Envisat/GOMOS Stellar Occultation: Inversion Schemes and First Analyses of Real Data

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Abstract. GOMOS (Global Ozone Monitoring by Occultation of Stars) on board Envisat measures O_3, NO_2, NO_3, neutral density, aerosols, H_2O, and O_2, in the stratosphere and mesosphere by detecting absorption of starlight in ultraviolet, visible and infrared wavelengths. During bright limb conditions GOMOS will also observe scattered solar radiation. GOMOS will deliver ozone concentration profiles at altitudes 15-100 km with a vertical resolution of about 1.5 km and with a global coverage. As a self-calibrating method stellar occultation measurements provide a basis for a long-term global monitoring of ozone profiles. We will present here the status of the GOMOS instrument and show samples of first results obtained in 2002.

1 Introduction

The GOMOS (Global Ozone Monitoring by Occultation of Stars) instrument is a spectrometer on board the European Space Agency's Envisat satellite that was launched on March 1st 2002. GOMOS uses the stellar occultation measurement principle in monitoring ozone and other trace gases in the Earth's stratosphere. The main wavelength region is the ultraviolet-visible region and additional two channels are located in the infrared. The species covered by GOMOS are O_3, NO_2, NO_3, neutral density, aerosols, H_2O, and O_2. The two fast photometers in blue and red wavelengths allow investigations of atmospheric turbulence. Photometer data can also be used to derive high resolution temperature profiles. Measurements cover the altitude region 15-100 km.

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GOMOS was proposed in 1988 by Finnish Meteorological Institute (FMI) and Service d'Aeronomie (SdA, France) as an AO-instrument for ESA's POEM-satellite [2]. POEM became later two satellites, Envisat and Metop. GOMOS was selected to fly on Envisat and ESA gave GOMOS the EFI (ESA Funded Instrument) status. Matra (Astrium) was selected to be the GOMOS main instrumental contractor. The ACRI industrial company was selected to develop GOMOS processing prototype with support from the scientific institutes FMI, SdA and IASB (Belgium) forming the GOMOS Expert Support Laboratories. The Space Systems Finland Ltd has developed the GOMOS data processor for the actual processing. The operational GOMOS processing takes place at ESA facilities in Kiruna and Frascati and at FMI's Arctic Research Centre in Sodankylä .

The important advantage of any occultation measurement is the self-calibration. The reference spectrum of a radiation source is first measured when the source can be seen above the atmosphere (120-150 km). During the occultation repeated observations through the atmosphere at descending altitudes provide spectra with absorption features. When these occulted spectra are divided by the reference spectrum, nearly calibration-free horizontal transmission spectra are obtained. Transmissions provide the basis for a retrieval of atmospheric constituent densities. The self-calibration means that occultation measurements can be used to create long time series which is necessary in monitoring the predicted slow recovery of the depleted ozone layer. In the case of GOMOS or any other stellar occultation instrument the limb viewing geometry, the point source nature of stars and the short enough measurement integration time mean a good vertical resolution. The maximum vertical integration distance for GOMOS is 1.7 km. The good vertical resolution is important in resolving altitude dependent chemical processes. Besides the self-calibration and the good vertical resolution the advantage of the stellar occultation method is the good global coverage provided by the multitude of suitable star targets. During 24 hours, the total number of occultations is 400-600. Measurements are obtained from both night and day side of the Earth.

The GOMOS is the first operational stellar occultation instrument, but first stellar occultation measurements were made already 30 years ago ([9], [11]). Solar occultation technique (see e.g., [4]) has been in the central position in deriving the ozone trends 1979-2000. Recently the UVISI instrument on MSX-satellite has carried out successfully stellar occultations during 1996-2001 providing ozone concentrations in the stratosphere ([15], [5], [14]).

