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Review of ground surveillance radars and optoelectronic scanning systems for ground target detection

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Abstract

This review paper presents a technical overview of contemporary battlefield ground surveillance radars and critically examines their capabilities and inherent limitations from a system and signal-processing perspective. The analysis covers radar architectures, operating principles, detection performance, and key constraints associated with near-ground propagation, clutter non-stationarity, Doppler ambiguities, and scanning trade-offs. The paper compares representative ground surveillance radar systems to show how architectural choices affect achievable detection ranges and target classes in practical deployments. Building on this assessment, the paper reviews optoelectronic sensing systems, with particular emphasis on laser scanning technologies and thermal imaging, in three distinct roles: complementary sensing, radar cueing, and replacement of selected surveillance functions. Drawing on advances originally developed for autonomous vehicle perception and recent studies on optical and thermal object detection, the review discusses how optoelectronic systems may mitigate selected limitations of classical radar-based approaches under favourable operational conditions, especially in the detection and classification of slow-moving personnel and small vehicles. The discussion further highlights the relevance of multi-sensor architectures, integrating radar, optoelectronic and spaceborne sensing, for modern intelligence, surveillance, and reconnaissance systems.

1. Introduction

Battlefield radars, referred to in English literature as ground surveillance radars (GSRs), are a specialised class of radar systems designed to detect, locate and track objects moving on the surface of the Earth and in its immediate vicinity. Unlike classic aerial observation radars, GSR systems are designed to work in an environment heavily disturbed by reflections from the terrain, vegetation, and infrastructure where the useful target echo is sometimes weaker than the background by several tens of decibels. For this reason, GSRs should be seen not only as measurement devices, but as complex detection and information systems, in which both the hardware architecture and the algorithms for processing radar signals play a key role.

The primary task of GSRs is to detect and track movement in the observed area. In military and paramilitary applications, this primarily includes detecting individual people and groups of infantry, wheeled and tracked vehicles, as well as monitoring traffic in border areas, buffer zones, and around critical infrastructure facilities. In recent years, the range of applications of GSRs has expanded to include tasks related to detecting unmanned aerial vehicles moving at very low altitudes, which, from the point of view of ground radar, often appear against a background of strong terrain clutter. Artillery radars constitute an additional, specialised category, their purpose is to detect the flight paths of missiles and locate fire sources based on ballistic observation.

The operational capabilities of the GSR depend on a set of key technical parameters. One is range resolution, which depends directly on the bandwidth of the transmitted signal and determines the ability to distinguish targets at short ranges along the line of sight. Equally important is angular resolution, which results from the antenna effective aperture and architecture; this parameter affects the ability to separate targets at similar azimuths. In battlefield radars,

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angular resolution is particularly important in urban environments and areas with high object density.

Another important parameter is the minimum detectable target velocity, which determines the system ability to detect slow-moving objects. In GSRs, this parameter is crucial for detecting infantry and slow-moving vehicles because the radial velocities of such targets often match the speeds of dynamic clutter elements (e.g., moving vegetation). In practice, this limitation results from both the properties of the radar signal and the characteristics of the Doppler detection algorithms.

Another important design aspect of battlefield radars is resistance to interference, including both natural interference (terrain clutter, weather conditions) and intentional electronic interference. Contemporary GSR systems use a variety of resiliency techniques, including adaptive detection algorithms, multi-channel processing, and flexible antenna beam management. At the same time, the ability to operate in various weather conditions, such as rainfall, fog, or smoke, which affect radar-wave propagation to varying degrees, remains an important requirement, depending on the frequency band used.

The literature emphasises that the effectiveness of GSR should not be evaluated solely on the basis of a single technical parameter, but as a result of a trade-off between range, resolution, robustness to clutter and interference, and system complexity, both hardware and computational. The classification structure adopted in this review is summarised in Fig. 1.

2. Battlefield radar classification (GSR)

Battlefield radars (GSRs) do not form a homogeneous class of devices either in terms of design or functionality. Their architecture and technical parameters largely depend on the working environment, the nature of the objects detected, and operational requirements. For this reason, there is no single, commonly accepted "canonical" taxonomy of GSRs in the scientific literature. Instead, a multidimensional classification approach is used, in which radar systems are organised according to various technical and functional criteria. This article adopts a taxonomy based on four main factors: operating frequency band, radar technology used, antenna and channel architecture, and operational purpose.

2.1. Classification by frequency band

One of the basic parameters determining the properties of the GSR radar is the operating frequency band. In practice, systems of this type mainly use the L, S, X, Ku, and W bands, with the choice of band being a compromise between range, resolution, antenna dimensions, and resistance to weather conditions. The lower bands (L and S) allow observation at longer distances and are characterised by lower atmospheric attenuation but require large antenna apertures to achieve acceptable angular resolution. For this reason, they are mainly used in stationary or vehicle systems.

