The Wuhan Ionospheric Sounding Systems

Gang Chen, Zhengyu Zhao, Guoqiang Zhu, and Shuzhu Shi

Abstract—The ionospheric laboratory of Wuhan University, Wuhan, China, has developed a new ionospheric sounding system for about seven years. The first system is used for ionospheric oblique backscattering detection and is called the Wuhan ionospheric oblique backscattering sounding system (WIOBSS). The WIOBSS is a portable monostatic backscatter ionosonde for ionospheric research and high-frequency (HF) channel management, adopting alternate transmitting and receiving patterns to transmit long coded pulse trains for high pulse-compression gain. However, it is difficult to recognize the echo path and mode only with the backscatter ionogram. Therefore, a separate remote digital receiver has been developed for auxiliary detection. The receiver is a compact radio system used to receive the transmitting signal of the WIOBSS, and it includes a Global Positioning System receiver for clock and frequency standard synchronization. Combined with the WIOBSS, the receiver has been used for ionospheric bistatic backscatter sounding and oblique incident sounding. The WIOBSS and several remote digital receivers can compose a detection network for ionospheric research and HF channel management.

Index Terms—Backscatter sounding, ionogram, ionospheric detection, oblique sounding.

I. INTRODUCTION

EVER since the remote sensing of the ionosphere by means of radio sounding was first described [1], ionosondes have been widely used for ionospheric monitoring and research. Nowadays, there are many kinds of ground-based ionospheric remote-sensing methods developed, such as vertical incident sounding [2], oblique incident sounding [3], and oblique backscatter sounding [4]. Each sounding method has particular advantages and limitations. A special method is oblique backscattering, where the ionosonde obliquely transmits high-frequency (HF) radio waves. These waves, when received, have propagated from the sounder, experienced refraction by the ionosphere, then undergone backscattering from the earth’s surface, and, finally, returned to the sounder after a second ionospheric refraction [5]. The oblique backscatter-detecting ionosonde has the ability to monitor the ionosphere over a large geographical area. However, the echo propagation path and mode cannot be clearly recognized in the backscatter ionogram. To recognize the echo path and mode and to facilitate the ionogram interpretation, the oblique backscatter-sounding ionosonde is typically operated along with a vertical incident ionosonde or an oblique ionosonde [6].

Fig. 1. Operation schematic diagram of Wuhan ionospheric sounding systems.

The ionospheric laboratory of Wuhan University, Wuhan, China, began to develop the ground-based ionospheric sounding systems for ionospheric research and HF channel management in 2001. The prototype is designed as a portable low-power digital HF radio system with a high range and Doppler resolution. The first system—the Wuhan ionospheric oblique backscatter sounding system (WIOBSS)—has been used for ionospheric oblique backscatter detection [7]. It is a portable monostatic digital ionosonde, applying special transmitting and receiving patterns to increase the pulse-compression gain and improve the signal-detecting performance. Additionally, a remote digital receiver using GPS for frequency and clock synchronization has been developed to receive the transmitted signal of the WIOBSS in 2008. Combined with the WIOBSS, the receiver can be used for ionospheric bistatic backscatter sounding, oblique incident sounding, and sky-wave sea-state sounding, as shown in Fig. 1.

In this letter, the hardware structure, sounding waveform, and signal processing of the WIOBSS and the remote digital receiver are introduced, and some recorded wide-sweep backscatter ionogram and oblique ionogram are displayed.

II. SYSTEM DESCRIPTION

A. Waveform Design

Different from the traditional ionosonde using a phase-coded or frequency-modulated continuous waveform, the Wuhan ionospheric sounding systems are developed as a monostatic radio system periodically transmitting phase-coded pulse-train waveform and receiving the echoes during the interpulse periods. Due to the alternate transmitting and receiving pattern, long periodic pseudorandom codes can be applied to the waveform for a high pulse-compression gain and good sensitivity. The commonly used waveform parameters of the radio system are 83-μs pulsewidth, 20% duty cycle, and 511-bit m sequence.
used as a modulating signal. A pulse-train repetition number of 5, 16, 32, 64, 128, or 256 can be chosen. When the 128 pulse-train repetition number is applied, after pulse compression and coherent integration, the radio system gets 27-dB pulse-compression gain and 21-dB frequency-integration gain, and then displays the ionogram with a 12.5-km-range resolution, a $[-2.35 \text{ Hz}, +2.35 \text{ Hz}]$ unambiguous Doppler measuring range, and a 0.037-Hz Doppler resolution.

