

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

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Previous talks at OPAC workshops

- OPAC-1: “ Exploring the fine structure of the stratosphere by means of stellar occultation data” (invited) by A.S. Gurvich
- OPAC-2: “Bi-chromatic Scintillation Observed by GOMOS on Envisat: Results from Statistical Analyses” (invited) by A. Gurvich, F. Dalaudier, V. Sofieva



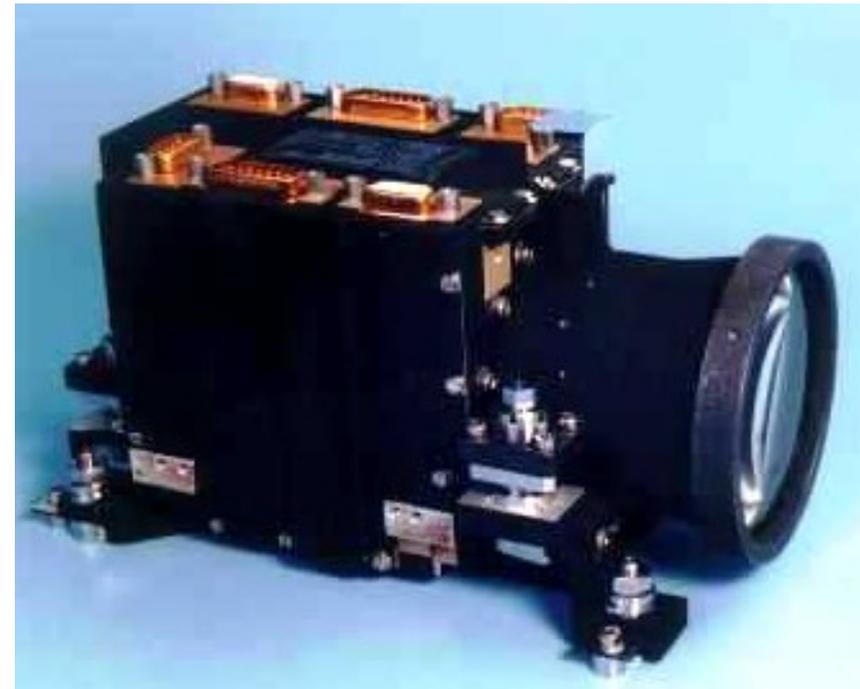
Outlines of this talk

- Methodology
- Overview of recent results from GOMOS stellar scintillation measurements

Scintillation measurements by GOMOS

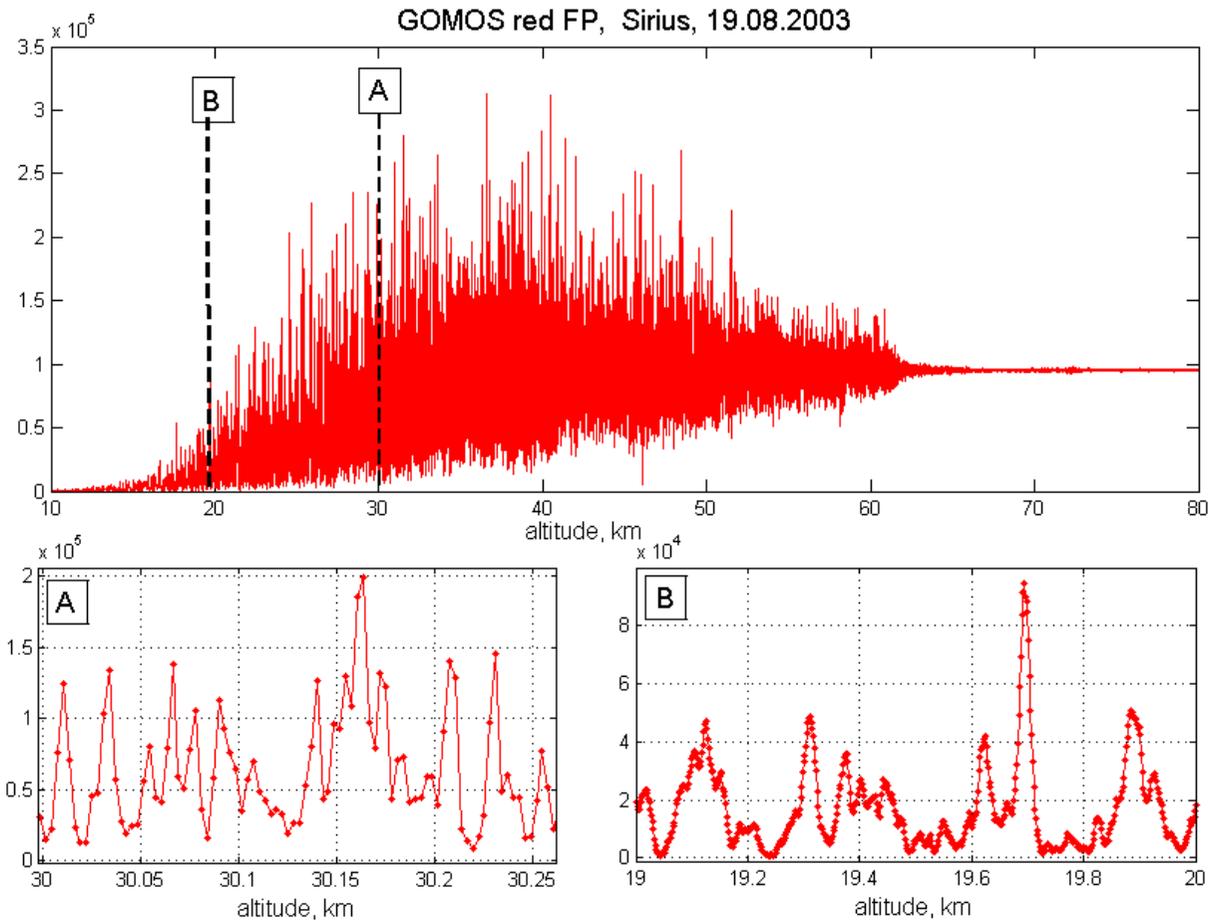
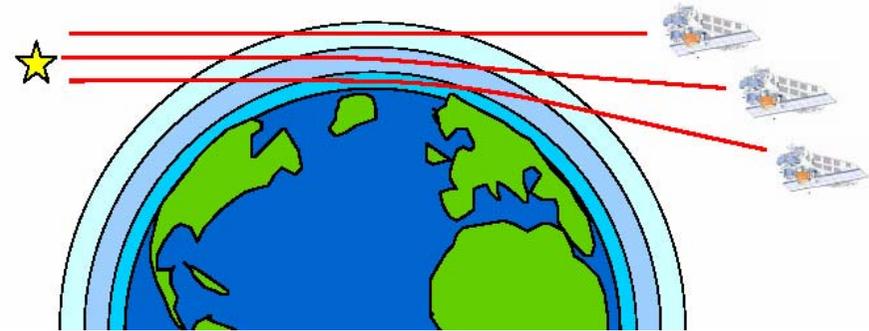


- Two fast photometers
 - Blue 470-520 nm
 - Red 650-700 nm
- Sampling frequency 1 kHz
- Objectives
 - Scintillation correction of spectrometer data
 - High resolution temperature profile → poster tomorrow
 - **Small scale structures of air density, stratospheric dynamics**



