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Anisotropy of stratospheric irregularities inferred from stellar scintillation measurements by GOMOS/ENVISAT

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Abstact. In this paper, we discuss the methods for evaluation of the anisotropy of small-scale atmospheric irregularities using satellite stellar occultation measurements. These methods are based on coherency analysis of bi-chromatic scintillation observed in occultations of double stars and in tangential (horizontal) occultations. These methods are applied to scintillation measurements by two fast photometers of the GOMOS (Global Ozone Monitoring by Occultation of Stars) instrument on board ENVISAT. The estimates of the anisotropy of air density irregularities generated by saturated gravity waves are obtained for altitudes 30-45 km. The anisotropy coefficient varies from 50 down to 10 with decreasing vertical scales from 60 m to 10 m.

1. Introduction

Random irregularities of air density and temperature, which are generated by internal gravity waves (GWs) and turbulence, cause fluctuations in light intensity (scintillation) when a star is observed through the atmosphere. Nowadays stellar scintillations in occultation experiments are actively used for studying atmospheric irregularities [1-4]. The phase screen approximation [5] and the theory of weak scintillations [6] provide the basis for analyses of scintillation measurements and reconstructing the parameters of atmospheric irregularities.

Based on stellar scintillation measurements on board the orbital station MIR, A S Gurvich has proposed an empirical model of three-dimensional (3D) spectrum of air density irregularities. In this spectrum, the model of saturated gravity waves is used for description of the anisotropic component, and the Kolmogorov model of turbulence is used for the description of the isotropic component [7]. The anisotropy coefficient is defined as a ratio of characteristic horizontal and vertical scales for the GW component. The methodology for reconstructing the parameters of the 3-D model of atmospheric irregularities from scintillation auto-spectra has been successfully applied for analyses of observations on board the MIR station [1, 2], and then for mass reconstruction of the atmospheric irregularity from GOMOS scintillation measurements [3, 4]. This method allows reconstructing all parameters of the 3-D spectral model, except for the anisotropy coefficient.

There are several estimates of the anisotropy coefficient corresponding to large-scale irregularities (with the vertical scales from one to ten kilometers). The analyses on refractive disturbances of extended light sources, such as the Sun and the Moon, observed in occultations from the orbital station have shown that the anisotropy is about 100 for atmospheric irregularities with vertical scales 0.5-1.0 km. Analyses of temperature profiles retrieved from satellite infrared measurements in limb geometry (instruments CRISTA, HIRLDS, SABER), radiosonde measurements and radio-occultation measurements by COSMIC also indicate on large anisotropy of the dominant (large-scale) gravity waves in the stratosphere, with typical anisotropy from one to several hundreds.

The anisotropy of small-scale irregularities is much less investigated. In particular, the anisotropy ~10 for the vertical scales of a few meters has been estimated using the angular dependence of backscattered radar signals. Although small-scale irregularities also have a pronounced anisotropy, it is significantly smaller than for large-scale irregularities.

The main challenge in the study of anisotropy is that, even assuming the statistical symmetry of the atmospheric irregularities field in the horizontal plane, the anisotropy is a two-dimensional characteristic, while the measurements are usually one-dimensional data along the trajectory of observations. Therefore, it is necessary to use such observations, which allow simultaneously obtaining the information about both the vertical and horizontal structure of atmospheric irregularities.

Recently, two methods based on a coherent analysis of chromatic (at different wavelengths) scintillation of stars have been developed. In the first method, occultations of double stars are used [8, 9], while the second method uses tangential (horizontal) occultations [10]. This paper is a short overview of these two methods. Scintillations are mainly sensitive to small-scale air density irregularities [6], therefore we focus in our studies on small scales, close to scales of gravity wave breaking, where the most significant changes in the anisotropy are expected.

