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IONOSPHERE PROBING WITH A HIGH FREQUENCY SURFACE WAVE RADAR

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Abstract—This paper describes how the ionosphere reflected echoes observed by a high frequency surface wave radar (HFSWR) can be processed to extract information regarding the ionosphere sporadic E (Es) and F2 layers. It is shown that the range/time spectrum contains the data to estimate the occurring time and virtual heights of both the still and drifting Es layer clouds. In addition, for the drifting Es the data can be processed to extract the time-varying ranges and estimate virtual heights, horizontal drifting speeds. Information regarding the F2 layer such as the time-varying virtual heights can also be extracted. The time-frequency distributions (TFD) of the Es and F2 layer echoes calculated after the range migration compensation can be used to extract the intrinsic Doppler patterns. This is further used to obtain information on the internal non-uniform structures and disturbances such as the travelling ionospheric disturbances (TID) that are due to the acoustic gravity waves (AGW). Processing results of echo data collected by the portable HFSWR system named OSMAR-S demonstrate the validness of the above methods.

1. INTRODUCTION

Ionospheric propagation of radio waves impact human activities, such as wireless communication, broadcast, radio navigation and radar positioning. The height and electron density of the ionosphere are affected by the solar radiation energy, which results in frequency shift, phase fluctuation and polarization state variations in radio signals [1–3]. At times, solar disturbances lead to remarkable deviations to the regular ionosphere state, e.g., ionosphere storms and sudden

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ionosphere disturbance (SID), which may severely interfere with the communication signals that propagate via the ionosphere. Detection and analysis of the ionospheric variations can help diagnose the solar activities and provide measurement supports for forecast of the solar-terrestrial environment. The ionosonde [4, 5] is a ground-based instrument used to measure the ionosphere. The instrument measures the structure and state of the ionosphere, up to the F2 layer, by measuring the virtual heights, Doppler shift and polarization of reflected high-frequency (HF) radio waves. When operated in the ionogram mode, the ionosonde radiates a band of frequencies to provide height profiles of the electron density. However, the Doppler resolution obtainable from an ionosonde is too low to accurately detect the ionosphere disturbance. The Doppler shift of the ionosphere reflected HF echoes is one major parameter for the ionosphere research. Doppler observing networks [6, 7], have resulted in a greater understanding of the regional disturbance characteristics such as, ionospheric variations and irregularities, and the Doppler shift and group delay of the HF radio waves. These Doppler observing systems have the disadvantage of being band limited, but they are relatively simple systems and are very sensitive and provide long observation periods. They also have low system and operating costs which make these Doppler observing systems an effective means for ionosphere probing. Other systems that can be used for ionospheric monitoring include HF sky wave radar [8, 9], and HF surface wave radar (HFSWR) [10, 11]. There are a limited number of HF Sky wave radar systems that tend to require very large sites and come at a high price, and like the Doppler observing system, the information obtained is not local to the site.

HF surface wave radar (HFSWR) is routinely used to remotely sense the sea surface dynamics and surface traffic [12]. Currently there are more than ten HFSWR sites in operation in China, and more than two hundred worldwide. Typically a HFSWR uses a vertical whip antenna to radiate electro-magnetic waves along the sea surface, but due to the undesired antenna pattern in the zenith zone, part of energy is directed upward to the sky and reflected by the ionosphere, thus resulting in ionospheric clutter [13, 14]. The ionospheric clutter is a main adverse factor in both the extraction of the sea echo as well as surface vessels. However, this ionospheric clutter contains significant information regarding the ionosphere [15]. The analysis of the ionosphere-reflected echoes obtained from HFSWR reveals information on the ionospheric structure and Doppler patterns, and accurately detects the ionospheric disturbances. To enhance the ionospheric echoes and weaken the sea echoes, traveling wave delta antennas can be used in place of the whip antennas to transmit and receive [16, 17]. In this paper, echo data from OSMAR-S (Ocean State Measuring and Analyzing Radar), a portable HFSWR with crossed loops/monopole antenna developed by Wuhan University of China, are used to extract the virtual heights and Doppler patterns on different ionosphere layers. Like the Doppler observing systems, the OSMAR-S HFSWR works at a single fixed frequency and has relatively low range resolution (several kilometers). However, it has the advantage of high Doppler resolution and accuracy, long detection duration and low operation cost. Moreover, the HFSWR provides the ionospheric information of the local region. It is shown that this ionospheric data is a useful by-product for HFSWR and that the growing use of HFSWR networks can serve as an effective supplement of the existing ionosphere probing network.

