelines. The higher number was mainly the result of the very variable durations of moon related orbit segments. In the 7 days of a monthly lunar window, moon-fixed timelines were sometimes needed which differed by about 1400 sec in length.

In the Commissioning Phase more than 40 OSDFs were required, some only a few orbits long. Once the routine operations phase had progressed, the number of OSDFs generated each year amounted to less than 10 (Fig. 16).

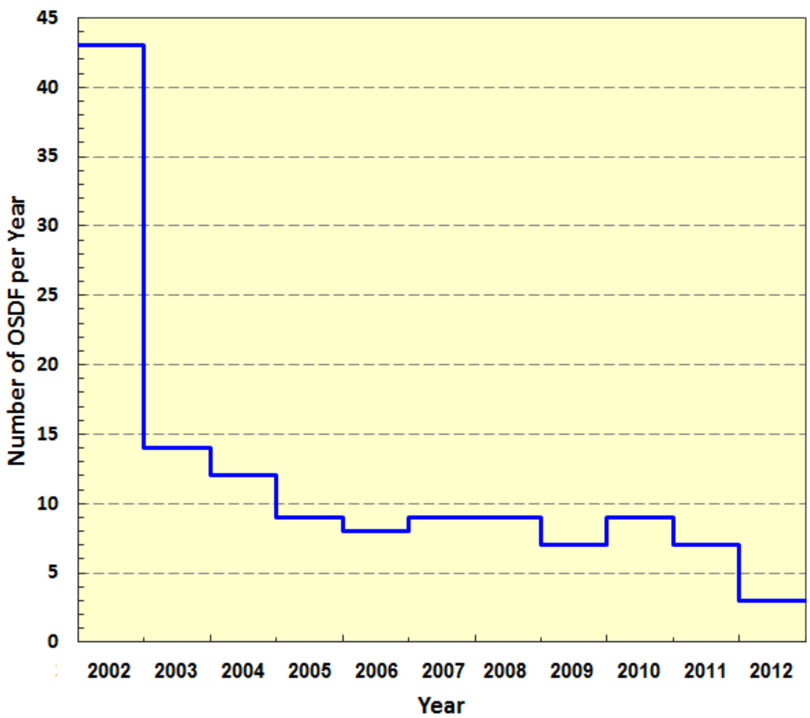


Fig. 16: OSDFs required for mission planning between 2002 and 2012.

All OSDFs submitted to RGT never caused a scheduling mismatch, e.g. overlapping timelines or non-existent timeline versions. Only twice RGT could not process the provided OSDF as expected. This was due to a format failure in the timeline exchange records in one case and a short piece of s/w code in the SCIAMACHY part of the RGT which had not been updated to reflect the modified ENVISAT orbit.

5.3 Detailed Mission Operation Plan

The DMOP generated at FOCC contained for SCIAMACHY all activities which could be handled by the MPS. These were all related to measurement execution such as

- timeline start/stop with timeline duration
- high data rate on/off with duration of high rate data generation
- parameter CTI table uploads according to the validity start time specified in the CTI file
- timeline uploads according to the exchange orbit specified in the OSDF

with the corresponding times (UTC and time elapsed since ANX). The DMOP entries triggered the actual commanding of the instrument for such particular cases. SOST extracted the above listed events from the ENVISAT DMOP to form the SCIAMACHY DMOP (SDMOP). This was an ASCII file covering the same period as the DMOP, typically 2 days, with the scheduling information provided in a user friendly manner. The goal was to provide the SDMOP via the SOST website, throughout the mission, to mission participants for having immediate knowledge about the measurement schedule.

For having full insight into the scheduling, SOST operated its own scheduler. It was developed applying the same scheduling rules as the ENVISAT MPS, but was limited to timeline start/stop and high data rate on/off. Orbit propagation and Sun/Moon target visibility utilised CFI results based on the reference orbit. Each OSDF was processed with SOST's scheduler before submission to RGT to form the simulated SDMOP (SIM_SDMOP), a schedule identical in format to the SDMOP. Successful generation of the SIM_SDMOP ensured that RGT verification would not fail and provided a reference for comparison with the individual SDMOPs. The difference in times between the SDMOP and the SIM_SDMOP was smaller than 1 sec as long as ENVISAT's orbit followed the stable 35 days / 501 orbits repeat cycle. Even when the ENVISAT orbit parameters started drifting in the modified mission extension orbit, the accuracy of the SIM_SDMOP still amounted to better than 1.5 sec on average.

In the Commissioning Phase the SIM_SDMOP was a prerequisite for executing the challenging engineering and measurement sequences. It was always available as soon as the OSDF existed, i.e. much earlier than the FOCC provided SDMOP. This permitted preparation of the FOP inputs by industry and SOST with sufficient time margin, even when short-notice replanning was required.

Additional output of the SOST scheduler comprised, for each orbit, a list of states with start/stop times, a list of all nadir states with geolocation of the ground pixel – given in longitude and latitude – at start/stop of the state and the same list for all limb states where the geolocation of the ground pixel was defined by the longitude/latitude of the tangent point at state start/stop. The nadir and limb ground pixels also appeared as separate orbital maps (Fig. 17). This scheduler functionality was particularly useful for validation campaigns when the exact time of an ENVISAT overpass at a validation site, within the accuracy of the reference orbit, was required for preparing the validation instruments.

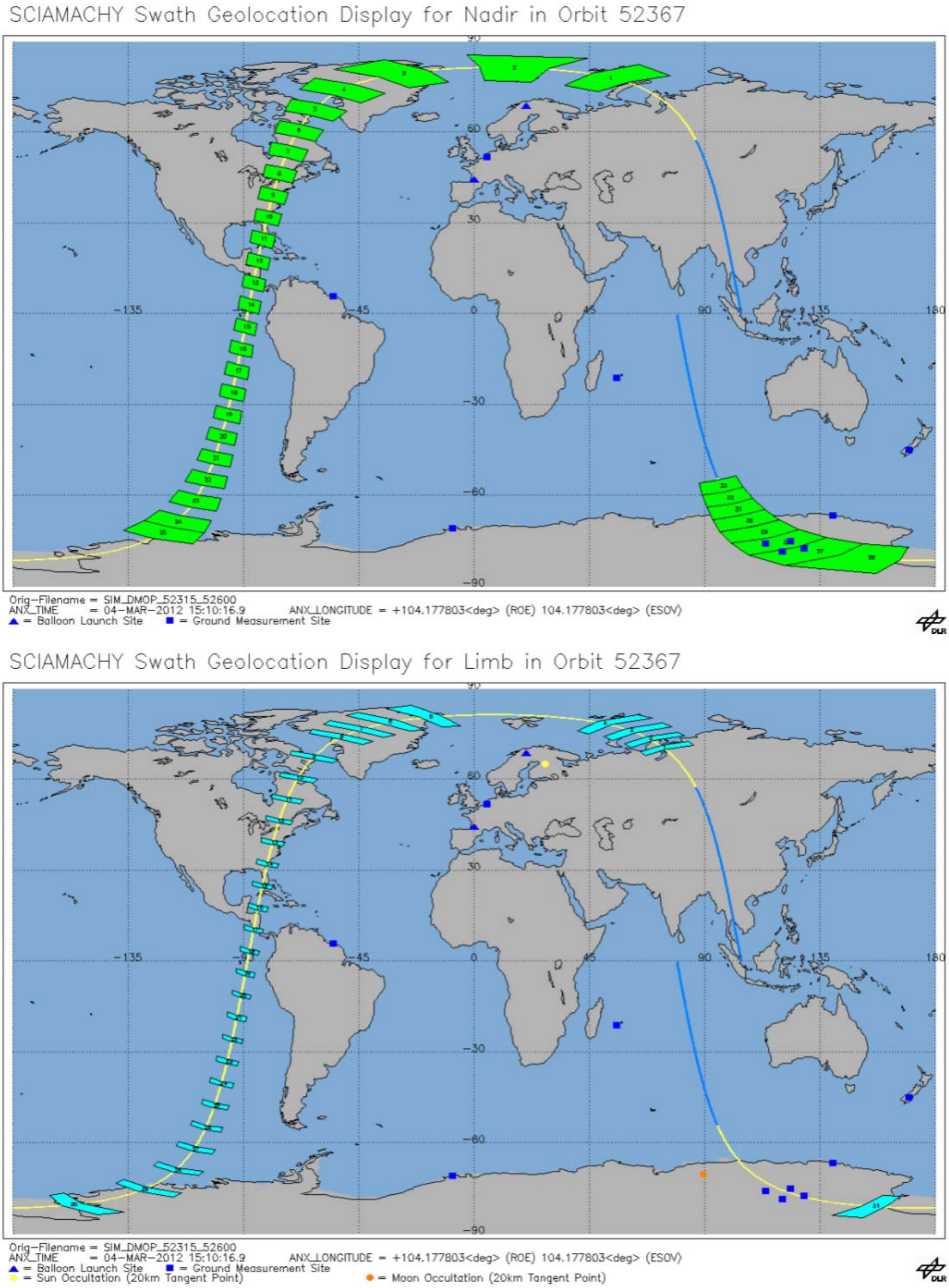


Fig. 17: Example for the nadir and limb geolocation in orbit 52367 (March 4, 2012) as derived with the SOST scheduler. In the limb graph the tangent point for solar (yellow dot in northern hemisphere) and lunar (reddish dot in southern hemisphere) occultation measurements had been indicated as well.

6. Instrument Unavailabilities

The measurement programme as planned in an OSDF was occasionally interrupted either due to anomalies on various levels or particular scheduled activities. This included

- instrument anomalies
- platform anomalies
- ground segment anomalies
- orbit control manoeuvres (OCM)
- platform maintenance
- instrument maintenance

In all cases the goal for SCIAMACHY operations was to keep the instrument unavailability period as short as possible without introducing unnecessary risks when recovering back to the nominal measurement status.

Over the entire in-orbit mission lifetime (Commissioning Phase plus routine operations phase), a total of 133[2] engineering activities / measurement interrupts had occurred. They could be classified as in Table 13.

Type	Number of Occurrences	Number of Unavailable Orbits
Instrument anomaly	63	1403
Platform anomaly	18	742
Ground Segment anomaly	13	26
OCM	31	348
Platform maintenance*	7	101
Instrument maintenance	4	40

* some platform maintenance executed in conjunction with OCMs; includes safety switch-off during 2002 Leonid meteor shower.

Table 13: SCIAMACHY unavailability statistics 2002-2012.

The period from first switch-on of the instrument in orbit 147 until the loss of the platform in orbit 52868 covered 52722 orbits in total. Only 2660 orbits (5%) could not be used for engineering activities / measurements. For only the routine operations phase, the number of unavailable orbits is reduced to 2000 orbits, i.e. 4.1%.

Fig. 18 displays the entire availability record of SCIAMACHY. Unavailabilities showed different length, but extended usually to not more than 1-4 days (Fig. 19). This is particularly true for instrument anomalies (see below), where, after having gained experience in 2002-2003, the recovery of the instrument could be accomplished in about 20 orbits on average. Platform anomalies took always a bit longer while ground segment anomalies were confined to cases affecting only a few orbits.

[2] This number only includes cases where SCIAMACHY was transferred to a mode lower than Measurement Timeline for a complete orbit. Anomalies causing loss of individual states, e.g. blocking of the subsolar window by the Ka-band antenna, are not addressed.

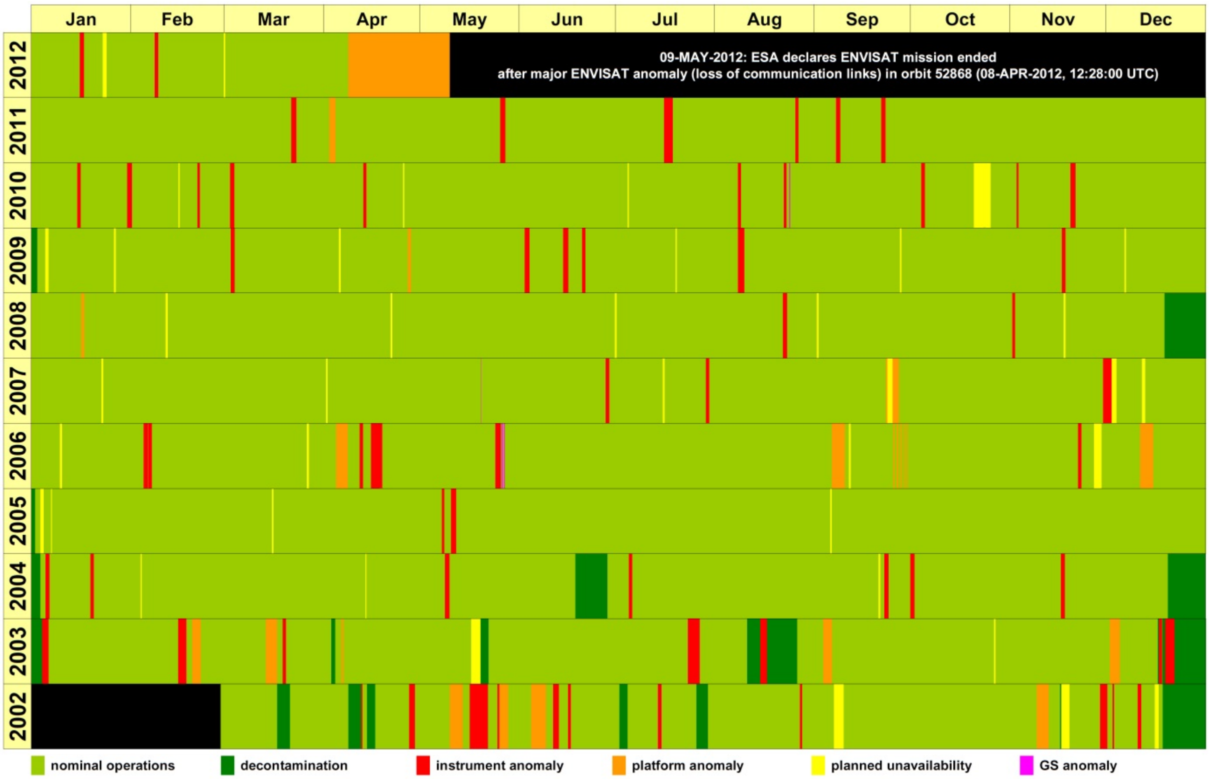


Fig. 18: SCIAMACHY availability 2002-2012.

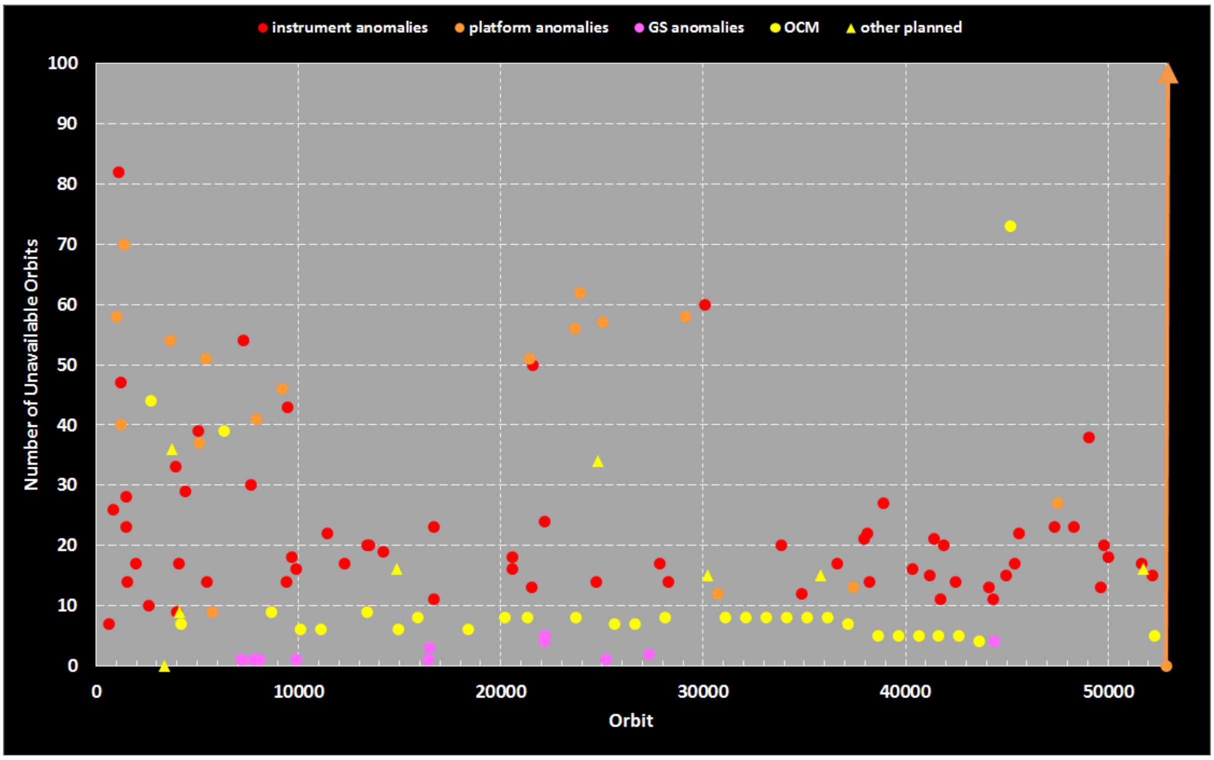


Fig. 19: Unavailable orbits as a function of anomaly type 2002-2012.

6.1 Instrument Anomalies

The response of SCIAMACHY on anomalies on instrument level was part of the autonomous on-board monitoring and control functions and specified in the IOM (AD [1]). All detected anomalies incremented the anomaly counter and caused an entry in the History Area for further verification on-ground. However not all anomalies triggered a transfer to a mode lower than Measurement. How Corrective Actions (CA), History Area entry and resulting modes were related is outlined in Table 14.

Corrective Action ID	Entry in History Area	Mode Triggered
0	Complementary Failure	continue MEASUREMENT
1	Autonomous Switching	HTR/RF
2	Autonomous Switching	STANDBY/RF-I
3	Autonomous Switching	STANDBY/RF-E
4	Autonomous Switching	R/W-WAIT
5	Autonomous Switching	OFF-FAIL
6	Autonomous Switching	STANDBY/RF-E
7	Autonomous Switching	R/W-WAIT
8	n.a.	n.a.
9	Complementary Event	continue MEASUREMENT

Table 14: Autonomous failure detection and Corrective Actions.

All events leading to a CA-1 to CA-7 sent the instrument to a Safe Mode with the need for verifying the underlying anomaly and, after successful analysis, initiating recovery back to the *Measurement* mode. Table 15 lists all such occurrences since launch. A specific aspect of the recovery was the need to establish stable thermal conditions once the instrument continued measurements. Applying the parameters *Thermal Wait* in the transition back to *Heater* mode ensured sufficient time for reaching thermal stability. For anomalies causing 'standard' downtimes, it took about 17 hours for achieving *Heater* mode. This is why the number of unavailable orbits after an instrument anomaly (Fig. 19) amounted to about 20 orbits, i.e. it comprised the time needed for anomaly detection, reacting appropriately and transiting back to *Measurement* mode.

The anomalies in Table 15 fall into four groups:

- parameter mismatches
- CCA MCMD Check Error
- Single Event Upsets (SEU)
- unidentified (all cases which could not be attributed to any of the other three types)

The first category includes 6 events with 4 occurring in the Commissioning Phase. It could always be tracked down to an error in the human/machine interface (too tight operations activities, selection of incorrect parameter values). Subsequent countermeasures in CTI parameter table generation reduced this already low figure further. In the routine operations phase this type of anomaly was well under control with only two more instances.

The second anomaly, the so-called 'CCA MCMD Check Error' was a rather persistent recurring anomaly in the Commissioning Phase and hampered SODAP activities between May and July 2002. Subsequent detailed failure analysis had led to the conclusion that a bug in the Instrument Control Unit (ICU) could temporarily block its interface to the ENVISAT Payload Management Computer, causing a transfer to a safe instrument mode lower than *Measurement*. In October 2002, a software patch had been uploaded to correct that ICU bug. It did not fully cure the problem – complete repair would have required a more extended patch – but since then the average rate of the check error was reduced drastically. In 9.5 years only 12 CCA MCMD Check Errors happened yielding a rate very close to the estimated occurrence of about 1/year.

For most anomalies, notably 30 in 10 years, no obvious cause could be identified but a spurious hang-up in the communication area, firmware or software seemed possible. Many of these were related to a 'buffer overflow' error. Only 10 anomalies could certainly be attributed to Single Event Upsets (SEU). The instrument could suffer from a SEU when high-energy particles, most likely protons, hit electronic components and switched their status information. The particle flux could increase in low-Earth orbits during phases of high solar activity in general, and when crossing the polar belts or the South Atlantic Anomaly (SAA) of the Earth's magnetic field in particular. However, no distinct pattern was found when plotting the geolocations of anomaly occurrence (longitude/latitude) onto a map. Particularly the SAA did not show up as a region with increased SEU triggered failures (Fig. 20).

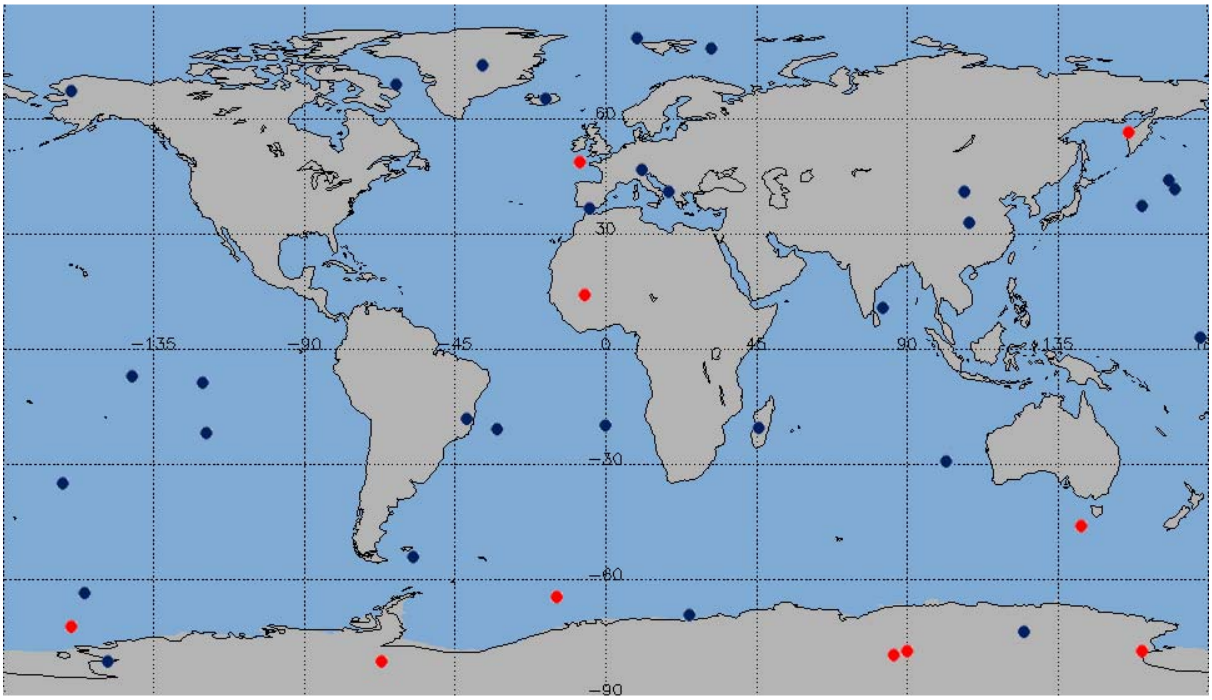


Fig. 20: Sub-satellite geolocation of ENVISAT at start of SCIAMACHY anomaly occurrences over the entire mission lifetime. Red dots illustrate SEU induced failures while blue dots indicate cases with unidentified cause.

Since the CCA MCMD Check Error, as well as some of the SEU triggered and unidentified anomalies had been analysed in detail in early phases of the mission, they were added to the pre-launch established list of 'expected failures', permitting immediate recovery at FOCC (AD [1]). This helped to shorten unavailability periods in such cases.

