Response to the reviewers comments on the paper “Fluctuations of radio occultation signals in sounding the Earth's atmosphere” by V. Kan, M. E. Gorbunov, and V. F. Sofieva

Reviewer #2

The difficulty of the developed stellar technique transformation for use in radio occultation remote sensing consists in a substantial difference, by several orders of magnitude, of the carrier frequencies, recording and processing methods, and also in the applicable altitude domains in the atmosphere.
1. Radioholograms containing the dependence on time of the amplitude and phase path excess (eikonal) are registered during RO experiments. The scintillations have been measured by GOMOS fast photometers (FP) on board the Envisat satellite at two wavelength $\lambda_B = 499$ *nm;* $\lambda_R = 672$ *nm.*
So, the RO method has very important additional informative highly accurate phase channel. This channel can be used for identification and separation of the regular layers and turbulence by joint analysis of the RO amplitude and phase data at a single frequency (Pavelyev et al., 2015). The manuscript does not indicate in the reference list or in the text any valuable information on the topic. It is not clear, how one can use the phase RO channel for IGW's analysis.
The suggested in the manuscript technique in the current state does use only the two component statistical model and it is not clear how it separates the possible influence of regular layers from the turbulence contribution in the RO signal. It is well known, that for statistical analysis it is necessary to exclude any systematic influence of regular component on the results.
Yes, unlike optical observations, radio occultations provide not only amplitude, but also phase, i.e. that complex wave field. This opens a prospective for the development and application of advanced radio holographic methods that permit enhancing the accuracy and vertical resolution of refractivity profiles retrieved (e.g. Gorbunov et al., 1998, 2004), as well as obtaining new information about the structure of the atmosphere (Pavelyev et al., 2012, 2015 and further references therein). For example, Pavelyev et al. (2015) demonstrated the power of the locality principle for the localization and estimation of parameters of layered structures and the separation of the contributions of turbulence and layered structures in RO signals.
In our work, we complement the observed amplitude and phase with the observation geometry. Although we use the amplitude and phase separately, the statistical analysis considering the obliquity angle allows us to separate and estimate the contributions of saturated IGWs and turbulence in RO signals. The application of advanced radio holographic methods, in particular the technique of Fourier Integral Operators (Gorbunov and Lauritsen, 2004), for the improvement of accuracy and resolution is our plan for the future work.
We interpret the layered structures discussed by Pavelyev et al. (2015) not as regular or deterministic ones, but as random strongly anisotropic inhomogeneities, approaching spherical layers. They are understood as realizations of a random ensemble of saturated IGWs (e.g. Dewan and Good, 1986; Smith et al, 1987; Gurvich and Brekhovskikh, 2001).
For the wave propagation study, we specify their statistical properties as a 3D model of the spatial spectrum, which is mapped to 2D and 1D spectra of the eikonal fluctuations in the phase screen plane, and, finally, to the fluctuation spectra of the observed amplitude and phase. We separate turbulence and layered structures, using the fact that the amplitude and phase fluctuation spectra of RO signals depend on the anisotropy and the slope of the spatial spectra of the inhomogeneities.

Note, Pavelyev et al. (2015), along with the deterministic description, also applied the statistical approach for the study of realizations of coherent and incoherent components of RO signal, obtained from the combined analysis of the amplitude and phase. For CHAMP occultations event, Pavelyev et al. (2015) showed that layered inhomogeneities play a dominant role in intensity fluctuations in the stratosphere, and that the diffractive slope of the intensity spectra is close to that predicted by the model of saturated IGWs.
Along the line of this remark of the reviewer, we made the following additions.
Page 17, line 14–15, Discussion:
Joint observations of the amplitude and phase of RO signals open new prospective for the development and application of radio holographic methods. These methods allow enhancing the retrieval accuracy and resolution (e.g. Gorbunov et al., 1998; 2004), as well as obtaining new information on the structure of the atmosphere (Pavelyev et al., 2012; 2015 and references therein). In particular, Pavelyev et al. (2015) demonstrated the potential of the locality principle for the localization and estimation of the parameters of layered structures, as well as the separation of the contributions of layered structures and turbulence in RO signals. In our study, we use the power spectra of the observed fluctuations of the amplitude and phase, correlated with the obliquity angle, in order to estimate and separate the contributions of anisotropic inhomogeneities (saturated IGWs) and isotropic turbulence. The application of radio holographic methods for the enhancement of the accuracy and resolution is our plan for future work.
Page 19, line 12–13, after "…with the saturated IGW model":
Pavelyev et al. (2015) analyzed a series of CHAMP occultation events and showed that layered inhomogeneities, as compared to turbulence, play a dominant role in the RO amplitude fluctuations in the stratosphere, and the diffractive slope of the intensity spectra for these inhomogeneities is close to that predicted by the saturated IGW model.