2. IONOSPHERIC ECHO SPECTRA IN HFSWR

HFSWR often works at a fixed frequency with linear frequency modulation (LFM). The data in this paper are all from the echoes collected by OSMAR-S, which transmits with a monopole and receives with a crossed loops/monopole antenna combination. The main system parameters of the OSMAR-S HFSWR are as follows:

Center frequency (f_0): 5, 7.5 or 13 MHz, can have some offset.

Bandwidth (B): 30 or 60 kHz.

Range resolution (ΔR): 5 or 2.5 km.

Maximum unambiguous range (R_{un}): $100 \times \Delta R$.

Sweep period (T): 0.38 s.

Coherent processing time (CPT): 393 s (1024 sweeps used for sea state measurement).

Doppler resolution (Δf): 0.0025 Hz.

Average power (P_{ave}): 100 W.

In HFSWR, the ionospheric clutter is a major adverse factor against detection performance. However, these ionospheric echoes can provide useful information on the ionosphere whilst still providing information on sea states and the location of surface vessels. Since the ionospheric echoes overwhelm the sea echoes in energy at the same ranges, high quality ionospheric information can be obtained. Typical range-time spectra of echoes from OSMAR-S at Penglai, Shandong Province of China (N37°49.87', E120°44.61') is shown in Figure 1, with (a) the long duration range/time spectra (about 13 hours) and (b) the short duration range/time spectra (about 6.5 minutes). The operating frequency is 7.5 MHz. The radar's range/time spectra are identical to

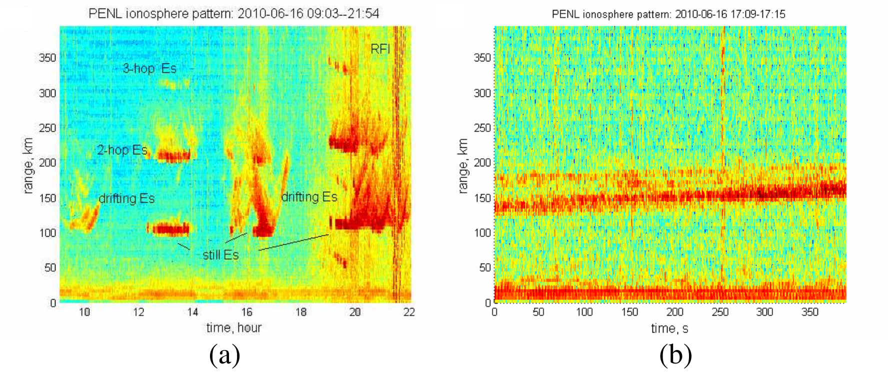

Figure 1. Ionospheric echoes received by OSMAR-S at Penglai, 7.5 MHz. (a) Long-duration range/time spectra (9:03 to 21:54 on June 16, 2010). (b) Short-duration range/time spectra (17:09 to 17:15).

the virtual height diagrams given by ionosonde at one frequency, and from them we can clearly see the layered structure of the ionosphere, whether there are multi-hop echoes and if the electron clouds are drifting or not. In Figure 1(a), the horizontal strips at about 110 km are from the Es layer, and those at about 220 and 330 km are of 2- and 3-hop Es, respectively. They are due to the reflection from still Es clouds, whose occurring time is clearly indicated in the spectra. Meanwhile, there are V-shaped (actually quasi-sinusoidal) or single-side V-shaped oblique traces, which results from reflection by horizontally drifting Es clouds. The long-duration reflection range variations, group delay, can be read from Figure 1(a). Within a short period, e.g., in one CIT, the range variation is not obvious from Figure 1(b), but the short-duration spectra provide finer Doppler patterns and variations, and thus further state information, of the clouds at a given range.