2 GOMOS instrument

The point source character of stars, and the weakness of their radiation, pose special requirements for instrument design and data retrieval that are not

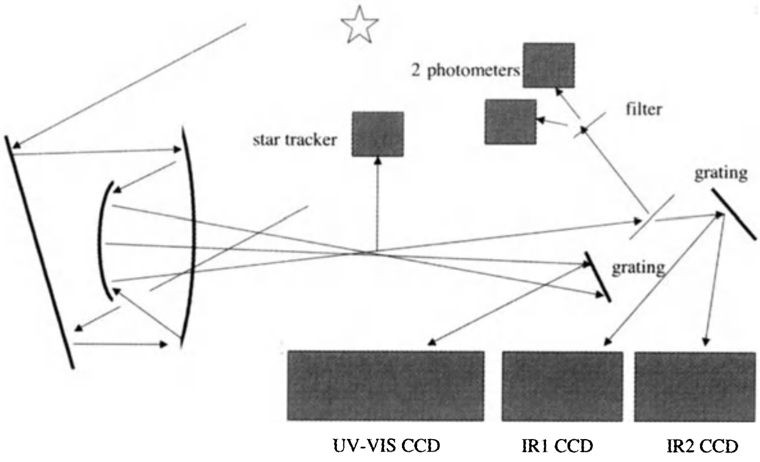

Fig. 1. GOMOS optical layout.

relevant to instruments looking for scattered solar radiation or even for solar occultation instruments.

Table 1. Main properties of GOMOS instrument

Property or module	**Value**
Size, power, telemetry	175 kg, 200 W, 226 kbit/s
Telescope	30 cm x 20 cm
Pointing system	Star tracker at 100 Hz. Stability better than 40 microradian.
Angular coverage	-10 deg. – 90 deg. in azimuth, 62 deg. – 68 deg. in elevation.
Targets	Stars visual magnitude of m=-1.4 – m=5 and temperature T=3000 K –T=30000 K
UV-VIS spectrometer	Coverage=248-690 nm, resolution=0.9 nm, sampling=0.31 nm, frequency=2 Hz
IR-spectrometer	Coverage=750-776 nm and 916-956 nm, sampling= 0.14 nm, frequency=2 Hz
Photometers	Blue: 470–520 nm, Red: 650–700 nm, frequency=1000 Hz

The optical layout of the GOMOS instrument is shown in Figure 1. The telescope and the pointing system capture a star at a tangent height around 150 km, lock to the star and follow the star down to about 10 km. On the day side of the orbit the GOMOS telescope will also receive scattered solar light. In order to minimise the scattered solar light a slit is incorporated. The challenge of the pointing system is too keep the star image in the centre of the slit with a good stability in order to minimise wavelength shifts. The incoming light is forwarded to several detectors. The first detector is the star tracker operating in 650-950 nm and working with 100 Hz to guide the pointing system. The remaining light is divided between the spectrometers and the two photometers. The photometers work in the blue and red wavelength regions with 1 kHz frequency. The spectrometers work in the ultraviolet-visible wavelengths 250-690 nm and two channels are in the infrared at 750-776 nm and 916-956 nm. The CCD detectors make it possible to estimate radiation coming from extended sources (mainly solar scattered light during bright limb measurements) and extract it from the stellar signal. The integration time of the UV-VIS-spectrometer and IR-spectrometers is 0.5 sec. The summary of the GOMOS instrument properties is shown in table 1 (for more information, see http://envisat.esa.int/dataproducts/gomos, and [3], [8]).

3 Measurement physics

The basic data GOMOS measures are stellar spectra above and through the atmosphere, diffuse radiation from the atmosphere and frequent samples of the incoming flux in the red and blue photometer window. The main derived data are horizontal transmissions that are calculated by dividing the spectra measured through the atmosphere (at tangent heights below 100 km) by the average reference spectrum measured above the atmosphere (tangent heights 120-150 km):

$$T_{\mathrm{obs}}(\lambda, z) = \frac{I_{\mathrm{occ}}}{I_{\mathrm{ref}}} \qquad (1)$$

Usually transmission measurements like this can be used as a basis for absorber retrievals using the well-known Beer-Lambert law but the nature of stars as point sources of light give rise to additional complexities. The parallel ray bundle from a star will be strongly disturbed by the refractive effects in the atmosphere (see Figure 2). These effects are: Bending of light rays, refractive dilution, scintillations, and chromatic propagation of light.