2. In the manuscript the regular altitude dependence of the refractivity in the atmosphere is described by an exponential model. This is a good approximation for altitudes greater than 20-30 km. However, there are clearly defined layers in the stratosphere and troposphere below 30 km. The influence of the regular layers should be taken into account in the formula for the average eikonal estimation (Page 7, line 1, psi=). This is underestimated value. For the troposphere and lower stratosphere this formula should include the bending angle according to the accurate phase path excess formula given by Pavelyev et al., 2015. This concerns also the formula (24) for the refractive attenuation.
The use of an enhanced model of the regular atmosphere is critical for the joint use of the amplitude and phase. In our theoretical estimates of the mean eikonal, refraction angle, and refractive attenuation, we employed the simple exponential model of the atmosphere. As shown by Vorob'ev and Krasil'nikova (1994), the relative error for the eikonal and refraction angle, caused by the straight ray approximation, is about 10% for the ray touching the Earth's surface. We were using the simple model, because, as stated in Introduction and Section 3.6, our aim was not the quantitative study of atmospheric inhomogeneities, but rather a demonstration of their qualitative features, in particular, demonstration of the qualitative and principal differences between the manifestations of turbulence and IGWs in RO signals. Strong natural variations of turbulence and saturated IGW parameters significantly exceed all the possible inaccuracies of our approximations.
As already stated above, we adopted the interpretation of the layered structures discussed by Pavelev et al. (2015) as random, strongly anisotropic inhomogeneities described by the saturated IGW model, rather than regular deterministic layers. In the first approximation of the weak fluctuation method, random inhomogeneities do not influence the mean amplitude, phase, and refraction angle (Tatarskii, 1971; Rytov et al., 1989b). The contribution of these inhomogeneities is taken into account by the 1D and 2D eikonal fluctuation spectra.

3. Besides the above mentioned remarks the paper should contain a clear Figure indicating the main geometrical parameters used in the manuscript (the incidence angle, refractive angle, impact parameter ...).
Reference
A.G.Pavelyev, Y.A.Liou, S.S.Matyugov, A.A.Pavelyev, V.N.Gubenko, K.Zhang, and Y.Kuleshov Application of the locality principle to radio occultation studies of the Earth's atmosphere and ionosphere. Atmos. Meas. Tech., 8, 2885-2899, 2015. www.atmos-meas-tech.net/8/2885/2015/. doi:10.5194/amt-8-2885-2015.
Along the line of this remark, we made the following modifications and additions:
Page 5, line 15, after "…to the incident rays":
The occultation geometry has been discussed in many papers: (Vorob'ev and Krasil'nikova, 1994; Ware et al., 1996, Gorbunov and Lauritsen, 2004; Cornman et al., 2004; Pavelyev et al., 2012, and references therein). The phase screen has been discussed in (Hubbard et al., 1978; Gurvich, 1984; Woo et al., 1980: Gurvich and Brekhovskikh, 2001). So we decided not to repeat the Figures from these papers.
Page 7, line 2, after "which is essential, if $\eta \geq \eta_{cr}$.":
Figure 1 in (Gurvich and Brekhovskikh, 2001) provides a good illustration of the influence of the Earth's sphericity upon the eikonal fluctuations in sounding isotropic and anisotropic atmospheric inhomogeneities.
Additional references:
Gorbunov, M. E. and Gurvich, A. S.: Algorithms of inversion of Microlab-1 satellite data including effects of multipath propagation. Int. J. Remote Sensing, 19(12), 2283-2300, 1998.
Pavelyev, A. G., Liou, Y. A., Matyugov, S. S., Pavelyev, A. A., Gubenko, V. N., Zhang, K., and Kuleshov Y.: Application of the locality principle to radio occultation studies of the Earth's atmosphere and ionosphere. Atmos. Meas. Tech., 8, 2885–2899, doi:10.5194/amt-8-2885-2015, 2015.
Pavelyev, A. G., Liou, Y. A., Zhang, K., Wang, C. S., Wickert, J., Schmidt, T., Gubenko, V. N., Pavelyev, A. A., and Kuleshov, Y.: Identification and localization of layers in the ionosphere using the eikonal and amplitude of radio occultation signals, Atmos. Meas. Tech., 5, 1–16, doi:10.5194/amt-5-1-2012, 2012.