# The Atmospheric Instruments and Their Applications: GOMOS, MIPAS and SCIAMACHY

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**Alarming reports on the impact of human activities on the stratospheric ozone layer, on the evolution of the global climate and on the increasing pollution of the troposphere have attracted considerable public interest during the past two decades. In an effort to try to understand the underlying chemical and physical processes and the role of anthropogenic gas emissions, the scientific community expressed a clear need for a global atmospheric observation platform. In response, a suite of three instruments dedicated to the monitoring of the lower and middle atmosphere have been embarked on ESA's polar-orbiting Envisat satellite.**

**These three instruments – GOMOS, MIPAS and SCIAMACHY – not only represent a continuation of the atmospheric ozone-monitoring mission of ERS-2/GOME, but significantly enrich the scope of the observational capabilities – mainly the number of detectable species and their vertical distribution – by making use of a variety of novel measurement techniques and enhanced spectral coverage. Their geophysical products will comprise a large number of atmospheric-state parameters, primarily trace-gas abundances, and will establish a high degree of complementarity in the information provided. Together, these data will give the user community unprecedented insight into the atmosphere's chemical and physical processes and facilitate major steps forward towards a better understanding of the future evolution of its chemical and climatological balance.**

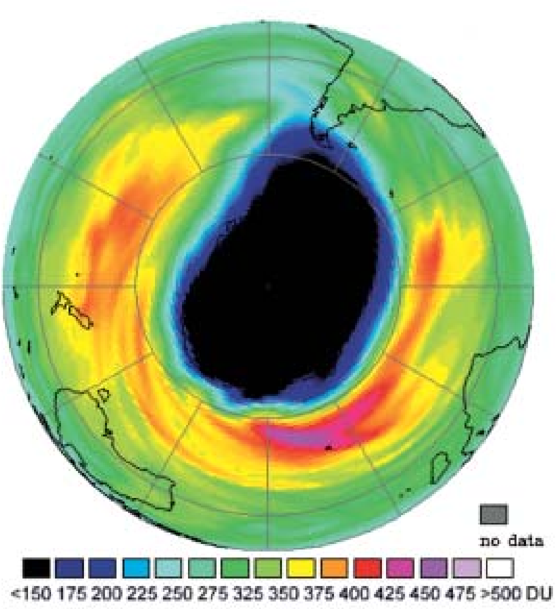


Figure 1. The ozone hole above Antarctica on 22 September 2000, from ERS-2/GOME data (courtesy of KNMI, The Netherlands)

## Envisat's atmospheric instruments: scientific rationale and mission objectives

The study of chemical and dynamical processes in the Earth's atmosphere has become of growing interest to researchers in various scientific disciplines within the past two decades. This reflects a growing public concern regarding the consequences of mankind's activities, such as:

- the dramatic ozone depletion in the Antarctic spring atmosphere, first observed in the mid-1980s
- the global warming of the lower atmosphere
- the increased pollution of the troposphere, particularly over industrial regions and biomass-burning areas.

Significant efforts have been undertaken to improve our understanding of the underlying chemical and physical processes and to establish reliable strategies for forecasting the future evolution of key atmospheric-state parameters. Various basic mechanisms, notably the catalytic destruction of stratospheric ozone due to the intake of chlorine compounds and the role of so-called 'greenhouse gases' in the Earth's radiation balance, were soon identified and led to international resolutions, such as the Montreal Protocol, seeking to limit the world-wide release of CFCs. It was, however, recognised that comprehensive modelling of the Earth's atmospheric system that takes into account primary chemical and physical interactions, relies critically on the availability of co-located, global measurements of various key trace gases, and that such measurements could best be realised by dedicated sensors carried on a (near-)polar-orbiting satellite. This concept had been exploited and successfully demonstrated by the Global Ozone Monitoring Experiment (GOME), on board Envisat's predecessor satellite ERS-2, which has been delivering total ozone column measurements since its launch in 1995 (Fig. 1).

An enhanced satellite-based observation platform should focus on a number of research objectives, in particular:
- stratospheric ozone chemistry/destruction cycles
- the role of increasing loads of chemically active species ($NO_x$, CO, $CH_4$) and of CFCs in the chemistry of the lower and middle atmosphere
- tropospheric/stratospheric exchange processes
- long-term monitoring of greenhouse gases ($H_2O$, $CH_4$, $N_2O$, $CO_2$, CFCs) and their impact on global climate
- dynamical processes in the stratosphere.

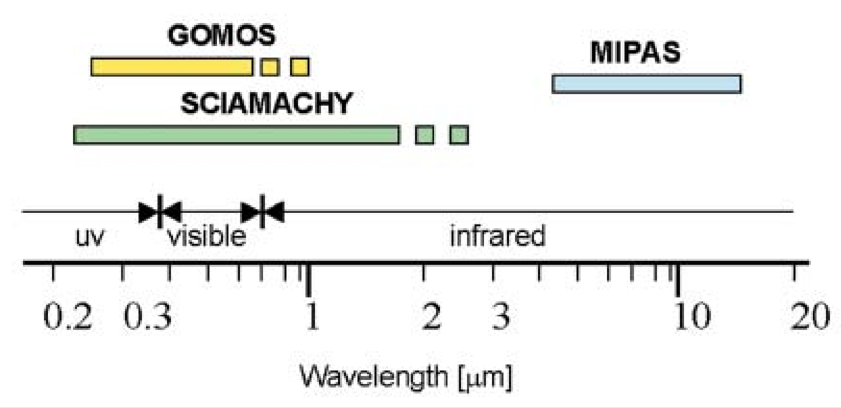


**Figure 2. Spectral coverages of Envisat's atmospheric sensors**

In response to the observational requirements formulated by a wide scientific community, a number of options for the implementation of an atmospheric mission were investigated. However, it was soon recognised that a single instrument, exploiting a single detection technique, would not be capable of serving all primary needs, both in terms of detectable species and of geographical and height range coverage. Instead, a suite of three atmospheric instruments was finally selected for Envisat:
- GOMOS (Global Ozone Monitoring by Occultation of Stars), a medium-resolution star-occultation spectrometer operating in the UV-visible-near-infrared spectral range. This instrument will primarily supply accurate middle-atmosphere ozone abundances and allow precise monitoring of global ozone throughout the mission's lifetime. Optimum performance will be achieved at altitudes between 15 and 80 km and under night-time conditions, whereas the effective sensitivity is a function of brightness and spectral characteristics of the actually tracked target star.
- MIPAS (Michelson Interferometer for Passive Atmospheric Sounding), a Fourier transform spectrometer detecting the Earth's limb emission in the mid-infrared. MIPAS will provide accurate vertical profiles of atmospheric temperature and a number of key trace gases, including the entire $NO_x$ family (except $NO_3$), and cover a height range from the upper troposphere to the lower mesosphere. As MIPAS detects the atmosphere's thermal emission, it is independent of sunlight conditions ('day- and night-side' measurements) and provides global coverage.
- SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography), a UV – visible – near-infrared spectrometer allowing observations in nadir, limb-emission and solar-occultation mode. Due to its novel observational strategy, it allows retrieval of both total vertical column densities and stratospheric concentration profiles of a number of target species. SCIAMACHY, although depending on solar illumination conditions, will be the only instrument to supply tropospheric column-density information for the primary target gases.

The spectral coverage provided by the three instruments is illustrated in Figure 2.

The three sensors together will allow unprecedented observations from the troposphere up into the mesosphere by combining novel, powerful measurement techniques with large spectral coverage – ranging from ultraviolet to mid-infrared wavelengths – and global detection capabilities.

