

Review

Ground Penetrating Radar in Forensic Science: Applications, Methodologies, Challenges, and Future Directions, A Comprehensive Review

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ABSTRACT: Ground-penetrating radar (GPR) has emerged as one of the most valuable non-invasive technologies in forensic science, enabling subsurface imaging in investigations involving clandestine graves, missing persons recovery, concealed evidence, and mass fatality incidents. The technique transmits short electromagnetic pulses into the ground and records the reflected energy generated by contrasts in dielectric properties between subsurface materials. These reflections allow forensic practitioners to delineate buried anomalies with centimetre-scale accuracy while preserving the integrity of the crime scene. This review documents the evolution of GPR from its earliest forensic applications through to current state-of-the-art systems, focusing on core methodologies, data acquisition and processing protocols, and integrated approaches combining electrical resistivity tomography (ERT), LiDAR, and artificial intelligence. Case studies drawn from diverse settings, including volcanic caves, urban environments, ice-covered water bodies, and tropical forests, demonstrate both the operational versatility of GPR and the contextual limitations that practitioners must recognise. Signal attenuation in high-moisture soils, interpretive ambiguity in heterogeneous environments, and inconsistent operator training remain the principal constraints on GPR performance. These challenges highlight the need for standardised protocols, certified training, and evidence-based deployment criteria. Emerging technologies, including drone-mounted GPR arrays, convolutional neural network-based radargram interpretation, and three-dimensional (3D) subsurface reconstruction, are expected to improve detection precision, reduce field time, and extend operational capability in challenging forensic scenarios. By critically evaluating the published literature and identifying research priorities, this review demonstrates that GPR is not merely a useful adjunct but an increasingly indispensable tool in modern forensic investigations, with the potential to support ethical, time-efficient, and scientifically defensible recovery operations.

Keywords: Ground-penetrating radar; Forensic geophysics; Clandestine graves; Missing persons recovery; Non-invasive investigation; Radargram interpretation; Hybrid geophysical methods; Drone-mounted GPR; AI-assisted detection; Forensic protocols

1. Introduction

Ground-penetrating radar (GPR) has fundamentally transformed forensic subsurface investigations by enabling the detection and characterisation of buried features without excavation, thereby preserving evidence integrity and allowing targeted recovery operations. The technique operates by transmitting short electromagnetic pulses into the ground and recording the two-way travel time of reflected signals, which arise from contrasts in dielectric permittivity between subsurface materials such as compacted soil, air voids, decomposition products, or metallic objects. These reflections manifest as characteristic hyperbolic signatures in two-dimensional radargrams, allowing trained operators to estimate burial depth to centimetre-scale accuracy as a function of antenna frequency and local soil conditions. The combination of portability, real-time data acquisition, and non-destructive operation makes GPR particularly well-suited to time-sensitive forensic scenarios across diverse environments, from urban parcels to remote cave systems [1,2].

The origins of GPR date to 1910, when Leimbach and Löwy patented borehole antenna systems for detecting buried objects through dielectric contrasts. Hülsenbeck's 1926 pulsed electromagnetic concept laid the theoretical groundwork for practical subsurface sounding, and the first documented field use occurred in 1929 when the technique was applied to measure glacier thickness in Austria [2,3]. Post-war advances, including military tunnel-detection programmes during the Vietnam War and the 1972 Apollo Lunar Sounder Experiment, accelerated hardware development. Commercial GPR systems became available during the 1970s, initially serving geological and engineering applications. Forensic adoption accelerated through the 1990s, culminating in the 1994 Fred West murder investigation in England, where GPR located victim remains beneath a concrete basement floor and demonstrated unambiguously that the technique could support criminal proceedings [4].

Since the mid-1990s, GPR has established itself as a central tool in forensic geophysics, with published case studies documenting its application to clandestine grave detection, missing persons searches, mass grave investigation, and concealed object recovery across diverse environmental contexts. A representative example is a 2013 investigation in volcanic tuff caves in Italy, where a 500 MHz antenna system detected a strong dielectric anomaly at 2 m depth corresponding to an air-filled burial cavity; subsequent excavation confirmed the presence of human remains [1,5]. In northern Spain, the combination of GPR with electrical resistivity tomography (ERT) allowed investigators to delineate Spanish Civil War mass graves by mapping both subsurface voids and soil resistivity changes attributable to bone mineralisation [6]. These examples reflect a broader trend toward hybrid geophysical strategies, particularly in clayey or highly conductive soils where GPR alone is insufficient. Published success rates vary substantially with context: under favourable conditions in sandy soils, detection rates reach 80 to 95 percent, while in Italy, overall missing persons search resolution rates average approximately 65 percent, with GPR contributing to target prioritisation and elimination of false leads [1].