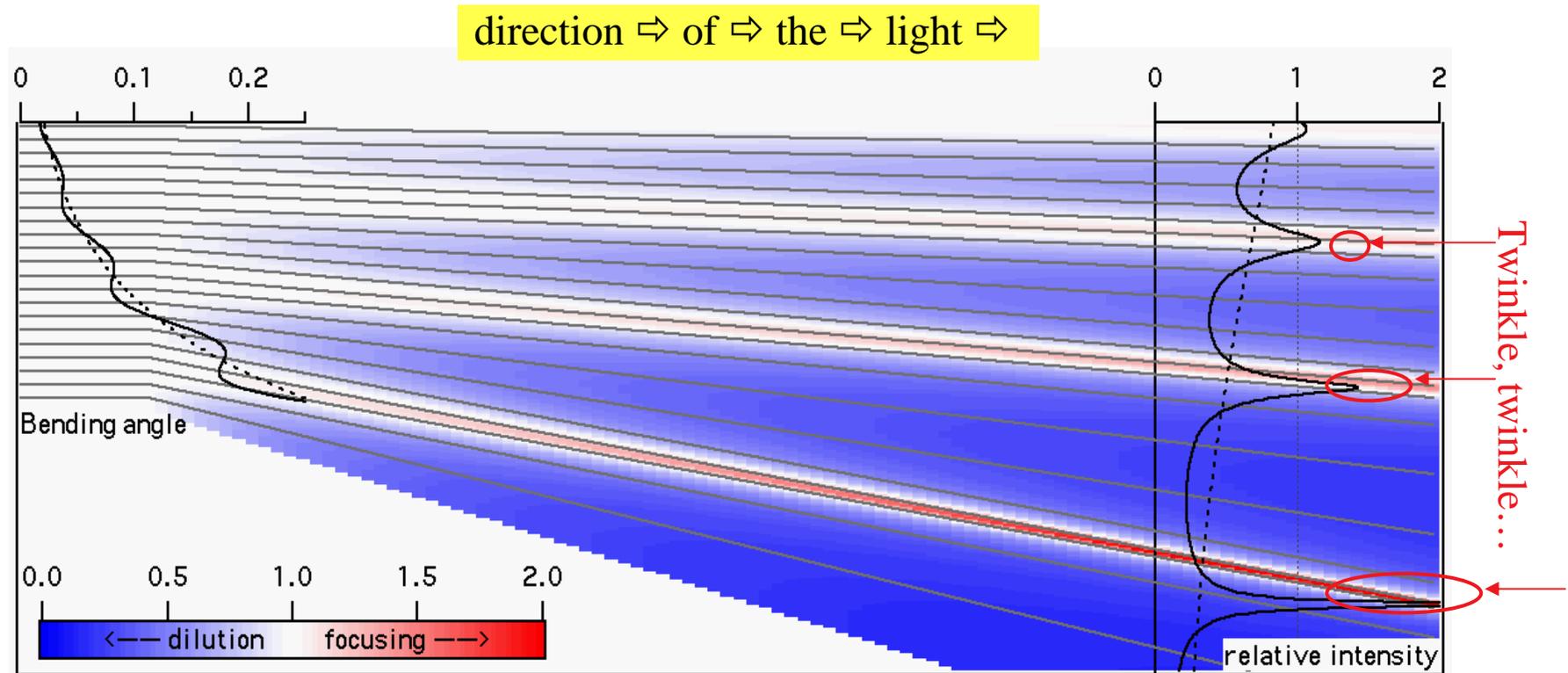
<http://envisat.esa.int/dataproducts/gomos/CNTR3-1-2.htm#eph.gomos.tgins.insdes.ifunc.tphot>

Scintillation of stars





Scintillation of stars: a simplified qualitative explanation





Main features of scintillations

- They are caused by small scale gravity waves (scales few meters → few kilometers) and turbulence
- They allow visualizing GW breaking
- The altitude range :
 - Now: ~30-50 km
 - In future: up to 70 km up and < 30 km down



The main idea of scintillation analysis

- 3D distribution of air density irregularities from 1D scintillation spectra? → the problem is severely ill-posed
- Compare measured scintillation spectra with modeled scintillation spectra

Modelled scintillation spectra

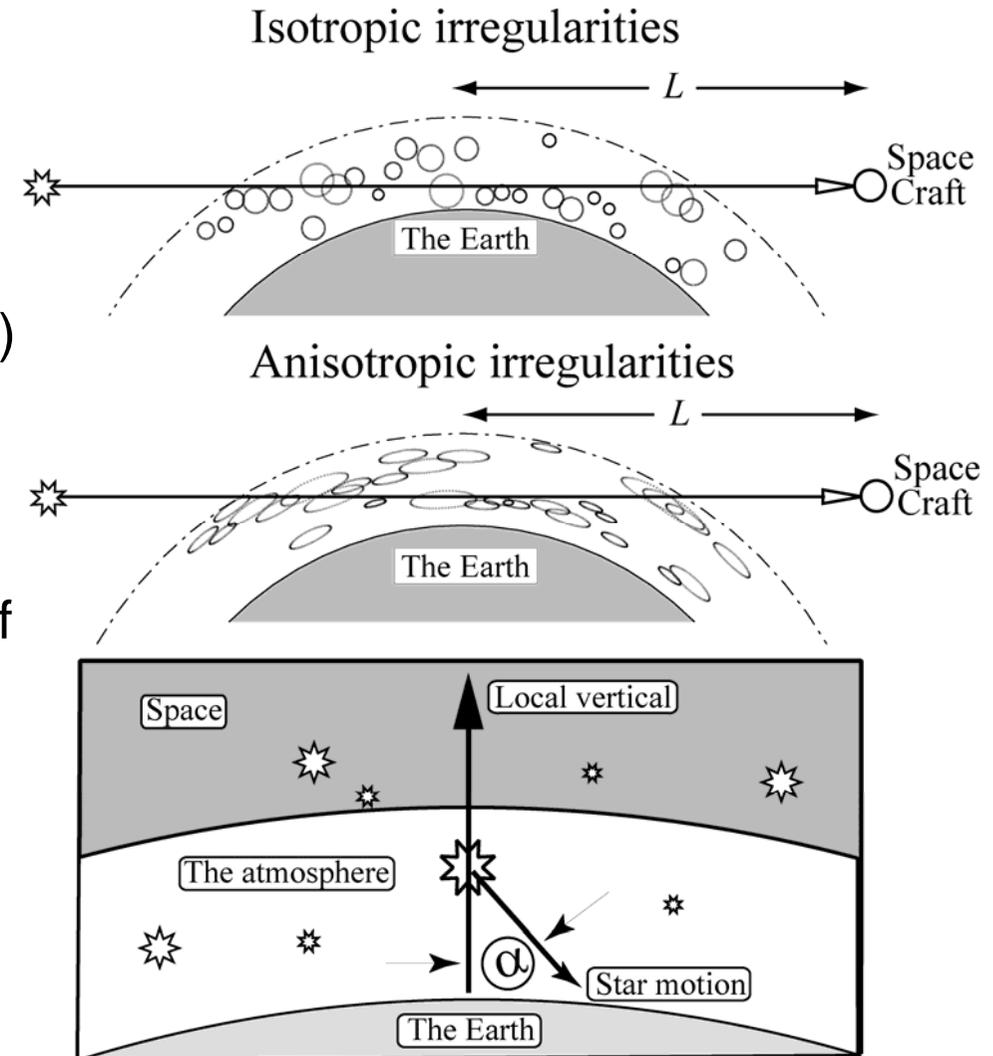
- The 3D spectrum of the air density irregularities is parameterized
- computing 1d-scintillation spectrum at observation point
(wave propagation in random media; [Gurvich and Brekhovskikh, 2001], [Gurvich, 2002], [Gurvich and Kan, 2003], MIR station measurements)

Measured scintillation spectra:

Usual computing power spectral density

Structure of air density irregularities

- Anisotropic irregularities
 - Elongated in horizontal direction
 - Generated by internal gravity waves
- Isotropic irregularities (turbulence)
 - Result from breaking of internal gravity waves
 - Dynamic instabilities
- Two-component spectral model of relative fluctuations of air density



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

anisotropic isotropic

Spectrum of anisotropic irregularities

- corresponds to anisotropic irregularities generated by a random ensemble of internal gravity waves

