Interactive comment on "Identification and localization of layers in the ionosphere using the eikonal and amplitude of radio occultation signals"

by A. G. Pavelyev et al.

A. G. Pavelyev et al.

pvlv@ms.ire.rssi.ru

Page 1474, Line 4: ***The developed analytical model allows ray tracing of the RO signals.***

Ray tracing does not require this model. It is based on the ray equation in an arbitrary inhomogeneous medium and any 3D model of the ionospheric refractivity and its gradient. The 3D field of the ionospheric refractivity can be specified either in the form of an analytical model or as an interpolated gridded field (like International Reference Ionosphere).

This concerns numerical ray tracing.

Analytical ray tracing uses analytical presentations of the amplitude and phase (eikonal) of propagating field by use of the analytical form of refractivity distribution (e.g., Pavelyev et al., 1996). Analytical ray tracing is useful to control different regimes of RO signal propagation (multipath, diffraction, waveguide, etc.), and appropriate, in particular, for analysis of the case when radio waves propagate in two significantly distinct parts of the ionosphere having different distributions of the electron concentration. Analytical ray tracing will be appropriate in more general case for analysis of conditions of radio communication in trans-ionospheric links (satellite-to-satellite, satellite-to-Earth).

A general formula for the amplitude of RO signal taking into account horizontal gradients can be found in the paper: M. E. Gorbunov and G. Kirchengast, Processing X/K Band Radio Occultation Data in Pres-ence of Turbulence, Radio Science, 2005, V. 40, No. 6, RS6001, doi: 10. 1029/2005RS003263.

Gorbunov and Kirchengast, 2005, found an analytical expression for "…*the amplitude of **the transformed field retrieved by the CT or FSI method…***". Therefore the amplitude of the field has been found as a function of the impact parameters. Gorbunov and Kirchengast, 2005, do not discuss how to find the actual altitude of a layer relative to the Earth surface by use of "…*the **effective impact parameter p computed from the Doppler frequency shift** by way of the classical geometric-optical bending angle retrieval* …". In the ionosphere the altitude of a layer does not always coincide with the height of the RO ray perigee (Sokolovskiy et al, 2002). Estimation of a layer' altitude as the height of the RO ray perigee contains a systematical error depending on the displacement of the center of spherical symmetry. In distinction with results obtained by Gorbunov and Kirchengast, 2005, the amplitude in the introduced analytical model depends on the spatial coordinates: distances from the centers of spherical symmetry, central angles, and other geometrical parameters. This model gives clear understanding of influence of horizontal gradients on the RO altitude estimation of layers, and is useful for solution of the direct and inverse problem of radio waves propagation in the ionosphere. Corresponding remarks will be introduced in the revised version.

Page 1475, Line 10: ***As follows from the introduced model the ionospheric contribution in the RO signals can be significant at different altitudes of the RO ray perigee in 40-90km interval if the following two necessary and sufficient conditions are fulfilled: (i) the ionospheric part of the RO signals path contains a tangent point; and (ii) there is a refractivity layer with sharp gradient perpendicular to the ray G1B1B2L in the vicinity of the tangent point. In the simplest case, when an inclined plasma layer exists only on one part of the ray G1B1B2L and the influence of the neutral atmosphere is weak, the analytical model predicts the displacement of the tangent point from the ray perigee T to a plasma layer. As a result one may observe unusually strong amplitude and phase variations of the RO signals in the 40-90 km interval of the RO ray perigee height h(T).***

This follows from the model, but by now the text does not present any substantiation that this model is really useful for the description of ionospheric fluctuations of RO signals.

The necessary substantiation and explanation will be introduced in the updated version.

Page 1470, Line 5: ***Strong ionospheric influence with diffraction structures in the RO signals is demonstrated in Fig. 4 (right) at the heights 98-105 km. This case can be considered as a consequence of diffraction of electromagnetic waves on sharp gradients of the electron density in a sporadic E-layer.***

Why should this case be considered as a consequence of diffraction effects? What is the criterion? Did the authors make any estimates of the difference between geometric optical and diffractive amplitude for this case?

