RADIO PROBING OF THE PERTURBATIONS ORIGINATING IN THE NEAR–EARTH PLASMA FROM NATURAL AND ANTHROPOGENIC ENERGY SOURCES

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INTRODUCTION

There are many papers concerned with search of the effects caused by rocket launches. They describe generally the effects occurring along the trajectory of a lifting rocket. The processes occurring at distances of $\sim 1,000-10,000$ km from the launch site and the rocket trajectory are investigated in this paper. Such perturbations are called large-scale or global-scale.

The comprehensive method and technique for search of the effects of rocket engine burns in the bottomside ionosphere (heights of $100-300$ km) are used in this study. It is important that observations were carried out for different rocket families at different ranges from launch sites, for different moments of a day- and night-time, and under different geophysical conditions.

TECHNIQUE

Non-stationary processes in the bottomside ionosphere have been studied with an HF Doppler radar taking vertical incidence measurements. The measurements were performed at 2.8 MHz and 3.0 MHz during $4-6$ hr period, beginning at 2–3 hr before the event. The data recording system acquired measurements at a repetition rate of 100 per second, which were subjected to a fast Fourier transform, and Doppler spectra were computed in a frequency band of –1 Hz to +1.5 Hz on 51.2 s time intervals with ~ 0.02 Hz resolution. In the case of quasi-periodic processes with periods of $T \approx 10-60$ min, a spectral analysis was undertaken on 128 min or 256 min intervals.

The minimum range to a launch site is $R \sim 700$ km, the maximum R is of about 10,000 km. The most distant sites are Edwards and Vandenberg (USA), the most "southern" site is Kourou (France), the nearest launch site is Kapustin Yar (Russia), and the most "northern" is Plesetsk.

LARGE–SCALE PERTURBATIONS DURING ROCKET BURNS

The Soyuz rocket was launched at 13:22 UT on October 18, 1999 (see Figure 1). Before the launch the ionosphere remained quiet. From about 12:55 UT to 13:03 UT, the main and additional modes of the reflected signals were observed, and a quasi-periodic process appeared with the period $T \approx 10$ min. After 13:45 UT, the amplitude of the oscillations increased significantly (amplitude of Doppler shift attained $f_{Da} = 0.5$ Hz), and the oscillation with $T \approx 20$ min became predominant over a period of about 30 min. Between 14:12 UT and 14:40 UT, the ionosphere was practically undisturbed. During the 14:40 – 14:50 UT interval, in addition to the principal mode of the signal, an additional mode shifted by $f_D = 0.3$ Hz (f_D is the Doppler shift) was recorded. After 14:50 UT, the disappearance of its persistent maximum was observed. This provides evidence to the appearance of random irregularities in the ionosphere below the reflection height (approximately of 150 km). Such perturbations persisted for more than 1 hr. In addition, the sunset at the ground occurred approximately at 15:20 UT and an hour later at the reflection level.

GLOBAL–SCALE PERTURBATIONS ASSOCIATED WITH ROCKET ENGINE BURNS

The Space Shuttle Endeavor was launched at 08:35 UT on December 4, 1998 (see Figure 2). On this day, the ionosphere was disturbed, and the effect of spectrum spreading was recorded during the whole period of observation. Prior to and shortly after the lift-off, a quasi-periodic process with $T \approx 10$ min and $f_{Da} \approx 0.1$ Hz was observed. Between 08:50 UT and 09:25 UT the ionosphere remained relatively quiet, and from 09:25 UT

