**Atmospheric
Chemistry
and Physics**

Technical note:
Scintillations of the double star α Cru observed by GOMOS/Envisat

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Abstract. In this paper, we discuss scintillation time-spectra of the double star α Cru, which were measured by the GO-MOS/Envisat photometer. The components of α Cru are not resolved by the angular field of view of the detector. The double structure of the light source reveals itself in the modulation of the observed scintillation spectra; this modulation is caused by anisotropic irregularities of the stratospheric air density. We present a qualitative and quantitative explanation of the properties of the double-star scintillation spectra. Possibilities of using double star scintillations for studying atmospheric air density irregularities are also discussed in the paper.

1 Introduction

Statistical properties of scintillation (i.e. fluctuations in intensity when a light source is observed through the atmosphere) are defined by the structure of air density in the atmosphere, and by the spatial structure of the light source. Scintillations measured during star occultations have a broad application for carrying out research on the atmospheres of planets and their satellites (Hubbard et al., 1988; Raynaud et al., 2004), and they had been used actively during the last decade for satellite sounding of Earth air density irregularities (Gurvich and Kan, 2003a, b; Sofieva et al., 2007a, b). For the Earth's atmosphere, photometers with an effective aperture of ∼20 cm can register stellar scintillations in the altitude range ∼10-60 km with a vertical resolution down

to meters/fraction of a meter. The theory of weak scintillation (Tatarskii, 1961, 1971) allows the analysis of scintillations measured aboard low-orbiting satellites for altitudes above ∼25–30 km (Gurvich and Kan, 2003a, b; Sofieva et al., 2007a, b).

Scintillations data with global coverage became available with the launch of the GOMOS (Global Ozone Monitoring by Occultation of Stars) instruments on board the Envisat satellite (Kyrölä et al., 2004). GOMOS is equipped with two fast photometers, which record the stellar flux synchronously in the blue (473–527 nm, $\lambda_B \approx 500$ nm) and red (646–698 nm, $\lambda_R \approx 672$ nm) wavelength ranges with a sampling frequency of 1 kHz, as a star sets behind the Earth limb (for illustration of the occultation geometry, see Fig. 1 in Kyrölä et al., 2004). The scintillation measurements are used for the correction of scintillations in the spectrometer data to achieve a better accuracy of trace gases retrievals (Dalaudier et al., 2001; Sofieva et al., 2009b), for temperature profiling with a high vertical resolution (Dalaudier et al., 2006), and for studying small-scale processes in the stratosphere (Gurvich et al., 2005, 2007; Sofieva et al., 2007a, b; 2009a).

Recently, the algorithm for the reconstruction of gravity wave (GW) and turbulence spectra parameters was developed (Sofieva et al., 2007b). During the data analyses, we have noticed that the scintillation spectra of α Cru are often radically different from those of other stars. This is illustrated in Fig. 1, which shows the scintillation spectra for the mean altitude of 35 km. The left panel a shows the "standard" scintillation spectrum from occultations of Canopus. The majority of scintillation spectra of α Cru are quite different: a deep quasi-harmonic modulation of scintillation spectra is clearly observed (as in Fig. 1b). However, sometimes scintillation spectra of α Cru look normal (Fig. 1c).
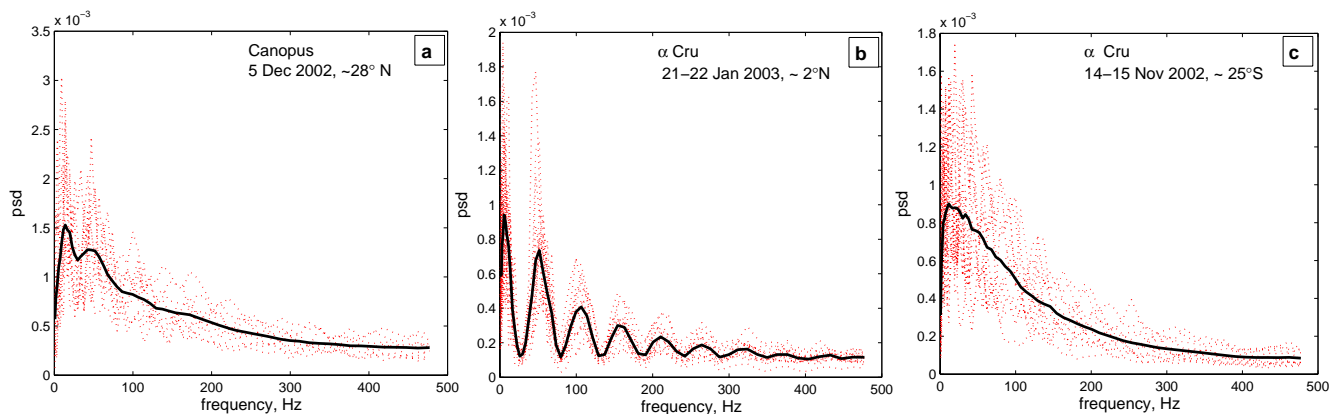
Fig. 1. (a): "standard" scintillation spectra (from occultations of Canopus); (b): scintillations spectra from several occultations of α Cru carried out on 21–22 January 2003; (c): scintillation spectra of α Cru on 14–15 November 2002 (usual spectra). Red lines: individual scintillation spectra estimations, black line: mean spectra, for altitude 35 km. GOMOS successive occultations of each star are performed nearly at the same latitude and at nearly the same local time. Locations of the selected night-time occultations are indicated in the figure. Scintillation spectra are presented on a linear scale.