3. ESTIMATION OF VIRTUAL HEIGHT AND DRIFTING SPEED OF ES CLOUD

The V-shaped traces in HF radar range/time spectra can be used to estimate the height and drifting speed of the reflection cloud. In the vertical plane coordinate system, with the radar as the origin (see Figure 2), the refection point's coordinate is $(x,\ z)$. Assume that the Es cloud is drifting horizontally. The vertical movement of the cloud is neglected since the height of the Es layer has small variations and the radar's range resolution is relatively low (often several kilometers).

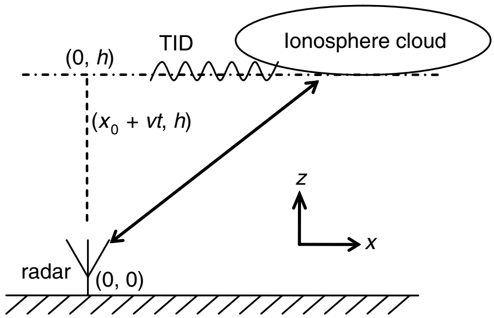

Figure 2. Oblique reflection of a horizontally drifting cloud.

The range of the reflection cloud to the radar is given by

$$R(t) = \sqrt{x^2(t) + z^2} = \sqrt{\left(x_0 + \int_0^t v(\tau)d\tau\right)^2 + h^2} \tag{1}$$

where x_0 is the initial abscissa (when $t = 0$), $v(t)$ is the horizontally drifting speed, and h is the reflection height. By extracting the V-shaped traces in the range/time spectra, the reflection range $R(t)$ can be estimated. We can estimate h by the bottom of the trace, calculate the abscissa, x, of the cloud, and then obtain the horizontally drifting speed by $v(t) = dx/dt$. For simplicity, a constant drifting speed is assumed so Equation (1) reduces to $R(t) = \sqrt{(x_0 + vt)^2 + h^2}$, from which we can obtain h, x_0 and v by fitting the traces. For example, the heights and drifting speeds of the 5 traces in the long-duration range/time spectra in Figure 1(a) are calculated and shown in Figure 3. The estimated drifting speeds are between 50 to 100 m/s.

4. IONOSPHERIC DOPPLER PATTERNS

Based on the range/time spectra, a further Fourier transform (FT) on the temporal sequences at each range bin gives the range/Doppler spectra. Or alternatively, time-frequency analysis (TFA) can be used to obtain the time-frequency distributions (TFD). Spectrogram is the approach used in this paper. The stationary or time-varying Doppler characteristics provide Doppler patterns of the ionosphere, which contain fine detail information of the ionospheric disturbances, such as occurrence of the Es layer, traveling ionospheric disturbance (TID) and ionospheric storms.

The range/Doppler spectra of the data in Figure 1(b) are presented in Figure 4(a), and the TFD at range 150 km, in Figure 4(b).

From the figure we observe that, the oblique Es reflection echo spreads in both range and Doppler dimensions. It can also be observed that the TFD has a large spread and appears like colored noise, with the Doppler spread exceeding the range of the Doppler analysis bandwidth (± 1.3 Hz). This spread results from the non-uniform structures in the Es cloud, where the summation of random echoes of the independent reflections both blur and spread the TFD.

Another data set of range/Doppler spectra, collected using OSMAR-S at Weihai, Shandong Province of China (N37°31.61', E122°96.19'), is shown in Figure 5(a). The 1-, 2- and 3-hop Es echoes from vertical reflection at about 110, 220 and 330 km respectively can be observed, as well as the Es echo occurring from oblique reflection

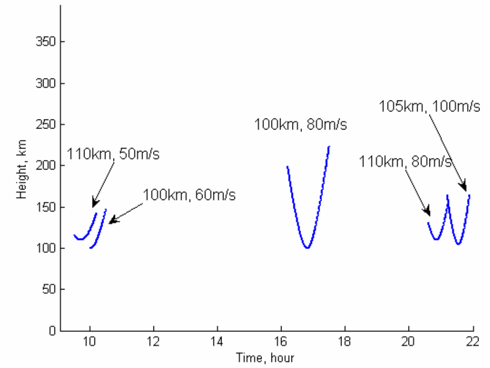

Figure 3. Traces of drifting Es clouds and their heights and speeds.

