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Review of Full-Polarimetric Ground Penetrating Radar

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Abstract

As an important means of underground information acquisition, the develop-ment of ground penetrating radar technology is rapidly evolving in the direction of multi-polarization information fusion. Full-polarimetric ground penetrating radar (FP-GPR) has attracted much attention because it can break through the limitations of traditional single-polarization mode. This technology fully char-acterizes the anisotropic characteristics, geometric structure and dielectric characteristics of the target body through the fully polarimetric scattering ma-trix, which significantly improves the target recognition accuracy and classifi-cation ability in complex media environments. Its core lies in the application of polarization decomposition technology : Pauli decomposition has the advantage of high resolution in the analysis of deterministic targets with clear physical meaning ; freeman decomposition is based on three types of models such as volume scattering and dihedral angle scattering to achieve classification without ground data support. The H-Alpha decomposition effectively analyzes the scat-tering characteristics of the linear target through the entropy value and the av-erage scattering angle parameter. At present, FP-GPR has been successfully ap-plied in military explosive disposal, underground engineering detection, Mars water ice exploration and other fields, and continues to expand to more complex scenarios. With the breakthrough of multi-band polarization data fusion tech-nology and intelligent interpretation algorithm, FP-GPR is accelerating to ex-tend in the fields of urban underground space digitization, geological disaster warning and deep space resource exploration, providing more adaptive solu-tions for high-precision underground exploration.

Keywords

Application of full polarization ground penetrating radar; Pauli Decomposition; Freeman Decomposition; H-Alpha Decomposition

1. Introduction

With the acceleration of urbanization and the deepening of underground space development, underground target detection has gradually evolved towards high-resolution and multi-dimensional information interpretation. As a non-destructive geophysical detection technology, ground penetrating radar (GPR) realizes shallow geological structure imaging through the dielectric response of electromagnetic wave and underground medium [1]. It is widely used in urban underground pipeline survey [2], fault identification [3], geological disaster prevention [4] and tunnel advanced detection [5]. However, the traditional single-polarization GPR system is limited by the fixed polarization basis configuration, which can only obtain the single polarization scattering response of the target, resulting in insufficient information dimension and difficulty in fully characterizing the electromagnetic scattering characteristics of the target [6]. In the complex geological environment, the target signal is susceptible to background noise interference, and the misjudgment rate and missed detection rate are significantly increased. In addition, relying on limited data inversion is easy to produce multiple solutions, and the algorithm has high redundancy.

In order to break through these bottlenecks, the full-polarimetric ground penetrating radar (FP-GPR) simultaneously receives four sets of polarimetric scattering components of the target by transmitting horizontal and vertical polarized electromagnetic waves, including the co-polarized components Horizontal-Horizontal (HH), Vertical-Vertical (VV) and cross-polarized components Vertical-Horizontal (VH), Horizontal-Vertical (HV) (as shown in Figure 1). And construct a complete 2×2 complex scattering matrix (Sinclair matrix) [7]. The matrix can be expressed as

$$[S]=\begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}. \tag{1}$$

FP-GPR obtains the full polarization information of the target through the polarization scattering matrix, fuses multi-dimensional data such as amplitude, phase and cross-polarization response, extracts characteristic parameters such as polarization entropy and anisotropy, breaks through the limitations of the traditional single-polarization system, significantly improves the target recognition accuracy and anti-interference ability, and effectively reduces the ambiguity of geological interpretation.