The first effect is related to the density gradient in the atmosphere. The density gradient will cause a larger deflection to a grazing ray compared to a ray with a larger impact parameter. The change of the propagation direction in the atmosphere will result to dilution of the related intensity. A closely related effect is the scintillation effect. In explaining the dilution we assumed that the atmospheric density decreases monotonically from the ground upwards. If there are fluctuations added to this decrease the ray deviations will also show inhomogeneity. A satellite crossing this inhomogeneous light field will record a fluctuating intensity. This is shown schematically in Figure 2a. If the ray modifications are strong enough, different rays, originally parallel, can even cross each other. This is called the strong scintillation regime. At this regime

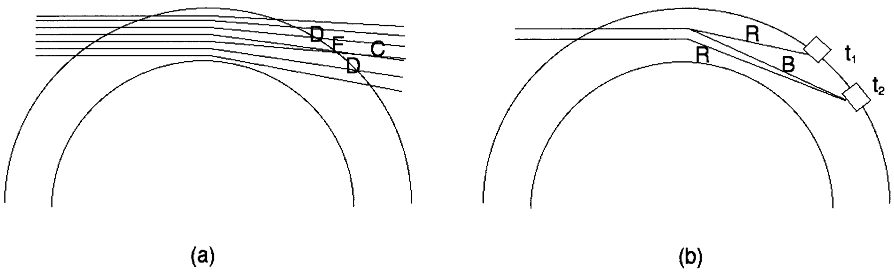

Fig. 2. In (a) the refractive dilution and scintillation effects are shown. D=defocusing area, F=focusing area, C=ray crossing area, In (b) the chromatic effects are illustrated. Blue rays (B) are refracted more strongly than red rays (R). From a given altitude blue rays reach the satellite later than red rays ($t_2 > t_1$) (if setting occultations are used). At any moment blue rays are coming from higher tangent heights than red rays.

multiple star images can be formed in the atmosphere. The last effect caused by refraction is the chromatic refraction which leads to a spatial separation of different colours. A multi-wavelength measurement of a stellar spectrum through the atmosphere cannot therefore be attached with an unique ray connecting the satellite and the star. If we describe rays by their tangent heights, we see that at a given time a measurement will be characterised by a range of tangent heights. If we want to attach only one tangent height we have to combine data from measurements at different tangent heights.

The refractive effects discussed above are not restricted to the stellar occultations in the Earth's atmosphere. In fact they all have been detected and exploited in the data retrieval of stellar occultations of planetary atmospheres (see [6], [13]).

4 Inversion strategy and data processing

In the nominal (ESA) GOMOS data processing the data set processed at a time are the measurements from one occultation. Even if some occultations would probe the same atmospheric region at successive orbits these occultations are treated separately. Therefore, the possibility to carry out some kind of atmospheric tomography by GOMOS will not be considered in the nominal Level 2 processing.

In Level 1b (see Figure 3) data are geolocated using the ECMWF prediction/analysis for the ray tracing calculations. All engineering corrections are applied and the diffuse background radiation is removed from the stellar signal. The Level 1b products are transmission spectra, photometer fluxes and limb radiance spectra from day side occultations. In the present GOMOS ground processing limb spectra are not processed further. Potentially they

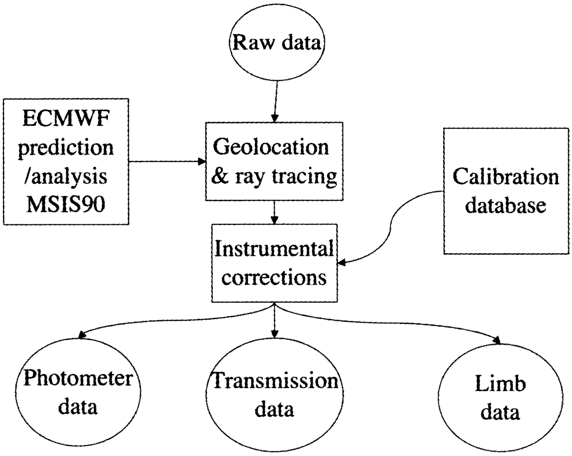

Fig. 3. GOMOS Level 1b processing.

provide the possibility to derive constituent profiles in the same way as in OSIRIS/Odin processing [1].

