PROBING OF THE ARTIFICIAL HOLE IN THE IONOSPHERE WITH THE HF SKYWAVE RADAR

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ABSTRACT

This paper explains the experiment that HF skywave radar probed the artificial ionospheric hole, which is caused by the flames of the rocket vertically launched and penetrated the ionosphere. After the rocket had passed through the ionosphere, the minimum time-delay P_{min}-f on the backscatter ionograms obviously appeared with wave and focusing stripes resulting from the irregular structure etc. The results indicated that there was a low electron density zone, the artificially created hole in the ionosphere along the propagation path. Under the asymmetry quasi-cosine ionospheric hole model, the experimental P_{min}-f was simulated with the technique of ray tracing. It was deduced that the range size of the hole in ionosphere along the radar beams was some 573 km and the critical frequency of the center was 2.6 MHz lower than the background critical frequency (12MHz). The ionospheric environment 350km away from the launching site was disturbed and the propagation velocity of the ionospheric disturbance was about 50m/s.

Key words: HF backscatter propagation, artificial ionospheric hole, HF sky-wave radar, 2- D ray tracing

Ⅰ INTRODUCTION

On 14 May 1973, the US Scientists observed the ionospheric effects of the launching of the Space Laboratory with the launching rocket of Saturn V by Faraday effect technique along the Atlantic Coast in the northern part of USA. They found that there were large quantity of electron compound in the ionosphere due to the spurt flames of the rocket which contained large quantity of hydrogen and water molecules thus the artificial ionospheric hole was formed which had the electron density much lower than that of the background in range of about 1000km[1]. In 1980s three observations with vertical ionosphere sounding for the vertical launching of large sized rockets penetrating the ionosphere in China showed that there were obvious descend of ionospheric critical frequency with the abnormality of the echo[2,6].

We first observed the ionospheric effect with the HF skywave backscattering radar after the launching of a large sized rocket penetrating the ionosphere and obtained the expected results. This was the first successful observation of the artificial ionospheric hole with such radar. Under the asymmetry quasi-cosine ionospheric hole model, the experimental P_{min}-f curve was simulated to fit with the technique of ray tracing. The range size of the hole in ionosphere and the propagation velocity of the ionospheric disturbance had also been deduced.

Ⅱ DESIGN AND BASIS OF THE EXPERIMENT

We have done the analysis with the

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technique of ray tracing for the affection of the minimum time delay (P_{min}-f) of the backscattering ionogram caused by the disturbed ionosphere [3,4] and found that the bend fluctuation of the P_{min}-f in the ionospheric backscattering ionogram could be caused by the small scaled disturbance of the electron density of ionosphere which shape was relevant to the horizontal gradient of the ionosphere and its changes. This had been verified by the observation of the annular solar eclipse effect happened on 23 Sept. 1987 with the HF Sky-wave Radar. So, if the there was large quantity electron compound emerging in the ionosphere due to the rocket flame thus causes the artificial zone of low electron density, then there should be bend fluctuation of the P_{min}-f in the ionospheric backscattering ionogram. When the hole was formed, there should be obvious horizontal positive and negative ionospheric sectional gradient changes and the corresponding turning point at $\partial P_{min}/\partial f \Rightarrow 0$ in ionospheric backscattering ionogram. So, the frequency sweep backscattering ionogram was taken as the basic data for analysis.

The beam azimuth of the probing radar was offset about 200km northwest from the launching site in order try to obtain the information of scale, existent period and the horizontal disturbance velocity of the artificial ionospheric hole. So, the beam was not pointed to the center of the launching site but intersected with edge of the imaginary hole.

The HF radar was working in the auto-frequency sweep mode with the sweeping range from 5-25MHz. The experimental record was the backscattering frequency sweeping ionogram P~f but the curves of minimum time delay P_{min}-f have been analysed as a main data.

On the launching day, from 15^h30^{min} to 19^h00^{min} the ionosphere was observed twice every ten minutes, other time once every 30 minutes.

Ⅲ THE OBSERVED DATA

A. Fluctuated P_{min}-f of the HF backscatter ionogram

The launching time of rocket was 16^h10^{min} and the observed backscattering ionogram kept normal without fluctuation till $17^h\,05^{min}$. From $17^h\,05^{min}$ to $17^h\,50^{min}$, there appeared a clear bending in the minimum time delay P_{min}-f between 13~20MHz frequency and in the distance region of 700-1700km. At 17^h23^{min} the obvious fluctuation reached the maximum. And it was recovered to normal till 18^h00^m to the shape of sunset and night. Fig. 1 shows the variation of time sequence of P_{min}-f in the backscattering ionogram after the launching of the rocket at $16^h04^{min.}$ the dot line showing the non-fluctuated minimum time delay as reference.

