A full-polarimetric GPR system and its application in ice crack detection

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Abstract. The warming season of Antarctica, where sea ice melts and breaks, is often the golden time for Antarctic research. But this season is also a high frequency season for the formation of ice crack, the existence of which poses a serious threat to Antarctic scientific research. Therefore, it is of important significance to monitor the trend, location, and depth of Antarctic sea ice crack in real time. Ice crack detection often uses ground penetrating radar (GPR) technology. Compared with the single-polarimetric GPR, full-polarimetric GPR can obtain more comprehensive polarization information. Therefore, a full-polarimetric GPR system based on the horn antenna is built in this paper to obtain more abundant ice crack information. Then we apply it to detect a small-scale ice crack atop frozen lakes. The analysis of the experiments and data fusion processing results can verify the effectiveness of the system for the detection of ice crack and lay the foundation for subsequent actual detection.

1. Introduction
The warming season of Antarctica, when sea ice melts and breaks, is often the golden time for Antarctic research, but this season is also a high-frequency season for the formation of ice crack [5]. For more than 30 years, China’s Antarctic scientific research has used snowmobiles to replenish supplies almost every year, but many dangerous situations have occurred because of the ice crack [3]. Therefore, the rapid and real-time monitoring of the trend, location, and depth of the Antarctic ice crack is of important significance. In addition, the prediction of the location and depth of the ice crack is also important for understanding the disintegration process of Antarctic glaciers [1].

GPR is a new technology that has been approved by the scientific community, and it is very suitable for ground-based surveys and ice crack detection [9]. GPR is also an effective non-destructive tool for detecting shallow underground based on electromagnetic reflection information. Polarization technology is one of the most important technologies in the field of microwave remote sensing during recent decades [4,13]. With the rapid development of polarization technology, it has also been introduced into the field of GPR to improve its detection capability [2,18]. In order to obtain richer information about ice crack, we choose the full-polarimetric GPR for research.
In recent years, major research institutions and universities have constructed various GPR systems and applied them in different fields [16]. Kong et al. developed a GPR system which uses step frequency signals [14]. Daniels et al. developed multi-channel GPR systems for mine detection [6]. Plettemeier et al. developed a full-polarimetric GPR antenna system for the mission of water ice and subsurface deposit observations on Mars [17]. Li Lili developed a full-polarimetric GPR acquisition system and calibration technique [15]. Dong Zehua et al. developed a vehicle-mounted GPR system for rapid detection of asphalt pavement thicknesses [7]. Gianluca et al. developed a low frequency airborne GPR system for wide area geophysical surveys [12]. While continuously developing and improving the performance of the hardware system, it also performs GPR antenna performance analysis, target body attribute analysis, target body recognition and etc. [10, 11]. Therefore, we built a full-polarimetric GPR system in this paper to achieve a faster and more accurate assessment of ice crack.

2. Full-polarimetric GPR system based on horn antenna

2.1. Composition of full-polarimetric GPR system

The full-polarimetric GPR system built in this paper is mainly composed of a PC control unit, a vector network analyzer, a switch driver, and two horn antennas, which is shown in Figure 1. The PC control unit is mainly responsible for controlling the vector network analyzer and the switch driver. The vector network analyzer is used to generate electromagnetic wave signals and receive echo signals from the antennas. The switch driver sends opening and closing instructions of the corresponding channel to the coaxial switch by receiving a command from the PC control unit. The horn antennas are responsible for transmitting the electromagnetic wave signal and receiving the echo signal from the target. The hardware composition of the system is shown in Figure 2.

![Figure 1. Schematic diagram of the full-polarimetric GPR system.](image1)

![Figure 2. System hardware.](image2)

2.2. Horn antenna

Generally, antennas suitable for GPR systems can be roughly divided into two categories: dielectric-coupled antennas and air-coupled antennas. The former includes various dipole elements, bow ties and helical antennas. The latter mainly includes horn antennas of various bandwidths. Due to the large volume and weight of air-coupled antennas relative to dielectric-coupled antennas, they are usually used in high-frequency bands above 1 GHz [8]. The system built in this paper is mainly used for the detection of shallow targets, so the horn antenna ranges from 1 GHz to 4 GHz is selected as the transmitting and receiving antenna of the system, which is shown in Figure 3.
Figure 3. Physical view of horn antenna (a) front and (b) radiation surface

Figure 4 is a measurement diagram of the horn antennas. Among them, T11 and T12 correspond to port 1 of antenna 1; T21 and T22 correspond to port 2 of antenna 1; R11 and R12 correspond to port 1 of antenna 2; R21 and R22 correspond to port 2 of antenna 2. When one port in antenna 1 transmits and one port in antenna 2 receives, there are four combinations in total, calling polarization modes (HH, HV, VH, VV), as shown in Table 1.

