GOMOS: Envisat's Contribution to Measuring Long-Term Trends in Ozone and Other Trace Gases

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Atmospheric chemistry is one of the key mission targets for the Envisat satellite, being prepared for launch in 2000. With the recent delivery of the GOMOS instrument (manufactured by Matra Marconi Space in Toulouse) to the Prime Contractor for integration into the satellite flight model, a major programme milestone has been achieved. Given the outstanding performance of the instrument that has been demonstrated in testing, GOMOS can be expected to deliver high-quality observations of ozone and other trace gases from space.

GOMOS on Envisat

General background

GOMOS (Global Ozone Monitoring by Occultation of Stars) is an atmospheric-chemistry instrument that forms part of the payload of Envisat. It operates in the ultraviolet and visible and exploits a stellar occultation concept (Fig. 1) to observe ozone and other trace species, plus temperature and water vapour. The main role of GOMOS will be the observation of ozone in the stratosphere and the monitoring of trends.

Atmospheric ozone is the main absorber of ultraviolet radiation from the Sun. Without ozone, life as we know it would not exist. Any substantial reduction in ozone would lead to damage to crops and human health. The radiation absorbed by ozone is responsible for skin-cancer in humans. Furthermore, the absorption of sunlight by ozone in the stratosphere is a source of heat, so that any reduction in levels would impact on our climate.

The level of ozone in the stratosphere represents a balance between ozone production and destruction. In the mid-upper stratosphere, ozone is formed by the dissociation of molecular oxygen by ultraviolet sunlight, followed by a reaction between the atomic oxygen and molecular oxygen. It is removed by a variety of catalytic cycles involving the oxides of hydrogen, nitrogen, bromine and chlorine.

Most of the cycles involving the oxides of hydrogen and nitrogen arise naturally, though there is some concern about aircraft emissions. This may be contrasted with the situation for stratospheric chlorine and bromine, where only small amounts arise from natural sources; in this case most is of anthropogenic origin, e.g. refrigerators, fire-extinguishers and agricultural fumigants.

Over the Antarctic, ozone depletion occurs in the lower stratosphere where the catalytic cycles – referred to above – cannot operate because there is too little atomic oxygen present. The situation is similar in the Arctic, although there reductions in ozone are masked to a certain extent by atmospheric motions. Reductions in ozone levels are also observed at mid-latitudes, but the mechanisms responsible are not clear.

In addition to the 'gas-phase chemistry' (above), it is now known that 'heterogeneous chemistry', involving aerosols and cloud particles, plays a key role in stratospheric ozone depletion. This type of reaction occurs in polar regions on polar stratospheric clouds (PSCs) and throughout the lower stratosphere on sulphate aerosols. Also important is transport since, because of the finite lifetime of ozone in the stratosphere, its distribution is determined by a combination of transport and chemistry.

Scientific issues

In many of the areas listed above, there are important questions that still need to be answered. GOMOS should bring significant contributions in many of these areas.

Stratospheric ozone content has been declining worldwide since the 1970s. Apart from the spectacular Antarctic ozone hole, there has been a very worrying decline at