The developed methods are applied to scintillation measurements by the fast photometers of GOMOS (Global Ozone Monitoring by Occultation of Stars) on board the European satellite ENVISAT (2002 - 2012) [11]. GOMOS was equipped with two fast photometers at blue ($\lambda \approx 500$ nm) and red ($\lambda \approx 670$ nm) wavelengths and sampling frequency of 1 kHz. The scintillation measurements recorded by the fast photometers have been used for studying the parameters of atmospheric irregularities [3, 4, 12]; they are also used in the methods discussed in the current paper.

2. Main approximations

In our work, we use the following main approximations:

- A two-component model of the 3D spectrum of atmospheric irregularities;
- The equivalent phase screen approximation;
- The weak scintillation assumption (Rytov's approximation).

For the description of scintillation, the random field of atmospheric irregularities is described by a 3D spectrum of relative fluctuations of air density (or refractivity) ν. For reconstruction of the 3D spectrum of atmospheric irregularities, we first define its model with a few essential parameters and compute the scintillation spectra using the theory of wave propagation in random media. Then the parameters of the 3D spectrum are retrieved by fitting the modelled scintillation spectra to the experimental ones.

The 3D spectrum air density irregularities $\Phi_\nu(\vec{\kappa})$ is modelled as a sum of two statistically independent components, anisotropic $\Phi_W(\vec{\kappa})$ and isotropic $\Phi_K(\kappa)$ [7]:

$$\Phi_\nu(\vec{\kappa}) = \Phi_W(\vec{\kappa}) + \Phi_K(\kappa) \tag{1}$$

where $\vec{\kappa}$ is wavenumber vector. The anisotropic component Φ_W in equation (1) is generated by a random ensemble of saturated gravity waves, while the isotropic component Φ_K corresponds to Kolmogorov's locally isotropic turbulence. Φ_W has a power spectrum with the slope -5 and the following parameters: the structure characteristic C_W, outer L_W and inner scales l_W, and the anisotropy coefficient η. The spectrum of Kolmogorov's turbulence Φ_K has a slope -11/3 and it is defined by a structure characteristic C_K and the inner scale l_K or the diffraction Fresnel scale ρ_{Fr}. The phase screen is placed in the plane perpendicular to incident rays and going through the Earth center (figure 1, left). The phase screen approximation and weak scintillation assumption are traditional for occultation measurements; therefore, we will not discuss them in detail. We note only that the sphericity of the atmosphere has been taken into account for determination of the phase screen for anisotropic fluctuations. For the spherical atmosphere, due to changes in the orientation of the inhomogeneities relative to the sounding ray, the phase fluctuations saturate with increasing anisotropy. Approximation of weak scintillations makes it possible to obtain simple linear relations connecting the spectra of inhomogeneities with the spectra of scintillations. It is important to note that, for weak scintillations, the measured scintillation spectra can also be considered simply as the sum of statistically independent isotropic and anisotropic components. For low-orbit satellites (MIR, GOMOS), the weak scintillations regime is realized for ray perigee altitudes above 30 km. We also note that the scintillation powers corresponding to GW and Kolmogorov turbulence at altitudes of 30-50 km are approximately the same. The high velocity of the line of sight in the satellite experiments allows using the "frozen field" approximation for relationships between spatial and temporal scintillation spectra.

The effective atmospheric thickness along the line of sight is ~400 km. Therefore, the phase fluctuations at the exit from the atmosphere are the result of interaction of light with a representative ensemble of gravity waves and turbulence. Further, the statistical parameters of scintillations are obtained by averaging over realizations having lengths on the phase screen from several kilometers for vertical occultations to several hundred kilometers for horizontal occultations.

3. Occultations of double stars

Figure 1 shows the scheme of an occultation of a double star. Due to dispersion of regular refraction in the atmosphere, the blue and red trajectories on the phase screen are vertically separated by a chromatic shift Δ_c. The chromatic shift grows with decreasing altitude; it is ~5.5 m at 34 km. For analysis, we used occultation of α Cru. The components of α Cru are bright and have similar visual magnitude. In the beginning of 2000th, two components α Cru were separated by ~ 4.5 arcsec, and, correspondingly, their spatial separation in the phase screen was ~70 m. The binaries of α Cru are not resolved by the field of view of GOMOS photometers, therefore each photometer registers the light from both star components.