Changes in the numbers of radio rays, multi-path propagation, and oscillation of the amplitude due to interference of different rays follow transaction of radio occultation path through caustics boundaries. The interference oscillations are clearly seen in Fig. 4 (right). These oscillations can be connected with diffraction effects near a caustic boundary. Necessary remarks will be given in the updated version of paper.

Page 1470-1471: ***According to the analysis of CHAMP RO amplitude and phase data, five types of ionospheric influence on the RO signals can be established at the RO ray perigee altitudes between 40 km and 90 km: ... These types can be compared with the results obtained***

earlier by Karasawa et al. (1985) ... This coincidence in the types of CHAMP RO amplitude scintillations and the amplitude variations observed in the Earth-based experiments indicates common ionospheric mechanisms of their origin.

*Where in the paper can we find such an analysis of CHAMP RO data that allows for the classification of ionospheric influence? Where in the paper can we see any quantitative comparison of the CHAMP RO data with the data of Karasawa? What means the statement that these types can be compared with the results by Karasawa? Were they really compared? What means, for example, the statement that "****The C-type is similar to noisy variations without any significant regular or periodical structure in the amplitude changes of the transionospheric signals****"! Did the authors compute the spectral density of these fluctuations and compared it to that obtained from the data by Karasawa?*

Are just 5 examples sufficient for these far-reaching conclusions?

In this paper attempt to reveal different types of the ionospheric impact on RO signals has been made. The results can be compared and supported by data of Karasawa et al., 1985, for communication link satellite to Earth. Karasawa et al., 1985 introduced two types of the ionospheric impact on the amplitude of radio waves: regular (S-type) and noisy (C-type).

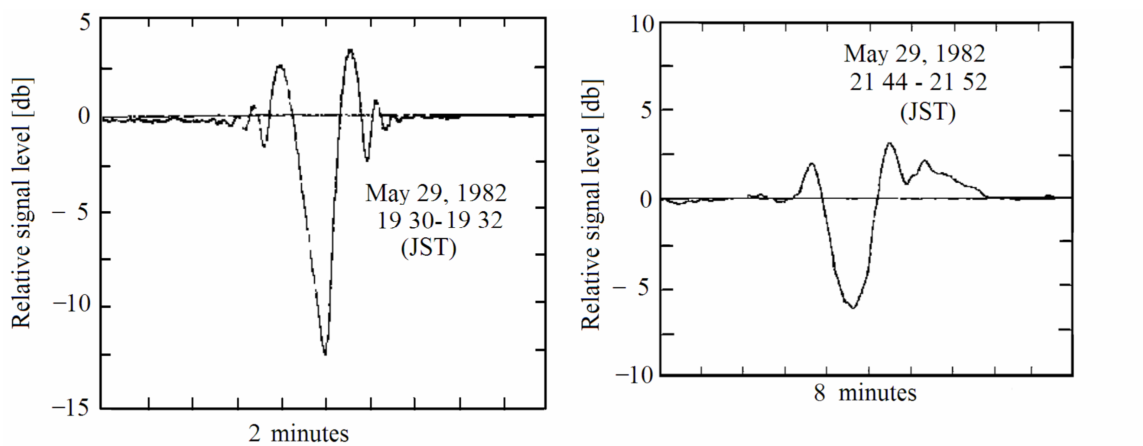

Fig. 1. Two examples of the S-type variations of the relative signal level in the trans-ionospheric communication link geostationary satellite-Earth at frequency 1.5415 GHz (Karasawa et al., 1985).

