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Research Progress in the Application of Remote Sensing Technology in Geological and Mineral Exploration

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Abstract. Remote sensing technology has evolved from an auxiliary tool to a core technology for breakthrough discoveries in geological mineral exploration. This paper systematically reviews research progress in this field over the past five years. Hyperspectral remote sensing, with dozens to hundreds of narrow bands, enables precise identification of alteration minerals and boasts a detection depth of 500-1000 meters, tripling exploration efficiency compared to traditional methods. The integration of full-band hyperspectral sensors and magnetometers on Unmanned Aerial Vehicle (UAV) platforms overcomes complex terrain limitations, establishing an air-ground collaborative system of "satellite macro-scanning — UAV target area fine identification — ground verification," reducing the field verification cycle by 60%. Artificial intelligence algorithms are deeply involved throughout the exploration process; Random Forest (RF) and 3D Convolutional Neural Networks (3D-CNNs) improve mineral identification accuracy to 85% in multi-source heterogeneous data fusion, while reinforcement learning models optimize drill target layout, reducing costs by 40%. Empirical evidence shows that after applying intelligent remote sensing technology in Kazakhstan, exploration costs dropped from USD 1200 per square kilometer to USD 400, and the discovery cycle for new deposits was compressed by 65%. Current challenges include barriers to multi-source data standardization, insufficient generalization ability of AI models, and real-time bottlenecks in edge computing. The future focuses on the "green exploration + intelligent perception" paradigm, leveraging solar-powered UAVs and biogeochemical collaborative detection technology to advance exploration towards zero-carbon and intelligent transformation.

Keywords: Hyperspectral Remote Sensing, Unmanned Aerial Vehicle (UAV), Artificial Intelligence, Mineral Exploration, Data Fusion.

1. Introduction

Mineral resources form the material foundation of national economic development. Their efficient exploration and development are closely linked to national resource security and sustainable development strategies. Traditional geological prospecting methods (such as drilling, pitting, etc.) often encounter issues of high cost, low efficiency, and significant safety risks in densely vegetated areas, remote mountainous regions, and high-risk overseas locations [1].

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Modern geological mineral exploration relies heavily on remote sensing technology due to its significant advantages like macro coverage, speed, efficiency, non-contact detection, and low cost. With continuous innovation in data sources and processing methods, its application prospects are increasingly broad. In recent years, remote sensing technology in geological prospecting has experienced explosive development, following a systematic research paradigm of "data acquisition → information extraction → comprehensive verification." Regarding data acquisition, the multi-source remote sensing data system is becoming increasingly sophisticated. Multispectral satellite images like Landsat ETM+, ASTER, OLI, and Sentinel-2 play a foundational role in global alteration information extraction. For detailed mineral identification, hyperspectral data from China's Gaofen series satellites (e.g., GF-5, ZY1-02D) provide strong support with global land coverage. The emergence of Unmanned Aerial Vehicle (UAV) hyperspectral sensors like Headwall and HySpex enables accurate sub-meter level identification of lithology and mineral assemblages at the mining district scale, significantly enhancing local detection capabilities. In the information extraction phase, artificial intelligence algorithms like deep learning are deeply integrated into processes such as automatic lithology classification, enhanced extraction of weak mineralization alteration information (like iron staining, hydroxyl minerals), and intelligent interpretation of ore-controlling structures.

Although there are numerous current research achievements, key bottlenecks remain to be broken through. These include the extraction of weak mineralization information in vegetated areas, effective fusion and scale conversion of multi-source or multi-scale remote sensing data, and enhanced identification of weak anomaly signals against strong interference backgrounds.

Future research needs to further focus on the synergy of multi-source heterogeneous remote sensing data and the optimization of AI-driven intelligent prospecting models. Their applications in deep prospecting prediction and environmental effect monitoring also need deepening. This review systematically summarizes the latest research progress of remote sensing technology in geological mineral exploration, emphasizing multi-spectral/hyperspectral data acquisition systems and intelligent information extraction methods. It also discusses current challenges and future development trends to provide references for related research and practice.