Date	Orbit		Orbits Lost	Transferred to	Remark
	Start	Stop			
13-Apr-2002	627	634	7	STB/RF	SRC cold stage T limit exceeding
28-Apr-2002	842	868	26	HTR/RF	Switch to dump mode
17-May-2002	1113	1195	82	R/W WAIT	CCA MCMD check error
26-May-2002	1238	1285	47	R/W WAIT	CCA MCMD check error
12-Jun-2002	1483	1511	28	HTR/RF	OB Monitor OOL
13-Jun-2002	1488	1511	23	R/W WAIT	CCA MCMD check error
17-Jun-2002	1550	1564	14	R/W WAIT	CCA MCMD check error
15-Jul-2002	1952	1969	17	R/W WAIT	CCA MCMD check error
28-Aug-2002	2586	2596	10	HTR/RF	OB Monitor OOL
30-Nov-2002	3925	3958	33	HTR/RF	Parameter mismatch
04-Dec-2002	3981	3990	9	HTR/RF	Parameter mismatch
12-Dec-2002	4093	4110	17	HTR/RF	Parameter mismatch
04-Jan-2003	4428	4457	29	HTR/RF	ASM overcurrent
15-Feb-2003	5034	5073	39	R/W WAIT	CCA MCMD check error
20-Mar-2003	5502	5516	14	R/W WAIT	CCA MCMD check error
24-Jul-2003	7309	7363	54	HTR/RF	Repeated fault OOL 0260
16-Aug-2003	7634	7664	30	HTR/RF	Parameter mismatch
18-Dec-2003	9412	9426	14	HTR/RF	MDI Process Alive Alarm
20-Dec-2003	9439	9482	43	HTR/RF	PMTC_Tx buffer overflow
05-Jan-2004	9667	9685	18	R/W WAIT	CCA MCMD check error
19-Jan-2004	9867	9883	16	HTR/RF	SDPU_Tx buffer overflow
08-May-2004	11449	11471	22	HTR/RF	Actual HSM datarate
05-Jul-2004	12269	12286	17	R/W WAIT	CCA MCMD check error
22-Sep-2004	13410	13430	20	HTR/RF	ESM overcurrent
01-Oct-2004	13526	13546	20	R/W WAIT	CCA MCMD check error
17-Nov-2004	14198	14217	19	HTR/RF	Latch-up thermal board
09-May-2005	16675	16686	11	HTR/RF	Latch-up thermal board
11-May-2005	16716	16739	23	R/W WAIT	ICU suspended
05-Feb-2006	20570	20588	18	R/W WAIT	CCA MCMD check error
06-Feb-2006	20590	20606	16	HTR/RF	PMTC_Tx buffer overflow
13-Apr-2006	21534	21547	13	HTR/RF	SDPU_Tx buffer overflow
16-Apr-2006	21584	21634	50	HTR/RF	SDPU_Tx buffer overflow
25-May-2006	22139	22163	24	HTR/RF	SDPU_Tx buffer overflow
23-Nov-2006	24740	24754	14	HTR/RF	SDPU_Tx buffer overflow
29-Jun-2007	27856	27873	17	HTR/RF	SDPU_Tx buffer overflow
30-Jul-2007	28304	28318	14	HTR/RF	Parameter mismatch
01-Dec-2007	30076	30136	60	STANDBY	PMTC_Tx buffer overflow & PMTC driver timeout & OCM with ENVISAT SM maintenance

Date	Orbit		Orbits Lost	Transferred to	Remark
	Start	Stop			
22-Aug-2008	33870	33890	20	STANDBY	SDPU HK data timeout & SDPU_Tx buffer overflow
01-Nov-2008	34894	34906	12	HTR/RF	Latch-up
04-Mrz-2009	36647	36664	17	STANDBY	PMTC Tx buffer overflow & PMTC driver timeout
03-Jun-2009	37959	37980	21	STANDBY	PMTC_Tx buffer overflow & PMTC driver timeout
15-Jun-2009	38131	38153	22	STANDBY	PMTC_Tx buffer overflow & PMTC driver timeout
21-Jun-2009	38216	38230	14	HTR/RF	SDPU Tx buffer overflow
09-Aug-2009	38911	38938	27	HTR/RF	ASM mean motor current OOL & ASM control difference OOL & ESM overcurrent OOL
18-Nov-2009	40355	40371	16	R/W WAIT	CCA MCMD check error
15-Jan-2010	41186	41201	15	STANDBY	PMTC Tx buffer overflow & PMTC driver timeout
30-Jan-2010	41409	41430	21	R/W WAIT	CCA MCMD check error
21-Feb-2010	41722	41733	11	HTR/RF	Latch-up
03-Mrz-2010	41867	41887	20	R/W WAIT	CCA MCMD check error
14-Apr-2010	42462	42476	14	R/W WAIT	CCA MCMD check error
09-Aug-2010	44135	44148	13	HTR/RF	MDI Process Alive Alarm
23-Aug-2010	44340	44351	11	HTR/RF	SDPU Tx buffer overflow
05-Okt-2010	44953	44968	15	STANDBY	PMTC Tx buffer overflow & PMTC driver timeout
04-Nov-2010	45379	45396	17	R/W WAIT	CCA MCMD check error
20-Nov-2010	45619	45641	22	R/W WAIT	CCA MCMD check error
22-Mrz-2011	47370	47393	23	STANDBY	PMTC Tx buffer overflow & PMTC driver timeout
26-Mai-2011	48302	48325	23	STANDBY	PMTC Tx buffer overflow & PMTC driver timeout
16-Jul-2011	49034	49072	38	HTR/RF	Switch to dump mode OOL I0100
26-Aug-2011	49620	49633	13	HTR/RF	SDPU Tx buffer overflow
08-Sep-2011	49800	49820	20	HTR/RF	SDP2 ProcAliveStatus & PMTC Mode
22-Sep-2011	50003	50021	18	HTR/RF	SDPU Tx buffer overflow
16-Jan-2012	51670	51687	17	HTR/RF	SDPU Tx buffer overflow
22-Feb-2012	52204	52219	15	HTR/RF	ASM overcurrent

Table 15: SCIAMACHY instrument anomalies 2002-2012.

The occurrence of the CCA MCMD Check Errors, SEU induced events and anomalies with unidentified cause over the in-orbit mission lifetime did not indicate an increasing anomaly rate (Fig. 21). They followed a linear trend with a rate of 1.3 per year for the CCA MCMD Check Error (not counting SODAP), 1.0 per year for SEU anomalies and 3.0 per year for the unidentified cases.

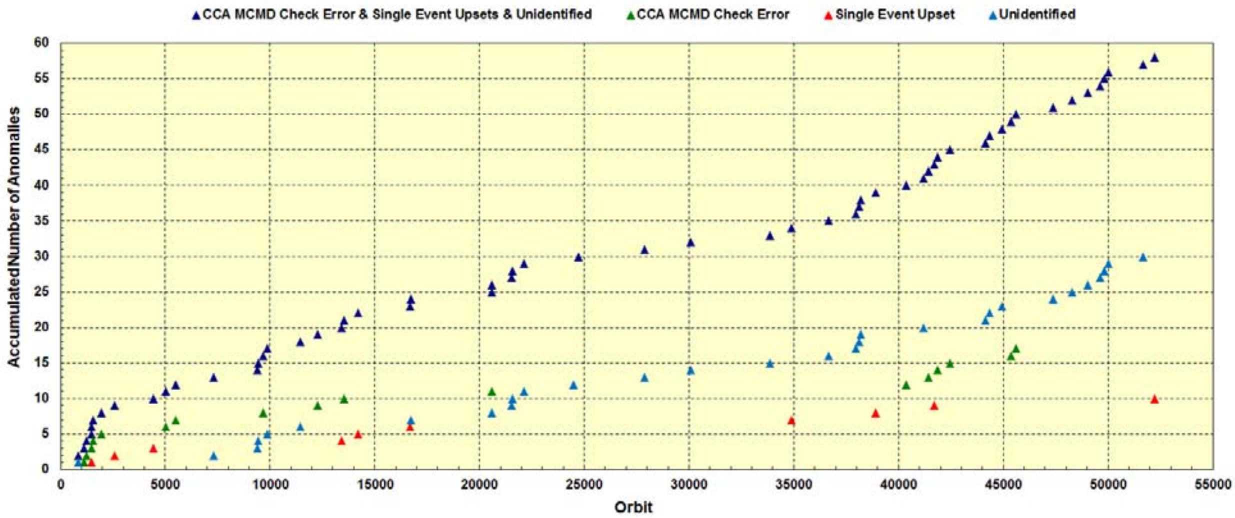


Fig. 21: Accumulated number of instrument anomalies (CCA MCMD Check Error, SEUs and unidentified failures).

The anomalies not triggering a transfer to a mode lower than Measurement comprised those listed in Table 16. None of them was considered a serious problem for measurement operations. For avoiding the messages with fault ID 86 (parameter I0107) the planning of lunar occultations was changed. Since it had turned out that the surface brightness of the Moon was similar to a cloudy Earth's atmosphere leading to a 'loss of object' in the Sun Follower (SF) control, the occultations were limited to the nightside of Earth.

Fault ID	Parameter	Fault Name	Remark
1	I6000	Detector Module latch-up	
53	I0260	SDPC Warn1 OB-Monitor	
71	I6291	MDI Overflows	Data rate limit exceeding
86	I0107	Single Event Warnings W1	Sun Follower loss of object (Sun, Moon)
89	I0110	Measurement mode warnings	Missing ancillary data
94	I0119	ASM Control Difference	Caused by fault ID 86
100	I0129	ESM Control Difference	Caused by fault ID 86

Table 16: Autonomously detected failures not interrupting the measurements programme.

7. Instrument Performance Evolution

The quality of the measurement data was determined by the performance of the instrument subsystems such as

- optics
- thermal systems
- Line-of-Sight pointing knowledge
- Life Limited Items status

All these items underwent regular monitoring to derive their actual status, which was changing with time – mainly due to degradation in the space environment. Various long-term monitoring efforts quantified these effects. The information derived thereof was then used either in payload operations for maintaining specified conditions or in data processing for applying the most actual calibration and characterisation status.

When the ENVISAT mission had successfully finished the specified 5 years in-orbit mission lifetime with starting the first extension phase, new SCIAMACHY monitoring tasks had been defined. Their purpose was to elaborate the status of components which had not been subject to monitoring in the first years due to supposed non-criticality. A similar approach followed at the beginning of the second phase of the extension in October 2010. As the instrument became older and operational expertise grew larger, SCIAMACHY was operated under an ever increasing monitoring control.

7.1 Optical Performance

The optical performance of the instrument was decreasing with time due to degradation of optical components, e.g. build-up of contaminants on optical surfaces. This degradation was subject to regular monitoring on channel and detector level.

7.1.1 Optical Throughput

By measuring a constant light source such as the Sun or the WLS through the three main light paths of the instrument – the nadir, limb and calibration light path – a continuous record of optical throughput measurements was generated. From such measurements either the channel averaged or spectrally resolved throughput values, referenced to the start of quasi-routine operations on August 2, 2002, could be inferred.

The overall throughput behaviour was best illustrated by the channel averages. Although the results for the various paths differ slightly, all results provided a consistent view of the optical performance (Fig. 22 and Fig. 23).

– UV: Even with the observed degradation of 60% (channel 1) and 35% (channel 2) in 8 years, SCIAMACHY maintained a high sensitivity at UV wavelengths. The GOME mission with similar detectors suffered from a faster and larger decrease in sensitivity at short wavelengths. Early in 2011 the throughput began to recover, most pronounced in channels 1 and 2. The reason is not yet fully understood. One likely origin is a thermally different behaviour of the OBM, either caused by the switch from KBS-2 to KBS-3 (see chapter 7.2) or the fact that one of the ATC parameters had to be operated at its lower limit thus increasing the related ATC temperature (see chapter 7.2). Further analyses are required by SCIMACHY's calibration experts in phase F. However these studies will no longer fall into the operational area but will be reported as progress in instrument calibration and characterisation.

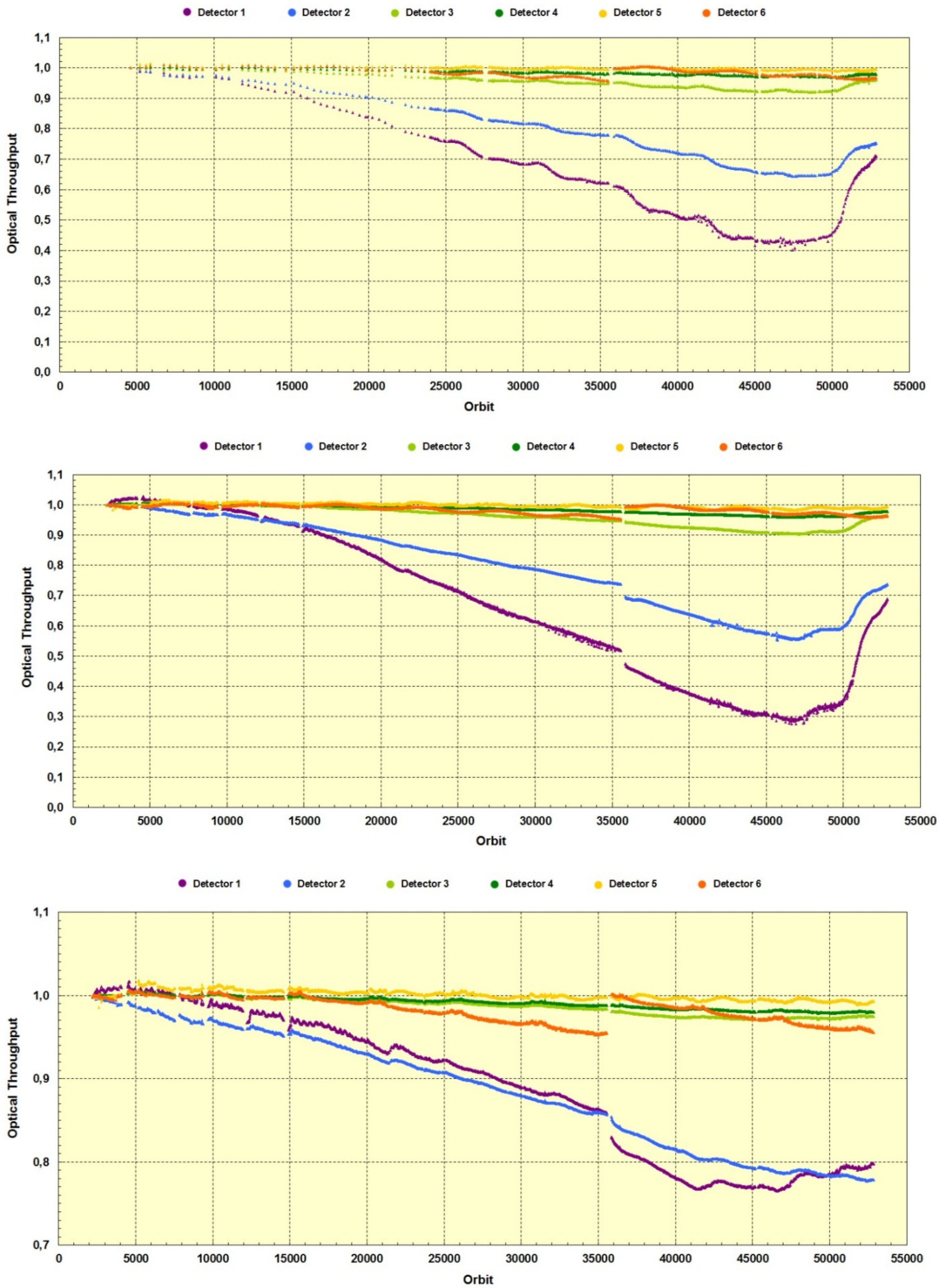
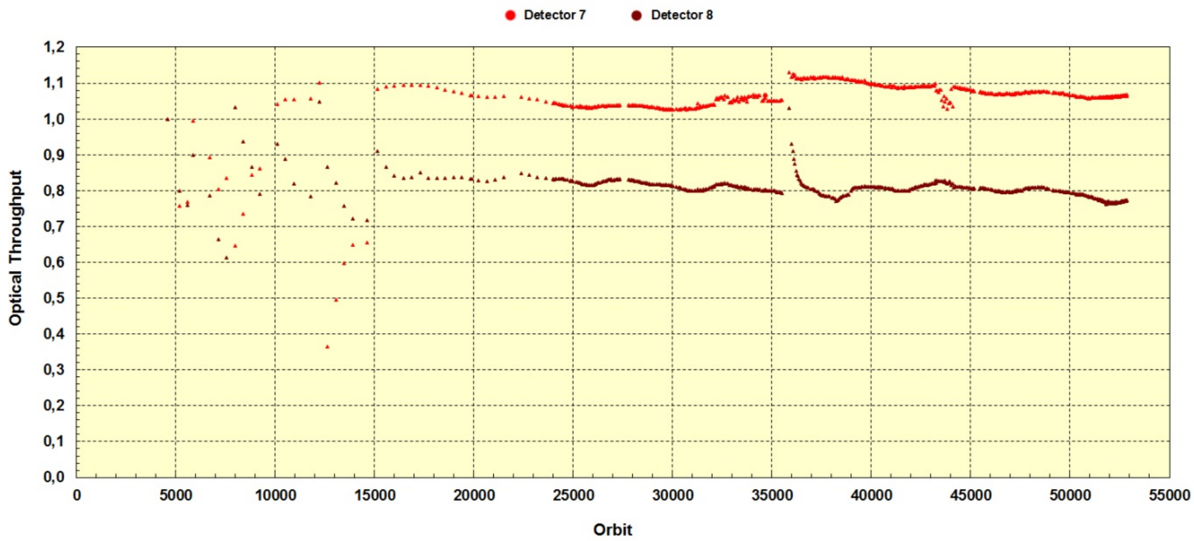
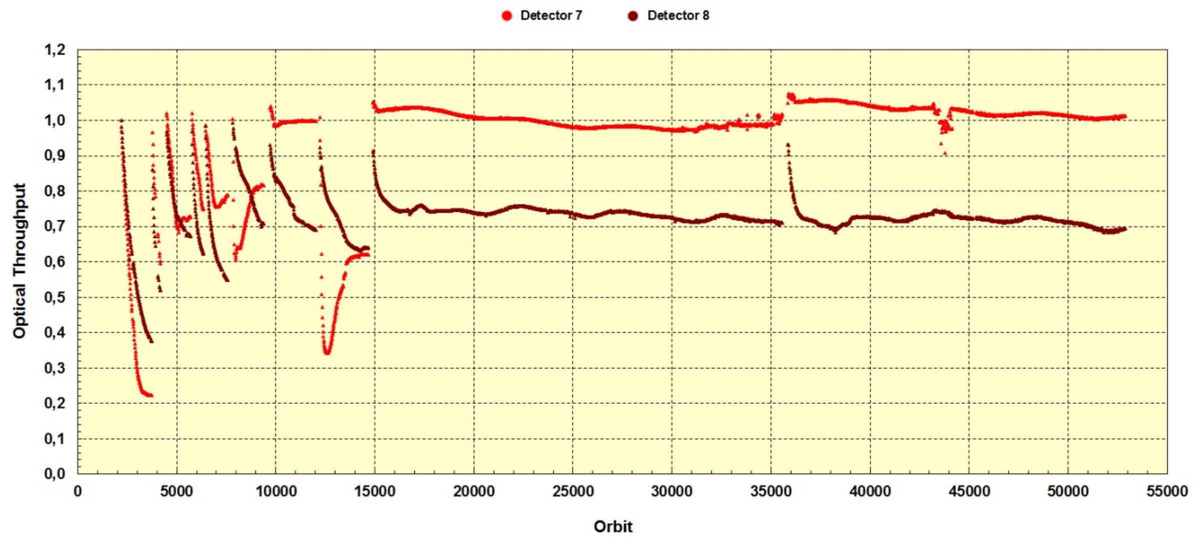


Fig. 22: Degradation of the SCIAMACHY throughput relative to August 2002 in channels 1-6 in the nadir light path (top, based on subsolar pointing measurements), limb light path (middle, solar occultation measurements) and the calibration light path (bottom, ESM diffuser measurements).





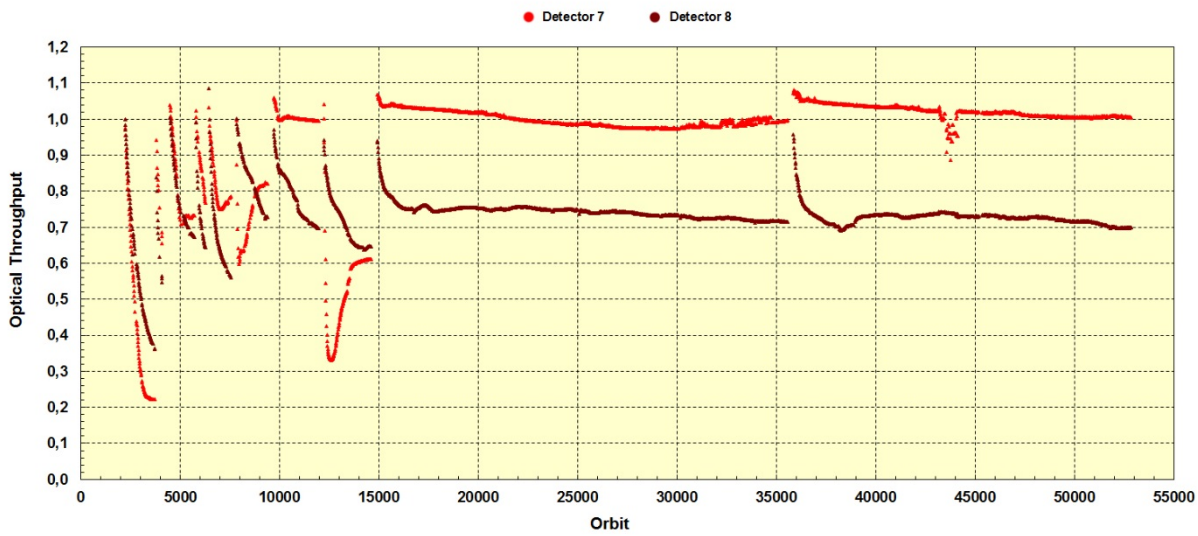


Fig. 23: Same as Fig. 22 but for channels 7 and 8 (nadir light path top, limb light path middle and calibration light path bottom).

– VIS-NIR-SWIR: For detectors 3-6, annual variations were detected on a sub-percent level. The excellent stability permitted correlation of the overall throughput with large scale features due to seasonal variations. Over short timescales even solar activity sensed via the effective sunspot area were reflected in the data (not shown in Fig. 20).
– SWIR: The throughput of the infrared channels (7 and 8) was in the beginning hampered by the growth of an ice layer in the optical light path (Fig. 21). Even regular decontaminations failed to remove the contaminant from the channels. As soon as the detectors were cooled to operating temperatures, the ice layer began accumulating again and the throughput decreased rapidly. A real improvement could be achieved, however, when the decontamination procedure was modified for the decontamination occurring late December 2004 / early January 2005 (see chapter 7.2.3) with throughput losses at relatively low levels.

An example for a spectrally resolved, i.e. wavelength dependent instrument degradation, is depicted in Fig. 24-26. They display the relative variation of the throughput – again for the nadir, limb and calibration light paths – as a function of time (horizontal axis) and wavelength given in pixel numbers (vertical axis) for all 8 channels. Grey bars denote times of reduced instrument performance, e.g. switch-offs or decontamination periods. As in the case of the channel averaged throughput, the measured signals were referenced to August 2, 2002. It is obvious from Fig. 24-26 that the degradation was wavelength dependent. In the UV channels pronounced increasing broadband degradation towards lower wavelengths could be identified together with individual peaks on smaller scales. For channels 3-6 the spectrally resolved monitoring data showed the excellent absolute radiometric stability of SCIAMACHY in the VIS-NIR channels.

M-Factors

The spectrally resolved throughput monitoring results have been used in the operational data processing to compensate for the radiometric degradation of SCIAMACHY. This degradation correction is performed by so-called *m-factors*. An m-factor is defined as the ratio between a measured spectrum of a constant light source, typically the Sun, at a certain time to a spectrum obtained for the same optical path at a reference time. M-factors therefore provide an end-to-end degradation correction for each individual light path.

