Connection between the Amplitude Variations of the GPS Radio Occultation Signals and Solar Activity

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Abstract The classification of the effect of ionospheric disturbances on the radio occultation signal amplitude has been introduced based on an analysis of more than 2000 seances of radio occultation measurements per formed with the help of the CHAMP German satellite. The dependence of the histograms of variations in the radio occultation signal amplitude on the IMF variation index has been revealed. It has been indicated that it is possible to introduce the radio occultation index characterizing the relation between ionospheric disturbances and solar activity. An amplitude radio occultation (RO) method is proposed to study connection between the ionospheric and solar activity on a global scale. Sporadic amplitude scintillation observed in RO experiments contain important information concerning the seasonal, geographical, and temporal distributions of the ionospheric disturbances and depend on solar activity. The probability of strong RO amplitude variations (RO S_4 index greater than 0.2) in the CHAMP RO signals diminishes sharply with the weakening of solar activity from 2001 to 2008. The general number of RO events with strong amplitude variations can be used as an indicator of the ionospheric activity. We found that during 2001-2008 the daily globally averaged RO S_{4a} index depends essentially on solar activity. The maximum occurred in January 2002, minimum has been observed in summer 2008. Different temporal behavoir of S_{4a} index has been detected for polar (with latitude greater than 60°) and low latitude (moderate and equatorial) regions. For polar regions S_{4a} index is slowly decreasing with solar activity. In the low latitude areas S_{4a} index is sharply oscillating, depending on the solar ultraviolet emission variations. The different geographical behavoir of S_{4a} index indicates different origin of ionospheric plasma disturbances in polar and low latitude areas. Origin of the plasma disturbances in the polar areas may be connected with influence of solar wind, the ultraviolet emission of the Sun may be the main cause of the ionospheric irregularities in the low latitude zone. Therefore, the S_{4a} index of RO signal is important radio physical indicator of solar activity.

Introduction

Origination of sporadic plasma structures in the near-Earth space is largely related to disturbances caused by the effect of the solar wind on the Earth's magnetosphere and by the variations in the ionizing solar radiation at different wavelengths. After the appearance of the GPS/GLONASS satellite navigation systems with more than 50 satellites, which are located in circular orbits with an inclination of about 70° and a height of ~ 20000 km above the ground surface and emit at wavelengths of 19 and 24 cm, it became possible to globally observe and control the processes in the Earth's plasma sheath. Plasma disturbances cause variations in the amplitude and phase of high-accuracy signals of navigation satellites during the propagation of these signals through the Earth's magnetosphere, ionosphere, and mesosphere on satellite–satellite paths. Variations in electron density differently affect the amplitude and phase of navigation satellites. The parameter characterizing the effect of plasma disturbances on a radio occultation signal has been revealed: an rms value of amplitude variations related to perigee altitudes of a radio occultation signal trajectory higher than 40 km.