2. Technical progress

2.1. Hyperspectral and multispectral remote sensing technology

Hyperspectral technology can capture diagnostic absorption features of minerals (e.g., sericite at 2203 nm, dolomite at 2320 nm), and its nanometer-level spectral resolution enables precise alteration mineral mapping [2]. Spaceborne hyperspectral satellites (e.g., Sentinel-2A, ASTER) offer large coverage, capable of scanning 2000 square kilometers within 24 hours. Their application in Kazakhstan's Balkhash metallogenic belt successfully identified chlorite-sericite alteration zones, indirectly indicating deep copper-gold ore bodies. China's "Geology-1" satellite optimized its band design, enhancing the response of hydrothermal alteration minerals ($Al\text{-}OH/CO_3^{2-}$) in the shortwave infrared bands, improving mineral resource classification accuracy by 40%. Where satellite data resolution is insufficient, UAV hyperspectral technology compensates. The Pegasus V10 UAV equipped with a Headwall HP imager (400–2500 nm full band) synchronously collected data from 607 spectral channels in the Fengxian mineral district, Shaanxi Province. Combined with a ground-measured spectral library, it effectively distinguished confusing alteration assemblages like alunite and jarosite.

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Deep learning models have revolutionized mineral information extraction capabilities. For weak anomalies in vegetated areas, Convolutional Neural Networks (CNN) and Long Short-Term Memory networks (LSTM) jointly break through the spectral masking effect. CNN decomposes mixed pixels, while LSTM analyzes vegetation phenological cycle changes, eliminating seasonal interference through dynamic baseline modeling, thereby increasing alteration recognition accuracy in vegetated areas by 30%. In the study of igneous rock-limestone contact zones, 3D-CNN models utilized shortwave infrared hyperspectral data (Specim SWIR) to map mineral phase transition spatial distribution with an accuracy of 97.5%, revealing the pattern where intrusion caused an 80% loss in the economic value of limestone.

2.2. UAV-based remote sensing and multi-platform collaboration

The demonstration in the Fengtai mineral district adopted a "Sky-Air-Ground" collaborative model, specifically a three-level process of satellite anomaly delineation, UAV fine identification, and ground verification. This shortened the prospecting target verification cycle by 60% and improved exploration efficiency tenfold.

UAV technology, with its ability to adapt to complex terrain and integrate multiple sensors, has reshaped field exploration models. On the edge of the Taklamakan Desert, a UAV aeromagnetic system equipped with a cesium optical pump magnetometer with a sensitivity of 0.001 nT acquired centimeter-level magnetic field data flying at low altitudes of 50 to 150 meters. Three days of work equivalent to one month of traditional helicopter aeromagnetic survey, it also penetrated densely forested areas to identify the trend of magnetic ore bodies.

2.3. Artificial intelligence and multi-source data fusion methods

The core of intelligent prospecting lies in the integration of multi-source heterogeneous data. For geological mapping in the Tsagaan-uul area of Mongolia, Sentinel-2A multispectral data and ALOS PALSAR topographic data (DEM, TRI index) were fused using the Random Forest (RF) algorithm, achieving an overall accuracy of 64.4% [3]. This indicates that topographic parameters are the primary indicators for bedrock classification, and Graph Neural Network (GNN) frameworks perform better. In a case study in Kazakhstan, integrating UAV hyperspectral data, ground gamma spectrometry, and drill core data constructed a 3D mineralization alteration field model, increasing the target prediction success rate to 78%.

The innovative practice of Shaanxi Coal Geological Geophysical Surveying Company, which integrated BeiDou positioning, InSAR deformation monitoring, and hyperspectral technology to build a "digital twin" for mining areas, is particularly noteworthy. The BeiDou system, acting as the neural center, enables millimeter-level displacement monitoring of geological hazards and real-time location of microseismic events, solving time synchronization challenges during shale gas fracturing monitoring. This air-ground-well stereo network optimized drilling paths in the exploration of the East Tianshan Gold Mine in Xinjiang, reducing prospecting costs by 40%.

