Simultaneous observation of the vertical gradients of refractivity in the atmosphere and electron density in the lower ionosphere by radio occultation amplitude method

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[1] It is shown that the refractivity and temperature vertical gradients may be retrieved using radio occultation (RO) amplitude data only. For the considered RO events the vertical gradient of refractivity found from the amplitude data shows good correspondence at two frequencies and changes in interval ±2−±5 N-units/km (between heights 5–10 km) up to ±1−±2 N-units/km (between heights 12–21 km). The corresponding magnitudes of temperature gradient change from negative values 4– 9°K/km at the height 8–14 km to positive 1–3 °K/km above 20.5 km. Sharp changes of temperature gradient ±6−±9 °K/km are found in the tropopause at the heights between 14–20 km. The height of the equatorial tropopause is found to be equal 16.8 km in correspondence with UCAR data. The vertical gradient of electron density in the sporadic E-layer of the ionosphere has been retrieved from the same RO event. Two maximum values of the positive gradient of about $29 \cdot 10^9$ and $28 \cdot 10^9$ [$m^{-3}km^{-1}$] are located at heights 93.5 and 99 km. Simultaneous observations of the vertical gradients of refractivity in the atmosphere and ionosphere would be useful to investigate connections between meteorological and space weather phenomena. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0689 Electromagnetics: Wave propagation (4275); 1640 Global Change: Remote sensing; 2427 Ionosphere: Ionosphere/atmosphere interactions (0335). **Citation:** Liou, Y. A., A. G. Pavelyev, C. Y. Huang,, K. Igarashi, and K. Hocke, Simultaneous observation of the vertical gradients of refractivity in the atmosphere and electron density in the lower ionosphere by radio occultation amplitude method, *Geophys. Res. Lett.*, *29*(0), XXXX, doi:10.1029/2002GL015155, 2002.

1. Introduction

[2] Practical testing of the RO method began in 1989 using telecommunication line between the orbital station "MIR" and geo-stationary satellites (MIR/GEO) at wavelengths of 2 and 32 cm [*Yakovlev et al.*, 1995]. A satellite known as "Microlab-1" was launched into Low Earth Orbit (LEO) for the RO GPS/MET experiments with high-precision GPS radio navigational signals in the two coherent frequency bands F1 = 1575.42 MHz and F2 = 1227.6 MHz. Since mid-1995 many thousands of refractive index, temperature, density and pressure profiles of the atmosphere, distributed over both land and ocean areas, from 1 to 40 km or more altitude were determined [*Ware et al.*, 1996; *Kursinski et al.*, 1997; *Rocken et al.*, 1997; *Feng and Herman*, 1999]. Electron density distribution was also obtained in different areas of the Earth's ionosphere, mainly in the F-layer region [*Schreiner et al.*, 1999; *Hajj and Romans*, 1998; *Vorob'ev et al.*, 1999]. However these experiments revealed a new problem: high precision of radio navigational fields requires more accurate and effective scientific methodology to infer atmospheric, mesospheric and ionospheric parameters. Usually only phase data are used to retrieve vertical profiles of the refraction index, temperature in the atmosphere and electron density in the ionosphere. The radio holographic approach has been proposed to improve the vertical resolution and accuracy of the RO method by analysis of both amplitude and phase data of the RO signals [*Pavelyev*, 1998; *Hocke et al.*, 1999; *Igarashi et al.*, 2000, 2001]. *Igarashi et al.* [2001] demonstrated high vertical resolution of the radio holographic method (of about 70 m) through retrieval of weak signals reflected from the sea surface in GPS/MET RO data. They presented also first results to measure vertical gradients of electron density in the lower ionosphere using amplitudes of GPS pseudoranges signals at F1, F2. The aim of this paper is to present preliminary results of measuring the vertical gradients of the refractive index in the atmosphere and electron density in the lower ionosphere through analysis of the amplitude data of the RO signals.