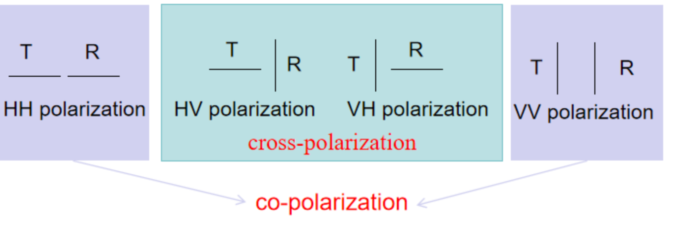

Figure 1. Two or more references

This paper reviews the theoretical development and engineering application progress of FP-GPR technology. At the theoretical level, focus on system construction and polarization decomposition methods; at the application level, combined with typical scenarios such as geological exploration, urban engineering, and cultural heritage, the advantages and accuracy breakthroughs of FP-GPR in complex media environments are demonstrated. Specifically, section 2 introduces the FP-GPR technology system and core methods, section 3 introduces the typical application of FP-GPR, and section 4 summarizes the article.

2. FP-GPR Technology System and Polarization Decomposition Method

The efficient use of FP-GPR technology depends on the high-precision design of hardware system and the deep analysis of polarization information. On the one hand, the technical implementation system of FP-GPR is constructed from hardware architecture optimization, system error calibration to intelligent imaging algorithm (Section 2.1). On the other hand, the polarization decomposition method (such as Pauli, Freeman and H-Alpha decomposition) provides a theoretical analysis basis for underground target classification and parameter extraction by analyzing the physical mechanism (target shape, dielectric properties, anisotropy, etc.) in the scattering matrix (Section 2.2).

2.1. FP-GPR Technology System

Hardware and System Design: Xuan Feng et al. [6] developed a FP-GPR system. The hardware includes PC, Agilent E5071C network analyzer, Cartesian coordinate robot, Agilent 11713C switch driver and Vivaldi polarized antenna array. Wenjing Liang et al. [8] proposed a FP-GPR system based on polarized antenna array. Through the joint acquisition and experimental verification of common / cross-polarization signals, the recognition accuracy of underground target shape and orientation is significantly improved. Zhaofa Zeng et al. [9] proposed a new method based on multi-polarized MIMO ground penetrating radar. By combining the array antenna with the plane wave source, the target detection accuracy and anti-interference ability are effectively improved. Saito and Sato [10] proposed a fully polarized MIMO ground penetrating radar system ' X-Yakumo ', which uses a cross bowtie antenna array and RTK-GNSS positioning to achieve high-precision polarization detection of buried targets in the laboratory and field.

Calibration and Error Correction: Xuan Feng et al. [7] proposed a high-order calibration method for FP-GPR. The scattering matrix is obtained by 0° and 45° dihedral corner reflectors, and the channel imbalance and crosstalk phase error are corrected by combining high-order terms, which significantly improves the accuracy of cross-polarization calibration. Zejun Dong et al. [11, 12] combined Kirchhoff scalar approximation to reveal the influence of dielectric constant and roughness on the transmission coefficient, and proposed FP-GPR forward modeling and high-precision calibration method, and established calibration discriminant template and anti-interference strategy for the influence of rough surface induced field rotation on H-Alpha decomposition.

Imaging and Intelligent Processing: Lele Qu et al. [13] proposed a FP-GPR imaging method based on multi-measurement vector model, which effectively suppresses clutter and improves target imaging quality by combining sparsity and multi-task Bayesian compressed sensing algorithm to process multi-polarization channel data. Jingxia Li et al. [14] proposed a multi-branch deep convolutional neural network FP-GPR method based on channel attention module, which improves the classification accuracy of underground targets through feature fusion and attention mechanism. Haoqiu Zhou et al. [15] proposed a predictive rotation fusion method based on physical model. By optimizing the antenna angle and embedding the predictive filter, the phase conflict problem of FP-GPR data is effectively solved, and the imaging accuracy and anti-noise performance of complex underground structures are significantly improved.

2.2. Decomposition Technique

Pauli Decomposition: Yue Yu et al. [16] applied Pauli decomposition to FP-GPR, and effectively classified underground targets such as metal plates, dihedral angles, and metal balls through α, β, and γ parameter analysis. Experiments verified its recognition ability based on scattering mechanism. Xuan Feng et al. [17] developed the polarization migration imaging technology of FP-GPR, which generates color-coded images through Pauli decomposition and Kirchhoff migration fusion to improve the target recognition effect.

