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MONITORING OF OZONE TREND BY STELLAR OCCULTATIONS: THE GOMOS INSTRUMENT

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ABSTRACT

As a part of the payload of the first European Polar Platform, the GOMOS instrument has been proposed by a group of 25 scientists from six countries. It consists of a telescope feeding two spectrographs, mounted on a dedicated steerable platform. The transmittance of the atmosphere between 250 and 675 nm is measured by comparing the spectrum of a star outside the atmosphere, and through it. The ozone tangential column is determined from its UV and Chappuis band absorption. This self-calibrated method is particularly well suited for the study of ozone long term trend. The altitude of each single measurement is precisely known (± 50 m), independently of attitude uncertainties. About 25 stellar occultations per orbit, and 350 per day, spread over all latitudes can be performed from 90 km down to 15-20 km of altitude. NO_2, NO_3, H_2O, T(z) and aerosols are also simultaneously determined, important parameters associated to the ozone equilibrium. The ability to measure ozone long-term trends is calculated.

1. INTRODUCTION

In response to the growing concern about the threatened ozone equilibrium in the stratosphere, the GOMOS instrument (Global Ozone Monitor by Occultation of Stars) was proposed to ESA by a group of 25 European Scientists from 10 institutes and 6 countries, to be flown on the European Polar Platform /1/. A phase A study of GOMOS was conducted by Matra and a group of Finnish industries, at the joint request of CNES and Finnish Meteorological Institute, resulting in a stage of definition of the instrument sufficient to warrant feasibility and scientific performances.

2. METHODOLOGY OF STELLAR OCCULTATIONS

From its polar orbit, the GOMOS instrument allows to measure the atmospheric transmission in the stratosphere, from 15-20 km of altitude up to 60 km and above, from UV wavelength λ (250 nm) to near IR (950 nm) with a spectral resolution of 0.6 nm. This transmission is measured along tangential lines-of-sight from the spacecraft to stars, which spectrum measured outside the atmosphere is compared to the spectrum seen through the atmosphere when the star sets below the Earth's limb, in the area opposite to the velocity vector. Its full UV-visible-near IR spectrum is recorded continuously in a multispectral mode (the full spectrum is recorded simultaneously).,This *full spectrum* method, which is differential in the sense that it is the shape of the spectrum which counts, ensures that the various absorbing species can be safely identified, and their tangential column densities easily derived from a comparison to the unattenuated stellar spectrum measured outside the atmosphere a few seconds before with the same instrument. The method is also *self-calibrated*, as it allows to derive an absolute concentration of atmospheric molecules from relative measurements and is therefore protected from instrumental drifts. This intrinsic long term stability is a requisite feature for addressing the delicate objective of detecting small trends in the ozone distribution.

Standard equations are :

$$F(\lambda,p) = F_0(\lambda) \exp[- \Sigma\, \sigma_i(\lambda)\, N_i(p)] \quad (1)$$

where $F_0(\lambda)$ is the unattenuated stellar spectrum, $F(\lambda,p)$ is the stellar spectrum seen through a line of sight with an impact parameter $p = R_{Earth}$ + altitude z, $N_i(p)$ is the integrated tangential column density of constituent i, $\sigma_i(\lambda)$ is the absorption cross-section of constituent i at wavelength λ, and $T(\lambda,p) = F(\lambda,p)/F_0(\lambda)$ is the tangential atmospheric transmission at p or altitude $z = p - R_{Earth}$. Assuming spherical symmetry of the constituent i concentration distribution, with a vertical profile $n_i(r)$, we have :

$$N_i(p) = \int_p^{\infty} \frac{n(r)\, dr}{(r^2-p^2)^{1/2}} \qquad \text{with } r = R_{Earth} + z \quad (2)$$

During one single occultation, a series of spectral transmissions $T_j(\lambda,p_j)$ are obtained at various altitudes z_j. For each $T_j(\lambda,p_j)$, a set of values of $N_i(p_j)$ are obtained for the various absorbing species by a least square fit using a data bank of the cross-sections $\sigma_i(\lambda)$. Then, several inversion schemes can be used to retrieve a vertical concentration profile $n_i(r)$, including the well known "onion-peel" algorithm. In the case of O_2 band at 760 nm and H_2O at 936 nm, the recorded spectra must be compared to synthetic profiles convoluted with the instrumental profile in order to retrieve O_2 and H_2O. From the vertical derivation of O_2, the temperature profile may be obtained.

