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Location of layered structures in the ionosphere and atmosphere by use of GPS occultation data

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Abstract

A method is introduced to locate the layered structures in the atmosphere and ionosphere based on simultaneous observations of radio wave intensity and phase variations in trans-ionospheric satellite-to-satellite links. The method determines location of a tangent point on the trans-ionospheric ray trajectory where gradient of refractivity is perpendicular to the ray trajectory and influence of a layered structure on radio wave parameters is maximal. An estimate of the location of a layer can be obtained from a combination of the phase and intensity variations. This new technique was applied to measurements provided during FORMOSAT-3 and CHAMP radio occultation (RO) missions. For the considered RO events the location of the inclined plasma layer in the lower ionosphere is found and the electron density distribution is retrieved. The method is checked by measuring the location of the tangent point on the ray trajectory in the neutral gas in the atmosphere. The results showed a fairly good agreement.

Keywords: Radio-holography; Ionosphere; Atmosphere; GPS occultation; Internal waves

1. Introduction

RO experiments carried out by use of coherent signals emitted by the Global Positioning navigational System (GPS) provide many possibilities to deduce the physical properties of the atmosphere and ionosphere (Kursinski et al., 1997). Of particular importance are new ways to investigate location of the layered plasma structures in the ionosphere. This paper describes for the first time those specific characteristics of the phase and intensity variations, which provide an independent technique for estimating the location of layered structures in the ionosphere. It is a cornerstone of RO experiments that the GPS RO technique is based on an implicit assumption of global spherical symmetry of the atmosphere and ionosphere with a centre, which nearly coincides with the centre of the Earth. In this case the location of layered structure is assumed at the ray trajectory perigee (Hajj et al., 2002). The horizontal gradients of the refractivity produced by inclined plasma layers in the ionosphere can change the location of the centre of spherical symmetry (Sokolovskiy et al., 2002; Wickert et al., 2004), and one can observe significant variations of the amplitude and phase of RO signals in the 40–80 km height interval of the ray perigee, in which the expected contributions from the neutral gas or the electron density in the RO signal changes are negligible. Previously

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(Gorbunov et al., 2002; Sokolovskiy et al., 2002) proposed a radio-holographic back-propagation method to locate plasma irregularities in the ionosphere. In this paper we introduce a simpler approach, which can be used to find location and estimate parameters of inclined plasma layers in the ionosphere.

2. Main relationships and analysis of the experimental data

The scheme of the GPS radio occultation (RO) experiment in trans-ionospheric satellite-to-satellite link is shown in Fig. 1. Point O is the centre of spherical symmetry of the Earth's atmosphere. Radio waves emitted by a GPS satellite (point G) arrive at a receiver on board the LEO satellite (point L) along the ray GTL, where T is the ray perigee. At point T, the ray's distance from the Earth's surface h is minimal and the gradient of refractivity $N(h)$ is perpendicular to the ray trajectory GTL (Fig. 1). The projection of point T on the Earth's surface determines the geographical coordinates of the RO region. Records of the RO signal along the LEO trajectory at two GPS frequencies $f_1 = 1575.42$ MHz and $f_2 = 1227.6$ MHz are radio holograms, which contain the amplitudes $A_1(t)$ and $A_2(t)$, respectively, along the phase path excesses $\Phi_1(t)$ and $\Phi_2(t)$ of the radio field as functions of time. The vertical velocity of the occultation beam path $v_\perp$ is about of 2 km/s. This value of $v_\perp$ is many times greater than those corresponding to motion of layers in the ionosphere and atmosphere. Therefore the RO data are, in essence, instantaneous 1-D radio holograms of the ionosphere and atmosphere.

In the case of global spherical symmetry of the ionosphere and atmosphere there are simple relations between the phase path excess $\Phi(p)$ and the refraction attenuation of radio waves $X(p)$ (Pavelyev et al., 2004; Liou et al., 2005)

$$\Phi(p) = L(p) + \kappa(p) - R_0, \tag{1}$$

$$X(p) = pR_0^2[R_1R_2d_1d_2 \sin\theta \mid \partial\theta/\partial p \mid]^{-1}, \tag{2}$$

$$\partial\theta/\partial p = \mathrm{d}\xi/\mathrm{d}p - (1/d_1 + 1/d_2), \tag{3}$$

$$L(p) = d_1 + d_2 + \xi(p)p, \tag{4}$$

where $\kappa(p)$ is the main refractivity part of the phase path excess, $\xi(p) = -\mathrm{d}\kappa(p)/\mathrm{d}p$ is the refraction angle, $\theta(p)$ is