As seen in figure 1 (right), if binaries are located not horizontally, their scintillations will be shifted in time, or, respectively, vertically. If the rays from binaries pass successively through the same irregularities, then the signal in each photometer is the sum of the same (accurate within amplitudes) but shifted in time random realizations. Then, the power spectrum of the sum of such shifted intensity fluctuations is the scintillation spectrum of a single star, which is cosine-modulated with the maximum modulation coefficient equal to

$$M_{\max} = 2I_{01}I_{02} / (I_{01}^2 + I_{02}^2) \tag{2}$$

where I_{01} and I_{02} are vacuum intensities of binaries. For α Cru, the modulation coefficient is 0.85.

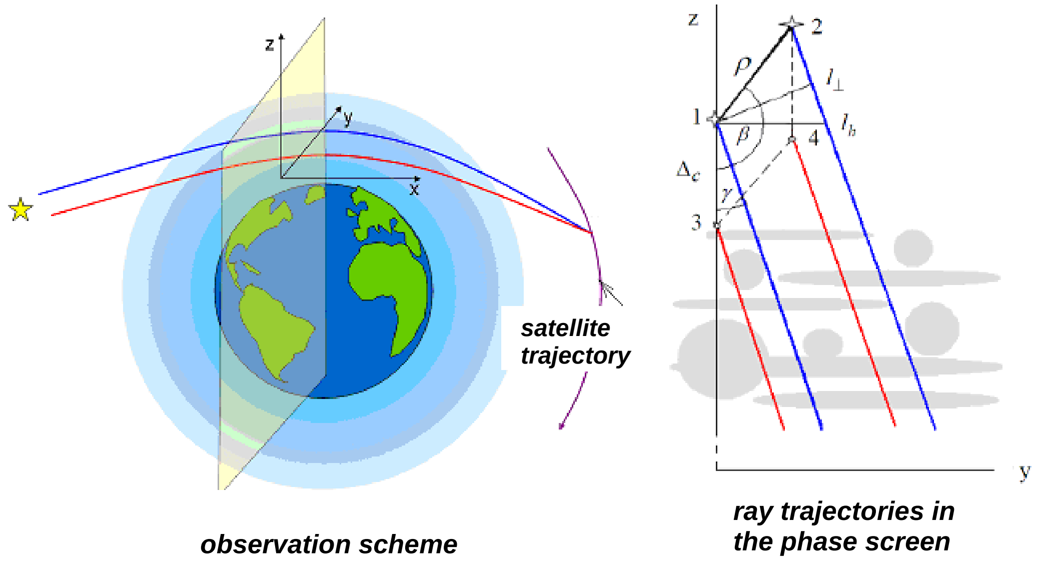

Figure 1. From [9]: Left: illustration of occultation geometry. Yellow plane represents the phase screen. Blue and red lines denote colored ray trajectories for a single star, which are recorded simultaneously by the instrument. Right: a sketch of ray trajectories of binaries in the phase screen during double-star occultations. The points 1–4, which are located in vertices of a parallelogram, are the points of intersection of light rays with the phase screen (1–2 for the blue photometer and 3–4 for the red photometer). Δ_c is the chromatic shift, i.e. the vertical distance between red and blue rays (1–3 for the first component of a double star, 2–4 are for the second component). Atmospheric irregularities are schematically shown by grey circles and ellipses.

If the rays from binaries pass through different irregularities, the modulation of the scintillation spectrum can be weakened or even completely absent. Thus, the coherence of scintillations from components of double star is manifested in the modulation amplitude of the scintillation spectrum [8].