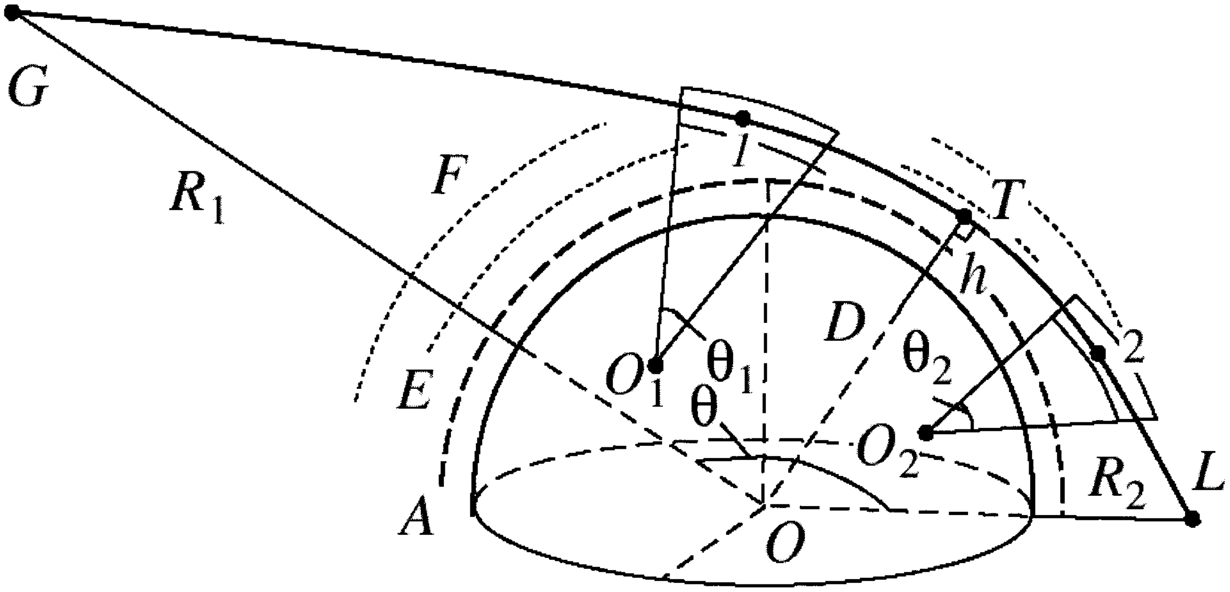

Fig. 1. Radio occultation measurements near point T can be distorted by the contribution of the nonstationary ionosphere and magnetosphere during radio wave propagation near turning points 1 and 2 of a ray trajectory. The appearance of additional turning points 1 and/or 2 in the near Earth plasma can cause considerable variations in a radio occultation signal amplitude and phase.

The aim of this paper is to analyze the main mechanism of the effect of ionospheric disturbances on the characteristics of a radio occultation signal, to preliminarily classify the types of signal variations due to the effect of the ionosphere, and to illustrate a possible rela tion between solar activity and variations in a radio occultation signal amplitude based on data of the CHAMP German satellite.

Scheme of measurements

During the radio occultation experiment, the ray path between a receiver on the LEO low-orbiting satellite and the GPS satellite (shown in Fig. 1 by points L and G, respectively) successively crosses the lower magnetosphere, ionosphere, and mesosphere. A relatively small zone, extended along the GTL beam and centered at the turning point T (Fig. 1) makes the main contribution to the amplitude and phase of a radio occultation signal. In this zone the ray path direction is approximately perpendicular to the local gradient of refractivity.

Amplitude and phase of a radio occultation signal are the functions of a minimal ray path height *h* above the ground surface (Fig. 1), location of the satellites, and satellite velocities. These functions are used to determine the altitude variations in a tilt angle from the known satellite trajectory data [Ware et al., 1996; Kursinski et al., 1997]. Electron density vertical profiles in the ionosphere and mesosphere are then determined with the help of different methods [Hocke et al, 1999; Pavelyev et al., 2002, 2007]. . Signal amplitude is also used to determine the vertical gradient of electron density [Liou et al., 2002].

Physical changes in the near-Earth space caused by the effect of the solar wind and radiation result in the origination of disturbances in the magnetosphere, ionosphere, and mesosphere. Nonstationary phenomena in the ionosphere cause variations in the amplitude and phase of a radio occultation signal. Pronounced variations in a radio occultation signal are often observed in the altitude interval of the ray path perigee from 40 to 100 km. The origination of strong variations in the amplitude and phase of a radio occultation signal in this altitude interval can be related to the appearance of turning points on a ray path trajectory in the near-Earth plasma. Turning points 1 and 2 (Fig. 1) can appear as a result of the effect of regular horizontal gradients in the ionospheric E and F regions and, possibly, in the lower magnetosphere. Regular gradients of electron density can originate at the day–night boundary as a result of motion of the subsolar point. Horizontal gradients can also appear due to different electron densities in the meridional direction. Radiowave propagation in a non stationary plasma can be described by the model [Pave 2003a] relating amplitude and phase variations in different sections of a ray path of a radio occultation signal in the presence of horizontal gradients in the near-Earth plasma. According to the [Pavelyev et al. 2003] occultation signal amplitude is a valuable source of information about characteristics of the near-Earth plasma [Sokolovskiy et al., 2002; Liou et al., 2002].