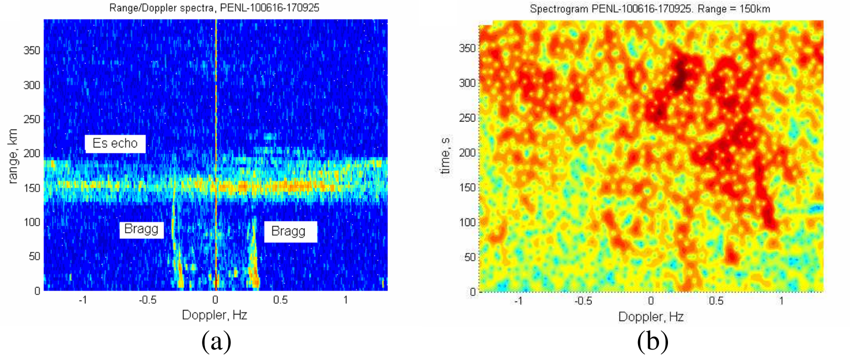

Figure 4. Echo spectra by OSMAR-S (17:09 on June 16, 2010, Penglai, 7.5 MHz). (a) Range/Doppler spectra; (b) TFD (spectrogram) at range 150 km.

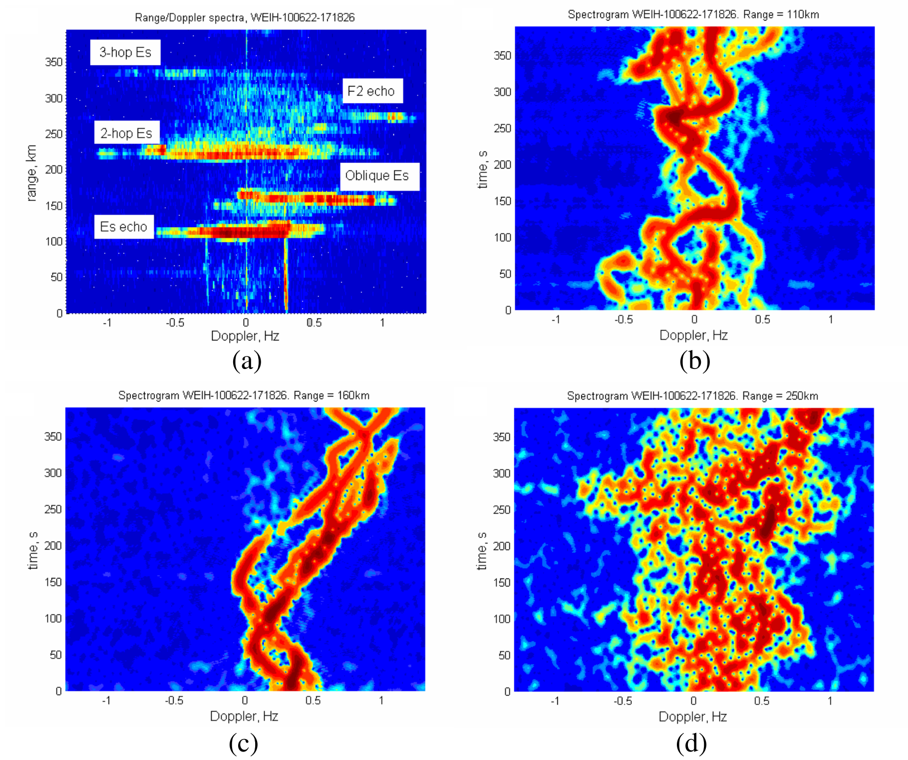

Figure 5. Echo spectra collected by OSMAR-S (17:18 on June 22, 2010, Weihai, 7.5 MHz). (a) Range/Doppler spectra; (b) TFD (spectrogram) at 110 km; (c) TFD at 160 km; (d) TFD at 250 km.

