A method for separating O-wave and X-wave and its application in digital ionosonde

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ABSTRACT

Separation for O wave and X wave is a very important job in interpretation of ionograms, which is premise for automatic scaling. In this paper, a new digital method for separating O wave and X wave is presented, based on a numerical synthesizing technique, which is different from using image recognition to separate trace O and trace X in the ionograms, and from using the electrical method to synthesize and detect circularly polarized waves. By replacing analog phase shifters and switches in existing ionosonde with digital phase shifters with different initial phase, 0°, +90°, −90°, circularly polarized waves are synthesized digitally within the range of 1-30 MHz, which eliminates the nonlinearity and expands the bandwidth of the ionosonde, and there is no need to switch the analog switches continuously. The new method has been successfully applied to CAS-DIS ionosonde and testing results show that the new digital method is capable of separating O wave and X wave well.

1. Introduction

Vertical sounding of the ionosphere is a standard technique to study the electron density profile in the lower ionosphere. By scanning the transmitted frequency from 1 MHz to 30 MHz and measuring the time delay of any echoes, a vertically transmitting sounder can provide a profile of electron density vs. height. This is possible because the relative refractive index of the ionospheric plasma is dependent on the density of the free electrons Ne. This simplified principle is somewhat more complex in practice since the group velocity of the radio wave is slower in the ionosphere so the height obtained using the time delay of the echo is an overestimation of the actual height of reflection.

According to the magnetoionic theory, the propagation of radio waves through the ionosphere is significantly affected by the presence of the Earth's magnetic field. With regard to this, the Appleton equation shows that the refractive index can assume two values, this results in the splitting of wave incident into the ionosphere in two components, known as the ordinary wave (O-wave) and extraordinary wave (X-wave). The O and X waves propagate with different velocity and therefore appear as two distinct echoes in ionograms; it is then necessary to distinguish the ordinary mode of reflection for implementing the true height analysis as the one performed by the Polan program [Titheridge 1998] or the ARTIST system [Huang and Reinisch 1996].

Currently, there are mainly two kinds of method used for separating the O-wave and X-wave, using image recognition technique and using antenna arrangements. Image recognition technique for the separation of O-wave and X-wave has no requirement to the antenna of the ionosonde, such methods extract the trace O and trace X in ionograms by digital image processing technology. A more detailed review of these methods can be found in Pezzopane and Scotto [2007], Scotto [2009] and Krasheninnikov et al. [2010]. The separation of O-wave and X-wave can be done in an alternative way, electrically combining signals from perpendicularly orientated receiving antennas, in such a way that the two modes of the echoes can be determined. A typical representative of such an equipment is DPS-4 digisonde produced by the University of Massachusetts, Lowell [Reinisch et al. 2009] or the VIPIR ionosonde developed by Scion Associates, supported by the US Air Force Research Laboratory and their Small Business Innovative Research Program [Bullett et al. 2010]. In DPS-4, a cross antenna system, an analog ±90° phase shifter (2-32 MHz) and a series of analog switches are used to synthesize broadband circularly polarized waves, and consequently recognize the polarization of the ordinary and extraordinary wave. Anyway, the ultimate effect depends heavily on the linearity and bandwidth limitation of analog phase shifters, still, this method needs to switch analog switches between consecutive observations.

In this paper, a new digital method for separating O-wave and X-wave is presented. Just as it is in DPS-4, two orthogonal antenna arrangements are used for transmitting and receiving, but removing phase shifters and switches in analog domain and introducing ±90° phase shifters in digital domain, implemented in digital down convertor process. Circularly polarized waves are synthesized within the range of 1-30 MHz, which eliminates the nonlinearity and expands the bandwidth of the whole system. Also there is no need to switch the analog switches continuously. Currently, the method has been successfully applied to the Chinese Academy of Sciences-Digital Ionosonde system (CAS-DIS) [Shun et al. 2013] and testing results show that the new digital method can separate O-wave and X-wave well.