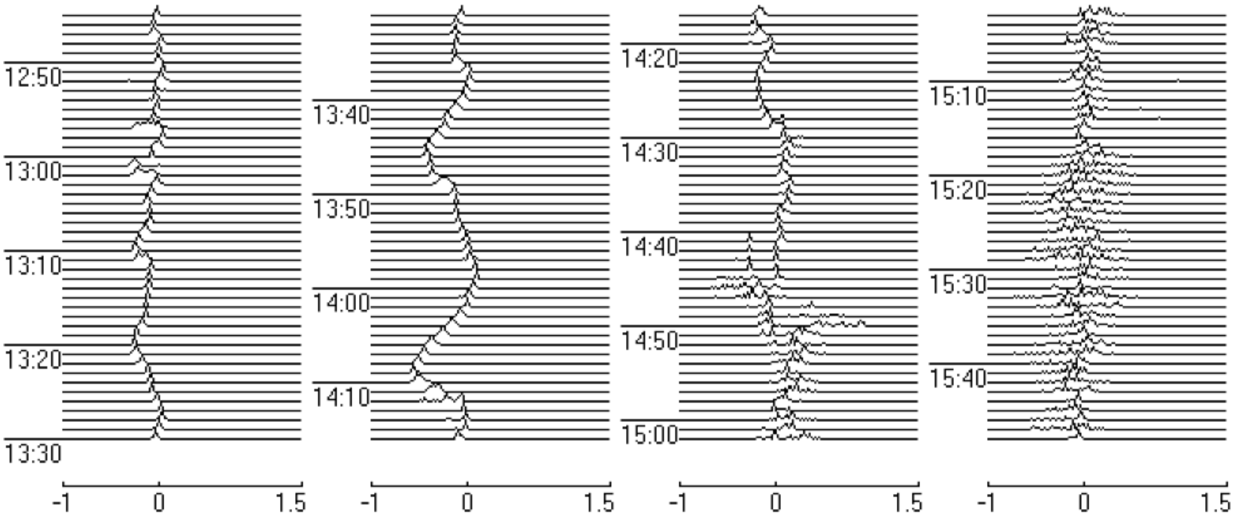

Figure 1: Doppler spectra acquired after Soyuz rocket launch at 13:22 UT on October 18, 1999

to 10:00 UT a significant spectrum spreading, as well as a quasi-periodic process with $T \approx 15 - 20$ min were recorded. At 10:05 UT to 10:10 UT, an additional mode appeared with the maximum Doppler shift of 0.5 Hz. After 10:22 UT, a spectrum spreading persisted for a long time interval, and a quasi-periodic process with amplitude of 0.2 Hz and $T \approx 10$ min occurred.

The launch of a rocket occurred at 21:04 UT on February 7, 1999. Approximately at 21:10 UT, an additional mode and the quasi-periodic process with $T \approx 8 - 10$ min, $f_{Da} \approx 0.1$ Hz, and $\Delta T \approx 40$ min appeared. After 21:50 UT, the ionosphere remained quiet, and within the 22:05–22:25 UT time interval, an abrupt decrease in f_{Da} by $0.4 - 0.6$ Hz and spectrum spreading occurred. After 22:25 UT, the ionosphere remained quite undisturbed, and the faintly discernible quasi-periodic process with $T \approx 25$ min and $f_{Da} \approx 0.10 - 0.15$ Hz occurred.

GLOBAL–SCALE PERTURBATIONS DURING SPACE VEHICLE LANDINGS

Over the interval 14:35–15:24 UT during the Space Shuttle landing at 17:04 UT on November 7, 1998, the Doppler spectra variations exhibited the $T \approx 10$ min periodicity with $f_D \approx 0.2 - 0.4$ Hz, and the signal remained one-mode or two-mode with small frequency variations in the second mode. The sharp decrease of $0.5 - 0.6$ Hz in f_D occurred between 15:24 UT and 16:05 UT, and even of 1 Hz between 15:46–15:50 UT. The next significant decrease in f_D was recorded over the 16:22–16:55 UT interval, and between 16:42 UT and 16:55 UT the signal was two-mode and the difference reached values up to 1 Hz. After 17:00 UT, the ionosphere remained weakly perturbed. During the interval 18:00–18:50 UT, marked variations in f_D of not more than 0.5 Hz and two modes were observed. We have to point out that the sunset at the ground occurred at 14:30 UT, and almost an hour later in the lower part of the F region.