For isotropic irregularities, scintillations are strongly influenced by irregularities with scales close to the Fresnel scale. For GOMOS observations, the Fresnel scale was much smaller than the distance between trajectories of binaries. Therefore, isotropic scintillations from binaries are not coherent in each photometers, and, consequently, the scintillation spectrum of isotropic scintillations is not modulated.

In the conditions of analyzed occultations, anisotropic scintillations of two photometers were coherent, while isotropic scintillations were fully not coherent at altitudes 30-40 km. Therefore, experimental cross-spectra were represented by anisotropic scintillations only. If we subtract the isotropic component from the measured scintillation auto-spectra, the remaining (anisotropic) components, along with the measured cross-spectrum, should give a coherence spectrum equal to unity. The spectrum of isotropic scintillations in the diffraction approximation for both wavelengths is determined by a single parameter, the turbulent structure characteristic C_K. We fit the value of C_K so that the coherency spectrum of detected anisotropic scintillation is equal to unity. Figure 2 illustrated the procedure of this detection for one occultation. As seen in figure 2 D, the experimental coherency has deep oscillations, while the coherency spectrum of the anisotropic component is smooth and close to 1. Some reduction of coherency spectrum of anisotropic scintillations at high frequencies is due to aliasing.

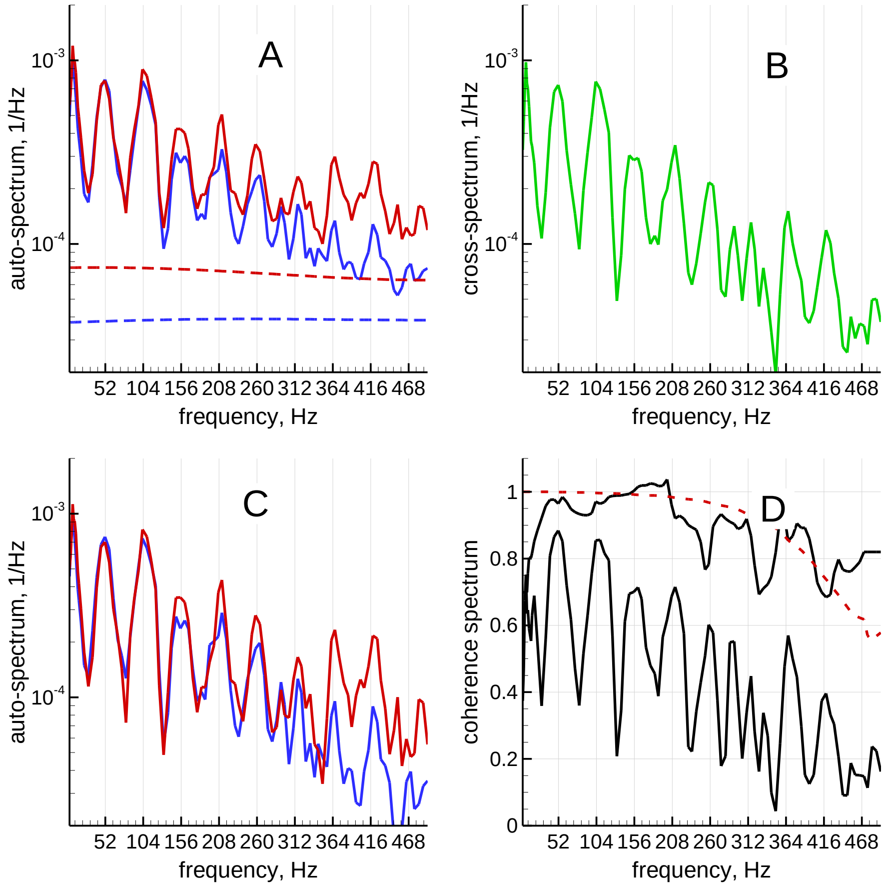

Figure 2. Selection of anisotropic and isotropic scintillation components. A - experimental scintillation auto-spectra (solid lines) and fitted spectra of isotropic scintillations (dashed lines); B – The modulus of experimental cross-spectrum; C – the detected auto-spectra of anisotropic scintillations; D – experimental coherency spectrum (oscillating curve), coherency spectrum of detected anisotropic scintillations (smooth black line) and the theoretical coherency of anisotropic scintillations (red dashed line).