2. Principle for separating O-wave and X-wave

2.1. A-H equation

In the presence of the Earth's magnetic field, as regards the propagation of high-frequency radio waves, the ionosphere behaves as a bi-refractive medium. On the assumption that the collisions between electrons and heavy particles are negligible, the corresponding refractive index μ is given by the well-known Appleton-Hartree (AH) equation:

$$\mu^2 = 1 - \frac{X}{1 - \frac{Y_T^2}{2(1-X)} \pm \sqrt{Y_L^2 + \frac{Y_T^4}{4(1-X)^2}}} , \quad \text{(1-a)}$$

where:

$$X = \frac{f_p^2}{f^2} , \qquad Y = \frac{f_H}{f} ,$$

$$Y_L = Y\cos\theta \quad \text{and} \quad Y_T = Y\sin\theta \qquad \text{(1-b)}$$

f_p is the plasma frequency, f is the radio wave frequency, f_H is the electron gyrofrequency, and θ is the angle between the Earth's magnetic field and the propagation vector of radio wave. A wave incident vertically into the ionosphere will be reflected when $\mu = 0$, and according to Equation (1-a) this happens when the following relations are satisfied:

$$X = 1, \qquad \text{(2-a)}$$

$$X = 1 \pm Y. \qquad \text{(2-b)}$$

The relation (2-a) represents the reflection condition of the O mode of propagation, the relation (2-b) represents the reflection conditions of the X mode of propagation.

2.2. Separating O-wave and X-wave

Ionospheric echoes usually consist of the superposition of two elliptically polarized waves, corresponding to the cited ordinary and extraordinary waves. At the magnetic dip equator the electric field of the ordinary wave is North-South and electric field of the extraordinary wave is East-West so that the waves can be separated by the use of two linear antennas oriented North-South and East-West. In sufficiently high latitudes, or on sufficiently high radio frequencies, the polarization ellipses are essentially circles [Davies 1990]. The two circularly polarized waves can be separated by two orthogonal dipoles oriented in the x and y directions. Consider two oppositely rotating waves of amplitude E_o and E_e incident on the antennas. The outputs E_x and E_y are

$$E_x = E_o \cos\omega t + E_e \cos(-\omega t) =$$
$$= E_o \cos\omega t + E_e \cos\omega t \qquad \text{(3-a)}$$

$$E_y = E_o \sin\omega t + E_e \sin(-\omega t) =$$
$$= E_o \sin\omega t - E_e \sin\omega t \qquad \text{(3-b)}$$

We now introduce a phase shift of ±90° into one of the signals, take E_x for example,

$$E_{x1} = E_o \cos(\omega t + \pi/2) + E_e \cos(\omega t + \pi/2) =$$
$$= -E_o \sin\omega t - E_e \sin\omega t \qquad \text{(4-a)}$$

$$E_{x2} = E_o \cos(\omega t - \pi/2) + E_e \cos(\omega t - \pi/2) =$$
$$= E_o \sin\omega t + E_e \sin\omega t \qquad \text{(4-b)}$$

Addition of E_{x2} and E_y gives ordinary wave, and addition of E_{x1} and E_y gives extraordinary wave.

$$E_O = E_{x2} + E_y = 2E_o \sin\omega t \qquad \text{(5-a)}$$

$$E_X = E_{x1} + E_y = -2E_e \sin\omega t \qquad \text{(5-b)}$$

The addition of the signals can be done numerically, when the data are recorded digitally, or electrically. A numeric method is employed in CAS-DIS, different from the electrical method used in DPS-4.