Despite these advances, GPR deployment in forensic contexts remains subject to significant technical and operational constraints. Signal attenuation in conductive clay soils or saturated environments can restrict useful penetration depth to less than 1.5 m, and features such as tree roots, rocks, and animal burrows produce hyperbolic reflections that may be misinterpreted as burial signatures without extensive operator experience [7]. Equipment cost and training requirements limit accessibility for underfunded agencies and humanitarian programmes. However, recent developments, including multi-channel antenna arrays, machine learning algorithms for automated anomaly classification, and improved data fusion techniques, are systematically reducing operator subjectivity and expanding the range of environments in which reliable GPR surveys are achievable. UAV integration is further extending operational capability in areas of difficult access, subject to the signal coupling constraints discussed in Section 6.

This review traces the technological evolution of GPR from its earliest forensic applications to present-day AI-assisted and drone-integrated systems, with the specific aim of evaluating what has been established,

where methodological gaps persist, and what standardisation measures are needed to improve reliability across forensic contexts. Unlike purely descriptive overviews, this paper critically examines the conditions under which GPR succeeds and fails, highlights the interpretive complexity often underappreciated by end users, and identifies the research priorities most likely to improve forensic outcomes. It covers grave detection, missing persons searches, mass disaster response, and object recovery, evaluating interdisciplinary integrations with electrical resistivity tomography, LiDAR, and machine learning, while also identifying the persistent limitations in signal interpretation, operator training, and legal admissibility that constrain the technology's full potential in criminal justice.

2. Principles and Historical Background of GPR in Forensics

Ground penetrating radar operates by emitting high-frequency electromagnetic pulses into the subsurface, where these signals reflect off interfaces between materials with contrasting dielectric properties. The receiving antenna records the two-way travel time of the backscattered energy; combined with signal amplitude, this allows calculation of reflector depth and material contrast. GPR systems employ antennas across a broad frequency range, typically 100 MHz for deeper penetration to 2 GHz for finer resolution, and results are visualised as radargrams in which point reflectors such as burial cavities or artifacts produce characteristic hyperbolic signatures. Unlike seismic reflection methods, GPR uses electromagnetic waves and is therefore sensitive to electrical conductivity and moisture content, which cause signal attenuation in clay-rich or saline environments. Pulse-based systems radiating repetitive impulses enable real-time subsurface profiling essential in time-sensitive forensic searches [2,3].

The forensic adoption of GPR evolved from its earlier use in archaeology, where the technique had demonstrated effectiveness in non-invasively locating buried structures and voids. During the 1980s, researchers recognised that the same sensitivity to subsurface dielectric contrasts that revealed archaeological features could also detect clandestine burials. Early forensic applications focused on cemetery surveys and the identification of unmarked graves, with Bevan (1991) among the first to apply GPR systematically in a forensic context [7]. The pivotal moment in criminal forensics came in 1994 with the Fred West investigation in England, where GPR was used to locate victim remains buried beneath concrete, a case that demonstrated the technique's potential in law enforcement and triggered broader adoption by police agencies internationally [4]. Through the late 1990s and 2000s, controlled experiments using pig cadavers as human proxies refined understanding of how burial age and decomposition stage affect GPR signal quality, establishing that detection rates are highest in the first 0–92 weeks when active decomposition produces strong dielectric contrasts [5]. By the 2010s, integration with complementary geophysical methods such as electrical resistivity tomography had become standard in complex soil environments, and software advances enabled 3D volumetric visualisation of anomalies for court presentation [1].

This evolution from an exploratory geophysical technique to a mainstay of forensic investigation reflects both hardware miniaturisation and substantial improvements in processing software, including 3D visualisation platforms. Nevertheless, GPR performance remains highly site-dependent, and hybrid geophysical strategies integrating complementary methods have become standard practice in complex or challenging forensic environments [3,4].

3. Applications in Forensic Science

GPR has been applied across a broad spectrum of forensic contexts, from single-burial detection to mass disaster victim recovery. Its primary advantage is the ability to generate subsurface images non-invasively, preserving scene integrity while guiding targeted excavation. However, the technique's effectiveness is not uniform: detection rates of 80–95% reported for recent burials in sandy soils contrast

sharply with rates below 50% in clay-rich, waterlogged, or heavily vegetated environments. These disparities reflect the fundamental sensitivity of GPR to soil electrical properties, decomposition stage, antenna frequency, and operator expertise. Understanding these context-dependent factors is essential to interpreting both the published success rates and the conditions under which GPR should or should not be deployed as a primary search tool.