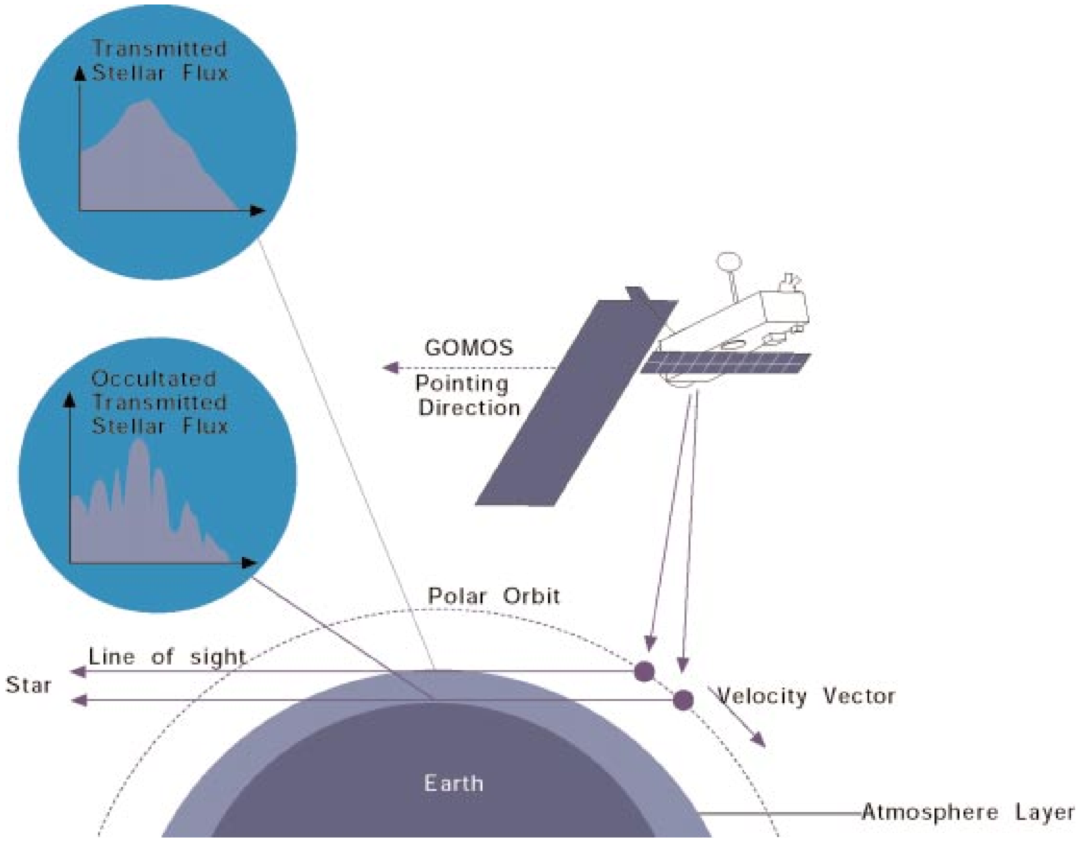

Figure 1. GOMOS measurement principle

northern mid-latitudes, above Europe and other heavily populated areas. Here total ozone is currently declining by between 4 and 8% per decade. Although measurements suggest that most of this decline ozone occurs in the lower stratosphere, in agreement with current hypotheses, the observations of trends in ozone profiles lack sufficient accuracy to make definitive statements. Worse, current models of stratospheric chemistry do not predict the magnitude of the observed decline in levels of ozone.

It is now clear that conditions favourable to ozone loss are also found most years within the Arctic vortex but, unlike its southern counterpart, this vortex is highly variable and very mobile. Further study of the Arctic is necessary to investigate whether this is a consequence of natural variability, or whether it is indicative of a trend towards colder winters, in which case Arctic ozone depletion will become more severe. It is also essential to clarify the mechanisms underlying the decreases in ozone in the Arctic and at mid-latitudes. The role of heterogeneous chemistry is not clear, nor is that of ozone chemistry in the mesosphere.

Stratospheric circulation is characterised by ascent in equatorial regions, poleward transport and descent at high latitudes. Extra-tropical pumping, as well as planetary waves, imposes upward equatorial motion and the global injection of tropospheric air into the stratosphere. The main mechanism involved is deep convection with cumulo-nimbus clouds extending to the tropopause. However, the minimum in the water-vapour mixing-ratio profile (hygropause) is not encountered at the tropopause, but a few kilometres above it. The reason for this difference is not fully understood.