We have analyzed 20 occultations of α Cru at altitudes 30-40 km and evaluated the parameters of atmospheric irregularities, including the anisotropy coefficient. The evaluated structure characteristics and character scales of GW and turbulence are in good agreement with previous estimates using scintillations of single stars. The estimates of anisotropy coefficient are new here. They correspond to irregularities with vertical scales ~10-20 m, and the estimated anisotropy is 10-20 [9].

The scales 10-20 m are comparable with the inner scale of anisotropic irregularities, which corresponds to transferring the GW energy to turbulence (i.e., the scale corresponding to GW breaking). This, in particular, explains why it was not possible to obtain an estimate of the anisotropy for smaller scales: at scales smaller than the inner scale, the anisotropic scintillation spectrum decays quickly, while the isotropic component remains the same, so that the measured coherence decreases rapidly. For estimates of anisotropy at larger scales, it is necessary to use double stars with larger separation of binaries.

4. Tangential occultations

If a star is observed close to the orbital pole, tangent occultations are realized. In this case, a star descends down to some minimal height, and then rises back, i.e. the situation is similar to movement of the Sun in polar regions in summer. Near the ray perigee altitude, the sounding ray moves practically parallel to the Earth limb for several hundreds of kilometers. If measurements are performed at two wavelengths, we have simultaneously two horizontal cross-sections of the atmosphere, because rays of different colors are separated vertically due to chromatic refraction. The chromatic shift Δ_c, being computed using the standard atmosphere model, is ~10 m at 30 km for GOMOS photometers.

Let us consider the case of anisotropic irregularities. If the vertical scale of irregularities is larger than the chromatic separation, the light rays of different colors pass through the same irregularities and the scintillations generated by such irregularities are coherent. In the opposite situation, if the characteristic vertical scale of irregularities is smaller than the chromatic shift, corresponding chromatic scintillations will not be correlated. Therefore, by estimating the cross-correlation function or the coherency spectrum, we get the horizontal scale of those irregularities, which have the vertical scale equal to the chromatic shift and, consequently, get an estimate of the anisotropy coefficient for this vertical scale. By performing tangential occultations for different ray perigee altitudes, i.e., for different values of chromatic shift, one can get estimates of anisotropy coefficient in some range of vertical scales. In the previous method (double stars), observations give us the information about the vertical structure of irregularities; coherency of chromatic scintillations is defined by the horizontal separation of binary star trajectories. In the method of tangential occultations, coherency estimates give us characteristic horizontal scales for irregularities, whose vertical scale is equal to the chromatic separation of light rays.

Analogously to the double star method, we need to detect the anisotropic component in auto-and cross-spectra of scintillations. In this method, the detection is based on dependence of contributions of anisotropic and isotropic components into the resulting scintillations on obliquity angles (angles of star motion, [7]). With increasing obliquity angle, the temporal auto-spectrum of anisotropic scintillations is shifted toward lower frequencies, while the spectrum of isotropic scintillations is displaced to higher frequencies [3, 13, 14], and the best frequency separation is for pure horizontal occultations. The cut-off frequency of anisotropic scintillations in horizontal occultations is only a few Hz, while the Nyquist frequency is 500 Hz. Therefore, it can be assumed that the high-frequency region, ~ 450-500 Hz, in the experimental spectra is represented only by the isotropic component. Using the additivity of the components of the spectrum of weak scintillations and subtracting the isotropic component from the measured scintillation spectra, we can obtain estimates of the anisotropic auto-spectra and the components of the cross-spectrum.