Early theoretical work on stellar occultations /2/ was based upon a single wavelength monitoring of the star spectrum ; ozone profiles were obtained in 1975-76 from OAO-2 and OAO-3 orbital telescopes /3,4/ with derived concentrations somewhat higher than expected from a model. This may have been caused by an incorrect knowledge of the orbit (a few km). However, working with only one single wavelength implies some assumptions about other absorbing species than ozone, introducing an uncertainty which is eliminated when working with a full set of wavelength, as is now possible with multi-element detectors. NO_3 was first measured in the stratosphere from a balloon-borne stellar occultation spectrometer /5/, together with NO_2 and O_3. Multi spectral occultations were also used by Voyager UVS spectrometer, as reviewed recently /6/.

3. TRENDS IN VERTICAL OZONE DISTRIBUTION AS MEASURED BY SAGE I/SAGE II

SAGE I and SAGE II are both orbiting multi-wavelength radiometers employing the solar occultation technique, measuring ozone in the Chappuis band at 600 nm. According to the Ozone Trend Panel analysis /7/, up to now "only data from the SAGE instruments appear to have the long term stability to allow trend detection", because of the self-calibrating occultation method. Figure 2 represents the changes (%) in O_3 concentration measured from 1979-1980 to 1984-1985 for mid-latitude regions, compared to model predictions. Ground based Umkehr measurements are also represented, but their reliability is questionable because of interference from volcanic aerosols. Several features must be pointed out. There is a strong vertical structure of the observed trend, similar for the Northern and Southern hemispheres peaking at ≈ -4% at 40 km. This structure does not coincide completely with model predictions, in particular there is an observed decrease below 25 km not predicted.

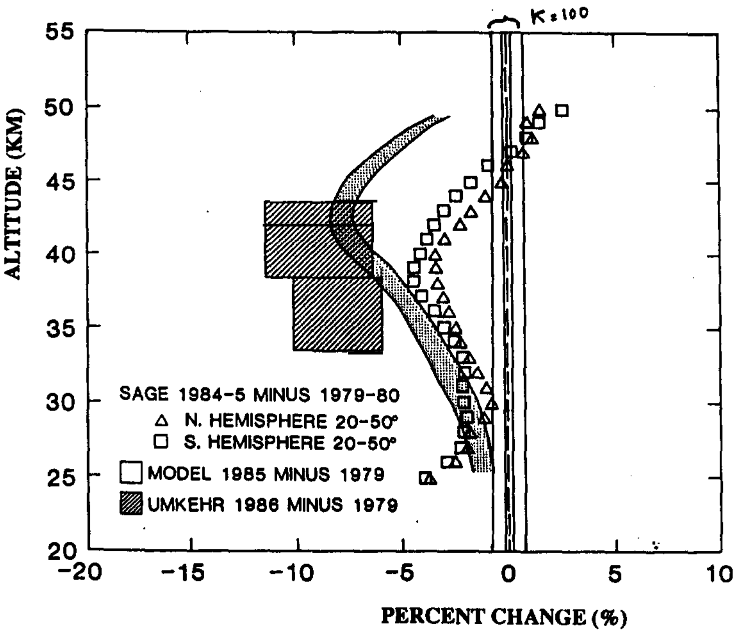


Figure 1 - Changes (%) in mid-latitude ozone profiles from 1979 to 1987. Differences based on SAGE I-II (1979-80 vs. 1984-85) averaged over 20x-50x latitude are shown by small squares (S. hemisphere) and triangles (N. hemisphere); averaged Umkehr data for the Northern mid-latitudes (1979 vs. 1986) are denoted by the hatched boxes; model predictions (1979 vs. 1985) are given by the grey band. Around the 0% change in O_3 concentration, the wider vertical band (K = 100) notes the minimum trend detectable with GOMOS, using 100 geographical regions on the globe. The smallest band corresponds to an averaging of the data using ~10 latitude zones (adopted from /8/).