Another important mechanism is the meridianal transport of air, depleted in ozone, from high latitudes in the form of polar filaments formed at the edge of the polar vortex. The contribution of this mechanism to observed trends in ozone at middle latitudes is not clear. Neither is the role of turbulent layers associated with the breaking of gravity waves. These waves are generated in the troposphere above mountains, above convective clouds and in the jet stream. They are the main controller of mesospheric circulation and may also play a role in stratospheric circulation, but our knowledge is poor.

Water-vapour concentrations in the lower stratosphere appear to have increased between 1981 and 1994, but the level of increase is larger than expected. This must be resolved as water vapour is a potent greenhouse gas and so the amount present affects the Earth's radiation balance. A high-resolution global climatology of humidity in the upper atmosphere is required to clarify the impact of these changes in water vapour on climate.

Also of some concern are polar mesospheric or noctilucent clouds, which are cirrus-like clouds of small particles, confined to the altitude range of 82 to 85 km, where the atmospheric temperature is at a minimum (i.e. the mesopause). It is argued that the appearance of these clouds is strong evidence for global change, but again our knowledge of them is quite limited.

The scientific requirements

One of the key requirements associated with GOMOS's monitoring role is the long-term accuracy of its measurements over the four years of the Envisat mission. Another major requirement is good vertical resolution, which should be as small as 2 km. Finally, good daily geographical coverage at all latitudes is needed to allow a proper understanding of the dynamics of the processes.

GOMOS must be able to detect the spectral signatures of all the target molecules (Table 1). For ozone, a broad spectral range (250 – 675 nm) is required, but it is also necessary to measure the temperature locally as it has an impact on the ozone absorption. This particular problem is addressed by observing the A-band of oxygen (at 760 nm).

All of the other target species lie within the range 250 – 800 nm, with the exception of water vapour, for which it is necessary to extend the spectral range. Hence, it has been decided that GOMOS should cover the spectral range 250 – 952 nm. Gaps in coverage within this overall range have been limited to regions devoid of relevant spectral information. Furthermore, to ensure that ozone spectra are not corrupted by the spectra of other species, a spectral resolution of better than 1 nm is required. For oxygen and water vapour, the spectral signature varies on a scale smaller than 1 nm, calling for a resolution of better than 0.2 nm, but only over a limited part of the spectrum.

Finally, it is necessary to consider the signal-to-noise ratio. This has to be specified for a given integration time linked to vertical resolution. Simulations have shown that, in order to retrieve ozone densities to an accuracy of better than 1% over the relevant altitude range, a signal-to-noise value of 100 is required for each 0.3 nm spectral pixel in the ultraviolet/visible. In addition, account has to be taken of small-scale structures (or scintillation) in the temperature/density profile, which induce rapid variations in the intensity of signals observed by GOMOS.

The GOMOS instrument

The concept

The original GOMOS concept was proposed in the late 1980s by a team of European scientists led by Service d'Aéronomie (CNRS) and the Finnish Meteorological Institute. The instrument exploits star occultation (Fig. 1), which is inherently self-calibrating and well-suited to meeting the main scientific requirements.

From its polar orbit, GOMOS observes stars whose lines-of-sight are tangential to the Earth's limb. For each individual star, the spectrum measured outside the atmosphere is compared to the spectrum seen through the atmosphere as the star sinks below the horizon. The difference reveals the presence of ozone and other trace gases. Occultation has already been demonstrated in space using the Sun as light source, but geographic coverage was limited. The specific advantage of GOMOS, related to the large number of observable stars, is that it combines the advantages of high radiometric accuracy with good Earth coverage.