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

$$k^2 = \eta^2 k_{\perp}^2 + k_z^2$$

$$k_{\perp}^2 = k_x^2 + k_y^2$$

- 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
- The associated 1D vertical spectrum for $\kappa_0 \ll k_z \ll \kappa_W$ corresponds to the model of the saturated gravity waves

$$V(k_z) \approx C_W \frac{2\pi}{3} k_z^{-3}$$

$$V_{\delta T/T} = A \frac{\omega_{BV}^4}{g^2} k_z^{-3}$$

Spectrum of isotropic irregularities

- Spectrum of locally isotropic turbulence (Kolmogorov model)

$$\Phi_K(k) = 0.033 C_K k^{-11/3} \exp(- (k / \kappa_K)^2)$$

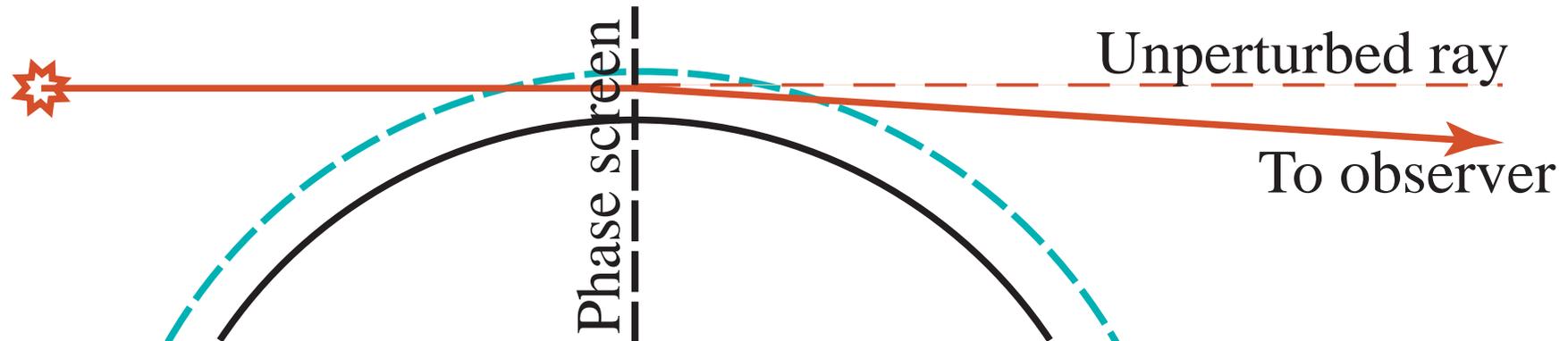
$$k^2 = k_x^2 + k_y^2 + k_z^2$$

- C_K is the structure characteristic
- κ_K is the inner scale of isotropic irregularities
- The corresponding 1D spectrum follows well-known -5/3 power law

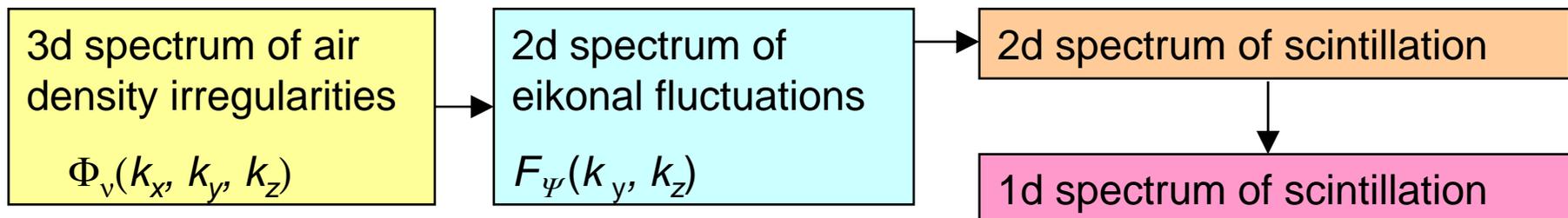
Modelled scintillation spectra

- Stratospheric distortion of light rays
 - Distortion of optical path (eikonal)
- Phase screen approximation

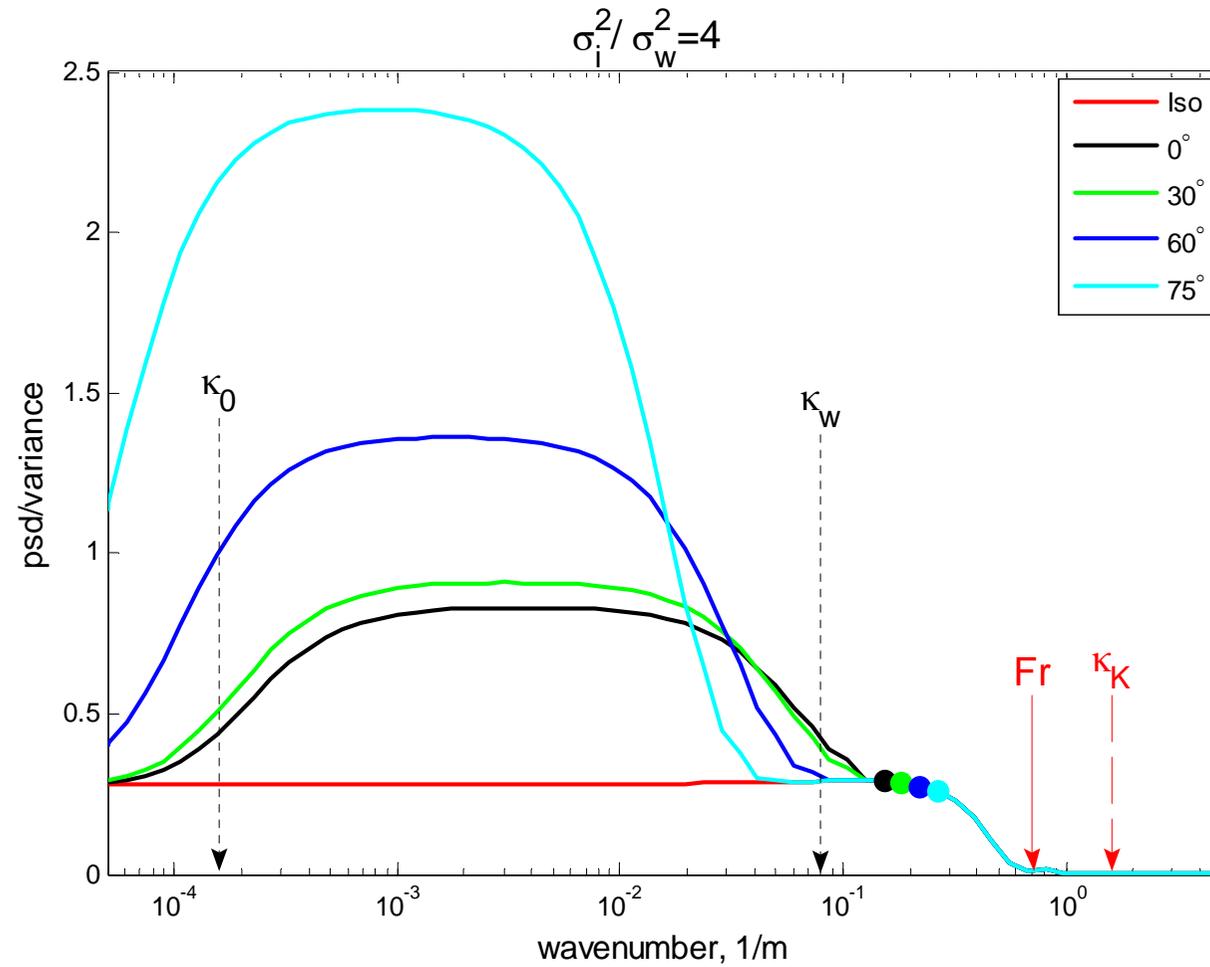
$$\Psi = \int_{\text{ray}} dl N(\mathbf{r})$$