The most common compromise in GSRs is the X band, which allows for good resolution with moderate antenna size and acceptable propagation resistance. The Ku and W bands are mainly used in short-range radars and systems designed to detect small objects, such as unmanned aerial vehicles, where high resolution is more important than maximum range. Works on specific radar techniques, e.g., frequency modulated continuous wave (FMCW) and linear frequency modulated continuous wave (LFMCW) radars, often discuss the consequences of band selection indirectly, where the band directly determines achievable range resolution and susceptibility to propagation interference [1].

2.2. Classification by radar technology

The second important criterion for classifying GSRs is the signal generation and processing technology used. Classic pulse radars, including pulse-Doppler radars, remain widely used in medium- and long-range systems. Their main advantage is their flexibility in selecting operating parameters and their ability to achieve long detection ranges. In the GSR environment, however, the effectiveness of

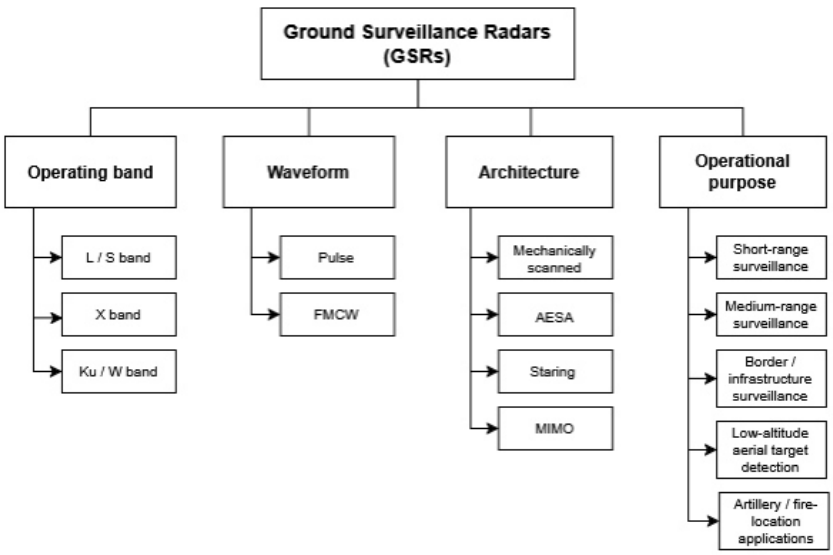


Fig. 1. Taxonomy of ground surveillance radars.

pulsed radars is strongly dependent on the quality of algorithms for detecting and adapting the threshold in the presence of a heterogeneous clutter, which is the subject of classic and still current research on constant false alarm rate (CFAR) algorithms [2].

An alternative and increasingly common technology are FMCW radars and their linear variants – LFMCW. In these radars, the range information is encoded in the beat frequency, and the range resolution depends directly on the modulation bandwidth. Stove's classic work remains the primary reference for analysing the advantages and limitations of FMCW radars, including the influence of modulation nonlinearity and frequency-path stability on measurement quality [1]. In the context of GSR, FMCW technology is particularly attractive in short-range radars and mobile systems, where compactness and low-emission power are important.

2.3. Classification by antenna and channel architecture

A key dimension of modern GSR taxonomy is the system spatial architecture. Phased array (AESA) radars enable fast space search, flexible management of observation time, and multi-mode operation. In practice, these solutions increase observation efficiency, although they do not solve clutter-based detection problems on their own.

Multiple-input, multiple-output (MIMO) radars constitute a special class, which the literature has well classified. In collocated MIMO configurations, the emphasis is on creating a virtual aperture and improving angular resolution without physically increasing antenna size, as discussed extensively in Li and Stoica [3]. In contrast, MIMO radars with widely separated antennas exploit the target geometric and signature diversity, increasing the system resistance to adverse observation conditions and RCS fluctuations, as described in detail in the review by Haimovich *et al*. [4]. Both classes of MIMO architectures can be used in GSRs, albeit at the expense of increased hardware and computational complexity.

2.4. Classification by operational purpose

From a practical point of view, GSRs are also classified by operational purpose. Short-range radars (SR-GSR) are used for the protection of facilities, patrols, and borders, and are characterised by high mobility and short deployment time. Medium-range radars are designed to observe larger areas and are often mounted on vehicles or stationary platforms. Anti-drone radars, optimised for detecting objects with a very small effective radar cross-section, where the analysis of time-frequency signatures plays an important role, are playing an increasingly important role [5, 6].