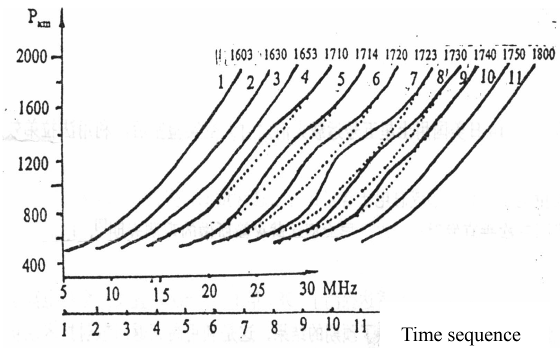

Fig.1 Variation of time sequence of P_{min}-f in backscattering ionogram

B. Abnormal additional tracks in ionogram

6^{min} after the launching of the rocket, namely at 16^h10^{min}, except the quasi-vertical reflection echo in the quasi-vertical reflection zone in the ionogram, there emerged some abnormal additional tracks (it is also called branch tracks) which was a little bit lower than the quasi-reflecting track in F layer with the virtual height of about 260km, and the reflecting frequency from 9.4--13.2MHz point out by the arrow in Fig. 2a. The strange tracks had appeared three times in the ionogram obtained in the vertical sounding station 50 km away from the launching site when the rocket penetrating the ionosphere [2]. and the time were 154s, 164s, 190s respectively.

Fig. 2 a) The abnormal tracks in ionogram at 16^h10^{min}, b) the focus stripe of the irregular in ionogram at 16^h23^{min} (point out by the arrow). the white line is the calculated value of P_{min}-f with the ionospheric hole model

C. Focus-strips of irregular in ionogram

After 17^h14^{min} there were focus-strips of the irregular in the backscattering ionogram along the oblique range of 1000 km. The focus strips of the irregular in the backscattering at 16^h23^{min} as shown by the arrow in Fig.2b

Ⅳ ANALYSIS AND DISCUSSION

A. Model of artificial ionospheric hole

In order to study the artificial ionospheric hole with the technique of fitting of two-dimensional ray tracing, a model of asymmetric quasi-cosine hole of the variation of electron density with height and the distance of geocentric angle θ was considered, if it could be simply expressed with the critical frequency, it should be

$$N_e(r,\theta) = \frac{f_c^2(\theta)}{80.6}\left\{1 - \left(\frac{r - r_m}{r_m - r_b}\right)^2\right\}$$

where,

$$f_c(\theta) = \begin{cases} f_c(0) + x\theta - \Delta f_c Cos(2\pi R(\theta - V_1)/\lambda_1) \\ \qquad V_1 < \theta \le V_2 \\ f_c(0) + x\theta - \Delta f_c - \Delta f_c Cos(2\pi R(\theta - V_2)/\lambda_2) \\ \qquad V_2 < \theta \le V_3 \\ f_c(0) + x\theta \qquad \theta \le V_1 \text{»ò} \theta > V_3 \end{cases}$$

$$\frac{df_c(\theta)}{d\theta} = \begin{cases} x - \frac{2\pi R\Delta f_c}{\lambda_1} Sin(2\pi R(\theta - V_1)/\lambda_1) \\ \qquad V_1 < \theta \le V_2 \\ x + \frac{2\pi R\Delta f_c}{\lambda_2} Sin(2\pi R(\theta - V_2)/\lambda_2) \\ \qquad V_2 < \theta \le V_3 \\ x \qquad \theta \le V_1 \text{»ò} \theta > V_3 \end{cases}$$

Where v_1, v_2, v_3 are the geocentric angle positions (rad) of the front, center and the back calculated from the radar station. f_c (0) the critical frequency(MHz) of the top side of the radar station. x is the background negative gradient of the critical frequency (MHz/rad). $(\lambda_1+\lambda_2)/2$ is the disturbed range (km) of the ionosphere in the reflecting area along the direction of radar beam. Δf_c is the fluctuation amplitude of the critical frequency of the hole (MHz/rad). r_m, r_b, are the height of maximum electron density and the bottom height in ionosphere calculated from the geo-center respectively. The model was at about θ = v_1, v_2, v_3 and f_c (θ) and the value of first order differential coefficient respectively as:

$$f_c(v_1)_+ = f_c(v_1)_- = f_c(0) + xv_1, \frac{df_c(V_1)_+}{d\theta} = \frac{df_c(V_1)_-}{d\theta} = x;$$

$$f_c(v_2)_+ = f_c(v_2)_- = f_c(0) + xv_2 - 2\Delta f_c, \frac{df_c(V_2)_+}{d\theta} = \frac{df_c(V_1)_-}{d\theta} = x;$$

$$f_c(v_3)_+ = f_c(v_3)_- + f_c(0) + xv_3, \frac{df_c(V_2)_+}{d\theta} = \frac{df_c(V_3)_-}{d\theta} = x;$$

It can be seen from the above that, f_c (θ) and its differential coefficient at the joint point θ = v_1, v_2, v_3 are successive, because the vertical distribution of electron density is also successive.

B. Parameters of artificial ionospheric hole

With the technique of two-dimension ray tracing and in the model of the above stated ionospheric model of asymmetric quasi-cosine hole, the P_{min}-f of the ionogram at 17^h30^{min} was simulated. It shows that model below with the parameters of the ionospheric hole, the calculated value of P_{min}-f has good agreement with that of the experimental data. The parameters of the ionospheric hole model were: r_b=6570km, r_m=6700km, $f_c(0)$ =12.4MHz, x= -5MHz/rad, Δf_c = -1.3MHz/rad, λ_1=764.4km λ_2=382.2km V_1=0.035rad, V_2 =0.095rad, V_3=0.125rad, so, the maximum disturbing amplitude of the critical frequency was 2.6MHz lower than the background critical frequency and the width of the disturbed zone along the detecting path was 573.3km.