DISCUSSION

The additional mode with $-0.2 \div -0.3$ Hz shift with the delay of about $60 - 80$ min for the day and night or Doppler spectrum spreading is the characteristic feature of launching sites removed from the observation site at 2,500 km. The duration of these effects is of $5 - 10$ min, and the apparent propagation speed of the perturbations is of about $410 - 570$ m/s. The speed of such an order of magnitude is a characteristics of the acoustic waves.

The faster perturbations associated with a rocket launch are observed in Doppler data randomly. Quasi-periodic processes arose in the ionosphere soon ($\Delta t \approx 2 - 4$ min) after the launch of rockets on March 22, 1999 and October 18, 1999. These time delays correspond to speeds of $v \approx 10 - 20$ km/s. Such propagation speeds are distinctive features of the gyrotropic waves in the plasma of the ionospheric E and F regions. Since rockets of the same family (Proton) were launched on March 21, 1999 and on July 5, 1999, but the latter launch was to be not followed by quasi-periodic processes, then it could be suggested that the oscillation observed on March 21, 1999 was of natural origin. In addition, it is necessary to take into account that the first launch occurred at night and the second one at the day-time, that is under vastly different conditions. It cannot be discarded such a fact that on July 5, 1999 the rocket exploded at the height up to 120 km did not possibly reach the region

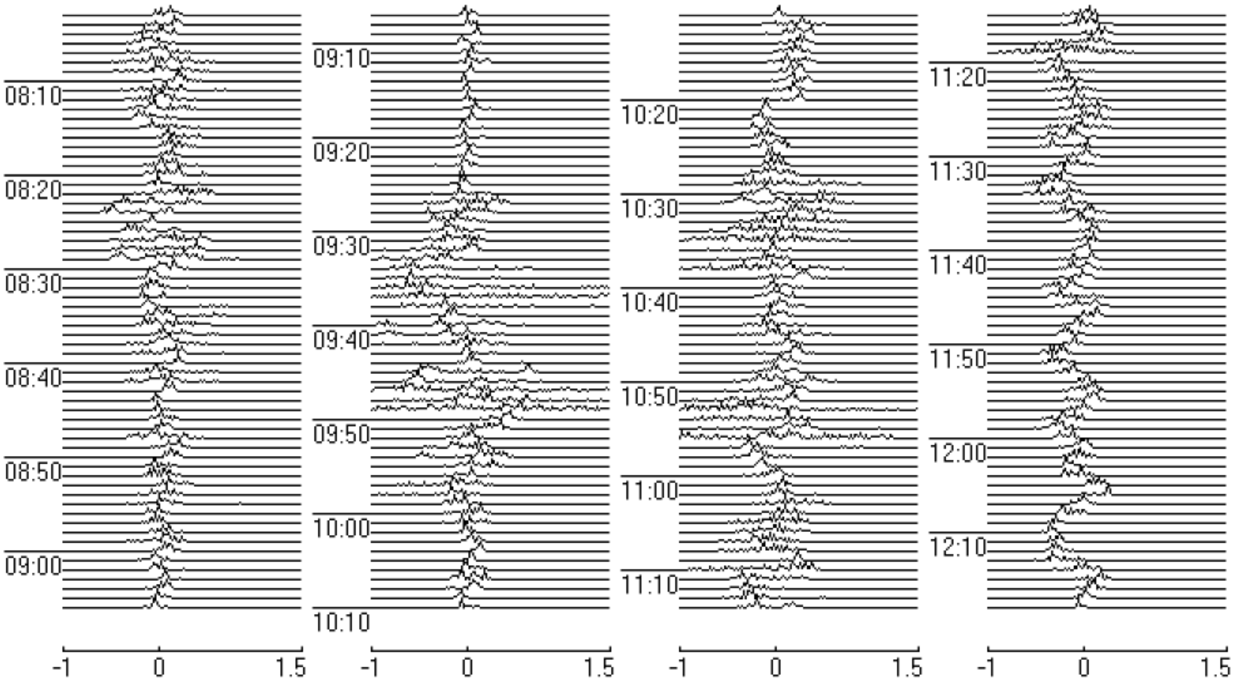

Figure 2: Doppler spectra acquired after the Space Shuttle Endeavor launch at 08:35 UT on December 4, 1998

where the gyrotropic waves were effectively generated. Regarding the acoustic momentum from the explosion, it was apparently observed from 15:04 UT to 15:05 UT and from 15:08 UT to 15:09 UT.