Table 1. Main GOMOS products and potential applications

Product	Potential Application
O_3, NO_2, NO_3, H_2O, O_2, air (horizontal column densities)	Higher order GOMOS products Monitoring of trends
Aerosol extinction coefficients	Aerosol research Atmospheric-chemistry research
O_3, NO_2, NO_3, H_2O, O_2, air (vertical density profiles)	Atmospheric-chemistry research Monitoring of trends
Temperature and density profiles Turbulence product: High-resolution T and density	Atmospheric research and GOMOS Atmospheric-dynamics research

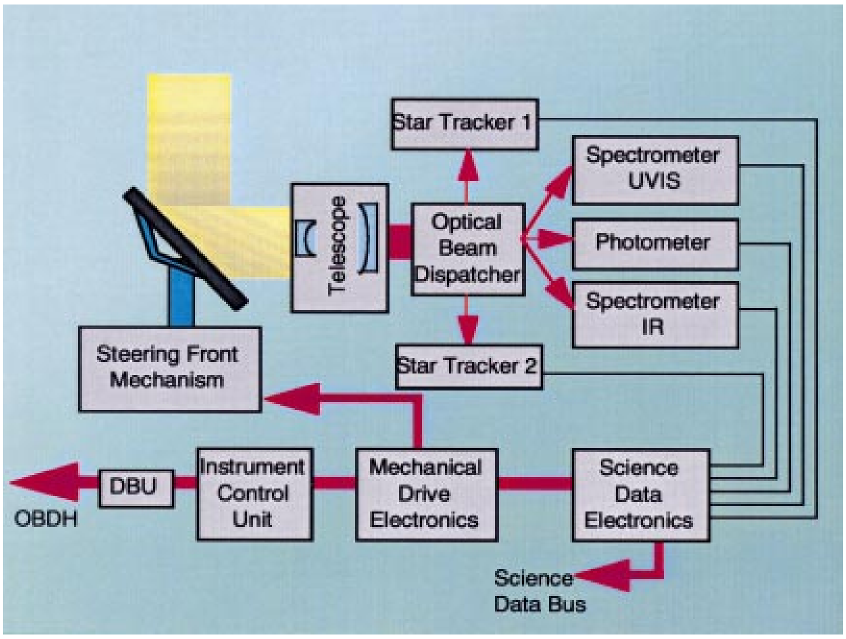

Figure 2. GOMOS functional block diagram

The design

A functionality of GOMOS is shown in Figure 2. The instrument is based on a 20 cm x 30 cm Cassegrain telescope, which simultaneously feeds, through an optical beam dispatcher placed at its focal plane, an ultraviolet/visible medium-resolution spectrometer (for signal measurements in the Huggins and Chappuis bands: 250 – 675 nm), a near-infrared high-resolution spectrometer (for O_2 and H_2O, around 760 and 930 nm, respectively). These are complemented by two fast photometers, operating in the 470 – 520 nm and 650 – 750 nm spectral bands, with a 1 kHz sampling rate, for observing scintillation.

By using a large steerable flat mirror (30 cm x 40 cm) in front of the telescope (Fig. 3), GOMOS is able to acquire and track stars down to magnitude 5 over a very large angular range (100 deg in azimuth). A complex star-tracking system – using two redundant star trackers – allows the star to be tracked within 20 µrad during the 50 sec of a typical scan. The star trackers are able to operate under both day and night conditions, i.e. over both the bright and the dark limb.

GOMOS will provide data at a constant rate of 222 kbit/s during nominal operation. The instrument weighs 163 kg and its power consumption is 146 W. Its main performance characteristics are summarised in Table 2.

Figure 3. Cut-away drawing of GOMOS

Table 2. GOMOS instrument performances and major technical challenges

Requirements	**Typical GOMOS Performance**	**Design Driver for**
Number of occultations per orbit (45 on average)	~820 000 occultations during 4 year mission	Lifetime of pointing mechanism
Wide angular coverage	-10 to +90 deg. w.r.t flight direction	Large field of view of pointing mechanism
Altitude resolution/accuracy	1.7 km / 30 m pointing stability better than 20E-6 rad	High angular pointing accuracy (pointing servo electronics)
Spectral range of UVIS spectrometer	250 – 675 nm	High-transmission optics, high detector sensitivity in the UV
Spectral resolution accuracy	0.89 nm in UVIS; 0.12 nm in IR1/IR2	Detector size, grating and pointing
Photometer frame rate	1 kHz in the spectral range: 470 – 520 nm / 650 – 700 nm	Fast, high-sensitivity detectors