The stellar occultations used by GOMOS will extend the SAGE results with several additional advantages :

- the use of the sun, an extended source, introduces in solar occultations a systematic error of ± 6% on O_3 concentration because of attitude pointing uncertainties, a problem eliminated with the use of stars;
- full latitude and seasonal coverage, where only two latitudes would be covered by solar occultation on Polar Platform;
- about 25 occultations per orbit instead of 2 only with the Sun. The statistical uncertainty due to sampling is therefore reduced by a factor ≈ 3.5;
- with only 7 detectors, SAGE II tries to determine 5 quantities : O_3, NO_2, H_2O, aerosols, air density, allowing marginal redundancy. GOMOS will have about 1,000 independant spectral elements, ensuring a better identification of absorbing species;
- deep polar night is accessible. Measurements in both polar regions are possible on the same orbit.

4. INSTRUMENT DESCRIPTION

The main characteristics of the instrument resulting from the Phase A study are summarized in Table 1. The optical box, including one telescope, two spectrometers, a stellar sensor and a fast photometer (figure 2), is mounted on a pointing mechanism with 2 degrees of freedom, allowing to aim in any direction in the space region below the horizontal plane of the Polar Platform and in the hemisphere opposite to the velocity vector. Only stellar sets are observed. For a given occultation, the telescope is first oriented in the direction of the star to be occulted (rallying phase). Then, the stellar sensor helps to acquire the star and keep it, in the focal plane, in the slit common to both spectrometers (acquisition phase). The full spectrum of the star is recorded each 0.5 sec, while setting behind the Earth's limb, giving a 1.7 km vertical resolution for a star occulted in the vertical plane, and better for an oblique occultation (measurement phase). Once terminated, another star is being rallied for a subsequent occultation. Stars are selected through a sample of the 50 brightest stars to provide a reasonnable latitude coverage, up to $M_V = 2$ on the bright limb, and $M_V = 3$ on the dark limb.

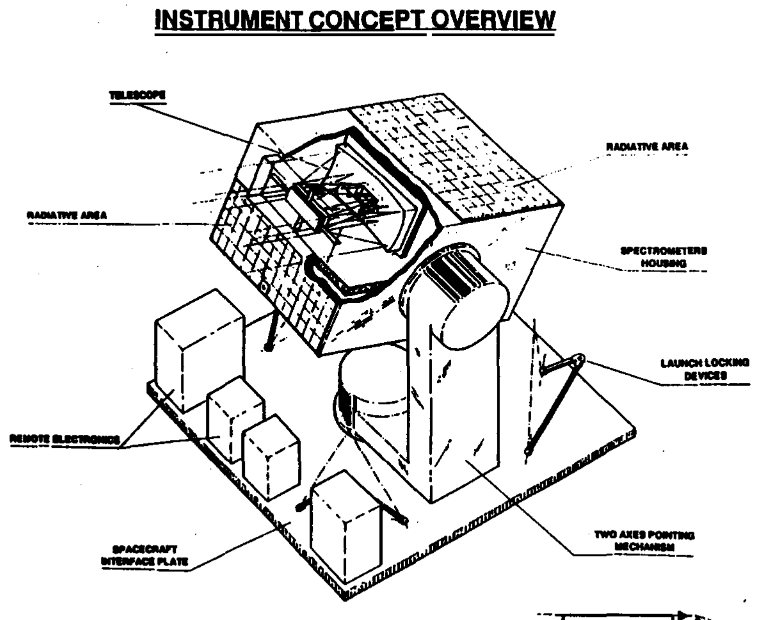
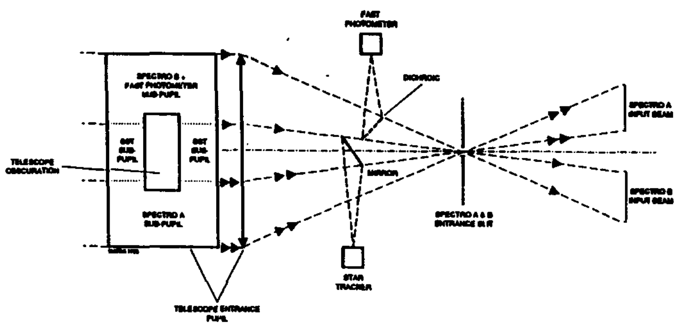