Next, consider global-scale perturbations. Thirty-two launches of space vehicles of different rocket families have been examined. A steady enough ionospheric response to launches from launch sites in the USA and France was observed most often in $60-80$ min after their launch. The trajectories of the rockets differed, and this could explain the variations in delay of $60-100$ min. The apparent speed is equal to $v \approx 2-3$ km/s, provided that the mean value $R \approx 10,000$ km. Such propagation speeds are exhibited by the slow MHD waves in the ionosphere. They are weakly attenuated, and, therefore, could transfer global-scale perturbations. A mechanism for perturbation transfer could be as follows. The perturbations are not from zero and first rocket stages, but from orbital maneuvering system engine burns. Although their power is significantly lower, it should be taken into account that they release the exhaust gases directly into the plasma, and electromagnetic and MHD waves are effectively generated in this case. The perturbations are often observed with delays of $6-7$ min ($R \approx 9,000-$10,000 km) and duration of tens of minutes, which correspond to a speed of 25 km/s. As mentioned above, the gyrotropic waves have such speeds.

Let us consider possible global-scale effects occurring during space vehicle landings. Six landings of Space Shuttle Orbiters have been examined. A steady enough ionospheric response was observed to occur $70-90$ min prior the landing with the temporal duration of tens of minutes. For example, for landing on December 28, 1999, the delay of 12 min was determined from the decrease in direct bias in a long-period Doppler shift and from the appearance of new spectral components with $T \approx 2$ min, $T \approx 4$ min, and $T \approx 8$ min, giving an apparent perturbation transfer speed of a few tens of km/s.

The second group of quasi-periodic perturbations has delays of $\Delta t \approx 80$ min, $\Delta T \approx 40$ min, and $T \approx 10$ min and $T \approx 20$ min. Provided these processes are associated with deorbit burns of orbital maneuvering system engines, their apparent speed is of the order of unit of km/s. The slow MHD waves have the same speeds.

CONCLUSIONS

1. Acoustic perturbations (sound and acoustic gravity waves) propagate from rocket engines along the earth's surface in the ionosphere at distances not less than 2,300 km. The ionospheric F region often becomes turbulent and Doppler spectra spread after the arrival of these perturbations.

The perturbations are quite often observed to exhibit propagation speeds vastly exceeding the limits of ionospheric acoustic propagation at distances up to 2,300 km from a rocket. They have velocities of $10-20$ km/s. This statement, however, needs further investigations.

2. Global-scale perturbations are observed in the ionosphere during rocket launches at distances of about 10,000 km. The mechanism for their transfer might be linked to both main engine burns in the near-earth atmosphere and orbital maneuvering system or upper rocket stage burns in the ionosphere. The latter suggestion is preferable because the mechanism for the generation of electromagnetic and MHD waves by a plasma jet in the plasma is well understood, and the waves in question are most probably the gyrotropic waves. According to our observations, they have speeds of $10 - 25$ km/s.

3. Approximately $60 - 80$ min before the landing of a space vehicle, perturbations are recorded a few tens of minutes in duration, which is plausibly associated with deorbit burns of orbital maneuvering system engines. The apparent propagation speeds of these perturbations are of about $10 - 20$ km/s, while for the second group of perturbation $v \approx 2 - 3$ km/s.

4. Three groups of speeds are observed in these experiments: $0.5 - 0.7$ km/s and less, $2 - 3$ km/s, and $10 - 25$ km/s. They apparently correspond to the acoustic and acoustic gravity waves, the slow MHD waves, and the gyrotropic waves, respectively.

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