To realise such a performant instrument, specific technical developments have been necessary. State-of-the-art technology has been achieved in particular for the CCD manufacture (EEV) and for the design of the steering mechanism by Matra Marconi Space in Bristol (Fig. 4). The entire instrument has been developed by a consortium led by Matra Marconi Space in Toulouse, under Dornier's supervision. The flight model was delivered to the Envisat mission prime in October 1998, for integration into the flight-model satellite at Matra Marconi Space in Bristol.

The operation of GOMOS

The main mode of operation is the 'occultation' mode. Following a sequence of star observations uplinked to the satellite by the Envisat flight-operations control centre, GOMOS will acquire and track stars as they set through the atmosphere. The sensors are operated in such a way that the star and the surrounding background light are recorded simultaneously. The detector is fully programmable in order to ensure optimum alignment over the instrument's lifetime and the best possible signal-to-noise ratios.

In addition to this occultation mode, the GOMOS instrument's design also supports three other observing modes for in-orbit monitoring of performance and the re-calibration of the instrument's performance parameters.

GOMOS mission planning

GOMOS mission planning has been optimised to maximise the instrument's scientific return. The mission objectives can be grouped under two general headings (Table 3):

- 'Long-Term Objectives', which are specific to the atmospheric-chemistry objectives of GOMOS.
- 'Campaign Objectives', which are needed to validate GOMOS products and to compare them with the other two chemistry instruments on Envisat.

Depending on the specific mission objectives, with attached priority factors, the stars to be observed are selected from the star catalogue. The sequencing of observations is done according to the instrument's time-line capabilities. The observing schedule will be encoded as a macro-command for uploading to the satellite.

Various simulations have been performed to determine the merit functions of the different observing strategies. Figure 5 gives an example of a set of stars selected to observe stratospheric ozone over a period of 3 days near the spring equinox.

The mission-planning software is designed to include scenarios for long-term observations (over days or weeks) as well as for 'targeted' short-duration observations such as those related to a volcanic eruption.

GOMOS payload data segment

All data received on the ground are systematically processed and the following products are routinely generated within the ESA Payload Data Segment (PDS): Level-0, Level-1b (transmittance), and Level-2 (profiles

Figure 4. GOMOS telescope assembly during integration at Matra Marconi Space, in Toulouse (F)

Table 3. GOMOS science objectives

Long-Term Objectives	Stratospheric ozone monitoring
	Stratospheric chemistry: upper stratosphere 35 – 50 km
	Stratospheric chemistry: lower and middle stratosphere 15 – 35 km
	Large-scale dynamics at mid and high latitudes: polar vortex, planetary waves
	Dynamics of the equatorial lower stratosphere: dehydration
	Small-scale dynamics: gravity waves, turbulence
	Mesospheric ozone monitoring
	Noctilucent clouds
Campaign Objectives	Tangent occultation
	Validation of GOMOS products
	MIPAS and SCIAMACHY validation
	Arctic campaign
	Special events: solar proton event
	Special events: volcanic eruption
	Antarctic winter troposphere
	Stellar spectra

of ozone and other species). These products are generated in near real time (i.e. within 3 h of sensing) and then regenerated off-line using updated auxiliary data (precise orbits instead of predicted orbits, meteorological analysis fields instead of meteorological predictions, etc.).

With the exception of the quality of the auxiliary data, the algorithms used in the 'near real time' and 'off-line' processing are identical. All ESA processing centres (the Kiruna and ESRIN stations) for the near-real-time products and the German processing and archiving centre (supported by the Finnish Meteorological Institute) for the off-line products, will use the same processing algorithm, so that the user will get consistent products irrespective of the processing centre.