2. Data Analysis

[3] The scheme of the RO experiment is shown in Figure 1. The terrestrial atmosphere is modeled locally as spherically symmetrical, with a local center of curvature at O. One of the "ray paths" followed by radio signals propagating from GPS to LEO satellites (points G and T, respectively) lies in the plane of Figure 1. This plane also contains the point O. The ray has impact parameter p and corresponding refraction angle $\xi(p)$. In the case of single ray propagation, the amplitude and phase of RO signal may be considered as two independent information channels of radio holograms at frequencies F1 and F2. The phase channel is more sensitive to vertical distribution of the refractivity and may be used for estimation of the Doppler frequency displacement F_d [e.g. *Liou and Huang*, 2002]

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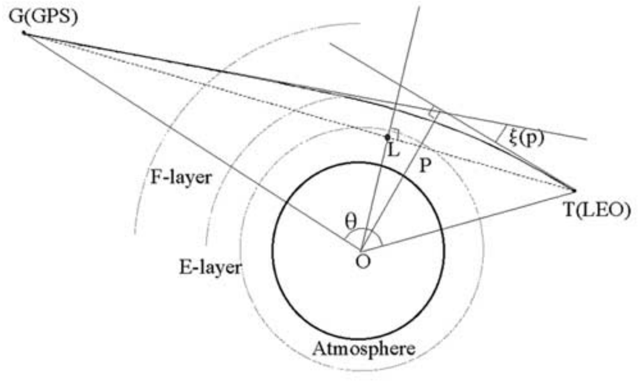

Figure 1. Setup of GPS/MET radiooccultation experiment.

relative to free space propagation and then for evaluating the impact parameter of the main ray p (Figure 1)

$$p - p_s = F_d\lambda/(d\theta/dt)_s \quad F_d = \lambda^{-1}dS/dt \tag{1}$$

where λ is the wavelength, S is the phase excess path of RO signal, p_s is the impact parameter corresponding to propagation in free space along straight line TLG (Figure 1), R_T, R_g are the distances TO and GO, and θ is the angle between directions TO and GO at the point O. The refraction angle ξ(p) may be evaluated using Figure 1

$$\xi = \sin^{-1}(p/R_g) + \sin^{-1}(p/R_T) - \sin^{-1}(p_s/R_g) - \sin^{-1}(p_s/R_T). \tag{2}$$

Taylor expansion of the right part (2) gives ξ(p) as function of $p - p_s$. Abel's transform may be applied to find vertical distribution of the refractivity N(h) [*Hocke*, 1997]

$$\ln[n(h)] = 1/\pi\int_p^\infty d\xi(x)\ln\left[x/p + \left(x^2/p^2 - 1\right)^{1/2}\right], \quad n(h) = 1 + N(h) \tag{3}$$

Equations (1)–(3) give the refractivity N(h) = n(h) − 1 and height h from phase part of radio hologram S(t) and orbital data, which are described by the functions of time θ, p_s, R_T, and R_g. The amplitude variations in amplitude channel of radio hologram may be used separately for obtaining vertical distribution of the vertical gradient of the refractivity. According to *Pavelyev and Kucherjavenkov* [1978], *Pavelyev et al.* [1986], the impact parameter p may be found from equation:

$$p(t) - p(t_o) = \int_{t_o}^{t} dt\ X[t(p_s)]dp_s/dt \tag{4}$$

where X is the power attenuation relative to free space owing to refraction effect. Equation (4) describes connection between derivatives dp/dt and dp_s/dt and allows finding the temporal dependence of the impact parameter p(t) from amplitude data if an initial condition is given. The power attenuation X(t) is connected with derivative of the Mrefraction angle on impact parameter dξ/dp

$$d\xi/dp = [1 - 1/X(t)]B(p_s)\,;\ B(p) = \left(R_T^2 - p^2\right)^{-1/2} + \left(R_g^2 - p^2\right)^{-1/2}. \tag{5}$$

Temporal dependencies p(t), ξ(t), and dξ/dp(t) may be used to find the vertical distribution of dN(h)/dh

$$J(p) = 1/\pi\int_p^\infty d\xi_x'(x)\left(x^2 - p^2\right)^{1/2};\ N_h' = -n^2(h)J(p)/\left\{p[1 + J(p)]\right\}; \tag{6}$$

As shown by *Pavelyev et al.* [2001] the amplitude information may be used for retrieving vertical gradient of temperature in the atmosphere and electron density in the mesosphere.