3. Application and case analysis

Practices in Kazakhstan validate the scale benefits of intelligent remote sensing technology. In the exploration of sedimentary uranium deposits in central Kazakhstan, a CNN model fusing radar and hyperspectral data reduced the exploration cycle by 60%. UAV LIBS (Laser-Induced Breakdown Spectroscopy) could collect samples from 10 square kilometers per day [4], automatically generating mineral heat maps. According to statistics from the national geological company, the exploration cost per square kilometer dropped from USD 1200 to USD 400. The Koktas lead-zinc deposit (reserves of 800,000 tons) discovered in 2022 required only 35% of the upfront investment compared to traditional methods.

More profoundly impacting industrial chain synergy, Astana Mining Group linked the beneficiation plant and logistics center through a remote sensing digital twin system, reducing gold grade control error from ±15% to ±5%, thereby increasing annual revenue by USD 230 million.

4. Existing challenges

4.1. Data integration and standardization issues

Mineral exploration involves multi-modal data such as satellite, aeromagnetic, and seismic data, but differences in format and coordinate systems hinder data fusion. The "MineralSystems" model developed by Australia's CSIRO attempts to build an ontological knowledge graph, but progress remains slow in digitizing historical paper reports using OCR technology and unifying interdisciplinary terminology. The "Sky-Air-Ground-Well" system proposed an adaptive correction framework using Kalman filtering to dynamically correct sensor bias, but spatio-temporal registration algorithms for multi-source data in coal mining areas are not yet mature.

4.2. Insufficient generalization ability and interpretability of AI models

The geological specificity of different metallogenic belts makes model generalization difficult. During geological mapping in Mongolia, scarce samples resulted in an F1-score of only 0.18 for the Tugrug complex. A project in Quebec, Canada, used StyleGAN2 to synthesize spectral data of alteration zones to alleviate bottlenecks caused by small sample sizes. Purely data-driven models might violate physical laws, necessitating the embedding of constraints like Maxwell's equations, i.e., Physics-Informed Neural Networks (PINNs) [5].

4.3. Performance bottlenecks in real-time and edge computing

UAV onboard AI needs to complete anomaly detection within 10 milliseconds. However, lightweight models like MobileNetV3 can suffer accuracy losses of up to 30%. Kilometer-level deep exploration generates TB-level point cloud data. The "Digital Orebody" system from China University of Geosciences used Spark+GPU to reduce the modeling cycle from 72 hours to 8 hours. The daily incremental satellite data of 5 PB exceeds the stream processing capacity of Flink [6, 7].

5. Future development trends

5.1. Green exploration technology

The demand for sustainable development drives technology towards zero-carbon evolution. In the Xinjiang Gobi, unmanned exploration vehicles are solar-powered, and low-power sensor networks are also solar-powered, enabling zero-emission operations and reducing exploration energy consumption by 70%, while maintaining magnetometric accuracy at 0.1 nT. Furthermore, biogeochemical collaborative detection utilizes the characteristics of plant root element enrichment coupled with hyperspectral analysis to establish an eco-friendly concealed ore indicator system, reducing surface damage [8].

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5.2. Quantum detection and next-generation satellite remote sensing

5.2.1. Technological breakthroughs in quantum magnetometers

The core of quantum detection technology lies in achieving ultra-high sensitivity magnetic field measurement based on atomic spin effects. The cold atomic quantum magnetometer developed in China has a sensitivity of 0.0001 nT, an order of magnitude higher than traditional optical pump magnetometers (0.001 nT), with a detection depth reaching over 2000 meters. In a 2024 trial by a team from China University of Geosciences in the East Tianshan Gold Mine, Xinjiang, this technology identified concealed magnetite ore bodies buried at 1800 meters depth, with a resolution five times that of conventional aeromagnetics, significantly reducing deep target verification costs [9].