at about 160 km, and F2 layer echo at greater than 250 km. All these reflections can be observed to have a Doppler spread of greater than 1 Hz. Figure 5(b) presents the TFD in one coherent processing time (CPT) at 110 km, where multiple, continuous, S-shaped time-frequency components with Doppler variations between -1 and $+1$ Hz can be observed. These components are due to reflections from regular structures in the Es layer that contain traveling ionospheric disturbances (TID). This is the result of acoustic gravity waves (AGW) with periods of several minutes. Figure 5(c) presents the TFD at 160 km, which also consists of multiple, continuous, S-shaped time-frequency components. Again these are due to oblique reflection by Es cloud containing a TID component. Figure 5(d) illustrates the TFD at 250 km, corresponding to echoes of the ionosphere F2 layer. Although multiple continuous time-frequency components can be observed, they

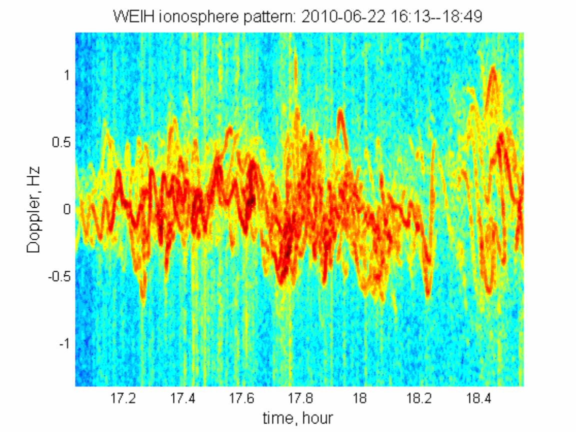

Figure 6. Es Doppler pattern at 110 km, recorded by OSMAR-S, 16:13 to 18:49 on June 22, 2010, Weihai, 7.5 MHz.

are blurred and cannot be clearly separated. This is due to the F2 layer being much thicker than the Es layer, where frequently appearing non-uniform structures, multiple-path effect and flicker phase noise result in randomness in the echoes.

Figure 6 presents the TFD of the Es echoes at 110 km, where the pattern of quasi-sinusoidal Doppler variation is obvious. There are multiple time-frequency components, with Doppler range within ± 1 Hz and periods of several to more than ten minutes, where small-scale fluctuations are superimposed on the larger ones. This is due to the TID caused by the AGW, and the related parameters can be estimated by the Doppler pattern. Moreover, there are components with similar instantaneous Doppler but different strengths. They may correspond to ordinary and extraordinary waves.

Figure 7 shows the F2 echoes recorded by OSMAR-S at Dachen Island, Zhejiang Province of China (N28°27.41', E121°55.29'). The radar carrier frequency is 7.5 MHz. Figure 7(a) shows the range/time spectra, where the F2 echoes between 220 and 340 km are readily distinguishable. It can be observed that their virtual heights have large variations as a function of time. According to the Appleton formula [1], when collisions and the magnetic field are negligible, the refraction index is given by $n = \sqrt{1 - \frac{80.5N}{f^2}}$, where f is the frequency of radio wave in Hertz and N is the electron density in electrons per cubic meter at the reflection point. At the reflection point, we have $n = 0$, and thus $N = \frac{f^2}{80.5}$. Therefore, since the HFSWR uses a fixed frequency