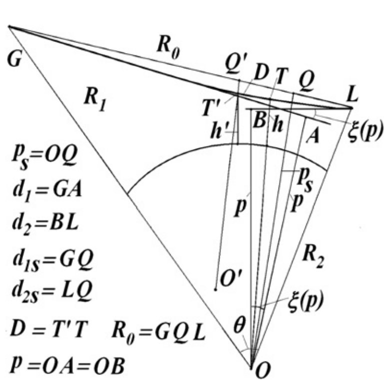

Fig. 1. Scheme of trans-ionospheric link satellite-to-satellite.

the central angle, p, p_s are the impact parameters of the ray trajectory GTL, and line of sight GQL, respectively, R_0, R_1, R_2 are the distances GQL, OG, and OL, respectively, and L(p) is the distance GABL, which is the sum of two short lengths d_1 (GA), d_2 (BL), and the term $\xi(p)p$. The module of the term $\xi(p)p$ is equal to the arc AB (Fig. 1). In the case of the ionosphere the refraction index is less than unity, the ray trajectory is bended upward (or concave) and the refraction angle and contribution of the term $\xi(p)p$ to the distance GABL is negative. Fig. 1 corresponds to the ionospheric case. In the case of the neutral atmosphere the refraction index is greater than unity, the ray trajectory is bended downward (or convex) and the refraction angle and contribution of the term $\xi(p)p$ to the distance GABL is positive. In both cases Eqs. (1)–(4) have the same form and results of our analysis do not depend on the type of refraction (ionospheric or atmospheric) and also are independent on the GPS ray path curvature. Note that the distance d_2 is nearly equal to the distance TL because the absolute value of the refraction angle $\xi(p)$ is small as compared with unity. There exists a possibility to find d_2 by combination of the second temporal derivative of the phase path excess $\Phi(p)$ and $X(p)$. Under condition $|p-p_s| \ll p_s$ the first derivative of the phase path excess $\Phi(p)$ on time t (Doppler frequency F_d) has a form:

$$\mathrm{d}\Phi(p)/\mathrm{d}t = F_d \approx -(p - p_s)\mathrm{d}p_s/\mathrm{d}t(1/d_{1s} + 1/d_{2s}), \tag{5}$$

where d_{1s}, d_{2s} are the distances GD and DL, respectively (Fig. 1). As shown by Pavelyev et al. (2007), the second derivative of the phase path excess $\Phi(p)$ can be evaluated by differentiation from (5):

$$1 - X(t) = ma, \tag{6}$$

$$a = \mathrm{d}F_d(t)/\mathrm{d}t \tag{7}$$

$$m = q/(\mathrm{d}p_s/\mathrm{d}t)^2, \tag{8}$$

$$q = d_{1s}d_{2s}/R_{0,}, \tag{9}$$

Formula (6) connects the refraction attenuation $X(t)$ and the phase acceleration $a = \mathrm{d}^2\Phi(t)/\mathrm{d}t^2$ variations via relationship similar to classical dynamics equation. Eqs. (6) and (7) indicate equivalence between the variations of the phase path excess acceleration a, derivative of the Doppler frequency $F_d(t)$, and refraction attenuation $X(t)$. Usually during the RO experiments parameters m and $\mathrm{d}p_s/\mathrm{d}t$ are known from the orbital data because the location of the spherical symmetry centre O and its projection on the line of sight – point Q are known, and the distance GT d_1 and TL d_2 can be easily estimated as $d_{1,2} = (R_{1,2}^2 - p^2)^{1/2}$ (Fig. 1). Therefore, Eq. (6) give a possibility to recalculate the phase acceleration a and/or Doppler frequency F_d to the refraction attenuation X_p. This is useful for estimation of the absorption in the atmosphere. The refraction attenuation X_a is determined from the amplitude data as a ratio of intensity of radio signal propagating through the atmosphere $I_a(t)$ to its intensity in free space I_s:

$$X_a(t) = I_a(t)/I_s \tag{10}$$

The experimental value X_a is the sum of the refractive and absorption contributions. However, the phase acceleration depends on the refraction effect only. This gives a possibility to determine the absorption in the atmosphere $Y(t)$ as a ratio:

$$Y(t) = X_a(t)/(1 - ma), \quad or\ Y(t) = X_a(t)/(1 - m\mathrm{d}F_d(t)/\mathrm{d}t). \tag{11}$$