3. Application of the method in digital ionosonde

3.1. The digital ionosonde of CAS-DIS

A new ionosonde, called CAS-DIS is developed for the sake of testing the new method for separating O-wave and X-wave. The new design of the ionosonde is based on the thinking of Software Defined Radios, which can be divided into five parts. Specifically, these parts are Timing & Control unit, Transmitting Path, Receiving Path, Antenna System and Display Terminal. In order to
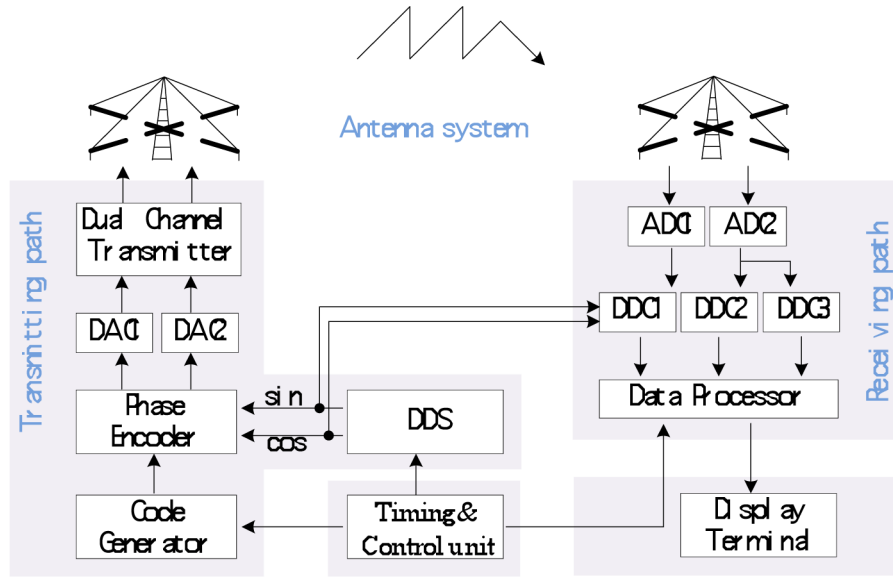
Figure 1. Block diagram of CAS-DIS ionosonde.

realize the function of polarization separation, two transmitting channels, two receiving channels and three DDCs with different initial phase are included in CAS-DIS. Figure 1 shows the block diagram of the whole system.

The whole system of CAS-DIS work as follows, the configuration parameters are downloaded to parameter RAM and a corresponding reset signal is generated after power on. Once the Timing & Control unit detects the reset signal, the control logic will generate the timing and control signals according to the configuration parameters. The DDS module of the Transmitting Path generates the carrier signal, and the phase encoded signals are fed to two orthogonal transmitting antennas by two parallel coaxial cable after D/A convertor, low pass filter and amplifier. Echo signals received by the two orthogonal receiving antennas are fed to the Receiving Path: after digitizing and digital down converting processing in three DDCs with different initial phases, a baseband signal is obtained; the coherent integration and the pulse compression processing are implemented in Data Processor unit, and eventually the ionogram is produced by the Display Terminal.

CAS-DIS system works in the frequency range of 1-26 MHz with step of 50 kHz; it can detect layers within the range from 90 km to 990 km with the range resolution of 5 km. The 16 bit complementary code pair used in CAS-DIS is modulated onto the odd-numbered pulse and even-numbered pulse, and the maximum transmitted power is about 600 W. The specifications of CAS-DIS are shown in Table 1.

3.2. The timing for separating O-wave and X-wave

Just as we have discussed above, when the frequency of the transmitted wave is sufficiently high the polarization ellipses of the echoes are essentially circles and two circularly polarized waves can be separated by two orthogonal dipoles. In CAS-DIS, there is a couple of orthogonal antennas for transmission and another couple for reception. According to equations of (3), (4) and (5), when a left-handed circularly polarized wave is transmitted the O-wave can be separated from the echoes by adding the two antenna signals after the signal captured by one of the receiving antennas is phase shifted by $-90°$. Similarly, when a right-handed circularly polarized wave is transmitted the X-wave can be separated from the echoes by adding the two antenna signals after one antenna signal is shifted by $90°$. Transmitting two pulses, alternatively with left and right circular polarization, it is possible to separate O-wave and X-wave correctly, provided that the interval between the two transmitted pulses is small enough with respect to the typical timescale of ionospheric variations.

