GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L24801, doi:10.1029/2004GL020607, 2004

Amplitude variations in GPS signals as a possible indicator of ionospheric structures

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Received 26 May 2004; revised 12 October 2004; accepted 5 November 2004; published 18 December 2004.

[1] The noisy and impulsive fluctuations in the CHAMP radio occultation (RO) amplitude data are similar to the C-type and S-type ionospheric amplitude scintillations formerly observed at 1.5 GHz in the mid-latitude region in satellite-to-Earth Inmarsat links. These amplitude scintillations can be associated with different types of ionospheric structures. S-type amplitude variations can be explained by the influence of inclined plasma layers in the ionosphere where the RO signal trajectory is perpendicular to the sharp plasma gradient. Simulation indicates the possibility to reveal the spatial distribution of the electron density in the inclined ionospheric layers from analysis of the S-type RO amplitude variations. The seasonal, geographical and temporal distributions of CHAMP RO events with high S_4 index values observed during the years 2001–2003 indicate their dependence on solar activity. *INDEX TERMS:* 0933 Exploration Geophysics: Remote sensing; 2435 Ionosphere: Ionospheric disturbances; 6979 Radio Science: Space and satellite communication; 6964 Radio Science: Radio wave propagation; 6934 Radio Science: Ionospheric propagation (2487). **Citation:** Wickert, J., A. G. Pavelyev, Y. A. Liou, T. Schmidt, C. Reigber, K. Igarashi, A. A. Pavelyev, and S. Matyugov (2004), Amplitude variations in GPS signals as a possible indicator of ionospheric structures, *Geophys. Res. Lett.*, *31*, L24801, doi:10.1029/2004GL020607.

1. Introduction

[2] The Global Positioning satellite System (GPS) radio signals emitted at two frequencies, f_1 = 1575.42 and f_2 = 1227.60 MHz, are used for RO investigations of the F- and E-layers in the ionosphere [*Hajj and Romans*, 1998; *Vorob'ev et al.*, 1999; *Igarashi et al.*, 2001; *Sokolovskiy et al.*, 2002; *Liou et al.*, 2002]. During an RO experiment, the ray linking a receiver installed on a low earth orbit (LEO) satellite and a GPS satellite (marked by the points L and G in Figure 1) moves sequentially into the ionosphere and atmosphere. Its direction is changed by the bending angle $\xi(p)$, depending on the impact parameter p, because of the refraction effect (Figure 1). The main contribution to the amplitude of the RO signal in the case of a quiet ionosphere is introduced by relatively small area along ray GTL, centered at the tangent point T (Figure 1), where the ray trajectory is perpendicular to the local gradient of the refractivity. The height h of point T can be evaluated, assuming the spherical symmetry of the ionosphere and atmosphere, centered at point O (Figure 1), if precise orbital data are given. The amplitude of RO signals, as a rule, does not undergo strong scintillations when the height h is changed within a 40–80 km interval. However for some occultations, strong amplitude scintillations have been observed at height intervals above the neutral atmosphere and below the E-layer of the ionosphere [*Sokolovskiy et al.*, 2002]. Also, in trans-ionospheric propagation, sporadic amplitude scintillations at GPS frequencies have been experienced [*Yeh and Liu*, 1982; *Karasawa et al.*, 1985]. *Karasawa et al.* [1985] have shown that sporadic amplitude scintillations can be caused by plasma disturbances in the ionospheric E- and F- layers.

[3] In this paper we indicate that the inclined plasma layers in the ionosphere can be an additional source of sporadic amplitude scintillations in long-range satellite trans-ionospheric communications. We also show that the sporadic amplitude scintillations, observed in the RO experiments in the 40–80 km height interval h, contain important information concerning the seasonal, geographical and temporal distributions of the ionospheric disturbances on a global scale.