Clandestine grave detection represents the most established forensic application of GPR, primarily due to the radar's sensitivity to soil disruptions and decomposition-related dielectric changes. Burials generate subsurface contrasts through the formation of voids, accumulation of decomposition fluids, and variations in backfill compaction, all of which produce characteristic hyperbolic reflections in radargrams. At Youngstown State University, controlled experiments using a GS8000 GPR system located buried pig carcasses at approximately 1.5 m depth in mixed soils with 85% accuracy at six months post-burial [8]. Critically, it must be understood that GPR detects the air-filled cavity or dielectric anomaly associated with a burial, not the remains themselves; confirmation of human origin always requires subsequent excavation or corroborating evidence. During the 2013 search in volcanic caves of Italy, a 500 MHz antenna identified a strong anomaly at approximately 2 m depth; the reflector corresponded to an air-filled cavity within the tuff, consistent with a burial void, and later excavation confirmed the presence of human remains, demonstrating GPR's utility in geomorphologically complex sites where conventional probing is impractical. Detection is strongly time-dependent: the first 0–92 weeks post-burial represent peak detectability as active decomposition produces strong fluid-induced dielectric contrasts, whereas signal strength weakens by up to 70% after 111 weeks as skeletonisation reduces these contrasts [5]. Combining GPR with cadaver dogs has achieved 90% detection rates in Australian trials for graves up to five years old. A multidisciplinary study in Colombia compared GPR signals over pig and human simulants, finding that human remains generated stronger and more persistent hyperbolas attributable to higher fat content, providing guidance on antenna selection for different decomposition scenarios [9,10].

To illustrate the interpretive process, the 2013 Italian cave investigation provides a representative example of GPR data processing and visualisation. In the raw B-scan radargram, a 2D time–distance plot with the horizontal axis representing antenna position and the vertical axis representing two-way travel time in nanoseconds. A prominent hyperbolic reflection appears at approximately 20 ns, corresponding to a depth of ~2 m using a propagation velocity of 0.10 m/ns determined by hyperbola fitting. At this raw stage, the anomaly is visible but surrounded by geological clutter from the cave walls and stratified tuff layers, making unambiguous interpretation difficult. Following standard processing steps, including dewow filtering to remove low-frequency induction artefacts, background subtraction (mean-trace removal) to suppress horizontal banding from surface coupling, and bandpass filtering (200–800 MHz) to isolate the relevant spectral range, the anomaly becomes more clearly defined against the background. Application of Kirchhoff migration then collapses the hyperbola to a focused point reflector, improving lateral resolution by approximately 30–40% and confirming the compact nature of the source. Finally, three-dimensional amplitude slices stacked at 0.2 m depth intervals isolated the anomaly volumetrically, allowing investigators to delineate a target area of approximately 0.5 m² for directed excavation, where human remains were subsequently confirmed [1,5]. This step-by-step transformation from a noisy raw radargram to a focused, localised anomaly underscores both the interpretive skill required and the critical role of processing in converting geophysical data into actionable forensic intelligence.

Beyond clandestine grave detection, GPR has been applied to missing persons searches in challenging environments where conventional methods are ineffective. In frozen settings, Giesbrecht et al. (2023) demonstrated that a 400 MHz sled-mounted system could identify air-filled cavities beneath 20–30 cm of ice at –10 °C using pig proxies, achieving a 75% detection rate and providing a validated protocol for ice-recovery operations [11]. In tropical and humid forest environments, where GPR signal penetration is reduced by up to 50% due to soil conductivity, integration with electrical resistivity tomography and

geographic profiling has improved targeted search efficiency; a Colombian study over 2014–2022 using UAV-collected data showed that this hybrid approach sustained detection capability in conditions where GPR alone was insufficient [12,13].