- Scintillation spectrum (weak scintillation)



Scintillation spectra





The main approach to scintillation analysis

- To separate the anisotropic and isotropic components
- To retrieve essential parameters of IGW and turbulence spectra

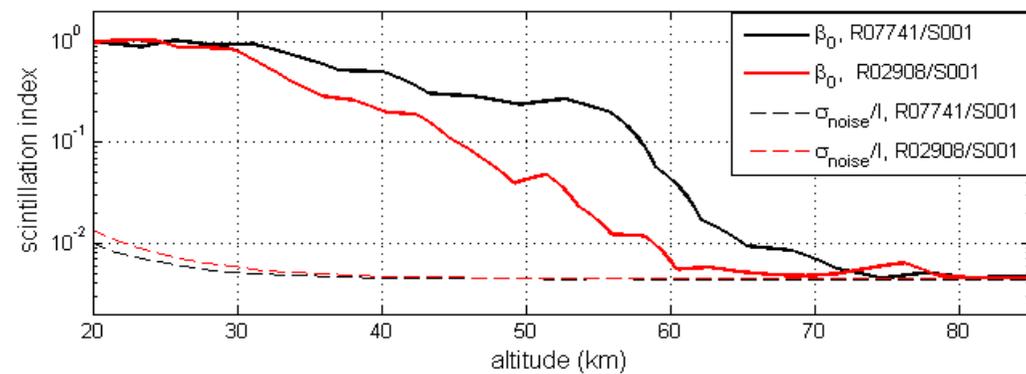
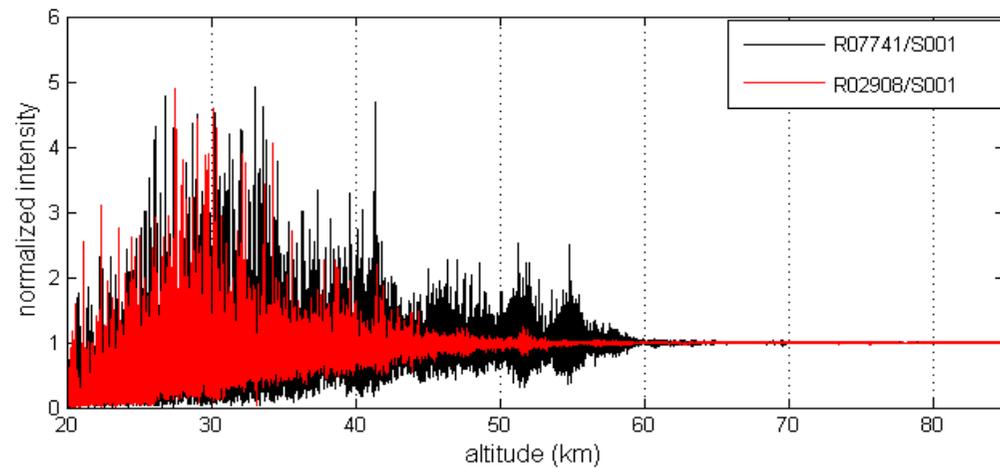
A qualitative approach: analysis of scintillation variance (GRL, 2007)



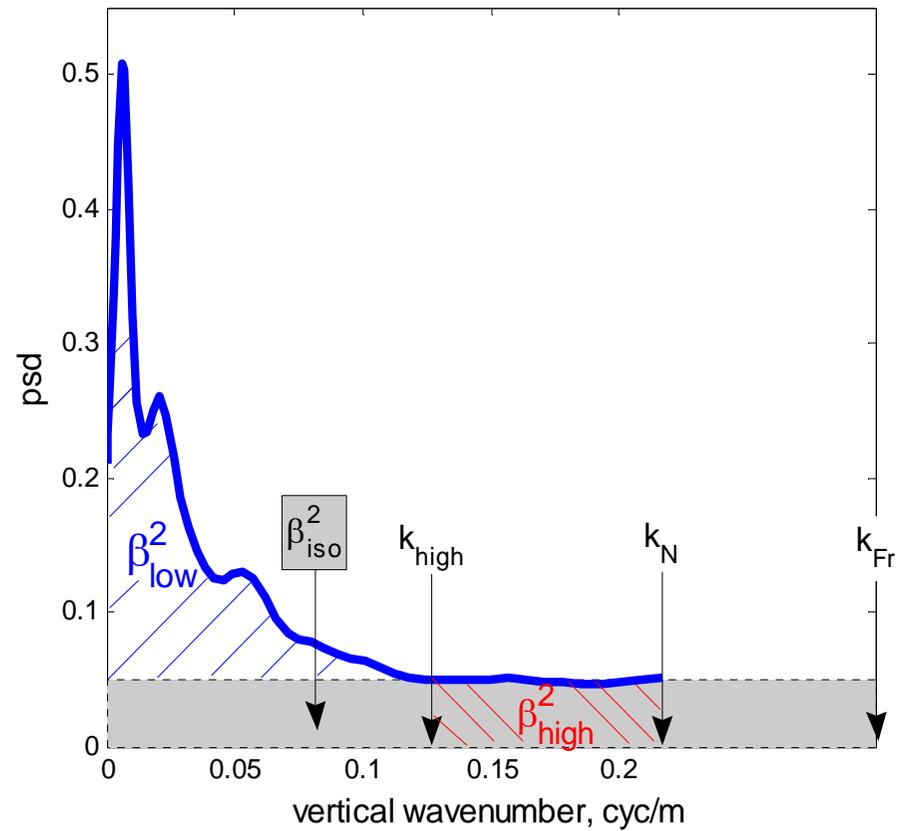
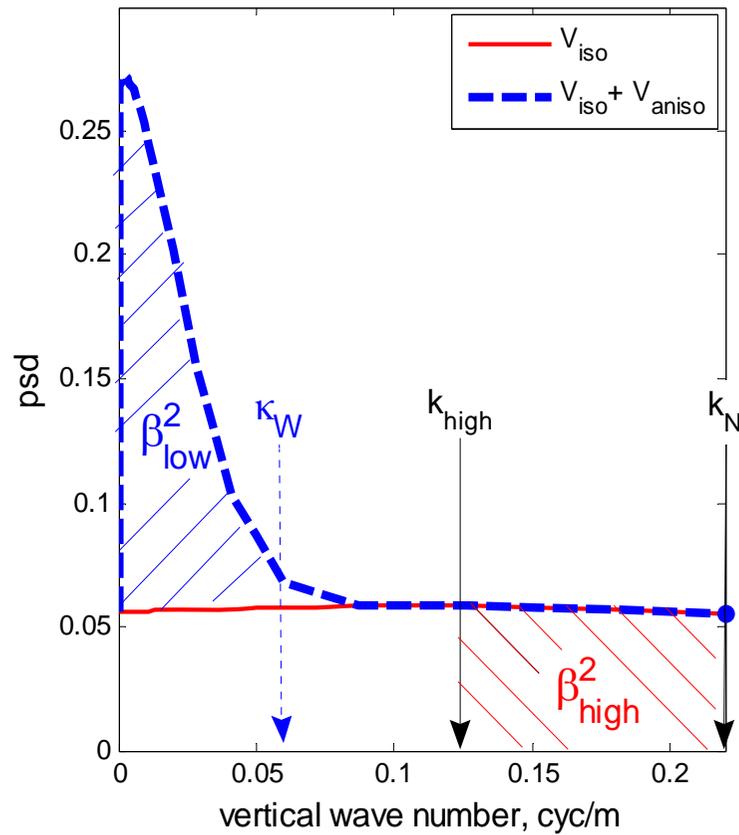
- Scintillation variance:

$$\beta^2 = \frac{\langle (I - \bar{I})^2 \rangle}{\langle \bar{I} \rangle^2}$$

- Contains contributions from both anisotropic and isotropic scintillations



Data processing

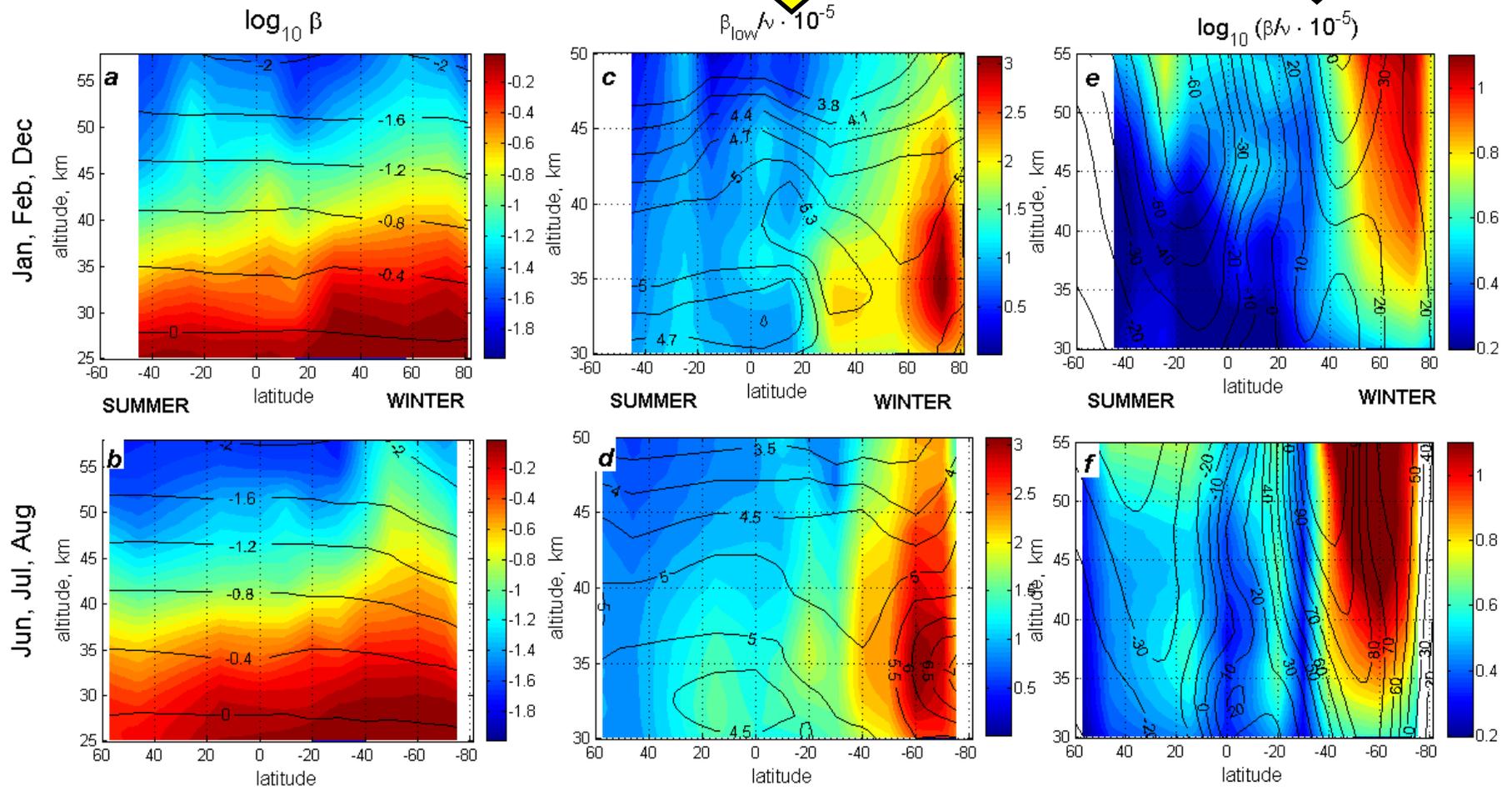


Results



Indication on gravity waves

Turbulence
 $\beta_{iso}/\nu \sim C_n^2$



Sofieva et al. (2007), Global analysis of scintillation variance: Indication of gravity wave breaking in the polar winter upper stratosphere, *Geophys. Res. Lett.*, 34, L03812, doi:10.1029/2006GL028132

Quantitative analysis: reconstruction of IGW and turbulence spectra parameters

- Solving the inverse problem:

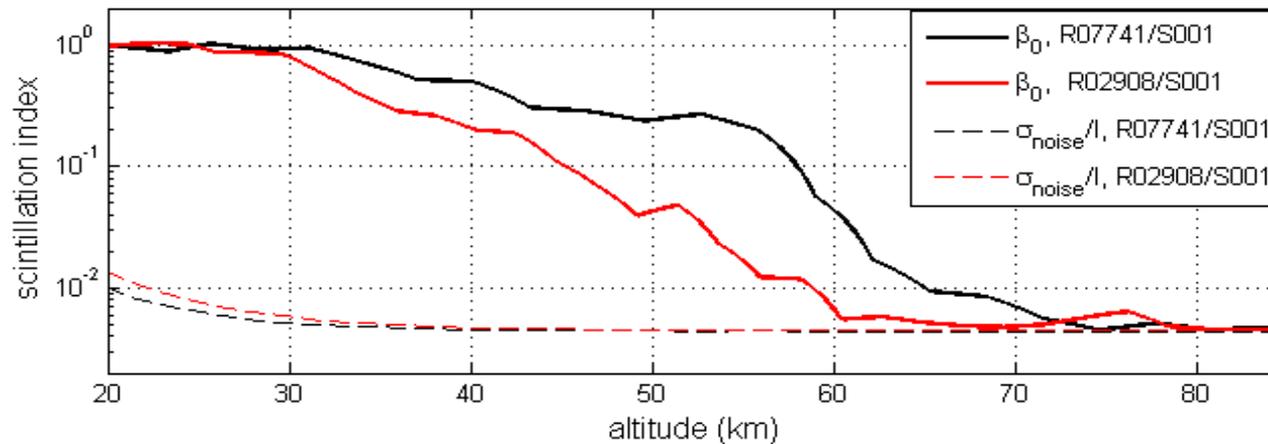
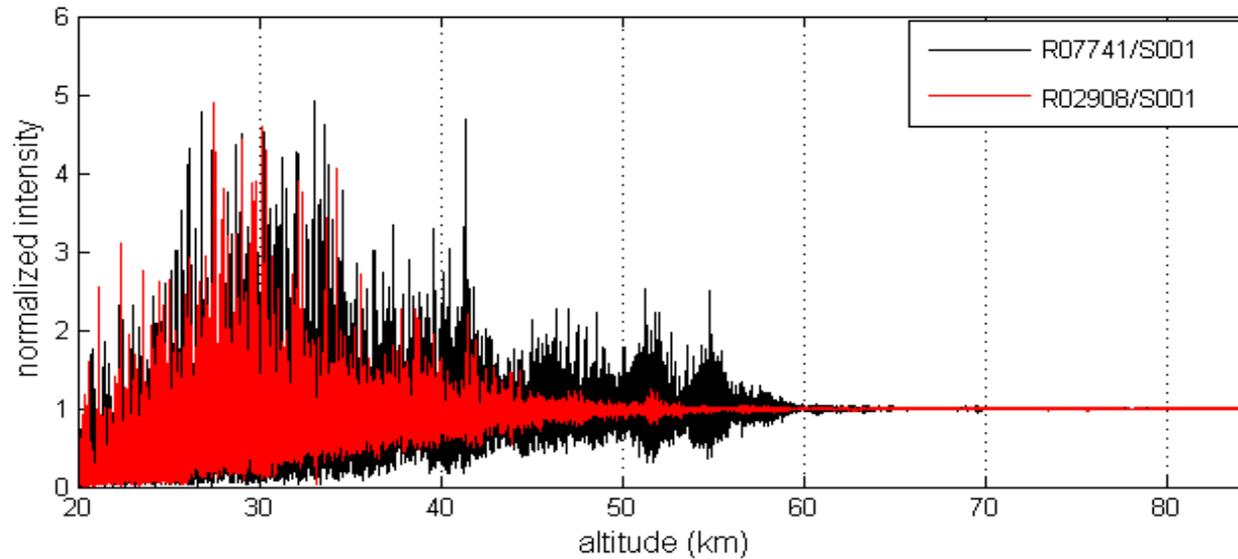
$$\mathbf{V}_{\text{meas}} = \mathbf{C}_K \mathbf{V}_{\text{iso}} + \mathbf{C}_W \mathbf{V}_{\text{aniso}}(\kappa_W, \kappa_0) + \delta$$