On a routine basis, the instruments will deliver global measurements of a number of primary geophysical parameters, in particular:
- vertical temperature/pressure profiles ranging from the upper troposphere to the lower mesosphere
- abundancy profiles of molecular species ($O_3$, $H_2O$, $CH_4$, $N_2O$, $NO_2$, $NO_3$, $HNO_3$, CO, $O_2$ and BrO)
- vertical total column densities of a number of target species, and information on clouds and aerosols.

In addition to the above 'standard' products that will be processed and disseminated on a regular basis, various other species will be observable, taking advantage of dedicated, enhanced data-analysis techniques.

## Instrument concepts and observational strategies

### *GOMOS*

*Instrument design*

GOMOS operates in the ultraviolet, visible and near-infrared spectral regions and exploits a stellar occultation technique for the detection of atmospheric ozone and other trace gases. The measurement principle allows the acquisition of spatially high-resolution atmospheric transmission spectra. These spectra are computed as the ratio between the undisturbed spectrum

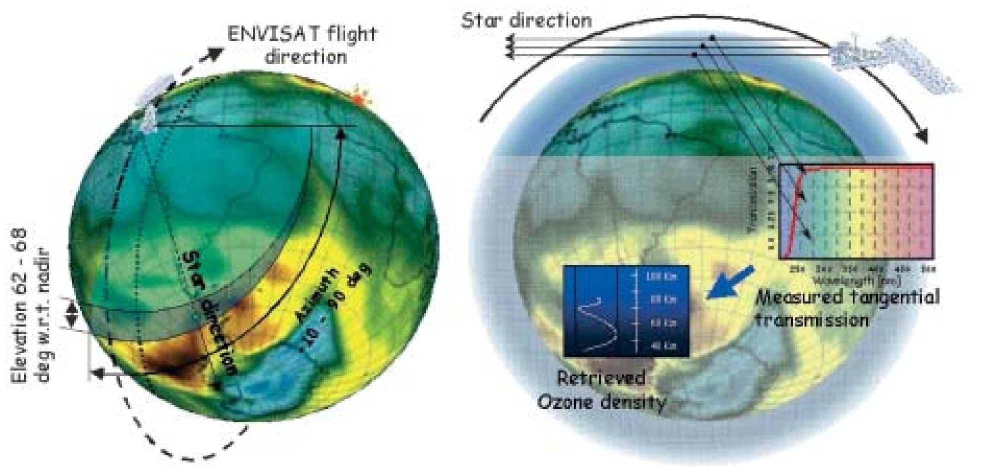


Figure 3. GOMOS viewing geometry and measurement principle. The left panel illustrates the instrument-pointing envelope (range of all possible pointing directions), whilst the right panel shows an occultation sequence. As the satellite moves away from the star, it will appear to fall behind the horizon. As the atmosphere occults the star, the acquired spectra will increasingly show absorption features (due to ozone and other gases)

of a target star, detected at tangent heights well above the atmosphere, and the occulted spectra as modified by the atmospheric absorption, obtained while the star sets behind the horizon. Using these transmission spectra and the known molecular cross-sections, the vertical trace-gas profiles are retrieved.

The primary goal of GOMOS is the accurate detection of stratospheric ozone, allowing one to monitor global trends in this species over long periods. Whilst providing ozone profiles from UV-visible occultation spectra in an altitude range of ~15 – 80 km and with a vertical resolution of better than 1.7 km, the instrument will yield small-scale turbulence measurements and high-resolution temperature profiles using two fast broadband photometers in the visible spectrum.

The instrument's line-of-sight (LOS) can be pointed over a large contiguous range, reaching from the anti-flight direction to the across-track direction (Fig. 3). It is controlled by a steering front mirror, allowing the LOS to be pointed in azimuth from -10 to 90 deg (w.r.t. the anti-flight direction), and in elevation from 68 down to 62 deg (w.r.t. nadir direction).

Initially the mirror is controlled in open loop to a fixed pre-programmed position. Once the star is detected, it is controlled in closed loop via the star tracker (Fig. 4). The observation of a particular sequence of star occultations requires the uploading of a set of star parameters that control the initial pointing direction and the apparent angular velocity (due to the satellite's motion) of individual target stars. The selection of the stars and the optimisation of the overall measurement sequence are performed on the ground for a series of orbits, and take into account the various scientific objectives. The target objects are selected from a catalogue containing about 1000 stars down to magnitude 4.5, ensuring global occultation measurement coverage throughout the year (Fig. 5).

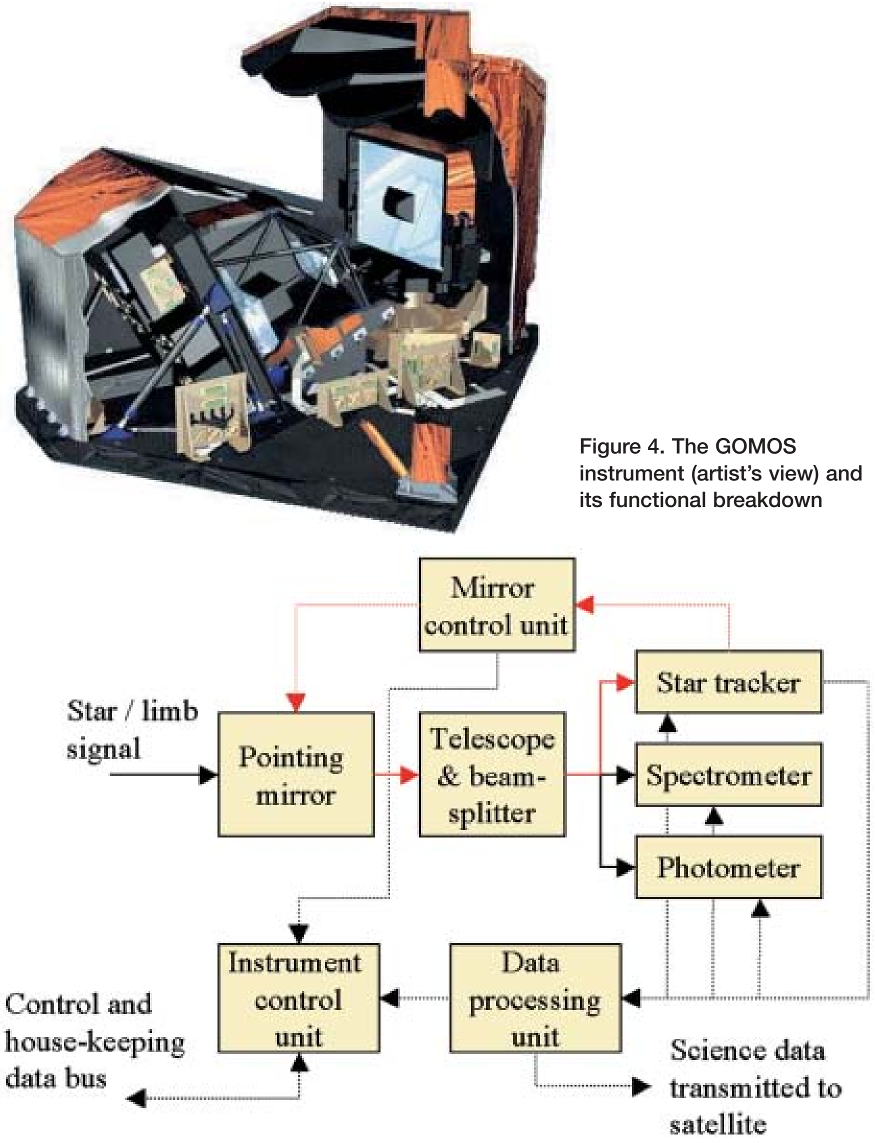


Figure 4. The GOMOS instrument (artist's view) and its functional breakdown

During the occultation, a star will appear to move in a downward and slightly lateral direction. This effect is compensated for by the fine-pointing mechanism mounted on top of the coarse pointing mechanism, which is used only for the initial acquisition of the star. In addition, the fine-pointing control loop corrects for short-term perturbations induced by both refraction and scintillation effects.