Freeman Decomposition: Xuan Feng et al. [18] used Freeman decomposition to separate surface, double rebound and volume scattering mechanisms to accurately identify metal plates, dihedral angles and metal balls under the sand. Xuan Feng et al. [19] used Freeman decomposition, combined with polarization characteristics and geometric information, to optimize the recognition of targets of different shapes, significantly improved the classification ability of underground targets of FP-GPR, and enhanced the accuracy and effectiveness of data interpretation. Minghe Zhang et al. [20] proposed a FP-GPR underground target classification method based on random forest. Combined with Freeman-Durden three-component decomposition parameters, and the sphere and multi-branch scatterers were effectively distinguished. Hao Zhouqiu et al. [21] proposed a local Freeman decomposition method, which uses shaping regularization to process misplaced FP-GPR data, significantly improves imaging robustness, effectively identifies underground anomalies, and verifies it in ice crack detection.

H-Alpha Decomposition: Xuan Feng et al. [22] combined H-Alpha decomposition and migration techniques to enhance the underground target classification ability of GPR. Yue Yu et al. [23] proposed a polarimetric GPR data processing method based on H-alpha entropy classification method. By analyzing the scattering entropy and α parameter, the automatic detection and classification of UXO in low SNR environment are realized. Yue Yu et al. [24] proposed a four-region H-α classification method based on improved entropy. By analyzing the influence of noise and clutter on polarization characteristics, they optimized the classification of ground penetrating radar fully polarized targets and improved the recognition accuracy under low signal-to-noise ratio conditions. Xuan Feng et al. [25] proposed a FP-GPR underground target classification method based on PCSP, combined with particle swarm optimization algorithm to optimize the sample center. Compared with traditional H-Alpha decomposition and SVM, this method is more efficient and the classification accuracy is significantly improved. Zejun Dong et al. [26] proposed a mathematical modeling method for FP-GPR signals in uniaxial bi-anisotropic media. The polarization rotation coefficient was defined and the target decomposition diagonal matrix was constructed. The nonlinear effects of dielectric constant, conductivity anisotropy and antenna spacing on the H-α decomposition results were revealed.

The polarization decomposition method has gradually developed from the traditional physical model (Pauli, Freeman, H-Alpha decomposition) to the multi-method fusion and expansion (Yamaguchi decomposition). Based on the Sinclair matrix, the Pauli decomposition decomposes the scattering into three basic mechanisms, which have clear physical meaning but are limited to deterministic target analysis [27]. Freeman decomposition achieves target classification through surface, double bounce and volume scattering models, but its accuracy is limited by preset model assumptions [28]. H-Alpha decomposition uses entropy (H) and average scattering angle (α) to improve the interpretation ability of complex targets through two-dimensional classification templates [29]. Xuan Feng et al. [30] combining the advantages of the above methods with the migration imaging technology to jointly extract multi-polarization features, which significantly enhanced the accuracy of underground target classification and 3D imaging, reflecting the technical evolution from a single model to multi-mechanism collaborative analysis. Ran Wang et al. [31] proposed a FP-GPR method based on improved Yamaguchi decomposition, which accurately distinguished plane scattering and dihedral angle scattering components, and verified its effectiveness by numerical simulation.

3. Typical Applications of FP-GPR

In the military field, FP-GPR technology can accurately identify dangerous objects such as underground unexploded ordnance and landmines (Section 3.1). In engineering applications, the technology can penetrate concrete, rock and soil and other media, effectively detect cracks (Section 3.2), steel corrosion and arrangement (Section 3.3), underground pipelines and leakage location and pollutant distribution (Section 3.4), tunnel structural hazards and geological fault investigation (Section 3.5). In addition, this technology has also been applied to the field of Mars exploration, analyzing the shallow structure of Mars, detecting the distribution of water ice and the traces of geological evolution (Section 3.6). Through multi-angle measurement, unipolar ground penetrating radar can indirectly obtain equivalent full polarization information (Section 3.7).