5.2.2. Technical challenges and countermeasures

In the field of advanced geological exploration, several critical technological challenges remain to be overcome. Firstly, the interference resistance of quantum sensors constitutes a core bottleneck. While cryogenic shielding currently achieves approximately 30% noise suppression, future efforts will focus on embedding quantum error correction algorithms directly into hardware to further enhance measurement accuracy and stability. Secondly, to address the real-time processing demands of vast remote sensing and geological datasets, satellite-borne artificial intelligence chips have been deployed. The next step involves establishing low Earth orbit (LEO) edge computing satellite links to augment in-orbit computational power and reduce data transmission latency. Finally, the lack of unified standards for multi-source data fusion has long constrained industry development. While the ISO 19156-2025 geological data model provides a foundational framework, future efforts will leverage blockchain technology to establish a globally traceable mineral database, enabling secure sharing and transparent management of geological information (Table 1).

Table 1. The current difficulties and the corresponding solutions

Technical bottleneck	Current progress	Future direction
Quantum sensor's anti-interference capability	The low temperature shielding device reduces noise by 30%.	Embedding quantum error-correction algorithms into hardware
Real-time processing of massive data	Spaceborne AI chip	Satellite link at the edge of low Earth orbit
Multi-source Data Fusion Standard	ISO 19156-2025 Geological Data Model	Blockchain-enabled global mining database

5.3. Intelligent perception architecture with all-weather response capability and technical implementation

5.3.1. Multi-layer collaborative architecture of IoT platform

All-weather response capability is achieved through an "edge-cloud" collaborative IoT platform, with a core architecture divided into three layers. Edge Perception Layer: Equipment such as vibration sensors, microseismic monitors, and hyperspectral imagers are deployed in mining areas. 5G/LoRa networks transmit data from these devices in real-time. Lightweight AI models like

MobileNetV3 are embedded in edge computing nodes, enabling preliminary anomaly screening within 10 milliseconds and achieving data compression rates over 90%, reducing the cloud load.

Network Transmission Layer: The daily incremental data for InSAR deformation reaches 5 PB, and hyperspectral stream data has 256 bands. The Time-Sensitive Networking (TSN) protocol ensures synchronous transmission of these two data types, controlling delay within 50ms to meet mine emergency response requirements.

Cloud Analysis Layer: Tencent Cloud Big Data Platform (TBDS) integrates time-series data and utilizes the stream computing engine Oceanus for real-time correlation analysis of InSAR deformation and spectral anomalies, shortening the warning instruction generation cycle to 45 seconds [10].

5.3.2. Core technological innovations

Second-Level Multi-Source Data Alignment: BeiDou timing modules (nanosecond-level synchronization) are adopted to unify sensor time benchmarks, solving the time delay difference between InSAR phase and spectral collection. After application in the Xuzhou mining area, time-series alignment error was reduced from ±3 hours to ±0.5 seconds, and deformation inversion accuracy improved by 57%.

Dynamic Deformation Field Inversion: The supercomputing platform of the Chinese Academy of Surveying and Mapping uses distributed parallel processing, increasing the computational efficiency of national surface deformation by 10 times. 7612 scenes of Sentinel-1 imagery can be processed in just 3 months, supporting dynamic updates of mining area deformation rates with millimeter-level accuracy (4.58 mm/year).

Spectral Anomaly Migration Modeling: Mineral absorption peaks exhibit time-series drift phenomena; for instance, the migration of the Al-OH peak towards longer wavelengths indicates enhanced hydrothermal activity. We introduced LSTM networks to analyze this and constructed a "spectrum-resource quantity" regression model ($R^2 = 0.91$ for this model), enabling minute-level inversion of mineral reserves [11].

6. Conclusion

Remote sensing technology has propelled geological mineral exploration into a new era of "intelligent perception, green exploration, and full-domain collaboration." Hyperspectral and UAV technologies break through spatial and spectral limitations, AI algorithms reshape data interpretation paradigms, and multi-source fusion technology achieves full-element linkage of "space-sky-ground-well." Empirical cases in Kazakhstan, Mongolia, and elsewhere confirm its core value in enhancing prospecting accuracy and reducing exploration costs. Future efforts must tackle challenges like multi-source data governance, AI interpretability, and edge computing, while deepening the development of green exploration equipment and all-weather intelligent perception. With the ongoing deployment of the "Geology-1" satellite constellation and the establishment of international joint laboratories, remote sensing technology will not only safeguard strategic mineral resource security but also lead the zero-carbon and intelligent revolution in geological exploration.

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