Eq. (11) allows removing the refraction attenuation effect from the amplitude data. Parameter $\mathrm{d}p_s/\mathrm{d}t$ can be found from trajectory data, describing the motions of the GPS and LEO satellites relative to the centre of spherical symmetry – point O (Fig. 1):

$$\mathrm{d}p_s/\mathrm{d}t = v + (w - v)d_{1s}/R_0, \tag{12}$$

where v, w are the velocity components of the GPS and LEO satellites, respectively, which are perpendicular to the straight line GL in the plane GOL. The components v, w are positive when oriented in direction to the point O and are negative in the opposite case. Eqs. (6)–(9), and (12) give a way to find the distance LT d_{2s} from simultaneous observation of the phase and intensity variations:

$$d_{2s} = 2mw^2[1 + 2\beta(v/w - 1) + (1 - 4\beta\ v/w)^{1/2}]^{-1},$$
$$\beta = mw^2/R_0. \tag{13}$$

Therefore, if the magnitude of parameter m will be estimated from the experimental data, it is possible to find the new value of distance T′L d_2' and thus to determine the location of the new tangent point T′ relative to the point T (or L). For the determination of parameter m from the experimental data, we can assume that the value m is a slowly changing function of time. If the noise is very small, the averaging is not necessary and parameter m can be determined directly from Eq. (6) as a ratio:

$$m = [1 - X(t)]/a. \tag{14}$$

In the presence of noise, the value $m(t_k)$ corresponding to some instant of time t_k can be determined by two ways: from a correlation relationship

$$m(t_k) = -\sum_{i=k-M}^{i=k+M}[X(t_i) - 1]\ a(t_i)\Big/\sum_{i=k-M}^{i=k+M}[a(t_i)]^2. \tag{15}$$

or from the RO data as a ratio of average of the squared refraction attenuation and phase acceleration variations:

$$m(t_k) = \Big\{\sum_{i=k-M}^{i=k+M}[X(t_i) - 1]^2 \Big/ \sum_{i=k-M}^{i=k+M}[a(t_i)]^2\Big\}^{1/2}, \tag{16}$$

where $2M$ is a number of samples for averaging, and $X(t_i)$, $a(t_i)$ are the current values of the refraction attenuation and phase acceleration variations, respectively, at the time instant t_i. Eqs. (15) and (16) give different estimations for the parameter m, respectively. Then, by use of Eq. (13), one can estimate the displacement $D = d_2' - d_2 = d_2' - (R_2^2 - p^2)^{1/2}$. In the case of full correlation between the refraction attenuation and phase acceleration, the influence of the layered structures prevails, the magnitudes of the parameter m and displacement D can be evaluated exactly.

Below examples of application of suggested method is given by use of FORMOSAT-3 RO events. A preliminary description of the FORMOSAT-3 mission is given by Liou et al. (2007). An example of determination of the displacement D is shown in Fig. 2. The data shown in Fig. 2 correspond to the FORMOSAT-3 RO event 0106, April 23, 2006, 04 h 11 min LT, with geographical coordinates 11.1 N 310.7 W. Curves 1 and 2 in Fig. 2, left panel, demonstrate significant correspondence between the refraction attenuations X_p and X_a evaluated from the phase acceleration and amplitude data (Eqs. (6) and (10), respectively) at the first GPS frequency f_1. This correspondence allows one to determine the horizontal displacement of the tangent point T D. The results of evaluation of the displacement D by use of Eqs. (13), (15), and (16) are shown in Fig. 2, right panel. Curves 1 and 2 correspond to the values D found by use of the relationships (13), (15); and (13), (16), respectively. According to Fig. 2 (right panel) the displacement D estimated from Eqs. (15) and (16) is bounded between ±25 km in the 10–16 km altitude interval and between ±50 km in the 16–35 km height interval. This experimental result opens a possibility to apply suggested method for location of the layered structures in the atmosphere.

Two examples of layered structures in sporadic Es layers are given in Figs. 3 and 4 for FORMOSAT-3 RO events 0081 (April 29, 2006, 13 h 21 min LT, geographical coordinates 48.0 N 107.8 W) and 0094 (April 22, 2006, 17 h 28 min LT, geographical coordinates 50.2 S 40.3 E). The refraction attenuations calculated from phase acceleration X_p and intensity variations X_a in the 80–115 km and 80–105 km height interval are shown in Figs. 3 and 4, respectively (curves 1 and 2, left panel). The phase acceleration a has been estimated numerically with fixed value of time interval Δt for double differentiation. The value of Δt was equal to 0.42 s. As a result of double differentiation the high frequency noise level increases. This effect is seen in Figs. 3 and 4 (left panel) from comparison of the refraction attenuations calculated from amplitude and phase data (curves 1 and 2, respectively). The results of determination of the deflection d of point T are shown by curve 3 in Figs. 3 and 4 (left panel). Value d has been estimated from Eqs. (13) and (15) by using of averaging in the 1.5 s time interval. In Fig. 3 (left panel) the distance d changes from 640 km up to 540 km with statistical error ±100 km and average value $d_a = 590$ km. In Fig. 4 (left panel) the distance d oscillates between 440 km and 690 km with statistical error ±170 km and average value $d_a = 620$ km. This indicates the ionospheric origin of the intensity variations shown in Figs. 3 and 4 (left panel). It is possible to find the actual height h' (T′) and the inclination δ of a plasma layer in the ionosphere from results of determination of distance D by use of the relationships introduced previously (Wickert et al., 2004):