A separate category are artillery radars, whose task is to detect shell trajectories and locate fire sources. Although technically different from classic ground-based surveillance radars, they are closely related to GSRs in many aspects, such as detection rate and interference-immunity requirements.

3. Methodology of the literature review

This review is based on a structured survey of scientific and technical literature related to GSR and optoelectronic sensing systems used in battlefield surveillance and reconnaissance. The primary search window covered publications from 2019–2025, while selected earlier publications were included when they constituted widely cited foundational contributions or provided the theoretical basis for methods used in contemporary GSR and optoelectronic sensing systems. The literature search used major scientific databases, including IEEE Xplore, Scopus, and Web of Science, supplemented by targeted searches on Google Scholar to identify additional relevant publications and technical reports. The review includes both recent studies and earlier foundational works that are widely cited in the radar signal processing and sensing literature. The review includes classical contributions on FMCW radar techniques, CFAR detection, micro-Doppler phenomena, and MIMO radar architectures because they form the theoretical basis of contemporary GSR systems.

The search strategy used combinations of keywords related to the review main topics, including *ground surveillance radar*, *battlefield radar*, *FMCW radar*, *pulse-Doppler radar*, *radar clutter*, *micro-Doppler*, *LiDAR object detection*, *thermal imaging detection*, *and radar–LiDAR sensor fusion*.

Publications were included in the review if they satisfied at least one of the following criteria:

- peer-reviewed journal or conference publications addressing radar architectures, radar signal processing, or ground target detection,
- studies presenting experimental validation of radar or optoelectronic sensing systems,
- methodological works describing detection or classification algorithms applicable to ground surveillance.

Publications were excluded if they consisted solely of marketing material without technical description of the sensing methodology or were not available in English.

In addition to peer-reviewed publications, we selectively used manufacturer datasheets and technical brochures to obtain publicly available performance parameters of representative operational GSR systems. These sources were used exclusively to illustrate the capabilities of existing radar platforms and were not treated as primary scientific evidence.

For the purpose of qualitative assessment, the reviewed works were grouped according to the dominant type of contribution:

- theoretical studies addressing signal models, detection theory, and radar phenomenology,
- simulation-based analyses of radar signal processing or sensing architectures,
- experimental studies based on laboratory or field measurements,
- operational or system-level reports describing deployed surveillance systems.

This categorisation reflects the different levels of technical validation typically encountered in radar and sensing research and enables a structured comparison of theoretical developments, algorithmic studies, and practical sensing systems.

The methodology described above provides the basis for the selection and comparison of representative GSR systems discussed in section 4.

4. Review of selected modern battlefield radars (GSRs)

4.1. Assumptions of comparison and criteria for the selection of systems

This section compares a representative group of modern battlefield radars (GSRs) in real operational use for which public comparable technical data are available. Unlike marketing statements, we adopted selection criteria that allow engineering analysis, not only functional analysis.

Only the following systems were included in the comparison:

1) designed to detect and track ground targets (pedestrians, vehicles),
2) operating in the mode of continuous sector or omnidirectional observation,
3) enabling automatic multi-target tracking (TWS),
4) having explicitly declared detection parameters (range, bandwidth, target class) as reported in publicly available manufacturer documentation (datasheets or technical brochures),
5) representing different technology classes described in section 2.

The review includes both pulse-Doppler radars and FMCW radars, systems with classic architecture and solutions with "staring radar" and AESA elements. Such a selected group makes it possible to analyse design trade-offs that determine the practical capabilities of GSR radars. Because certain operational parameters (e.g., SWaP, refresh rate, or measurement accuracy) are rarely available and inconsistently defined, the comparison is limited to parameters explicitly and consistently reported in open sources.

Further difficulty concerns the comparability of the available data rather than their availability. Declared detection ranges are quoted for target classes that are named but not parameterised: none of the five sources specifies the radar cross-section assumed for a "pedestrian" or a "vehicle", and none states the detection criterion – probability of detection and false-alarm rate, at which the range is defined. Since detection range depends on both quantities, figures published by different manufacturers cannot be treated as measurements of the same physical quantity. The comparison presented below therefore treats declared ranges as indicative and, where possible, examines their internal consistency rather than their absolute values.

4.2. HENSOLDT SPEXER® 2000 – pulse-Doppler GSR with AESA antenna

The SPEXER 2000 radar represents a class of GSRs using an AESA antenna operating in the X band [7].

The AESA antenna enables the SPEXER 2000 radar to perform several functions simultaneously: sector search, tracking selected objects, and low-altitude aerial observation, including detection of low-flying aerial targets such as UAVs. In practice, this means the beam revisit time can be adapted to the tactical situation, directly affecting the quality of tracking slow-moving targets.