These features of the α Cru scintillation spectra are because α Cru is a multiple (triple) star. Only two components of α Cru, which are separated by θ_0=4.4 arcsec, are visually distinguishable. They have comparable visual magnitudes mv_1=1.4 and mv_2=2.09. The GOMOS field of view is 138.4×49.4 arcsec (the larger angle is in the vertical direction), thus the components of α Cru are not resolved by the detector. The intensity fields from the two components of α Cru, which are shifted with respect to each other, are registered simultaneously by GOMOS.

In this paper, we explain qualitatively and quantitatively the specific features and time evolution of scintillation spectra of double unresolved stars. The paper is organized as follows. Properties of scintillation spectra of double unresolved stars are explained in Sect. 2. Section 3 is dedicated to the comparison of experimental scintillation spectra with that computed using a two-component spectral model of air density irregularities. A discussion of the possible use of double star scintillations for studying atmospheric air density irregularities and a short summary conclude the paper.

2 Scintillation spectra of double unresolved stars

Satellite stellar scintillation measurements in the occultation geometry have been discussed in many papers (e.g. Gurvich, 1984; Dalaudier et al., 2001). We will use the phase screen approximation for the description of light wave propagation through the atmosphere (Little and Hewish, 1966). This means that the influence of the atmosphere is replaced by a plane screen that produces the same phase modulation of the propagated light waves. Such screen is placed in the plane, which is perpendicular to the incident light rays and contains the Earth's centre. For calculations of scintillation spectra

of a double star with the components unresolved by a detector, let us take into account (Tatarskii, 1971, §42 and §54) that the components create distributions of intensity $I_{01}I_1(\boldsymbol{r})$ and $I_{02}I_2(\boldsymbol{r})$ in the observation plane. Here $\boldsymbol{r}$ is the vector in this plane, I_{01} and I_{02} are spatially constant intensities without refractivity fluctuations, and $I_1(\boldsymbol{r})$ and $I_2(\boldsymbol{r})$ are random functions with mean value 1. Provided the angular distance θ_0 between the components is small $\theta_0 \ll 1$, we can consider $I_2(\boldsymbol{r})=I_1(\boldsymbol{r}+\boldsymbol{\rho})$ (Little and Hewish, 1966; Cohen et al., 1967; Ishimaru, 1978), where the components of the vector $\boldsymbol{\rho}=\boldsymbol{\theta}D$ are $\rho_z=D\theta_{0,z}/q, \rho_y=D\theta_{0,y}$, q is the refractive dilution (Dalaudier et al., 2001), D is the distance between observation plane and the phase screen. In other words, the fields of relative intensity fluctuations corresponding to the components of a double star are only shifted with respect to each other. Then the 2-D spatial spectrum $F_\Sigma(\boldsymbol{\kappa})$ of the sum of the signals $\Sigma=I_{01}I_1(\boldsymbol{r})+I_{02}I_2(\boldsymbol{r})$ registered by the detector is equal to (the shifting theorem for the Fourier transform)

$$F_\Sigma(\boldsymbol{\kappa})=\frac{I_{01}^2+I_{02}^2+2I_{01}I_{02}\cos(\boldsymbol{\kappa}\boldsymbol{\rho})}{(I_{01}+I_{02})^2}F_I(\boldsymbol{\kappa}), \quad (1)$$

where $F_I(\boldsymbol{\kappa})$, $\boldsymbol{\kappa}=(\kappa_z,\kappa_y)$ is the 2-D scintillation spectrum of a single star discussed in detail in (Gurvich and Brekhovskikh, 2001; Gurvich and Kan, 2003a; Sofieva et al., 2007b).