2. Local Mechanism of RO Signals Variations

[4] In the absence of global spherical symmetry a new tangent point 1 may appear in the ionosphere, where the sharp gradient of the electron density in an inclined plasma layer is perpendicular to the ray trajectory GTL (Figure 1). This point can appear on either side of ray GTL (GT or TL), according to which part of the ray trajectory is occupied by an inclined sporadic plasma layer. In this case the height h(T) of the observed RO amplitude variations depends on the inclination δ of the plasma layer relative to the local horizontal direction (Figure 1). As a consequence, an apparent height displacement Δh in the estimated value of the altitude of the inclined plasma layer can arise (Figure 1). The layer's inclination δ and its horizontal displacement d can be evaluated using Figure 1 as follows

$$\delta = (2\Delta h/r)^{1/2},\ d = (2\Delta hr)^{1/2}, \qquad (1)$$

where r is the distance OT (Figure 1).

[5] Below we describe the amplitude variations of the RO signal connected with the ionospheric influence by

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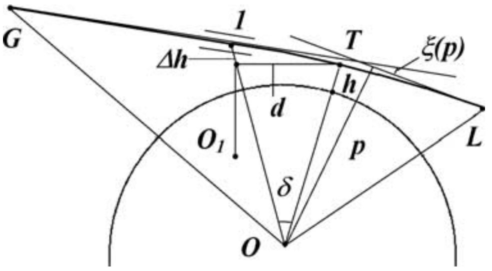

Figure 1. Key geometrical parameters of RO experiment. Line GTL indicates the curved RO signal trajectory in the atmosphere and ionosphere. Inclined plasma layer 1, where gradient of the electron density is perpendicular to RO ray, may be the cause of the ionospheric scintillations measured at point L.

the magnitude of the S_4 scintillation index [*Yeh and Liu*, 1982]:

$$S_4 = \left[\left\langle (I(t) - \langle I \rangle)^2 \right\rangle / \langle I \rangle^2 \right]^{1/2}, \qquad (2)$$

where $\langle\rangle$ is the average relevant to the height h(T) above 40 km, and $I(t)$ is the intensity of the RO signal. The averaging time was dependent on the vertical velocity of the RO beam and was changed in 25–35 s interval. For analysis we used the amplitude data obtained during the CHAMP RO experiment described by *Wickert et al.* [2001].

[6] The CHAMP RO amplitude variations for some RO events, which can be recognized as the C- and S- types of amplitude scintillations classified previously by *Karasawa et al.* [1985] in the communication Inmarsat link at 1.5 GHz, are shown in Figure 2.

[7] The noisy C-type amplitude variations in the RO signals are shown in Figure 2 (top). Curves 1–3 and 6 describe scintillations observed in the local evening in the equatorial region during RO events No. 0051 (November 19, curve 1); No. 0053 (July 5, curve 2); No. 0069 (February 24, curve 3), and No. 0135 (July 4, curve 6) in 2003. The S_4 index was equal to 0.19, 0.32, 0.20, and 0.50 respectively. Event 0159 corresponds to local morning (May 3) in the polar ionosphere, with S_4 = 0.16 (curve 4). Curve 4 corresponds to the noisy event near the north geomagnetic pole. Curve 5 is related to the quiet ionosphere, with S_4 = 0.03 (event No. 0198, May 3); the amplitude fluctuations in the height interval h(T) 30–110 km were caused mainly by random receiver noise. The geographical position and local time of the noisy RO events correspond to the same parameters of the noisy amplitude scintillations observed formerly in trans-ionospheric communications [e.g., *Yeh and Liu*, 1982].