Fig.3 shows the profile of the electron density of the ionosphere of the model F (the variation of the ionospheric electron density with θ) and the trace of the minimum time delay P_{min} vs all frequencies at17^h30^{min}. In fig.3 ray a, b, … j is corresponding P_{min} at frequency 13, 14, … 24MHz respectively.

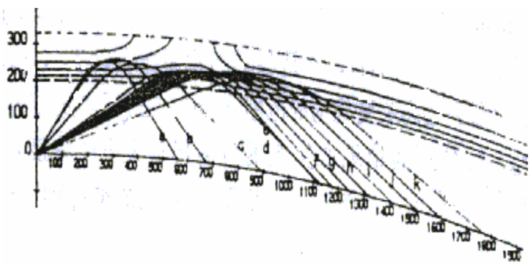

Fig.3 At 17^h30^{min} the P_{min} of model of asymmetric quasi-cosine hole simulate by ray tracing

Because the ray was offset 200 km from the launching site, the above parameters are not the parameters of the artificial ionospheric hole, but that of the tangential section of the radar ray around the edge of the hole. Therefore, according to the relative geometric positions of the radar ray and the launching site, it was deducted that ionosphere 350 km away from the launching site had also been disturbed by the rocket flame. In other words if assume the artificial ionospheric hole is a circular hole, then the size of hole was deduced about 700km. It is a pity that the parameters of the ionospheric hole is not approved because of the lack of the vertical sounding data from the directions of eastward or northeastward from the launching site.

C. Existent duration of hole and propagation velocity of the disturbance

The HF backscattering ionogram shows that the ionosphere along the direction of radar beam (200 km away from the launching site) was disturbed 60 minutes after the launching and the deducted propagation velocity of the disturbance is 50.5m/s. The apparent ionospheric disturbance along the direction of radar beam lasted more than 40 minutes.

Considering the fact that the ionospheric disturbance above the launching site lasted two hours and ten minutes, which was shown by the data obtained by a vertical ionospheric sounder near the launching site, it can be deducted that the Maximum time of the disturbed zone caused by the rocket flames 17^h23^{min} namely, 79 minutes after the launching of the rocket and the ionosphere 350 km away from the launching site was also disturbed. Later, the edge of the Maximum disturbed zone began to recombine gradually, and the ionosphere along the direction of radar beam recovered after 27 minutes. Then the disturbed area continually narrowing till 18^h16^{min} the recovery of the ionosphere above the launching site. The whole course lasted 132minutes.

D. Explanation of the energy focus strips of irregular

There was obvious horizontal gradient along the direction of radar beam because of the existence of the low electron density area.

At this time, usually, the uniqueness characteristics of the extremum of the time delay P vs angle in the backscattering ionogram obtained from the stratified homogeneity model, had been damaged to form two multi extremum of the complex curves or more [5]. Therefore, the time delay corresponding to the points of extremum would not be the minimum time delay. And near the points of extremum $dP/d\alpha = 0$, the flux of the ray within the angle or the unit time increased, so the energy outside of these time delays focused. From this, it is known that among these extremums, the one corresponding to the minimum time delay was the minimum time delay. Otherwise, it was the time delay of focused energy. Time delays of the focused energy at different frequencies formed the focused strips on the ionogram. So, focused strips were the important characteristics of the backscattered ionogram of the disturbed ionosphere.

E. The Target Characteristic of the Rocket

Researches show [7] that the radar cross section of the rocket body is determined by its physical dimension which exists in the resonance range in the HF band. But the radar cross section of the rocket flame varies with the height in HF band and the maximum value of RCS reaches 40dB. The spectrum analysis shows that echo of the rocket has the characteristics of double peak spread, namely the combination of spectrums of the rocket body and that of the flame. The latter usually has wider spreading in spectrum. If the rocket turns off without flame, it is very difficult for the HF Sky-wave radar to find the rocket target. However, the artificial ionospheric hole due to the ionospheric electron combined by the large quantity of neutral molecular caused by the rocket flame that makes descending of the electron density can be fond by the HF sky-wave radar. Therefore it is possible to fond and trace the target like rocket from the launching of the rocket till the rocket enter the ionosphere by the HF sky-wave radar.

Ⅴ CONCLUSIONS

The analysis of the experimental data shows that it is feasible to probe the artificial ionospheric hole with HF Backscatter Radar. As the first experiment for such purpose it was also a successful one. And it was also feasible and reasonable for the deduction of the parameters of the low electron density zone of the ionosphere with the technique of fitting of two-dimensional ray tracing and the experimental data under the model of asymmetric quasi-cosine hole.

The target characteristic of the rocket shows that it is possible to fond and traced the target like rocket from the launching of the rocket till the rocket to enter the ionosphere by the HF sky-wave radar.

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