In Level 2 the main data are the transmission spectra at different tangent heights from Level 1b (see Eq. (1)). Photometric data from the two fast photometers are used for correcting the transmissions from the refraction effects and for retrieving a high resolution temperature profile of the atmosphere.

The geophysical retrieval strategy in the GOMOS Level 2 data processing assumes that the observed (actually calculated) transmission can be taken as the product of two transmissions:

$$T_{\mathrm{obs}} = T_{\mathrm{ref}} T_{\mathrm{ext}} \tag{2}$$

The transmission T_{ref} is due to refractive effects (dilution and scintillations) and the transmission T_{ext} is due to absorption and scattering processes in the atmosphere. The Level 2 processing first aims to estimate the refractive part using the fast photometer data and the geolocational data and then removes it from the measured transmission. The remaining transmission can then be connected to the atmospheric constituent densities, the retrieval of which is the main mission objective of the GOMOS instrument. This transmission can be written as

$$T_{\mathrm{ext}}(\lambda, \ell) = e^{-\tau} \tag{3}$$

where the optical depth τ is given by

$$\tau(\lambda, \ell) = \int_{\ell} \sum_{j} \sigma_j(\lambda, \mathrm{T}(\bar{r}(s)))\rho_j(\bar{r}(s))ds \tag{4}$$

Here σ_j is the extinction (absorption or scattering) cross section of a constituent j and ρ_j its local density. The cross section can depend on temperature T. The integration is along the line of sight ℓ that depends on wavelength, the satellite position, and the refractive state of the atmosphere.

Equations (1)–(4) determine the GOMOS inversion problem. The problem can be solved using at least three different inversion schemes displayed in Figure 4 (see [10]). The direct route, the route in the center of Figure 4) from transmissions to constituents is called one-step inversion. The problem with this approach is the size of the input data and the number of the estimated parameters. Data consist of spectra with 1500 spectral points (we consider here only the UV-VIS spectrometer) from at least 70 altitudes. This means something like 105 000 data points during one occultation. We aim to retrieve at least 5 gases at 70 (or more) levels i.e. we have at minimum 350 model parameters. In the middle of 1990 this inversion problem appeared dangerously large for an effective retrieval (for early studies of GOMOS one-step inversion, see [12]. Currently several studies are ongoing at FMI for one-step inversion algorithms with the help of more powerful computers. The problem of insufficient memory is shared with the right hand route in Figure 4.

The left hand route in Figure 4 is the one adopted in GOMOS processing. The essential simplification is the factorisation of the inversion problem to spectral and vertical problems. This can be done by writing (see [12])

$$\tau(\lambda, \ell) = \sum_j \sigma_j^{\text{eff}}(\lambda, \ell) N_j \tag{5}$$

where N_j is the line density of the species j

$$N_j = \int_\ell \rho_j(\bar{r}(s))\, ds \tag{6}$$

and

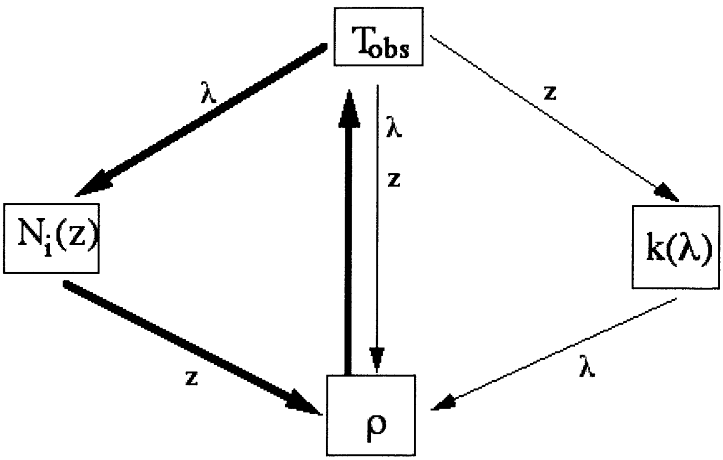

Fig. 4. Retrieval possibilities for GOMOS data.