3.1. Mine and Unexploded Ordnance Detection

Haoqiu Zhou et al. [32] proposed a multi-parameter classification method of FP-GPR based on particle center AdaBoost, which improves the accuracy of mine detection by automatically screening polarization features, and combines color coded imaging to distinguish the target surface and internal scattering mechanism.
Yue Yu and Chi-Chih Chen [33] proposed a broadband FP-GPR method based on H-α entropy polarization characteristics, which realizes the detection of unexploded ordnance by automatically classifying boundaries and linear scattering characteristics.

3.2. Crack Detection

Enhedelihai Nilot et al. [34] proposed the L-band fully polarized stepped-frequency airborne ground penetrating radar system, which identifies ice cracks and underground targets through multi-polarization mode differences. Combined with GPS calibration and experimental verification, it shows the potential of high-resolution imaging and classification in complex environments.Chaopeng Luo et al. [35] proposed an ice crack detection method based on full-polarization ground penetrating radar and Pauli decomposition. The feasibility of the method was verified by numerical simulation and experiment, and it was successfully applied to the imaging of small-scale ice cracks on the lake surface. Zejun Dong et al. [36] proposed a method combining time-shifted full-polarization GPR and anisotropy analysis to realize the super-resolution detection of millimeter-scale fractures containing fluid, and verified its effectiveness through numerical simulation and field tests.

3.3. Rebar Corrosion Assessment and Steel Fiber Orientation Analysis

Hai Liu et al. [37] proposed a hybrid polarization ground penetrating radar system, which combines H-Alpha polarization decomposition and migration imaging to achieve non-destructive detection of early corrosion of concrete steel bars.
Abdullah Aksoy et al. [38] proposed a fully polarized B-scan ground penetrating radar method based on H-alpha decomposition, which can effectively evaluate the orientation of steel fibers in concrete through multi-polarization data and scattering mechanism analysis.

3.4. Pipeline Hazard Detection and LNAPLs Contamination Imaging

Hyoung-sun Youn and Chi-chih Chen [39] introduced the two-step artificial neural network into FP-GPR. The underground pipeline was identified by polarization characteristics, and its high detection rate at low signal-to-noise ratio was verified by Monte Carlo simulation. It was successfully applied to the positioning of farmland drainage pipes. Ran Wang et al. [40] proposed a pipeline leakage detection technology based on FP-GPR.By introducing the stable parameters h and q through the improved H-α decomposition method, a new planar classifier was constructed, which significantly improved the accuracy and efficiency of leakage identification in complex environments.

B. Y. Shi et al. [41] combined Pauli decomposition and Kirchhoff migration technology to effectively locate the pollution depth of light non-aqueous phase liquids (LNAPLs) in soil and realize three-dimensional imaging.

3.5. Tunnel and Fault Identification

Jiarun Yang et al. [42] proposed FP-GPR technology based on dominant scattering mechanism analysis, which can effectively identify tunnel structures in complex environments through Freeman decomposition and cavity identification coefficient.

Ran Wang et al. [31] proposed a FP-GPR method based on improved Yamaguchi decomposition, which can effectively identify the fault tendency under thick coal seam by electromagnetic wave propagation modeling and scattering component separation.