3. Vertical gradients in the atmosphere and lower ionosphere

[4] The amplitude variations at two frequencies are shown in Figure 2 for RO event 0583 (curves A1, A2). Occultation event No. 0583 took place in the northern equatorial part of the Pacific Ocean in the middle of daytime. The time-spatial coordinate of the main ray's minimal

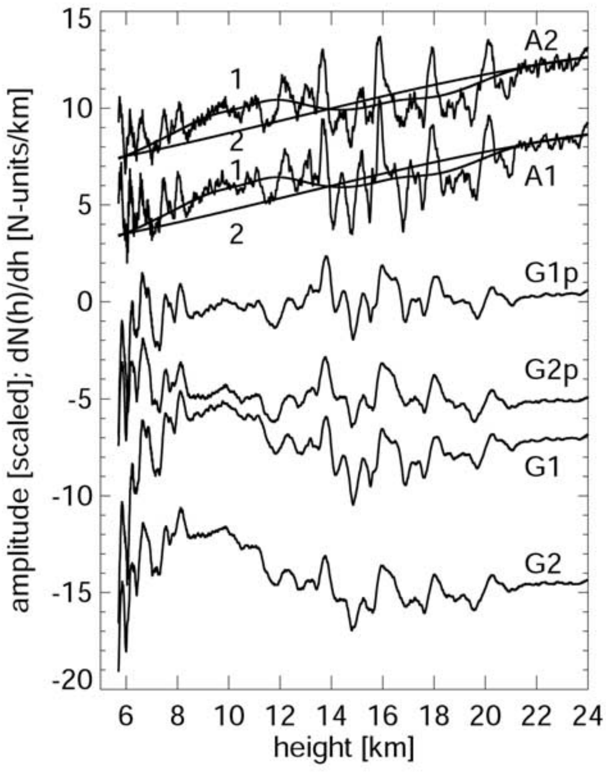

Figure 2. Vertical gradients of the refractivity G1, G2, displaced below for comparison by 8 and 15 N-units/km. Smooth curves 1, 2 indicate approximations of the amplitude data following to equatorial (1) and standard (2) atmosphere.

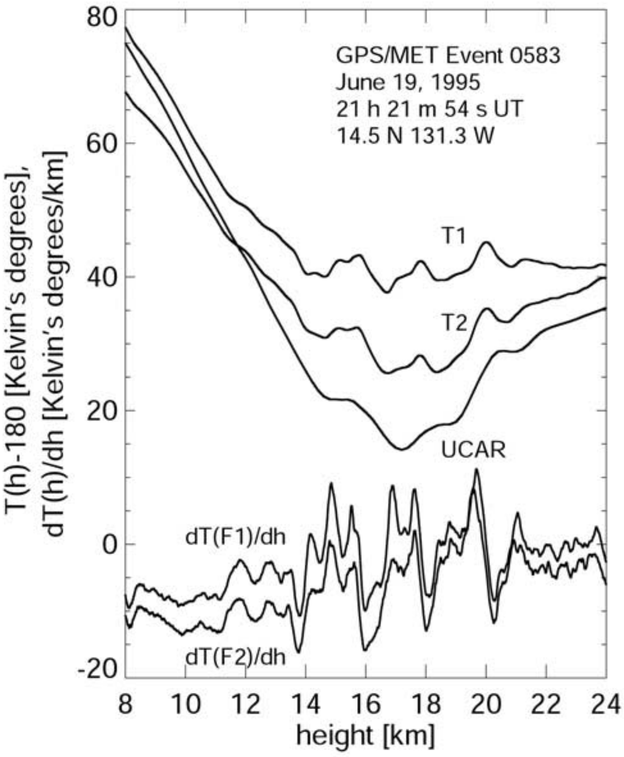

Figure 3. Vertical profiles of temperature and its gradient.

