GENERALIZATION OF RADIOHOLOGRAPHIC METHOD FOR STUDY THE IONOSPHERE, TROPOSPHERE AND TERRESTRIAL SURFACE FROM SPACE

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ABSTRACT

Generalization of radio holographic method for 3-dimensional case is presented. Application of this method to analysis of radio occultation data gives high vertical resolution and accuracy in estimating physical parameters of the ionosphere and atmosphere and allows recovering vertical temperature gradients and wave structures in the atmosphere and in the ionosphere.

INTRODUCTION

Practical testing of radio occultation (RO) method demonstrated its efficacy for investigation of the atmosphere and ionosphere with the GPS receiver onboard of the low Earth orbit (LEO) satellite "Microlab-1" in the two coherent frequency bands F1=1575.6 MHz and F2=1227.6 MHz [1-3]. However high precision of radio navigational fields requires elaborating more accurate and effective methodology for inferring atmospheric, mesospheric and ionospheric parameters. The backward method [4,5] and new algorithms [6,7] were proposed to heighten accuracy of RO inversion. Radioholographic approach has been derived for combined analysis of phase and amplitude variations of RO signal [8-10]. High vertical resolution of the radioholographic method (about of 70 m) has been demonstrated by means of retrieving weak reflected from the sea surface signals in GPS/MET RO data [11,12]. First results of measuring vertical gradients of the electron density in the lower ionosphere have been considered in [11,12]. The aim of this contribution is to present generalization of radioholography approach for 3-D case and to consider first results of measurements of vertical gradients of the refractivity in the atmosphere.

RADIOHOLOGRAPHIC METHOD

The geometry of radio occultation scheme is shown in Fig. 1. Navigational satellite GPS emitted radio waves, which propagated along two paths 1 and 2 shown in Fig. 1. The point D is the specular reflection point disposed on the smooth sphere of radius *a* corresponding to average Earth surface (Fig. 1). Reflected radio waves were registered with direct radio signal penetrated through atmosphere to receiver disposed on Low Orbital (LEO) satellite. The receiver installed on LEO satellite registered phase and amplitude of radio waves at two frequencies F1, F2 corresponding to wavelengths 19 and 24 cm. Thus two radio holograms were obtained during every event of radio occultation experiment. The basic principles of the radio holography application to analysis of GPS/MET radio occultation data for recovering parameters of the atmosphere and ionosphere were described in [8-12]. For practical use it is necessary to obtain more general connections, which allow accounting for polarization properties of radio fields and, in principle, obtaining 3-D image of the ionosphere and atmosphere. Generalization of radio holography approach consists in application of vector equation given by Stratton and Chu [13], for back-propagated field [14]. Vector equation for radio holographic method has been obtained in [14] in the next form for Gauss units system:

$$\mathbf{E}(\mathrm{P_i})=\mathrm{i}k(4\pi)^{-1}\iint \mathrm{d}S R_d^{-1}\exp(-\mathrm{i}kR_d)\mathbf{Q_E}(\mathbf{E},\mathbf{H});\quad \mathbf{Q_E}(\mathbf{E},\mathbf{H})=[\mathbf{nH}]-[[\mathbf{nE}]\mathbf{g}_-]-(\mathbf{nE})\mathbf{g}_-, \quad (1)$$

$$\mathbf{H}(\mathrm{P_i})=\mathrm{i}k(4\pi)^{-1}\iint \mathrm{d}S\, R_d^{-1}\exp(-\mathrm{i}kR_d)\mathbf{Q_H}(\mathbf{E},\mathbf{H});\ \mathbf{Q_H}(\mathbf{E},\mathbf{H})=[\mathbf{En}]-[[\mathbf{nH}]\mathbf{g}_-]-(\mathbf{nH})\mathbf{g}_-, \quad (2)$$

$$\mathbf{g}_-= (1-\mathrm{i}/kR_d)\mathbf{grad}R_d,\ R_d=[(x--x')^2+(y-y')^2+(z-z')^2]^{1/2}, \quad (3)$$

where (x,y,z) are coordinates of element da on the interface S and k is the wave number of radio waves. Equations (1)-(3) restore the electromagnetic field $\mathbf{E}(\mathrm{P_i})$ $\mathbf{H}(\mathrm{P_i})$ inside homogeneous part of the volume V if the fields **E**, **H** are known on the interface *S*. It may be noted that information on the field distribution on some part of the surface *S* may be used for constructing image of refractive volume as follows from holography practice known in optic. Spatial resolution depends on the size of the part of the interface S where the field distribution is given. One may obtain an equation corresponding to two-dimensional case using equations (1)-(3). This equation describes the field in some plane inside the volume V as function of the field along a given curve *L* in the same plane as shown in [14]:

$$\mathbf{E}(\mathrm{P_i})=(k/2\pi)^{1/2}\int \mathrm{d}L\, R_d^{-1/2}\cos\mu\, \exp(\mathrm{i}\pi/4-\mathrm{i}kR_d)\mathbf{E_o}, \quad (4)$$

where μ is the angle between normal to the curve *L* and direction to the point of observation. Equation (4) is a basic for practical implementation of the radio holographic method when experimental data $\mathbf{E}_o$ are given along the LEO orbit as function of time. The focused synthetic aperture principle is applied for constructing