- Maximum likelihood method, which is equivalent to minimization of

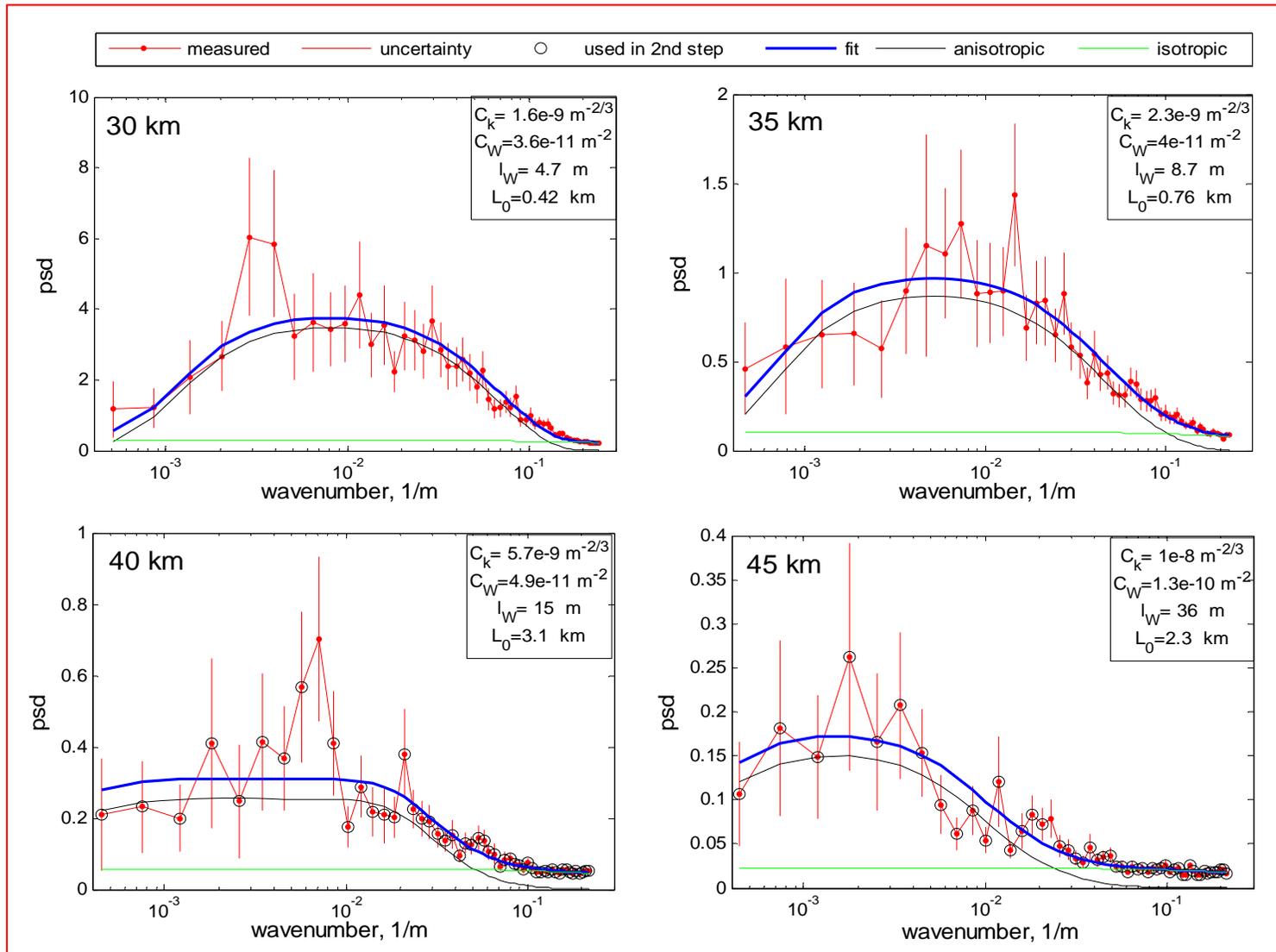
$$\chi^2 = \left(\mathbf{C}_K \mathbf{V}_{\text{iso}} + \mathbf{C}_W \mathbf{V}_{\text{aniso}}(\kappa_W, \kappa_0) - \mathbf{V}^{\text{meas}} \right)^T \mathbf{S}^{-1} \left(\mathbf{C}_K \mathbf{V}_{\text{iso}} + \mathbf{C}_W \mathbf{V}_{\text{aniso}}(\kappa_W, \kappa_0) - \mathbf{V}^{\text{meas}} \right)$$

- Combination of linear and non-linear optimization
 - Non-linear fit (Levenberg-Marquardt) for κ_W and κ_0
 - Linear fit (weighted least-squares method) for \mathbf{C}_K and \mathbf{C}_W

Examples of retrievals : 1. photometer data



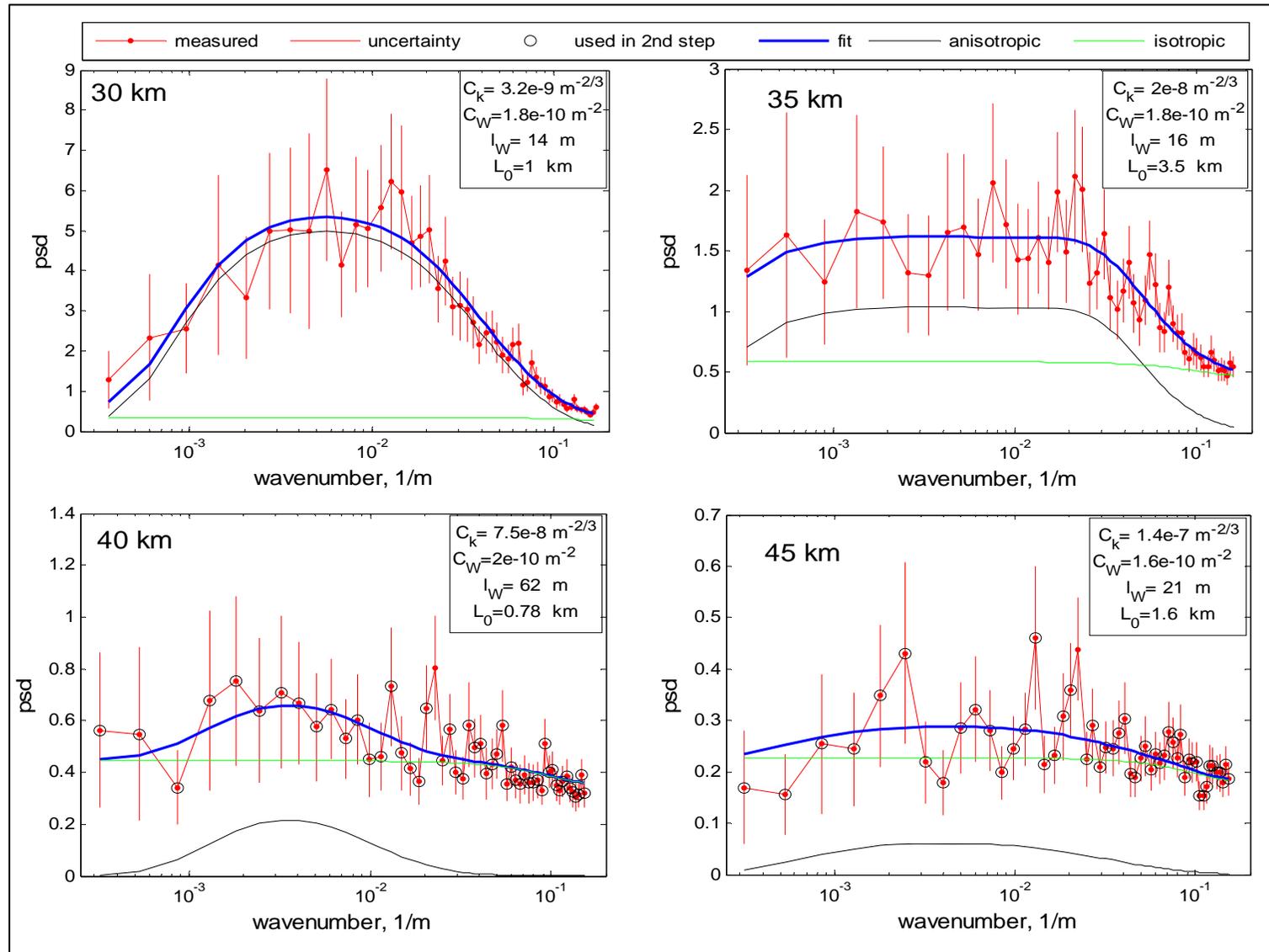
Examples of retrievals: moderate turbulence