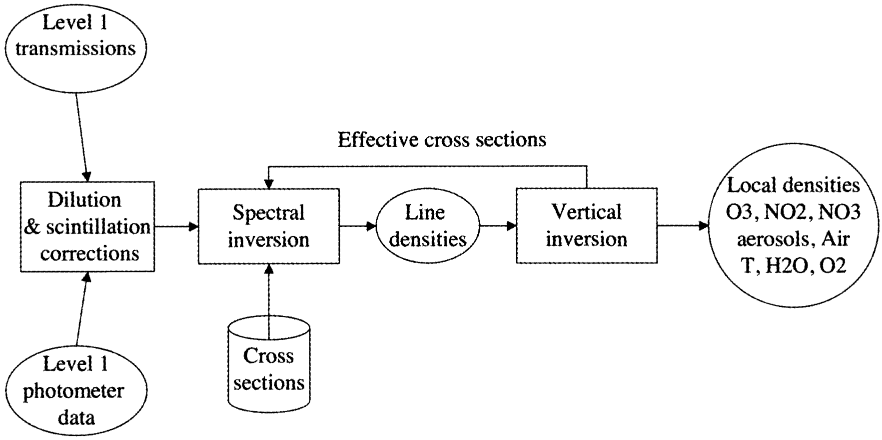

Fig. 5. Level 2 GOMOS data processing.

$$\sigma_j^{\mathrm{eff}}(\lambda, \ell) = N_j^{-1} \int_\ell \sigma_j(\lambda, \mathrm{T}(\bar{r}(s)))\rho_j(\bar{r}(s)))\, ds \tag{7}$$

is the effective cross-section of species j. The use of the effective cross-section has formally separated the inversion problem into two parts. The spectral inversion part is given by Eqs. (3) and (5) with the line densities N_j as unknowns. The vertical inversion part is given by Eq. (7) with ρ_j as the unknowns. The two parts are, however, coupled together by the unknown effective cross sections. An iterative loop over spectral and vertical inversion is needed in order to solve the problem. The refracted rays through the atmosphere are calculated using ECMWF data.

In the spectral inversion of the UV-VIS spectrometer data the inversion is done by minimising χ^2. This problem is nonlinear (see Eq. (3)) and data are noisy. Therefore, the problem cannot be linearized (see [10]) and we use the well-known Levenberg-Marquard method to find the solution. All constituents are retrieved simultaneously and all wavelengths are used ([10], [12]). The more familiar vertical density profiles are the result of the vertical inversion of horizontal column densities, assuming local spherical symmetry. The inversion method is the familiar onion peel inversion. Spectral and vertical dependence of aerosol extinction will also be estimated from transmission data. From the analysis of fast photometers the high resolution temperature and density profiles are calculated. A simplified GOMOS Level 2 processing diagram is shown in Figure 5.

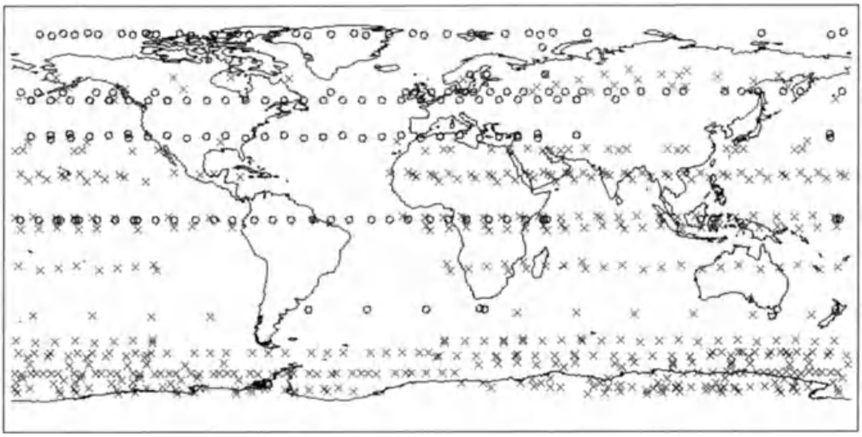

Fig. 6. The distribution of GOMOS measurements during 27.–31.7. 2002. Dark limb occultations have been shown by crosses and bright limb occultations by circles. Notice that during short period like this, occultations of a given star are located at a fixed latitude. This leads to an easy zonal averaging in results.