Table 1. Four polarization modes

| antenna2 | port 1         | port 2         |
|----------|----------------|----------------|
|          | R11 | R12 | R21 | R22 |
| port 1   |      |     | HH  |     |
| T11      |      |     |     |     |
| T12      |      |     |     |     |
| port 2   | T21 |     | VH  | VV  |
| T22      |     |     |     |     |

2.3. Composition of full-polarimetric GPR data
There are four polarization modes for full-polarimetric GPR, as shown in Figure 5: horizontal transmission-horizontal reception (HH), horizontal transmission-vertical reception (HV), vertical transmission-horizontal reception (VH) and vertical transmission-vertical reception (VV). The measurement matrix at each measuring point can be obtained from these four polarization modes (Yu, 2016), which is shown in formula (1):

\[
\begin{bmatrix}
S_{i,j,HH} & S_{i,j,HV} \\
S_{i,j,VH} & S_{i,j,VV}
\end{bmatrix}.
\]
where, $S_{i,j,HH}$ is the data measured in HH polarization mode, $S_{i,j,HV}$ is the data measured in HV polarization mode, $S_{i,j,VH}$ is the data measured in VH polarization mode, $S_{i,j,VV}$ is the data measured in VV polarization mode. Because the system's transmitting and receiving antennas are interchangeable, HV data is equal to VH data [11]. Therefore, we only need to measure the data in the three polarization modes: HH, HV, and VV.

![Figure 5. Four polarimetric modes](image)

### 2.4. Data fusion processing

Data fusion technology is an effective method for full-polarimetric GPR data processing. It fuses the acquired polarized data to make the fused data have the characteristics of various polarized data, which can improve the recognition ability of target. The data fusion processing technique used in this paper is weighted average method, as shown in formula (2) [11].

$$S_{i,j,F} = w_{i,j,HH} \times S_{i,j,HH} + w_{i,j,HV} \times S_{i,j,HV} + S_{i,j,VV},$$  \hspace{2cm} (2)

where, $S_{i,j,F}$ is the data fusion result, $w_{i,j,HH}$ is the weight parameter of $S_{i,j,HH}$, $w_{i,j,HV}$ is the weight parameter of $S_{i,j,HV}$. To simplify the problem, we use mean fusion, and set $w_{i,j,HH} = w_{i,j,HV} = 1$. Then we combine the three-polarization data into one fusion data, which can be used for subsequent experimental analysis and processing.

### 2.5. Ice crack experiments and data analysis

In order to demonstrate the overall performance of the constructed full-polarimetric GPR system, an ice crack detection experiment was performed on a frozen lake as shown in Figure 6. The length of the survey line is 1m, and the interval between two measuring points is 1cm. The survey line runs perpendicular to the ice crack, and the ice crack is located at the line of 0.5 m. The width of the upper end of the ice crack is about 1.5cm, and the width of the ice crack is basically unchanged when it extends downward. The frequency band we choose ranges from 1 GHz to 4 GHz with the center frequency of 2.5 GHz, and the time window ranges from 0 ns to 15 ns, with 1024 frequency sweep points in total. The GPS antenna in Figure 6 can record latitude and longitude information, thereby giving an approximate trajectory of the survey line.

The acquired experimental data is subjected to inter-channel equalization processing to obtain radar profile of three polarization modes, as shown in Figure 7 (a), (b), and (c). Among them, Figure 7 (a) and 7 (b) are co-polarized profiles, and Figure 7 (c) is a cross-polarized profile. Figure 7 (d) shows the data fusion processing results of the weighted average method for the three polarization modes (Feng et al., 2017). In Figure 7 (a) and 7 (b), a series of obvious hyperbolas can be seen in the black box with abscissa from 0.35 m to 0.75 m and ordinate from 8ns to 14 ns, and the intensity of the hyperbola down gradually from top to bottom. It is inferred that the series of hyperbolas are generated by ice crack, and the apex positions of the series of hyperbolas obtained from the profile are all at 0.5 m on the abscissa, which is basically consistent with the position of the ice crack on the actual survey line. In addition, it can be seen that the electromagnetic wave signal does not reach the surface until 8ns, which is owing to the high position of the feed point of the horn antenna and the certain transporting time of the electromagnetic wave signal in the antenna. In Figure 7 (c), the discontinuity of the
coincidence axis can be seen in the black ellipse which is due to the ice crack, and the position of the coincidence axis coincides with the actual ice crack location. Compared with Figure 7 (a) and 7 (b), the series of hyperbolas can be seen more clearly and completely in the black box in Figure 7 (d), and the hyperbolas have no significant intensity decay. Also, clear hyperbolas can still be seen at the three arrows in Figure 7 (d), which reflects deeper information of ice crack, but only fuzzy hyperbolas can be seen at the corresponding positions in Figure 7 (a) and 7 (b). In addition, a hyperbola with strong intensity can be seen in the range of 0.35 m to 0.75m on the abscissa and 13.8ns to 14ns on the ordinate in figure 7 (d), which we speculate may be caused by the bottom tip of the ice crack. In summary, the data fusion processing results of the three polarization modes can reflect the information of deep ice crack, and can also improve the recognition ability of ice crack.