**B. Design of the WIOBSS**

The WIOBSS is a sky-wave over-the-horizon radar system developed for ionospheric research and HF channel management. As shown in Fig. 2, the radar is monostatic, and its transmitting and receiving channels share one log-period antenna system. To prevent receiver saturation when transmitting, the high-speed and high-isolation transmit/receive (T/R) switches as well as some attenuators are used. The transmitting and receiving channels are built on two Versa modular Eurocard extension for instrumentation C-size modules for the sake of favorable electromagnetic compatibility and maneuverability. The GPS receiver is used to correct the 10-MHz frequency standard from an oven-controlled crystal oscillator (OCXO) and provide the precise clock and the radar-position information. The system controller consists of a field-programmable gate-array circuit, and its program controls the whole system. The controller outputs the digital baseband signal to the quadrature digital upconverter to produce the detection waveform, controls the T/R switch using the transceiving time sequence, commands the receiver to record echoes at the operating frequency, and so on. The recorded data are processed in a digital signal processor and then transferred to the computer. The computer stores the data and displays the ionograms.

The system is designed to operate in two sounding modes: One is the fixed-frequency mode, and the other is the swept-frequency mode. The waveform parameters, such as the pulselwidth, the duty cycle, the modulating codes, and the pulse-train repetition times, are user-defined for appropriate pulse-compression gain, range, and Doppler resolutions. The frequency, range, amplitude, phase, Doppler shift, and spread of the ionospheric echoes are measured.

**C. Design of the Remote Receiver**

The remote digital receiver can be regarded as a compact WIOBSS without a transmitting channel, as shown in Fig. 3(a). The receiver is a portable system input in a suitcase, the size of which is $700 \times 511 \times 225$ mm. Because the remote receivers are operated relatively far from the transmitters, the T/R switches and attenuators are not necessary and not built in. The same GPS receiver is used in the WIOBSS and the remote receiver for clock and frequency standard synchronization. The GPS clocks have a very good long-term stability, but the 1-pulse-per-second (pps) output of the commercial receiver turned out to be frequently disturbed, resulting in poor short-term stability. Therefore, the GPS receiving system is extended, as shown in Fig. 3(b), to get a steady continuous clock and frequency output. A 10-MHz OCXO generates a second 1-pps output, which is compared with the GPS one by a time and frequency difference measurer. The difference is fed into a processor that outputs the GPS clock as well as the correction parameter for a time and frequency corrector. In this way, the GPS with very good long-term stability and the OCXO with very good short-term stability provide stable and continuous 1-pps and frequency standard even when the GPS signal is temporarily corrupted. The remote receiver can also be operated in the fixed- and swept-frequency modes, receiving the echo of the WIOBSS with the arbitrary waveform parameters and obtaining the echo frequency, range, amplitude, phase, Doppler shift, and spread values.

**D. Data Processing**

The echoes are recorded with a 24-kHz sampling frequency and stored as a complex echo array composed by the in-phase and quadrature components within the receiver. To present these data in the form of an ionogram, several processing steps given in Table I are required. The complex echo array is compressed to get echo peaks, and the pulse-compression depth is limited to 800 range bins for a short processing time. The repetitious detection results comprise the bitemporal ionospheric response (BTIR) \cite{8}. When the signal-to-noise ratio (SNR) is high enough, the phase method...
TABLE I
DATA PROCESSING STEPS

<table>
<thead>
<tr>
<th>#</th>
<th>Step Contents</th>
<th>Comments</th>
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<td>3</td>
<td>Doppler spectral analysis</td>
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</tr>
<tr>
<td>4</td>
<td>PFI Mitigation</td>
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</tr>
<tr>
<td>5</td>
<td>Echo recognition</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Plot ionogram</td>
<td></td>
</tr>
</tbody>
</table>

could be used to obtain the echo amplitude and phase, and then Doppler values are calculated by the echo phase [9]. Usually, the fast Fourier transform (FFT) is applied to the BTIR to obtain the complex Doppler spectra for each range bin. After pulse compression and Doppler-spectrum transform, the echoes are integrated/accumulated to certain range bins and Doppler frequencies, but the radio-frequency interferences (RFIs), which are narrow-band interferers from other transmitters, in many cases broadcasting stations with unpredictable occurrences at a priori unknown frequencies, form bandings distributed all over the range bins with a certain Doppler frequency. The RFI mitigation algorithm is to subtract this interference signal from the Doppler spectra of each range bin by the interference sample [10]. After RFI mitigation, the echoes are distinguished from the noise by the power, the Doppler value, and the distribution, and then the echo SNR and Doppler/velocity values are calculated to plot the SNR and Doppler/velocity ionogram.