3.6. Martian Surface Structure Detection

Dirk Plettemeier et al. [43] developed an ultra-lightweight Vivaldi antenna for the ExoMars mission WISDOM FP-GPR. Through frozen soil test and extreme environment verification, they supported high-resolution detection of shallow Mars. Zejun Dong et al. [44] revealed the influence mechanism of depth, rough interface and dielectric constant on the circular polarization ratio in Tianwen-1 FP-RoPeR water ice detection, and proposed that the superposition effect of IFR interference in the multi-interface layered model leads to significant shallow error. Hao Zhouqiu et al. [45] proposed polarization direction calibration and multi-strategy processing methods for Tianwen-1 fully polarized Mars ground penetrating radar data to effectively suppress noise and channel imbalance, and verified the feasibility through ground experiments. Hai Liu et al. [46] analyzed the difference of low-entropy surface scattering and dipole scattering characteristics of dry ice and water ice in fully polarimetric radar data, which provided a key theoretical basis for ice layer identification and data interpretation of Zhurong Mars radar. Hao Zhouqiu et al. [47] proposed a maximum likelihood data fusion method based on optimal similarity constraints for FP-RoPeR imaging, which effectively integrates the characteristics of multi-polarization channels and significantly improves the analytical accuracy of Martian weathering layer structure.

3.7. Full Polarization Extension of Single Polarization Radar

Yue Yu et al. [24] proposed a full-polarization scattering matrix inversion method based on three single-polarization antenna angle measurements, and verified the feasibility of single-polarization ground penetrating radar to achieve target polarization classification through experiments. Yue Yu and Chi-Chih Chen [48] proposed a full-polarization target classification method based on unipolar ground penetrating radar. The scattering matrix is reconstructed by using the three-antenna direction data, which overcomes the high cost limitation of the traditional full-polarization system.

4. Conclusion

FP-GPR significantly improves the accuracy of underground target detection and has become a cutting-edge technology for target recognition and classification in complex media environments. Its core advantage is to break through the limitations of the single-polarization mode. Through the fully polarized scattering matrix, the anisotropic characteristics, geometric structure and dielectric properties of the target body are completely characterized, thus showing unique potential in military, engineering applications, Mars exploration and other fields. However, this technology still faces many bottlenecks : at the hardware level, the design of FP-GPR instrument is not fully mature, only exists in the laboratory, and has not been applied in the field; at the data processing level, the feature extraction and interpretation of polarization information depend on the polarization decomposition algorithm, which is susceptible to environmental noise and multipath effects in non-uniform media or rough surface scenes, and lacks a unified standardized interpretation framework. In the future, the polarization information fusion method based on deep learning will be developed to solve the problem of small target classification, and multi-band and multi-modal data will be explored to enhance the robustness of interpretation. The technological evolution of fully polarimetric ground penetrating radar not only marks the transformation of underground detection from ' geometric imaging ' to ' physical parameter inversion ', but also provides breakthrough technologies for smart cities, deep ground detection and environmental sustainable development through deep integration with artificial intelligence and other technologies.

References

[1] D. Feng, Y. Liu, B. Zhang, et al.: Special Issue on Ground Penetrating Radar: Theory, Methods, and Applications, Applied Sciences-Basel, Vol. 13 (2023) No. 17, p.9847.

[2] X. Liang, D. Hu, Y. Li, et al.: Application of GPR Underground Pipeline Detection Technology in Urban Complex Geological Environments, Geofluids, Vol. 2022 (2022) No. 1, p.7465919.

[3] L.S. Chamyal, P. Joshi, S. Vasaikar, et al.: Neotectonic Characterization of the Narmada-Son Fault (NSF) Using Field and GPR Data, Gujarat, Western India, Journal of the Palaeontological Society of India, Vol. 67 (2022) No. 1, p.72-84.

[4] W.S. Giamboro, F. Maskuri,W. Hidayat: Hazardous Potential Analysis from Landslide Slip Plane Delineation Based on Ground Penetrating Radar (GPR) Methods in Karangsambung, Kebumen, of Central Java, 2nd International Conference on Earth Science, Mineral, and Energy (Yogyakarta, INDONESIA, 2020 Oct 03), Vol. 2245 (2019), p.030009.

[5] L. Zheng, X. Li, Z. Liu, et al.: Accuracy Evaluation of Advanced Geological Prediction Based on Improved AHP and GPR, Mathematical Problems in Engineering, Vol. 2020 (2020) No. 5, p.1-12.