height h was close to 14.5°N 131.3°W, 21 h 21 m 54 s UT. The amplitude variations shown in Figure 2 are scaled by factor 10 and displaced for comparison. Amplitude variations are intense in the height interval 5–8 km and 12–21 km. Above the tropopause, the amplitude variations are smaller. Curves G1, G2 in Figure 2 show the retrieved vertical gradients variations in the troposphere. For convenience curves G1, G2 indicate difference between measured gradient and the standard gradient height dependence dN(h)/dh = −42 exp(−h/8) N-units/km used for calculating curve 2 in Figure 2. Curves G1p, G2p in Figure 2 show perturbed part of the vertical gradient corresponding to deflection of the amplitude data from curve 1. Curve G2p is displaced by 5 N-units/km. At the height levels between 5–11 km variations of the vertical gradient of refractivity are of about ±2.5 N-units/km. In the tropopause area (heights between 14–21 km) the variations of vertical gradient dN/dh are about ±1–±2 N-units/km. Features in the vertical gradient distribution correspond to height positions of the amplitude variations. Vertical gradients of the refractivity may be recalculated to find vertical temperature gradients by the method described by *Pavelyev et al.* [2001]. Results of restoration of the temperature profile T(h) and its gradient are shown in Figure 3. Curves T1, T2 and UCAR correspond to temperatures retrieved from amplitudes of RO signals at frequencies F1, F2 and UCAR data. Curves T1, T2 and UCAR are displaced by 180 °K. Curves dT(F1)/dh, dT(F2)/dh (displaced by 5 units) show variations in the vertical gradient of temperature expressed in °K/km. The main temperature minimum is observed at the height of about 16.8 km. This position of the tropopause corresponds to results of retrieving the temperature profile published by UCAR for considered RO event. Positive values of dT(h)/dh are seen in the tropopause region at levels 15, 17, 19.5 km. Negative values of dT(h)/dh ∼7...9 °K/km are observed at levels 13, 16, 18 and 20.3 km. The features in the vertical gradient distribution may correspond to wave structure in the tropopause with vertical periods of about 2–3 km.

[5] The amplitude and phase components of radio holograms of the E-region of the ionosphere that correspond to the same GPS/MET occultation event (June 19, 1995, No. 0583) are shown in Figure 4. Curves F1, F2 in Figure 4 demonstrate the experimental phase excess variations at the first and the second frequency F1, F2 (scaled by factor 5) as functions of height. The upper ionosphere usually produces slow trend in the phase data and does not introduce essential changes in the amplitude of RO signals. In the case of quiet ionosphere the phase trend may be subtracted from the phase excess data by using the IRI-95 F-layer model [*Bilitza*, 2001] for time and region of radio occultation region as shown by *Igarashi et al.* [2001]. The variations in amplitude (top pair of curves in Figure 4) are strongly correlated. The phase excess connected with sporadic E-layer structures changes in the interval ±5 cm, with a random noise contribution of about ±1 mm. In the amplitude data two sporadic E-layer structures can also be seen at the heights 94 and 99 km. Analysis of Figure 4 indicates that the amplitude data are sensitive to high spatial frequency components in the refractivity. Results of the restoration of the vertical electron density profile $N_e(h)$ and its gradient $dN_e(h)/dh$ are shown in Figure 5, curves 1, 2 respectively. Curve 2 is displaced by $30 \cdot 10^9$ [$m^{-3}km^{-1}$] for comparison with curve 1. Two maximum values of the positive gradient of about $29 \cdot 10^9$ and $28 \cdot 10^9$ [$m^{-3}km^{-1}$] are located at heights 93.5 and 100