Mass grave investigation and concealed object recovery represent two further established forensic applications of GPR. In mass fatality contexts, GPR is used to non-invasively delineate site boundaries, estimate the spatial extent of burials, and prioritise excavation areas, thereby supporting forensic humanitarian operations while minimising unnecessary soil disturbance. Investigations of Spanish Civil War mass graves used 250 MHz antennas to image a 10-m-long burial trench, identifying 15 discrete anomalies subsequently confirmed as human remains; complementary ERT surveys corroborated the findings by detecting soil resistivity changes attributable to bone mineralisation [6]. In the context of drone-integrated GPR, Nijeholt et al. (2023) developed and tested a prototype drone-based GPR system specifically for clandestine grave localisation, using simulated graves and cadavers at a Dutch research facility over 2021–2023; the system demonstrated promising applicability across different decomposition stages and soil types, though detection performance remained dependent on altitude control and soil conditions [14]. For object recovery, NIJ-funded trials demonstrated that multi-frequency GPR systems could locate buried firearms in sandy-clay soils at 1 m depth, though false alarms generated by root systems necessitated 3D modelling for result verification [8]. The integration of LiDAR with GPR has improved boundary delineation accuracy in forested environments by approximately 40% compared with GPR alone, as shown in a 2022 NIJ-backed project surveying wooded burial sites [13]. In tropical environments, botanical indicators, particularly anomalous spectral reflectance patterns in overlying vegetation, provide independent corroboration of GPR anomalies; a Colombian study found that spectral changes co-located with GPR signals in approximately 70% of confirmed grave locations [6]. The following Table 1 summarises key case studies, illustrating the variable efficacy of GPR across forensic contexts:

Table 1. Applications of Ground Penetrating Radar (GPR) in Forensic Investigations: Case Studies, Configurations, and Reported Success Rates [1,8,11,14].

Application Type	Location and Year	GPR Configuration	Key Findings	Success Rate
Clandestine Grave	Italy, 2013	500 MHz antenna	Air-filled void/burial cavity anomaly detected at 2 m depth in volcanic tuff cave; subsequent excavation confirmed human remains (GPR identified the cavity, not remains directly)	85% (with verification)
Missing Persons (Ice)	Finland, 2023	400 MHz sled-mounted	Air-filled cavities beneath 20–30 cm ice detected using pig proxies; reflections from ice–body interfaces interpreted as possible submerged remains (Giesbrecht et al., 2023) [11]	75%
Mass Grave	Spain, undated	250 MHz with ERT	Imaged a 10 m trench with 15 anomalies	90% boundary accuracy
Object Recovery	U.S. NIJ tests, 2012	Multi-frequency	Located buried firearms in mixed soils	80%, reduced by clutter
Drone GPR (Clandestine Graves)	The Netherlands, 2021–2023	Drone GPR	Prototype drone-GPR system (DJI M600 Pro) tested over simulated graves and cadavers; system demonstrated potential for clandestine grave localisation across decomposition stages; performance dependent on altitude control and soil type	Promising (feasibility prototype; no single accuracy figure reported)

These case studies collectively illustrate that GPR performance varies considerably with soil conditions, burial age, antenna configuration, and the degree of methodological integration employed. In arid sandy environments, useful detection depths can exceed 4 m, whereas tropical humidity and high clay content typically restrict penetration to 1.5 m or less, underscoring the need for site-adapted protocols and hybrid geophysical strategies. Advances in 3D subsurface reconstruction are also expanding GPR’s evidentiary

role, enabling the production of volumetric models that translate geophysical findings into court-admissible spatial records [15,16].

4. Methodologies and Protocols

Forensic GPR surveys constitute a multi-stage workflow encompassing acquisition planning, field data collection, digital processing, interpretive analysis, and protocol-compliant reporting. Each stage is subject to specific methodological requirements dictated by the forensic context, where non-invasiveness, evidence chain-of-custody, and data reproducibility are as important as detection sensitivity. Well-designed acquisition schemes maximise signal quality across variable field conditions while maintaining the survey speed necessary for large-area forensic searches.

Field acquisition begins with the establishment of a georeferenced survey grid using GPS or physical markers, defining orthogonal transect lines to ensure complete, non-overlapping coverage of the search area. For clandestine grave detection, transect spacing of 0.25 to 0.50 m is standard, providing sufficient spatial density to capture anomalies via multiple overlapping reflections. Antenna orientation relative to the suspected burial axis is a critical but often overlooked parameter: alignment perpendicular to the long axis of the grave yields superior hyperbolic signatures, while parallel orientations risk missing elongated features entirely, as demonstrated by Berezowski et al. (2023) in controlled burial simulations [9]. Frequency selection represents the fundamental trade-off between penetration depth and spatial resolution. Antennas in the 400 to 500 MHz range are most commonly employed in forensic surveys, providing penetration to approximately 3 m with centimetre-scale resolution in moderate-conductivity soils. Lower frequency options (250 MHz) extend penetration to 5 m in dry terrain but generate lower spatial resolution and increased clutter in vegetated sites; high-frequency antennas (1 GHz and above) offer sub-centimetre resolution but are limited to the uppermost 0.5 to 1.0 m of the profile. Additional acquisition parameters, including time window (typically 50 to 100 ns in forensic work), samples per trace (512 to 2048), and stacking folds (8 to 32 for noise averaging), are selected to balance data quality against survey speed. A 2019 cave investigation in Italy exemplifies optimal parameter selection: 16-fold stacking with a 500 MHz bistatic antenna and a derived propagation velocity of 0.10 m/ns from hyperbola fitting enabled accurate depth conversion and confident anomaly delineation [1]. Commercial field units such as the MALÅ GX (MALA Geoscience, Malå, Sweden) and GSSI SIR-4000 (Geophysical Survey Systems, Inc., Nashua, NH, USA) support on-site processing and real-time anomaly identification, reducing the time between acquisition and investigative decision-making.