From a technical point of view, the SPEXER 2000 is characterised by:

1) high angular resolution resulting from a large effective aperture,
2) the ability to detect pedestrians at speeds close to the Doppler detection limit,
3) extensive clutter filtering and automatic tracking algorithms.

It is typically deployed as a fixed-site or transportable surveillance radar system, with higher energy and infrastructure requirements than man-portable systems, while offering extended detection range and electronically steered sector observation.

4.3. SRC SR Hawk™ – tactical pulse-Doppler GSR in the Ku band

The SR Hawk™ is a classic military GSR, an evolution of earlier ground surveillance systems (the AN/PPS family). The radar operates in the Ku-band and uses the pulse-Doppler detection method, optimised for long observation ranges and stable operation in complex field environments [8].

An important element of the SR Hawk™ architecture is a clear definition of the minimum detectable velocity, which in practice determines the effectiveness of infantry detection. The manufacturer also explicitly declares the instrument range and detection ranges for several vehicle classes, allowing precise comparison with other systems.

From the point of view of operational applications, the SR Hawk™:

1) can be carried in a backpack configuration,
2) can work as a fixed radar,
3) can be installed on a vehicle.

A key feature is its large instrument range relative to the system mass, which is relevant for tasks such as base protection, approach-route reconnaissance, and observation of large areas.

4.4. Ground Observer 12 (GO12) – man-portable pulse-Doppler

The GO12 represents a compact man-pack GSR design focused on high mobility and reduced SWaP. The radar uses pulse-Doppler processing with a mechanically scanned antenna providing a continuous 360° coverage and employs an agile frequency-hopping mode intended to reduce its probability of interception by hostile electronic intelligence [9].

The GO12 is a typical team/platoon man-pack system (sensor mass ≈ 17 kg, power demand ≈ 70 W), designed to be deployed in under five minutes by a small team. Its compactness and low-power budget come at the expense of a shorter detection range compared with larger, higher-power pulse-Doppler systems.

4.5. PGSR-3i 'Beagle' Mk II – portable FMCW GSR low emission

The PGSR-3i 'Beagle' Mk II is a portable GSR that employs digital signal processing and automated detection functions. The radar operates in the X band and uses FMCW technology, enabling high-range resolution with low transmit power [10].

From the point of view of algorithmic architecture, the 'Beagle' Mk II includes:

1) CFAR-based detection algorithms,
2) clutter maps,
3) automatic tracking of multiple targets,
4) the possibility of automatic classification of detected objects.

The manufacturer declares not only detection ranges, but also the accuracy of range and azimuth measurements, which is rare in GSR datasheets. This radar illustrates how portable systems can use DSP algorithms to compensate, to a certain extent, for hardware constraints.

4.6. Leonardo DRS MSTAR V6 – military, man-portable GSR

The MSTAR V6 is a man-portable military GSR. The radar operates in the Ku band and is intended for military field deployment, with a comparatively fixed functional configuration [11].

The system offers a continuous surveillance range from approximately 100 m to about 27 km and is optimised for motion detection rather than precise imaging. In practice, the MSTAR V6 is often used as an early warning sensor, generating indications for EO/IR systems, an arrangement referred to in this review as radar cueing.

Detection ranges reported in Table 1 are manufacturer-declared values derived from datasheets or technical brochures. Therefore, these values should be regarded as indicative performance rather than directly comparable measurements.

The internal consistency of each pair of declared figures can nevertheless be examined, since both ranges quoted by a given manufacturer refer to the same radar and the same detection criterion, and under noise-limited conditions, the detection range varies with the fourth root of the radar cross-section. The declared range ratios imply vehicle-to-pedestrian cross-section ratios of approximately 16, 51, 16, 33, and 14 for the SPEXER 2000, SR Hawk, GO12, 'Beagle' Mk II, and MSTAR V6, respectively. All lie within the span of published values for personnel and ground vehicles, so no individual figure is implausible, but they differ by nearly a factor of four, indicating that the underlying target models are not common across manufacturers. Treat this as a consistency check rather than a range model, since GSR detection at low grazing angles is often clutter-limited and subject to multipath; it still confirms that ranking these systems by declared range alone is not methodologically justified.