The ESA Level-1b and Level-2 algorithms have been defined following the Envisat Expert Support Laboratory (ESL) approach, whereby a scientific team provides support to an industrial contractor (ACRI, Sophia Antipolis, F). This scientific team includes members of the Service d'Aéronomie (Paris, F), the Finnish Meteorological Institute (Helsinki, SF) and the Institut d'Aéronomie Spatiale (Brussels, B). These algorithms have been prototyped by the ESL and then implemented, within the Payload Data Segment consortium led by Alcatel Space, by SSF Finland.

Data analysis and scientific products

Approach

The role of the GOMOS ground-segment algorithms is to convert the readings of the instrument into scientific products. Complex simulation and analysis codes have been generated for the purpose:

– A system simulator deriving the digital output of the instrument from the spectral intensity of stellar light received by GOMOS's telescope.
– A data-processing chain that performs a stepwise conversion of the ADC counts to vertical profiles of atmospheric constituents. This processor forms the central element of the GOMOS ground segment, as it will process the acquired data and generate the scientific products.

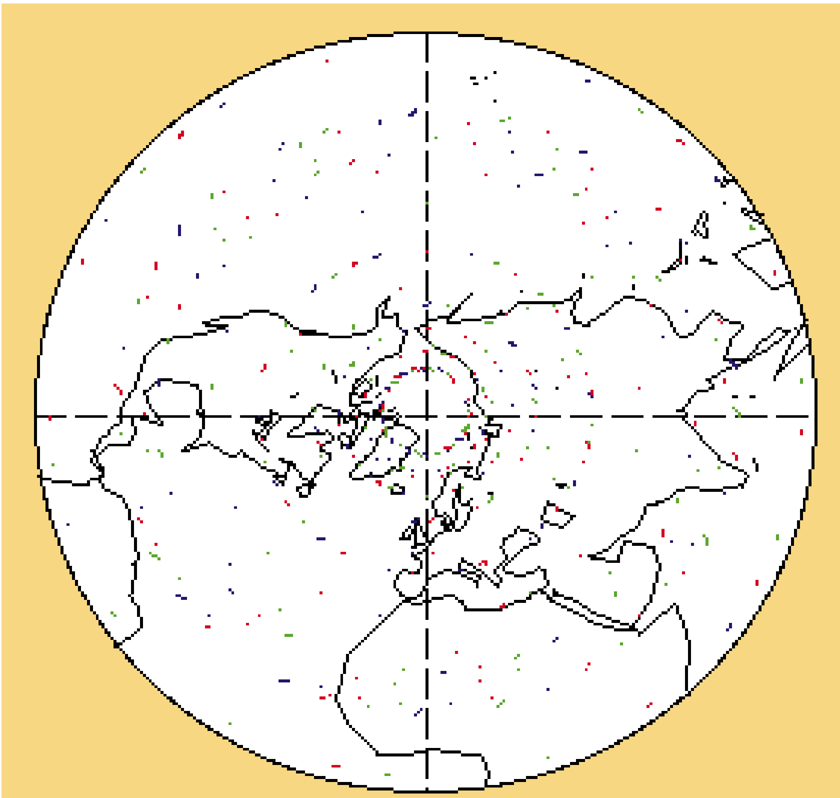

Figure 5. Locations of ozone measurements in the Northern Hemisphere after three consecutive days (around 21 March) with a specific star selection

– A calibration facility using in-flight data to update the calibration database of the data processor.

With these tools, ESA will support the data analysis up to the level of geophysical products related to a single occultation, thus covering the part that requires intimate knowledge of the instrument and of remote-sensing inversion techniques.

Scientific products and algorithms

The generation of scientific products, after low-level data handling, is sub-divided into two basic processes, namely the calibration into physical quantities (Level-1b) and the transformation into atmospheric composition parameters (Level-2).