Post-acquisition data processing transforms raw radargrams into interpretable subsurface maps through a sequential series of signal corrections and enhancements. Initial steps include dewow filtering, which removes low-frequency induction artefacts introduced by direct antenna coupling, and time-zero correction to synchronise traces and ensure accurate depth conversion. Background removal by mean-trace subtraction eliminates horizontal banding caused by surface reflections and system ringing; this step is particularly important in urban forensic contexts where metallic debris generates coherent clutter that can obscure burial signatures. Gain functions, including automatic gain control (AGC) and spreading-and-exponential-compensation (SEC) gain, compensate for geometric spreading and attenuation-related amplitude decay with depth. In the Spanish Civil War mass grave surveys, AGC processing was essential in rendering soil anomalies at 2 m depth visible against background variation [6].

Migration algorithms collapse diffractive hyperbolas back to their true subsurface positions, improving lateral resolution by 30 to 50% in heterogeneous media. Kirchhoff migration and finite-difference time-domain (FDTD) modelling are the most commonly employed approaches; FDTD additionally allows generation of synthetic radargrams from assumed burial geometries, enabling direct comparison with field data to verify interpretations from controlled experiments [10]. Advanced spectral filtering, including frequency-wavenumber (f-k) filtering to suppress coherent noise such as airwave multiples, and bandpass

filtering (200 to 800 MHz) to isolate forensically relevant signal components, further improves signal-to-noise ratio. Standard processing platforms used in forensic GPR include Reflexw, GPR-SLICE, and RADAN. GPR-SLICE is particularly valued for generating horizontal amplitude depth slices at user-defined intervals (typically 0.2 m), enabling time-lapse 3D amplitude maps from repeated surveys over monitored grave sites, as used in studies tracking signal evolution across the 0 to 111-week decomposition window [5].

Radargram interpretation translates geophysical signal patterns into forensically actionable findings, demanding expertise in both GPR physics and the investigative context. In B-scan displays, amplitude is rendered as wiggle traces or colour-coded intensity values. Point-source reflectors such as burial voids generate hyperbolic diffractions, while undisturbed stratigraphic horizons appear as laterally continuous sub-horizontal reflectors. Anomaly strength is assessed by amplitude and hyperbolic continuity: strong, symmetric hyperbolas at 1 to 2 m depth are characteristic of recent burials with high fluid contrast, whereas weak or diffuse reflections are more consistent with skeletonised remains. From multi-transect gridded data, 3D amplitude slice volumes provide a volumetric perspective on burial geometry. A 2024 Colombian study demonstrated that 3D slice analysis could differentiate pig simulants from human remains based on hyperbolic asymmetry attributable to differences in body fat composition, providing a basis for target prioritisation in multi-burial scenarios [10]. False positive management is a critical challenge: roots, animal burrows, and buried debris frequently generate hyperbolic reflections similar in amplitude to grave signatures. Velocity analysis by hyperbola fitting, combined with multi-algorithm cross-validation and GIS integration of botanical surface indicators, substantially reduces false positive rates. Hybrid interpretive workflows incorporating ERT are now standard in conductive soil environments; in a 2023 Australian protocol, GPR provided initial anomaly delineation, and ERT confirmed mineralisation signatures in targeted areas, reducing unnecessary excavations by 60% [9]. NIJ guidelines specify a signal-to-noise ratio threshold of 3:1 as the quantitative criterion for classifying a target as a probable hit requiring verification [8]. In drone-integrated forensic GPR, Nijeholt et al. (2023) demonstrated that prototype systems evaluated over simulated graves could detect subsurface anomalies consistent with burials, with RTK-GPS integration enabling precise spatial referencing. However, performance remained contingent on low-altitude operation and soil type [14].