In occultation experiments, we obtain estimates of a 1-D scintillation spectrum along the occultation trajectory with an angle γ to the local vertical (Gurvich and Brekhovskikh, 2001; Gurvich and Kan, 2003a):

$$V_\Sigma(k_s,\gamma)=\int_{-\infty}^{+\infty}dk F_\Sigma(-k\sin\gamma+k_s\cos\gamma, k\cos\gamma+k_s\sin\gamma).(2)$$

The angle $\gamma = 0$ corresponds to a vertical spectrum (and to a vertical, in-orbital-plane occultation). Therefore, the additional parameters that define properties of the scintillation spectra of double unresolved stars are: the ratio of intensities I_{01}/I_{02} of the star components, the angular θ_0 (or spatial ρ) separation, and the angle β between $\boldsymbol{\rho}$ and the local vertical.

As follows from (1), the scintillation variance for a double star is smaller than the variance of a single star of intensity $(I_{01}+I_{02})$. Previously, the reduction of scintillation variance in the turbulent media caused by the finite angular size of the light source was already discussed by Tatarskii (1961, 1971). In particular, the known fact that planets scintillate less than stars for the same zenith angles has received its quantitative explanation in these works.

Another specific feature of unresolved double star scintillation spectra, which is caused by the factor $\cos(\boldsymbol{\kappa}\boldsymbol{\rho})$ in the Eq. (1), is a modulation. The modulation of the 1-D scintillation spectra observed by GOMOS photometer depends not only on the orientation of the star components and occultation geometry (angles γ and β), but also on the structure of atmospheric irregularities. It is known that there are two types of air density irregularities in the Earth atmosphere: anisotropic irregularities, which are of relatively large scale (generated by gravity waves), and isotropic irregularities (turbulence), which appear as a result of gravity wave breaking and due to different instabilities. The two-component spectral model of air density irregularities was proposed in (Gurvich and Brekhovskikh, 2001; Gurvich and Kan, 2003a). The scintillation spectra corresponding to this spectral model, for a single star, were discussed in detail in (Gurvich and Brekhovskikh, 2001; Gurvich and Kan, 2003a; Gurvich and Chunchuzov, 2005; Sofieva et al., 2007b). Due to the limited sampling frequency of GOMOS photometers, relatively large-scale anisotropic irregularities play an important role in forming the scintillations observed by GOMOS. As a result, scintillation spectra of α Cru are often modulated (Fig. 1b).

When oscillations in the 1-D anisotropic scintillation spectrum are observed, the modulation period T_m in the frequency space increases with increasing β. It is defined by the vertical component of the projection of the satellite velocity onto the observation plane, v_v, and the vertical component of the stellar separation:

$$T_m = v_v/(\rho\cos\beta). \qquad (3)$$

The maximal modulation coefficient (contrast) for the anisotropic spectrum is

$$m = \frac{2I_{01}I_{02}}{I_{01}^2 + I_{02}^2}. \qquad (4)$$

For α Cru, which has two stars of similar intensities, m is close to unity, $m \approx 0.9$.

3 GOMOS observations of α Cru: a quantitative account

In this section, we present the comparison of the experimental scintillation spectra of α Cru, from the GOMOS measurements, with that computed using the two-component spectral model of air density irregularities.

Information about four occultations of α Cru, selected for illustration, is collected in Table 1. The angle β changes from $\sim 90°$ to $\sim 30°$ during the selected time interval. The angle β was computed using the information about vertical velocity and the observed modulation period of the scintillation spectra, Eq. (3). The experimental values of the angle β agree well with the theoretical estimations of this parameter, which can be calculated using the occultation geometry. The spatial separation of α Cru components is $\rho = \theta_0 D \approx 69$ m. The spatial sampling of GOMOS is from 3 to 8 m, depending on obliquity of an occultation. For processing, we used scintillation measurements corresponding to an altitude of ray perigee of ~ 34 km, to satisfy the condition of weak scintillations (rms of scintillations are given in Table 1).

Figure 2 shows the experimental scintillation spectra for the selected occultations (red lines). The experimental spectra were computed using the method of smoothed periodograms. The periodogram smoothing was performed with the window of variable width, analogous to that discussed in (Gurvich and Chunchuzov, 2005; Sofieva et al., 2007b). Instrumental noise was removed in computing experimental scintillation spectra.