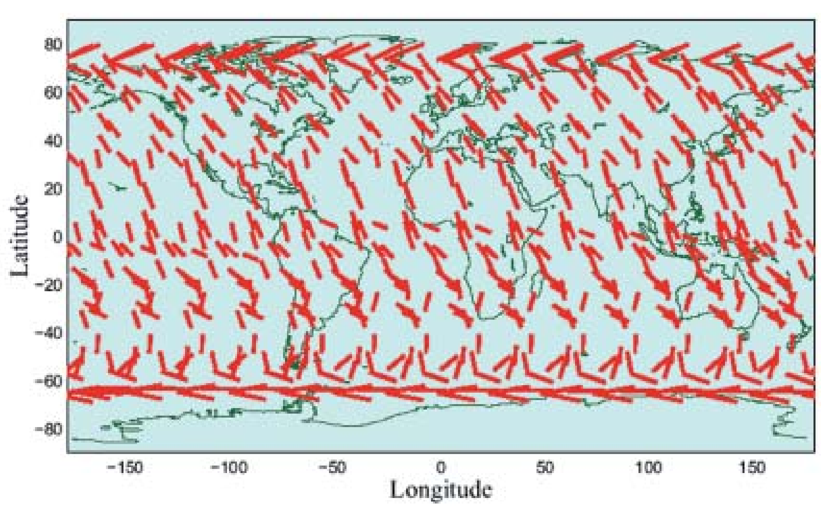


**Figure 5. Typical GOMOS coverage during one day in March. The map indicates the geo-location of limb tangent points during the acquisition of a realistic sequence of star occultations (courtesy of FMI, Finland)**

Towards the end of an occultation sequence, the starlight eventually becomes so attenuated that the instrument can no longer observe and track the star. The star is finally lost behind the horizon and the instrument changes its pointing direction (i.e. points the mirror) to the next star on the observation list. In this manner, the instrument will typically acquire 45 stars per orbit, yielding a total of 178 000 occultations per year.

In summary, with a star-parameter table loaded, the instrument will operate fully autonomously for up to 25 orbits before a new star table has to be uploaded.

A schematic of the instrument and its primary functional components is provided in Figure 4, whilst Table 1 lists the basic instrument characteristics.

*Table 1. Basic characteristics of the instruments*

| Performance parameter | Value (Dark limb) |
|---|---|
| Spectrometer spectral range [nm] | UV : 250 - 375, VIS : 405 - 675, IR1 : 756 - 773, IR2 : 926 - 952 |
| Spectrometer spectral sampling [nm per pixel] | UV : 0.314, VIS : 0.314<br>IR1 : 0.0465, IR2 : 0.057 |
| Spectrometer spectral resolution [nm] (FWHM of line spread function) | UV : 0.89, VIS : 0.89<br>IR1 : 0.12, IR2 : 0.14 |
| Spectral stability knowledge [nm] | UV : 0.04, VIS : 0.04<br>IR1 : 0.007, IR2 : 0.008 |
| Spectrometer integration time [Sec] | 0.5 |
| Photometer spectral range [nm] | Blue : 470 - 520,<br>Red : 650 - 700 |
| Photometer integration time [sec] | 0.001 |
| Star tracking visual magnitude limit :<br>Blue star = 30,000K Red star = 3000 K | Blue : 4.64<br>Red : 6.81 |

GOMOS is inherently a self-calibrating instrument. This means that long-term drifts in the instrument's radiometric response are compensated for as only the ratios of measurements, acquired over a relatively short time interval (~40 s), are used to compute transmission spectra. Changes in instrument response are negligible over such short intervals. Although GOMOS is specifically optimised for night observations, it will also perform measurements during daytime (bright-limb conditions). During daylight measurements, the bright background limb spectrum needs to be removed from the star spectra, via the simultaneous measurement of the pure limb signal just above and below the star LOS. The interpolated limb spectrum is then subtracted from the star band.

### *Ground processing*

The geophysical products of GOMOS are vertical density profiles of ozone, $O_2$, $NO_2$, $NO_3$, $H_2O$, OClO, air and aerosol extinction. They are retrieved from the horizontal transmission spectra via a spectral inversion followed by a vertical inversion (Fig. 6). In addition, high-resolution temperature profiles are retrieved.

- *Level-1B data processing (pre-processing)*

The main objectives of this processing stage are:
- measurement-data quality control
- correction for instrument effects
- geo-location of tangent point due to refraction effects ('bending' of LOS)
- computation of atmospheric-transmission and limb-background spectra.

Prior to the retrieval of geophysical parameters, a number of corrections are applied to the absorption spectra during the Level-1B processing stage. These corrections primarily account for non-uniformity of detector sensitivity and wavelength shifts due to residual pointing errors. Additional steps include the verification (internal consistency check) of observational data, the computation of geo-location parameters and various radiometric corrections (detector-uniformity effects and stray-light removal). The final step includes the subtraction of a background signal and the generation of transmission spectra.

The photometer computations are achieved using a similar processing chain.

- *Level-2 processing (geophysical-product generation)*

The Level-2 processing stage comprises the retrieval of trace-gas abundances, aerosol

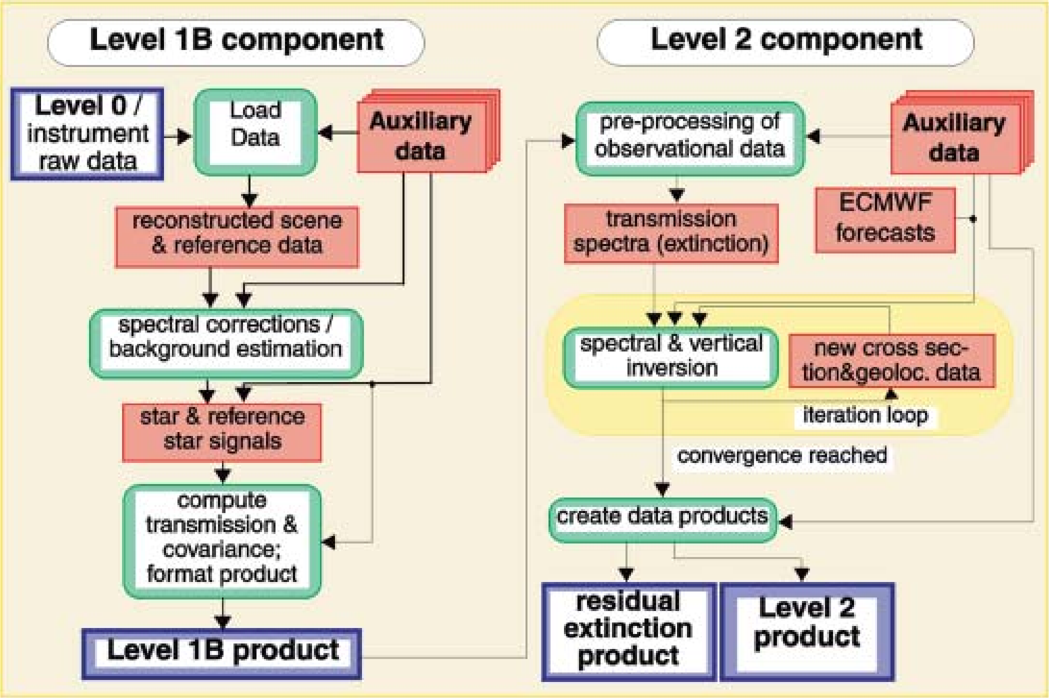


Figure 6. The GOMOS ground-processing chain

extinction parameters including wavelength dependence, air density and temperature profiles. The major processing steps are:
- retrieval of processing configuration data, instrument physical characteristics, Level-1B products and cross-section information
- correction of transmission spectra for scintillation effects and dilution.
- chromatic refraction correction (if necessary)
- spectral and vertical inversion
- product formatting.