[8] Quasi-regular amplitude variations are shown in Figure 2 (bottom). Curves 1, 2, 4 correspond to the CHAMP RO events No. 0093, 0239, 0010, February 24 (mid-latitude nighttime and equatorial daytime ionosphere); curves 3, 5 relates to events No. 0050, 0171, November 19; and curve 6 corresponds to event No. 0246, July 5, 2003 (daytime mid-latitude ionosphere). The quasi-regular amplitude variations may be caused by inclined plasma layers in the E- or F-regions of the ionosphere. Using the apparent displacement in height of a plasma layer Δh from its normal location, one can use equation (1) to estimate the inclination δ and horizontal displacement d of the layer (Figure 1). If the plasma layer is located in the E-region, then $\Delta h \approx$ 50 km, $\delta \approx 7.5°$, $d \approx 450$ km. If it is located in the F-region $\Delta h \approx 200$ km then one obtains sufficiently larger values $\delta \approx$ 18°, and $d \approx 1500$ km. Exact location of the inclined layer is a difficult problem for the RO method. However the back propagation method [*Sokolovskiy et al.*, 2002] appears to hold considerable promise for solving this task.

[9] The results of the simulation of the local ionospheric influence mechanism on the amplitude of the RO signal are shown in Figure 3. Curves 1a and 1b describe the model of the electron density distribution in two patches of sporadic E-layers with a horizontal inclination of 0° and 5°. Both sporadic E-layers are disposed at the same height, 96–104 km, but the second patch is displaced along the ray path by 500 km relative to the first one. The electron density distribution for the second patch (curve 1a in Figure 3) is displaced, for better comparison with the first patch (curve 1b). The influence of the first patch on the amplitude variations (curve 2b) is evident in the 96–106 km height interval and the influence of the second patch (curve 2a) is seen in the 63–75 km height interval h.

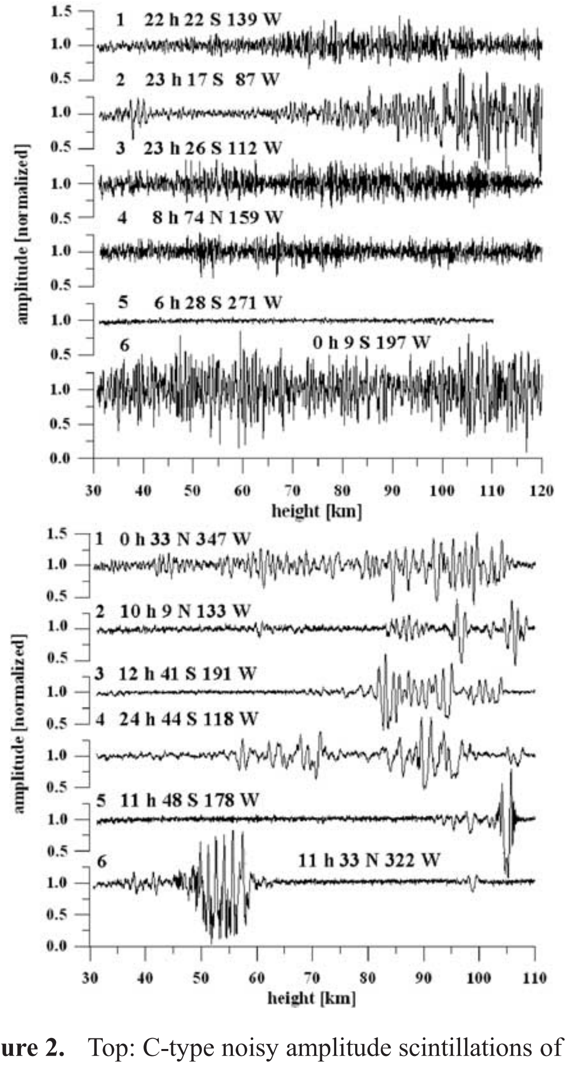

Figure 2. Top: C-type noisy amplitude scintillations of the RO signal. Bottom: S-type quasi-regular amplitude variation. The legends indicate the local time (LT) and the geographical coordinates of the RO experiments.