In general, m-factors impact the polarisation correction and the absolute radiometric calibration. The m-factors for the science detectors are multiplicative factors to the absolute radiometric calibration of SCIAMACHY. The m-factors for the PMD channels influence in a non-linear way the polarisation correction of SCIAMACHY. Currently, i.e. for level 1 V7 / level 2 V5, only the science channel m-factors are used in operational data processing. During the SCIAMACHY mission, these m-factors have been regularly calculated by SOST (see RD [15]) and provided to ESA. An extended degradation correction considering the PMD changes and also scan angle dependences will be further elaborated in phase F.

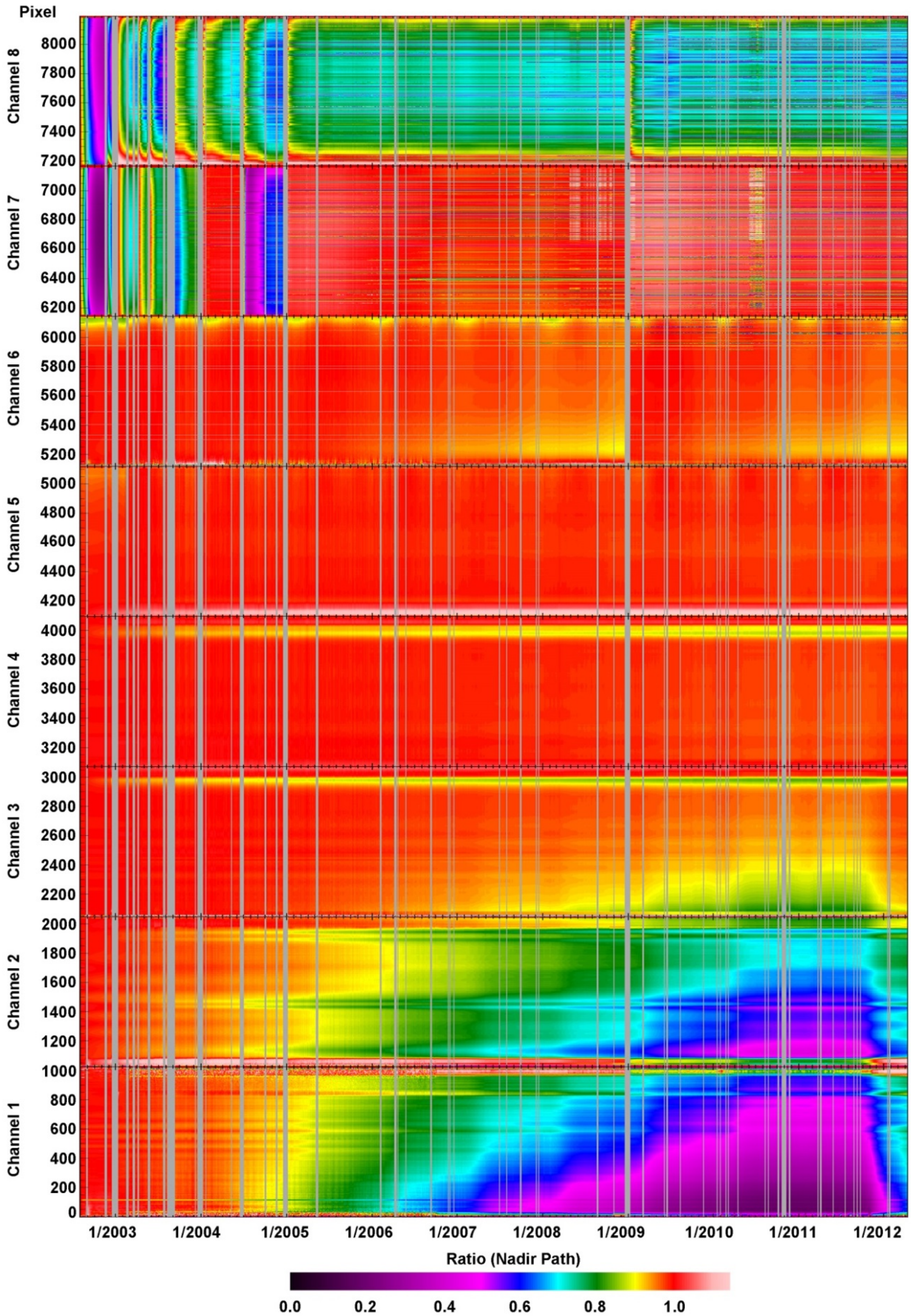


Fig. 24: Spectrally resolved degradation of the SCIAMACHY throughput relative to August 2002 in channels 1-8 in the nadir light path (based on subsolar pointing measurements).

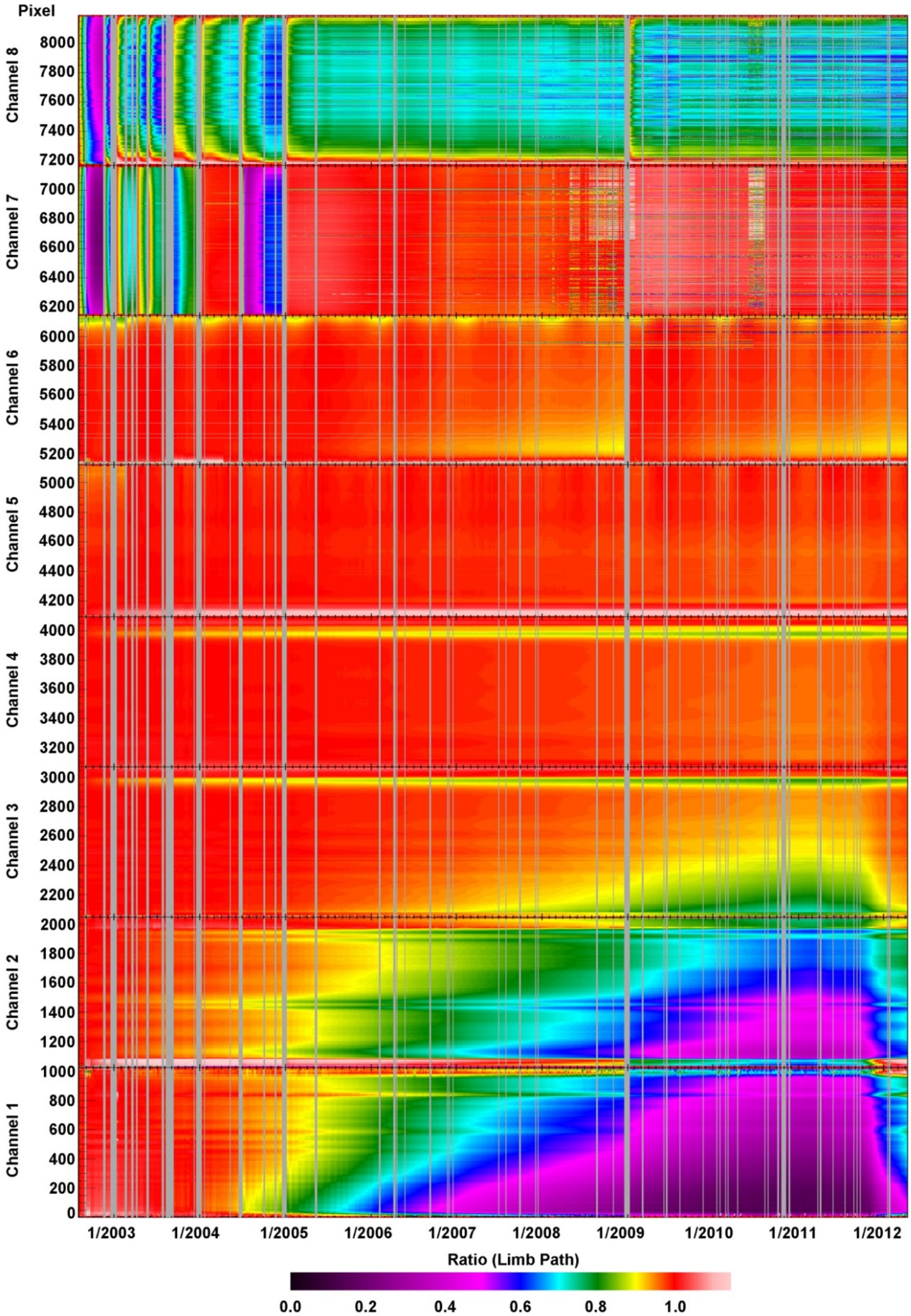


Fig. 25: Spectrally resolved degradation of the SCIAMACHY throughput relative to August 2002 in channels 1-8 in the limb light path (based on solar occultation measurements).

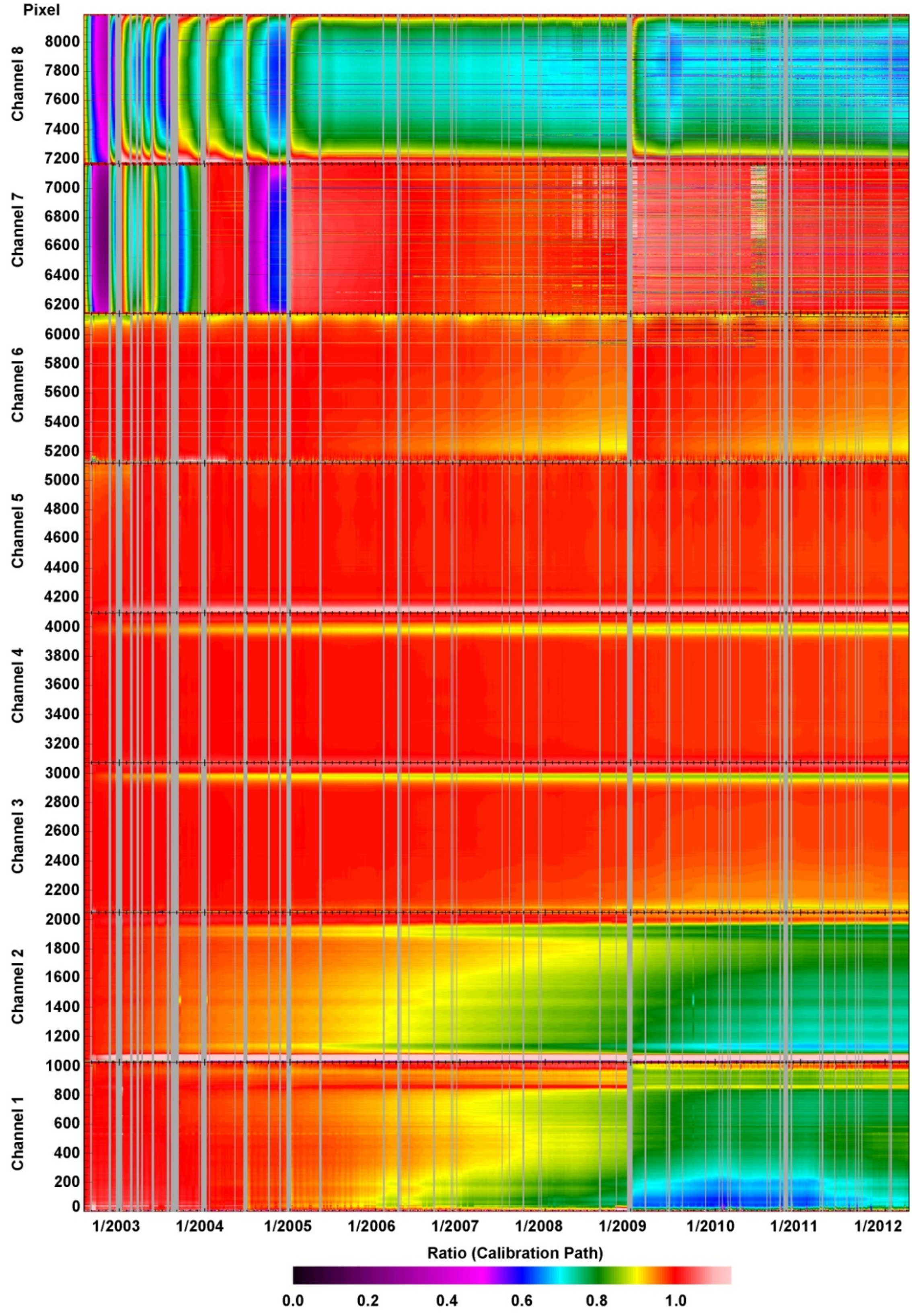


Fig. 26: Spectrally resolved degradation of the SCIAMACHY throughput relative to August 2002 in channels 1-8 in the calibration light path (based on ESM diffuser measurements).

7.1.2 Detector Performance

While the optical throughput described in chapter 7.1.1 was the result of the performance of the complete optical path, channel specific degradation had been also addressed.

Channels 1 to 6 (excluding 6+)

The detectors of channels 1 to 6 – excluding channel 6+ – maintained a stable behaviour throughout the in-orbit mission lifetime. Channel 2 had displayed some degradation in detector response, but this was negligible compared to the overall throughput loss for wavelengths in channel 2. Channels 1-6 were also subject to an increase in dark current over time, which had roughly doubled since launch. However, the dark current remained very small and was negligible after dark correction.

Channels 6+ to 8

The detectors of channels 6+ (the part in channel 6 above pixel #794 – see chapter 2.1.1), 7 and 8 showed distinct pixel degradation. Occasionally, a high energy particle damaged the detector material and a pixel became noisy, in particular the dark current may have increased and became unstable.

Pixels affected by degradation were flagged as 'bad'. Initially, the number of bad pixels had increased linearly with time, and ever fewer pixels had been available for trace gas retrieval. Fig. 27 displays the evolution of the percentage of flagged pixels as a function of time. The increase for the relevant channels 6 to 8 reached up to about 6% per year in the first years of instrument operations. Experience showed that such a linear trend could not persist over the entire mission duration, since the prime reason of the increasing number of bad pixels were random hits by protons such that the number of healthy pixels decreased with time, i.e. with progressing mission lifetime the probability of a high energy particle to 'find' and hit an intact pixel is reduced. There were indeed indications that the linear trend began levelling off in the years 2010-2011.

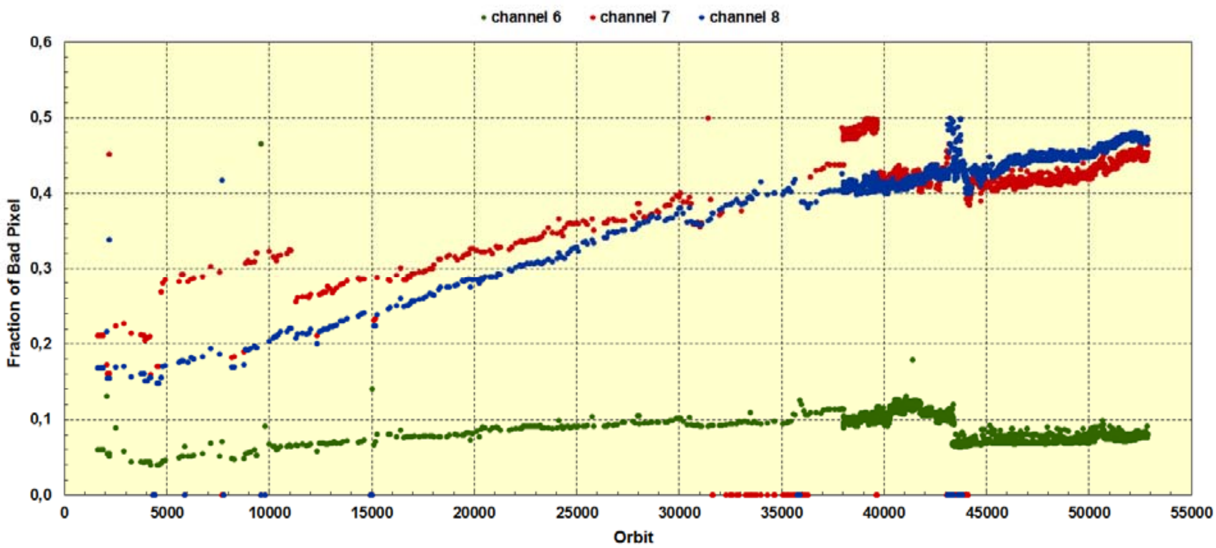


Fig. 27: Flagged pixel development as a function of orbit number for channels 6, 7 and 8. After orbit 38000 (June 2009) the rate of estimating bad and dead pixel has been increased.

7.2 Thermal Performance

Usually platform operations did not affect the thermal status of SCIAMACHY. Once the appropriate thermal settings had been selected in SODAP, both the Active Thermal Control (ATC) and the Thermal Control (TC) subsystems were operated as specified in the IOM (AD [1]). One exception did exist, however. Shortly before the ENVISAT orbit manoeuvre in October 2010 an anomaly occurred in the Ka-band antenna subsystem (KBS). This required switching from KBS-2 to KBS-3 and to change its operating procedure. While KBS-2 had been intermittently turned 'on' and 'off', for safety reasons KBS-3 remained 'on' the whole time. Therefore about 120 W more energy were dissipated thus changing the thermal environment of ENVISAT, including the payload instruments. The effect on SCIAMACHY could be described by

- stable ATC temperatures
- reduced ATC heater powers (-0.1 W to -0.5 W, heater dependent)
- increased detector temperatures (0.3 K to 0.5 K, channel dependent)
- increased PMD temperature (0.1 °C)
- increased Electronic Assembly subsystem temperatures (1.1 to 2.7 °C, subsystem dependent)

An analysis of additional instrument HK parameters revealed that also the Electronic Assembly (EA) subsystems displayed higher temperature readings. The increase ranged between 1.1 and 2.7 °C and was subsystem dependent (Fig. 28).

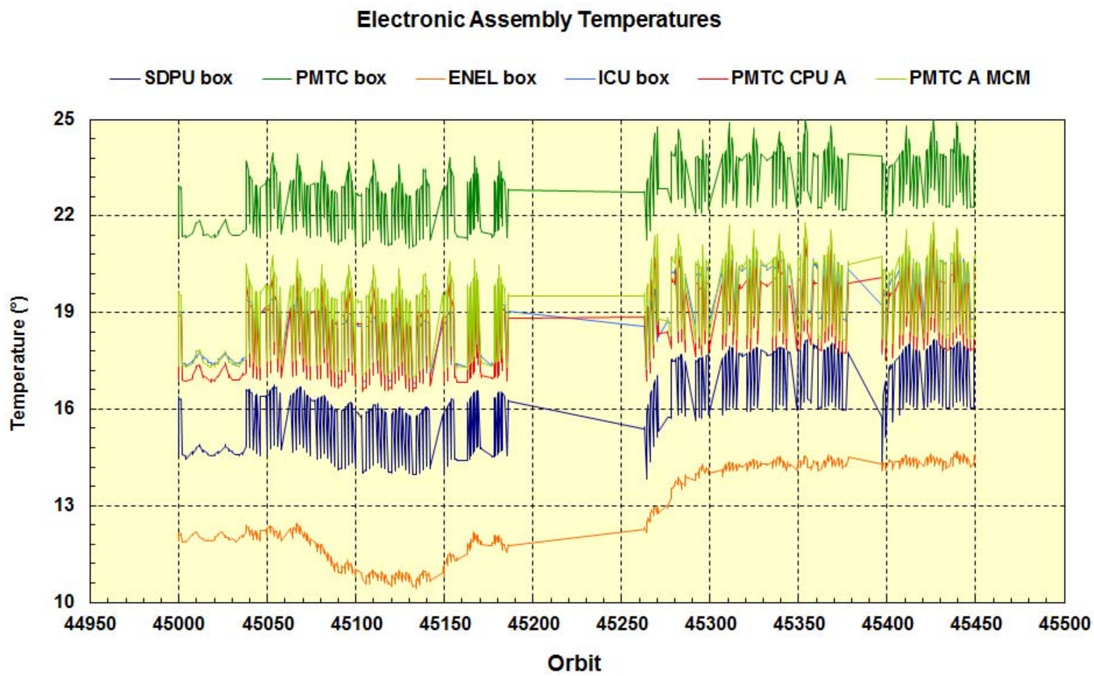


Fig. 28: Evolution of Electronic Assembly subsystem temperatures around the time of the orbit manoeuvre (indicated by the gap). After the manoeuvre all temperatures were higher than before.

7.2.1 Active Thermal Control – ATC

The ATC controlled the thermal stability of the OBM. It consisted of 3 control loops with heater circuits and thermistors. Each circuit included a dedicated heater – limb, nadir, RAD A – which had to be operated at a certain duty cycle to maintain the required temperature. The full duty cycle (100%) and its operational limits corresponded to power settings as listed in Table 17.

	ATC limb heater	ATC nadir heater	ATC RAD A heater
Full range min - max (W)	0.30 - 10.83	0.30 - 10.84	0.54 - 19.40
Limits low - high (W)	1.62 - 9.20	1.63 - 9.21	2.91- 16.49
Heatflow offset (W)	0.3	0.3	0.54

Table 17: ATC heater power ranges and offset settings.

Operational ATC Monitoring

Operationally the OBM thermal status was monitored via the procedure P-I-N 402 as described in the IOM (AD [1]). It was based on the HK telemetry readings (Fig. 29-31)

- I0773D: ATC nadir sensor temperature derived from HK parameter I0136 (ATC nadir YSI sensor readout)
- I0772D: ATC limb sensor temperature derived from HK parameter I0134 (ATC limb YSI sensor readout)
- I0799D: ATC nadir heater power derived from HK parameter I0143 (ATC nadir heater control)
- I0798D: ATC limb heater power derived from HK parameter I5340 (ATC limb heater control)
- I0800D: RAD A heater power derived from HK parameter I0144 (ATC RAD A heater control)

In addition, ATC information was also obtained via the HK reading I0774D (ATC RAD A sensor temperature) which had been derived from HK parameter I0135 (ATC RAD A YSI sensor readout).

Nadir and limb sensor temperatures yielded the OBM temperature according to

$$T_{OBM} = 0.5 \times (T_{LIMB} + T_{NADIR}) - 2.2\ °C, \quad -17.6\ °C \geq T_{OBM} \geq -18.2\ °C \qquad (1)$$

with T_{LIMB} = I0772D and T_{NADIR} = I0773D. The constant term in eq. 1 has been derived using information from the HK parameter I0165 (RAD A HK temperature). Being subject to radiation degradation it was only used in the early phase of the mission. Although the sensor is termed 'RAD A' the corresponding sensor is located on the OBM (Fig. 31).

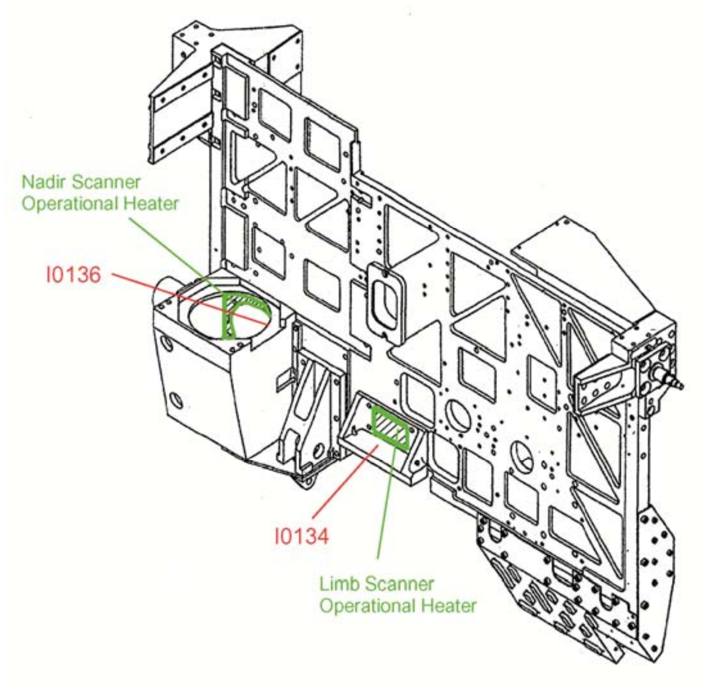


Fig. 29: Location on the OBM of the sensors providing I0134 and I0136 HK information together with the corresponding ATC heaters.