### *MIPAS*

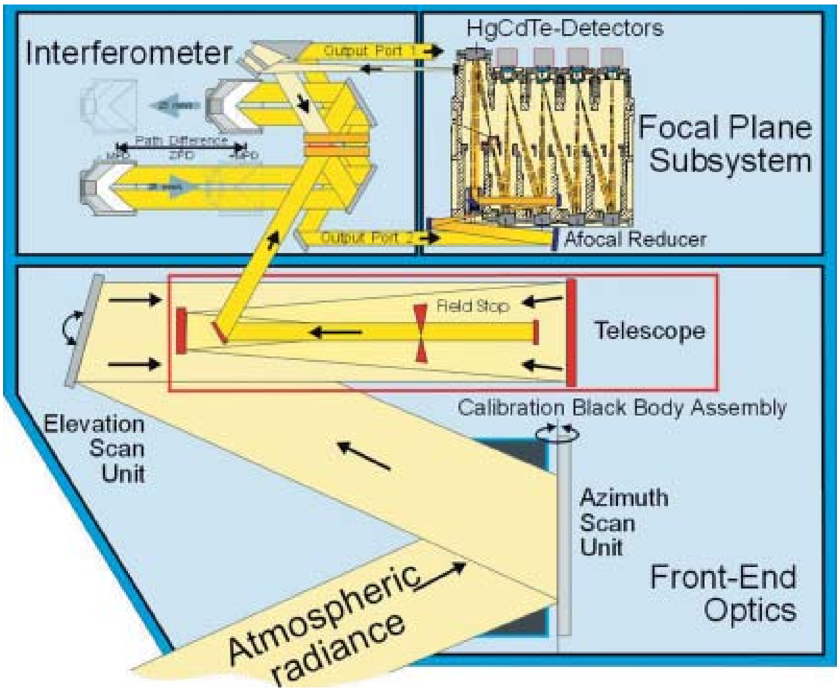
The MIPAS instrument has been designed to acquire global measurements of the Earth's limb emission, ranging from the upper troposphere to the mesosphere. Analysis of numerous trace gases exhibiting spectral features in the 685 – 2410 cm$^{-1}$ wave-number interval (14.6 – 4.15 micron wavelengths) is envisaged, with a focus on stratospheric ozone chemistry and dynamics. In particular, MIPAS will provide global observations of NO$_y$ compounds and of all important greenhouse gases. Moreover, it will allow the sensing of various species in the upper troposphere and in the mesosphere. Such measurements are relevant for studies of tropospheric chemistry, tropospheric/stratospheric exchange processes, and the Earth's global energy budgets.

*Instrument design*

The scientific objectives of MIPAS impose a number of challenging requirements in terms of radiometric sensitivity, spectral resolution and pointing stability. The concept finally selected is based on a dual-slide interferometer in conjunction with an anamorphotic telescope at the instrument's input and a set of eight Hg:Cd:Te detectors located at the two output ports of the interferometer. A schematic of the instrument's optical layout is shown in Figure 7.

The atmospheric radiance enters the front-end optics through the azimuth and elevation scan mirrors, which allow one to control the instrument's line-of-sight (LOS) in the horizontal and vertical viewing directions, respectively. The azimuth scan unit also allows switching of the viewing direction between sideways (orthogonal to the orbit plane, 'anti-Sun' direction) and rearward ('anti-flight' direction) geometries, and to view the internal blackbody target for periodic radiometric calibration. The

Figure 7. The MIPAS optical design (schematic)



elevation scan unit controls the LOS viewing direction according to pre-defined tangent altitudes, and also the pointing to high altitudes (~200 km) required for radiometric offset correction (‘deep-space’ calibration).

The elevation scan mirror reflects the input scene into the telescope, which reduces the beam size by a factor of 6 in azimuth, with no reduction in the elevation direction. An aperture stop located near the intermediate focus defines the effective overall field-of-view (FOV) of the instrument, which is 0.9 mrad in elevation by 9 mrad in azimuth. Primary components of the interferometer are the beam-splitter assembly, two corner-cube reflectors mounted on linearly moving slides, and the optical-path-difference sensor (ODS). The latter provides information on the actual optical path difference during the acquisition of interferograms, and controls the discrete sampling of the detector output signals.

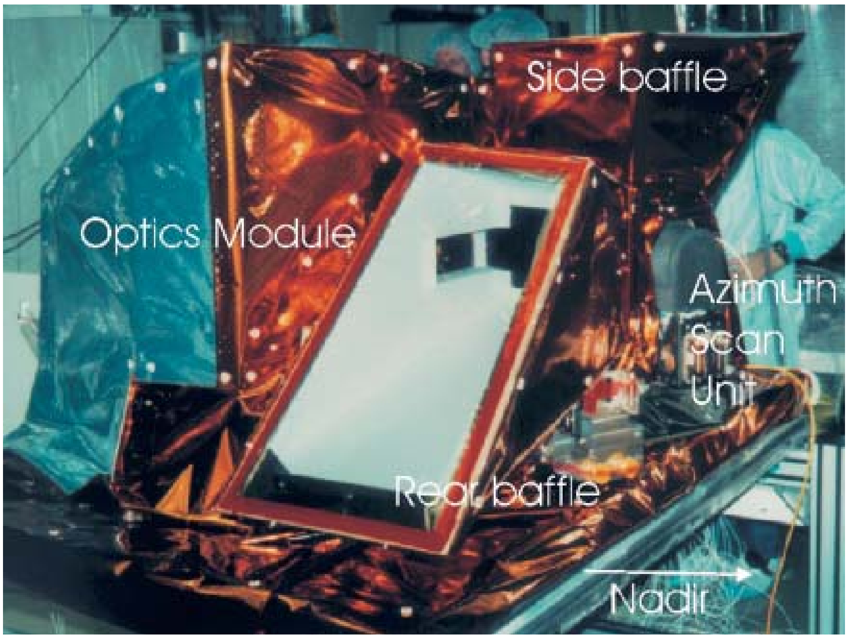


**Figure 8. The MIPAS optics module, with the side and rearward (front) baffles removed**

A major driver for the overall instrument design is the achievable spectral resolution, which is directly related to the maximum optical-path difference (MPD) of a two-beam interferometer. The required resolution for MIPAS is 0.035 $cm^{-1}$, which translates into an MPD of 20 cm, taking into account various effects that result in a degradation of resolution, such as internal misalignment, beam divergence and the finite field-of-view. The actual mechanical excursion of each reflector slide is ± 5 cm, taking into account the doubling of the optical path due to reflection and the opposite direction’s of the slides’ movements. Various additional optical elements, primarily folding mirrors, have been included in the optical path, in order to reduce the overall size of the instrument. An impression of the instrument’s dimensions is provided in Figure 8, which shows the optics module, with the two baffles for the rearward and sideways viewing geometries clearly visible.

The chosen interferometer design provides two separate input and output ports. While one input port is fed by the signal from the input telescope, the second port is terminated by a cold absorber. The two output ports are directed to two sets of four detectors, each set covering the entire spectral range of MIPAS. This set-up allows the radiometric performance to be enhanced through the co-addition of spectrally overlapping channels, and provides redundancy in the event that one or more detectors experience performance degradation or failure during in-flight operation. The detectors, together with their fore-optics (lenses, dichroics), are mounted in a common housing that is cooled to 70 K by means of a pair of Stirling-cycle coolers, in order to achieve optimum sensitivity and to reduce excessive noise due to thermal emissions in the input-signal path.