The width of anisotropic scintillation spectra is defined by the vertical inner scale l_W: $f_{a,\max} = v_v/l_W$ (see Table 1). For frequencies higher than $f_{a,\max}$, the anisotropic scintillation spectra rapidly decrease. The strong modulation of the scintillation spectra at frequencies $f < f_{a,\max}$ for orbits 4677, 4200 and 3945 (Fig. 2) is caused by prevailing anisotropic scintillations over isotropic ones in this spectral range. At frequencies $f > f_{a,\max}$, scintillations caused by isotropic irregularities prevail, thus the modulation of scintillation spectra rapidly decreases for $f > f_{a,\max}$.

Depending on β, the modulation period changes from 53 Hz for the orbit 4677 to 192 Hz for the orbit 3945. For the orbit 3705, the components of α Cru are located nearly horizontally, their vertical separation was much smaller than l_W. In this case, the anisotropic component of the scintillation spectrum is nearly the same as for a single star, while the spectral density of the isotropic component is approximately twice as small as that of a single star. The observed scintillation spectrum in this case is not modulated, as seen in Fig. 2.

Black lines in Fig. 2 show the fit of the experimental spectral to the modeled scintillation spectra, which were computed using the two-component spectral model of air density irregularities, including anisotropic (saturated gravity waves) and isotropic (Kolmogorov turbulence) components (Gurvich and Kan, 2003a; Sofieva et al., 2007b). A brief
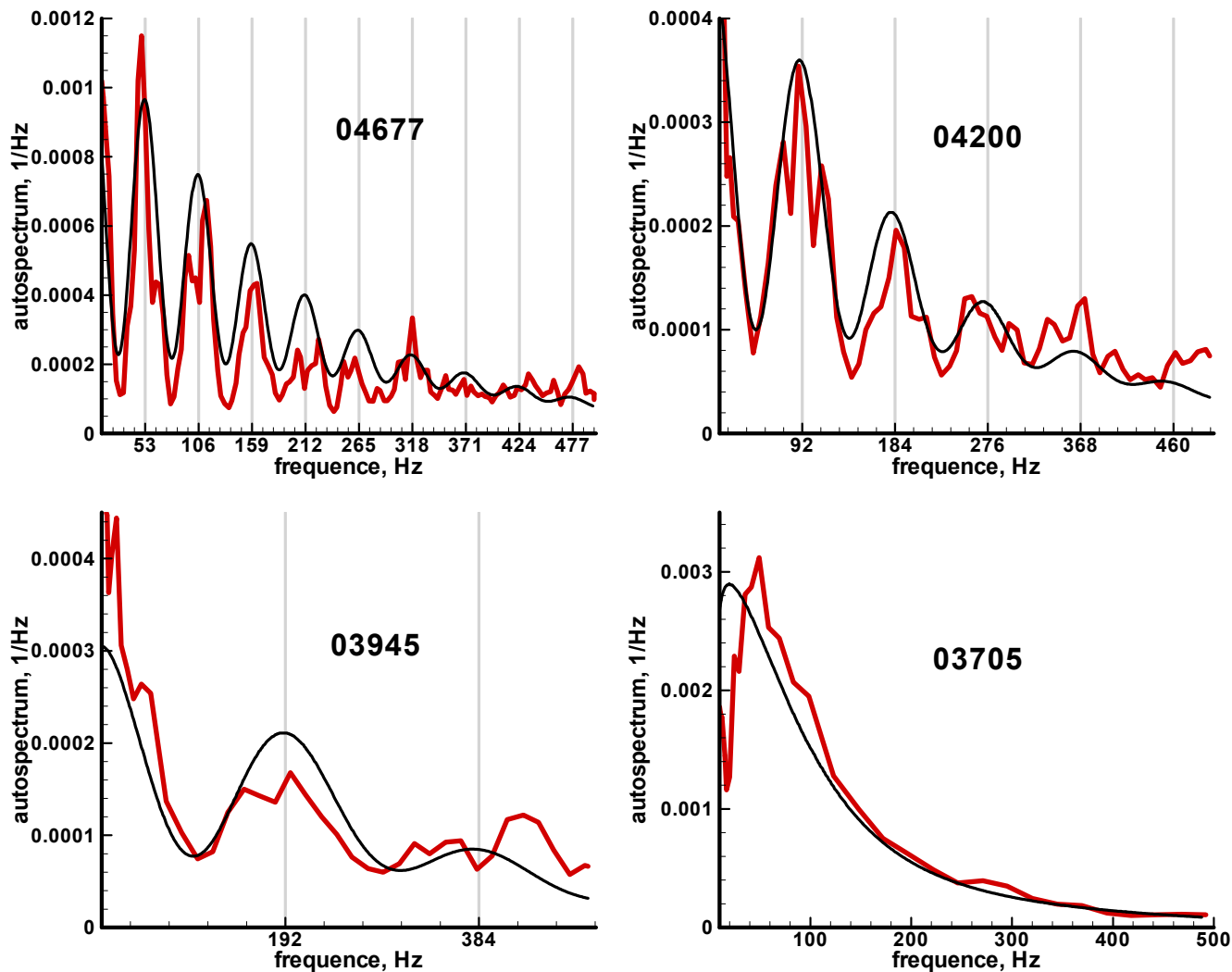
Fig. 2. Experimental scintillation spectra on a linear scale of α Cru (red lines) and their fit using the two-component spectral model of air density irregularities (black lines). Vertical gray lines correspond to modulation periods T_m.