Parameters reported in Table 2 are based on publicly available manufacturer documentation. For several operational military radar systems, detailed signal-processing parameters, refresh rates, measurement accuracies, and complete SWaP data are not consistently disclosed; therefore, we include only characteristics explicitly stated in open sources.Influence of radar architecture on the achieved detection parameters

A comparison of the presented GSR systems shows that the achieved detection ranges for pedestrians and vehicles result from several key design decisions: frequency band used, type of transmitted signal (pulse *vs*. FMCW), antenna architecture, and the spatial scanning strategy. Pulse-Doppler radars operating in the X or Ku band (SPEXER 2000,

Table 1.
Detection performance of selected battlefield radars (GSRs).

System	Band	Technology	Platform class	Range (pedestrian)	Range (vehicle)	Source type
HENSOLDT SPEXER® 2000	X	pulse-Doppler, AESA	fixed site/transportable	18 km	36 km	datasheet
SRC SR Hawk™	Ku	pulse-Doppler	man-portable	12 km	32 km	datasheet
Thales GO12	not disclosed	pulse-Doppler	man-portable	10 km	20 km	manufacturer website
PGSR-3i 'Beagle' Mk II	X	FMCW	portable	10 km	24 km	brochure
MSTAR V6	Ku	pulse-Doppler	man-portable	> 13 km	> 25 km	datasheet

Table 2.
Architectural and operational characteristics of selected battlefield radars (GSRs).

System	Azimuth coverage	Scanning method	Minimum detectable velocity	Source
HENSOLDT SPEXER® 2000	sector with modular 360°	electronic beam steering	not publicly disclosed	datasheet
SRC SR Hawk™	sector/360°	scanning surveillance radar	0.5 m/s	datasheet
Thales GO12	360°	mechanically scanned antenna	not publicly disclosed	manufacturer website
PGSR-3i 'Beagle' Mk II	sector/360°	sector scan or continuous rotation	not publicly disclosed	brochure
MSTAR V6	sector/360°	mechanically scanned antenna	0.85 m/s	datasheet

SR Hawk™, MSTAR V6) achieve the longest detection ranges, resulting from the ability to use high peak power and high antenna gain. In systems with an AESA antenna (SPEXER 2000), electronic beam steering adds another factor affecting detection performance by enabling adaptive allocation of observation time within the selected sector and increasing dwell time or coherent integration time for selected directions, depending on the operating mode. Compact man-pack pulse-Doppler systems such as the Thales GO12 trade this peak-power advantage for mobility and low-energy consumption, resulting in shorter practical detection ranges despite sharing the same waveform class.

FMCW radars such as the PGSR-3i 'Beagle' Mk II, on the other hand, are characterised by shorter maximum ranges, while offering high-range resolution and favourable conditions for detecting slow-moving targets. This is due to continuous emission of a wide-band signal and high processing gain, which compensates for low instantaneous power. A further architectural distinction concerns the scanning strategy: staring architectures, in which a fixed beam continuously illuminates a selected sector, eliminate the revisit time inherent to scanning radars and thus improve the detection of short-lived motion signatures, at the expense of restricting coverage to a narrow sector. The differences between the detection ranges of pedestrians and vehicles in Table 1 primarily reflect the impact of the effective radar cross-section of the target and the available energy budget of the radar, rather than the operating band itself.

4.7. Summary of the comparison of selected GSRs

The presented systems confirm that GSR detection parameters depend strongly on the trade-off between range, resolution, hardware complexity, and mobility. Pulse-Doppler radars with larger dimensions and higher power requirements provide the greatest range and sector flexibility, making them well suited to base protection and area reconnaissance tasks. Low-emission FMCW systems, although limited in range, can provide favourable conditions for detecting slow-moving targets and short update intervals within the observed sector, which makes them suitable for short-range tactical reconnaissance tasks. The lack of a single "optimal" solution confirms the validity of the taxonomy presented in section 2 and indicates that GSR selection should always be subordinated to the specific operational scenario and expected detection characteristics.

The comparative analysis of the representative GSR systems indicates that the observed performance differences are primarily driven by architectural trade-offs rather than implementation details, which motivates a systematic discussion of the fundamental technical limitations of GSR presented in the following section.

5. Technical limitations of battlefield radars (GSRs)

5.1. Constraints of the energy budget and radar equation

In practice, the effectiveness of detecting ground targets with battlefield radars (GSRs) depends not only on the system maximum instrument range, but also on its ability to maintain an appropriate signal-to-noise ratio after processing in the presence of strong, variable ground clutter under near-ground propagation conditions. Unlike aerial observation radars, GSR systems operate at low grazing angles, where terrain-induced multipath, shadowing, local screening, and strong backscatter from land cover significantly affect the received signal. As a result, target echoes are often several tens of decibels below the background; in addition, targets frequently move at low radial velocities, making Doppler separation difficult.