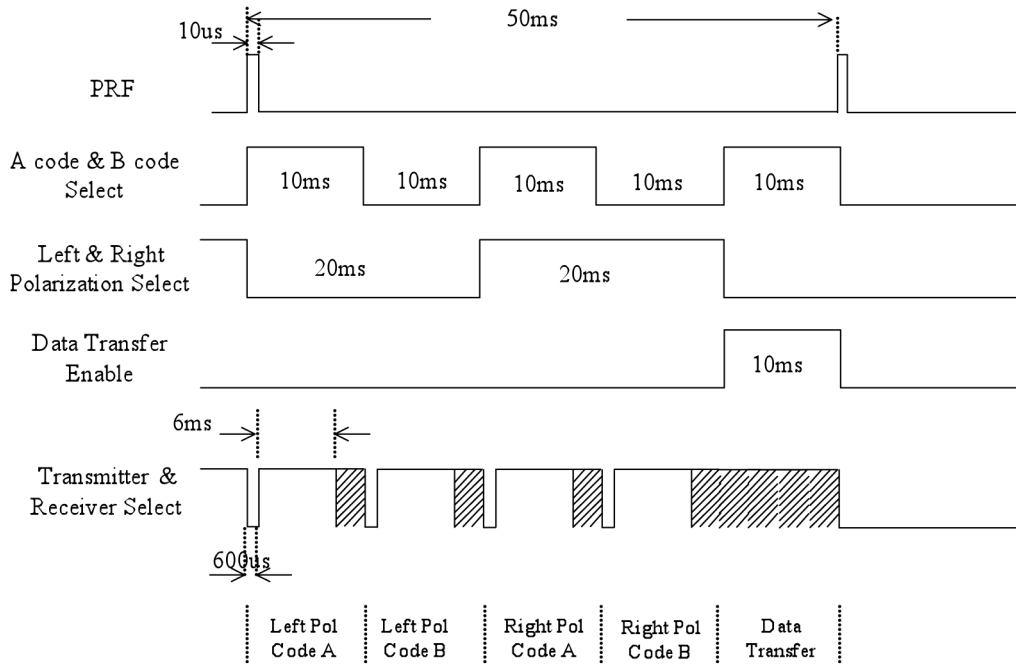| Symbols	Description
Frequency range:	1-26 MHz
Height range:	90 km~990 km
Range resolution:	5 km
Tx power:	600 W (Max. peak)
Frequency point num:	500 (Max)
Code type:	16 bits complementary
ADC sampling rate:	60 MHz
ADC bit number:	14 bits
Receiver sensitivity:	-120 dBm @ 150 KHz (the useful bandwidth of the baseband signal)
Antenna:	Crossed delta antenna

Table 1. CAS-DIS specifications.

Figure 2. The timing for separating O wave and X wave in CAS-DIS.

Figure 2 shows the timing of the separation process in CAS-DIS. The PRF (Pulse Repetition Frequency) is 20 Hz, corresponding to the pulse repetition interval, PRI, is 50 ms, of which 40 ms is used for transmitting and data sampling, and 10 ms is used for data transferring. For the purpose of separating for O wave and X wave, there are five operating modes switching in a PRI in CAS-DIS system.

3.3. Transmitting Path

The Transmitting Path contains DDS unit, Code Generator unit, Phase Encoding unit, DACs unit, Low pass filters and Dual Channel Amplifier. In CAS-DIS, the DDS unit is implemented by the logic resources within the FPGA, which generates the sine and cosine signals from 1 MHz to 26 MHz, and the frequency of the DDS can be tuned to a fixed frequency or be modified real time by the parameters. The initial phase of the DDS should be fixed, for example, 0°, 90° or 270°(which is used to substitute −90°), and this is the premise for separating O-wave and X-wave.

The Phase Encoding unit generates the 16 bits complementary code to modulate the carrier signal generated by the DDS unit. After filtered by the lowpass filter with a band of 27 MHz, the modulated signal is converted to analog signals by two DACs. The outputs of DACs can be amplified to 600 W when fed to antennas by the dual channel transmitters in Figure 1. In order to get good performance in separator O-wave and X-wave, the dual channel transmitters should have the same characteristics in amplitude and phase response.

3.4. Receiving Path

The Receiving Path is comprised of ADCs, DDCs and Data Processor, as shown in Figure 1. In CAS-DIS, two high performance 14 bits ADCs are used, with 60 MHz sampling rate. Testing results show that the sensitivity of the Digital Receiver is −120 dBm. It should be noted that the receiver sensitivity is measured in the baseband and the useful bandwidth with −3dB attenuation is 150 kHz.

Because of the higher sampling rate, a process of DDC is applied before pulse compression processing. The four parts of the DDC are digital mixers (M1, M2), the cascaded integrator-comb filter (CIC), compensation filter (CFIR) and programmable filter (PFIR). Figure 3 shows the block diagram of DDC.