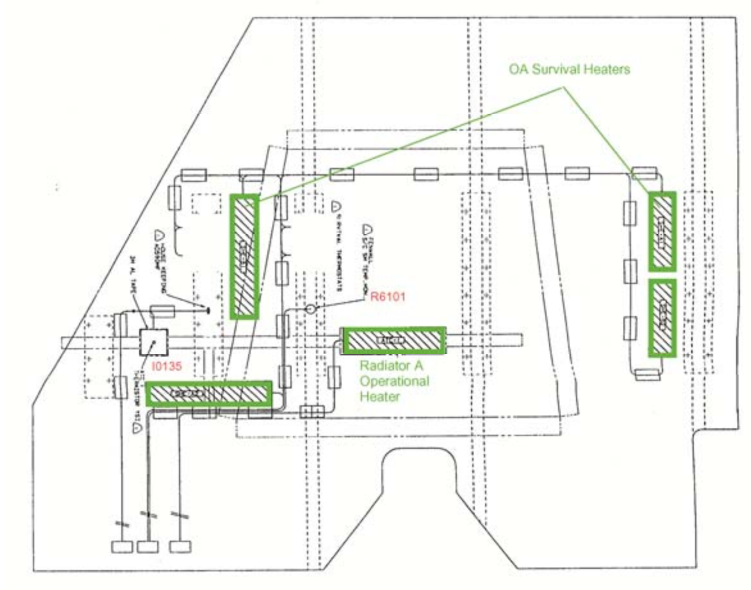


Fig. 30: Location on RAD A of the sensor providing I0135 HK information together with the corresponding ATC heater.

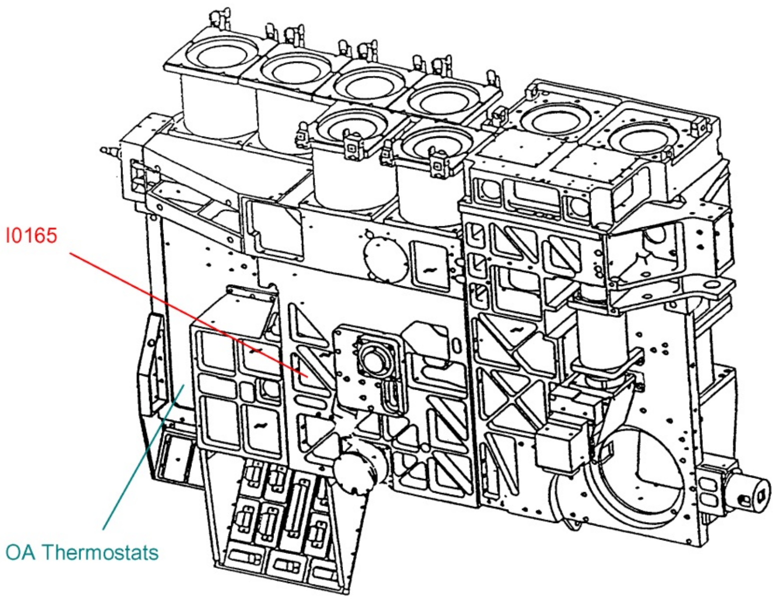


Fig. 31: Location on the OBM of the sensor providing I0165 HK information.

Orbital Mean ATC Parameters

The orbital mean OBM temperature derived in the P-I-N 402 monitoring was maintained at the specified value with high stability (Fig. 32). This indicated that the ATC control loops functioned well and compensated any degradation of the ATC which had been predicted before launch (RD [9], RD [10]).

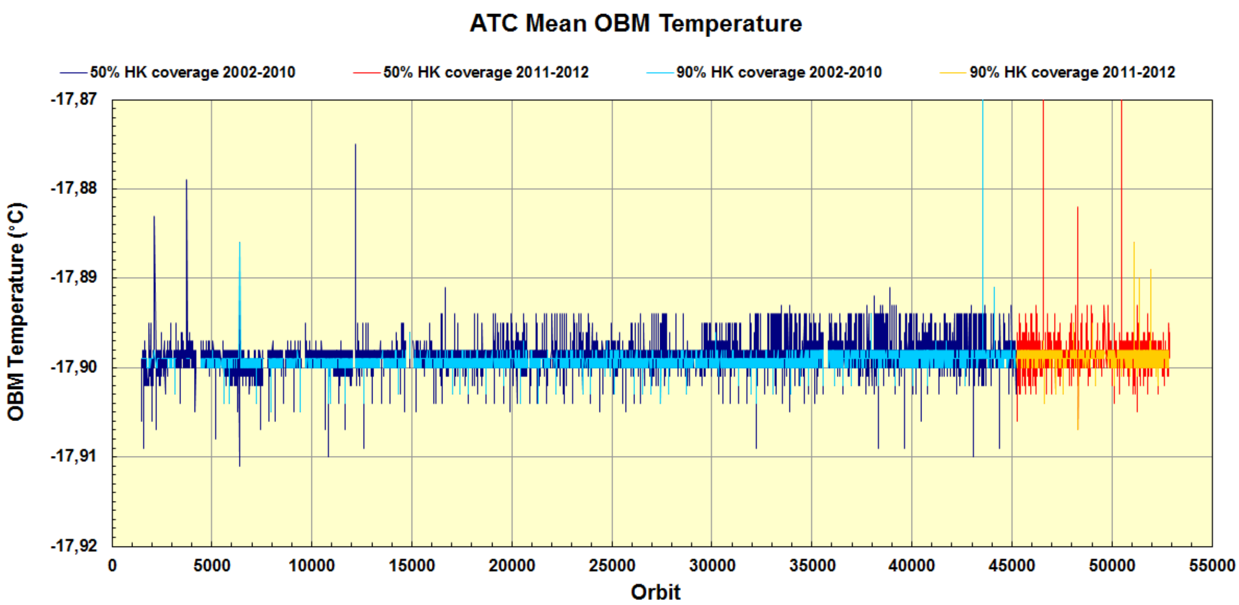


Fig. 32: Orbital mean OBM temperature derived from orbits with 50% (dark colours) and 90% (light colours) HK telemetry. Blue indicates the period before the October 2010 orbit manoeuvre, red the remaining part of the mission.

Monitoring of the RAD A, nadir and limb heater powers revealed the degradation of the ATC system. All three heaters dissipated less power as compared to the beginning of ATC operations (Fig. 33). The decrease was most pronounced for the nadir heater while limb and RAD A heater showed smaller effects. The two glitches just before orbit 35000 and after orbit 45000 were caused by the ATC adjustment in October 2008 (see below) and the switching to KBS-3 in October 2010 (see above), respectively.

While Fig. 33 displays heater power as a function of orbit number, Fig. 34 presents the same parameters related to the annual phase. The seasonal power minimum, i.e. the phase with closest approach to their lower limits, occurred for the nadir and limb heater in December and November each year, for the RAD A heater around June. The maxima were broader. They was reached in September for the nadir and limb heater and in February for the RAD A heater. Degradation caused small shifts in these periods.

In the ATC limb display of Fig. 34 the ATC adjustment from October 2008 is obvious as two distinct power levels. In the ATC nadir part the thermal impact of the KBS-3 operations has smeared out both levels. For the RAD A power only the elevated heat dissipation of KBS-3 has caused a change.

From the results presented in Fig. 33 and Fig. 34 the average ATC heater degradation can be deduced. It corresponded to

- nadir heater = -0.25 W/year
- limb heater = -0.11 W/year
- RAD A heater = -0.15 W/year

with the absolute values being shifted by -0.5 W end of October 2010 for the nadir heater and -0.1 W for the limb and RAD A heater.

The ATC settings as implemented in SODAP had proven extremely reliable. Although regular monitoring has revealed some degradation – less than what was predicted before launch – only a single adjustment was necessary keeping the OBM temperature within the specified limit. This adjustment occurred October 15, 2008 in orbit 34643. It changed the ATC setpoints and gain factors as listed in Table 18.

	Applicable Period	
	10-Jun-2002 to 15-Oct-2008	**15-Oct-2008 to 08-Apr-2012**
Setpoints		
RAD A	-21.60 °C	-21.60 °C
Nadir	-16.40 °C	-16.25 °C
Limb	-15.00 °C	-15.15 °C
Gain Factor *		
RAD A	-0.092	-0.092
Nadir	-1.120	-1.135
Limb	-1.200	-1.183

* the sign of the gain factors is 'as commanded'

Table 18: History of ATC settings.

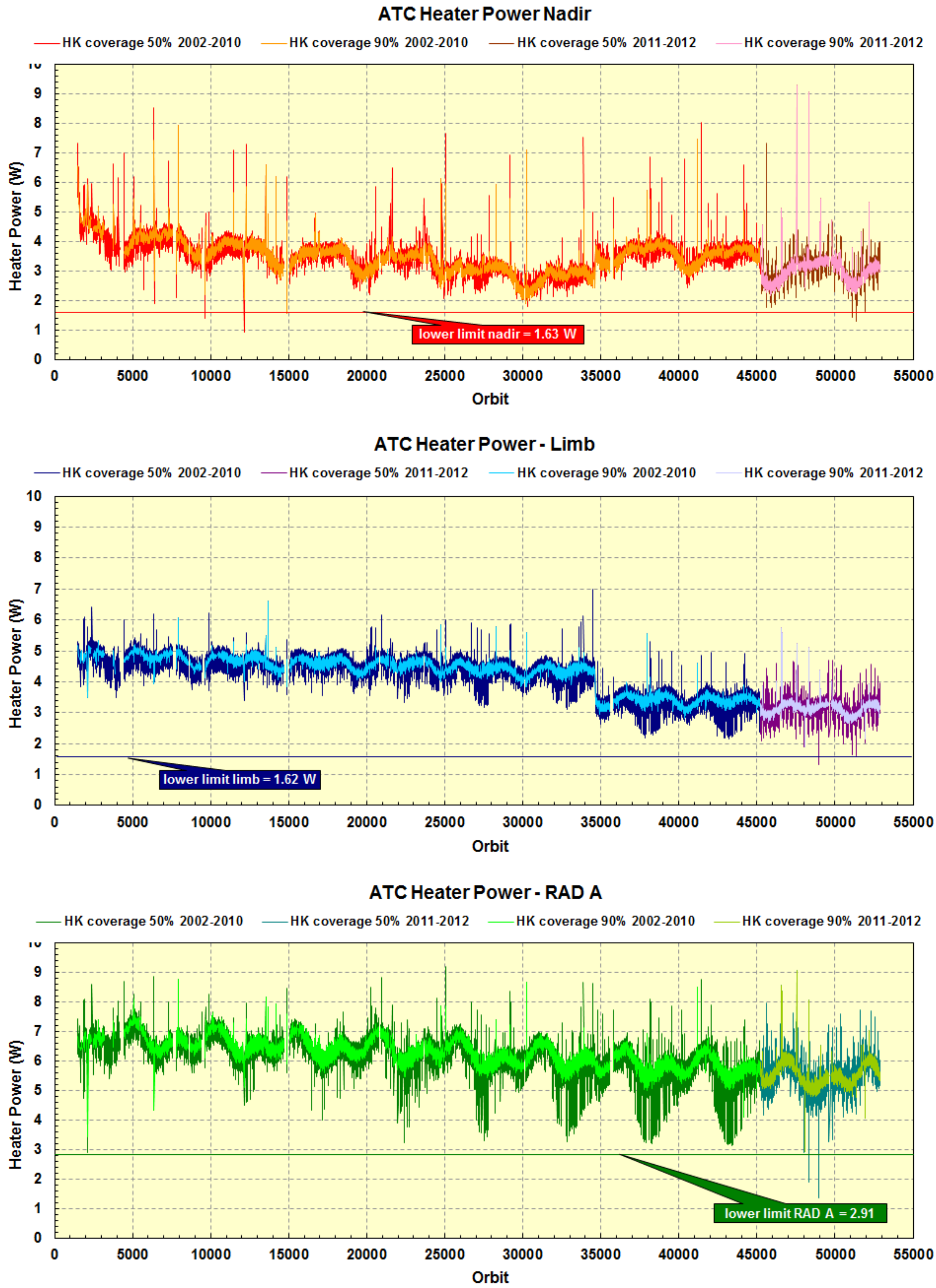


Fig. 33: Mean ATC heater powers. Dark and light coloured curves stand for 50% and 90% HK coverage. The lower limits as specified by the IOM (15% duty cycle) are indicated.

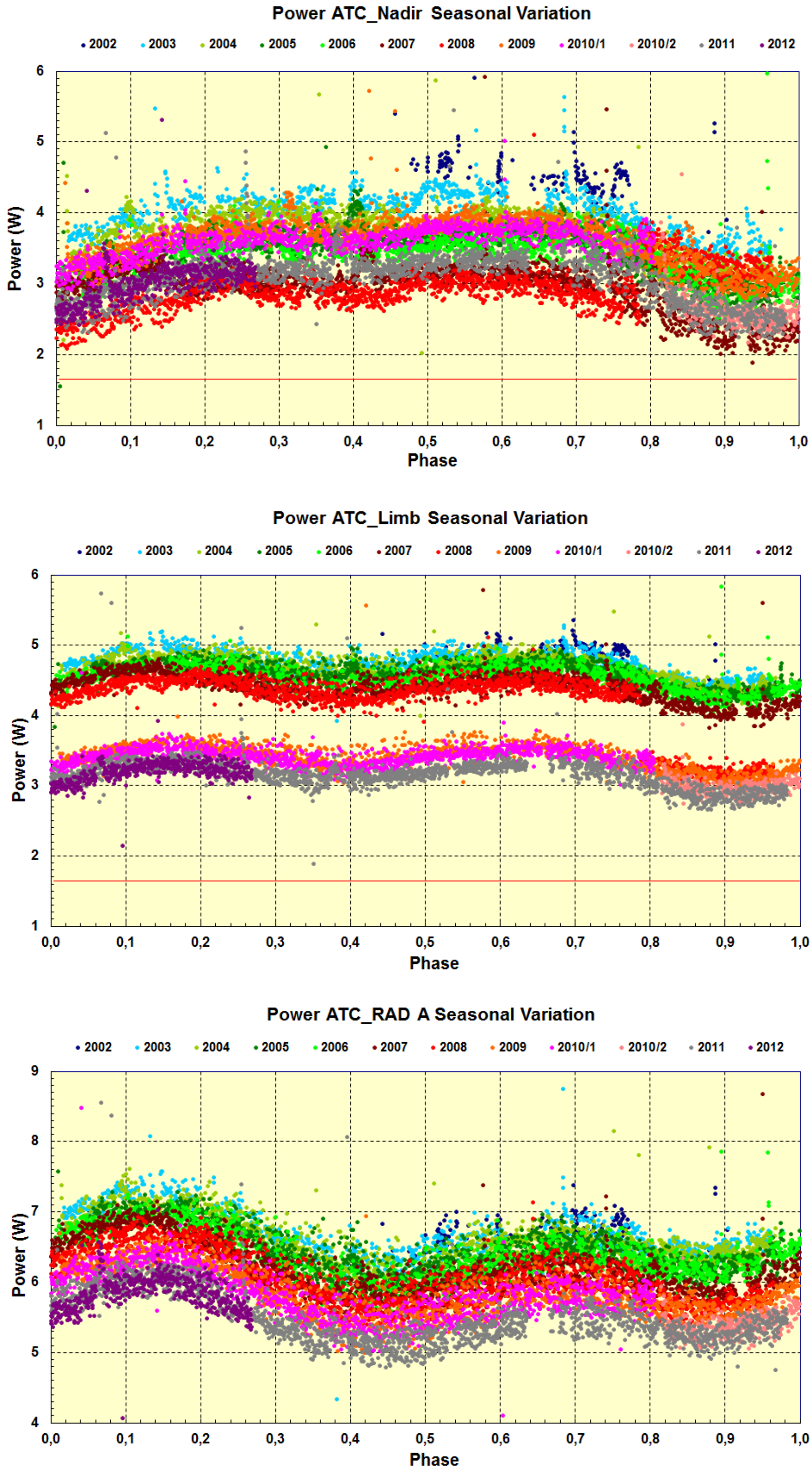


Fig. 34: Mean ATC heater powers as a function of annual phase. 2010/1 and 2010/2 stand for the part of 2010 before and after the orbit manoeuvre.

Orbital ATC Parameter Profiles and In-orbit Mission Lifetime Effects

Although the monitoring of orbital variations of ATC parameters was not an explicitely required operational task, SOST – in preparation of the planned mission extension beyond 2013 – also investigated how these parameters changed over one orbit. This addressed both the entire mission lifetime and seasonal effects (RD [8]).

Overall the derived OBM temperature showed an almost identical orbital variation[3] from 2002 to 2011 (Fig. 35). The orbital temperature profiles matched well with a variation (min/max) of about 0.025 °C. This variation started at Sunrise (occurring at elapsed time = 1300 sec, i.e. orbit phase = 0.21 in winter) when the control loops took some time to compensate for elevated temperatures.

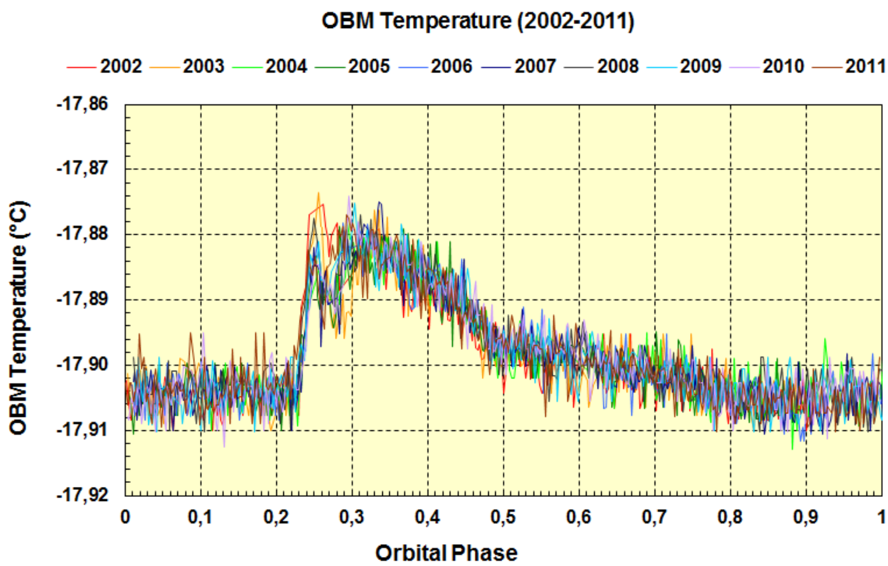


Fig. 35: Orbital OBM temperature profiles for the December 2002 to 2011 when the ATC nadir heater had reached its orbital mean minimum.

As expected, the nadir and limb sensor temperatures appeared in two distinct temperature levels due to the ATC adjustment in October 2008 (Fig. 36). The horizontal temperature levels at the beginning and end of the orbit were about identical to the selected setpoints in the ATC system. As could be expected from the stable OBM temperatures, both the nadir and limb sensor temperature profiles did not change over the mission lifetime. This was also true for the RAD A sensor temperatures which was unused in OBM temperature calculations.

All ATC degradation effects were obvious in the orbital variations of the nadir, limb and RAD A ATC powers (Fig. 37). They illustrate the continuously occurring reduction of heater power because of the slowly increasing inefficiency of the ATC system. In addition the KBS-3 phenomenon reduced the power readings for the nadir heater in 2010 and 2011 to a level which was similar to that before the ATC adjustment in 2008.

[3] Orbital phase = 0 refers to Ascending Node Crossing (ANX)

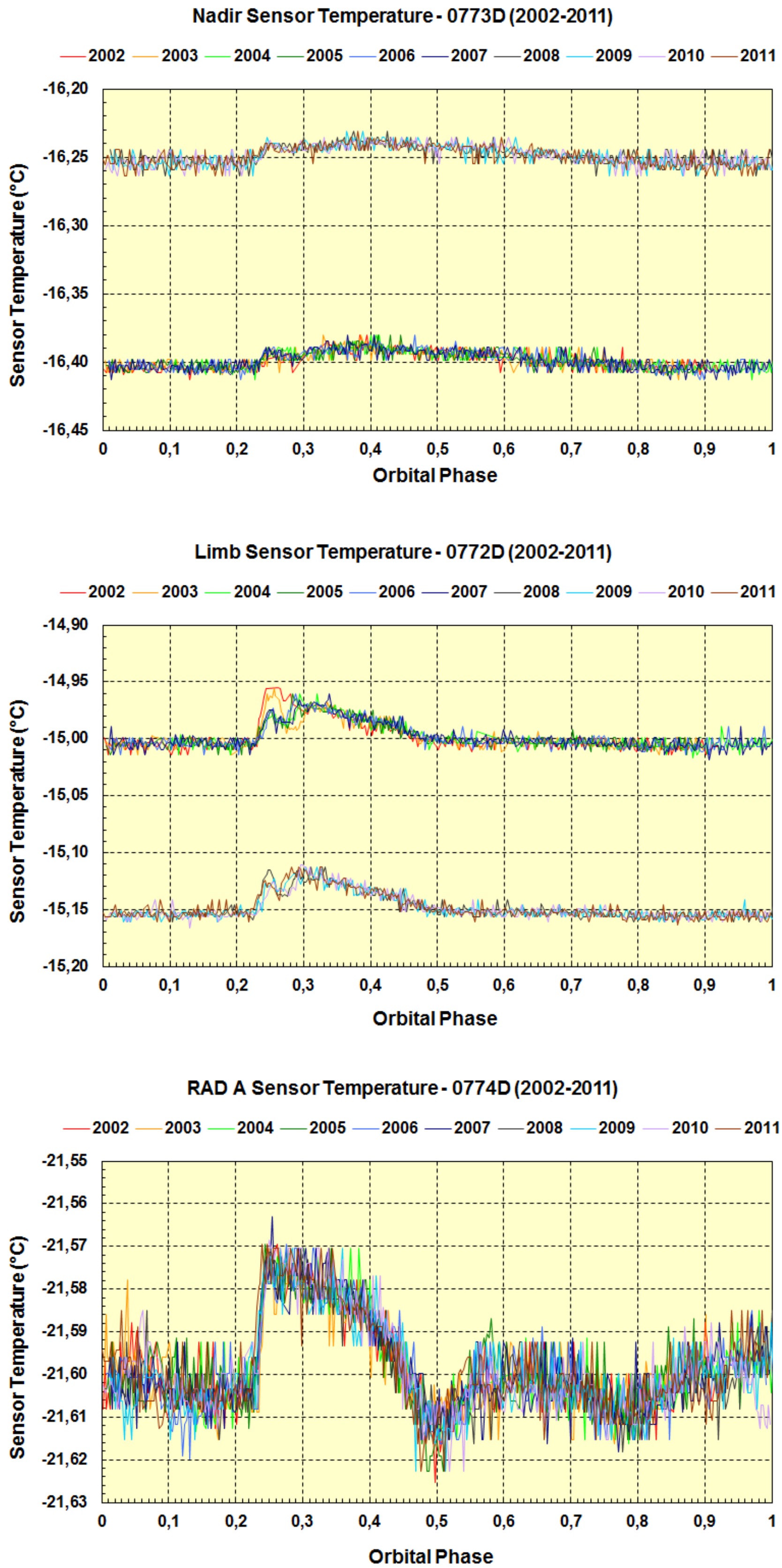


Fig. 36: Orbital ATC sensor temperature profiles for the years 2002 to 2011 at phases when the dissipated ATC nadir heater had reached the orbital mean minimum (December each year).