Level-1b

The objective of the Level-1B processing is to estimate the set of horizontal transmissions using the spectra measured by the instrument during the occultation. The main processing steps will be:

– *Geo-location* providing the location of the tangent point above which the measurements are performed.
– *Wavelength resampling* to a common wavelength grid with correction for instrumental or platform pointing instabilities.
– *Correction of instrumental effects*.
– *Calculation of the transmission spectrum*. After estimation and subtraction of the atmospheric background signal, the atmospheric transmission will be calculated as the ratio of the occulted stellar spectrum to an average of several stellar spectra observed above the atmosphere (‘reference spectra’).

The main Level-1b scientific data handed over to Level-2 processing will therefore be the transmission spectrum, the photometer data and the geo-location for every atmospheric acquisition. The background spectra will also be made available, providing supplementary atmospheric information under bright-limb conditions.

Level-2

In the Level-2 processing, the transmission spectra will be converted into parameters representative of the state of the atmosphere. This implies taking into account three different processes:

1. Absorption by gaseous atmospheric constituents, most prominently by ozone (O_3), but also by nitrogen dioxide (NO_2), nitrogen trioxide (NO_3), oxygen (O_2), water vapour (H_2O), chlorine dioxide (OClO) and others.
2. Extinction of the stellar light by scattering from molecules (Rayleigh scattering) and from aerosol and high cloud (Mie scattering). Rayleigh scattering is well understood, but aerosol represents a considerable complication for GOMOS data analysis since its characteristic spectrum depends on droplet size distribution and chemical composition, both of which are *a priori* unknowns.
3. Refraction, i.e. bending of the light ray due to the vertical gradient in air density, and scintillation in the signal.

The analysis of the transmission spectra starts with correcting for the refractive and scintillation effects. In the next step, a ‘spectral inversion’ is performed whereby each of the transmission spectra is converted to a set of horizontal column densities of atmospheric constituents, i.e. the concentrations integrated along the ray’s path. Finally, these horizontal column densities are converted to atmospheric concentration profiles in the ‘vertical inversion’, which can be visualised as ‘onion peeling’: once the contributions to the horizontal column of all atmospheric layers above the current one are known, they can be subtracted, and the remaining part divided by the path length through the current layer.

The time delay between the two photometer signals (red and blue) allows one to retrieve the refractivity, air density and temperature of the atmosphere. According to current simulations, these parameters could be provided with a vertical resolution of 200 m, representing a unique capability in terms of spaceborne remote-sensing experiments.

The main Level-2 data products are the horizontal column densities and concentrations of ozone, nitrogen dioxide, nitrogen trioxide, air, oxygen and water vapour, as well as the vertical profile of aerosol extinction and the high-resolution temperature profile.

GOMOS data are believed to be useful above 15 – 20 km altitude. An important feature is the high variability in precision caused by differences in the brightnesses and temperatures of the large ensemble of targeted stars. This is illustrated in Figure 6: in the lower stratosphere, the accuracy of ozone concentration is determined by the visual magnitude of the star, whilst at higher altitudes the star’s temperature is more important as hot stars produce significant emission in the UV part of the spectrum.

