Quantifying gravity waves and turbulence in the stratosphere using satellite stellar scintillation measurements

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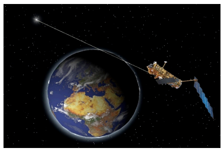
Summary: Stellar scintillations observed through the Earth atmosphere are caused by air density irregularities generated mainly by internal gravity waves (GW) and turbulence. The strength of scintillation measurements is that they cover the transition between the saturated part of the gravity wave spectrum and isotropic turbulence. This allows visualization of gravity wave breaking and of resulting turbulence. We analyzed the scintillation measurements by GOMOS fast photometers on board the Envisat satellite in order to quantify GW and turbulence activity in the stratosphere.

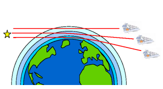
The analysis is based on reconstruction of GW and turbulence spectra parameters by fitting the modeled scintillation spectra to the measured ones. We use a two-component spectral model of air density irregularities: the first component corresponds to the gravity wave spectrum, while the second one describes locally isotropic turbulence resulting from GW breaking and other instabilities. The retrieval of GW and turbulence spectra parameters - structure characteristics, inner and outer scales of the GW component - is based on the maximum likelihood method.

In this presentation, we show global distributions and seasonal variations of the GW and turbulence spectra parameters retrieved from GOMOS data in 2003, for altitudes 30-50 km, as well as global distributions of GW potential energy per unit mass and of turbulent structure characteristic C_T^2. Since other measurements at such small scales are very scarce in this altitude range, the obtained global distributions provide unique and complementary information about small-scale air density irregularities. At altitudes and locations overlapping with other measurements, the IGW and turbulence parameters retrieved from scintillations are in a good qualitative and quantitative agreement with that obtains from other measurements. Our main findings and observations are:

(i) Strong enhancement of gravity wave activity at high latitudes in winter, accompanying with a strong turbulence appearing at altitudes above 40-45 km; indication on breaking of gravity waves in the polar night jet; (ii) The turbulent structure characteristic C_T^2 can reach values of 0.003 $K^2m^{-2/3}$ in high-latitude winter stratosphere; these values are comparable with that in the boundary layer; (iii) Moderate turbulence enhancements in the tropics, located mainly over continents and related probably to tropical deep convection; (iv) Increase of GW outer scale in the equatorial region; (v) Exceptional gravity wave spectra and a very strong turbulence during sudden stratospheric warmings.

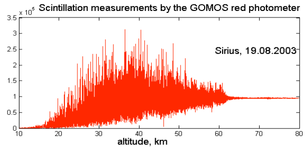
Stellar scintillation measurements by GOMOS





The GOMOS (Global Ozone Monitoring by Occultation of Star) instrument on board the Envisat satellite is equipped with two fast photometers with sampling frequency of 1 kHz, which perform synchronous scintillation measurements at blue (~500 nm) and red (~672 nm) wavelengths. The photometers measure stellar flux continuously as a star sets behind the Earth limb.

Scintillations are caused by air density irregularities and thus they contain information about small-scale processes in the atmosphere.



Two-component model of air density irregularities

We assume that the spectrum of relative fluctuations of air density is a sum of two statistically independent components:

$$\boxed{\Phi_\nu = \Phi_W + \Phi_K}$$

$\boldsymbol{\Phi_W}$ corresponds to **anisotropic** irregularities generated by a random ensemble of internal gravity waves

$$\Phi_W = C_W \eta^2 \left(k_z^2 + \eta^2 k_\perp^2 + \kappa_0^2\right)^{-5/2} \varphi\left(\frac{k}{\kappa_W}\right)$$

$$k^2 = \eta^2 k_\perp^2 + k_z^2 \qquad k_\perp^2 = k_x^2 + k_y^2$$

C_W is the structure characteristic, η is the anisotropy coefficient, $2\pi/\kappa_0$ is the outer scale, $2\pi/\kappa_W$ is the inner scale.

$\boldsymbol{\Phi_K}$ corresponds to **isotropic** irregularities generated by turbulence:

$$\Phi_K(k) = 0.033 C_K k^{-11/3} \exp(-(k/\kappa_K)^2) \qquad k^2 = k_x^2 + k_y^2 + k_z^2$$

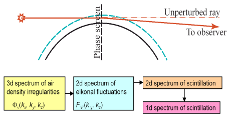
C_K is the structure characteristic, $2\pi/\kappa_K$ is the inner scale of isotropic irregularities

Scintillation spectra

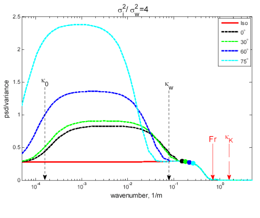
The theoretical relations: [Gurvich and Brekhovskikh, 2001], [Gurvich and Kan, 2003a].