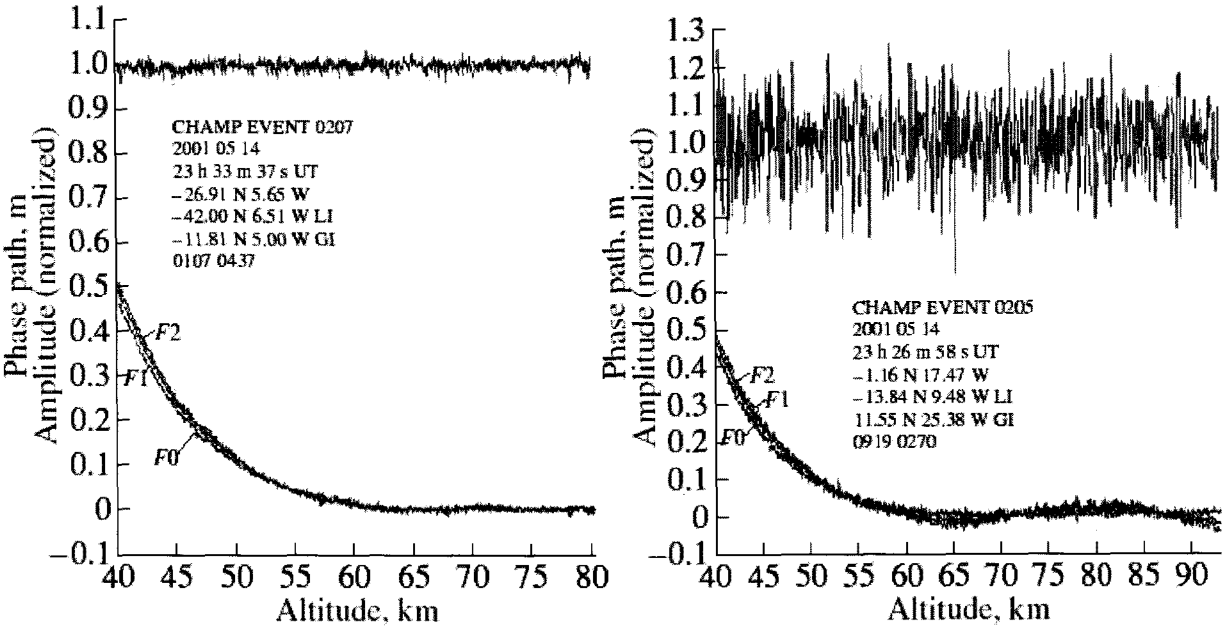

Fig. 2. Amplitude and phase of the CHAMP radio occultation signal (experiments 0207 and 0205 of May 14, 2001). Inserts indicate the time of the experiment, coordinates of the turning point (T) of the ray trajectory, and coordinates of the intersection of the ionosphere at an altitude of 280 km by the low-orbiting (LI) and navigation (GI) satellites. The 10000-fold rms value of amplitude variations, σ is also indicated.

Relation of the radio occultation index of amplitude variations to solar activity

The effect of a quiet ionosphere on the amplitude and phase of a signal is illustrated in Fig. 2 (left-hand panel). The amplitude curve has small values of the rms deviation, RMSD (RMSD =σ = 0.0107. The phase path increments at frequencies f_1 and f_2, $\Phi_1(t)$ and $\Phi_2(t)$ are shown in Fig. 2 (left-hand panel) by curves F1 and F2. The F1 and F2 curves were obtained after the elimination of a phase change due to the effect of the F region using its approximation by the second-degree polynomial. The F0 curve characterizes a phase change with regard to the ionospheric correction according to the formula: Figure 2 (right-hand panel) illustrates an event of measurements with a high level of amplitude fluctuations (σ = 0.0919). This event can be classified as a case of radio wave parameter fluctuations caused by intense ionospheric irregularities in the equatorial region at 2200 LT. The phase changes are relatively insignificant and indicate that the integrated electron density slowly varies in the ionosphere.