**Figure 6.** Ice crack experiments. (a) Ice crack orientation and width (b) measurement system based on horn antenna.

**Figure 7.** Profiles of HH (a), VV (b), HV (c), and after data fusion (d). The black boxes indicate the position of a series of hyperbolas. The black ellipse indicates the position of discontinuous coincidence axis. The black arrows indicate clear hyperbolas not found in HH and VV profiles.

3. Conclusions

In this paper, a full-polarimetric GPR system is built. The entire system is integrated and controlled by the PC control unit, which can realize the automatic measurement of the target's fully polarized information. Experiments of a small-scale ice crack on frozen lakes were performed using the constructed system and good results were obtained. In addition, we use the data fusion technology of weighted average method to process the obtained fully polarized data, and the processing results can better reflect the deep information of the target, improving the recognition ability of the ice crack.

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References

[1] Arcone S A 1991 Dielectric constant and layer-thickness interpretation of helicopter-borne short-pulse radar waveforms reflected from wet and dry river-ice sheets IEEE Transactions on Geoscience and Remote Sensing 29 768-777

[2] Chen C and Higgins M B 2000 UWB full-polarimetric horn-fed bow-tie GPR antenna for buried unexploded ordnance (UXO) discrimination IEEE 2000 International Geoscience and Remote Sensing Symposium 4 1430-1432

[3] Chang X M, Dou Y K, Qin J M and Dun Z 2013 Application of automatic detection device and system of sea ice crack in Antarctic sea ice monitoring Mathematics in Practice and Theory 43 96-102

[4] Cloude S R 2010 Polarization: Application in Remote Sensing (Oxford: Oxford University Press)

[5] Daiki N, Shigeru A, Daisuke S and Takahiro I 2018 Influence of sea ice crack formation on the spatial distribution of nutrients and microalgae in flooded Antarctic multiyear ice Journal of Geophysical Research 123 939-951

[6] Daniels D J, Brooks D, Dittmer J, Mitchell O and Hunt N 2002 Wide swathe multi-channel GPR systems for mine detection RADAR 2002, Edinburgh, UK 210-216

[7] Dong Z, Ye S, Gao Y, Fang G, Zhang X, Xue Z and Zhang T 2016 Rapid detection methods for asphalt pavement thicknesses and defects by a vehicle-mounted ground penetrating radar (GPR) system Sensors (Basel, Switzerland) 16 2067

[8] Fang G 2004 Designing of a low frequency ultra-wideband (UWB) antenna and its application in ground penetrating radar (GPR) system Proceedings of the Tenth International Conference on Grounds Penetrating Radar 109-111

[9] Feng X, Yu Y and et al. 2013 Application of freeman decomposition to full polarimetric GPR 2013 IEEE International Geoscience and Remote Sensing Symposium - IGARSS, Melbourne, VIC 3534-3537

[10] Feng X, Yu Y, Liu C and Fehler M 2015 Subsurface polarimetric migration for full polarimetric ground-penetrating radar Geophysical Journal International 202 1324-1338

[11] Feng X, Liang W, Liu C, Nilot E, Zhang M and Liang S 2017 Application of Freeman decomposition to full polarimetric GPR for improving subsurface target classification Signal Processing 132 284-292

[12] Gianluca G, Ilaria C, Giovanni L, Noviello C, Papa C, Pica G, Alberti G 2019 A low frequency airborne GPR system for wide area geophysical surveys: The case study of Morocco Desert Remote Sensing of Environment 233 111409

[13] Jin Y and Xu F 2013 Polarimetric scattering and SAR information retrieval (Singapore: John Wiley & Sons Singapore Pte. Ltd.)

[14] Kong F and Tore L 1995 Performance of a GPR system which uses step frequency signals Journal of Applied Geophysics 33 15-26

[15] Li L 2010 Full-Polarimetric GPR Acquisition System AND Calibration Technique Preliminary Study (Jilin University)

[16] Liang W, Feng X and Liu C 2018 Development of multiple-Input and multiple-output polarimetric stepped-frequency ground penetrating radar system Journal of Jilin University (Earth Science Edition) 48 483-490

[17] Pettemeier D and et al. 2009 Full polarimetric GPR antenna system aboard the ExoMars rover 2009 IEEE Radar Conference 1-6

[18] Sassen D S and Everett M E 2009 3D polarimetric GPR coherency attributes and full-waveform inversion of transmission data for characterizing fractured rock Geophysics 74 23-34

[19] Yu Y 2016 Research on H-a Feature Decomposition Technology of Full-Polarimetric GPR (Jilin University)