[6] X. Feng, W. Liang, C. Liu, et al.: Developing a novel full-polarimetric GPR technology, 2011 IEEE International Geoscience and Remote Sensing Symposium 24-29 July 2011),

(2011), p.858-861.

[7] X. Feng, L. Zou, Q. Lu, et al.: Calibration With High-Order Terms of Polarimetric GPR, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, Vol. 5 (2012) No. 3, p.717-722.

[8] W. Liang, X. Feng, C. Liu, et al.: Full-polarimetric GPR system for underground targets measurement, Proceedings of the 15th International Conference on Ground Penetrating Radar 30 June-4 July 2014), Vol. (2014), p.803-806.

[9] Z. Zeng, J. Li, L. Huang, et al.: Improving Target Detection Accuracy Based on Multipolarization MIMO GPR, IEEE Transactions on Geoscience and Remote Sensing, Vol. 53 (2015) No. 1, p.15-24.

[10] R. Saito, M. Sato,Ieee: Perfomance Evaluaion of Full-Polarimetric MIMO GPR, IEEE International Geoscience and Remote Sensing Symposium (IGARSS) (Kuala Lumpur, MALAYSIA, 2022 Jul 17-22), (2022), p.358-360.

[11] Z. Dong, X. Feng, C. Liu, et al.: Study on Polarization Rotation of Electromagnetic Plane Wave from Rough Surface, 2018 17th International Conference on Ground Penetrating Radar (GPR) 18-21 June 2018), (2018), p.1-4.

[12] Z. Dong, X. Feng, H. Zhou, et al.: Effects of Induced Field Rotation From Rough Surface on H-Alpha Decomposition of Full-Polarimetric GPR, IEEE Transactions on Geoscience and Remote Sensing, Vol. 59 (2021) No. 11, p.9192-9208.

[13] L. Qu, S. An, T. Yang, et al.: Full Polarimetric Ground Penetrating Radar Imaging Using Multiple Measurement Vectors Model, 2017 13th International Conference on Natural Computation, Fuzzy Systems and Knowledge Discovery (ICNC-FSKD) 29-31 July 2017), (2017), p.2662-2667.

[14] J. Li, J. Li, Z. Huang, et al.: Underground Target Classification From Full-Polarimetric GPR Data Using Deep Convolutional Neural Network With Channel Attention Module, IEEE Geoscience and Remote Sensing Letters, Vol. 21 (2024) No. p.1-5.

[15] H. Zhou, X. Feng, Z. Dong, et al.: Predictive Rotation Fusion: A Physical Model-Based Fusion Method for Full-Polarimetric GPR Data, IEEE Transactions on Geoscience and Remote Sensing, Vol. 63 (2025) No. p.1-20.

[16] Y. Yu, X. Feng, C. Liu, et al.: Radar polarimetry analysis applied to fully polarimetric Ground Penetrating Radar, Proceedings of the 15th International Conference on Ground Penetrating Radar 30 June-4 July 2014), (2014), p.642-646.

[17] X. Feng, Y. Yu, C. Liu, et al.: Subsurface Polarimetric Migration Imaging for Full Polarimetric Ground-Penetrating Radar, Geophysical Journal International, Vol. 202 (2015) No. 2, p.1324-1338.

[18] X. Feng, Y. Yu, Q. Lu, et al.: Application of freeman decomposition to full polarimetric GPR, 2013 IEEE International Geoscience and Remote Sensing Symposium - IGARSS 21-26 July 2013), (2013), p.3534-3537.

[19] X. Feng, W. Liang, C. Liu, et al.: Application of Freeman decomposition to full polarimetric GPR for improving subsurface target classification, Signal Processing, Vol. 132 (2017) No. p.284-292.