Forensic protocols organise these methods into phased workflows aligned with legal and ethical standards. According to NIJ guidelines, the process is staged as follows: (1) pre-survey evaluation, examining intelligence and soil properties to select appropriate equipment; (2) grid-based acquisition with real-time quality control; (3) laboratory processing to produce refined subsurface models; (4) on-site verification using probes or cadaver dogs; and (5) reporting with chain-of-custody documentation suitable for legal proceedings. For clandestine grave searches, GPR typically serves as the initial screening tool, followed by ERT confirmation in areas of high conductivity, a protocol that reduced unnecessary excavations by 60% in a 2023 technical trial [9]. Recent innovations from 2020–2025 include AI-driven real-time anomaly flagging during acquisition and LiDAR-GPR hybrid workflows for grave mapping in vegetated sites, improving boundary accuracy by approximately 40%. Temporal monitoring protocols have been refined to account for the declining detectability beyond 92 weeks post-burial, scheduling repeat surveys at defined intervals. Ethical protocols require certified operators, for instance, through Geophysical Survey Systems Inc. (Nashua, NH, USA) accreditation, and cultural sensitivity training, particularly for investigations involving indigenous burial grounds. The integration of infrared thermal screening as a complement to GPR, correlating thermal anomalies with radar signals over two-year monitoring periods in forested environments, represents a further methodological refinement [5,17].

These methodologies, honed through cases like the 1994 Fred West investigation and recent NIJ-backed trials, position GPR as a cornerstone of forensic geophysics, with ongoing refinements promising even greater precision in challenging scenarios.

5. Challenges and Limitations

Despite its demonstrated utility, GPR is subject to a range of environmental, technical, interpretive, and practical limitations that must be carefully considered in forensic deployment planning. These constraints affect both the probability of detection and the reliability of interpretation, with consequences ranging from false negatives that delay victim recovery to false positives that trigger unnecessary and potentially damaging excavations. Empirical studies consistently report detection accuracies of 70 to 90% in favourable conditions such as dry sandy soils, but performance can fall below 50% in challenging environments, a degradation that may not be immediately apparent during field operations [18].

Environmental factors represent the most pervasive source of GPR performance limitation. Soil electrical conductivity is the primary control on signal penetration depth: clay-rich soils and water-saturated environments significantly attenuate electromagnetic energy, restricting useful penetration to 1.0 to 1.5 m in the most conductive conditions, making deeper burials effectively invisible even to experienced operators [2]. Dense surface vegetation and near-surface root systems introduce scattering noise that can mask or mimic burial signatures, generating false hyperbolic patterns difficult to distinguish from actual anomalies without ground-truth verification. Seasonal moisture variation complicates survey planning: rainfall events can transform previously penetrable soils into highly attenuating media within hours, while prolonged drought can introduce desiccation cracks that generate spurious reflectors. Temperatures above 30 degrees Celsius alter near-surface moisture gradients and affect signal velocity, introducing depth estimation errors if velocity is not measured locally. Terrain roughness, including rocky slopes and urban rubble, disrupts antenna-ground coupling and introduces instrument noise. The challenges of complex geological settings are illustrated by surveys at Nova Scotia's Joggins Formation, where clay overlying rocky dipping strata caused severe antenna coupling losses and prevented reliable imaging of shallow subsurface structures [19,20].

Technical limitations are inherent to the physical principles underlying GPR measurement. The frequency-penetration trade-off is fundamental: high-frequency antennas (1 GHz and above) resolve small features but penetrate less than 0.5 m in typical soils, making them unsuitable for most burial depths; low-frequency antennas (200 to 250 MHz) reach 3 to 5 m but at spatial resolutions that may not resolve individual bone fragments or small objects. Electrical interference from nearby radio transmitters, power lines, and motorised equipment introduces noise that standard bandpass filters may not fully suppress without inadvertently attenuating genuine target signals. Metallic objects such as pipes, reinforcing bars, and discarded equipment generate strong specular reflections that dominate radargrams in urban environments, obscuring weaker biological signals. In structural forensics, anisotropic construction materials such as glued laminated timber exhibit dielectric constants varying from 1.50 to 2.75 across grain orientations, introducing depth estimation errors of up to 3% in layered media [20]. While drone mounting has extended operational reach, battery limitations and radio link reliability constrain survey duration and data quality in remote or topographically complex terrain.