Sofieva et al.,
JGR, 2007

R02908/S001 ($\alpha=67^\circ$, 35°S , 106°W , 20 September 2002)

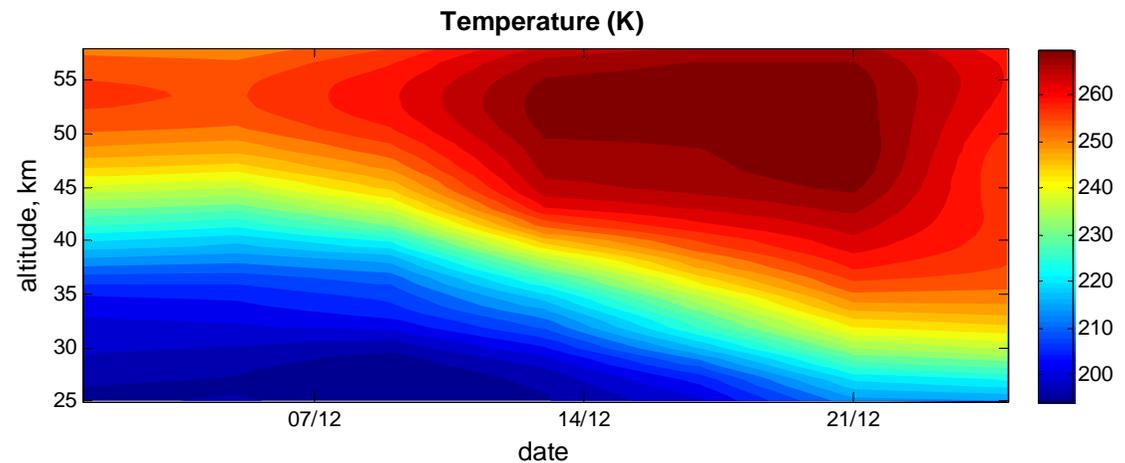
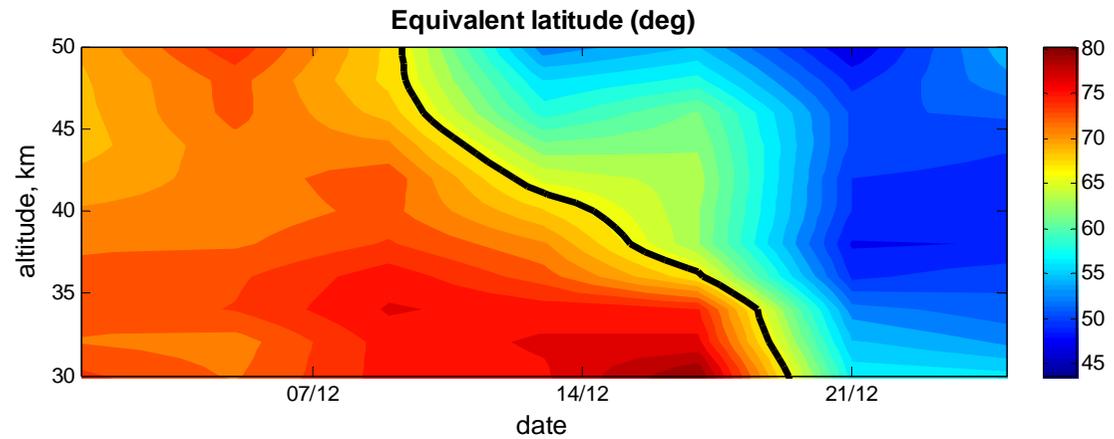
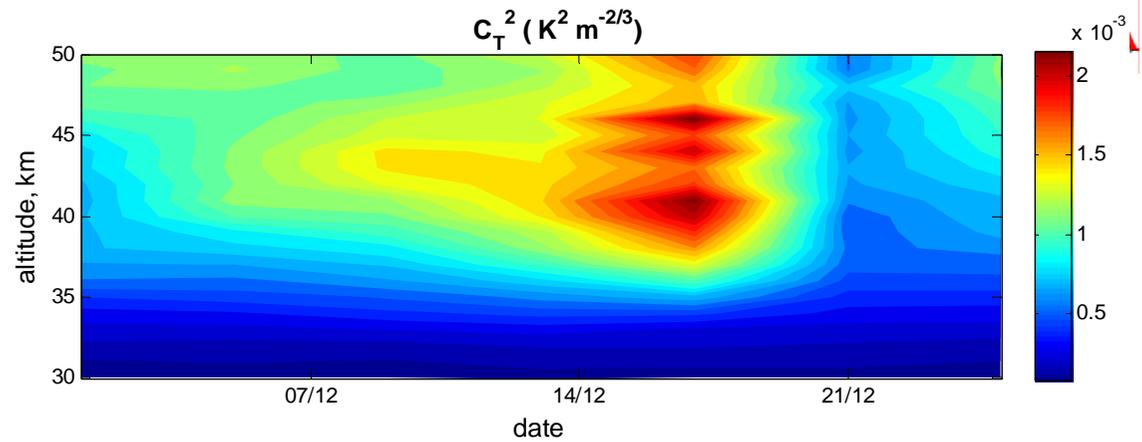
Examples of retrievals: strong turbulence



Sofieva et al.,
JGR, 2007

R07741/S001 ($\alpha=40^\circ$, 62°S , 7°E , 23 August 2003)