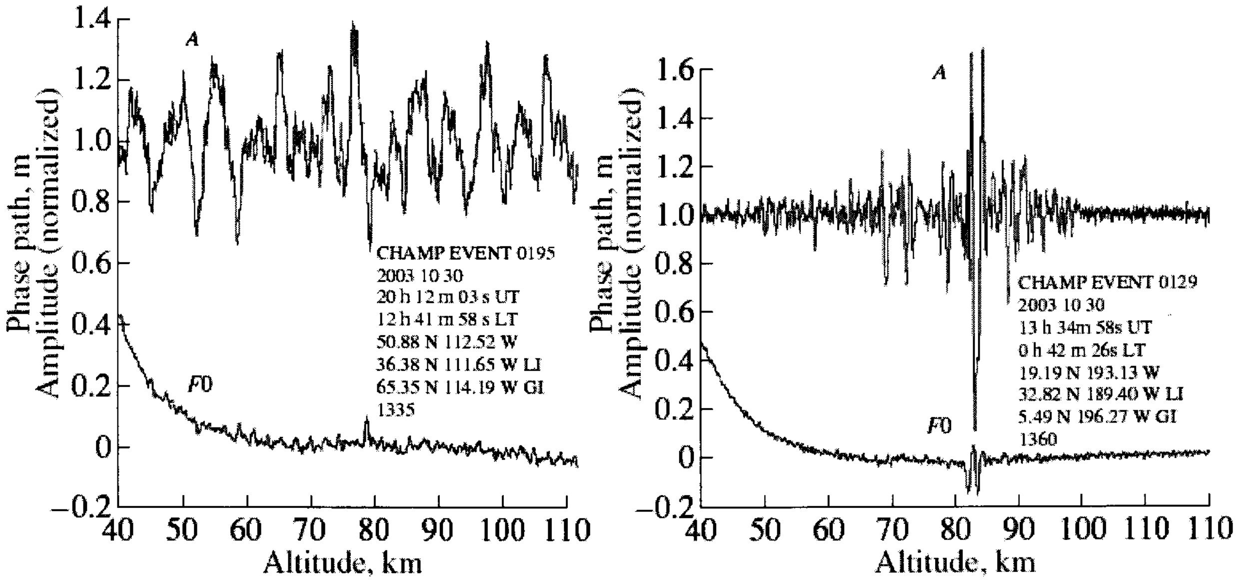

Fig. 3. The same as in Fig. 2 but for experiments 0105 and 0129 (October 30, 2003) characterized by quasiperiodic and isolated, respectively, amplitude variations caused by the effect of inclined plasma sheets projected on altitudes lower than 90 km.

An example of a quasi-regular and isolated change in the radio occultation signal amplitude caused by the effect of plasma sheets in the lower ionosphere is shown in Fig. 3 (left- and right-hand panels). Specific features in the signal amplitude behavior are related to the presence of sporadic plasma formations, the effect of which is observed at altitudes below 90 km, on the way of propagation of radio waves inclined with respect to the local horizontal. An actual location of these layers corresponds to altitudes higher than 90–100 km depending on their inclination to the horizon. Considerable quasi-regular variations in the signal amplitude with RMSD = 0.1335 (Fig. 3, left-hand panel) can be related to waves in the vertical distribution of electron density. Thus, we can distinguish the following types of the effect of the ionosphere on signal characteristics based on results of an analysis: (1) almost absent effect, (2) isolated quasi-regular bursts in the signal amplitude and phase, (3) quasi-periodic changes in the signal amplitude, and (4) events with noise-type changes in the signal amplitude caused by statistical irregularities of electron density in the disturbed ionosphere.

The algorithms of inverse transformation can be used to restore the vertical distribution of electron density and its gradients in inclined ionospheric layers for the second and third types of changes in occultation signal parameters.

To analyze the geographic and time distribution of amplitude disturbances in a radio occultation signal, we treated about 2000 seances of CHAMP measurements performed from October 27 to November 9, 2003. The histograms of the integrated distribution of the amplitude RMSD were obtained for each day of measurements shown in Fig. 4. The ratio of the number of cases with the amplitude RMSD larger than the value plotted on the abscissa to the total number of measurements for the corresponding day is plotted on the ordinates in Fig. 4. The histograms in the right-hand panel of Fig. 4 correspond to data of RMSD measurements on October 29–31, as well as on October 28, November 1, and November 4, 2003, performed during relatively strong and weak disturbances in a radio occultation signal, respectively. The initial histogram values for the entire period of observations are coincident and correspond to an amplitude RMSD of ~1.4%, which depends on the level of thermal fluctuations of receiver noise. Three days (October