Validation

Consistency checks on the algorithms and the

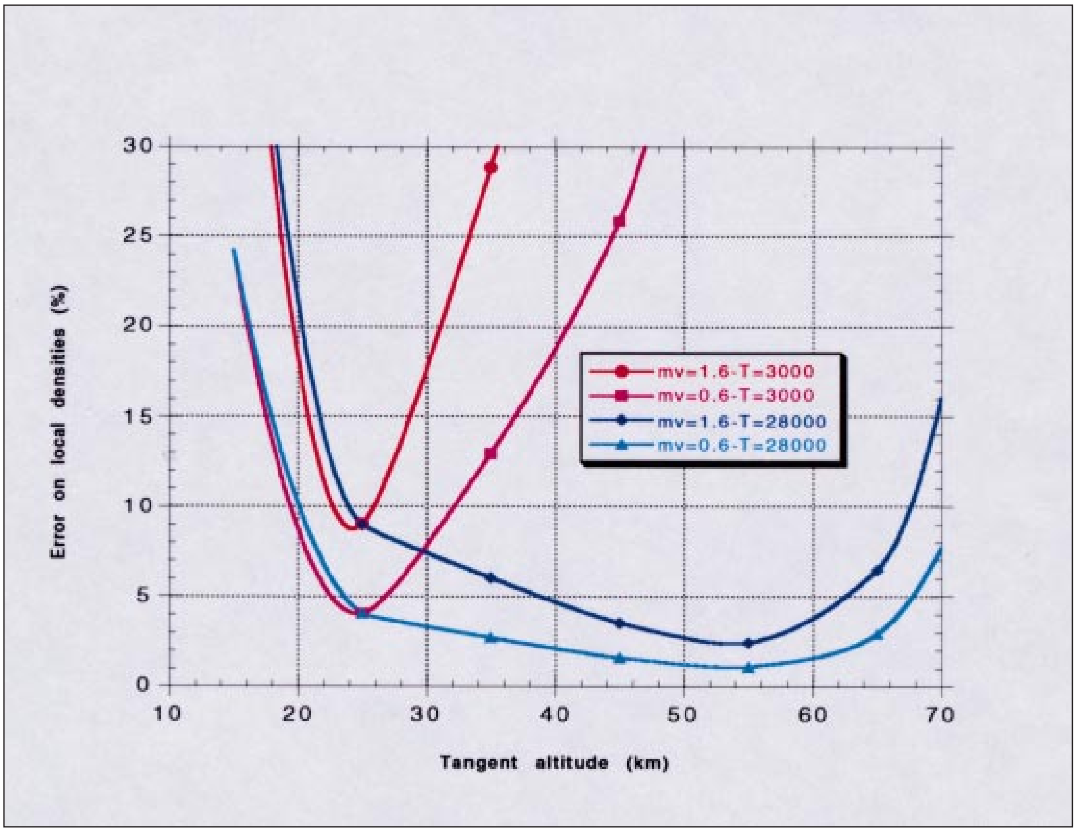

Figure 6. Expected accuracy of the ozone profile as a function of altitude for several star visual magnitudes and temperatures

precision estimates for the data products have been performed using the simulation tools mentioned above. During the Envisat commissioning phase, a geophysical validation campaign will be carried out. This will allow the Level-2 data from GOMOS and its companion instruments MIPAS and SCIAMACHY to be correlated with a large portfolio of independent observations by remote-sensing and in-situ experiments operating on other satellites, on aircraft, on balloon gondolas and on the ground. The air volumes and observation times of these validation instruments are unlikely to coincide precisely with those of the Envisat instruments; atmospheric models will be used to bridge the gap between the different measurements.

Conclusion

The decision to fly GOMOS on Envisat provides the opportunity not only to further our understanding of the chemistry of the Earth's atmosphere, but also to demonstrate the potential of the stellar occultation technique for ozone monitoring. In the latter context, it should provide very accurate global observations, well-distributed geographically, correcting what today is a serious observational deficiency. Current instruments either provide very accurate observations but with limited geographical coverage, or good geographical coverage but with limited accuracy. GOMOS should strike an excellent compromise between these two extremes.

On Envisat, GOMOS will serve a very useful role by providing observations that complement those from the other two chemistry instruments – a point well illustrated by the recent response to the Envisat Announcement of Opportunity, which revealed that many scientists were planning to exploit the synergy of these three instruments. Obviously, GOMOS will serve an additional role by providing a reference standard for monitoring the performance of the other two chemistry instruments.

Finally, looking to the longer term, it is anticipated that the star occultation technique will be capable of routinely monitoring ozone properly on a global basis. An operational concept derived from GOMOS is currently being evaluated.