5 First 50000 GOMOS measurements

The first GOMOS measurement took place on 20th of March, 2002. Since then GOMOS has successfully measured more than 50000 occultations during 2002. The last 9 months of 2002 have been the calibration and validation period for all Envisat instruments. As an instrument GOMOS has performed well during this period but with one serious exception. The CCD detectors of the UV-VIS channel have shown much more noise than originally expected. The reason for this behaviour is a stronger than assumed sensitivity of the CCD to proton radiation. The CCD also shows random telegraphic noise. In order to minimise the effects of noise sensitivity the GOMOS instrument temperature has been reduced twice with some improved results. At the same time data processing methods have been developed to counteract hot pixels in data.

The validation of GOMOS and other Envisat products have been started after the main calibration questions have been solved. For Envisats atmospheric instruments, GOMOS, MIPAS, and SCIAMACHY, an extensive validation program has been established including ground based measurements, ozone sondes, balloons, aircraft and other satellites. These validating measurements are either results of regular measurements or additional specific measurements for Envisat. In the case of GOMOS the most intensive work has concentrated on the two data sets measured during 27–31.7. 2002 and 30.9–3.10. 2002. Both data sets comprise over 700 occultations. The validation has concentrated on dark limb occultations because the quality of results in bright limb is expected to be much degraded compared to dark limb. The

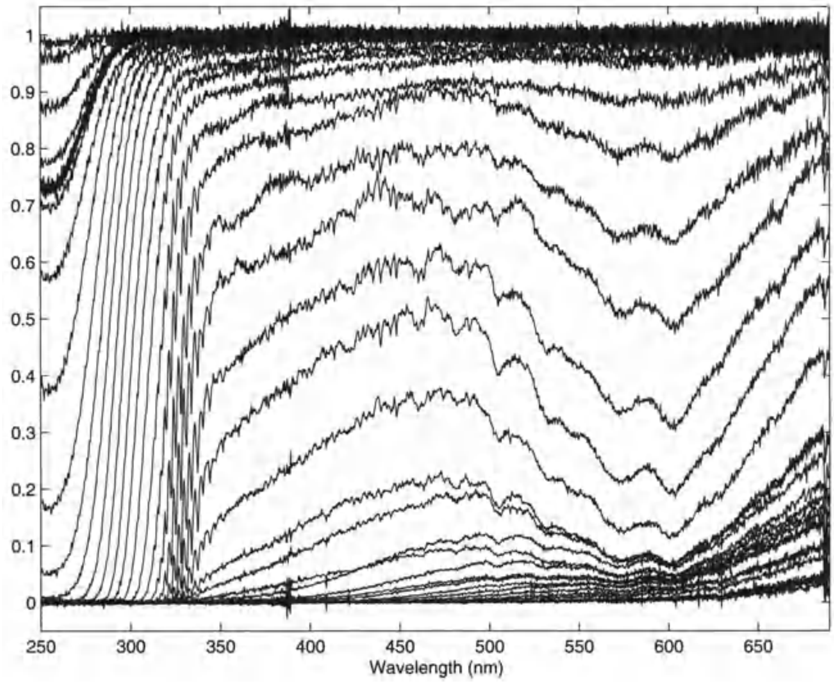

Fig. 7. Level 1b transmission from GOMOS. Altitude region is 5-100 km. The Chappuis band around 600 nm is easily recognisable as well as the Hartley-Huggins bands in the ultraviolet.

distribution of occultations, for example, in the July data set is shown in Figure 6.

In Figure 7 the main GOMOS Level 1b product, transmission spectra from one occultation, is shown. Figure 8. shows a snap shot from the photometer time series demonstrating beautifully the chromatic time delay. Figure 9 shows limb spectra and Figure 10 gives an example how GOMOS is able to measure ozone from troposphere to mesosphere. Profiles like this will be the main product of GOMOS.