description of this model is given in Appendix A. The computation of theoretical scintillation spectra was discussed in detail in (Gurvich and Brekhovskikh, 2001; Gurvich and Chunchuzov, 2005; Sofieva et al., 2007b). This model and Eqs. (1) and (2) were used for fitting 1-D modeled spectra to the observations. The estimates of the three parameters of the spectral model – the structure characteristic C_W of anisotropic irregularities, vertical inner scale l_W, and the structure characteristic C_K of Kolmogorov turbulence – retrieved in the fitting, are presented in Table 1. As seen in Fig. 2, the modeled and experimental scintillation spectra are in rather good agreement. The obtained estimates of gravity waves and turbulence parameters are within the range of previous results of the parameter reconstruction (Gurvich and Kan, 2003b; Sofieva et al., 2007b, 2009a).

4 Summary and discussion

We have considered the properties of scintillation spectra of double stars, which are not resolved by the field of view of the detector. The main features of the double-star scintillation are (i) reduction of scintillation variance (compared to that of a single star) and (ii) modulation of the scintillation spectra. It is the consequence of shifted intensity fields corresponding to the components of a double star. The period and the depth of the modulation depend on the structure of atmospheric irregularities, separation of the star components, ratio of their intensities, and on the observation geometry. The modulation of the observed scintillation spectra is caused mainly by anisotropic irregularities of air density (due to limited resolution of the GOMOS fast photometers, such irregularities play an important role in forming the scintillations observed by GOMOS).

Table 1. GOMOS occultations selected for the comparison.

Date and orbit	Ray perigee coordinates	Scintillation rms, %	γ, deg	β, deg	Modulation period T_m (Hz)	$f_{a,\max}$ (Hz)	$C_W \cdot 10^{11}$, m^{-2}	l_W, m	$C_K \cdot 10^9$, m$^{-2/3}$
21 Jan 2003 # 04677	1.5° N 45.3° E	35	34.5	31.2	53	210	8.25	15	5.8
19 Dec 2002 # 04200	14.3° S 162.6° E	25	23.0	59.3	92	215	3.7	15	2.2
1 Dec 2002 # 03945	21.2° S 94.4° E	26	9.4	75.5	192	470	2.5	7	1.4
14 Nov 2002 # 03705	25.5° S 7.7° E	64	−7.1	∼90	>500	130	28.9	25	4.3

The experimental scintillation spectra obtained by GO-MOS in occultations of the double star α Cru under different observation conditions are adequately (qualitatively and quantitatively) explained, if existence of anisotropic and isotropic irregularities of air density is assumed. Therefore, the performed analysis can serve as an additional confirmation of the existence of such irregularities in the atmosphere.

The scintillation spectra of double stars are more complicated compared to that of a single star, but they are more informative. For example, in (Gurvich and Kan, 2003a, b; Sofieva et al., 2007b), the amplitude of the isotropic component (and the turbulent structure characteristic C_K) was estimated using the high-frequency part of the scintillation spectra $f > f_{a,\max}$. Although the reconstruction of gravity wave and turbulence spectra parameters is formulated via the solution of the corresponding inverse problem in (Sofieva et al., 2007b), the information about the turbulent component is actually contained only in the high-frequency part of the scintillation spectrum, $f > f_{a,\max}$. For occultations close to vertical and /or provided the inner scale l_W of the anisotropic component is small, the turbulence parameters cannot be retrieved reliably. For double stars, the detection of the isotropic component (and thus its parameters) can be done in the whole spectral range.