For the sake of improving the SNR of the echo signal, the technique of coherent pulse integration is used in the new system design, the times of integration is in a range of 1-128, which can provide an improvement of more than 20dB to the SNR of the received signal. Also, the digital pulse compression technique is used, adding additional 12 dB to the previous gain, and
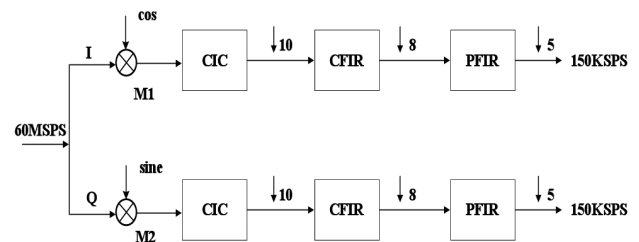

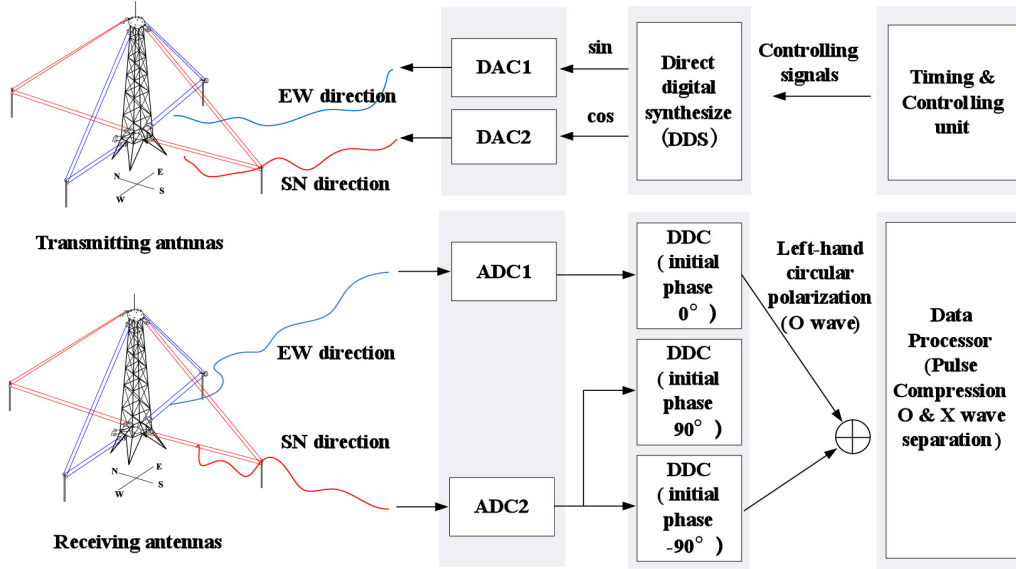**Figure 3.** Block diagram of DDC in Receiving Path.

Figure 4. Block diagram for separating O wave in CAS-DIS.

reaching more than 30 dB for the overall gain in the CAS-DIS system.

3.5. Antenna System

In CAS-DIS system, the orthogonal delta antennas or orthogonal dipoles can be used as transmitting or receiving antennas, the loads with the value of 600 ohm are installed on the top or center of antennas, and each has a balun used to match the balanced antennas with the unbalanced coaxial RF cable.

3.6. Implementation for Separating O-wave and X-wave

Let S_{EW} be the analog signal received by the antenna in EW (East-West) direction after quantization of ADC1, and S_{SN} be the analog signal received by the antenna in SN (South-North) direction after quantization

of ADC2, as shown in Figures 4 and 5. The process of separation of O wave in CAS-DIS ionosonde is shown in Figure 4. In the process of separation of O wave, the left-hand circular polarization signals are transmitted. In this case, the components of sin and cos from the DDS unit are fed to transmitting antennas in EW direction and SN direction, respectively. The received signals of S_{EW} and S_{SN} are fed to DDCs with initial phases of 0 and $-90°$, being the DDC process linear, the phases added by the DDCs are the same for the two channels, so there is no influence on the output. Suppose signals after DDC process are S'_{EW} and S'_{SN}, then