6 Summary

The first nine months of GOMOS measurements have shown that the instrument functions well and even exceeds the expectations in many respects. The sensitivity of the UV-VIS spectrometer to protons has been an unpleasant surprise and a lot of effort has been made to counteract this derogative effect. In the retrieval a surprise has also been encountered. It looks like our understanding of the stratosphere is not enough to fully model the observed transmissions at altitudes 20–45 km. Extinction caused by absorption and

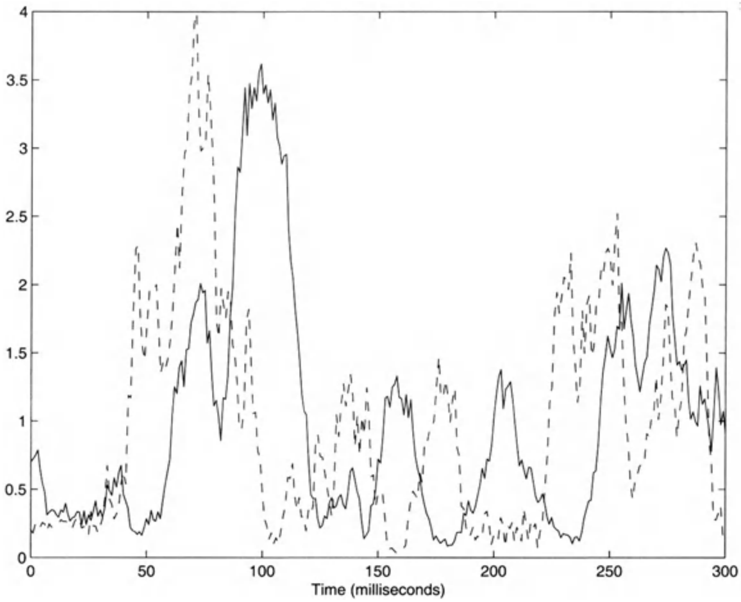

Fig. 8. Blue (solid line) and red (dashed line) photometer time series. Altitude is 22.6 km. This figure verifies the scheme shown in Figure 2, i.e., the red light from any atmospheric feature arrives earlier than the blue light.

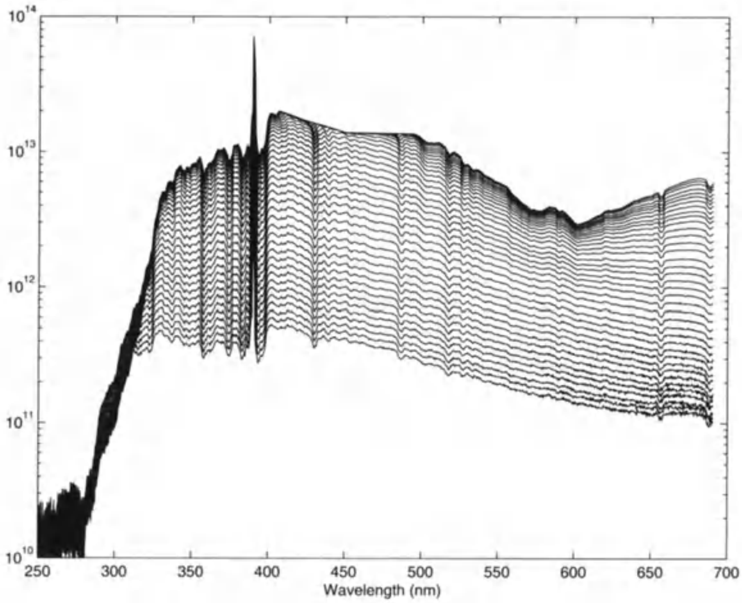

Fig. 9. Limb spectra between 17–50 km.