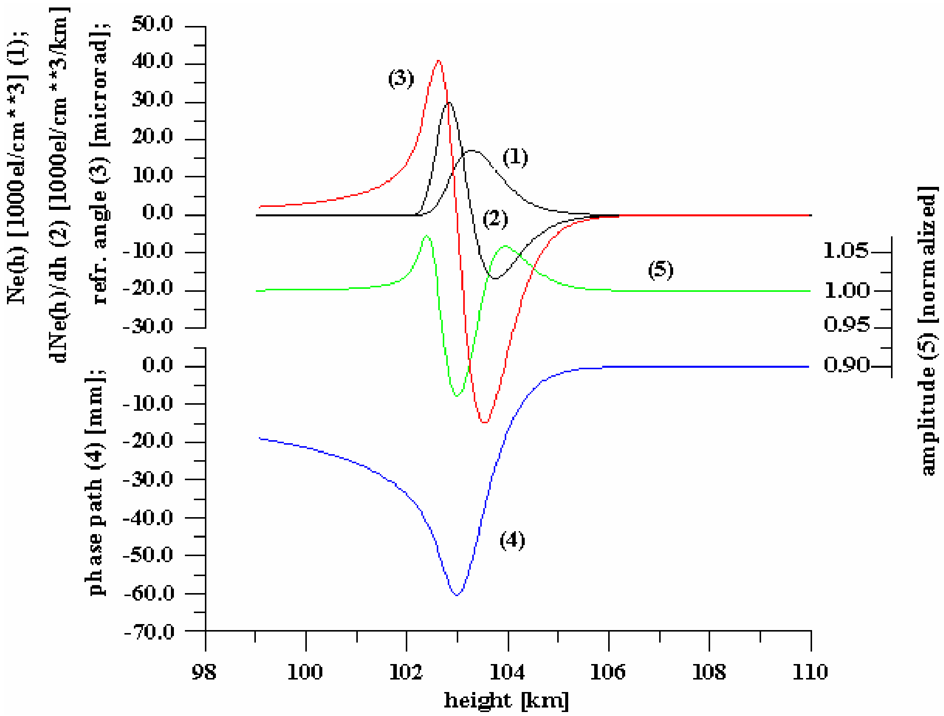

Fig. 2. Results of simulation of the ionospheric impact on RO signal as function of the altitude of the RO ray perigee by use of analytical model. Curve 1 and 2 are relevant to the altitude distribution of electron density and its vertical gradient, correspondingly. Curves 3-5 describe the altitude dependence of the bending angle, eikonal excess, and amplitude of RO signal, respectively.