Figure 2 - GOMOS instrument overview.The optical box, including one telescope, two spectrometers, a stellar sensor and a fast photometer is mounted on a L-shaped, 2-axis pointing mechanism which allows a coverage in any direction below the horizontal plane of the Polar Platform and in the hemisphere opposite to the velocity vector. The optical concept developed by MATRA includes a sectorial coating of the primary mirror to optimize flux transmission to the UV-visible A spectrometer (250-675 nm) and the near-IR B spectrometer (760 and 936 nm regions). The spectrum of the star is dispersed on a few lines of several CCDs (512 x 512 pixels). A fast photometer (10^3 measurements per second) in the red is used to measure light fluctuations due to scintillations at low altitudes (< 25 km). About 25 occultations per orbit, or ~ 350 per 24 hour can be performed, the instrument being run permanently.



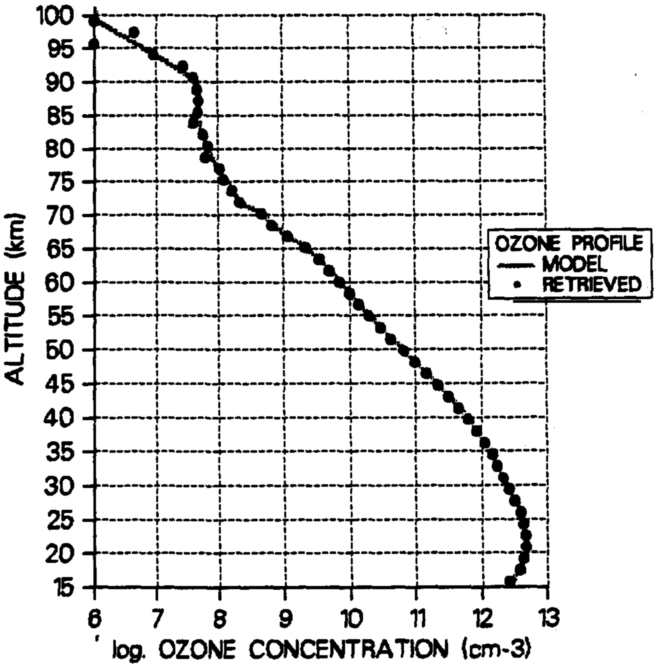
SPECTRAL BAND DEFINITION		SPECTRAL SAMPLING	SPECTRAL RESOLUTION
UV 1	250 - 300 nm (O_3)	0.3 nm	0.6 nm
UV 2	300 - 325 nm (O_3)	0.3 nm	0.6 nm
VIS 1	325 - 500 nm (NO_2, O_3, Aerosols)	0.3 nm	0.6 nm
VIS 2	500 - 675 nm (O_3, NO_3)	0.3 nm	0.6 nm
B1	758 - 772 nm (O_2, T(z))	0.035 nm	0.07 nm
B2	926 - 943 nm (H_2O)	0.035 nm	0.07 nm
MASS	(20% margin)	106 kg	
RELIABILITY OBJECTIVE		≥ 0.8 for a 4 years mission	
POWER :	- Operational (20% margin)	160 W	
	- Safe / survival	30 W	
SCIENCE DATA RATE: Operational		215 kbits/sec	

Table 1 - Instrumental characteristics of GOMOS.

5. NUMERICAL SIMULATIONS

The atmospheric transmission has been simulated for the GOMOS geometry, and a standard atmosphere profile, including O_2, O_3, NO_2, NO_3, aerosols and Rayleigh extinction) from 50 to 20 km of altitude. At 50 km of altitude, the most conspicuous feature is the UV sharp cut off due to ozone. At 40 km, NO_2, Rayleigh extinction and O_3 in the visible (Chappuis bands) begins to be significant, and becomes dominant at 30 and 20 km. Clearly, ozone dominates the absorption spectrum in the UV-visible, and in present almost everywhere with a well-defined spectral signature. The continuous spectral coverage of GOMOS allows to detect possible systematic biases introduced by unforeseen absorbing species, by comparing measured transmission to simulated transmission spectra. This could be the case of SO_2 from volcanic eruptions, or O_4, the dimer of O_2. For an instrument with only a limited number of spectral channels, such species could go unnoticed, and introduce an unknown bias in the ozone retrieval, catastrophic for trend estimation.

