A novel dual-channel HF radar system for ionospheric sounding

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Abstract: This paper presents a novel dual-channel HF radar system for ionospheric sounding, which is called Wuhan Multifunctional Ionosonde with dual channels (WMI-DC). Based on the Universal Serial Bus (USB), and a high performance FPGA, this newly designed WMI-DC has a complete digital structure, which makes it portable and flexible. And due to the application of m sequence waveform, the WMI-DC can achieve good results with low power. The primary modules and the data processing are illustrated in detail in this paper. The experimental results indicate that the dual-channel system can separate ordinary wave (O-wave) and extraordinary wave (X-wave) from the signals.

Keywords: HF radar, dual-channel, receiver, transmitter

Classification: Sensing

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1 Introduction

Since Breit and Tuve confirmed the existence of the ionosphere by means of radio sounding, HF sky wave radar has been widely used for ionospheric monitoring and research. In the past decades, great efforts have been made to develop different kinds of radar systems for ionospheric sounding, such as CADI, AIS-INGV, and DPS-4D [1, 2, 3].

Electronic Information School of Wuhan University began to develop its own ionospheric sounding system in 2001, and a series of equipments have been developed [4, 5, 6]. In this paper, a novel dual-channel HF radar system for ionospheric sounding, which is called Wuhan Multifunctional Ionosonde with dual channels (WMI-DC), is introduced. According to the formula of Appleton-Hartree, when the electromagnetic wave propagates through the ionosphere, the wave will be split into O-wave and X-wave. Distinguishing O-wave from X-wave is important for automatic measuring the ionogram [7]. The WMI-DC is developed to complete the task based on hardware. The general system diagram is shown in Fig. 1. The maximum transmitted power is about 1 kW, and the receiver sensitivity is −116 dBm. The frequency range is from 3 MHz to 30 MHz, and the detection range is from 100 km to 1000 km. The WMI-DC is based on USB and module designed. The computing part and the hardware part are separate. Therefore, the
system is portable and flexible. Pulse compression and pulse accumulation techniques are used in the system to achieve good results with low transmitter power. In addition, the dual-channel system can separate O-wave and X-wave from the signals.

The detailed description of the WMI-DC is set out in section 2. The experimental results are shown in section 3. Conclusions are given in section 4.

2 System description

2.1 Design of the synchronization module and control module

As shown in Fig. 1, the synchronization module and control module are used to connect various parts of the system. The synchronization module has two functions: one is to provide a high precision system clock (10 MHz), and another is to output trigger signal for system synchronization. It consists of an oven-controlled crystal oscillator (OCXO), a Micro Controller Unit (MCU), a Global Position System (GPS) receiver, and a Digital-to-Analog Converter (DAC). They compose a close-loop feedback system. By counting the pulse per second (PPS) signal from the GPS receiver with the OCXO 10 MHz clock, the difference between the results and $10^7$ is gotten. Then, the voltages codes are output to the DAC to calibrate the control voltage of the OCXO, and eventually the frequency difference is less than $3.2 \times 10^{-4}$ Hz.

The control module has two functions: one is to transmit the waveform parameters to the device, and another is to deliver the baseband data to the laptop. The Cypress’ USB 2.0 integrated microcontroller CY7C68013 is used in this module.

2.2 Design of the transmitter and waveform

The dual-channel transmitter is shown in Fig. 2(a). It mainly includes the direct digital synthesizer (DDS) chip AD9958, the analog switch ADG919, the amplifier Gali-74, and the filter circuits. The timing of the waveform is produced in the FPGA, and it is modified on the basis of the parameters of the waveform. The AD9958 consists of two DDS cores that provide independent frequency, phase and
amplitude control on each channel. Through the analysis of the output, the amplitude differences of the two channels are within ±0.3 dB, and the phase differences are within 1°. Therefore, the differences of the two channels have a negligible effect on the experiment results.

M sequence is employed in WMI-DC, which is one family of binary phase codes. Compared with the coding sequence with an ‘ideal’ aperiodic Autocorrelation Function (AACF), such as Barker code, complementary code and so on, m sequence has a good Periodic Autocorrelation Function (PACF) [8]. Highly accurate Doppler resolution can be achieved by transmitting the waveforms coded with m sequence of long bit repeatedly. In order to ensure that the code can be used by monostatic sounding systems, the interpulse scheme is adopted [9].