During the acquisition of interferograms, the signals of all eight detectors are individually amplified and digitised, using the sampling signal generated by the ODS. Subsequently, digital post-processing is performed for the individual detector channels in order to reduce the overall data rate. A total of six interferograms covering different spectral regions are finally generated for each interferometer stroke and formatted into a sequence of data units (source packets). These source packets also include various supplementary parameters and housekeeping information, required for the correct interpretation of the measured data on the ground.

A number of control and monitoring functions are required during the operation of MIPAS. These tasks, as well as the communications between the instrument, the Envisat platform and the control station on the ground (Flight Operations Segment, FOS), are handled by the Instrument Control Unit.

A simplified overview of the primary components of MIPAS is given in Figure 9, and the requirements and primary performance parameters are summarised in Table 2.

*Observational strategy*

MIPAS will periodically acquire atmospheric-limb emission spectra by scanning the instrument’s line-of-sight (LOS) elevation in discrete steps, to cover a typical tangent height range of 8 to 68 km. At the beginning of each elevation scan, the azimuth angle is adjusted

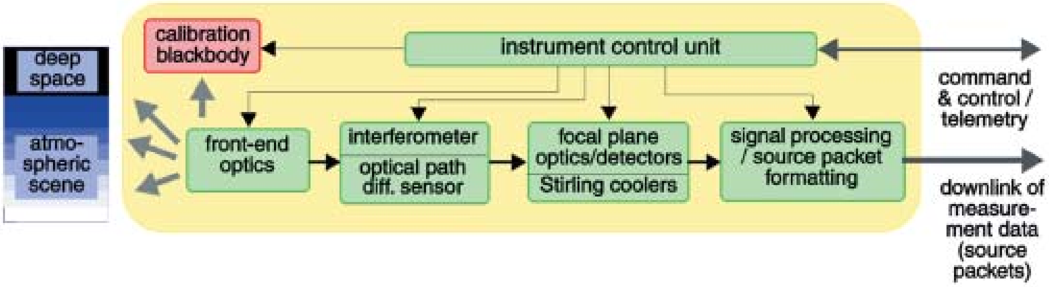


**Figure 9. Schematic of MIPAS primary functional components**

in a ±15 deg range around the nominal (rearward) direction, to compensate for the orbit's inclination (98.55 deg) and to view the polar areas (Fig. 10).

A single interferometer stroke is performed at each altitude while interferograms are recorded in the 8 detector channels (A1, A2, ..., D1, D2). Assuming 16 tangent heights per elevation scan, a measurement time of 4.45 s per stroke (high resolution, MPD = 20 cm), and taking into account periodic radiometric deep-space calibrations, about 75 complete scans will be acquired during each orbit (period = 100.6 min). The average data rate will be approx. 420 kbit/s.

*Ground processing*
The MIPAS ground-processing chain is composed of a Level-1B and a Level-2 component, which can be operated either in sequence or as independent stages. The Level-1B stage performs the conversion of instrument raw data (scene, blackbody and deep space) and auxiliary data into radiometrically and spectrally calibrated, geo-located radiance spectra. Also, a number of supplementary parameters are computed, which are required for the correct interpretation of the Level-1B data. The following functionalities are provided:

Pre-processing functions
- Extraction and reconstruction of interferogram data (scene and calibration data) from a Level-0 input product.
- Extraction/processing of additional ('auxiliary') input data and instrument housekeeping information (e.g. timing/pointing data, health status information).

Main processing functions
- Correction of detector non-linearity (for long-wavelength – band A, AB, B – detectors).
- Channel equalisation and combination (band-A detectors).
- Detection/correction of spurious signals ('spikes') and of possible ODS sampling ('fringe count') errors.
- Processing of radiometric gain and offset calibration data.
- Radiometric calibration of scene data, and correction of spectral-axis assignment (spectral calibration).
- Computation of geo-location parameters (for individual sweeps for elevation scans, refraction corrected).
- Assessment/verification of scene quality and noise equivalent spectral radiance (NESR).

*Table 2. MIPAS performance summary*

| | |
|---|---|
| ***Observation Geometry*** | |
| Field of view at limb tangent point | 3 km (vertical) x 30 km (horizontal) |
| line of sight viewing range | vertical: 5 ... 200 km (tangent height)<br>horizontal: 35$^0$ about rearward (anti-flight) direction<br>30$^0$ for sideways viewing geometries (speciaL events monitoring only) |
| ***Spectral Sampling*** | |
| total spectral range | 685 ... 2410 cm$^{-1}$ ($\lambda$ = 14.6 ... 4.15 µm) |
| spectral bands | A: 685 - 970 cm$^{-1}$, AB: 1020 - 1170 cm$^{-1}$, B: 1215 - 1500 cm$^{-1}$, C: 1570 - 1750 cm$^{-1}$, D: 1820 - 2410 cm$^{-1}$ |
| spectral resolution (unapodised) | ~ 0.03 cm$^{-1}$ (high resolution, MPD = 20 cm)<br>~ 0.25 cm$^{-1}$ (low res., MPD = 2 cm) |
| ***Radiometric Performance*** | |
| noise equivalent spectral radiance, NESR ('sensitivity') | 50 nW/cm$^2$/sr/cm$^{-1}$ (band A)<br>... 4.2 nW/cm$^2$/sr/cm$^{-1}$ (band D) |
| radiometric accuracy | 1 % (@ 685 cm$^{-1}$) ... 3 % (@ 2410 cm$^{-1}$) of input spectral radiance |
| ***Spatial Sampling*** | |
| total number of elevation scans per orbit (nominal mode) | ~ 80 (high resolution, 16 limb heights per scan) |
| along-track spacing between scans | 500 km |
| ground track of LOS tangetn point | almost polar (compensation of orbit inclination through azimuth steering) |