Given all the technical characteristics of instrument (optics transmission, read out noise, photon noise, sampling time...), the precision of ozone retrieval was estimated from simulations of the recorded signal by GOMOS on typical stars. For ozone tangential column densitie N(z) retreival, the error (model minus retrieval) is significantly less than 1% up to 85 km thanks to the UV, and down to 15 km, thanks to Chappuis band of ozone. This good precision in such a large vertical extent, covering column densities from ~ 10^{15} to 3×10^{20} ozone molecules cm^{-2} (more than 5 orders of magnitude), is possible, owing to the large variation of ozone cross section over the UV-visible range of GOMOS. Inversing the Abel's integral (2) with an onion-skin algorithm to yield the O_3 concentration profiles n(z) degrades somewhat the precision (figure 3). Being 0.3% for N(z) between 15 and 45 km, it degrades to about 0.7 % for n(z) in the same range of altitudes, for a star of magnitude $M_V = 0$. For a dimmer star, precisions are accordingly poorer because of smaller photon fluxes, by a factor of ≈ 3 when going to a star $M_V = 2.5$. Here, the term 'precision' refers to the random variations, or spread of values that an instrument would report when observing a constant ozone profile (or repeatability). As pointed out by the Ozone Trend Panel (1990), "most quantities compared in trend studies involve averaging a large amount of data, reducing the spread, so precision is often not of primary importance". However, high precision occultations on bright stars will be useful to detect and account for some systematic errors which could, for instance, come from unexpected absorbing species.



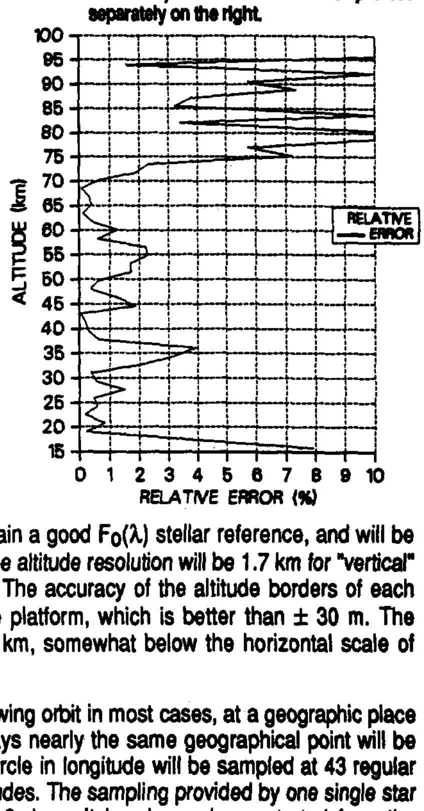


Figure 3 - Vertical profile of ozone local concentration $n_{O3}(r)$ retrieved from inversion of column density vs. tangent altitude ozone profile using a concentric layer model of the atmosphere and the onion-peeling method. Black dots are retrieved ozone concentrations $n_{O3}(r)$ and relative error with respect to the initial vertical profile of ozone is plotted separately on the right.

6. SPATIAL AND TEMPORAL SAMPLING

Altitude. Measurements will begin when the star is at 100 km of altitude to obtain a good $F_0(\lambda)$ stellar reference, and will be continued down to 10 km on the night side. With the sampling rate of 0.5 sec., the altitude resolution will be 1.7 km for "vertical" occultations, (a 1/5 of O_3 scale height), and smaller for oblique occultations. The accuracy of the altitude borders of each single measurement is limited by the accuracy on the orbital position of the platform, which is better than ± 30 m. The occultation geometry typically samples horizontally along about 200 km-400 km, somewhat below the horizontal scale of ozone field fluctuations.