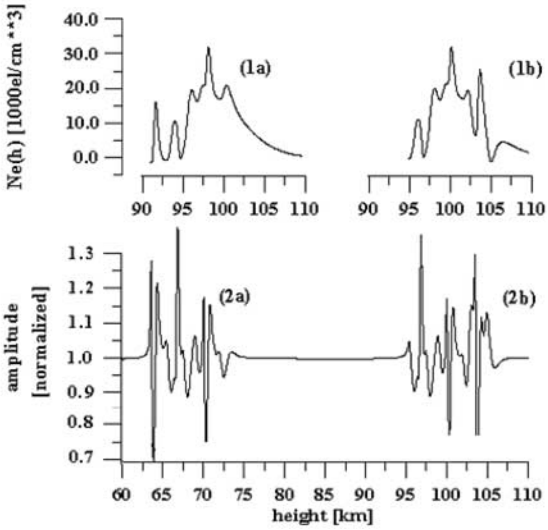

Figure 3. Results of modeling the amplitude of the RO signal and the electron density $N_e(h)$.

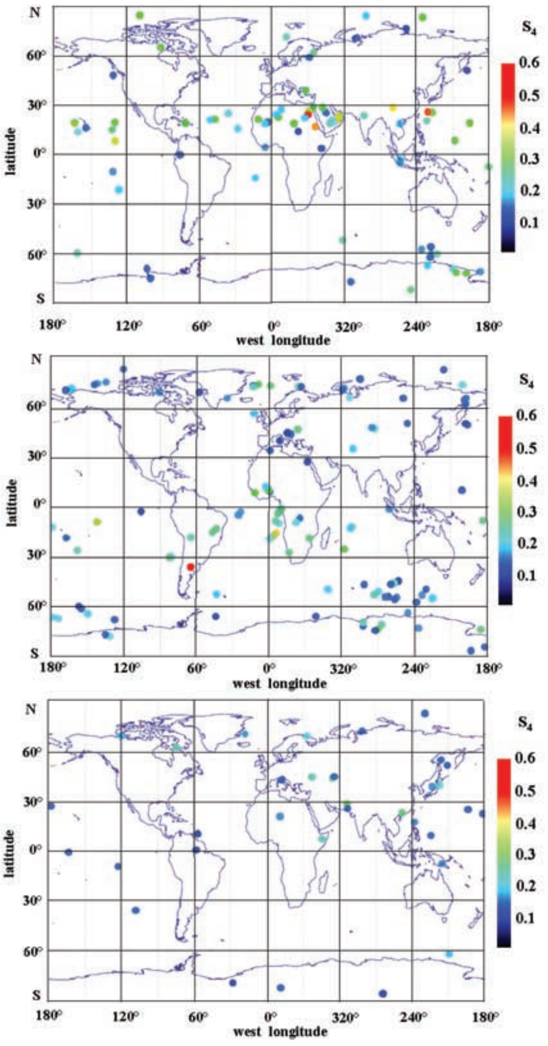

Figure 4. Maps of strong ionospheric events, with an S4 index larger than 0.2, for September 2001 (top), September 2002 (middle) and September 2003 (bottom). The circles show the geographical position of the tangent point T (Figure 1).

As seen in Figure 3, the width of the vertical distribution of the amplitude variations approximately coincides with the size of the vertical interval of the $N_e(h)$ variations. It follows that the simulation demonstrates nearly the same amplitude variations, which can be seen in the experimental data for the S-type variations. Note, that the proposed local mechanism of ionospheric influence on the RO signal also can be used for an analysis of the amplitude scintillations observed in trans-ionospheric links. Noisy scintillations can be associated with small-scale plasma irregularities in the F- or E- layers of the ionosphere [*Yeh and Liu*, 1982; *Karasawa et al.*, 1985].