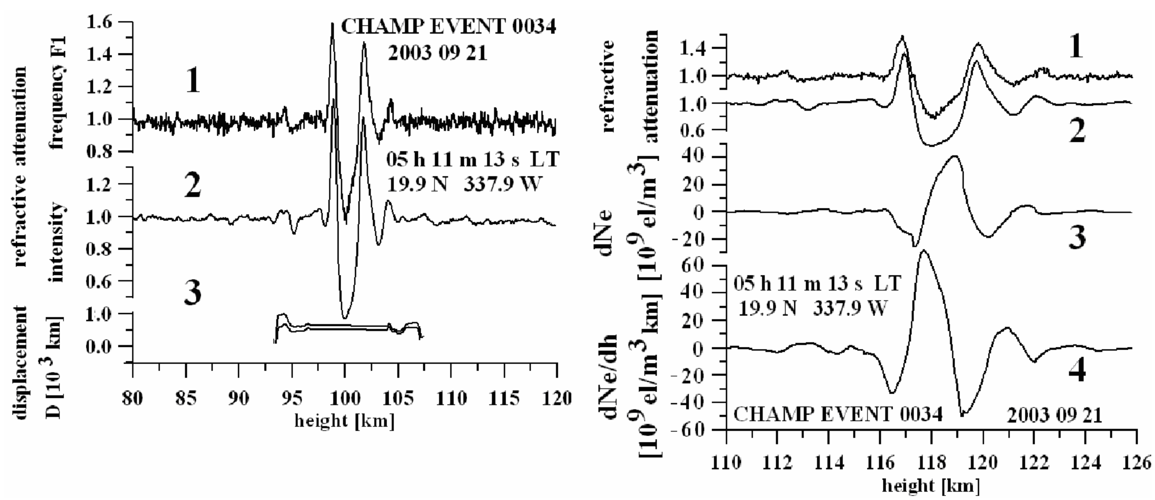

Fig. 3. Comparison of the refractive attenuation recalculated from the phase path excess data *Xp*, and refraction attenuation *Xa* found from the amplitude data at the first GPS frequency F1 (curves 1 and 2), results of estimation of distance D from RO ray perigee (curve 3) (left panel) and retrieved variations of the electron density and its gradients (curves 3 and 4) (right panel).

.

Two examples of the S-type variations of the relative signal level in the trans-ionospheric communication link geostationary satellite-Earth at frequency 1.5415 GHz (Karasawa et al., 1985) are demonstrated in Fig. 1. These examples can be compared with results of simulation of the ionospheric impact on RO signal using an analytical model of the radio waves propagation in a spherical-symmetric medium (Pavelyev et al., 1996) (Fig. 2). The height of the RO ray perigee changes nearly uniformly with time. Therefore dependence on height in Fig. 2 corresponds (in some scale) to dependence on time in Fig. 1. As follows from data in Fig. 1 and Fig. 2 there is a good coincidence of the temporal behavior of the intensity of signals in communication links satellite to Earth and satellite-to-satellite. Comparison of the refractive attenuation recalculated from the phase path excess data *Xp*, with the refractive attenuation *Xa* found from the amplitude data at the first GPS frequency F1 (curves 1 and 2) is given in Fig. 3 (left panel). Once again one can see a good correspondence between the S-type variations observed by Karasawa et al., 1985, and temporal variations of RO signal. As follows from Fig. 1 – Fig. 3 one can conclude that S-type of the amplitude scintillations observed by Karasawa et al., 1985, correspond to regular amplitude scintillations detected by analysis of GPS RO signals. Noisy type of the ionospheric impact actually coincides with S-type introduced by Karasawa et al., 1985. Instead of one C-type in the manuscript four types are considered: quiet, no clear ionospheric influence, regular isolated, similar to C-type suggested by Karasawa et al., 1985, quasi-regular wave-like structures, and diffractive events. Comparison with results obtained by Karasawa et al., 1985, will be included in the revised version.

Page 1468, Line 14: ***Previously, the RO technology has been based mainly on analyzing the phase of the electromagnetic wave after propagating through the ionosphere and atmosphere (Ware et al, 1996).***

Do the authors really know nothing about Back Propagation, Canonical Transform, Full Spectrum Inversion, Phase Matching, Wigner Distribution Function? All these methods utilize the full complex field and the use of amplitude is crucial.

The paper *Ware et al, 1996* is an excellent review of the state of RO method relevant to the 1995-1996 years. In this review there was nothing about the application of the radio-holographic or amplitude methods to GPS RO data analysis. The mainstream of the paper *Ware et al, 1996* is connected with using the phase of the high-stable synchronized by atomic clocks GPS signals to achieve high accuracy in RO measurements of temperature, pressure, electron concentration, and other parameters in the atmosphere and ionosphere.

The Back Propagation, and Canonical Transform methods have been analyzed, for example, in the paper Pavelyev et al., 2004 (see the manuscript reference list). The Back Propagation, Canonical Transform, Full Spectrum Inversion, Phase Matching methods have been analyzed, for example, in the book Liou Y.A., A.G. Pavelyev, S.S. Matyugov, O.I. Yakovlev, J. Wickert, 2010 Radio Occultation Method for Remote Sensing of the Atmosphere and Ionosphere. Edited by Y.A. Liou INTECH Published by In-The Olajnica 19/2, 32000 Vukovar, Croatia, 170 pp. 45 ill., ISBN 978-953-7619-60-2.