Longitude. A star which is occulted at one orbit will also be occulted at the following orbit in most cases, at a geographic place of the same latitude but displaced in longitude by 25.12° (figure 4). After 3 days nearly the same geographical point will be sampled again, because of the number of 14.33 orbits per day. In 3 days, a circle in longitude will be sampled at 43 regular intervals of 25.12°/3 = 8.37°, or 930 km at the equator, and 658 km at mid-latitudes. The sampling provided by one single star is therefore equivalent to 43 ground stations with one measurement every 3 days. It has been demonstrated from the analysis of TOMS total ozone data /10/ that the function $\phi = e^{-\alpha \Delta t}$ describing the correlation of ozone values measured over the same point at an interval Δt is characterized by $\alpha = 0.8$/day. In other words, GOMOS measurements taken at 3 days intervals over the same point are already decorrelated, and each one must be fully counted in a global sampling.

Latitude. The number of stellar occultations which can be performed along one orbit is limited by the time required to perform one occultation, and the time required to point GOMOS from one star to another star. Realistic simulations of Phase A have shown that, with no particularly great optimisation effort, an adequate latitude sampling is obtained, with no large gap whatever is the season, as shown on figure 4. With a limiting star magnitude of $M_V = 3$ for dark limb occultations and $M_V = 2$ for bright limb occultations, the number of occultations per orbit is more than 25, whatever is the season, distributed typically as 2 with $M_V < 0$, 8 with $0 < M_V < 1$, 13 stars with $1 < M_V < 2$, and 5 with $2 < M_V < 3$. If a star limiting magnitude $M_V < 2$ is selected on both bright and dark limb, there are still about 25 occultations. The average distance in latitude is 180/25 = 7.2° or 800 km between two occultations sites adjacent in latitude.

Overall, there are 360 to 430 vertical profiles obtained each day, regularly spaced in longitude, and adequatly sampling the whole range of latitudes. Working every day, GOMOS would provide as much data as more than one thousand ground stations with one measurement every 3 days, spaced with typical interstation distance of less than 10^3 km. Given the scale of ozone field variations as measured from TOMS, it is quite obvious that the spatial and temporal sampling is quite adequate for a global monitoring of ozone and related parameters (NO_2, NO_3, H_2O, aerosols, temperature).

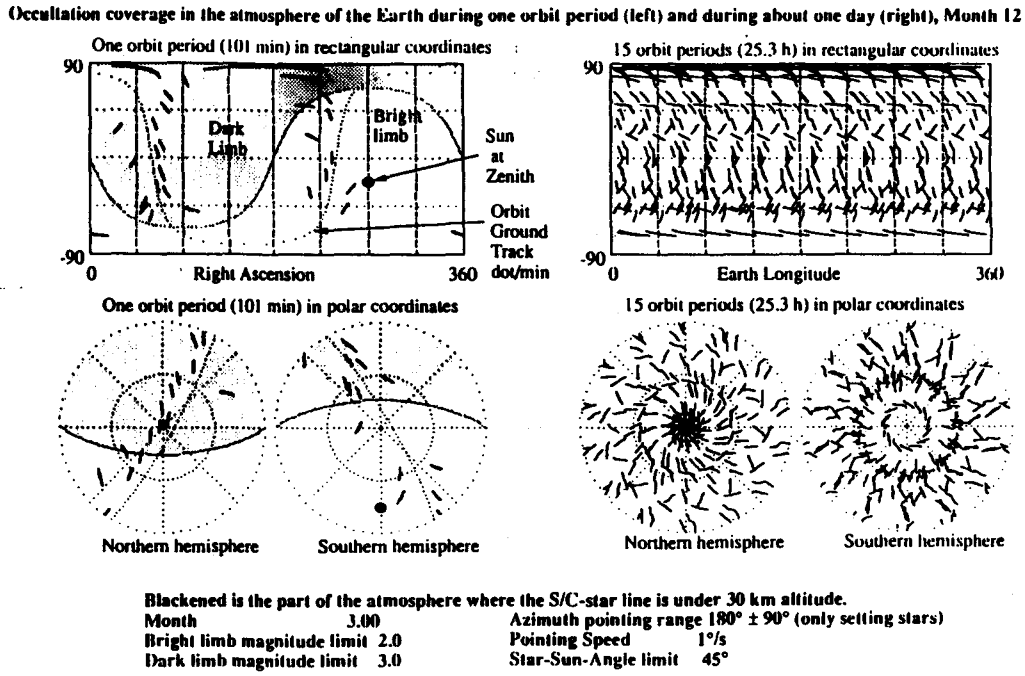


Figure 4- Occultation coverage of the Earth during one selected orbit period (left) and during a 15-orbit period (right). Rectangular figures are plane projections of the terrestrial globe, and circle figures are Northern and Southern polar views /9/.