Interpretive limitations arise from the inherently subjective nature of radargram analysis, particularly in heterogeneous subsurface environments. Roots, rocks, animal burrows, and buried debris routinely generate hyperbolic reflections that closely resemble grave signatures in amplitude and geometry, and differentiating these from actual burials without excavation or independent verification is one of the most persistent challenges in forensic GPR [18]. A systematic review of GPR burial detection studies found that misinterpretation rates were highest in heterogeneous soils where clutter signatures were broadly similar to decomposition void reflections. Temporal signal decay compounds interpretive difficulty: while GPR detects fresh burials effectively because of high-contrast fluid-induced dielectric anomalies, signal strength weakens by 50 to 70% after 92 to 111 weeks as decomposition fluids disperse and skeletonisation removes soft tissue contrasts, leading to markedly increased false negative rates in long-standing cases [5]. Velocity estimation error, caused by moisture variation or frequency-dependent dispersion, propagates into depth

conversion inaccuracies that can be consequential in shallow burial scenarios. Finally, operator skill and experience are significant sources of inter-survey variability: studies comparing interpretation results across operators of different training levels have found substantial disagreement rates, underscoring the importance of standardised certification and interpretation protocols [18].

Practical and ethical considerations further constrain GPR deployment in resource-limited and culturally sensitive contexts. Advanced multi-channel GPR systems can cost between USD 30,000 and 100,000, placing them beyond reach for many underfunded law enforcement agencies and humanitarian organisations. The combination of equipment cost, operator certification requirements, and post-processing expertise creates significant capability inequality between high-income and low-income country forensic services. Ethical challenges are particularly acute in investigations involving indigenous burial grounds or culturally significant sites, where even non-invasive GPR surveys may be perceived as a violation of community norms and where false positive-driven excavations can cause irreversible cultural harm. From a legal standpoint, GPR results are inherently probabilistic and require corroborating evidence before they are admissible as the basis for excavation decisions in formal judicial proceedings; courts in several jurisdictions have required combined GPR-ERT or GPR-cadaver dog verification before authorising exhumation [16]. The following Table 2 summarises the principal challenges in forensic GPR, with documented examples and evidence-based mitigation strategies:

Table 2. Key Environmental, Technical, Interpretive, and Practical/Ethical Challenges in Forensic GPR, with Impacts and Mitigation Strategies.

Challenge Category	Description	Examples/Impacts	Mitigation Strategies
Environmental	Soil moisture, clay content, vegetation clutter	Attenuation in wet clays limits depth to 1 m; roots cause false positives	Use lower frequencies; integrate ERT for conductivity mapping
Technical	Frequency trade-offs, signal contamination	Hyperbolae from debris obscure strata; metal absorption blocks detection	Apply bandpass filters, FDTD modeling for validation
Interpretive	Ambiguous hyperbolae, temporal signal decay	Misreads in heterogeneous sites; failure post-skeletonization	AI classification, repeated surveys for temporal tracking
Practical/Ethical	Cost, expertise gaps, and site disturbance risks	Low success (65%) in missing persons; ethical digs in heritage areas	Operator training, hybrid methods to reduce excavations

Addressing these limitations requires continued investment in AI-enhanced processing to reduce operator subjectivity, standardised international protocols to improve cross-context reliability, and accessible training programmes to narrow the capability gap between well-resourced and under-resourced forensic agencies.

6. Future Directions and Conclusions

The trajectory of GPR development over the past decade points toward systems that are more automated, more portable, more capable in challenging environments, and better integrated with complementary sensing and intelligence technologies. Artificial intelligence represents perhaps the most transformative near-term advance. Convolutional neural network (CNN) architectures trained on labelled forensic radargram datasets have demonstrated anomaly detection accuracies of up to 85% in controlled experiments, with substantially reduced false positive rates compared with manual interpretation [21]. Transfer learning approaches allow models trained on pig cadaver datasets to be adapted for human remains detection, and ongoing development of forensic-specific training corpora is expected further to improve generalisation across soil types and burial scenarios. Automated radargram labelling tools are also reducing the bottleneck of expert annotation, enabling larger and more diverse training sets. Beyond classification, deep learning-based velocity analysis and depth inversion are being developed to reduce operator

dependence in the depth conversion step, a significant source of error in heterogeneous subsurface conditions [21]. The global GPR market is projected to reach USD 2.5 billion by 2032, with forensic and archaeological sectors identified as primary growth drivers, reflecting both expanding demand and improving cost-accessibility of advanced systems [22].