[20] M. Zhang, X. Feng, Y. Zhang, et al.: Full-Polarimetric Ground Penetrating Radar Underground Objects Classification Using Random Forest, 2018 17th International Conference on Ground Penetrating Radar (GPR) 18-21 June 2018), (2018), p.1-5.

[21] H. Zhou, X. Feng, Z. Dong, et al.: Local Freeman Decomposition for Robust Imaging and Identification of Subsurface Anomalies Using Misaligned Full-Polarimetric GPR Data, Remote Sensing, Vol. 14 (2022) No. 3, p.804.

[22] X. Feng, Y. Yu, C. Liu, et al.: Combination of H-Alpha Decomposition and Migration for Enhancing Subsurface Target Classification of GPR, IEEE Transactions on Geoscience and Remote Sensing, Vol. 53 (2015) No. 9, p.4852-4861.

[23] Y. Yu, C.C. Chen, X. Feng, et al.: Application of entropy classification method to the detection of subsurface linnear targets in polarimetric GPR data, 2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 10-15 July 2016), (2016),

p.7438-7441.

[24] Y. Yu, C.-C. Chen, X. Feng, et al.: Modified Entropy-Based Fully Polarimetric Target Classification Method for Ground Penetrating Radars (GPR), IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, Vol. 10 (2017) No. 10, p.4304-4312.

[25] X. Feng, H. Zhou, C. Liu, et al.: Particle Center Supported Plane for Subsurface Target Classification Based on Full Polarimetric Ground Penetrating Radar, Remote Sensing, Vol. 11 (2019) No. 4, p.405.

[26] Z. Dong, X. Feng, H. Zhou, et al.: Effects of Uniaxial Bianisotropic Media on Full-Polarimetric GPR Signatures, IEEE Transactions on Geoscience and Remote Sensing, Vol. 61 (2023) No. p.1-20.

[27] S.R. Cloude,E. Pottier: A Review of Target Decomposition Theorems in Radar Polarimetry, IEEE Transactions on Geoscience and Remote Sensing, Vol. 34 (1996) No. 2, p.498-518.

[28] A. Freeman,S.L. Durden: A Three-Component Scattering Model for Polarimetric SAR Data, IEEE Transactions on Geoscience and Remote Sensing, Vol. 36 (1998) No. 3, p.963-973.

[29] S.R. Cloude,E. Pottier: An Entropy Based Classification Scheme for Land Applications of Polarimetric SAR, IEEE Transactions on Geoscience and Remote Sensing, Vol. 35 (1997) No. 1, p.68-78.

[30] X. Feng, E. Nilot, M. Zhang, et al.: Full polarimetric GPR data decomposition and imaging, 2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 10-15 July 2016), (2016), p.7477-7480.

[31] R. Wang, F. Cui, G. Dong, et al.: Study on the accurate detection method of full-polarimetric ground-penetrating radar faults in mines based on modified Yamaguchi decomposition, Geophysical Prospecting, Vol. 73 (2025) No. 1, p.233-250.

[32] H. Zhou, X. Feng, Z. Dong, et al.: Multiparameter Adaptive Target Classification Using Full-Polarimetric GPR: A Novel Approach to Landmine Detection, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, Vol. 15 (2022) No. p.2592-2606.

[33] Y. Yu,C.-C. Chen: Automatic subsurface unexploded ordnance detection using a wideband full-polarization ground penetrating radar and entropy-based polarimetric signatures, Journal of Applied Geophysics, Vol. 209 (2023) No. p.104913.

[34] E. Nilot, X. Feng, C. Liu, et al.: Design and performance of Full-polarimetric airborne GPR testing system, Proceedings of the 15th International Conference on Ground Penetrating Radar 30 June-4 July 2014), (2014), p.807-810.

[35] C. Luo, X. Feng, C. Liu, et al.: Full-Polarimetric GPR for Detecting Ice Fractures, 2018 17th International Conference on Ground Penetrating Radar (GPR) 18-21 June 2018), Vol. (2018), p.1-4.