7. OZONE TREND MEASUREMENT CAPABILITY OF GOMOS

Frederick (1984) /10/ has addressed the problem of the detection of ozone trend from one single ground station, performing a total of n measurements X at regular intervals Δt, over a duration $D = n\Delta t$. Annual, semi-annual and quasi-biennal variations are assumed to be regressed. When Δt is sufficiently large that two consecutive measurements are completely decorrelated, a simple least square fit linear regression shows that the minimum trend δ which can be detected with a confidence interval of 95% is :

$$\delta = 1.96\sqrt{12}\,\frac{\sigma(x)}{\mu}\,\frac{1}{\Delta t\, n^{3/2}} \qquad (3)$$

where μ is the average ozone value, and $\sigma(x)$ the variance of all measurements, due to the actual ozone fractionnal variance ε_{STV} and the instrument precision ε_{INST} :

$$\frac{\sigma(x)}{\mu} = \varepsilon^2_{STV} + \varepsilon^2_{INST} \qquad (4)$$

This approach can be applied to the set of all N_m measurements of GOMOS over its lifetime D, by dividing the globe in K geographical regions, each of them representing the equivalent of one "ground station" with $n = N_m/K$ measurements, separated by $\Delta t = KD/N_m$. Formula (3) becomes,

$$\delta_{GOMOS} = \frac{6.8}{D}\,\frac{\sigma(x)}{\mu}\,\sqrt{\frac{K}{N_m}} = \frac{6.8}{D^{3/2}}\,\frac{\sigma(x)}{\mu}\,\sqrt{\frac{K}{N_a}} \qquad (5)$$

where N_a is the number of GOMOS measurements per year, which is 25 x 14.33 x 365 = 131 x 10^3. During the nominal 4 years mission of GOMOS on the polar platform, taking a 4% variance of ozone at 40 km /10/, and the worst precision of ≈ 5% on stars of magnitude 3, the minimum ozone trend that can be detected by GOMOS when the K regions are 9 latitudes bands of 20° each is:

δ_{GOMOS}(lat) = 0.5 x 10^{-3} (± 0.05 % per year)

and δ_{GOMOS} (K = 100) = 1.5 x 10^{-3} (± 0.15% per year)

when the world is divided in 100 geographical regions where the ozone trend must be studied, as suggested from Dobson networks analysis /7/. These numbers compare quite favorably with the ozone variations already observed by SAGE instruments over 5 years (figure 2) at mid-latitudes, and with the design goals of future ozone measurements as defined by OTP.

Several remarks suggested by this analysis are :
- the subset of the brightest stars, yielding high precision vertical profiles of ozone (< 1%), can be used to actually measure the natural variance ε_{STV} of ozone.
- a higher precision on tangential column densities is obtained than on local concentrations, and all these primary data will be archived also for trend studies
- trends on other constituents (NO_2, NO_3, H_2O, T, aerosols...) will also be measured, and correlated with ozone trends for possible explanations of ozone depletion mechanisms, by confrontation to models.
- extending the duration D of GOMOS with several flights is of great advantage for accurate trend measurements, with a factor $D^{-3/2}$ dependence.

8. CONCLUSIONS

From space, the GOMOS instrument will provide every day a global geographical coverage of ozone vertical distribution with an unprecedented precision and reliability thanks to the self-calibration capability of the stellar occultation technique. It will monitor seasonal, latitudinal and long term trends, in response to recommendations issued by the Ozone Trend Panel set up by NASA and WMO. GOMOS provides also simultaneous measurements of NO_2, NO_3, H_2O, aerosol and temperature vertical distribution, species and parameters of primary importance for the ozone equilibrium, allowing a better understanding of the ozone depletion mechanism. From the European Polar Platform, it fulfills one major objective of the Global Change scientific program, worldly implemented.

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