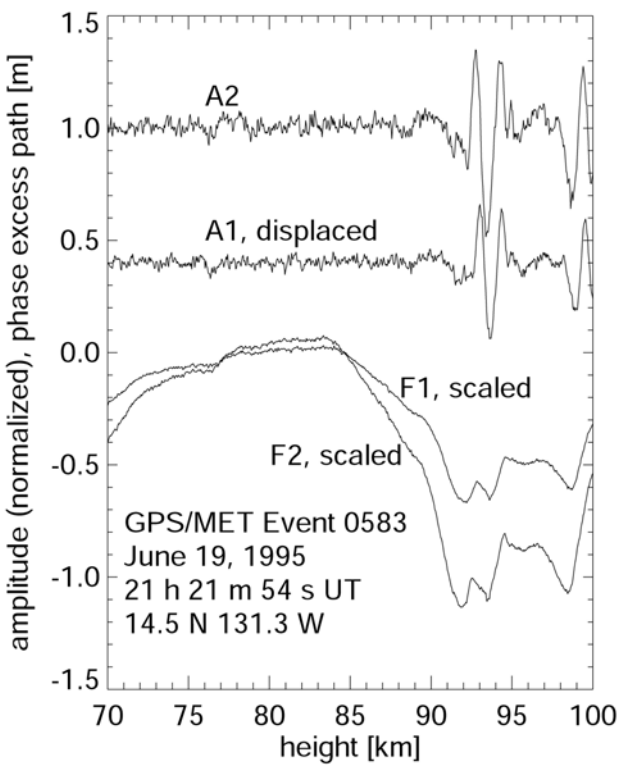

Figure 4. Phase and amplitude part of radio holograms.

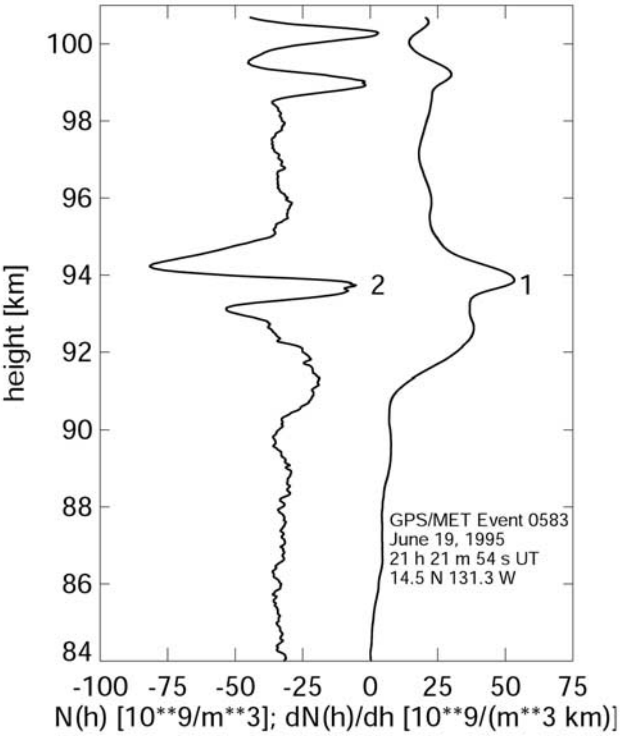

Figure 5. Vertical profiles of the electron density (1) and its gradient (2). Curve 2 is displaced by 25 units.

km (curve 2 in Figure 5). The electron density vertical distribution (curve 1 in Figure 5) coincides with its gradient (curve 2) showing features at 94 and 100 km with maximums $50{\cdot}10^9$ [m^{-3}] and $25{\cdot}10^9$ [m^{-3}]. As follows from Figure 5 analysis of information containing in amplitude channels of RO signal can indicate detailed picture of vertical gradient distribution in the lower ionosphere.

4. Conclusion

[6] It is shown that amplitude channel of RO signals may be used independently from phase channel for detailed retrieving the vertical profiles of the refractivity gradient in the atmosphere and electron density in the ionosphere. Radio occultation method of retrieving vertical profile of $dN_e(h)/dh$ is important because Earth-based tools usually give only the vertical profile $N_e(h)$ up to its maximum. The form of this profile above maximum is not available for most Earth-based observational means. Observation of the vertical temperature gradient in the atmosphere and electron density in the mesosphere are useful for revealing interactions of internal waves in the stratosphere and lower ionosphere. This opens new perspectives for simultaneous monitoring of natural processes in the atmosphere and lower ionosphere by radio occultation method.

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