Tangential occultations were not included in the operational GOMOS observations. The tangential occultations were performed with a dedicated mission planning in the year 2002. From 32 tangential occultations found in the GOMOS database, twelve were selected for further analysis. We selected the occultations having sufficiently long (300-400 km) quasi-horizontal part of trajectories and in which the weak scintillation assumption is satisfied. The minimal ray perigee altitudes were in the interval of 45-30 km, and the corresponding vertical chromatic scales ranged from 8 to 55 m [10].

Figure 3 A illustrated the detection of isotropic and anisotropic components of scintillation auto-spectra. As observed, anisotropic scintillations dominate at low frequencies. The panels B and C in figure 3 show comparison experimental and theoretical auto-spectra and coherency spectra, for three occultations. For demonstrating the capabilities of the method, we have applied visual fitting. As seen in figure 3 B, C the fitted scintillation spectra agree quite satisfactorily with experimental ones. As seen from figure 3 C, the characteristic coherency frequencies (horizontal scales) for the orbits 03455 and 03817, differ approximately 40 times, while the corresponding vertical chromatic scales differ only 5 times (the chromatic scale for the 03455 orbit is about 10 m, and for the 03817 orbit is 50 m). This indicates that the anisotropy increases with increasing scale of atmospheric irregularities.

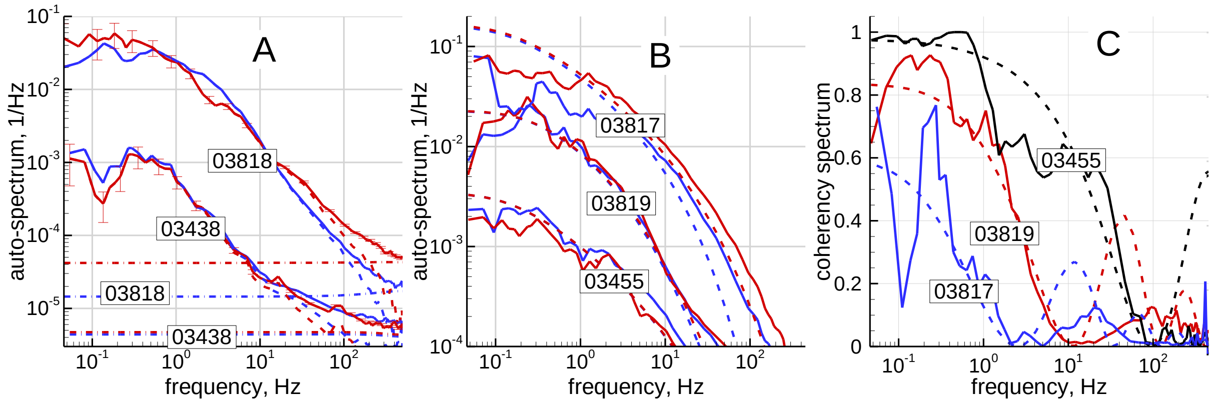

Figure 3. A – detection of anisotropic and isotropic componebts in scintillation auto-spectra. Solid lines: experimental auto-spectra, dashed and dashed-dotted lines: detected anisotropic and isotropic components, respectively. B and C – experimental (solid lines) and theoretical (dashed lines) auto-spectra and coherency spectra of anisotropic scintillations. Numbers in boxes indicate the Envisat orbit numbers.

Figure 4 shows the estimates of the anisotropy coefficient using the tangential occultations. The lower *x*-axis indicates vertical wavenumber κ_z, while the upper *x*-axis indicates vertical scale. As seen from figure 4, in the range of scale from 60 m to 10 m, the anisotropy coefficient decreases approximately linearly from 50 to 10. The black curve in Figure 4 is the approximation by a simple equation:

$$\eta(\kappa_z) = \eta_{\min} + (\eta_{\max} - \eta_{\min})(1 + |\kappa_z| / \kappa_{fit})^{-1} \quad (3)$$