Analysis of the radio-holographic methods was beyond the mainstream of the manuscript because identification and location of layers were considered in the geometrical optics approximation. However in the updated version some comparison will be made.

Page 1467, Line 13: ***The amplitude of RO signal presents new potential and capability for the research of the ionosphere (Sokolovskiy, 2000, 2002; Igarashi et ah, 2000, 2001; Pavelyev et ah, 2002, 2004, 2007, 2008a, b, 2009, 2010a; Liou et al, 2002, 2003, 2005, 2007; Liou and Pavelyev, 2006).***

There are some other papers where ionosphere was investigated by using both phase and amplitude of RO signals:

V. V. Vorob'ev, A. S. Gurvich, V. Kan, S. V. Sokolovskiy, O. V. Fedorova, and A. V. Shmakov, The structure of the ionosphere from the GPS-"Microlab-l" radio occultation data: Preliminary results, Cosmic Research, 1997, No. 4, 74-83.

M. E. Gorbunov, A. S. Gurvich, and A. V. Shmakov, Back-propagation and radio-holographic methods for investigation of sporadic ionospheric E-layers from Microlab-1 data, International Journal of Remote Sensing, 2002, 23(4), 675-685. These must be mentioned too.

V. V. Vorob'ev et al. paper contains in the manuscript's reference list:

V. V. Vorob'ev, A. S. Gurvich, V. Kan, S. V. Sokolovskiy, O. V. Fedorova, and A. V. Shmakov, The structure of the ionosphere from the GPS-"Microlab-l" radio occultation data: Preliminary results, Earth Obs. Remot. Sen. 15, 609-622, 1999 (English translation of paper, published in Russian: Issledovaniya Zemli iz kosmosa, 1997, No. 4, 74-83).

This paper will be cited also in the appropriate Sections of the updated version.

The paper M. E. Gorbunov, A. S. Gurvich, and A. V. Shmakov, Back-propagation and radio-holographic methods for investigation of sporadic ionospheric E-layers from Microlab-1 data, International Journal of Remote Sensing, 2002, 23(4), 675-685. was beyond the scope of the manuscript because identification and location of layers were considered in the geometrical optics approximation. This paper will be considered in the updated version where comparison of different methods will be made.

Page 1469, Line 12: ***These examples support suggestion that there exist the inclined ionospheric layers located along the RO ray trajectory.***

In the text I don't find any argumentation in support of this statement. In what way Figure 2 supports the assumption that the ionospheric layers are inclined?

Section 1 contains only introductory remarks. Identification of inclined layers and their location can be fulfilled by use a correlation between the derivatives of the eikonal and intensity of radio waves propagating through the ionosphere. An example has been described in Section 3.

Page 1477: ***The eikonal acceleration a has been estimated numerically by double differentiation over a fixed time interval Δt. The value of Δt is equal to 0.42 s. The strongest variations of the eikonal acceleration are observed almost in the same altitude intervals as for the refractive attenuation. In this interval the eikonal acceleration and refractive attenuation variations are strongly connected and may be considered as coherent oscillations caused by layered structures. It is important that at altitudes of below 72 km and higher than 98 km the refractive attenuation variations are small and do not have any connection with changes of the eikonal acceleration (Fig. 7, right panel). This indicates different incoherent mechanism of the significant eikonal variations at the heights*** $h<72$ **km *and*** $h>98$ **km.**

Why is Δt chosen to equal 0.42 s?

This value Δ*t* is optimal compromise between diminishing the influence of high-frequency noise and remaining information on layered structures. The chosen value Δ*t* corresponds to vertical size of the Fresnel zone ~ 0.7 – 1 km in the ionosphere.