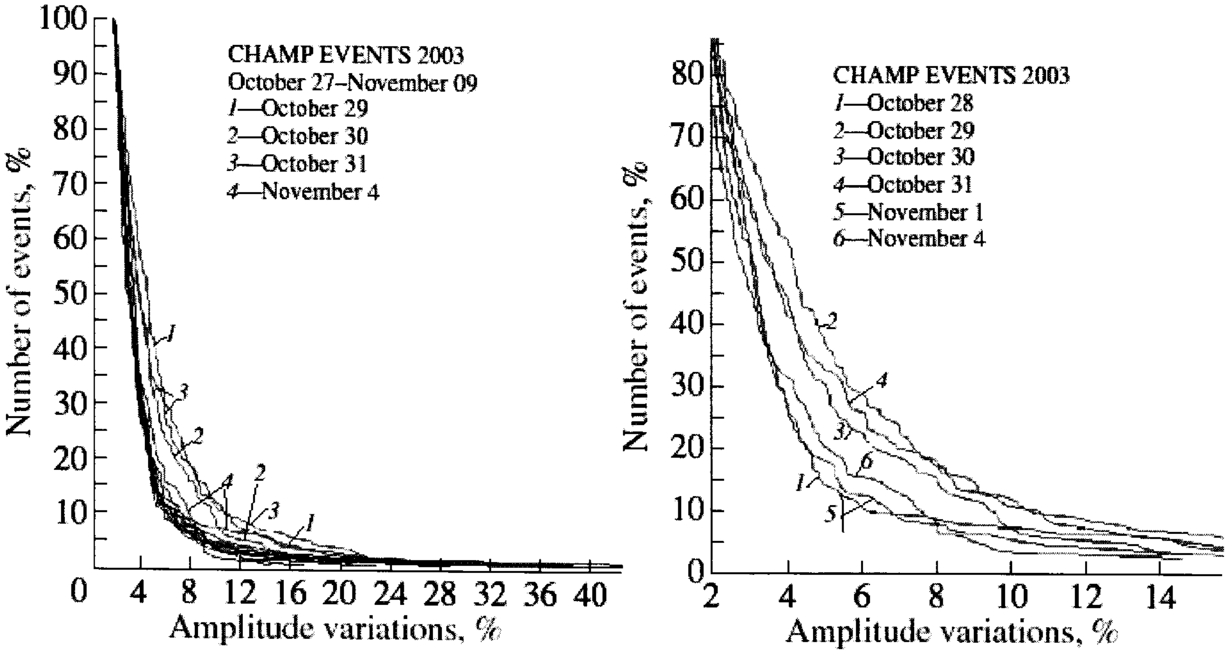

Fig. 4. Histograms of amplitude RMSDs corresponding to perigee altitudes of the CHAMP radio occultation signal trajectory (point T in Fig. 1) higher than 40 km. The curves corresponding to the histograms for October 27 and 28 and for November 1–3 and 5–9, 2003, are almost indiscernible in the left-hand panel. The right-hand panel indicates only the curves describing the response of the radio occultation signal to magnetospheric disturbances caused by solar activity.

29–31) with considerably higher RMSD levels than on the remaining days are distinguished in Fig. 4.