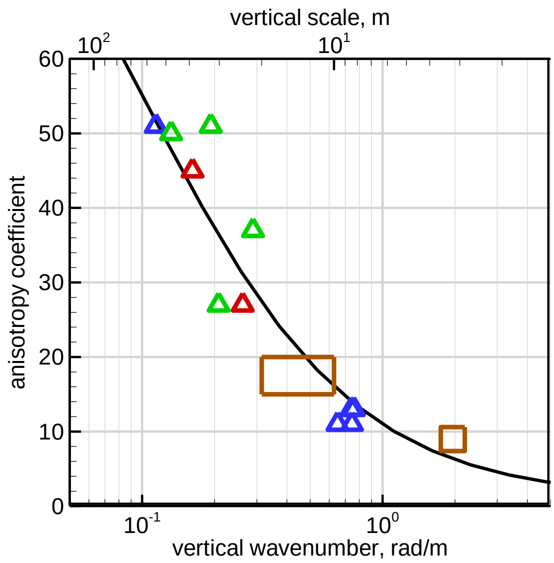

Figure 4. Experimental estimates of the anisotropy coefficient (triangles): blue for high latitudes, green for mid-latitudes, red for tropics. Black line: approximation by equation (3) of the experimental estimates. Brown square: the estimates using the angular dependence of backscatter radar signal for an altitude ~20 km; brown rectangle: the estimate obtained from the analyses of chromatic scintillations of a double star for altitudes 30–38 km.

The equation (3) has been constructed using the anisotropy estimates and additional assumption about asymptotic saturation of anisotropy to the limit values: unity at small scales and to 100 at large scales of the order of one kilometer. The parameter in the approximation equation (3) is the characteristic wavenumber κ_{fit} =0.12 rad/m.

For each tangent occultation, we get one estimate of the anisotropy coefficient corresponding to the minimal ray perigee in this occultation. The limited number of measurements does not allow investigating anisotropy for different observation condition (altitude, season, latitude etc.) To determine the functional dependence of anisotropy (equation (3)), we had to combine the occultation data and assume that they are random samples from the same statistical ensemble.

It should be noted, however, that other estimates of the anisotropy obtained in different conditions agree with our estimates and the approximation by equation (3). This supports the hypothesis of a weak dependence of the anisotropy coefficient on altitude. In addition, our method provides also other GW parameters. The agreement of the estimates of the structure characteristic and the inner scales with those previously obtained GOMOS data with a constant anisotropy assumption [3,4] also indicates a relatively weak dependence of the anisotropy on altitude in the range of 20-45 km. It is important to note that, according to our data, the anisotropy changes rapidly in the range of vertical scales of 10-60 m, which correspond to the scale of GW breaking. It is quite expected that the GW breaking is accompanied by rapid changes in the anisotropy. Another important fact is that sufficiently large anisotropy values ~50 are reached already at scales of ~50 m. This indicates that the anisotropy saturates at scales of the order of hundreds of meters.

5. Summary

Unique satellite measurements - double star occultations and tangential occultations - contain information on the anisotropy coefficient of small-scale stratospheric irregularities. In this paper, we present the methods for estimating the anisotropy coefficient from these measurements; these methods are based on the coherency analysis of bi-chromatic stellar scintillations.

The methods are applied to observations of star scintillations by fast GOMOS/ENVISAT photometers at two wavelengths. For the first time, the estimates of the anisotropy coefficient at altitudes 30-45 km are obtained for small-scale atmospheric irregularities, which are generated a random ensemble of saturated gravity waves. These estimates vary from 50 to 10 with decreasing vertical scales of irregularities from 60 m to 10 m. Rapid changes in anisotropy at scales corresponding to gravity waves breaking are observed.

The considered methods of anisotropy estimation, in addition to the method of reconstruction of structure characteristics and characteristic scales [1-4], allow reconstructing all statistical parameters of internal gravity waves and turbulence in the stratosphere from satellite occultation observations of stellar scintillations.

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