By looking at the plots in the right panel of Figure 7, I would say that amplitude variations are not well correlated with the eikonal acceleration also in the height interval 72-98 km. For example, near 72 km we see the first area of stronger amplitude fluctuations, but there is nothing special about the eikonal acceleration. Near 90 km, eikonal acceleration is slightly stronger, but again this does not correspond to the strength of the amplitude fluctuations. As to small-scale structure of the amplitude fluctuation, it is very different from that of the eikonal acceleration. But, to some extent, this should be expected, because small scale fluctuations (with scales 1 km and smaller) should be affected by diffraction, which is not described by equations (12,13) based on geometrical optics.

Figure 7 has been specially chosen to illustrate the case in which there are correlated and uncorrelated variations of the eikonal and intensity.

Page 1478, Line 18: ***The corresponding values Δh change in the 2-30 km interval. Identification of the sporadic Es layer justifies the application of the Abel transform for solving the inverse problem.***

And what about the initialization of the Abel transform at large heights? It is known that ionosphere occupies heights up to 1000 km (or even higher), its maximum is located at heights around 300-600 km. But CHAMP measurements are only available below 90-120 km.

To retrieve the refractivity or the electron concentration the Abel transform is used in the form that significantly reduce requirements to the initialization at large heights (Pavelyev, private communication, 2009). Instead of form suggested by Hocke, 1997:

$$N(p) = -\frac{1}{\pi}\int_{p}^{\infty}\frac{d\xi}{dx}\ln\left(\frac{x}{p}+\sqrt{\frac{x^2}{p^2}-1}\right)dx$$

it is useful to apply the integration on time depending on the eikonal acceleration $a(t)$

$$N(p) = -\frac{1}{\pi}\int_{t(p_s)}^{\infty}\ln\left(\frac{x}{p}+\sqrt{\frac{x^2}{p^2}-1}\right)a(t)\left(\frac{dp_s}{dt}\right)^{-1}dt,\ a(t)=\frac{d^2\Phi(p)}{dt^2}$$

where $N(p)$ is the refractivity, ξ is the bending angle, $\Phi(p)$ is the eikonal excess, p, p_s are the impact parameter relevant to the trajectory of RO signal and to the line of sight. The eikonal acceleration contains the second derivative with respect to time, so linear trend connected with influence of the upper ionosphere can be removed and one can neglect the contribution of the F-layer of the ionosphere as compared with contribution of a sharp sporadic layer (i.e. $a(t)=0$ at the altitudes greater than 120-130 km).

Page 1469, Line 24: $\Delta h = h' - h \approx 50\ km$.

In what way did the authors arrive at this estimate? Note, this repeats the statements from (Wickert et al, 2004): If the plasma layer is located in the E-region, then $\Delta h = 50\ km$. If it is located in the F-region $\Delta h = 200\ km$.But I didn't find any substantiation of these estimates in (Wickert, 2004) either. I don't understand either why (Wickert, 2004) with the same $\Delta h\,50\ km$ arrives at different estimates of δ and d. According to this paper, δ = 6° and d = 700 km. According to (Wickert, 2004), δ = 7.5° and d = 450 km. Where does this difference come from? What is the novelty of this material with respect to (Wickert, 2004) published 7 years ago? These estimations should be reconsidered in the updated version.

Conclusion of review

The declared goal (i) is not achieved as explained above. On the other hand, the description of task (i) lacks novelty, because this material was published 7 years ago in (Wickert, 2004). The model (ii) is derived, but it is not clear in what way it is used in this paper. In Section 4 I don't see any references to equations (4-11) describing the model.

So parts (i) and (ii) can be excluded. As to (iii), its description should be enlarged and more details about the electron density retrieval from CHAMP data must be provided.

Wickert et al., 2004, introduced hypothesis that the inclined plasma layers in the ionosphere can be a source of sporadic amplitude scintillations in the 40 - 90 km height interval of the RO ray perigee and introduced some evidences in support of this suggestion. The connection between the eikonal derivatives with respect to time and intensity was not used in this paper for identification and localization of layers.

In the revised version of paper more details will be presented with aim to make clear the current state of problem.