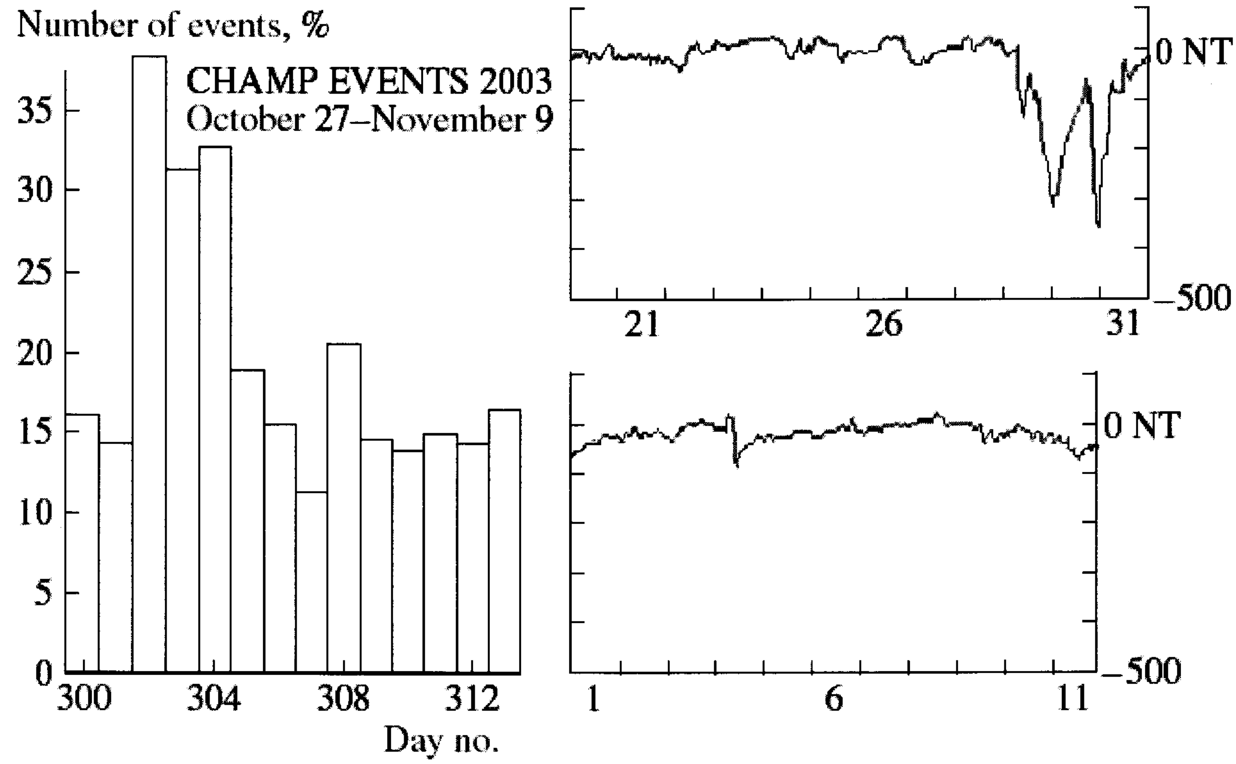

Fig. 5. Left-hand panel: the histogram of the radio occultation events with amplitude RMSD higher than 5% according to data of CHAMP measurements performed from October 27 to November 9, 2003. Right-hand panel: the dynamics of the hourly index of the solar wind (Dst, nT) according to data from http://swdcwww.kugi.kyoto-u.ac.jp/aeasy/index.html for October 26–31 (upper part of the panel) and November 1–11, 2003 (lower part of the panel).

The histograms for this time interval are much higher than for the remaining days. An analysis per formed makes it possible to introduce the radio occultation index of ionospheric activity (R_i). By definition, the R_i index is equal to the ratio of the number of radio occultation events with the RMSD value of a radio occultation signal at $h > 40$ km larger than three amplitude RMSDs caused by technical noise of the transmitter–receiver system to the total number of radio occultation events for a certain time interval (e.g., for a day). The R_i variations for the period from October 27 to November 9, 2003, are shown in Fig. 5 (left-hand panel). The histograms in Figs. 4 and 5 (left-hand panel) are in good agreement with the variations in the hourly index of the solar wind (Dst, nT) obtained from data of the satellite measurements. During October 26– 28 and November 1–3 and 5–9, the Dst index was almost constant, which corresponds to decreased values of the integrated distributions in the histograms (Figs. 4, 5, left-hand panel). Abrupt changes in the index of the solar wind magnetic field were observed on October 29–31 and November 4, which corresponds to a twofold increase in the number of events with increased (larger than 5%) RMSDs of the variations in the radio occultation signal amplitude (Fig. 5, left-hand panel).