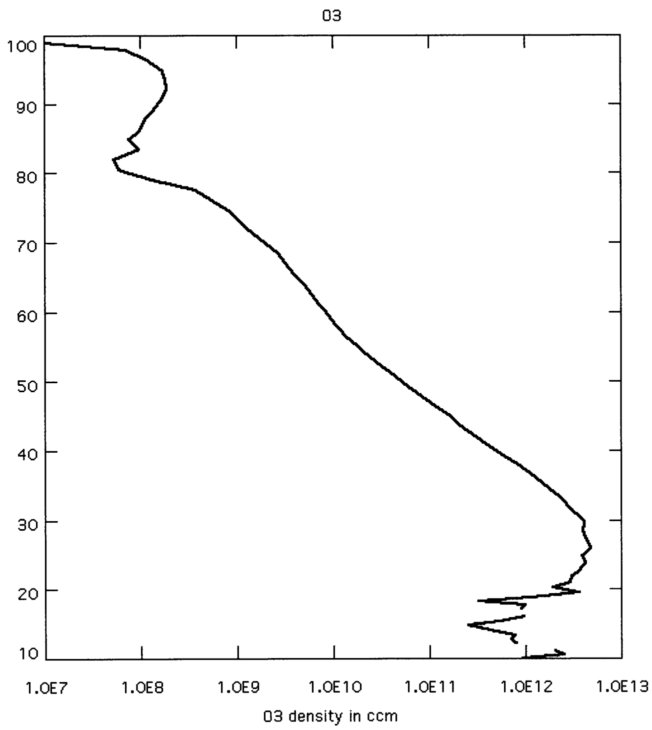

Fig. 10. GOMOS ozone profile from an occultation with a bright, hot star.

scattering and the modification of the transmission by vertically stratified refraction cannot fully explain the observed features. The exact content of this surprise is still under investigation. Albeit these surprises, the preliminary analyses show that ozone and neutral density profiles as well as the high resolution temperature profiles are very promising. The quality of the other minor constituent retrieval seems to suffer from the increased noise and modelling deficiencies and further work must be carried out in order to improve the retrievals.

References

[1] Auvinen H, Oikarinen L, Kyrölä E (2002) Inversion algorithms for recovering minor species densities from limb scatter measurements at uv-visible wavelengths. J Geophys Res 107(D13)

[2] Bertaux JL, Megie G, Widemann T, Chassefiere E, Pellinen R, Kyrölä E, Korpela S, Simon P (1991) Monitoring of ozone trend by stellar occultations: The gomos instrument. Adv Space Res 11(3): 237–242

[3] Bertaux JL, Kyrölä E, Wehr T (2000) Stellar occultation technique for atmospheric ozone monitoring: Gomos on envisat. Earth Observation Quarterly 67:17–20

[4] Chu WP, McCormick MP, Lenoble J, Brogniez C, Pruvost P (1989) SAGE II inversion algorithm. J Geophys Res 94: 8339–8351

[5] DeMajistre R, Yee J-H (2002) Atmospheric remote sensing using a combined extinctive and refractive stellar occultation technique, 2. inversion method for extinction measurements. J Geophys Res 107(15): ACH 6–1

[6] Elliot JL (1979) Stellar occultation studies of the solar system. Ann Rev Astron Astrophys 17: 445–475

[7] ESA Gomos data handbook. http//envisat.esa.int/dataproducts/gomos

[8] GOMOS ESL (2001) Envisat-GOMOS. An Instrument for Global Atmospheric Ozone Monitoring. ESA SP-1244

[9] Hays RG, Roble PB (1968) Stellar spectra and atmospheric composition. J Atmos Sci 25: 1141–1153

[10] Kyrölä E, Sihvola E, Kotivuori Y, Tikka M, Tuomi T, Haario H (1993) Inverse theory for occultation measurements, 1, Spectral inversion. J Geophys Res 98: 7367–7381

[11] Roble PB, Hays RG (1972) A technique for recovering the vertical number density profile of atmospheric gases from planetary occultation data. Planet Space Sci 94: 1727

[12] Sihvola E (1994) Coupling of spectral and vertical inversion in the analysis of stellar occultation data. Geophysical publications, no. 38. Finnish Meteorological Institute, Helsinki, Licentiate thesis at the University of Helsinki, Department of Theoretical Physics

[13] Smith GE, Hunten DM (1990) Study of planetary atmospheres by absorptive occultations. Reviews of geophysics 28: 117–143

[14] Vervack RJ, Yee J-H, Carbary JF, Morgan F (2002) Atmospheric remote sensing using a combined extinctive and refractive stellar occultation technique. 3. inversion method for refraction measurements. J Geophys Res 107(D15)

[15] Yee J-H, Vervack RJ, Jr, DeMajistre R, Morgan F, Carbary JF, Romick GJ, Morrison D, Lloyd SA, DeCola PL, Paxton LJ, Anderson DE, Kumar CK, Meng CI (2002) Atmospheric remote sensing using a combined extinctive and refractive stellar occultation technique. 1. overview and prof-of-concept observations. J Geophys Res 107(D14)