$$S'_{EW} = I_{0°} + jQ_{0°} \tag{6-a}$$

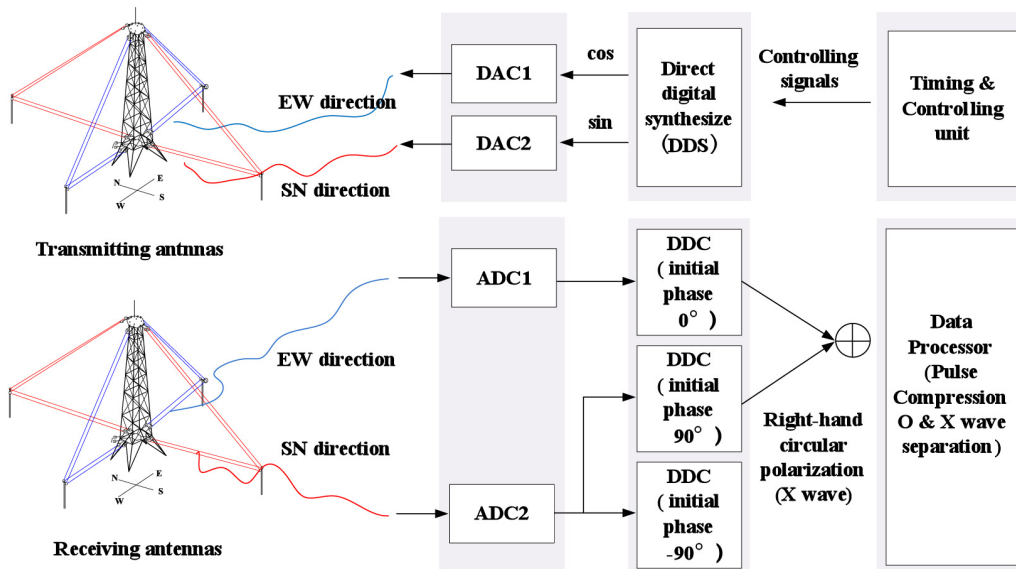$$S'_{SN} = I_{-90°} + jQ_{-90°} \tag{6-b}$$

Figure 5. Block diagram for separating X wave in CAS-DIS.

In Equation (6), $I_{0°}$, $Q_{0°}$, $I_{-90°}$, $Q_{-90°}$ are the real and imaginary parts of the signals received by the antenna in EW direction and SN direction after DDC. Let S_O be the O wave, then

$$S_O = S'_{EW} + S'_{SN} = I_{0°} + jQ_{0°} + I_{-90°} + jQ_{-90°} \qquad (7)$$

Figure 5 shows the process for separation of X wave in CAS-DIS. When the right-hand circular polarization signals are transmitted, the components of sin and cos from the DDS unit fed to transmitting antennas are interchanged, and the receiving signals of S_{EW} and S_{SN} are fed to DDCs with initial phases of 0° and 90°, respectively. Adding the results of the two DDCs, the X wave can be separated from the received signals. Let S_X be the X wave,

$$S_X = S'_{EW} + S'_{SN} = I_{0°} + jQ_{0°} + I_{90°} + jQ_{90°} \qquad (8)$$

In Equation (8), $I_{0°}$, $Q_{0°}$, $I_{90°}$, $Q_{90°}$ are the real and imaginary parts of the signals received by the antenna in EW direction and SN direction after DDC.

To illustrate the process of separation of O and X waves in CAS-DIS, Table 2 shows a summary to the relationship within different parts of ionosonde, which are transmitting and receiving antennas, ADCs, DDCs and the polarization of transmitted and received signals.

4. Testing result and Conclusion

4.1. Testing result

In order to validate the new design of separating O-wave and X-wave, two experiments have been made made in China, at Ji'an in Jiangxi Province and Wuhan in Hubei Province last year.

Figure 6 shows an ionogram observed in Ji'an in the south part of China. In the ionogram, the curve with green is the trace of O wave and red is X wave, the start frequency of E layer is about 2 MHz and the cut-off frequency of the F2 layer is about 18.5 MHz for O-wave. Since the station is located in southern China, the cut-off frequency of the F2 layer is much higher than the ionogram observed in other stations, especially in northern China. The transmitting antennas used in the experiment are two orthogonal Delta antennas with the height of 10 meters. The receiving antennas are two orthogonal dipole antennas with the length of 20 meters and are about 2 meters high from the ground.

Figure 7 shows an ionogram observed in Wuhan in the center part of China, in which the trace of O-wave and X-wave are separated clearly. The start frequency of E layer is about 1.8 MHz and the cut-off frequency of the F2 layer is about 10.6 MHz for O-wave. The transmitting and receiving antennas used in the experiment are orthogonal Delta antennas, with the height of 30 meters and 17 meters, respectively.