[36] Z. Dong, X. Feng, H. Zhou, et al.: Super-Resolution Detection of Millimeter-Scale Fractures With Fluid Flow Using Time-Lapse Full-Polarimetric GPR and Anisotropy Analysis, IEEE Transactions on Geoscience and Remote Sensing, Vol. 62 (2024) No. p.1-16.

[37] H. Liu, J. Zhong, F. Ding, et al.: Detection of Early-Stage Rebar Corrosion Using a Polarimetric Ground Penetrating Radar System, Construction and Building Materials, Vol. 317 (2022) No. 1, p.125768.

[38] A. Aksoy, E. Yigit, A.B. Caglayan, et al.: Interpretation and analysis of scattering in steel fiber alignment in concrete: The H alpha decomposition method using fully polarized B-scan ground penetrating radar (GPR) image data, Journal of Building Engineering, Vol. 105 (2025) No. p.112472.

[39] Y. Hyoung-sun,C. Chi-chih: Neural Detection for Buried Pipe Using Fully Polarimetric GPR, Proceedings of the Tenth International Conference on Grounds Penetrating Radar 21-24 June 2004), Vol. 1 (2004), p.303-306.

[40] R. Wang, F. Cui, G. Dong, et al.: A Pipeline Leakage Detection Technique Using Ground Penetrating Radar Polarization Method, Water Resour Manage, Vol. (2025) No. p.1-24.

[41] B.Y. Shi, Q. Lu, X. Feng, et al.: Imaging LNAPLs contaminated soils by polarimetrie migration, 2016 16th International Conference on Ground Penetrating Radar (GPR) 13-16 June 2016), Vol. (2016), p.1-5.

[42] J. Yang, X. Feng, M. Zhang, et al.: Target Identification Using Dominant Scattering Mechanism Analysis of Full Polarimetric Ground Penetrating Radar for Cavity Detection, IEEE Transactions on Geoscience and Remote Sensing, Vol. 62 (2024) No. p.1-14.

[43] D. Plettemeier, S. Balling, W.-S. Benedix, et al.: ULTRA LIGHT-WEIGHT ANTENNA SYSTEM FOR FULL POLARIMETRIC GPR APPLICATIONS, International IEEE Conference Devoted to the 150-Anniversary of Alexander S Popov (St Petersburg, RUSSIA, 2009 May 18-23), Vol. (2009), p.1557-+.

[44] Z. Dong, X. Feng, H. Zhou, et al.: Assessing the Effects of Induced Field Rotation on Water Ice Detection of Tianwen-1 Full-Polarimetric Mars Rover Penetrating Radar, IEEE Transactions on Geoscience and Remote Sensing, Vol. 60 (2022) No.

[45] H. Zhou, X. Feng, B. Zhou, et al.: Polarized Orientation Calibration and Processing Strategies for Tianwen-1 Full-Polarimetric Mars Rover Penetrating Radar Data, IEEE Transactions on Geoscience and Remote Sensing, Vol. 60 (2022) No. p.1-14.

[46] H. Liu, J. Li, X. Meng, et al.: Discrimination Between Dry and Water Ices by Full Polarimetric Radar: Implications for China's First Martian Exploration, IEEE Transactions on Geoscience and Remote Sensing, Vol. 61 (2023) No. p.1-11.

[47] H. Zhou, X. Feng, Z. Dong, et al.: Maximum Likelihood Data Fusion With Optimal Similarity Constraints for Full-Polarimetric RoPeR Imaging of Martian Regolith, IEEE Transactions on Geoscience and Remote Sensing, Vol. 62 (2024) No. p.1-14.

[48] Y. Yu,C.-C. Chen: Full-Polarization Target Classification Using Single-Polarization Ground Penetrating Radars, IEEE Transactions on Geoscience and Remote Sensing, Vol. 60 (2022) No. p.1-8.