In the wide-sweep backscatter ionogram, the Doppler values are transformed to velocity form by the formula $v = cf_d/f$ for comparison with different operating frequency $f$, where $c$ is the velocity of light, $f_d$ is the Doppler value, and $v$ is the velocity value.

III. SOME SOUNDING RESULTS

A. Monostatic Backscatter Sounding

The WIOBSS has been used for monostatic backscatter sounding for more than six years. Due to the high processing gain, the radio system is able to cover large-area ionosphere with very low peak power [11]. Fig. 4(a) shows a wide-sweep backscatter ionogram obtained at 10:26 UT, March 23, 2009 (LT = UT + 8 h). The log-periodic antenna pointed west, and the transmitted peak power was only 200-W. The common waveform was used with the 64 pulse-train repetition number, and the initial, end, and step frequencies were 6.2-MHz, 26-MHz, and 200-kHz, respectively. The swept-frequency mode repeats the fixed-frequency mode over 100 consecutive operating frequencies. The data of each operating frequency are processed and plotted in real time. When the sweep detection comes to an end, the wide-sweep backscatter SNR and Doppler ionograms are displayed. In the SNR ionogram shown in Fig. 4(a), the ground echoes were directly reflected to the receiver by objects, like house, metal masts, or hills, around the antenna and appeared at about 0 km and at all frequencies; the one-hop and multihop vertical incident echoes were clearly observed; and the backscattered ionospheric echoes from 600-

to more than 2000-km group range were also well recognized. Due to the suppression of the T/R switches when transmitting, there are narrow dead zones distributed throughout the range bins in the monostatic backscatter ionogram. The 64 pulse-train
repetition number gains the 0.0734-Hz Doppler resolution by FFT arithmetic. The echo Doppler shift and spread can be obtained to plot the velocity and velocity-spread ionograms [12].

B. Bistatic Backscatter Sounding

When the WIOBSS was operated, the remote digital receiver located 100-km south received ionospheric backscatter echoes from the west for bistatic backscatter sounding. The WIOBSS and the remote receiver both use the GPS receivers for clock and frequency standard synchronization. A simple oblique-pulling HF antenna is used for receiving. The detection parameters and the operating mode of the receiver are set up the same as the WIOBSS’s, and then the two systems began to detect at the same time. When the detection finished, the WIOBSS obtained the monostatic wide-sweep backscatter ionogram, as shown in Fig 4(a), and the remote receiver obtained the bistatic wide-sweep backscatter ionogram, as shown in Fig. 4(b).

The ionospheric backscatter echoes in the two ionograms are very similar, particularly their front end. The two systems received the vertical incident and backscatter echoes, but there is no ground echo in Fig. 4(b). Due to the pure electromagnetic environment and the cancellation of the T/R switches and the attenuators, the bistatic ionogram gains more backscatter echoes and a higher SNR, and it does not show any dead zones at equally distributed range intervals.

C. Oblique Incident Sounding

To carry out the oblique incident sounding experiment, an observation station is established in Qinzhou, Guangxi province, which is 1109 km away from Wuhan. The WIOBSS transmitted the signal south, and the remote receiver in Qinzhou used the log-periodic antenna pointing north to receive the ionospheric refracted signal. The power of the ionospheric refracted echoes is much higher than that of the ionospheric backscattered echoes; therefore, the pulse-train repetition number is decreased to 5, and the transmitted peak power is limited to 100-W. The operating frequency band is set from 6- to 16-MHz with a 50-kHz frequency step. The data-processing steps introduced before can also be applied to the oblique data. The wide-sweep oblique ionogram recorded at 4:40 UT, December 18, 2008, is displayed in Fig. 4(c). In the oblique ionogram, the Es-layer and the O-mode and X-mode F-layer echoes are distinctly recorded. The hardware delay is subtracted from the total delay for the coordinate registration. The Doppler of the oblique echoes can also be gained by the phase method or the FFT arithmetic.

IV. Conclusion

Due to the special alternate transmitting and receiving patterns applied to transmit the long periodic pseudorandom codes, the monostatic ionospheric backscatter ionosonde WIOBSS obtains high pulse-compression gain to cover large-area ionosphere with very low power. However, it is very difficult to recognize the echo path and mode only from the backscatter ionogram. Therefore, the remote digital receiver has been developed for auxiliary detection, and the GPS receiver has been applied in the two systems for clock and frequency standard synchronization. Combined with the WIOBSS, the receiver has been used for ionospheric bistatic backscatter sounding and oblique incident sounding. Therefore, the WIOBSS and several remote receivers could compose a novel ionospheric and HF channel research network, which is currently being built up.

REFERENCES