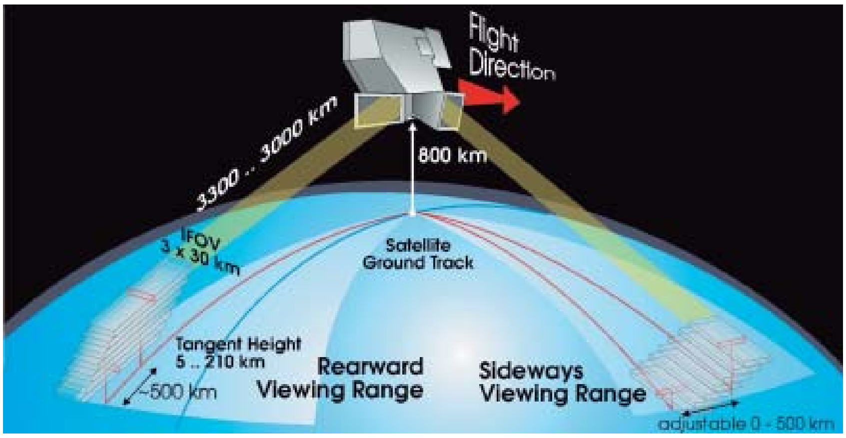


**Figure 10. MIPAS line-of-sight viewing geometry**

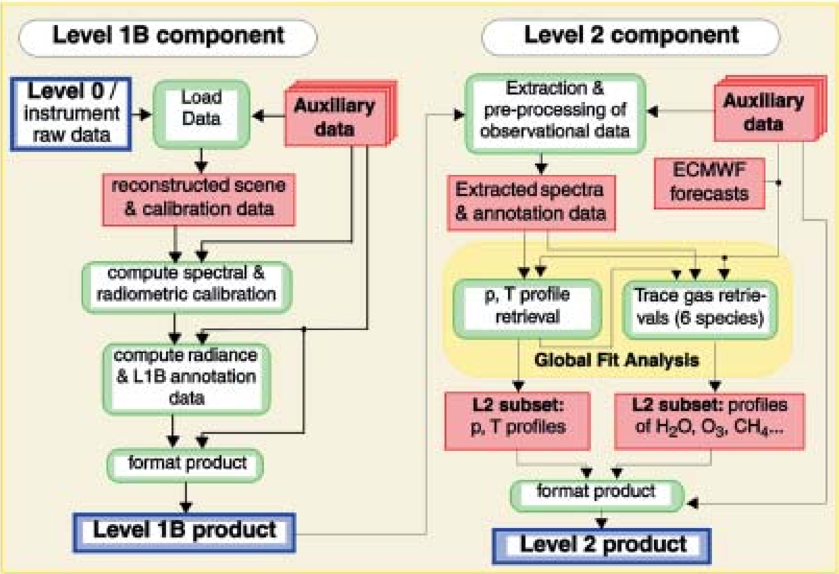
In a final step, a number of additional annotation data are generated and formatted, together with the calibrated limb-radiance data in a Level-1B product.

The Level-2 processing is based on the analysis of emission features of selected target gases from the Level-1B input data and is performed in two stages: (i) retrieval of pressure/temperature profiles, and (ii) sequential retrieval of Volume Mixing Ratio (VMR) profiles for the target species $O_3$, $H_2O$, $CH_4$, $N_2O$, $NO_2$ and $HNO_3$, using the pressure and temperature information retrieved in the first stage.

The underlying retrieval concept is derived from the so-called ‘global-fit technique’. This approach corresponds to the simultaneous analysis of the full set of available observations (i.e. Level-1B radiances at different limb altitudes within a given scan) and minimising the $CHI_2$ function, i.e. the weighted summation of quadratic differences between observations and simulated signals. This minimisation represents a non-linear problem and is achieved through simultaneous fitting of all selected unknowns, i.e. primarily the parameter profiles of an initially assumed model atmosphere. (More details on the mathematical background of the iterative fitting procedure and the atmospheric model can be found in the MIPAS Science Report, ESA Special Publication SP-1229).

A simplified overview of the Level-1B/2 processor stages is given in Figure 11.

Figure 11. The MIPAS ground-processing chain



### SCIAMACHY

#### Instrument design

The Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) will measure the sunlight and moonlight that is either transmitted, reflected or scattered by the Earth’s atmosphere. The double spectrometer is designed for the ultraviolet, visible and near-infrared wavelength domains (240 – 2380 nm), covering this range with a resolution of 0.24 to 1.5 nm. It was conceived to improve our knowledge and understanding of a variety of important issues relating to the chemistry and physics of the Earth’s atmosphere: troposphere, stratosphere and mesosphere. The scientific objectives are to study stratospheric chemistry, troposphere-stratosphere exchange processes and tropospheric pollution, by using a combined limb, nadir and occultation strategy.

SCIAMACHY is a passive remote-sensing instrument, designed to measure atmospheric constituents and parameters of importance in the stratosphere and troposphere. It comprises four subsystems:

- A scan-mirror system, which determines the instrument’s observational mode.
- A spectrometer (or optical bench), which breaks down the incoming signal into its spectral components
- A cooling system, which maintains the spectrometer and its detectors at selected temperatures to optimise the signal-to-noise ratio in the measured spectra.
- An electrical subsystem, which controls and operates SCIAMACHY and interfaces to the Envisat platform.

The first two subsystems are partly depicted in Figure 12. The input light is collected by the scan-mirror system and passed, via an off-axis parabolic mirror, to the spectrometer’s entrance slit. After subsequent collimation, light is directed to a pre-dispersing prism, which produces an intermediate spectrum in the middle of the instrument (see Fig. 12, where the prism is labelled the ‘channel separator’). The polarised reflection of this prism is sent to the Polarisation Measurement Devices (PMDs), which are broadband detectors observing in selected ranges throughout the spectral range of SCIAMACHY. The spectrum leaving the prism is directed, by use of reflective optics and dichroic mirrors, to the eight spectral channels of SCIAMACHY. Each channel comprises a grating, transmissive optics and a diode array detector. The optical bench and its array detectors are cooled to minimise their intrinsic noise, and thereby optimise the signal-to-noise ratio.

The onboard calibration hardware includes aluminium diffusers (on the rear sides of the elevation and azimuth scan mirrors), which are used for solar-irradiance measurements. These in turn are used to calibrate Earth-shine spectra, for use in ground processing. A hollow cathode discharge lamp is used for wavelength calibration. The detector pixel-to-pixel gain, as well as etalon effects, will be determined using a tungsten-halogen 5 W lamp, placed at the second level.

With its combination of two mirrors, the instrument is able to observe light reflected, scattered or transmitted from the atmosphere, in nadir, limb or occultation mode. It yields either trace-gas column densities from nadir measurements, or vertical profiles from limb and occultation measurements. In combination with the instrument's broad spectral coverage, this leads to a unique quantity of scientific targets and applications. Especially the combined analysis of limb and nadir measurements will make SCIAMACHY the only instrument on Envisat that can estimate tropospheric trace-gas columns (Fig. 13). In the future, these might be of considerable interest for tropospheric ozone detection and photo smog monitoring.

*Observational strategy*
The SCIAMACHY operations concept is built on a mission scenario – timeline – state scenario. The lowest level, an instrument state, represents a single measurement type with a specific set of (pre-)defined parameters. Several of the instrument states together build a timeline, defining a sequence of measurements. Both, states and timelines are stored on-board the satellite. Commanding these pre-defined timelines will allow autonomous instrument operation over long periods. Mission scenarios define the high-level sequence of activities.

Nominally, SCIAMACHY will be operated as follows. Coming out of eclipse, the instrument will start with occultation measurements by tracking the sunrise through the atmosphere. Alternating limb and nadir measurements will follow, performed with a nominal swath width of 960 km across-track. Whenever the Moon is visible (which occurs over the southern hemisphere of the day-side orbit), lunar occultation will be performed. Calibration measurements will be carried out when entering eclipse

Given Envisat's orbital period of about 100 minutes, SCIAMACHY will be able to observe the whole Earth. Global coverage at the equator is established within 6 days when using the alternating limb/nadir scan option. Using only the nadir or limb modes, global coverage is achieved within 3 days (for the 960 km swath width).