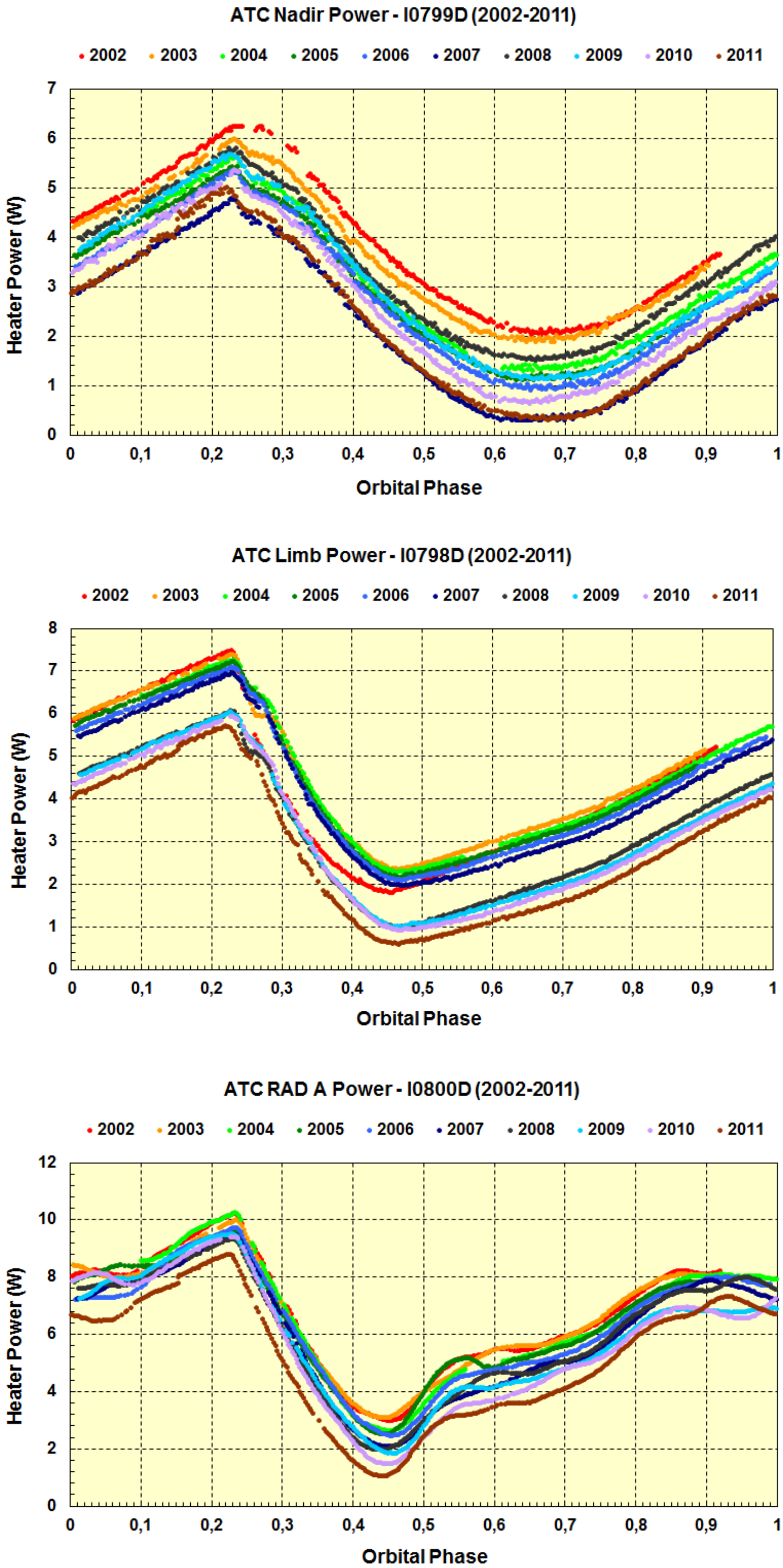


Fig. 37: Orbital ATC heater power profiles for the years 2002 to 2011 at phases when the dissipated ATC nadir heater had reached the orbital mean minimum (December each year).

The orbital profiles of the ATC temperatures and heater powers for the period when the limb heater was closest to its annual minimum were similar to what is illustrated in Fig. 33-35. However, the situation was different in June each year. Then the RAD A heater approached its minimum. The resulting orbital profiles are displayed in Fig. 38.

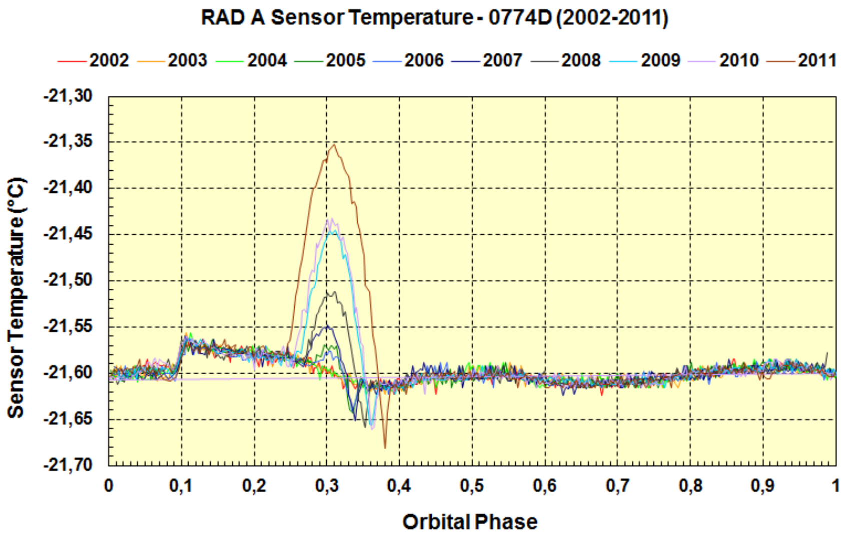


Fig. 38: Orbital RAD A sensor temperature profiles for the years 2002 to 2011 at phases when the dissipated ATC RAD A heater power reaches the orbital mean minimum (June each year).

Around 2005/2006 at an orbital phase = 0.3 the sensor temperature began to deviate from the orbital profile. In 2011 the orbital segment showing this behaviour had widened to about 0.15 with a maximum deviation of now +0.25 °C (T = -21.35 °C instead -21.60 °C). Since the RAD A HK temperature was never used in the calculation of the OBM temperature, this effect remained unnoticed. There was also no reported effect on the quality of the measurement parameters.

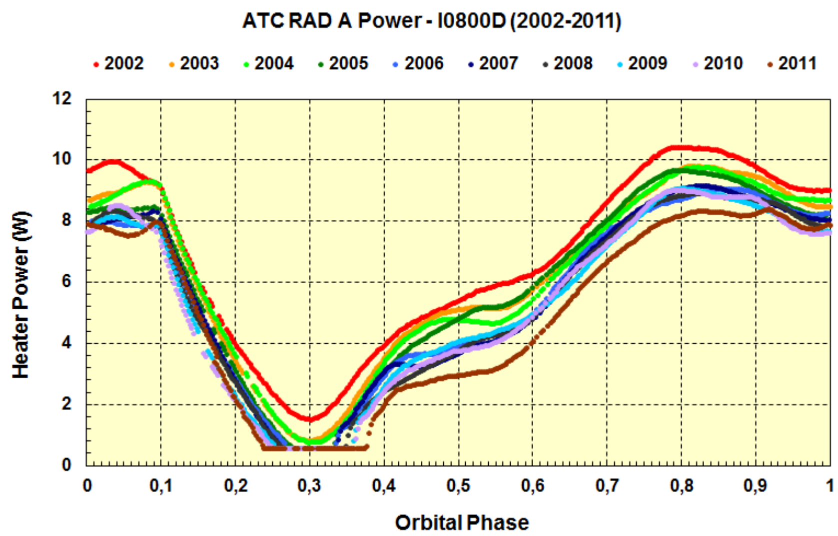


Fig. 39: Orbital RAD A heater power profile for the years 2002 to 2011 at phases when the dissipated ATC RAD A heater reaches the orbital mean minimum (June each year).

The reason why an obviously warmer environment at the location of the RAD A sensor could no longer be compensated is shown in Fig. 39. The elevated RAD A temperatures had been caused by the RAD A heater which reaches its lower limit of 0.54 W, the heatflow offset assigned to RAD A (see Table 16). For the nadir and limb heaters the corresponding offset would have probably been reached in 2013. The resulting nadir and limb sensor temperature excursions would have caused an OBM temperature no longer following the standard orbital profile displayed in Fig. 35. Further ATC adjustments would have been necessary to maintain a stable OBM temperature.

Orbital ATC Parameter Profiles and Seasonal Effects

The seasonal evolution of the OBM temperature is illustrated in Fig. 40. The shift of the profile reflects the varying illumination conditions over a year. This is also obvious in the nadir and limb sensor temperature profiles while the RAD A sensor temperature displays again the fact that the heater power could not be reduced any further. From May to July the sensor temperature increased by up to 0.25 °C between orbital phases 0.25-0.35 (Fig. 41). In the corresponding heater power graph (Fig. 42) the plateau is clearly visible for the same months even with an indication that it also began to develop in August.

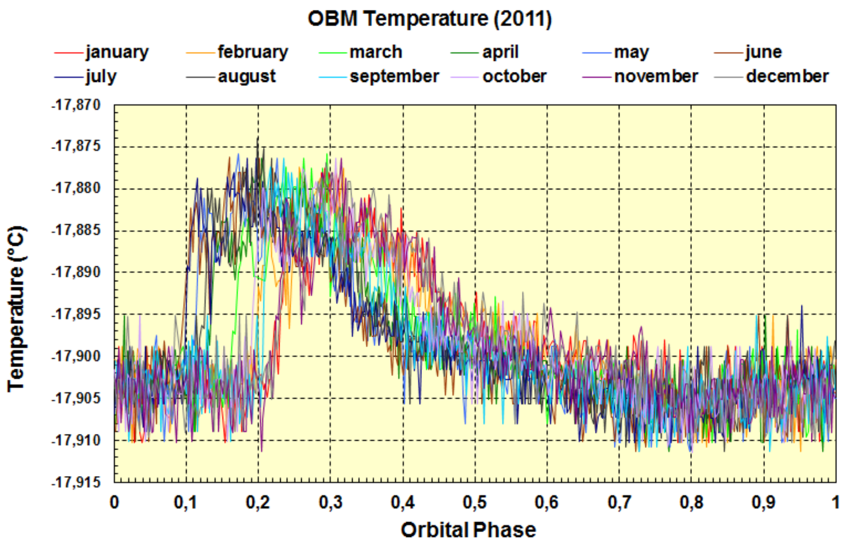


Fig. 40: Orbital OBM temperature profiles for the year 2011.

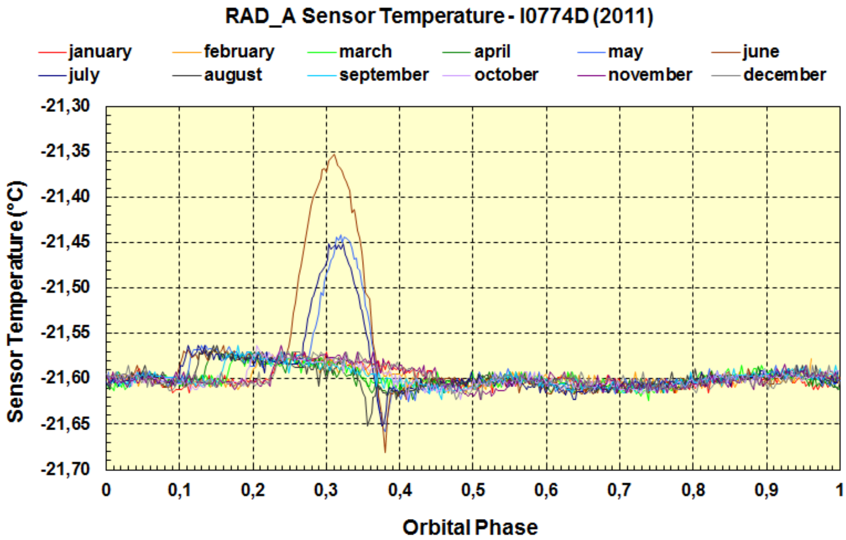


Fig. 41: Orbital RAD A temperature profiles for the year 2011.

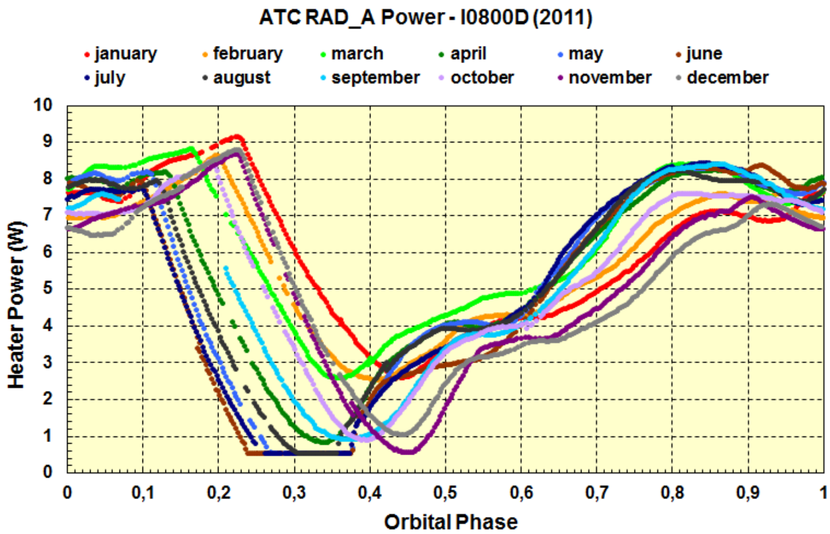


Fig. 42: Orbital RAD A heater power profiles for the year 2011.

7.2.2 Thermal Control – TC

Unlike the ATC, the TC heater powers were not autonomously adjusted by control loops but required occasional updates via MCMD once a temperature violated the assigned limits. Generally all 3 heaters impacted each detector. However the thermal sensitivity was such that DAC1 was most effective for detector 7 and 8, DAC2 for detectors 1-3 and 6 and DAC3 for detectors 4 and 5. Detector temperatures were monitored by determining orbital mean values according to P-I-N 401 (AD [1]).

TC settings for routine operations had been uploaded in June 2002. They were modified in February 2003 to account for modified calibration requirements. Since then infrequent TC adjustments have occurred (see Table 6). Early in the mission a TC adjustment occurred whenever a detector temperature limit was exceeded. Once yearlong mission extensions were considered a realistic approach and the calibration and characterisation efforts had progressed such that high quality retrieval could also be achieved with measurement data acquired under thermal conditions slightly out-of-spec, it had been decided to accept off-limit temperature excursions up to 0.5-1 °C in favour of a stable thermal setup.

TC Sensitivity Matrix

Each TC adjustment required to estimate the expected temperature as a function of the modified DAC settings. For that purpose a s/w tool had been provided by industry (SJT) early in SODAP. It described the relation between heater power and expected temperature, i.e. the detector temperature sensitivity according to the relation

$$\begin{pmatrix} \Delta T_{1,2,3,6} \\ \Delta T_{4,5} \\ \Delta T_{7,8} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \times \begin{pmatrix} \Delta DAC2 \\ \Delta DAC3 \\ \Delta DAC1 \end{pmatrix} \qquad (2)$$

with

$$A = \begin{pmatrix} 6.78 & 5.13 & 0.60 \\ 3.00 & 19.33 & 0.22 \\ 1.07 & 0.95 & 13.66 \end{pmatrix}$$

The large number of TC adjustments executed until December 2004 was considered a good repository for an improvement of the operational TC sensitivity matrix. From the estimated and measured temperature changes a new version of matrix ***A***

$$A = \begin{pmatrix} 5.13 \pm 0.26 & 1.81 \pm 1.06 & 0.65 \pm 0.87 \\ 3.99 \pm 0.83 & 24.29 \pm 3.41 & 0.95 \pm 2.66 \\ 1.41 \pm 0.57 & -0.91 \pm 2.36 & 12.28 \pm 1.84 \end{pmatrix} \qquad (3)$$

could be derived. Since 2005 it was used throughout the mission for TC adjustments. Fig. 43 displays the correlation between estimated and measured ΔT values.

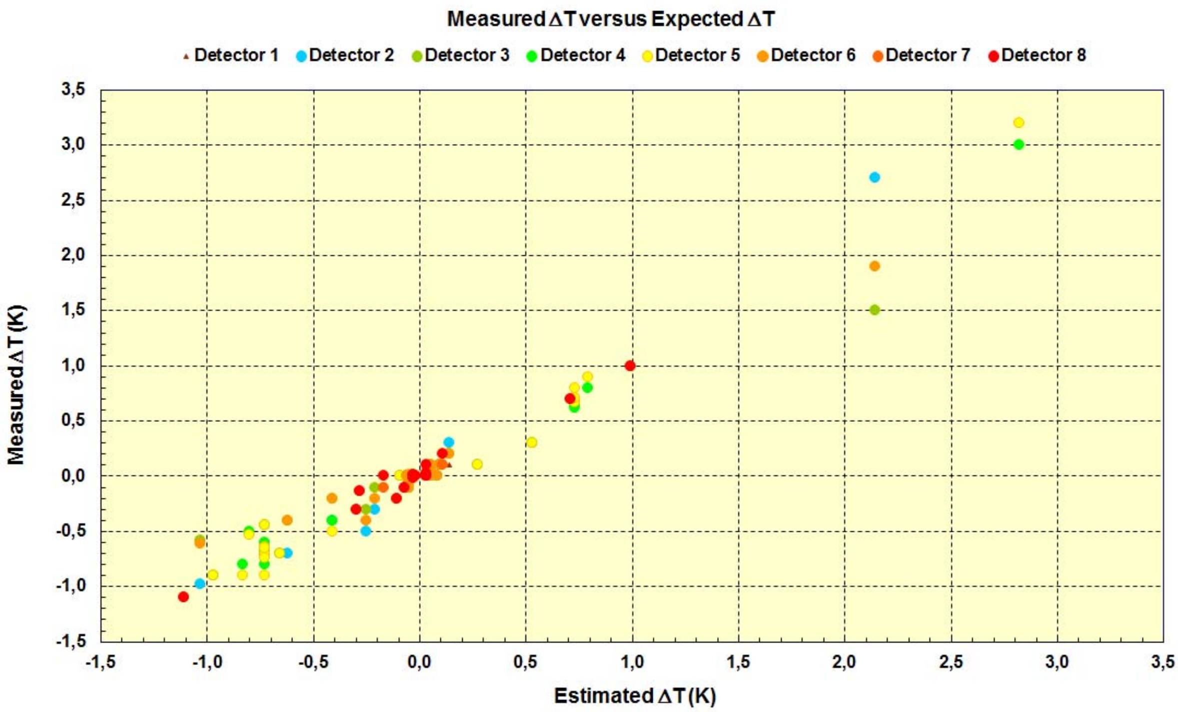


Fig. 43: Expected and measured temperature changes after TC adjustments using the modified thermal sensitivities.

TC Degradation

Regular monitoring revealed that the temperatures in all channels increased continuously (Fig. 44-47). For detectors 7 and 8 the trend became visible in 2005 when the modified decontamination procedure succeeded in removing the ice from the channel light paths. A summary of the detector temperature status is given in Table 19.

Channel	T_{min} (K)	T_{max} (K)	Seasonal variation (K)	Degradation (K/year)
1	204.5	210.5	2.0	0.32
2	204.0	210.0	2.0	0.32
3	221.8	227.8	1.5	0.22
4	222.9	224.3	1.6	0.21
5	221.4	222.4	1.7	0.22
6	197.0	203.8	2.3	0.29
7	145.9	155.9	1.2	0.77
8	143.5	150.0	1.2	0.77

Table 19: Detector temperature limits, observed seasonal variation and annual degradation.

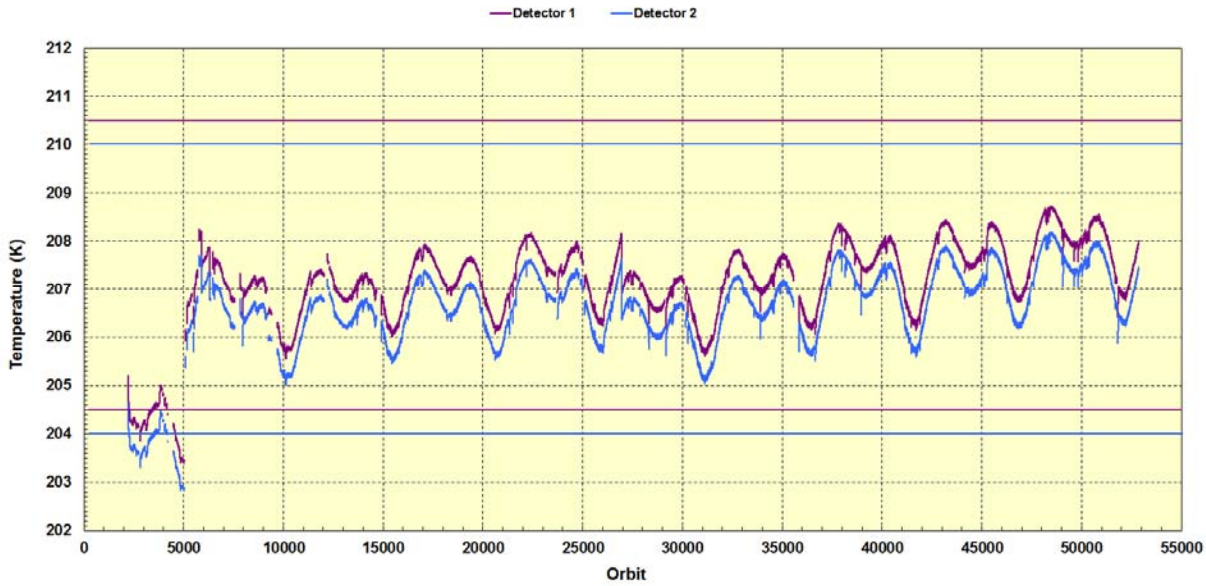


Fig. 44: Average orbital detector temperatures in channels 1 and 2. Periods with decontaminations or recovery after transitions to modes lower than MEASUREMENT are excluded. The solid horizontal lines display the lower and upper limits for each detector.

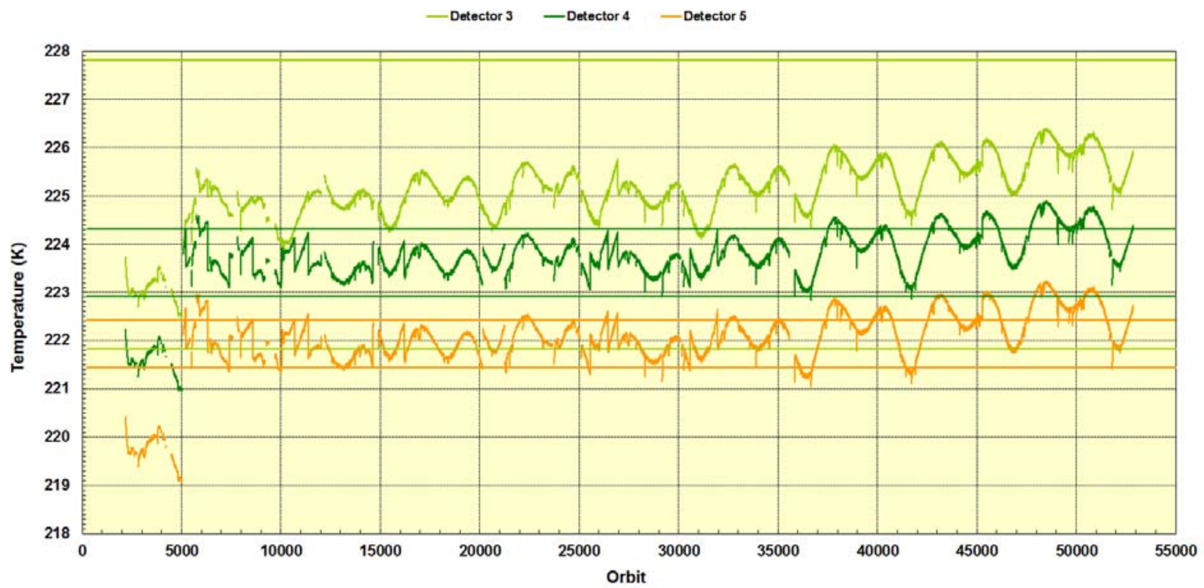


Fig. 45: Same as Fig. 44 but for channels 3, 4 and 5. Detectors 4 and 5 had the tightest limits. Both were operated above their upper limits for some time.