The availability of two photometers at different wavelengths allows a simultaneous sounding of the atmosphere along the trajectories separated in the vertical direction due to chromatic refraction. The chromatic shift between the sounding trajectories is defined by the mean refractivity; it depends on altitude. For GOMOS photometers, it does not exceed 10 m above 30 km (Dalaudier et al., 2001). Gurvich et al. (2005) have shown that bi-chromatic scintillations open new possibilities in studies of air density irregularities by using the chromatic effects. In particular, it was shown that the coherency spectra and cross-correlation function can be used for indicating regions with high intensity of isotropic turbulence. For a double star, the two GOMOS photometers perform the sounding of the atmosphere along four separated trajectories. The chromatic separation is variable (in the vertical direction), while the separation of stars can be in any direction. Smooth changes of occultation obliquity γ and the angle of stellar separation with respect to the local vertical β in successive occultations (due to satellite precession), can provide data with the distance between the sounding trajectories ranging from zero to ρ (depending on γ and β). A feasibility study on using double star scintillations for obtaining information about the structure of air density irregularities might be carried out in the future.

Appendix A

The spectral model of refractivity irregularities in the atmosphere. Scintillation spectra

For the optical wavelength range, relative fluctuations of refractivity $\nu = \delta N / \langle N \rangle$ (N is refractivity, angular brackets denote the statistical mean) are equal to relative fluctuations of air density. $\langle N \rangle$ depends on altitude with the atmospheric scale height of 6–8 km. The dependence $\langle N \rangle$ on wavelength is defined by the known dispersion relation for air.

The properties of the refractivity field are characterized by the 3-D spectrum $\Phi_\nu(\kappa)$ of relative refractivity fluctuations, $\kappa = (\kappa_x, \kappa_y, \kappa_z)$ being a wave vector (z is the vertical coordinate). Following (Gurvich and Brekhovskikh, 2001; Gurvich and Kan, 2003a), we assume that Φ_ν is the sum of two statistically independent components:

$$\Phi_\nu = \Phi_W + \Phi_K \qquad (A1)$$

The anisotropic component Φ_W corresponds to the saturated gravity wave model (Smith et al., 1987). It has the slope -5 between the inner scale l_W and the outer scale L_W. The structure characteristic C_W defines the power of anisotropic irregularities. The anisotropy coefficient η is defined as a ratio of

the characteristic horizontal and vertical scales. It is assumed that η=const$\gg$1 (Gurvich and Brekhovskikh, 2001; Gurvich and Kan, 2003a; Sofieva et al., 2007b). The associated one-dimensional vertical spectrum has the slope -3, as in the model of saturated gravity waves. The isotropic component Φ_K corresponds to locally isotropic turbulence (Monin and Yaglom, 1975) with the slope $-11/3$ of power spectral density. It has two parameters: the structure characteristic C_K and the inner (Kolmogorov) scale l_K. The one-dimensional spectrum corresponding to Φ_K follows the well-known $-5/3$ power law.

The scintillation spectra at the observation plane can be computed using the theory of wave propagation in a random media. The main approximions used in the evaluation of the scintillation spectra are:

– frozen field approximation;

– phase screen approximation;

– weak scintillation assumption (i.e. rms of scintillation is significantly smaller than 1).

The computation of theoretical scintillation spectra is discussed in detail in (Gurvich and Brekhovskikh, 2001; Gurvich and Kan, 2003a; Sofieva et al., 2007b).

Since the inner vertical scale l_W varies from $\sim$10 m to a few tens of meters in the stratosphere, $l_W > \rho_F$ for satellite measurements, where $\rho_F = \sqrt{\lambda D/2\pi}$ is the Fresnel scale, ($\rho_F \approx 0.5$ m for GOMOS). In this case, the diffractive effects are not important and the vertical scale of scintillations, which are generated by anisotropic irregularities, is defined by l_W. In contrast, scintillations caused by isotropic irregularities are defined by the diffractive effects when $\rho_F > l_K$. In this case, the characteristic scale of isotropic scintillations is the Fresnel scale. Scintillations caused by Kolmogorov turbulence are not sensitive to the outer scale L_K of turbulence (Tatarskii, 1961, 1971; Gurvich and Chunchuzov, 2005).

Edited by: P. Bernath

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