In Fig. 2(b), at regular equal intervals, the pulses are transmitted. The radar receives the echo in the intervals. The problem is that there is a narrow blind zone at regular distances. \( u_n (1 \text{ or } -1) \) represents the sub-pulse. A sub-pulse with 0 phase is characterized as “1”, and a sub-pulse with \( \pi \) phase is characterized as “-1”. \( L \) represents the length of the m sequence, \( T_p \) represents the pulsewidth, \( T_{\text{RI}} \) represents pulse repetition interval (PRI), \( T_{\text{SRI}} \) represents sequence repetition interval (SRI) and is equal to \( LT_{\text{RI}} \), and \( N \) represents pulse train repetition times. According to the ambiguity function, the Doppler resolution is equal to \( 1/(LT_{\text{SRI}}) \), the unambiguous Doppler detection range is equal to \( 1/T_{\text{SRI}} \), and the range resolution is equal to \( cT_p/2 \).

Let \( \Delta p_{1,2} \) be the phase difference of the two channels, then

\[
\Delta p_{1,2} = p_1 - p_2
\]

In Eq. (1), \( p_1 \) and \( p_2 \) are the phase of channel 1 and channel 2. In the experiment, first a left-handed circularly polarized wave is transmitted (\( \Delta p_{1,2} = 90^\circ \)), then a right-handed circular polarized wave is transmitted (\( \Delta p_{1,2} = -90^\circ \)). In this way, the O-wave and X-wave can be separated from the signals.

### 2.3 Design of the receiver

The dual-channel receiver includes two channels, which is shown in Fig. 1. The signal channel is composed of the analog front-end and the intermediate frequency (IF) digital receiver. In the analog front-end, the RF signal is amplified by a low noise amplifier (LNA) Gali-74. Then the RF signals mixed with the local signal to get the intermediate frequency (IF) signal. In order to achieve a clean spectrum, a bandpass crystal filter (41.4 MHz frequency center, 60 kHz bandwidth) is used for image rejection.

The IF signal is sampled by the LTC2202, which is a 16-bit A/D converter. It is perfect with AC performance that includes 81.6 dB SNR and 100 dB spurious free dynamic range (SFDR). In the digital down converter (DDC) unit, the IF signal is modulated to generate an in-phase signal and an orthogonal phase signal, thereby to be lowpass filtered and decimated in the cascade integrator comb (CIC) filter and the finite impulse response (FIR) filter. The DDC unit is integrated in the field programmable gate array (FPGA) chip, and the decimation value of CIC and FIR can both be set from 8 to 64. In general, the total decimation value of the CIC and FIR is 256, and the cutoff frequency of the FIR filter is 60 kHz.
2.4 Data processing

The signals with a 39.0625 kHz sampling frequency are transferred to the laptop through the USB for further calculations. The baseband signal is stored as the complex data composed of the in-phase and quadrature (I and Q) components. The first step is to separate O-wave and X-wave from the signals.

Let \( S_O \) be the O-wave, then

\[
S_O = S_{1,\text{left}} + S_{2,\text{left}} \times e^{j\pi/2}
\]

In Eq. (2), \( S_{1,\text{left}} \) and \( S_{2,\text{left}} \) are the signals received by the two receive channels, when the left circular polarized wave is transmitted.

Let \( S_X \) be the X-wave, then

\[
S_X = S_{1,\text{right}} + S_{2,\text{right}} \times e^{-j\pi/2}
\]

In Eq. (3), \( S_{1,\text{right}} \) and \( S_{2,\text{right}} \) are the signals received by the two receive channels, when the right circular polarized wave is transmitted.

The next step is the coherent integration processing. The complex echo array is multiplied by the replica of the emitted code to get echo peaks. After the coherent integration processing, the signal is flooded in the noise. The third step is the signal denoising. There are usually only white noise interference and side-lobe disturbance at the farthest hundreds of range gates, and the date is averaged to be as the noise floor. The noise floor is subtracted from the data of all range gates to get the eventually data. Through the signal denoising processing, the signal is easy to be identified. Then the results comprise the ionogram [10].

3 Experimental results

![Sweep ionogram of the WMI-DC](image)

Fig. 3 shows a sweep ionogram of the WMI-DC obtained at 8:15LT, March 14, 2015. The waveform parameters were 25.6 µs pulse width, 20% duty cycle, 255 bit m sequence, 125 pulse train repetition numbers, and the power of transmission was 150 W. The initial, end, and step frequencies were 7 MHz, 14 MHz, 200 kHz, respectively. In the ionogram, the trace of O-wave and X-wave are separated. The O-wave is shown in the left part, and the X-wave is shown in the right part.
4 Conclusion

In this paper, a novel dual-channel HF radar system for ionospheric sounding is described. Different from previous equipments, the newly designed WMI-DC has a completely structure based on the USB, a high performance FPGA and a synchronization module. This radar employs m sequence waveform and dual-channel system. The experimental results indicate that the WMI-DC shows good performance in the separation of O-wave and X-wave. This newly designed WMI-DC will play a more significant role in the studying of the ionosphere.

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