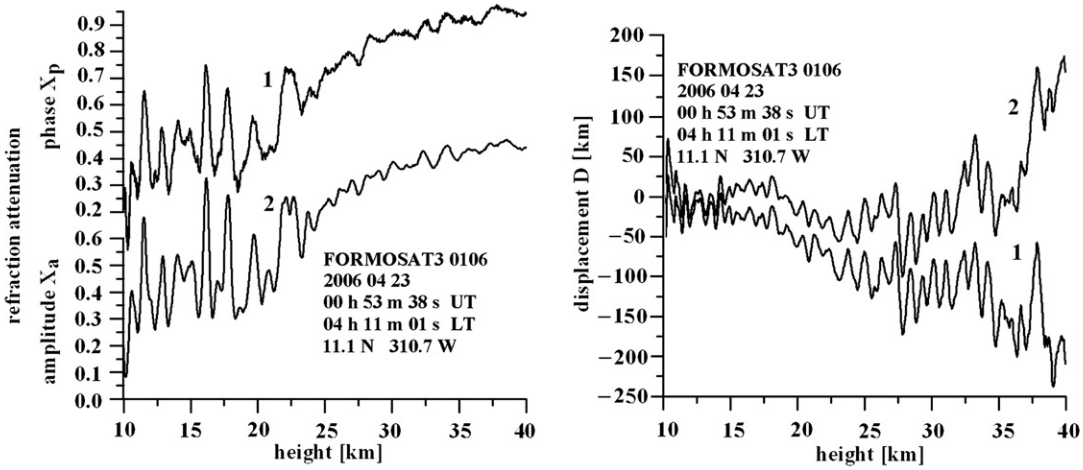

Fig. 2. (Left panel) Comparison of the refraction attenuations X_a and X_p calculated from the phase (curve 1) and amplitude (curve 2) data. (Right panel) Displacement of the tangent point T D calculated by use of Eqs. (15) and (16) (curves 1 and 2, respectively).

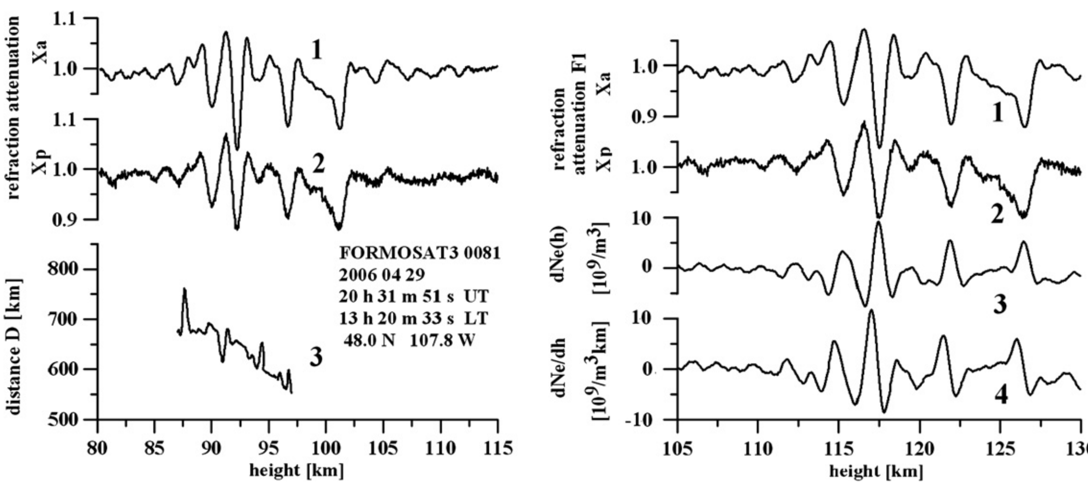

Fig. 3. (Left panel) The refraction attenuations X_a and X_p evaluated from the amplitude and phase data and results of the distance estimation D from combined analysis of the phase and amplitude variations. (Right panel) The refraction attenuations X_a and X_p (curves 1 and 2) and retrieved variations of the electron density d$Ne(h')$, and its vertical gradient d$\delta Ne(h')$/dh' (curves 3 and 4, respectively) as functions of real height of sporadic Es layer.