Main assumptions:

- "Frozen field" approximation
- Phase screen approximation
- Weak scintillation



3d spectrum of air density irregularities $\Phi_\nu(k_x, k_y, k_z)$ → 2d spectrum of eikonal fluctuations $F_\psi(k_y, k_z)$ → 2d spectrum of scintillation → 1d spectrum of scintillation



Scintillation spectra for the mixture of anisotropic and isotropic inhomogeneities, for different angles α of star motion

Reconstruction of IGW and turbulence parameters

Inverse problem:

$$V_{meas} = C_K V_{iso} + C_W V_{aniso}(\kappa_W, \kappa_0) + \delta$$

Method of solving (Sofieva et al., 2007, JGR)

❑ Maximum likelihood method, which is equivalent to minimization of

$$\chi^2 = \left(C_K V_{iso} + C_W \mathbf{V}_{aniso}(\kappa_W,\kappa_0) - \mathbf{V}^{meas}\right)^T \mathbf{S}^{-1}\left(C_K V_{iso} + C_W \mathbf{V}_{aniso}(\kappa_W,\kappa_0) - \mathbf{V}^{meas}\right)$$

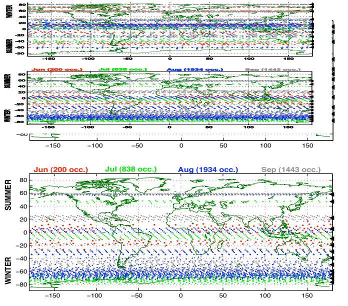
❑ Combination of linear and non-liner optimization

-Non-linear fit (Levenberg-Marquardt) for κ_W and κ_0

-Linear fit (weighted least-squares method) for C_K and C_W

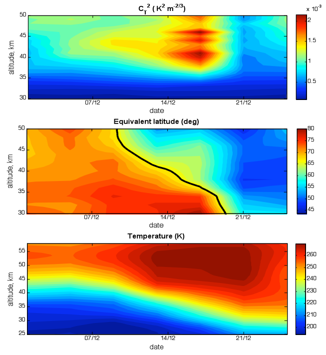
❑ Filtering quasi-periodic structures

Data selection (year 2003)

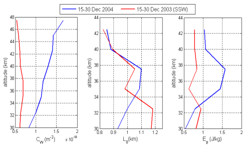


Location of selected night-time occultations of brightest stars (altogether, 8215 occultations). The filled triangles on the right side indicate the centers of latitudinal bins used for data averaging

Exceptional conditions: sudden stratospheric



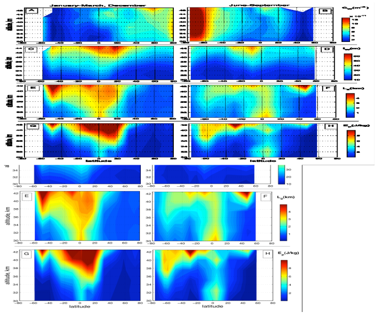
Top: C_T^2 in successive occultations of star 7 (visual magnitude 0.1, effective temperature 14 000 K) located at ~80° N in December 2003; 4-day zonal average data are presented. Middle: equivalent latitude at locations of the occultations computed using ECMWF data; the black line corresponds to 67° of equivalent latitude, which is used usually for indicating the polar vortex boundary. Bottom: temperature from ECMWF at latitude 80° N in December 2003.



Top: Mean GW parameters in a set of Sirius occultations at ~73 N. Blue: for the period 15-30 Dec 2004 ("normal" conditions), red: for the period 15-30 Dec 2003 corresponding to the sudden stratospheric warming.

Global distributions in 2003

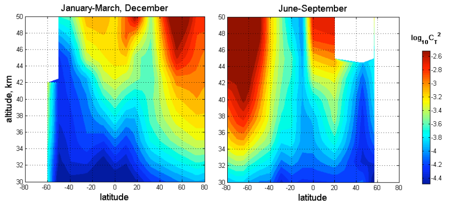
GW spectra parameters



GW potential energy per unit mass $E_p = \frac{2\pi}{3}\left(\frac{g}{\omega_{BV}}\right)^2 C_W \kappa_0^{-2}$

Turbulence structure characteristic C_T^2 ($K^2m^{-2/3}$)

Zonal mean distributions in 2003



Turbulence structure characteristic C_T^2 ($K^2m^{-2/3}$) at 42 km in 2003