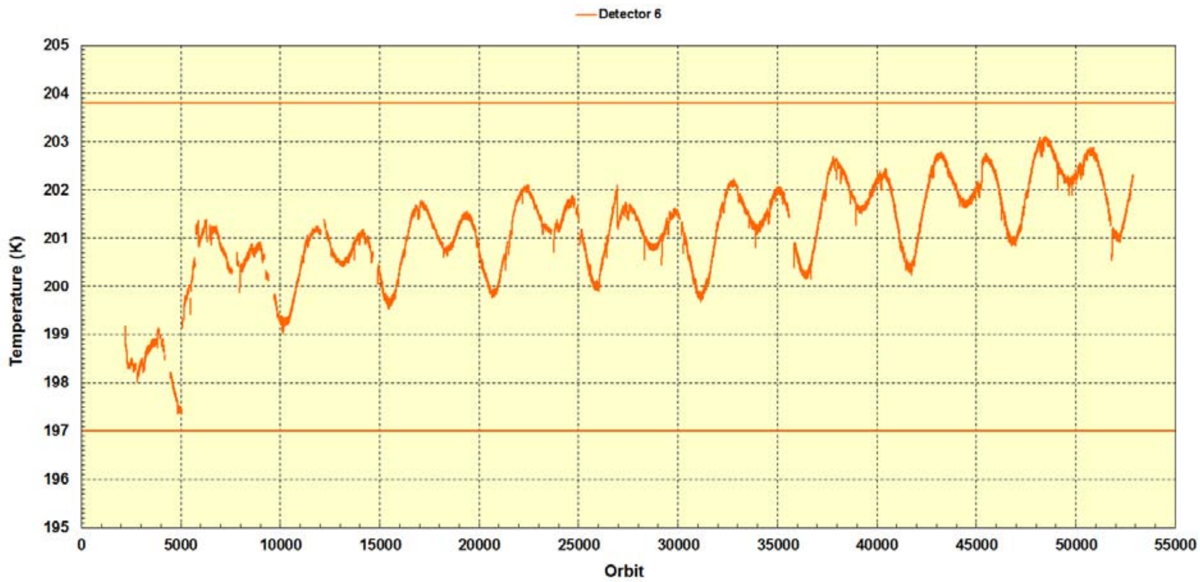


Fig. 46: Same as Fig. 44 but for channel 6.

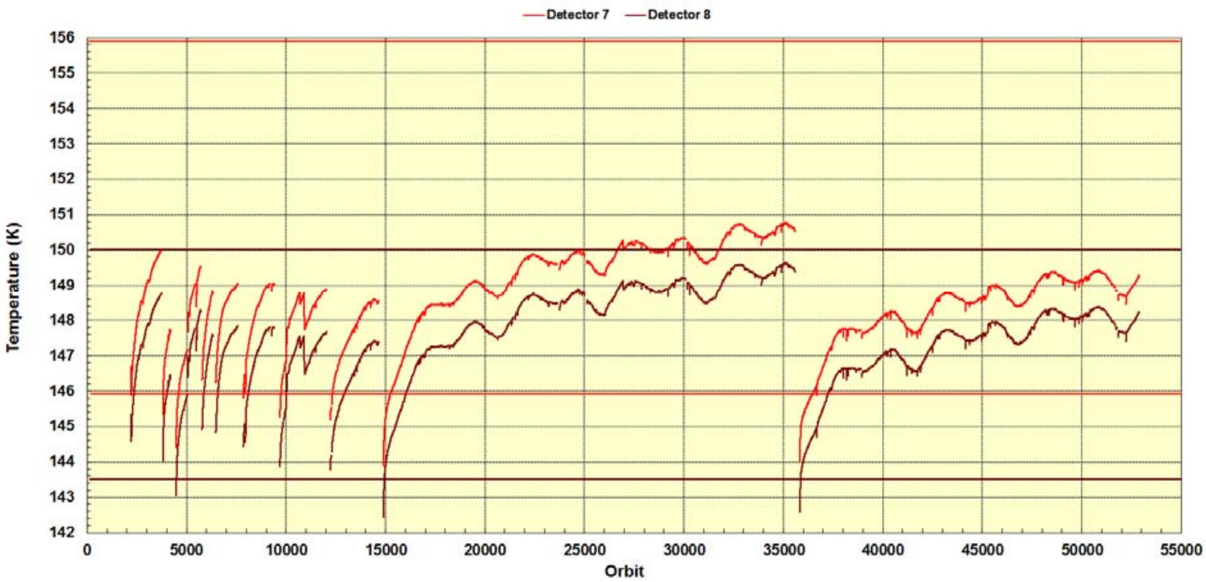


Fig. 47: Same as Fig. 44 but for channels 7 and 8. The temperature increase per year is larger than for the other channels due to the growing ice layer.

Two countermeasures existed for lowering detector temperatures. For channels 7 and 8 a decontamination could reduce the temperatures by several degrees. In addition, the heater power of the TC heaters had, even after about 10 years of in-orbit mission lifetime, still some margin left. The settings of the 3 heaters (the numbers in brackets indicate the detectors with highest sensitivity) at the end of the missions were:

- DAC_1 (7/8) = 0.53 W
- DAC_2 (1/2/3/6) = 0.50 W
- DAC_3 (4/5) = 0.00 W

These margins would have been sufficient for maintaining control of the detector temperatures even when ENVISAT/SCIAMACHY would have been operated beyond 2013.

7.1.3 PMD Temperatures

PMD HK parameter monitoring was required by P-I-N 404 for PMD/SF ADC calibration (AD [1]). Purpose was to detect glitches in the PMD ADC caused by SEUs. In case of an SEU, a distinct 'jump' of the HK telemetery signal should have occurred with the signal remaining at the modified value afterwards.

SOST monitored the HK parameters

- PMD detector temperature (I0009)
- PMD analogue supply voltage (I0012)

on a regular basis. In more than 9 years of routine operations, no PMD ADC glitch was observed. However, the PMD temperature provided additional information on how the thermal status of SCIAMACHY subsystems changed with time, both on a seasonal scale and longterm due to degradation (Fig. 48).

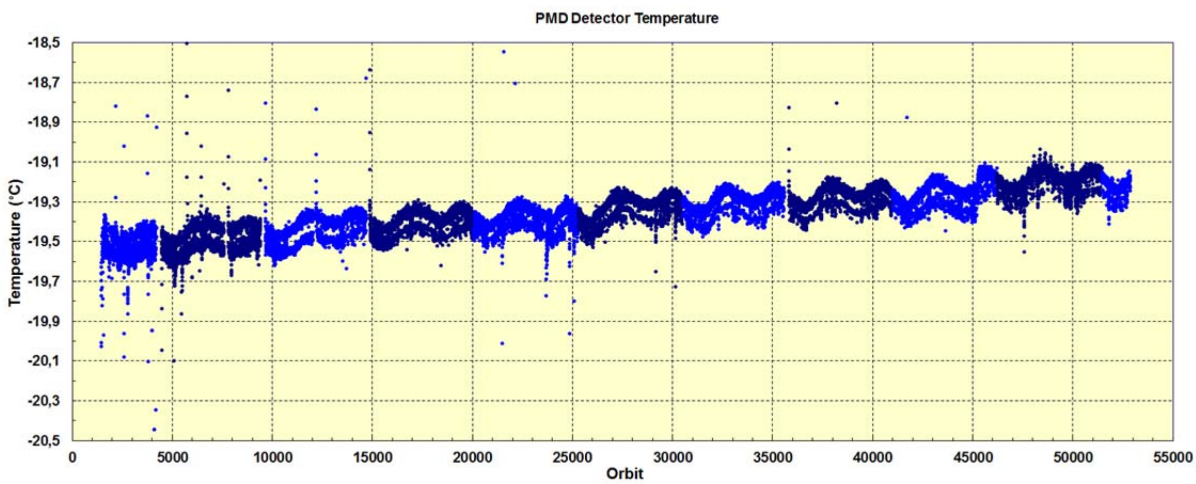


Fig. 48: PMD detector temperature. Individual years are separated by using bright/dark blue colours.

7.2.3 Ice in channels 7 and 8 and Decontaminations

Already during SODAP it became obvious that the infrared channels 7 and 8 began to show a significant loss of radiance response in the weeks after the SRC had been opened. Investigations indicated that an ice layer growing on top of the cylindrical lens covering the detectors was responsible for this. It affected only channels 7 and 8 because these were the detectors operated at lowest temperatures. Water from the carbon-fibre-reinforced plastic structure of ENVISAT was identified as the most likely source of the contaminant. The water contained in the compound started outgassing once the platform was in orbit and condensed on the cold surfaces in channels 7 and 8. Obviously, the venting holes in the multilayer insulation (MLI) covering SCIAMACHY could not efficiently support the outgassing of the instrument. Over a period of only a few months, the ice layer reduced the throughput in channels 7 and 8 by almost 80% (see Fig. 23). Methods to stop accumulation of ice were limited and only the application of decontaminations was finally selected to become the operational countermeasure.

The temperature behaviour of the IR channels 7 and 8 was largely driven by the ice conditions. Ice also covered the gold plated aluminium structures of the detector suspension leading to an increased infrared absorption and thus to radiatively heated detectors. This resulted in a slow but steady rising temperature. Immediately after a decontamination, ice was removed and temperatures were at the selected cold level from where they start to increase – caused by the growth of the ice layer – until the next decontamination was started or an equilibrium with a stable ice layer was reached (Fig. 47).

Decontamination

Detailed pre-launch analysis had shown that the efficiency of the RRU on the SRC to dissipate energy from the detectors to open space might decrease with time due to contamination of volatile molecules on the RRU surface. Cooling via the RRU usually yielded detector temperatures below the lower limit. Therefore, trim heaters counterbalanced this effect by additional heating. When contamination decreased the RRU efficiency, the detectors became less cold and thus, TC heater power (which was used to raise temperatures to keep detectors within limits) approached zero. To re-establish the initial RRU efficiency, a decontamination mode had been originally foreseen with the goal of removing any contaminants from the RRU surface by heating up the SRC for a few days. During this decontamination procedure any measurements would have been stopped. The SRC decontamination heaters would have been turned on for the warm-up phase while ATC and TC heaters would have remained at their current operational levels. Such an SRC decontamination would either have been required when one of the TC heaters would have reached a power of 0 W or, as originally required, at least twice per year.

Because of the necessity to heat up the detectors as much as possible to effectively get rid of the ice layers in channels 7 and 8, this decontamination procedure was redefined in the Commissioning Phase to form a Non-Nominal Decontamination (NNDEC) to be used during routine operations. During a NNDEC not only the SRC decontamination heaters provided energy to the optical subsystem but also ATC and TC heaters were switched to their maximum power. Measurements continued throughout warm-up and cool-down, contrary to what had been defined for the original decontamination procedure. In the warm-up phase of NNDEC, channels 7 and 8 reached temperatures of 267 K and the OBM approached a temperature of -3° C. The duration of the warm-up phase was also extended to 15 days. This method no longer created a long data gap since data analysis still permitted retrieval of – somewhat degraded – information from the UV-VIS channels even at elevated temperatures.

Orbit Start	Orbit Stop	Start Warm-up	Stop Warm-up
253	310	18-MAR-2002 / 17:44	22-MAR-2002 / 17:44
570	627	09-APR-2002 / 21:27	13-APR-2002 / 22:31
654	690	15-APR-2002 / 18:45	18-APR-2002 / 08:09
1780	1816	03-JUL-2002 / 10:14	06-JUL-2002 / 00:03
2124	2175	27-JUL-2002 / 11:28	31-JUL-2002 / 01:05
3746	3752	17-NOV-2002 / 20:04	18-NOV-2002 / 06:43
4204	4428	19-DEC-2002 / 20:02	04-JAN-2003 / 11:25
5718	5736	04-APR-2003 / 14:12	05-APR-2003 / 20:23
6384	6420	21-MAY-2003 / 02:46	23-MAY-2003 / 15:07
7574	7798	12-AUG-2003 / 06:00	27-AUG-2003 / 21:36
9407	9415	18-DEC-2003 / 07:30	18-DEC-2003 / 19:41
9427	9467	19-DEC-2003 / 17:05	22-DEC-2003 / 11:00
9482	9644	23-DEC-2003 / 12:17	03-JAN-2004 / 20:53
12031	12174	18-JUN-2004 / 14:46	28-JUN-2004 / 14:32
14675	14860	20-DEC-2004 / 08:05	02-JAN-2005 / 06:16
35574	35783	19-DEC-2008 / 08:20	03-JAN-2009 / 22:14

Table 20: Decontaminations executed between 2002-2012.

Early during the routine phase, decontaminations occurred more frequently since experience had to be gained about the most appropriate duration of the warm-up phase (Table 20). However these NNDEC achieved only a temporary removal of the ice layers. Only when the cool-down phase of the NNDEC was modified the throughput in channels 7 and 8 remained at high values for long periods. This new procedure mimicked the cooldown phase of the December 2003 / January 2004 decontamination when the CCA MCMD Check Error had transferred the instrument to R/W WAIT. For about 6 months both throughputs remained at rather high values indicating that the ice layer did not build up in the optical light path of channels 7 and 8. When in June 2004 the decontamination was again executed according to the specified standard procedure, throughputs eroded quite quickly afterwards. Obviously, cooling channels 7 and 8 via a transfer to STANDBY about 37 hours after the start of the cooldown phase and lasting about 8.5 hours could trigger a second cold trap where most of the contaminant water would condense. In fact, an ice layer in channel 7 was no longer visible via the throughput values. Even in channel 8 the throughput loss amounted to only 25% over a period of 4 years whereas before it had dropped by as much as 60% in about 4 months. The 'second cold trap' theory was supported by another decontamination late December 2008 / early January 2009 when the channel 7 and 8 throughput values exhibited exactly the same behaviour.

7.3 Line-of-Sight (LoS) Pointing Performance

Knowledge of the LoS was a key parameter in retrieving correct and reliable geolocation information. Particularly for SCIAMACHY's limb mode a necessity for obtaining useful measurements was the accuracy of reconstructing altitudes in general and tangent heights in particular from elevation and azimuth angles. Because of the large distances involved in limb geometry – about 3200 km from the instrument to the Earth's horizon – even small pointing uncertainties translated into large tangent height errors. For SCIAMACHY on ENVISAT, a pitch pointing error of 1 arcmin shifted retrieved profiles by 1 km.

7.3.1 Platform Attitude

Early in the mission, geolocations derived from SCIAMACHY limb data, using the TRUE (Tangent Height Retrieval by UV-B Exploitation) method, revealed that the operationally generated tangent height information differed by as much as 3 km from what was expected. The TRUE results were considered reliable as long as the technique was restricted to tropical latitudes, e.g. between 20°N and 20°S. The offset between the operational tangent heights and those derived with the TRUE method showed a strong seasonal variation with a mean amplitude of 0.8 km and a constant bias of 0.5 km. The sinusoidal seasonal modulation was superimposed on a linear trend with a gradient of about 0.4 km per year. ENVISAT's on-board processing of state vector parameters uplinked from ground was identified to be the source of the observed pointing inaccuracy. In a corrective action, the s/w algorithm for deriving such parameters on-ground was upgraded and implemented in December 2003 around orbit 9300. This resulted in a reduction of the tangent height jumps observed around the times of the daily updates of the on-board state vector and of the seasonal variation of the tangent height offset. When using residual ENVISAT platform pointing information in pitch, roll and yaw (AUX_FRA files), the mean amplitude of the offset amounted now to about 0.2 km with the linear gradient reduced by a factor of 3. However, the bias increased to 1.5 km and remained practically stable over a year (Fig. 49).

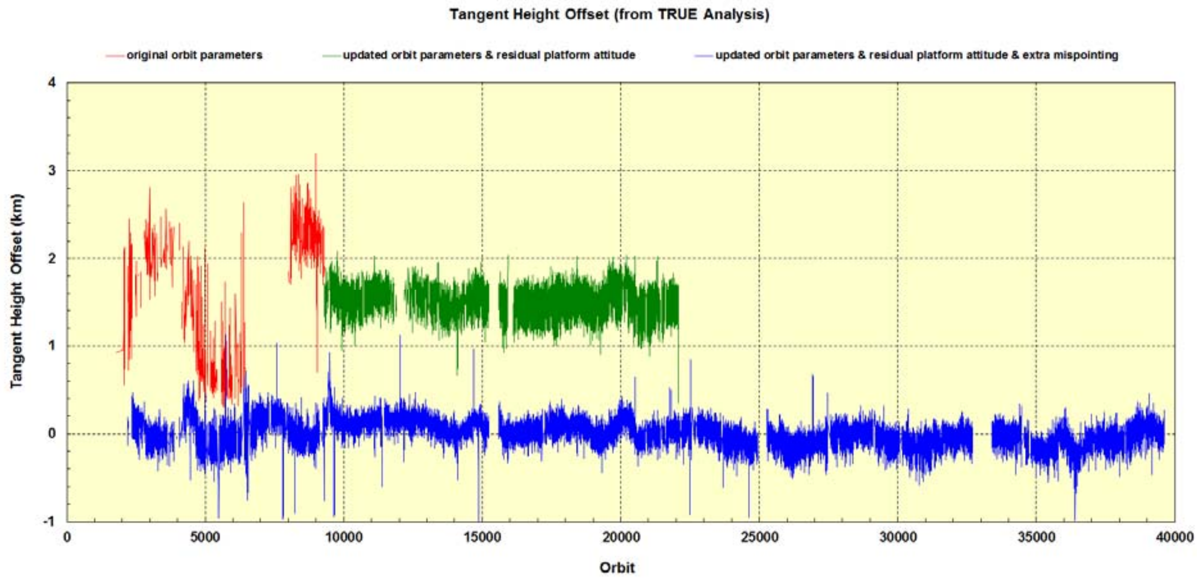


Fig. 49: Tangent height offsets as determined from operational data products and TRUE retrieved profile information. Prior to December 2003, the bias had a strong harmonic variation (red). After the update of the on-board propagator model and including residual platform mispointing, the variation was reduced but a constant offset persisted (green). When the extra mispointing was introduced in geolocation retrieval this offset vanished (blue).

7.3.2 Extra Mispointing

Since the Commissioning Phase it was well known that SCIAMACHY's LoS exhibits small inconsistencies. They became apparent in Sun occultation and subsolar measurements, particularly when the scanner control was switched to the Sun Follower (SF) and comprised

- in the SO&C window
  - an elevation jump of about -0.04° when acquiring the Sun with the SF in elevation above the atmosphere after following the solar track with a predicted elevation rate in the ESM control (state 47 – Fig. 50)
  - an azimuth jump of +0.1° when acquiring the Sun with the SF in azimuth at an altitude of 17 km (state 47 & 49 – Fig. 52)
- in the subsolar window
  - an elevation jump of about -0.02° when acquiring the Sun with the SF in elevation above the atmosphere (state 53 – Fig. 51)
  - a time shift of the maximum signal of the Sun w.r.t. the subsolar state center (state 53 – Fig. 53). Note: this is an extra shift compared to what was known from pre-launch misalignment measurements which were accommodated by timeline design.

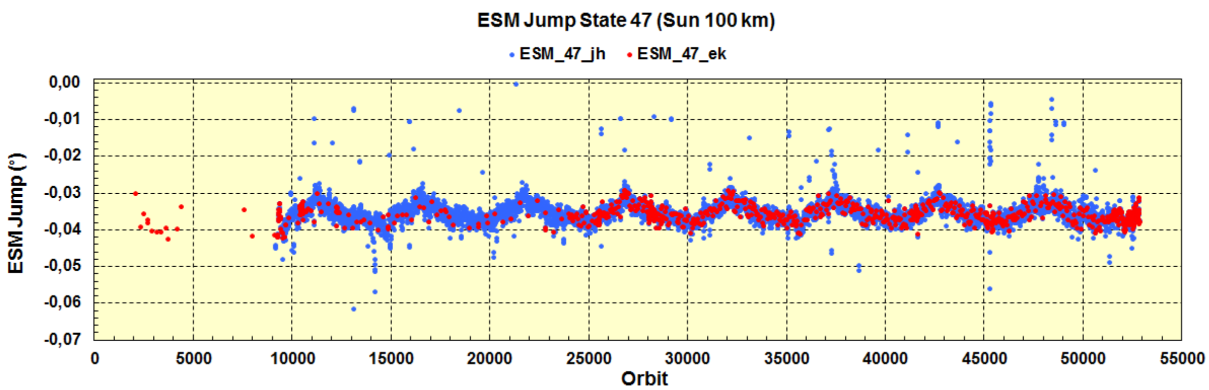


Fig. 50: Measured ESM jump in state 47 execution when acquiring the Sun with the SF. Red and blue dots are the results from two independent jump calculation algorithms.

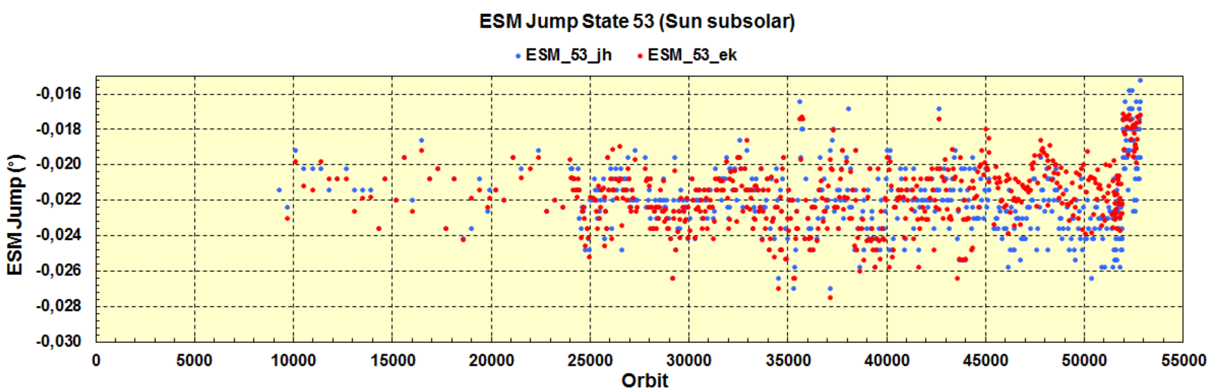


Fig. 51: Measured ESM jump in state 53 execution when acquiring the Sun with the SF. Again, red and blue dots are the results from two independent jump calculation algorithms.

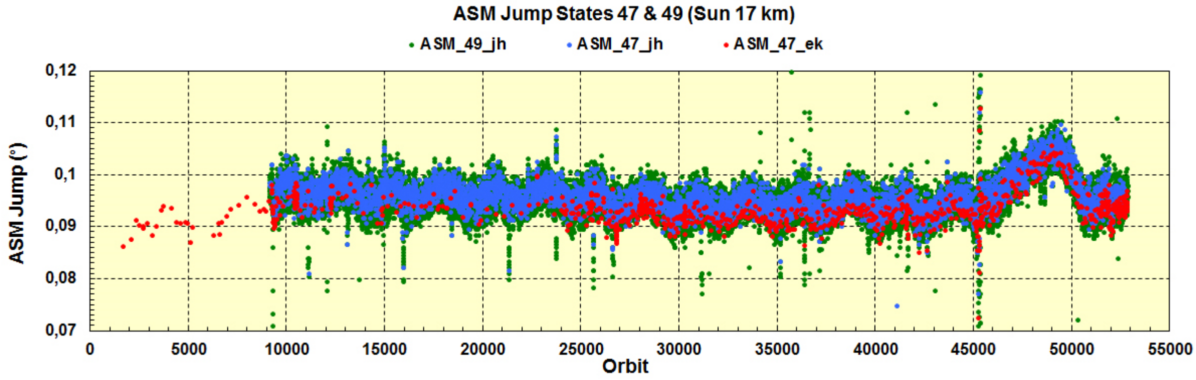


Fig. 52: Measured ASM jump in state 47 and 49 execution when acquiring the Sun with the SF. Different colours stand for different jump calculation algorithms.

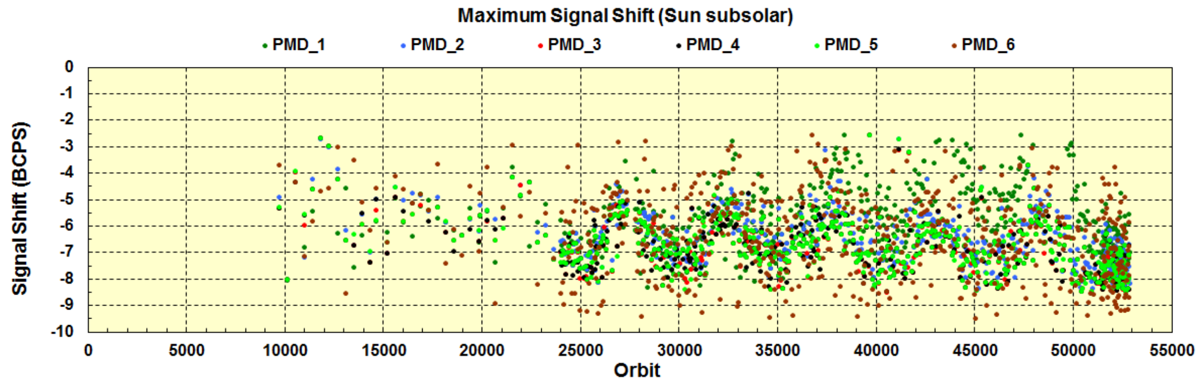


Fig. 53: Time shift between when the maximum PMD signal was measured and the time when it was expected in subsolar state execution.