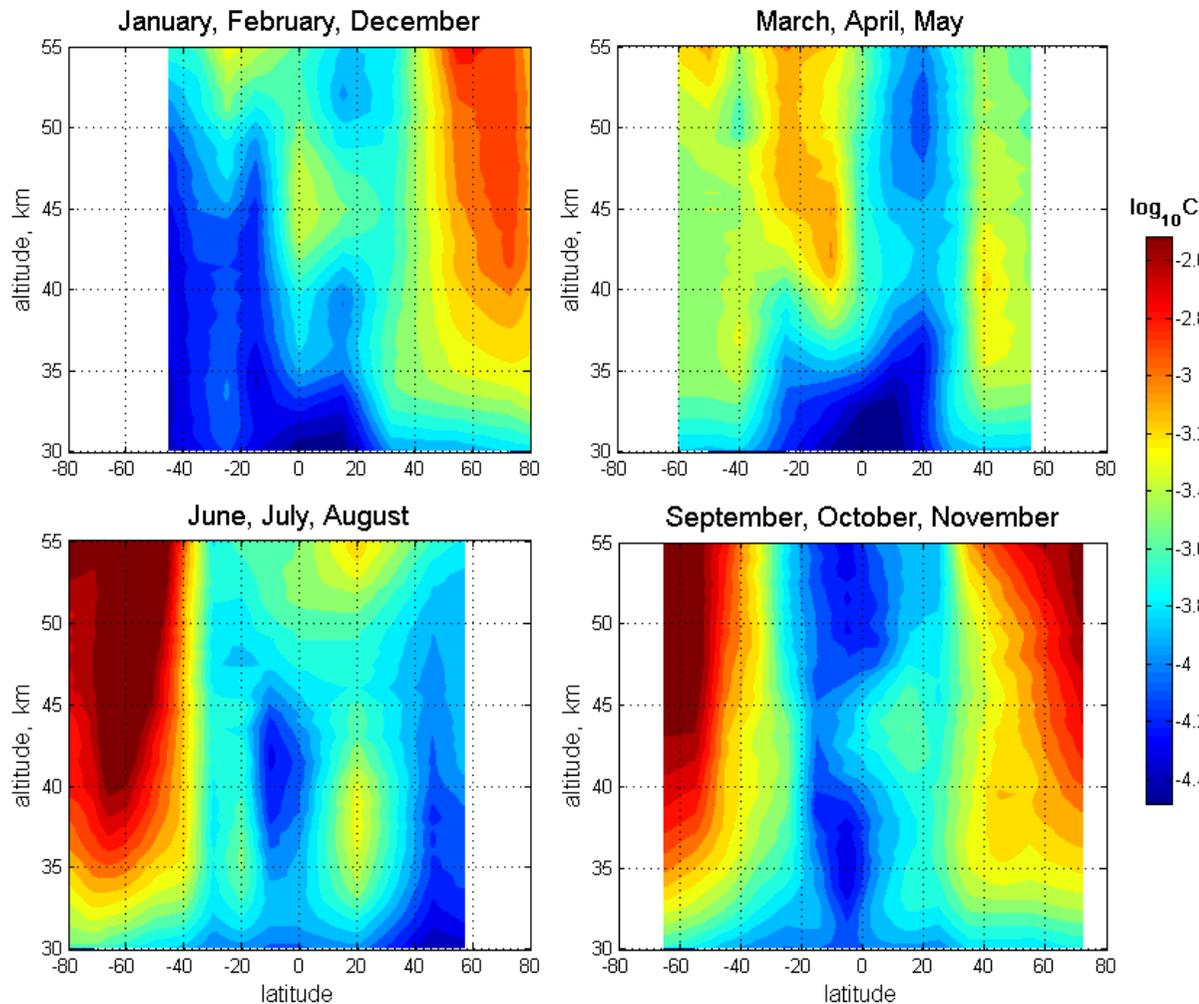
Evolution of C_T^2 at 80 N during the sudden stratospheric warming in December 2003



Sofieva et al., (2007): Reconstruction of internal gravity wave and turbulence parameters in the stratosphere using GOMOS scintillation measurements, *Journal of Geophys. Res.*, 112, D12113, doi:10.1029/2006JD007483

Zonal averaged C_T^2 in four seasons of 2003

$$C_T^2 = \langle T \rangle^2 C_K$$

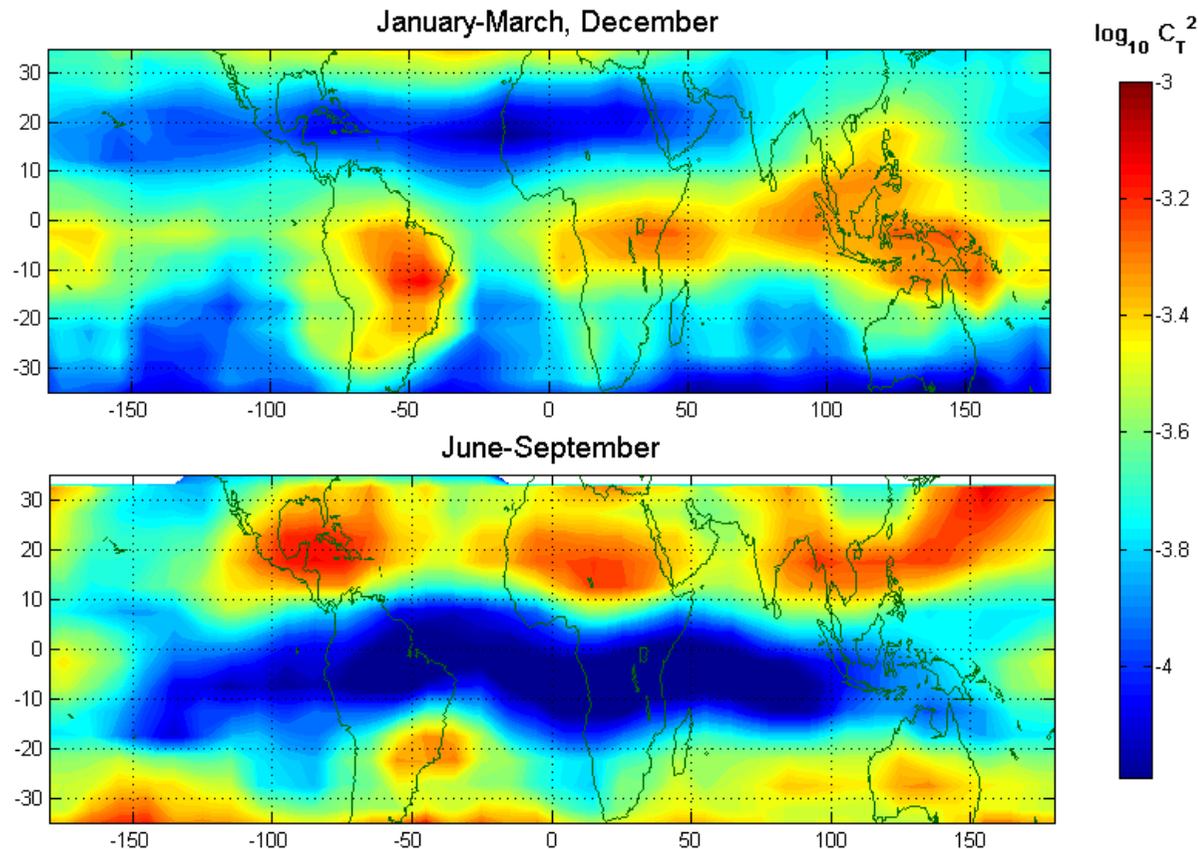


- Large variations: the range of C_T^2 values covers more than two orders of magnitude
- The largest values of C_T^2 are observed above 40-45 km in polar winter in both hemispheres; they are especially large in the southern hemisphere
- They can be related to a GW breaking in the polar night jet
- The C_T^2 enhancements at high latitudes in Sep-Oct-Nov plot are related most probably to the remaining (beginning) of the polar vortex.
- Weaker enhancements in tropics are observed

Gurvich et al., 2007, submitted to GRL

OPAC-3 International Workshop, 17-21 September 2007, Graz, Austria

C_T^2 in tropics (at 42 km)



- Turbulence intensity is smaller in tropics than in polar regions; it has a pronounced zonal structure
- Average values of C_T^2 follow the sub-solar latitude
- Almost all of the local enhancements are over continents
- Many of enhancements correspond well to the typical regions of deep convection
- No systematic increase of C_T^2 over large mountain regions is observed

Gurvich et al., 2007, submitted to GRL



Summary

- Using satellite stellar scintillation measurements for studying air density irregularities is a new and promising method
- The presented results are the start in studying small-scale (few meters – few kilometers) air density irregularities
- We look forward to new results after the processing the large GOMOS data set