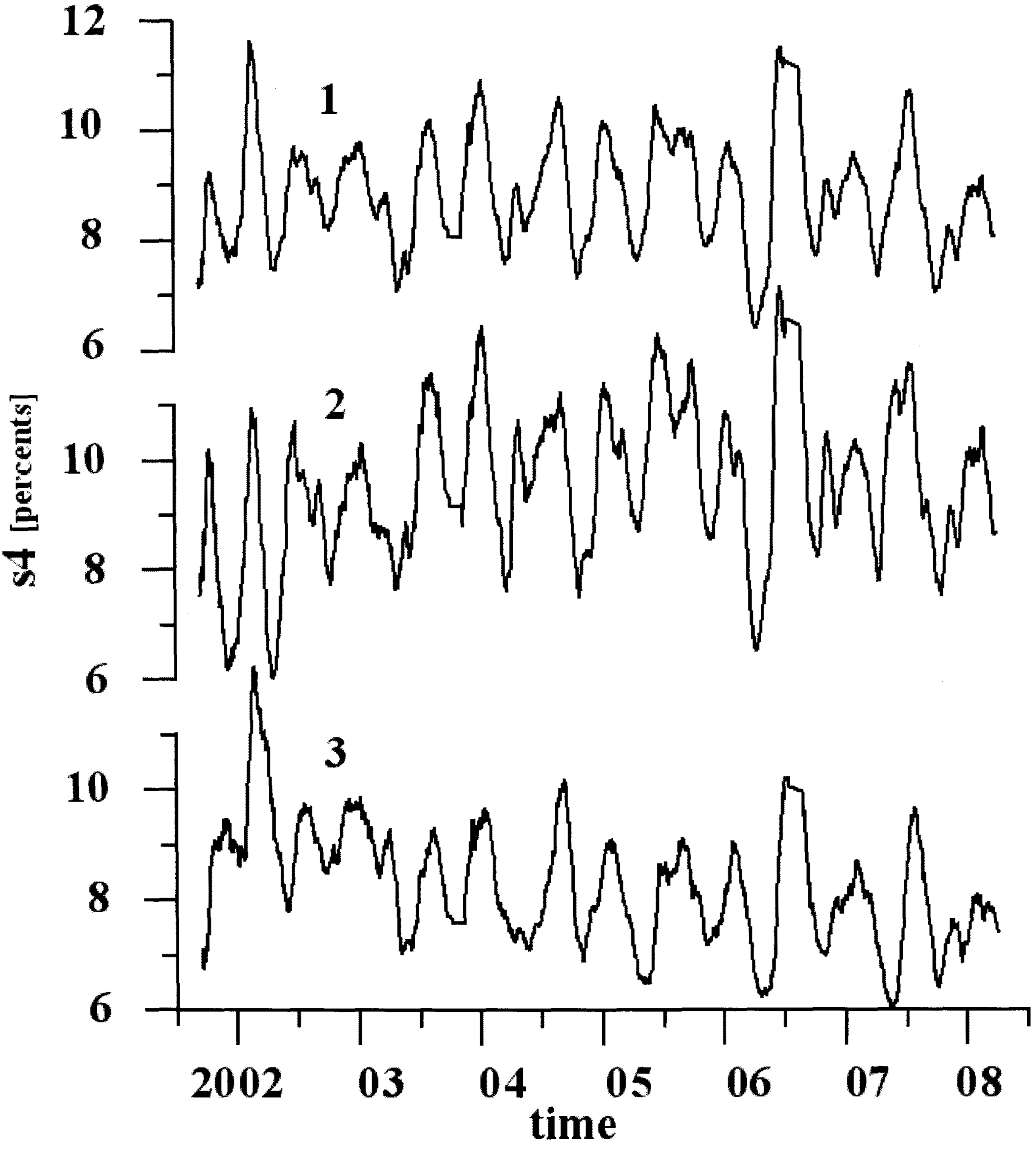

Fig. 6. Dependence of S_{4a} index measured from RO CHAMP experiments on time during 2001-2008.

The time dependence of S_{4a} index measured from RO CHAMP experiments during 2001-2008 is given in Fig. 6. Curve 1 corresponds to the averaged on a global scale value of the S_{4a} index. Curve 2 indicates the averaged in the equatorial and moderate latitude areas (with latitude below 60°) value of the S_{4a} index. Curve 3 demonstrates the averaged in the polar latitudes (with latitude greater than 60°) values of the S_{4a} index. It follows from analysis of Fig. 6, that during 2001-2008 the daily globally averaged RO S_{4a} index depends essentially on solar activity. The maximum occurred in January 2002, minimum has been observed in summer 2008. Different temporal behavoir of S_{4a} index has been detected for polar (with latitude greater than 60°) and low latitude (moderate and equatorial) regions. For polar regions S_{4a} index is slowly decreasing with solar activity. In the low latitude areas S_{4a} index is sharply oscillating, depending on the solar ultraviolet emission variations. The different geographical behavior of S_{4a} index indicates different origin of ionospheric plasma disturbances in polar and low latitude areas. Origin of the plasma disturbances in the polar areas may be connected with influence of solar wind, the ultraviolet emission of the Sun may be the main cause of the ionospheric irregularities in the low latitude zone. Therefore, the S_{4a} index of RO signal is important radio physical indicator of solar activity.

Conclusions

As a result of the performed study, we indicated that a radio occultation signal amplitude is an indicator of plasma disturbances in the near-Earth space. A radio occultation signal amplitude is mainly affected at critical (turning) points, where an electron density gradient is perpendicular to a radiowave propagation trajectory. A radio occultation signal amplitude is most sensitive to sharp gradients of electron density in plasma disturbances. An analysis of the histograms of radio occultation signal amplitude RMSDs made it possible to introduce the radio occultation index of ionospheric activity, which was in good agreement with changes in the hourly index of IMF (Dst) related to the solar wind. An analysis performed indicated interrelation between solar activity and natural processes in the ionosphere and mesosphere.

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