Hybrid sensor integration is the second major development axis. The operational complementarity of GPR and ERT is now well established: GPR provides high-resolution spatial imaging of dielectric contrasts while ERT maps bulk conductivity changes, together producing a more complete subsurface characterisation than either method alone. Combined GPR-ERT workflows reduced false excavation rates by 60% in a 2023 Australian field protocol [9]. Integration of LiDAR for surface topographic correction is becoming standard in forested environments, where canopy height models derived from LiDAR are used to remove topographic effects from GPR profiles and to co-register botanical anomaly maps with subsurface geophysical data [13]. The development of global forensic GPR signature repositories, in which annotated radargram datasets from diverse soil and climate conditions are pooled and made available for algorithm training and cross-case comparison, represents a high-priority standardisation target identified by multiple research groups. Digital twin technology, borrowed from drone forensics, offers a further methodological advance: by generating predictive 3D burial simulations from soil property inputs, digital twins allow scenario testing before survey deployment, optimising antenna selection and acquisition geometry without site disturbance [23]. Quantum sensing technologies, while still at an early stage of development, may in the future offer electromagnetic sensing modalities that surpass the current resolution limits of conventional GPR antennas, potentially enabling detection of skeletal fragments at greater depths or in highly cluttered environments. By 2030, the convergence of these advances is expected to push forensic GPR detection rates toward 95% in standardised scenarios and to substantially extend its operational envelope in challenging humanitarian contexts such as mass grave mapping in conflict-affected regions [22,23].

Drone-mounted GPR systems represent a third area of active development, but their operational capabilities and limitations require careful characterisation. The fundamental constraint of airborne GPR is antenna–ground decoupling: as antenna elevation increases, the air–ground interface generates strong near-field reflections that dominate the uppermost portion of the radargram, masking shallow subsurface targets, while diffraction hyperbolas become compressed and less distinct, degrading both velocity analysis and lateral resolution [24]. A 2025 drone GPR study at an archaeological site confirmed that shallow targets remained undetectable in the topmost profile because the signal required additional depth to re-couple to the subsurface after crossing the air–ground boundary. That detection of faint features is severely compromised in moist soils where signal attenuation is already high [25]. Reliable drone GPR operation therefore, requires maintaining antenna height within approximately half a wavelength above the ground surface, and performance benchmarking against ground-coupled reference datasets is recommended before operational deployment [24]. Within these constraints, drone-based GPR offers genuine advantages for large-area reconnaissance and coverage of terrain inaccessible to ground operators. Nijeholt et al. (2023) demonstrated that a prototype drone-GPR system using a DJI M600 Pro could detect subsurface anomalies consistent with clandestine graves across multiple decomposition stages and soil types in controlled field tests, with RTK-GPS integration providing precise spatial referencing [14]. For forensic grave detection specifically, Nijeholt et al. (2023) demonstrated that a drone-integrated GPR system could locate simulated clandestine graves in controlled conditions [14]. However, they emphasised that very low-altitude near-surface operation and careful altitude control are prerequisites for detecting the low-contrast dielectric anomalies associated with burials. Claims that drone GPR can routinely map unmarked graves at standard survey altitudes are therefore not supported by current evidence and overstate the technique's present capability [24,26].

Ground-penetrating radar has evolved from a niche geophysical instrument into a cornerstone of modern forensic investigation, with a demonstrated capacity to support clandestine grave detection, missing

persons recovery, mass grave delineation, and concealed object location across a diverse range of environmental and operational contexts. Under favourable conditions, detection accuracies of 70 to 90% have been documented, and hybrid workflows incorporating ERT, LiDAR, and cadaver dogs consistently outperform single-method approaches. However, the review has also made clear that GPR is not a universally reliable tool: its performance is profoundly sensitive to soil conditions, burial age, antenna configuration, and operator expertise, and these dependencies must be explicitly acknowledged in forensic reporting to avoid overstatement of confidence to legal decision-makers. The correction of the widespread misconception that GPR detects remains directly, rather than the dielectric anomalies associated with burial, is a particular priority for forensic training and reporting standards. Looking forward, the integration of machine learning-driven interpretation, near-surface UAV deployment, and global signature repositories will further expand GPR capability, but the foundational requirement for well-trained, critically reflective operators and standardised, evidence-based protocols will remain unchanged. Future research should prioritise longitudinal datasets across diverse soil and climate types, randomised field protocol trials, and the development of quantitative admissibility frameworks to support GPR evidence in international criminal and human rights proceedings.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

The authors used AI-assisted grammar and language tools solely for the correction of linguistic errors and improvement of readability. All research conceptualisation, literature selection, critical analysis, interpretation, and intellectual content of this review were produced exclusively by the authors without AI assistance in any substantive capacity.

Author Contributions

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