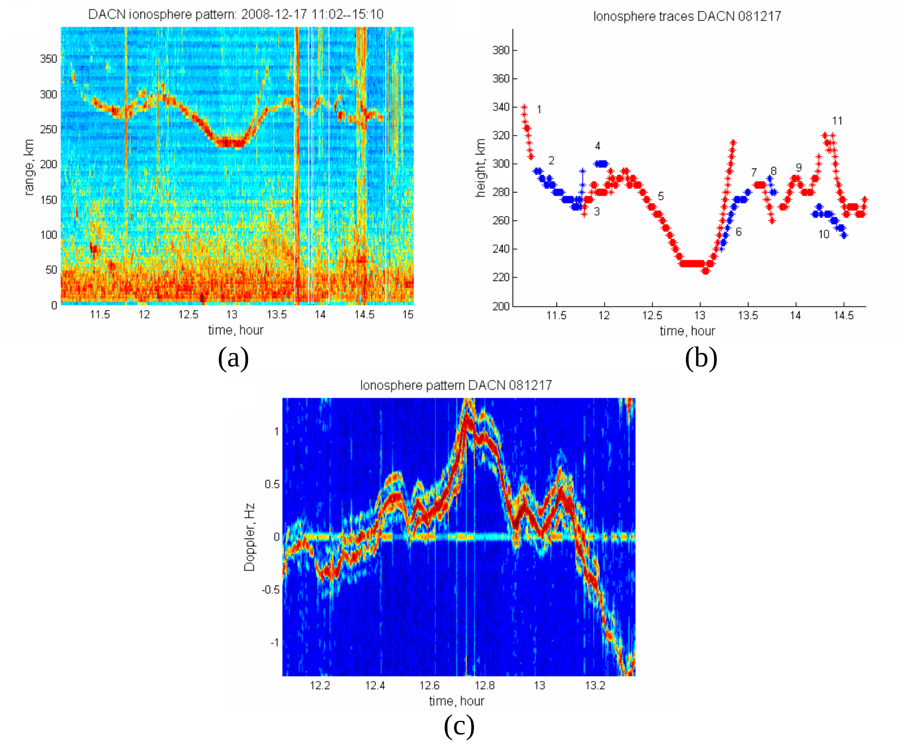

Figure 7. F2 layer patterns recorded by OSMAR-S, 11:02 to 15:10 on December 17, 2008, Dachen Island, 7.5 MHz. (a) Range/time spectra; (b) ionospheric traces extracted from (a); (c) doppler pattern of No. 5 trace after group delay (or range migration) compensation.

or linear frequency modulation (LFM) with a bandwidth of several tens of kHz, the virtual height and the corresponding electron density can be read out from the radar's spectra. The traces of the F2 echoes in the range/time spectra also give the profile of the electron density, i.e., $N \approx 7 \times 10^{11}(\mathrm{m}^{-3})$ for $f = 7.5\,\mathrm{MHz}$. Figure 7(b) illustrates the F2 traces extracted from Figure 7(a), consisting of eleven separated traces. The TFD of the fifth trace after group delay (or range migration) compensation is shown in Figure 7(c). The time-varying Doppler pattern is obvious, and it is noticeable that, around the major time-frequency component (with deviations of about $\pm 0.2\,\mathrm{Hz}$), there are two weaker components with similar instantaneous Doppler patterns. This may be due to ordinary and extraordinary waves by magneto-ionic splitting.

Using the TFD and Doppler patterns of the Es and F2 echoes, we can diagnose the occurring time of the Es clouds and other irregularities, whether there are disturbances such as TID, and further estimate the parameters of the disturbances such as amplitudes and periods.

5. CONCLUSIONS

Variations in the height of the reflection point and electron density on the wave path of ionospheric echoes are two main factors to form the Doppler shift, called differential effect and integration effect, respectively. Though the two effects cannot be completely isolated, a respective study is helpful for simple and direct description of the ionosphere. Fine Doppler patterns can be used in combination with the virtual heights obtained from the range/time spectra obtained with low range resolution, to better describe the state and motion of the ionosphere.

Usually the echo from a regular ionosphere has a concentrated TFD. However, the TFD will consist of multiple components when there are more than one reflection point at the same height with each point having a different speed, multi-path propagation or magneto-ionic splitting (resulting in ordinary and extraordinary waves). The superimposed time-frequency components cannot be readily separated, thus producing difficulties for further ionospheric information extraction. However, use of the directionality of the radar's receive antenna in both elevation and azimuth angles, can help separate the components, and using antennas with different polarization, e.g., crossed delta traveling wave antennas or horizontal whips, in place of the vertical whips, can help separate the ordinary and extraordinary waves.

In this paper, we obtained the ionospheric height diagrams based on the echoes collected by HFSWR OSMAR-S, extracted the occurring time and virtual heights of Es and F2 layer, estimated the drifting speeds of the Es clouds, and extracted the time-varying Doppler patterns of both layers. Although the HFSWR used worked at a fixed frequency and has low range resolution, the Doppler measurement of high accuracy and the long-duration continuous ionosphere probing capability make it an effective instrument for ionosphere probing, and is beneficial to accumulation of the ionosphere data and related researches and applications. Accompanied with the development of the HFSWR, new technologies of using time-divided or simultaneous multi-frequency and bi- or multi- static scheme can provide additional ionospheric data and information.

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