Before launch the misalignment of the instrument LoS in all three axes had been measured. The corresponding values are listed in Table 20. They were stored on-board (Scanner Constants table) and compensated in the scanner control via the *optical zero correction*. Thus, the observed pointing inconsistencies could not be attributed to this known misalignment. Assuming that the SF worked as specified, the jumps observed in ESM and ASM readings and the time offset could be interpreted as an additional instrument mispointing or an additional scanner encoder offset.

Known boundary conditions limited the possible range of the extra misalignment. These included

- Subsolar elevation: An extra roll misalignment must have been close to the size of the observed jump (-0.020 deg)
- Subsolar time shift: An extra yaw misalignment could not exceed a few 0.010° because otherwise the time shift would have been larger than about 5 BCPS (note: the known instrument misalignment of -0.227° caused a shift of the subsolar condition by about 2 sec and was corrected via the definition of the corresponding subsolar timelines).
- Limb tangent height offset: The observed limb tangent height offset of 1-2 km limited an extra misalignment in pitch to a few 0.010°.

In an iterative approach the observed scanner reading jumps and the time shifts were modelled by applying various mispointing angles in the ENVISAT CFI routines and simulating the azimuth and elevation angles during the SF acquisition. Best agreement with the measured pointing inconsistencies was achieved when assuming extra mispointings as listed in Table 21.

Axis	Instrument Misalignment (°)	Extra Mispointing (°)
pitch	+0.000630	-0.026 ± 0.003
roll	+0.001662	-0.020 ± 0.001
yaw	-0.227464	+0.009 ± 0.008

Table 21: SCIAMACHY instrument misalignment measured before launch and the modelled extra mispointing.

Particularly the values in pitch and roll helped to correct the retrieved altitudes from limb measurements. The tangent height bias was reduced to almost 0 km as obvious in Fig. 49 with an uncertainty of about 150-200 m.

Having obtained such a high accuracy in altitude determination will permit investigations of the remaining residual effects, e.g. a seasonal trend with an amplitude of 150 m became obvious or whether the observed ASM jump could be attributed to an ASM specific offset. Additional studies in phase F will try to improve the extra mispointing characterisation even further.[4]

7.3.3 Scanner Stability

Because of their design and qualification history, both the ESM and the ASM were not considered to be critical mechanical subsystems. When the end of the nominal specified mission lifetime was reached in March 2007, however, the scanners became subject of regular monitoring. This ensured early detection of potential degradation of the scanner performance and development of appropriate countermeasures. Since no dedicated scanner monitoring procedures were described in the IOM, three indirect methods were used to derive the scanner status

Scanner currents during state 65 execution – nominal telemetry

Taking the existing on-board resources into account the investigations related to the ENVISAT mission extension identified the periodic evaluation of the power consumption values of the scanners as a suitable method to identify degradation of the scanner mechanisms. From the list of 70 different nominal states only state 65, the 'scanner maintenance' state, had been selected for that purpose. This state was based on a uniform and fully reproducible motion of both scanners and did not depend on any orbit or target parameters. State 65 served three purposes

- to further the lubrication of the scanner bearings
- to recalibrate the encoder Zero-point of both scanners
- to perform the ADC calibration

At the start of state 65 the instrument was initialised including moving both scanners from their idle to their starting positions, which were defined by the state parameter settings for state 65.

[4] In the SQWG phase F an improved mispointing model is introduced which includes offsets for both the ASM and the ESM. Preliminary results comply, qualitatively, with the mispointing angles as derived in phase E. Quantitatively they constrain the roll, pitch and yaw mispointing further and by using scanner specific offset permit to consider state dependent effects.

This part also executed the Analogue to Digital Converter (ADC) calibration of all 8 Detector Module Electronics (DME) by the Science Data Processing Unit (SDPU) upon receipt of the first Broadcast Pulse for Synchronisation (BCPS). This phase took about 2 sec. In the second part of state 65 execution, the measurement part of state 65 occurred. The motion of both scanners was defined by the related scanner state parameter file and controlled by the Power Mechanism and Thermal Control Unit (PMTC). A 360° turn of both scanners and a reverse motion taking 10 sec each were specified. At the end of the measurement phase both scanners were commanded back to their idle position. After the measurement the close-up phase occurred. In that part the calibration of the encoder zero-point was executed. It started with sending the primitive command 'Scanner ON' to the ASM and 56 counts (1 count = 1/256 sec) later to the ESM. This command activated the scanner position control. It performed another unidirectional 360° rotation at a predefined speed of 45.837°/s from the already acquired idle position. In parallel the encoder initialisation routine searched during the scanner operation (duration ≈ 7.85s) for the zero reference position signal and initialised the encoder. When the encoder counter had been initialised, an encoder zero position initialisation flag was set. For each scanner this command took about 16 sec. Thereafter the state was terminated after a total duration of 42.2 s.

Scanner degradation was assumed to manifest itself as an increase of friction within the bearings. The scanner control system could overcome this by operating the scanners at higher currents. Current values of both scanners were continuously generated on-board with a time resolution of 1 sec and each 16^{th} sec value was recorded in the House Keeping (HK) telemetry. These recordings were not synchronised with the start of a state and also not with the BCPS providing the timing for the state execution. Due to this fact the readings occurred at different phases during the execution of the state. As the total duration of state 65 amounted to 42.2 s, 2 or maximum 3 values telemetry readings could be recorded with 1 or 2 values originating from the 20 s of the measurement phase. For each state execution 1 value could be taken during the close-up of the state.

The monitored scanner currents HK parameters *CW_Max* (*ClockWise*, parameter I0116 for ASM, I0126 for ESM) and *CCW_Max* (*CounterClockWise*, parameters I0117 and I0127) represented the maximum motor currents based on a 25 Hz sampling of the 2 directional drive chains of the ASM and the ESM. The *Mean* value (parameters I0118 and I0128) was calculated already on-board. The horizontal 'bands' visible in the diagrams (Fig. 54 and Fig. 55) indicated the existence of discrete current levels, which corresponded to higher consumption during acceleration/deceleration and lower levels during constant motion or when counterbalancing the accelerating/decelerating other drive. The mean current parameter was centered at 0 mA as expected. The one-sided outliers indicate that power peaks were present, being recorded at the low sampling rate of 1/16 Hz only occasionally at the maximum/minimum recordable values of ±170.5 mA.

Both the ASM and ESM currents displayed some variations over the mission lifetime. This was, however, far below the assigned current limits of ± 172 mA and therefore considered uncritical.

Scanner currents during execution of representative states – nominal telemetry

In addition to state 65, scanner currents were also extracted whenever a typical nadir state (ID 2), limb state (ID 33) and a Sun occultation state (ID 49) had been executed. This yielded further insight into the overall stability of scanner motions (Fig. 56 and Fig. 57). As for state 65, all observed variability beyond the regular patterns as a result of the particular scanner motions during state execution did not approach the limits or showed any other signs of degradation.

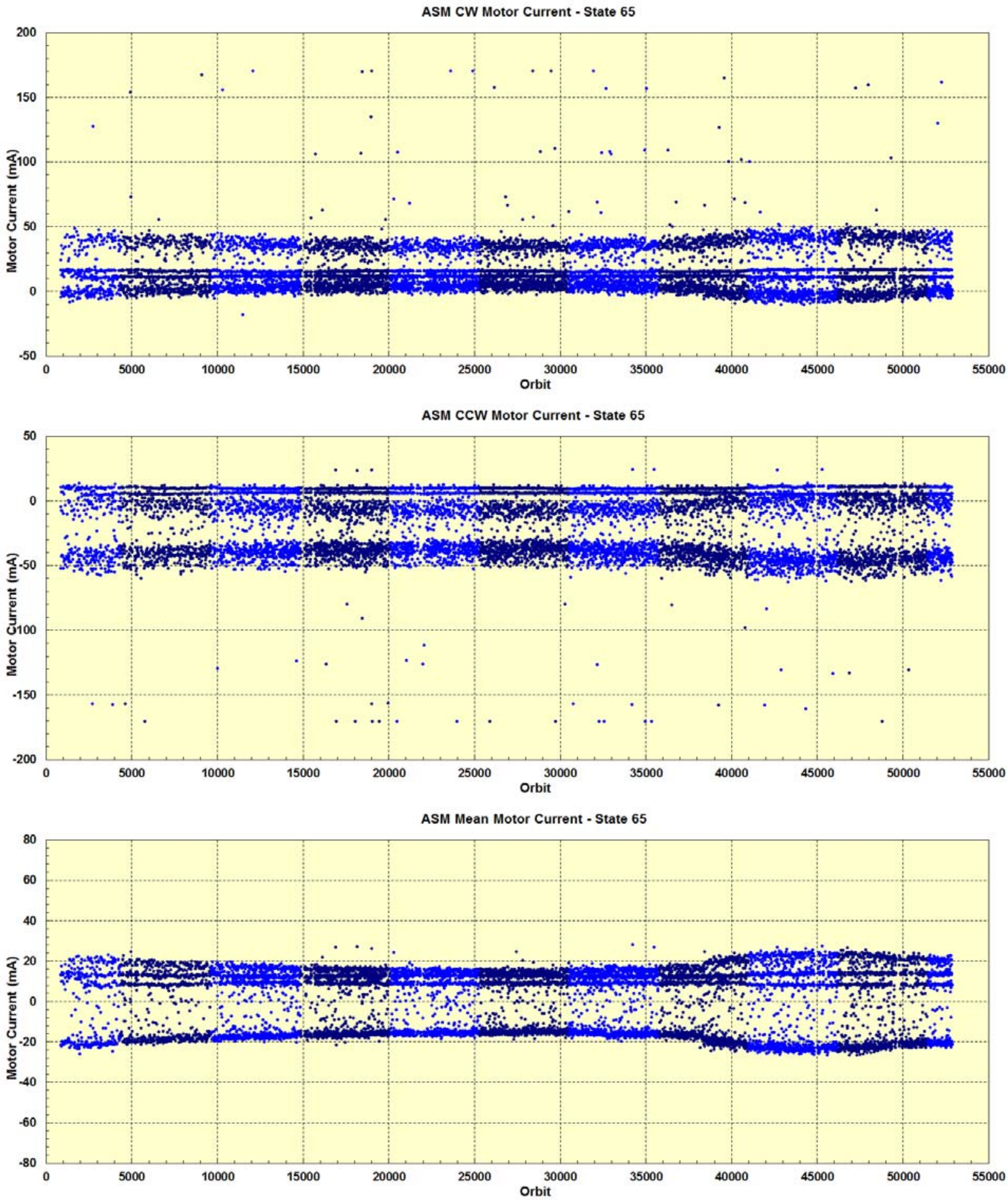


Fig. 54: ASM motor currents during state 65 execution. Individual years are separated by using bright/dark blue colours.

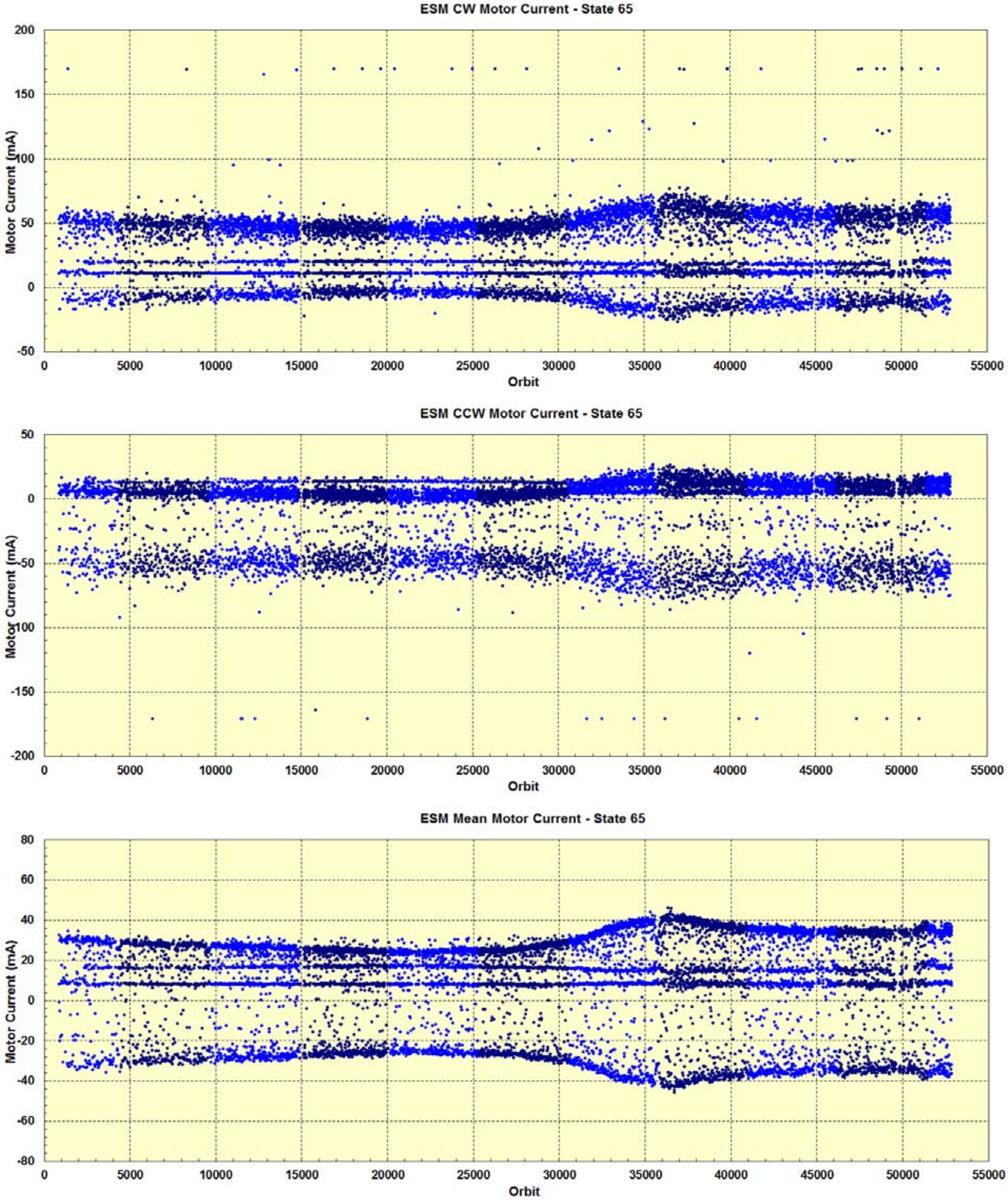


Fig. 55: ESM motor currents during state 65 execution. Individual years are separated by using bright/dark blue colours.

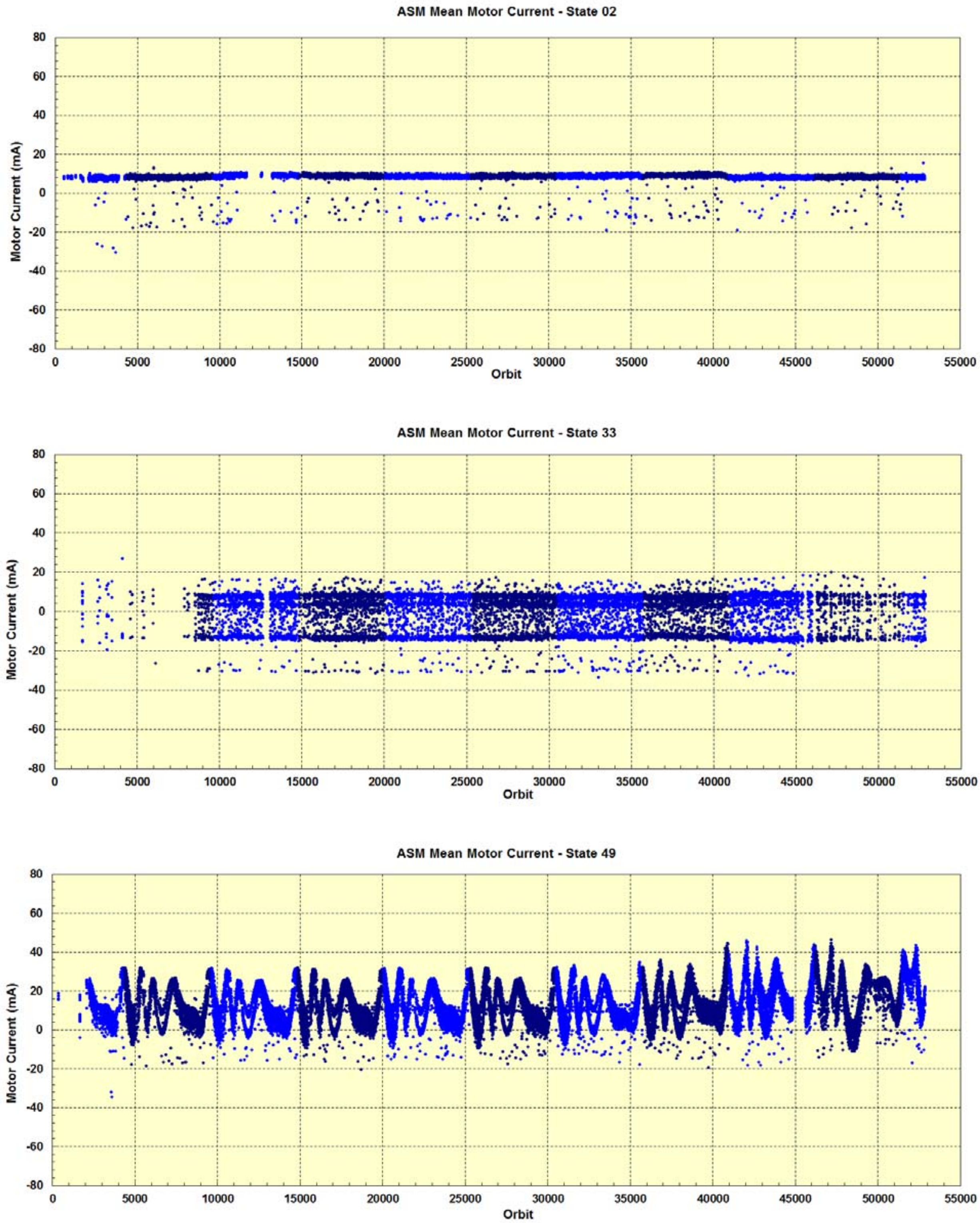
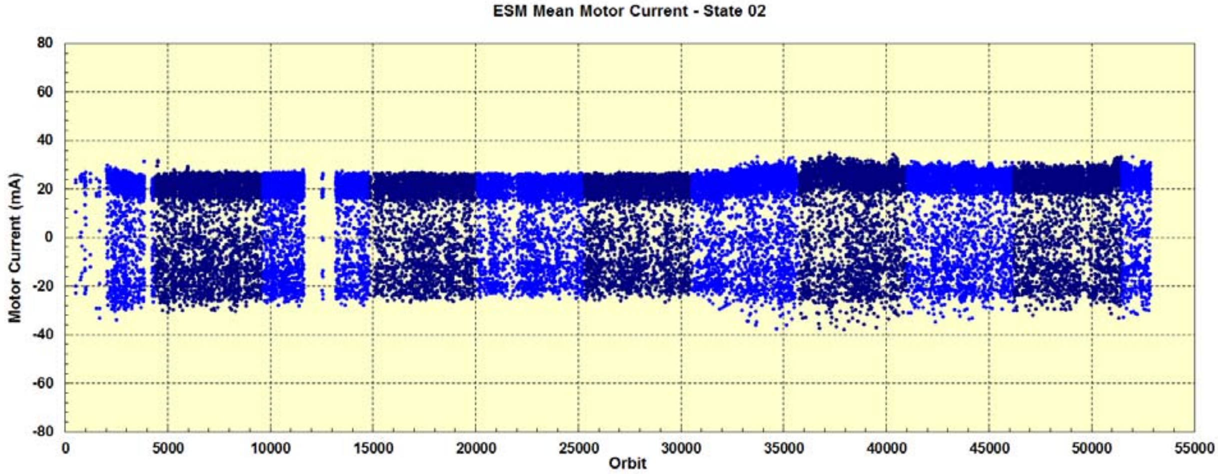
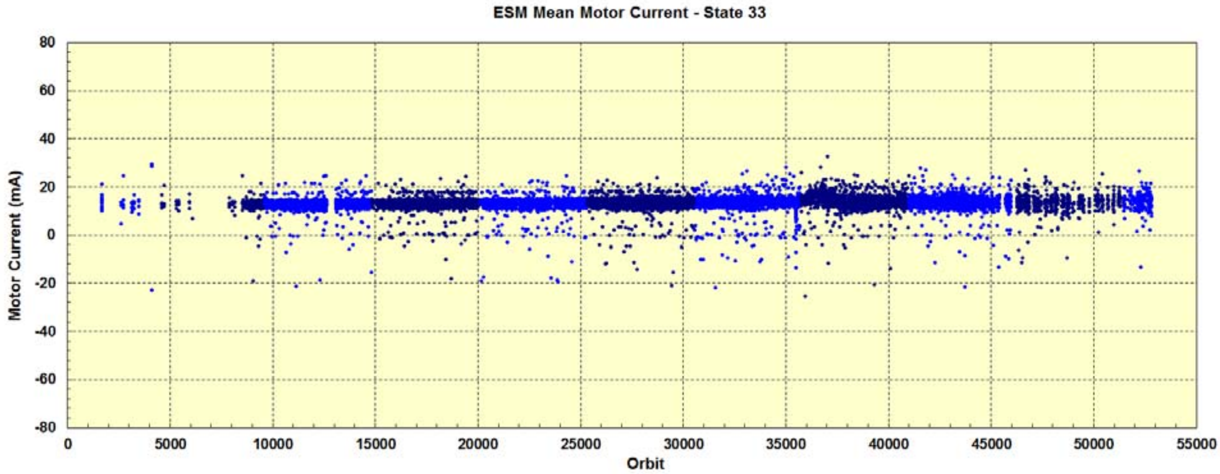


Fig. 56: ASM Mean motor currents during execution of a nadir state (ID 02, top), a limb state (ID 33, middle) and a Sun occultation state (ID 49, bottom).





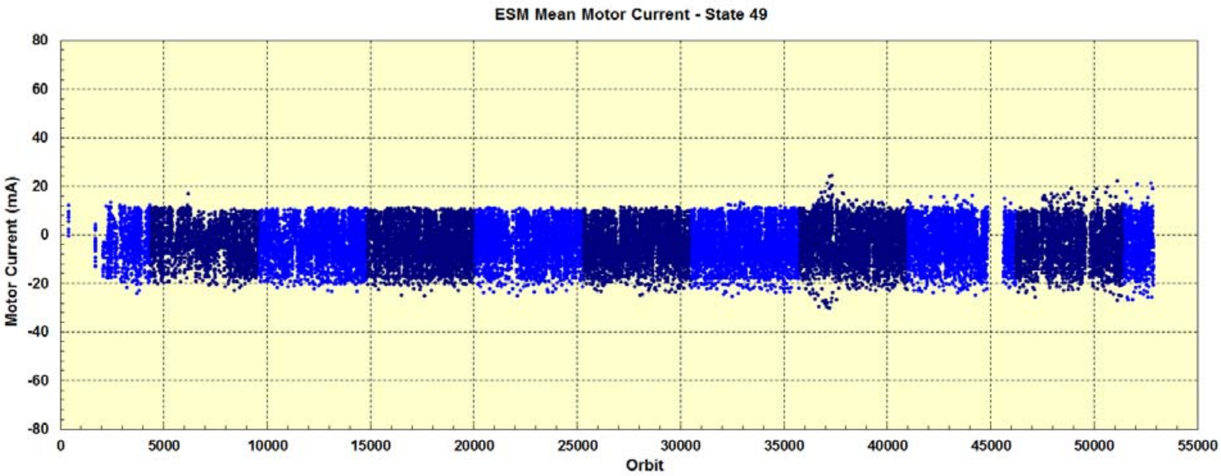


Fig. 57: Same as Fig. 54 but for the ESM Mean motor current.