The radar equation, although formally correct, does not fully reflect the operational limitations of the GSR because it does not account for losses from clutter filtering, adaptive CFAR detection, limited observation time [coherent processing interval (CPI)], and space-scanning strategy. In practice, the detection range of a pedestrian or small vehicle is often limited not by the energy balance, but by the detection threshold at a given false alarm level, which leads to the need for a compromise between Pd (probability of detection) and Pfa (probability of false alarm) already at the system design stage.

5.2. Ground clutter and its impact on the detection of slow-moving targets

Ground clutter in GSRs is characterised by strong spatial and temporal heterogeneity. Its properties depend on land-cover type, local terrain geometry, grazing angle, surface roughness, and weather conditions. In near-ground propagation, multipath and partial target obscuration further reinforce these effects, distorting both amplitude and Doppler signatures. Additionally, clutter elements such as moving vegetation generate Doppler components that can overlap with the velocity spectrum characteristic of infantry.

A key problem is the so-called clutter edge: a rapid change in background statistics between adjacent range or azimuth cells. In such conditions, classical detection algorithms, designed under the assumption of background uniformity, show significant performance degradation. Research on CFAR processing in heterogeneous environments shows that stabilising the level of false alarms requires the use of interference-tolerant algorithms in reference windows, which, however, is associated with additional detection losses [12].

In GSRs, this problem is particularly important because area observation (e.g., roads, buildings, tree lines) naturally leads to strong clutter heterogeneities within one observation sector. For this reason, modern detection schemes increasingly rely not only on classical CFAR adaptation, but also on clutter maps, track-before-detect (TBD) approaches, and, in some architectures, space-time adaptive processing (STAP) or related adaptive filtering methods. Recent STAP research, developed primarily for airborne radar, addresses cases where clutter heterogeneity limits the number of homogeneous training samples available for covariance estimation [13]; the same constraint applies to ground-based observation of structurally varied terrain.

5.3. CFAR detection and the problem of false positives

CFAR algorithms are the basic mechanism for stabilising the detection threshold in GSRs, but their effectiveness in

practical scenarios is limited by the presence of multiple targets, clutter edges, and the variability of background statistics. For this reason, CFAR is often complemented by additional mechanisms that exploit temporal persistence or spatial context rather than relying exclusively on a cell-by-cell threshold test.

An analysis of classical CFAR processors in a heterogeneous environment shows that algorithms such as GO-CFAR or OS-CFAR offer greater robustness to background nonhomogeneity (clutter), but at the expense of a higher detection threshold [12]. In GSR practice, this means precisely selecting the CFAR algorithm for a specific operational scenario and often using additional mechanisms such as clutter maps or adaptive censorship of reference samples. Clutter maps are particularly useful when the background is locally repeatable over time, whereas TBD-type methods can improve detectability of weak and slowly moving targets by integrating evidence over multiple scans before threshold declaration. Figure 2 illustrates these constraints schematically: the geometry of a CFAR reference window near a clutter edge, alongside a qualitative summary of how CA-, GO-, and OS-CFAR differ in robustness and detection-loss tendency.

5.4. *Blind speeds and MTI/MTD filtering limitations*

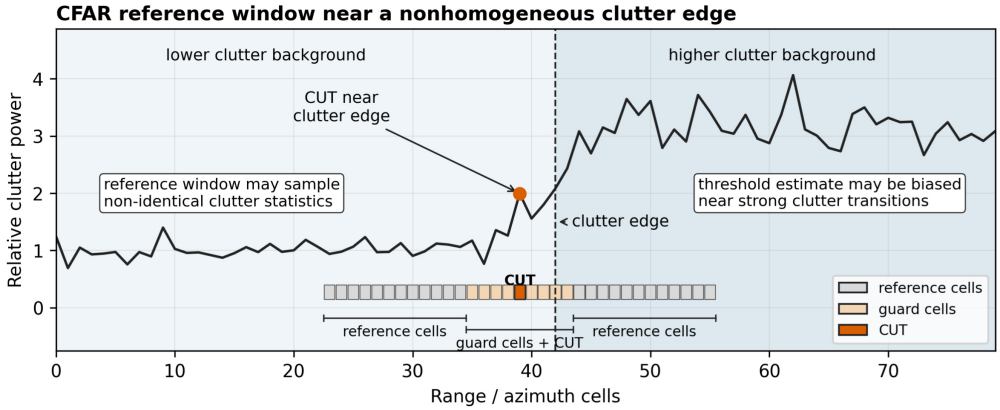
In pulse-Doppler radars, the so-called blind speeds, resulting from the periodic structure of MTI/MTD filters and the selection of the pulse repetition frequency (PRF), are an important limitation. For certain radial velocities, the Doppler filter response can be significantly attenuated, reducing target detectability.