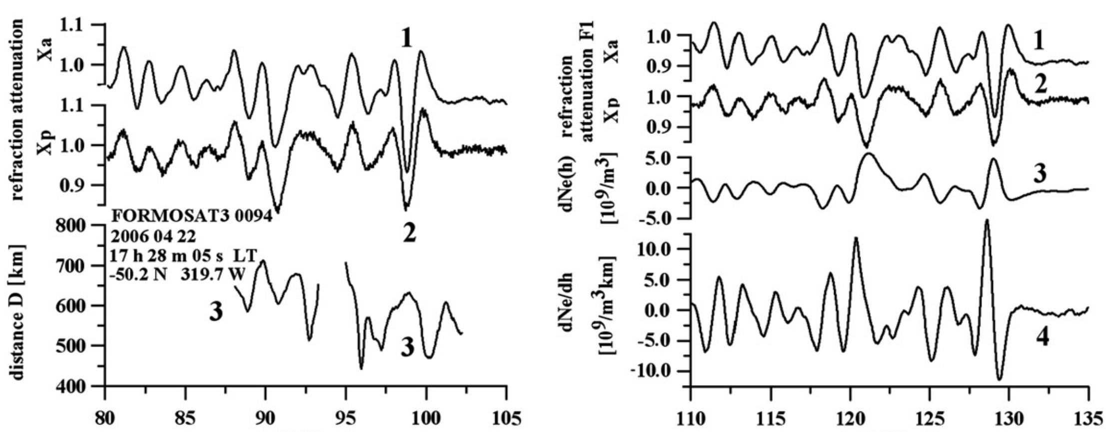

Fig. 4. The same as in Fig. 3 for FORMOSAT-3 RO event 0094.

$$h'(T') = h + D^2/2r_0, \quad (17)$$

$$\delta = D/r_0, \quad (18)$$

where r_0 is the Earth radius, and h is the height of the ray perigee. For data shown in Figs. 3 and 4 (left panel) the real height of the sporadic Es layer is greater than the height of the ray perigee h by 27.1 km, and 30.0 km, respectively, with average inclination about of 5.3°. The positive values D correspond to the displacement along the ray GTL from the ray perigee T to the GPS satellite. After estimation of the average height and the distance D one can apply the Abel transform to obtain the variations in the electron density $\delta Ne(h')$, and its vertical gradient $d\delta Ne(h')/dh'$. The refraction attenuations Xa and Xp and the results of restoration of $\delta Ne(h')$, and $d\delta Ne(h')/dh'$ are shown in Figs. 3 and 4 (right panels) as functions of estimated actual height h' of the tangent point T′ (curve 1 and curve 2; curve 3 and curve 4, respectively). As followed from Figs. 3 and 4, the variations of the electron density and its vertical gradients have wave-like character and are concentrated in the intervals $\pm 4 \times 10^9$ [el/m^3], $\pm 8 \times 10^9$ [el/(km m^3)]; and $\pm 2 \times 10^9$ [el/m^3], $\pm 6 \times 10^9$ el/(km m^3)] (curves 3 and 4 in Figs. 3 and 4, right panels) for events 0081 and 0094, respectively. As appears these values are typical for wave-like structures in sporadic Es layers (Igarashi et al., 2002; Wu et al., 2005). The provided analysis has a preliminary nature, however it reveals a possibility to establish in some cases the real location, height, and inclination of sporadic Es structures in the ionosphere by use of a single RO vertical profile.

3. Conclusions

As demonstrated above the new phase acceleration (Doppler frequency)/intensity ratio technique appears to provide a new method to locate layered structures in the ionosphere. This method is validated by use of FORMOSAT-3 RO data. Recent GPS/MET, and up-to-date CHAMP, SAC-C, GRACE, FORMOSAT-3 RO missions provide a growing data base for determining the location and estimation of the electron density distribution in the layered plasma structures in the ionosphere. Comparison with ionosondes data is desirable for further derivation and revealing the boundary of application of the suggested method. The application of this and other new techniques will generate a more extensive body of information on plasma structures and natural processes in the ionosphere and their connection with processes in magnetosphere and in interplanetary space.

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