Categories	Antennas	Signals	ADCs/DACs	DDCs initial phase
Separation for O wave (left-hand circular polarization signals are transmitted)	Transmitting Path (EW)	sin	DAC1	——
	Transmitting Path (SN)	cos	DAC2	——
	Receiving Path (EW)	——	ADC1	0°
	Receiving Path (SN)	——	ADC2	−90°
Separation for X wave (right-hand circular polarization signals are transmitted)	Transmitting Path (EW)	cos	DAC1	——
	Transmitting Path (SN)	sin	DAC2	——
	Receiving Path (EW)	——	ADC1	0°
	Receiving Path (SN)	——	ADC2	90°

Table 2. The relationship within parts of ionosode for separation of O wave and X wave in CAS-DIS.

Figure 6. Ionogram of CAS-DIS on April 23, 2012, in station of Ji'an (LT).
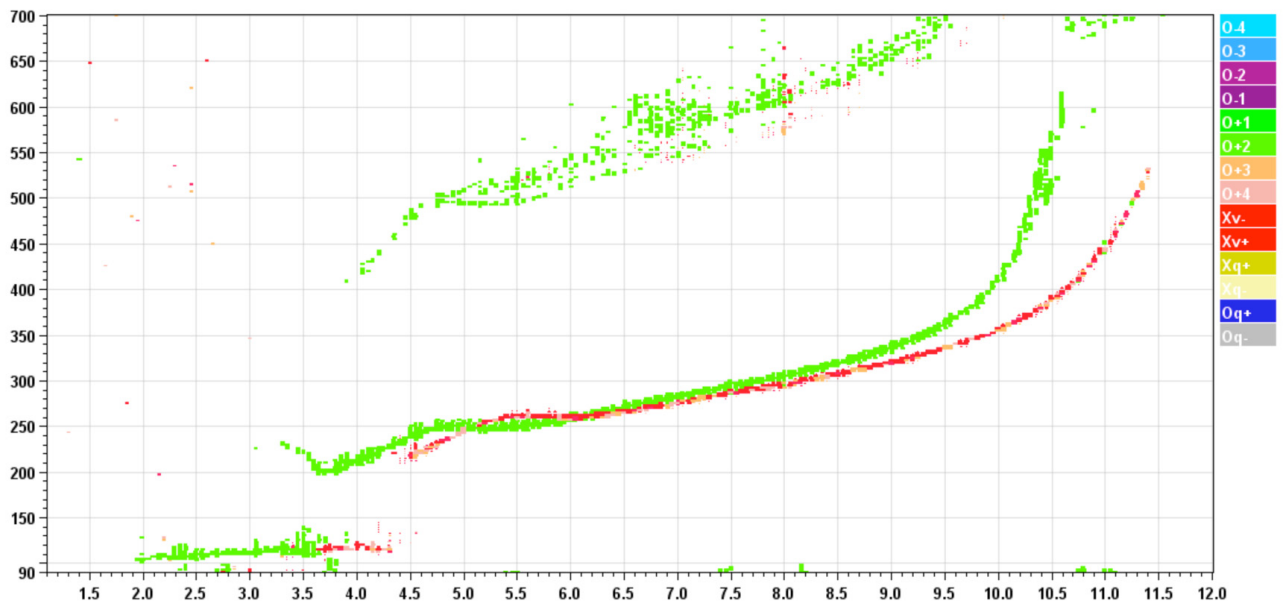

Figure 7. Ionogram of CAS-DIS on November 5, 2012, in station of Wuhan (UT).

4.2. Conclusion

The method for separating O wave and X wave in CAS-DIS presented in this paper is on the basis of digital technology, which is different from the analog method or by using image processing method. By using digital technology to implement phase shifter of ±90° and synthesizing of circularly polarized waves, the new method eliminates the nonlinearity and expands the bandwidth of phase shifter, and there is no need to switch the analog switch continuously, which

improves the reliability of the whole system of the ionosonde.

To verify the effectiveness of the new method, an ionosonde called CAS-DIS is developed and experiments have been made in 2012, the testing results show that the new method for separating O wave and X wave is effective and reliability in practice.

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