In the context of the GSR, this problem is particularly acute because the speeds of infantry and light vehicles are often within the range where the clutter spectrum and the characteristics of the MTI filters overlap. One way to reduce this phenomenon is to use staggered PRF and design MTI filters that account for this signal time structure. In more advanced architectures, clutter rejection may also be improved through adaptive space-time processing, provided that the antenna configuration and signal model support it. Analyses of MTI filter design for heterogeneous PRI show that it is possible to reduce the number of blind speeds, but at the cost of increased processing complexity and potential degradation of clutter attenuation [14]. A synthetic illustrative range-Doppler map for a GSR scenario is shown in Fig. 3. It shows a near-zero Doppler clutter ridge, a local vegetation-induced Doppler spread, a slow pedestrian target partially overlapping the clutter region, and a faster vehicle target separated in Doppler. The example uses an illustrative Ku band configuration and is intended to visualise qualitative detection challenges for slow-ground targets rather than to present measured radar data.

5.5. *Limitations of FMCW radars in GSR applications*

FMCW radars eliminate some of the problems characteristic of pulse radars, such as classic blind speeds, but introduce their own limitations. One of them is the coupling between range and velocity estimation (range-Doppler coupling), resulting from the fact that the Doppler shift directly affects the runout frequency. In practice, this can lead to range estimation errors for moving targets, especially with short chirp durations.

Another problem is the presence of strong short-range components, resulting from transceiver crosstalk and self-reflections, which limits the receiver dynamic range. In GSRs, which often must observe areas from several dozen meters, this phenomenon significantly affects target detection in the immediate vicinity of the radar. The classic development of FMCW techniques indicates that effective compensation requires precise RF-path calibration and appropriate signal processing [1].



Qualitative detector behavior

Detector	Homogeneous clutter	Clutter-edge robustness	Contaminated reference cells	Detection-loss tendency
CA-CFAR	high	low	low	low–medium
GO-CFAR	medium	medium–high	medium	medium
OS-CFAR	medium	high	high	medium–high

Fig. 2. CFAR operation in nonhomogeneous clutter.

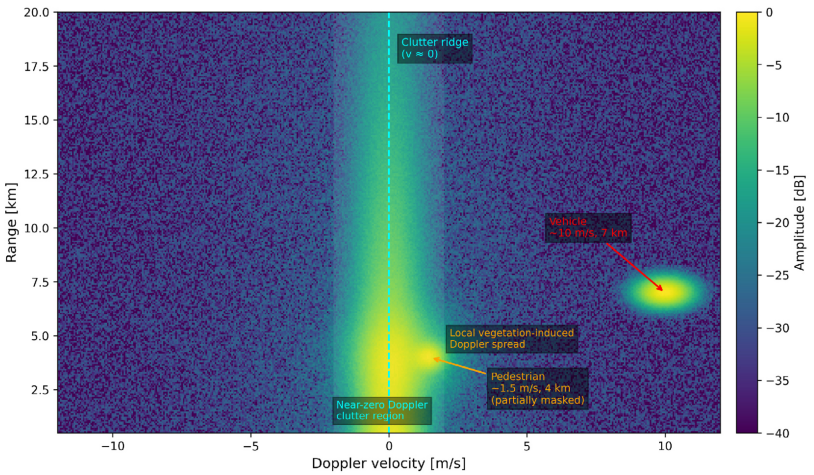


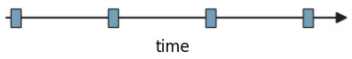
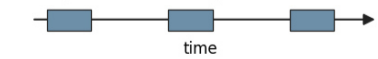
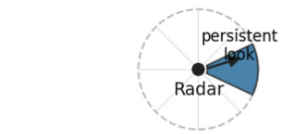
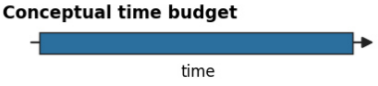
Fig. 3. Synthetic illustrative range-Doppler map for a GSR scenario.

5.6. Scanning strategy: sectoral vs. omnidirectional

The spatial scanning strategy is a fundamental limitation of GSRs. In omnidirectional mode, a radar must divide the available observing time among all azimuths, reducing the coherent integration time for a single direction and limiting the evidence that can accumulate for weak targets across successive revisits. This degrades detection of slow-moving targets and increases variability in background estimates, straining CFAR algorithms.