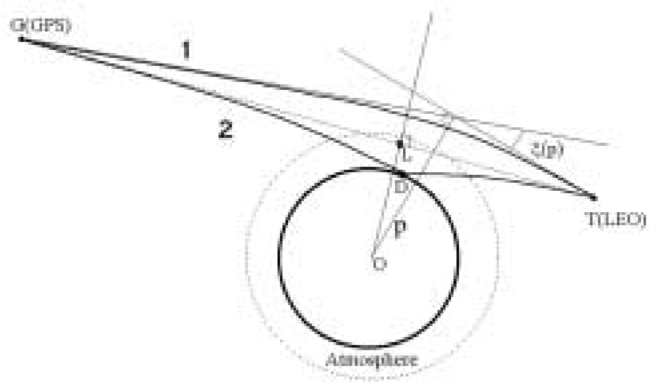


Fig. 1. Scheme of radio occultation experiments.

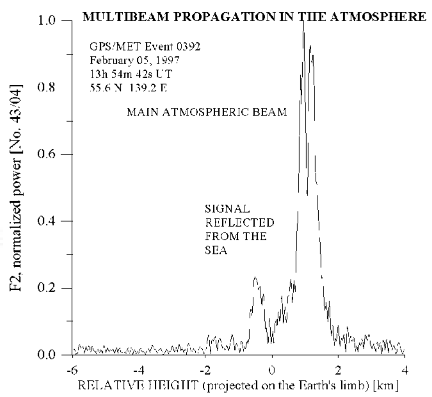


Fig. 2. Weak reflected signal retrieved by radioholographic method.

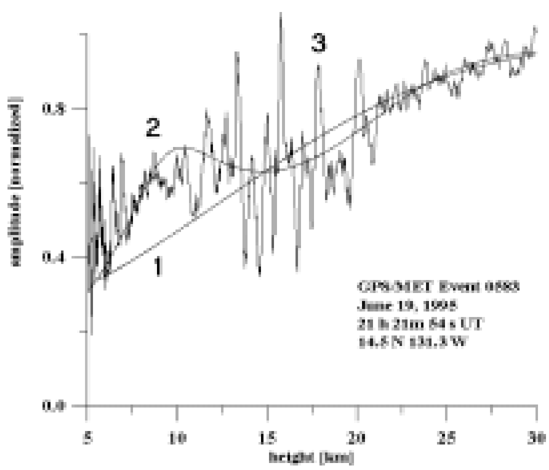


Fig. 3. Amplitude of reference beam (curves 1,2) and variations of amplitude at frequency F1 (3).

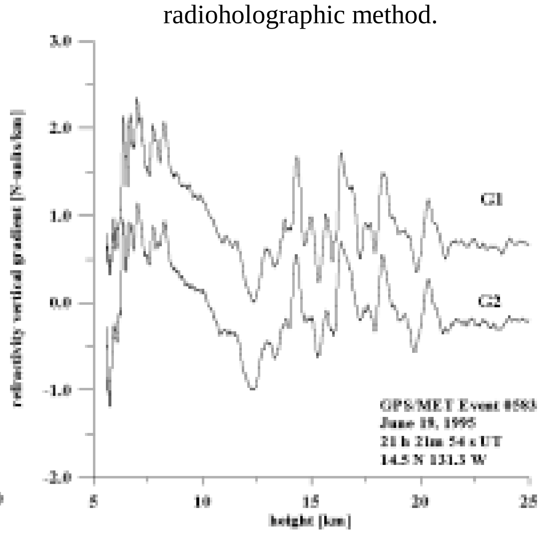
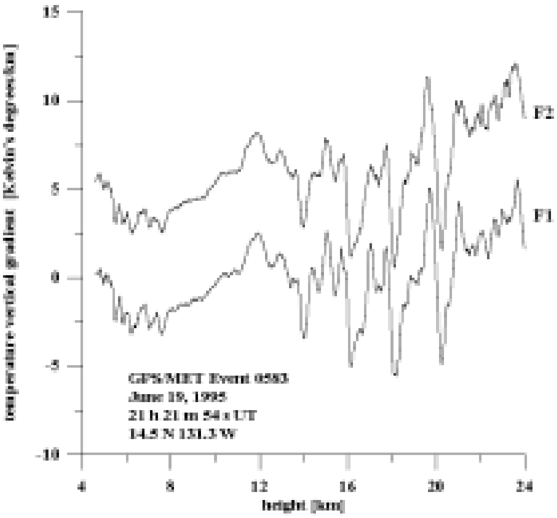


Fig. 4. Perturbations in the refractivity vertical gradients retrieved from amplitude parts of radioholograms at two frequencies (curve G1 is displaced by 1 N-units/km).