3. Geographical Distribution of Intense Ionospheric Disturbances as a Function of Time

[10] The geographical distribution of the strong ionospheric events (with an S_4 index larger than 0.20), for all types of amplitude scintillations, in the CHAMP RO signals at 1575.42 MHz is illustrated in Figures 4 and 5. The distribution of the ionospheric events indicates that they are concentrated in some regions (e.g., the equatorial and geomagnetic North and South polar zones in Figures 4 and 5). Strong activity in some equatorial regions may be connected with the evening ionospheric disturbances that arise after sunset, 20–24 hours local time, in accordance with earth-based measurements reviewed earlier [e.g., *Yeh and Liu*, 1982]. The number of strong ionospheric events and their intensity decreases from 2001 to 2003.

[11] This may correspond to a decrease in the level of solar activity. One interesting fact is the seasonal displace-

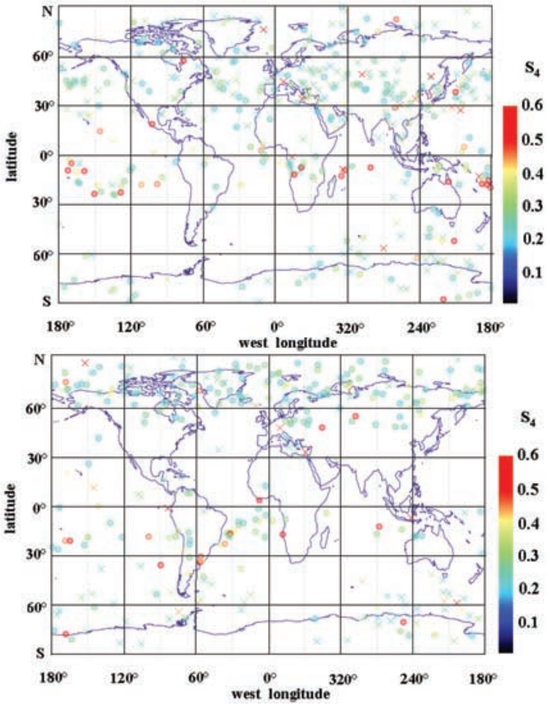

Figure 5. Seasonal dependence in the global distribution of the events with strong amplitude variations, with an S4 index larger than 0.2, for the time period May 14–July 14, 2001 (top), and November–December, 2001 (bottom). The circles correspond to the night events (20 h–08 h LT), while the crosses are related to day events (08 h–20 h LT).

ment of the region with intense ionospheric events in the south and north directions during the periods from May–July (Figure 5 (top))–September 2001 (Figure 4 (top)) and May–July–December 2001 (Figure 5 (top and bottom)). As follows from Figures 4 and 5 the CHAMP RO data give a new insight into the seasonal and temporal behavior of regions with intense ionospheric influence on the RO signal. The relative number of RO events with S_4 index values larger than 0.20 in the 40–100 km height interval show promise to be used for characterization of the intensity of the ionospheric processes important for radio wave propagation.

4. Conclusions

[12] The main contribution to amplitude scintillations in the CHAMP RO signal in the 40–100 km height interval can be associated with ionospheric structures of different types. The quasi-regular-S-type amplitude variations can be connected with influence of critical points (tangent points) in the ionospheric structures where the signal trajectory is perpendicular to the sharp gradient of the electron density. Simulation results give evidence that the isolated quasi-regular variations may be caused by the inclined plasma structures in the E- or F- layers of the ionosphere having sharp gradients but moderate electron density values.

[13] The geographical distribution of RO ionospheric events that have high values of the C- and S-type amplitude scintillations (S_4 index larger than 0.2) demonstrates seasonal and temporal variations, and also is dependent on solar activity. The probability of strong amplitude variations in the CHAMP RO signals diminished sharply with the weakening of solar activity from 2001 to 2003. This indicates that the general number of RO events with strong amplitude variations can be used as an indicator of the ionospheric activity, which is important for radio waves propagation in the decimeter range.

[14] **Acknowledgments.** We thank all members of the CHAMP team for their work, which is the base for our investigations. Our work has been partly supported by Russian Fund of Basic Research, grant No. 03-02-17414 and by a GFZ research contract.

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