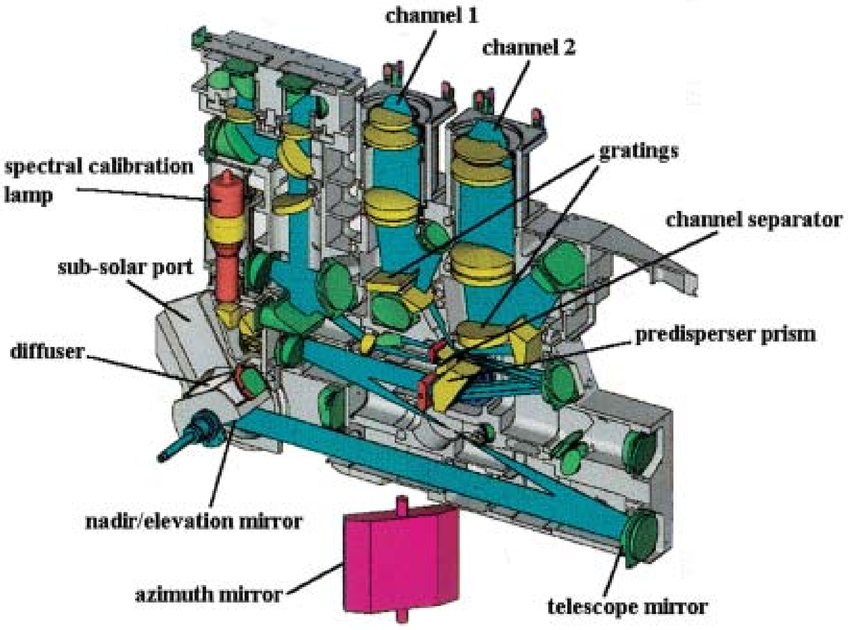


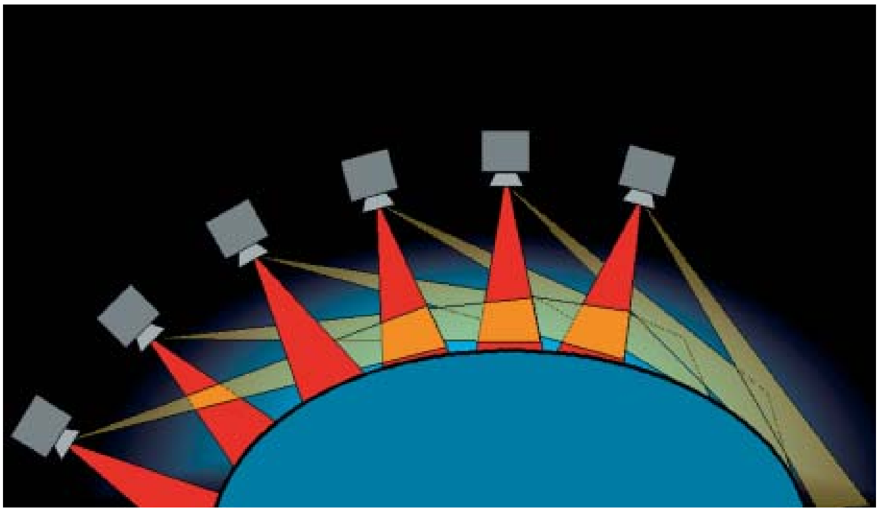
Figure 12. The SCIAMACHY level-1 optics. The second level (not shown here) consists of the remaining channels 3 to 6, PMD channels including a 45 deg sensor, and the on-board white-light source (courtesy of TPD/TNO, The Netherlands)

*Ground processing*
SCIAMACHY Level-1B processing comprises the following steps:

- Reading of Level-0 (raw) data and auxiliary files.
- Sorting data packets according to nadir, limb/occultation, calibration and monitoring categories.
- Determination of measurement data geo-location.
- Determination of calibration/correction parameters necessary for spectral and radiometric calibration.
- Write Level-1B product, containing the geo-located measurement data (still Level-0), plus all calibration/correction parameters.

The SCIAMACHY Level-1B product concept differs from the standard approach adopted for the other Envisat instruments in so far as a user has to apply various corrections and calibrations in order to obtain fully calibrated, geo-located radiance spectra. This rather specific interpretation of Level-1B is based on the ERS-2/GOME heritage. By maintaining the

Figure 13. SCIAMACHY limb/nadir matching. By assessing the difference between nadir total column and limb integrated stratospheric column, the tropospheric column can be obtained (courtesy of IUP, Bremen)



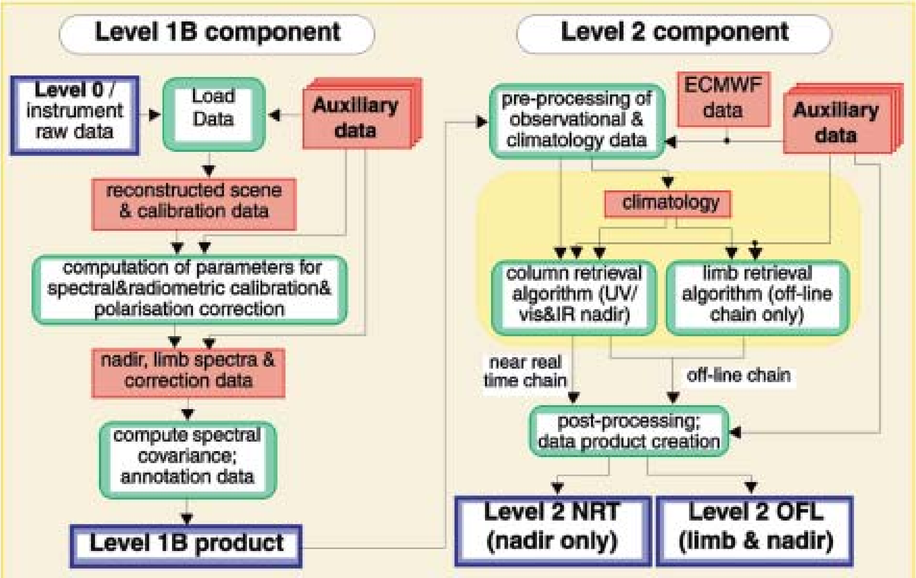


Figure 14. The SCIAMACHY ground-processing chain

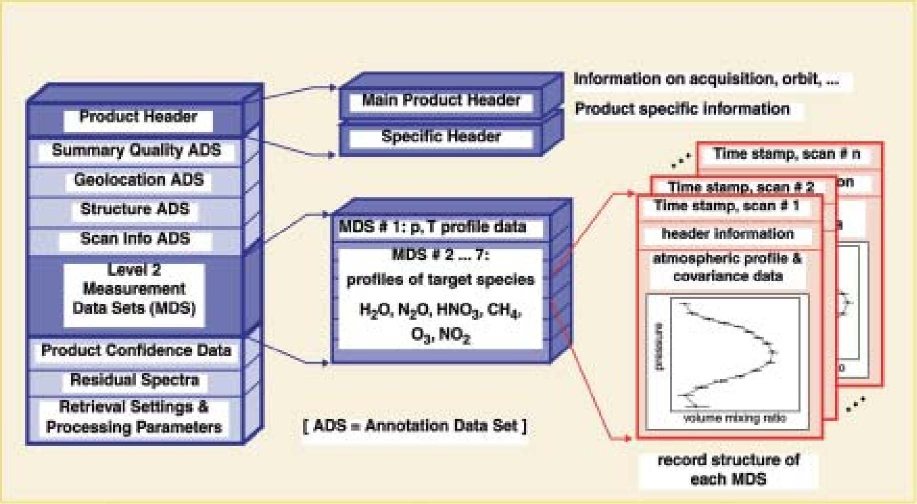
'raw' information content in the Level-1B product, it provides the users with a high degree of flexibility to perform calibrations according to their specific needs.

Taking Level-1B as input, Level-2 processing involves the following steps:

- Reading Level-1B data and auxiliary data (e.g. climatology, cross-section data).
- Applying calibrations for: leakage current, detector memory effect, etalon and pixel-to-pixel gain, stray light, spectral, polarisation and radiance.
- In NRT processing, only nadir data will be processed with DOAS-type (Differential Optical Absorption Spectroscopy) algorithms to retrieve vertical columns of trace gas.
- In off-line processing, nadir, limb and occultation data will be processed, to yield vertical profiles of trace gases.
- Finally, retrieval results are written into the Level-2 product.

A simplified overview of the Level-1B/2 processor stages is given in Figure 14.

Figure 15. Structure of a MIPAS Level-2 product file



## Scientific data products

During Envisat's routine operations, GOMOS, MIPAS and SCIAMACHY will acquire atmospheric data according to a nominal measurement scenario. These data will be interleaved with periodic, instrument-specific calibration and characterisation measurements, as required to perform the ground data processing and to monitor the performance of each instrument. The processing of scene and calibration data for each of the instruments will be conducted on a systematic basis, making use of the near-real-time (NRT) and off-line processing capabilities provided by the Payload Data Handling Stations (PDHS) and Processing Archiving Centres (PACs), respectively (see the 'Payload Data Segment' and 'Envisat User Services' articles elsewhere in this issue).