Scanner currents during state 65 execution – non-nominal telemetry

When the first phase of the mission extension had started, a better insight into the scanner current profiles was achieved by recording Non-Nominal Telemetry (NNTM) during execution of state 65. NNTM sampled HK parameters at a rate of 1 Hz. The first 4 orbits with state 65 NNTM occurred in June 2008 and were repeated each year afterwards at the same annual phase.

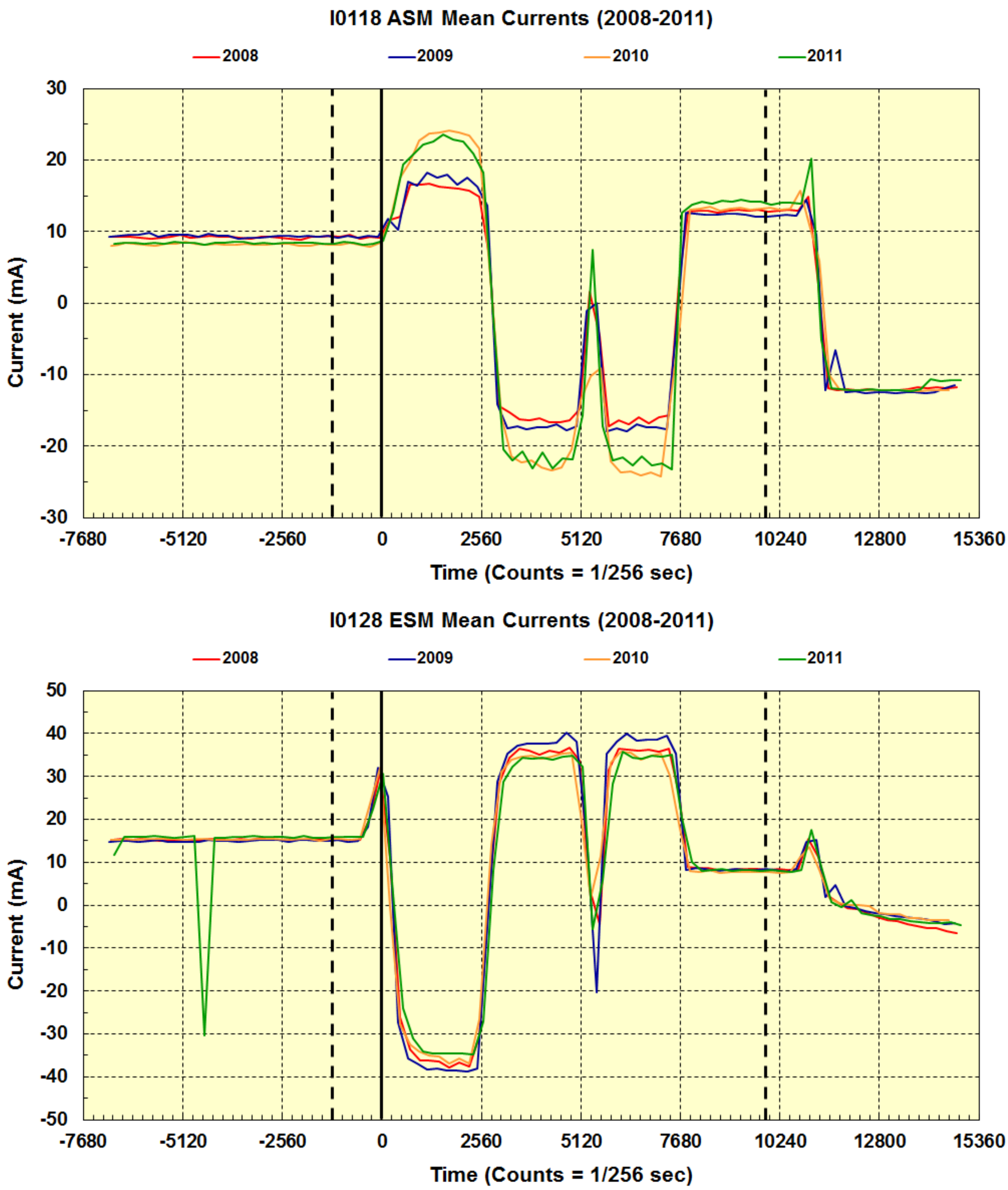


Fig. 58: ASM and ESM Mean motor currents, averaged over all 4 NNTM orbits each year. The dashed vertical lines indicate start of the state (left) and start of the next timeline (right) while the solid vertical line outlines the start of measurements in the state 65. Variations between consecutive years are minimal.

The NNTM profiles displayed the evolution of the motor currents in great detail. The horizontal levels obvious in Fig. 54 and Fig. 55 could be well resolved. They corresponded to certain phases of the state 65 when the currents remained stable for a while. Fig. 58 illustrates the Mean current of the individual NNTM campaigns, averaged over all 4 orbits. The variation between consecutive years is small, i.e. degradation was not considered an issue for both scanners.

Elevation and azimuth jumps in Sun states

The jumps in ESM and ASM readings used for extracting an extra instrument mispointing (see above) served also the purpose of scanner monitoring. As long as the jump patterns remained stable the performance of the complete chain leading to an accurate LoS pointing was understood not to change. Since this chain included the scanners but also items such as e.g. scheduling parameters derived on-ground in the ENVISAT mission planning s/w, platform stability or Sun Follower performance, the results derived via this method were less significant for judging scanner degradation than when monitoring scanner currents.

In Fig. 50-53 the overall patterns appear rather stable supporting the conclusions from the other scanner monitoring activities of no obvious scanner degradation. Only with the orbit lowering ENVISAT manoeuvre in October 2010 a change in Fig. 51-53 could be inferred. It is, however, unlikely that it originates in a different scanner performance. A more probable explanation is that the orbit propagation in scanner control algorithms and the associated parameters uploaded from ground via the START TIMELINE MCMD were not fully compliant. It would have been illustrative to acquire another year of jump behaviour helping to pin down the real cause for this phenomenon.

7.4 Life Limited Items – LLI

Life Limited Items included

- Aperture Stop Mechanism (APSM)
- Neutral Density Filter Mechanism (NDFM)
- Nadir Calibration Window Mechanism (NCWM)
- White Light Source (WLS)
- Spectral Line Source (SLS)
- Cryogenic Heatpipe

None of them was fully redundant. Due to their criticality, particularly for the APSM and NDFM, the usage of LLIs required close monitoring.

Except for the Cryogenic Heatpipe the use of LLIs depend on the implemented mission scenarios comprising for routine operations

- solar occultation every orbit
- daily calibration with 2 orbits
- subsolar measurement every day (or every third)
- weekly calibration with 2 orbits
- monthly calibration with 5 orbits

Usage of the Cryogenic Heatpipe was triggered in each decontamination. In the case of APSM and NDFM a dedicated in-flight procedure was executed every 2 months to check for the health of the mechanisms. This procedure supplemented the NDFM and APSM activations from solar observations.

Each LLI had a specified total budget (number of allowed switches, cycles or burning times). By considering the on-ground usage during test campaigns in phase C/D, the maximum allowed in-flight budget, i.e. the End-of-Life (EOL) budgets could be derived. For safety reasons a margin factor had been introduced which limited the maximum LLI usage as derived from lifetime tests to a certain percentage (AD [1] and RD [14]).

The NCWM, with a margin factor of 1 and a low EOL budget value required particular attention. Originally a first life cycle test yielded a total budget of 110000. With a margin factor of 2 this translated into an operations budget of 55000 cycles. However two non-conformances occurred during phase C/D. At very low temperatures the NCWM did not open as expected and the fixation of the motor's rotor to the shaft had to be improved. After modifications to the NCWM a second test sequence was run which verified that the mechanism executed 3000 cycles without any sign of degradation. The number of 3000 was selected because it corresponded to the predicted maximum number of subsolar measurements in 4.5 years of routine operations. This figure became the budgeted use of the NCWM in the IOM although the final NCWM verification test was not a lifetime test and the motor of the NCWM was identical to those for the APSM and NDFM which were assigned much larger in-flight budgets.

LLI	Specified Budget (EOL)	Margin Factor	Accumulated Budget (08-Apr-2012)	Relative Usage
NDFM*	49000	2	66832	0.68
APSM*	49000	2	61718	0.63
NCWM	2400	1	2360	0.98
WLS (cycles)	7500	1.5	1509	0.20
WLS (hours)	25	1.5	9.2	0.37
SLS (cycles)	24317	1.5	2143	0.09
SLS (hours)	477	1.5	10.3	0.02
Cryo Heatpipe	40	2	16	0.40

* margin factor not applied

Table 22: LLI usage as specified and as accumulated between 2002 and 2012.

Table 22 includes the EOL budgets together with the actual usage, both from the Commissioning Phase and the routine operations phase. In addition, an average number of about 1100 for the NDFM and APSM from the health tests was added. Because of extending SCIAMACHY operations well beyond the specified 5 years in-orbit lifetime, it became necessary in 2007 to adjust the NDFM and APSM EOL budgets to the envisaged much longer mission duration. This was accomplished by no longer considering the margin factor for both LLI. The NCWM accumulated usage would have violated its EOL value when operating throughout 2012. However this would have been uncritical because of the peculiar way the EOL budget had been determined.

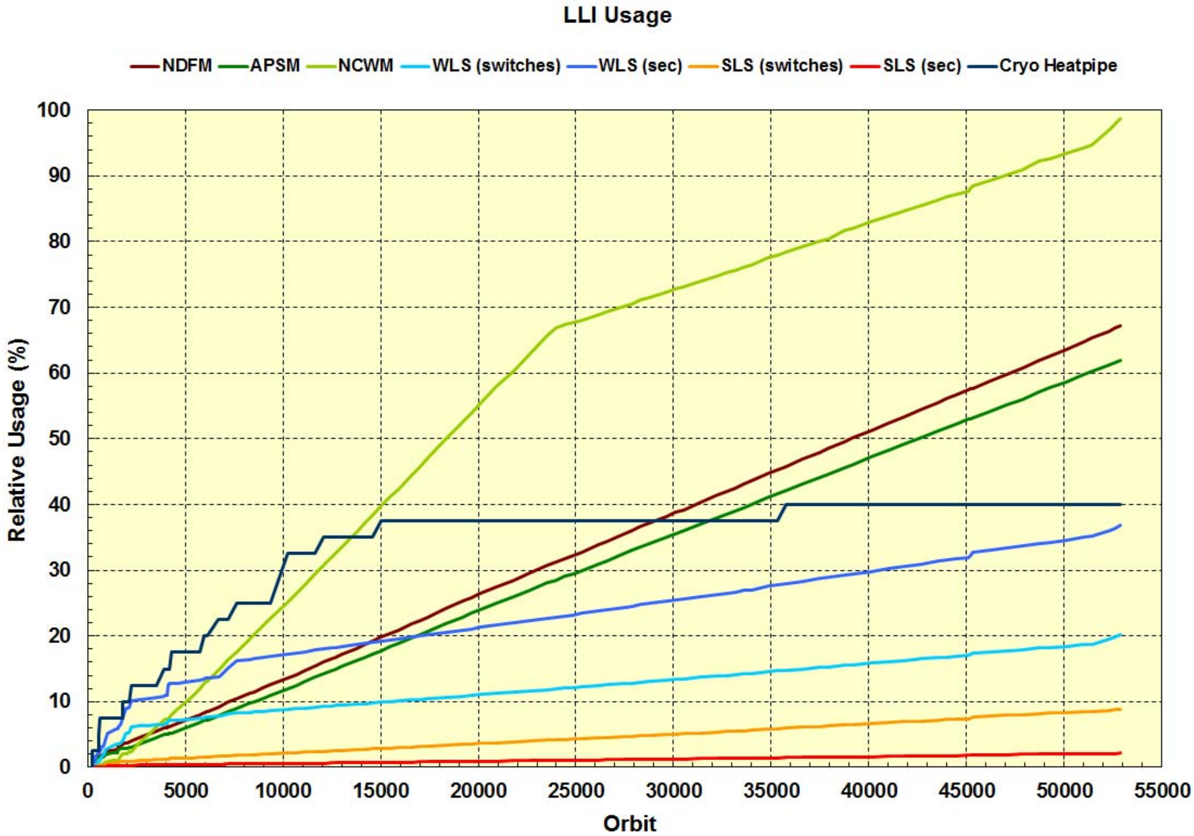


Fig. 59: Evolution of LLI usage with time.

Fig. 59 displays how the usage of individual LLIs evolved with time. In the routine operations phase the trend was linear. Only for the NCWM a change occurred mid 2006 when the rate of subsolar measurements was reduced from 1 per day to 1 every 3 days. In January 2012 this was reversed and the subsolar rate was back to 1 per day. The usage of the Cryo Heatpipe accumulated stepwise early in the mission because of the frequently occurring decontaminations. Later, only a single NNDEC had been added.

8. Consolidated Level 0 Availability

Consolidated level 0 (cL0) data represented the planned and executed measurements as good as possible. Each consolidated product started at the time when ENVISAT crossed the equator at a particular ANX and ended when this occurs for ANX+1. Therefore, the consolidated products were expected to contain all measurements for a specific orbit. Only in cases of instrument unavailability, either triggered by a planned transfer to a mode lower than MEASUREMENT or an unexpected spacecraft or instrument anomaly, the consolidated products did not exist or deviated from planning.

Since SOST maintained a complete record of operation execution information including planning and scheduling, SOST was the prime candidate for judging the quality of the cL0 data. Such cL0 performance verification was particularly useful for the entire processing chain level 0-1b and level 1b-2 because it relied on the availability of a consistent set of cL0 data. Any cL0 anomaly would propagate into level 1b and level 2 products and could spoil the quality of these repositories.

8.1 Consolidated Product Quality Issues

Consolidated products were generated at the Low Rate Archive Centre (LRAC) and delivered to D-PAC since early 2003. With the delivery of the first cL0 products it became obvious that the consolidation process was hampered by various inconsistencies leading to non-compliances between expected and delivered product content. These included:

- large time delays between sensing and archiving at the D-PAC up to 1 month and longer
- cL0 products with incorrectly assigned orbit number: occurred particularly frequently until late October / early November 2003.
- multiple products for one orbit: products could be identical or different in content.
- missing orbits: no cL0 product was generated although SCIAMACHY was in MEASUREMENT TIMELINE mode.
- orbits covered by cL0 products but the product duration did not comply with the actually planned and executed instrument operations in that particular orbit.
- cL0 products exceeding the Reed Solomon correction threshold: Reed-Solomon error flagged products occur non-uniformly.
- cL0 products with corrupt measurement data, often related to sync bit errors

Over the mission lifetime, the quality of the cL0 data increased considerably. However, inconsistencies persisted such that a continuous check of the cL0 performance remained necessary.

8.2 Consolidated Product Consistency Checking

A sequence of individual checking routines had been applied to each available cL0 product for verification of information retrieved from the

- filename
- Main Product Header (MPH)
- Secondary Product Header (SPH)
- data format: all data is read and format checked

If all related checks were passed successfully, the cL0 product was accepted. If not, the corresponding failure was analysed in more detail. In an iterative process with ESA it was finally tried to improve on the erroneous orbits via reconsolidation. This approach could not detect occasional cases such as

- missing data records in states where two NRT (unconsolidated) products were combined to yield the consolidated product
- missing or duplicated sequences of states

because it would have required analysis of the full data content on measurement state level. It is one of the goals for phase F to also identify and reconsolidate cL0 data affected by such flaws.

With the selected approach a high level of cL0 availability was achieved (Fig. 60). When considering those orbits with instrument unavailabilities, between 95-96% of the orbits with instrument availability were covered with cL0 products in the early years of the routine phase. Later, this number even came close to an unprecedented level of 98%.

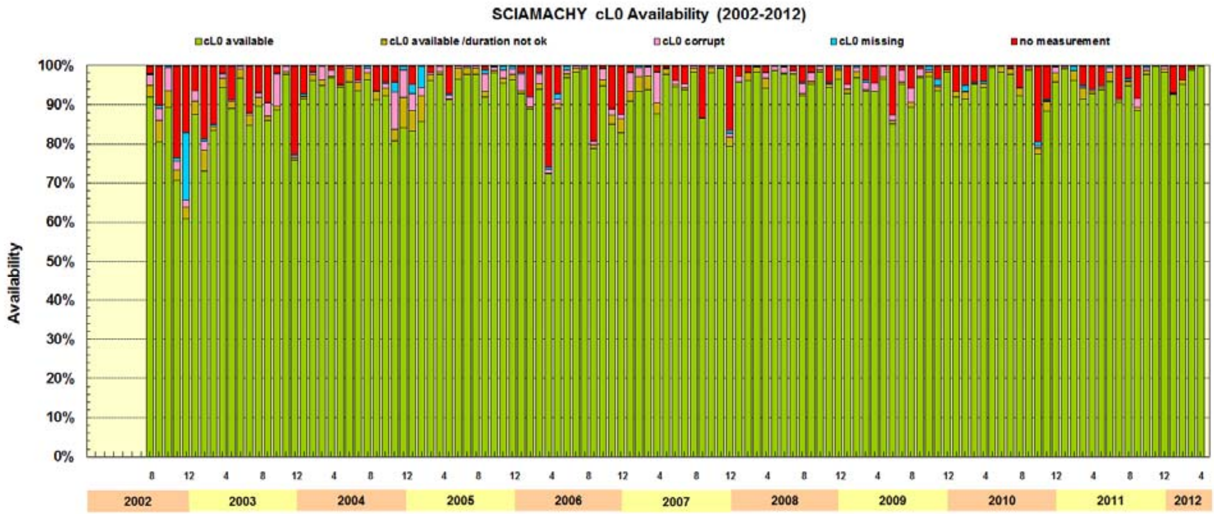


Fig. 60: Availability of cL0 products between 2002-2012. The red columns indicate when SCIAMACHY was not measuring, either because of planned idle orbits or an instrument/platform anomaly. For April 2012 the availability was calculated using only the period until the loss of the platform.

9. Lessons Learnt

The list of *Lessons Learnt* for a particular aspect of the SCIAMACHY mission has always to be given by the entity being responsible for just this aspect. Therefore, what SOST can present here is mainly driven by SOST's own experience. Calibration and monitoring experts, algorithm and processor developers, scientist using SCIAMACHY data, industry developing and agencies providing the instrument would come up with additional topics.

The *Lessons Learnt*, acquired in more than 10 years of SCIAMACHY in-orbit operations include

- **Hardware and operations concept**: Specifying and developing in phase C/D an instrument with the goal to achieve an excellent piece of hardware is a prerequisite for successful in-orbit operations. This should be accompanied by establishing an operations concept which is on one hand flexible to accommodate modified scientific or operational requirements during operations but on the other hand should provide continuity. It implies that the instrument and its command and control concept are designed such that instrumental settings can be easily changed from on ground. This worked quite well for SCIAMACHY.
- **Instrument control concept**: Instrument operations also gained a lot from the control logic for on-board monitoring and failure detection. This had turned out to be a very elaborate concept. No non-recoverable failures had occurred and the instrument anomalies could be recovered following predefined procedures.
- **Instrument characterization**: It should be possible to verify (better: determine) instrumental key data based on in-flight measurements to account for changes of the instrument between on-ground calibration and in-flight. For SCIAMACHY e.g. the detector memory effect could be re-determined in-flight using the on-board white light source.
- **Calibration and monitoring**: Several aspects can be addressed such as, e.g.
  - Instrument and operations should be designed such that calibration and monitoring information may be obtained in a redundant way. For SCIAMACHY it was e.g. possible to monitor the nadir light path via solar and internal lamp measurements.
  - Additionally, monitoring of all instrumental parameters, functional and performance, should be possible based on in-flight measurements.
  - For SCIAMACHY the radiometric calibration/monitoring concept assumed that the Sun is – except for geometric factors – a constant light source. To be able to account for changes in the solar flux, e.g. due to the solar cycle, it would have been useful to have an absolutely calibrated light source on-board.
  - The design of the instrument should consider the required on-board calibration/monitoring hardware. Particularly, if the instrument is polarisation sensitive, a polarised light source should be foreseen. For SCIAMACHY, polarisation changes could not be monitored in-flight.
- **Contamination**: One of the areas where operations – and even more retrieval – was hampered by the instrument status was the recurring ice layer in channels 7 and 8. It was discovered as a surprise in the Commissioning Phase but could perhaps already have been addressed in phase C/D. Contamination experts were hard to find before launch. The information SCIAMACHY was provided with in phase C/D turned out to be unrealistic. Properly addressing contamination might have resulted in suitable on-board devices for efficiently removing contaminants (ice) or even dedicated means for monitoring contaminants. However it also has to be mentioned that SCIAMACHY's flexible operations concept permitted to establish work-arounds, i.e. non-nominal

decontamination with a well defined sequence of warm-up/cool-down activities, which helped to recover the performance of the IR channels 7 and 8.

- **LoS pointing knowledge**: The SCIAMACHY LoS pointing knowledge had improved considerably over the mission lifetime, partially because of corrections on platform level and partially as the result of in-depth analyses of available pointing information. However the tight geolocation requirements in limb observations were particularly challenging and still left some questions unanswered. When improving the LoS pointing knowledge, SOST and partners could only use the available – but limited – information. Additional means for pointing analyses, e.g. SF data with higher data rate, would have been an asset.
- **cL0 verification**: Instrument monitoring used level 0 measurement data in consolidated format. Therefore an unambiguous cL0 data set was a must for all in-orbit mission phases. When the Payload Ground Segment was specified, this aspect had not been addressed such that a verification of the quality of the cL0 data had to be implemented at a later stage. Future missions should aim at generating an excellent record of consolidated data from the very beginning of a mission.
- **Involved teams**: A factor which contributed significantly to the mission success was highly motivated staff participating in industry, supporting science institutes and agencies. A good communication between the partners ensured open exchange of information and permitted to cooperate without always relying on formal rules.
- **Information exchange**: The SOST website, specified about half a year before launch and becoming operational at launch, was one of the big assets. It provided actual operations information to all mission participants, thus permitting to be always up-to-date on the instrument status. In addition, it relieved from generating numerous reports and formal documentation.

10. Summary

Since the start of quasi-routine measurements on August 2, 2002 a continuous stream of high quality data had been acquired by SCIAMACHY. With more than 10 years in orbit, SCIAMACHY's data 'harvest' considerably exceeded the original objective. Successful in-orbit operations was one of the necessary tasks for achieving this. This report illustrated the contributions of the various areas. Particularly notable were

- **Mission operations phases**: All of the mission phases – SODAP, validation, routine operations with two mission extensions – were passed with success. The ground segment functions for operating the instrument were implemented, tested and ready in time such that the planned engineering and measurement tasks could be accomplished without delays
- **Mission planning**: SCIAMACHY's planning was well integrated into the overall ENVISAT mission planning. Throughout the mission, ENVISAT planning input had been received and processed as specified. The resulting output, i.e. the SCIAMACHY input for the ENVISAT planning and scheduling tasks, was delivered in accordance with the interface control documents and no measurement time had ever been lost due to planning inconsistencies. The very rare cases where iterations between SCIAMACHY and ENVISAT had been required were handled via the well-established planning interfaces between SOST and ENVISAT.
- **Instrument availability**: The instrument executed the scheduled engineering and measurement programmes with very high availability. Throughout the in-orbit phase the instrument was well under control. None of the subsystems had failed. In cases of occasional instrument unavailabilities, recovery actions were quick and efficient. The sophisticated but flexible operations concept (elaborated back in 1995!) permitted successful operations until the end of the ENVISAT mission. It also supported implementation of modified scientific, calibration and monitoring and engineering requirements.
- **Instrument performance**: Although degradation was existent, as is always the case in the harsh in-orbit environment, the overall performance of
  - optical subsystems
  - thermal subsystems
  - LoS pointing knowledge
  - Life Limited Items

  exceeded expectations. Only water as the major contaminant hampered the usefulness of the IR channels 7 and 8 from an operations point of view[5]. However even here a solution was found by adopting the decontamination procedure appropriately such that stable conditions could be achieved for most of the in-orbit mission lifetime.
- **Data availability**: The excellent instrument performance was a precondition for accumulating an ever increasing repository of high quality measurement data. In an extra effort the level 0 data were verified based on operational experience such that finally their availability matched the status of the instrument.

When ENVISAT and its payload 'disappeared' from the screens in orbit 52868, SCIAMACHY was still in very good shape.

[5] Note that shortly after launch a light leak became apparent in channel 7. It made generation of useful retrieval results from channel 7 impossible.