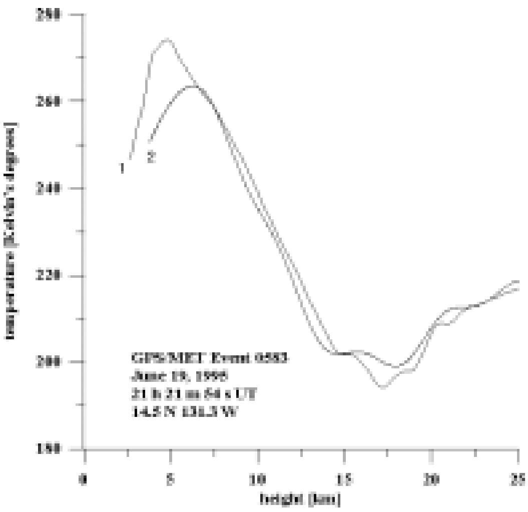


Fig. 5. Perturbations in the temperature vertical gradients retrieved from amplitude parts of two radioholograms. Curve F2 is displaced by 5^{o}K/km.

Fig. 6. Temperature vertical profile restored from amplitude part of radiohologram (curve 2) and result of UCAR temperature retrieval (1).

reference beam using knowledge of the average parameters of the atmosphere and ionosphere in the radio occultation region. Then one-dimensional radio image of the atmosphere and terrestrial surface may be restored. For obtaining of radio image of the Earth surface a spectral analysis method may be applied [11]. Example of radio images of the Earth surface and boundary layer of the troposphere is shown in Fig. 2. This radio image has been obtained by radio holographic method from GPS/MET radio occultation data (event No. 0392, February 05, 1997). The height along the visible Earth's limb as seen from the orbit of LEO satellite is shown along the horizontal axis (expressed in km). Negative values of height correspond to signals reflected from the Earth surface. The vertical distribution of the radio brightness in the troposphere (right peaks in Fig. 2) corresponds to the main ray. The width of partial peaks inside the main peak at the half-power level gives the magnitude of the vertical resolution of the radio holographic method to be around 70 m.

RETRIEVING VERTICAL GRADIENTS OF THE REFRACTIVITY

In the current state radio holography approach combines radar focused synthetic aperture principle and perturbation method. The main part of atmospheric contribution is accounted for in the amplitude and phase of reference signal. Then a perturbation method may be applied to find deflections of the atmospheric parameters from expected values. The amplitude variations at frequency F1 is given in Fig. 3 (curve 3) for GPS/MET RO event 0583 above the north equatorial part of the Pacific Ocean. Curves 1,2 in Fig. 3 describe influence of standard atmosphere and equatorial atmosphere on the amplitude of RO signal. Low-frequency part of amplitude variations, in average, is coinciding with curve 2, high-frequency changes correspond to deflections in vertical gradients of refractivity from expected values. The perturbation part of vertical gradient of refractivity retrieved from amplitude data at two frequencies is shown in Fig. 4 as function of height. Two areas of high-frequency variations of the refractivity gradient (at the height intervals 5…8 km and 13…22 km) may be seen in Fig. 4. Amplitude of high-frequency variations is about of ±0.5 N-unit/km. This value is some smaller than amplitude of low-frequency variations (about of 1.1 N-unit/km). Variations of the refractivity gradient are similar at both frequencies. Perturbation part of the refractivity gradient may be recalculated to variations in the temperature vertical gradient dT(h)/dh. The perturbation part of temperature gradient is indicated in Fig. 5. The curve F2 corresponding to amplitude variation at the second frequency F2 is displaced for comparison. Variations of temperature gradient are similar at both frequencies and changes from $\pm 1^{o}$K/km in the height interval 5…8 km up to $\pm 3.5\ ^{o}$K/km at heights between 13 and 22 km. The sum of expected part of reference signal and perturbations caused by atmosphere may be used for restoration of the temperature vertical profile T(h). The retrieved function T(h) is demonstrated in Fig. 6 by curve 2. Data of UCAR retrieval for GPS/MET event 0583 are shown by curve 1. Comparison shows correspondence both curves in the height interval 10…24 km. Deflections at heights below 10 km may be connected with more sharp influence of the water vapor on the amplitude variations than on the Doppler frequency changes used for UCAR restoration of T(h).

CONCLUSION

The 3-dimensional form of radioholographic method accounts for polarization of electromagnetic waves and may be used in future for elaborating new direction of investigation: polarization radio holography for recovering polarization-sensitive objects in the atmosphere and ionosphere. It is shown that combined analysis of amplitudes parts of radioholograms at two frequencies reveals altitude profiles of the vertical gradients of the refractive index in the atmosphere. Derived radioholographic algorithms may be used for recovering atmospheric and stratospheric wave structures and temperature gradients.

ACKNOWLEDGMENTS

We are grateful to UCAR for access to the GPS/MET data. We are grateful to National Science Council of Taiwan, R.O.C., for financial support under the grants NSC 91-2811-M008-001, NSC 90-2111-M008-047-AGC, and Office of Naval Research (ONR) of USA under grant N00014-00-0528. Work has been partly supported by Russian Fund of Basic Research, grant No. 01-02-17649.

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