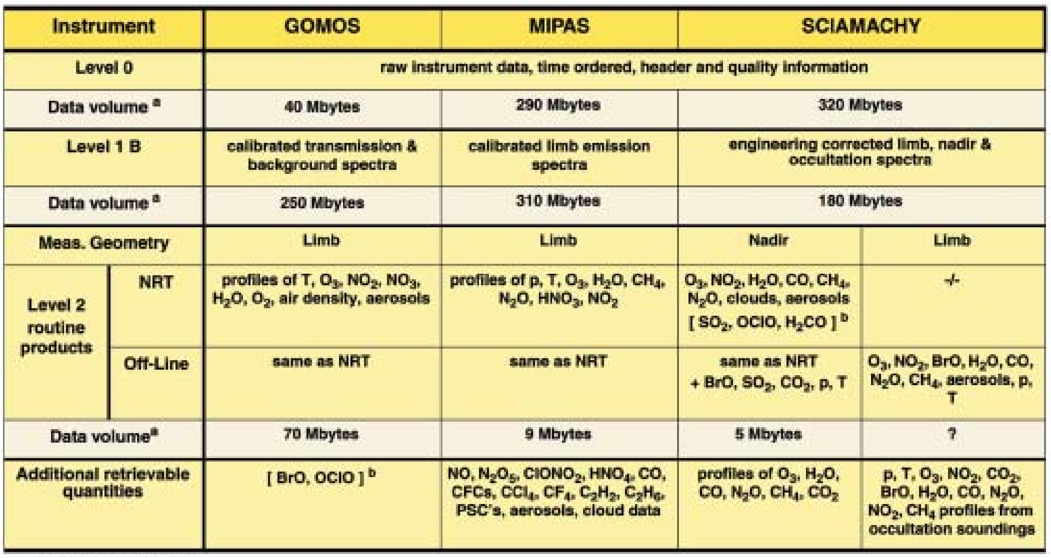
All product files are structured according to the general Envisat formatting rules that distinguish the following 'generic' building blocks:

- *Main/Specific Product Header (MPH/SPH)*: Product header, specifying both general and instrument-related information such as processing site, software version, orbit/geo-location parameters, sensing time, and references to auxiliary input data used.

- *Measurement Data Sets (MDS)*: Include actual processed instrument data, i.e. transmission/emission spectra in the case of Level-1B products and retrieved geophysical parameters (profile or column density data), in the case of Level-2 products.
- *Annotation Data Sets (ADS)*: Include MDS-specific information related to acquisition or processing of individual data segments, as required for full interpretation of the data.

Whereas in the case of GOMOS each individual occultation results in a set of Level-1B and Level-2 files, the MIPAS and SCIAMACHY products contain data for a full orbit. In the latter case, the MDS are formatted according to a specific record structure, whereas each record corresponds to an individual processed measurement data unit, for instance a limb sequence. The records within each data set can be identified by a unique time parameter, the so-called 'time stamp'. A typical product file structure (MIPAS Level-2) is illustrated in Figure 15. ESA will provide the users with specific software tools to support the handling of product files and the extraction of geophysical information.

*Table 3. Envisat's atmospheric data products*



| Instrument | | GOMOS | MIPAS | SCIAMACHY | |
|---|---|---|---|---|---|
| Level 0 | | raw instrument data, time ordered, header and quality information | | | |
| Data volume [a] | | 40 Mbytes | 290 Mbytes | 320 Mbytes | |
| Level 1 B | | calibrated transmission & background spectra | calibrated limb emission spectra | engineering corrected limb, nadir & occultation spectra | |
| Data volume [a] | | 250 Mbytes | 310 Mbytes | 180 Mbytes | |
| Meas. Geometry | | Limb | Limb | Nadir | Limb |
| Level 2 routine products | NRT | profiles of T, $O_3$, $NO_2$, $NO_3$, $H_2O$, $O_2$, air density, aerosols | profiles of p, T, $O_3$, $H_2O$, $CH_4$, $N_2O$, $HNO_3$, $NO_2$ | $O_3$, $NO_2$, $H_2O$, CO, $CH_4$, $N_2O$, clouds, aerosols<br>[ $SO_2$, OClO, $H_2CO$ ] [b] | -/- |
| | Off-Line | same as NRT | same as NRT | same as NRT<br>+ BrO, $SO_2$, $CO_2$, p, T | $O_3$, $NO_2$, BrO, $H_2O$, CO, $N_2O$, $CH_4$, aerosols, p, T |
| Data volume [a] | | 70 Mbytes | 9 Mbytes | 5 Mbytes | ? |
| Additional retrievable quantities | | [ BrO, OClO ] [b] | NO, $N_2O_5$, $ClONO_2$, $HNO_4$, CO, CFCs, $CCl_4$, $CF_4$, $C_2H_2$, $C_2H_6$, PSC's, aerosols, cloud data | profiles of $O_3$, $H_2O$, CO, $N_2O$, $CH_4$, $CO_2$ | p, T, $O_3$, $NO_2$, $CO_2$, BrO, $H_2O$, CO, $N_2O$, $NO_2$, $CH_4$ profiles from occultation soundings |

a. Typical figure, per orbit
b. observable under specific conditions (enhanced abundancies) or after averaging

A summary of the data products for the three instruments is provided in Table 3. In addition to the routine products that will be systematically processed in the various processing centres, a number of 'non-standard' target species/parameters are listed (bottom row of table). These products will require enhanced analysis strategies and are the subject of dedicated research efforts in a number of scientific research institutes located all over Europe.

## In-flight characterisation and validation

During Envisat's early in-orbit operation, its atmospheric sensors will undergo a number of checks and calibration measurements to verify the basic functionalities of the instruments and ground-processor components, and to assess essential performance parameters. Primary contributions to the validation of atmospheric products will be supplied by dedicated measurement campaigns providing independent observations of atmospheric parameters. Advantage is taken of a variety of well-proven measurement techniques, including various ground-based, airborne and space experiments.

Intercomparisons of GOMOS, MIPAS and SCIAMACHY data with such 'correlative' information will allow error budgets for the geophysical data products to be quantified and corrective actions to be identified in order to further enhance the overall performance of the ground processing chains.

The initial in-flight calibration/characterisation activities will be accompanied by dedicated geophysical measurements. These efforts will be complemented by a long-term validation programme ensuring continuous performance monitoring of the instruments and ground processors, and allowing the incorporation of future enhancements for critical algorithm components.

## Conclusions

With the GOMOS, MIPAS and SCIAMACHY instruments onboard Envisat, ESA's series of Earth-observation missions will be enriched with a suit of powerful sensors dedicated to the exploration of the entire lower and middle atmosphere. Whilst operating in different spectral bands spanning the ultraviolet to mid-infrared wavelength range, the three instruments will exploit a variety of detection techniques and observational strategies. Together, they will provide global data on a large variety of atmospheric-state parameters, primarily abundancy profiles for the trace gases that play a key role in understanding the atmosphere's chemistry and physics and which may contribute to the further improvement of meteorological forecasting models.

The concept of systematic processing, archiving and dissemination of scientific data products will ensure that the atmospheric research community is supplied with immediate and easy access to a large number of geophysical data products throughout Envisat's envisaged 5-year lifetime.

A co-ordinated validation programme including dedicated correlative measurement campaigns has been initiated to support both the initial and the subsequent routine in-orbit operation of the three instruments. This effort will ensure stable sensor and ground-processor performances throughout the entire lifetime, further improving the scientific exploitation possibilities for this unique atmospheric mission.