Sector scanning, on the other hand, extends the CPI and improves detection parameters in a selected area, but at the cost of losing situational awareness outside the observation sector. AESA-based solutions partially mitigate this trade-off by allowing adaptive observation-time allocation and fast beam switching, but they do not eliminate it entirely. In this context, modern detection approaches such as TBD or adaptive clutter suppression can improve performance, although they remain constrained by the available dwell time, revisit schedule, and clutter statistics. Table 3 summarises this trade-off across three representative scanning architectures.

Table 3.
Conceptual relationship between scanning strategy, dwell time, and revisit rate.

Scanning strategy	Characteristics
360° scan  **Conceptual time budget**  	Provides the widest azimuth coverage, but the available observation time must be distributed over all directions. As a result, dwell time and coherent integration opportunity for a single direction are limited, which can reduce detectability of weak or slow-moving targets.
Sector scan  **Conceptual time budget**  	Concentrates the observation time within a selected azimuth sector. Compared with 360° scanning, it provides longer dwell time and shorter revisit intervals inside the sector, improving conditions for weak-target detection and slow-target tracking at the expense of reduced spatial coverage.
Staring observation  **Conceptual time budget**  	Provides continuous observation of a selected direction or sector. This maximises dwell time and coherent integration opportunity, offering the most favourable conditions for weak- or slow-target detection, but with strongly limited azimuth coverage.

5.7. Micro-Doppler and target classification limitations

Micro-Doppler analysis is a tool for classifying targets in GSRs, but several factors limit its effectiveness. Micro-Doppler components are usually much weaker than the main signal, making them susceptible to clutter and noise. In addition, their observation requires a sufficiently long CPI and stable target tracking [15].

The literature on micro-Doppler indicates that although this phenomenon provides valuable information about the nature of target movement [16], practical GSR systems often limit its use to initial classification and may require support from other sensors, such as optoelectronic systems. Figure 4 illustrates this discriminative potential using synthetic spectrograms. The richer time-frequency modulation of the walking pedestrian compared with the quasi-rigid vehicle signature indicates why micro-Doppler can support target classification, provided that the target is observed over a sufficiently stable interval [17].

5.8. Electromagnetic interference and mutual interference

The modern battlefield environment is characterised by an increasing density of radar and communication systems, which leads to an increase in the level of interference. In FMCW radars, mutual interference between radars with similar modulation parameters is a particular problem, which can generate artifacts in range-Doppler maps. In pulsed radars, interference most often manifests as increased noise levels and false alarms.

Research on radar interference mitigation shows that effective mitigation requires a combination of hardware strategies (frequency variation, beam management) and algorithmic strategies (detection and elimination of interference in the time and frequency domain) [18].

5.9. Geometric and propagation constraints

In addition to strict radar limitations, geometric and propagation factors play an important role. The low height of the radar installation and small grazing angles favour terrain masking, multipath propagation, and angularly localised clutter returns, which lead to fluctuations in signal amplitude, apparent target signatures, and spatially nonuniform detectability. In practice, this means that the instrument range of the GSR often significantly exceeds the range of effective detection in undulating or urbanised terrain.

These limitations, rooted in geometry and near-ground propagation, suggest that further improvements within the radar domain alone may not fully address detection and identification challenges, motivating exploration of alternative sensing modalities.

6. Optoelectronic sensing in relation to GSRs

6.1. Motivation for the use of optoelectronic sensors in battlefield reconnaissance

The limitations of battlefield radar (GSR), discussed in section 5, largely stem from the nature of the ground-based propagation channel and the need to separate the target signal from strong, non-stationary ground clutter. Detecting and identifying slow-moving objects with a small effective radar cross-section, such as a single soldier or small groups of infantry, is particularly difficult. In such scenarios, it is reasonable to include optoelectronic sensors in the reconnaissance system, which operate in a different physical domain and are not burdened by the Doppler limitations typical of radars.

In this article, an optoelectronic system is either an active laser scanner (LiDAR) or a passive imaging sensor (daylight or thermal infrared camera) capable of scanning the environment and providing information about scene geometry or thermal radiance distribution. From a surveillance-system taxonomy perspective, these modalities differ in at least four practically relevant dimensions: sensing principle (active/passive), primary output representation (image, thermal image, or 3D point cloud), susceptibility to atmospheric degradation, and sensor-operation signature. These modalities can enter a reconnaissance architecture in three ways, which this review distinguishes. In complementary sensing, the optoelectronic sensor and the radar operate concurrently and independently and their outputs are fused, neither sensor controlling the other. In radar cueing, the relationship is sequential: the radar detects and pre-tracks, then hands over a region of interest to the optoelectronic sensor for verification and classification, so that optoelectronic utility is bounded by radar detection performance. In place of selected functions, the optoelectronic sensor performs surveillance without radar participation, for

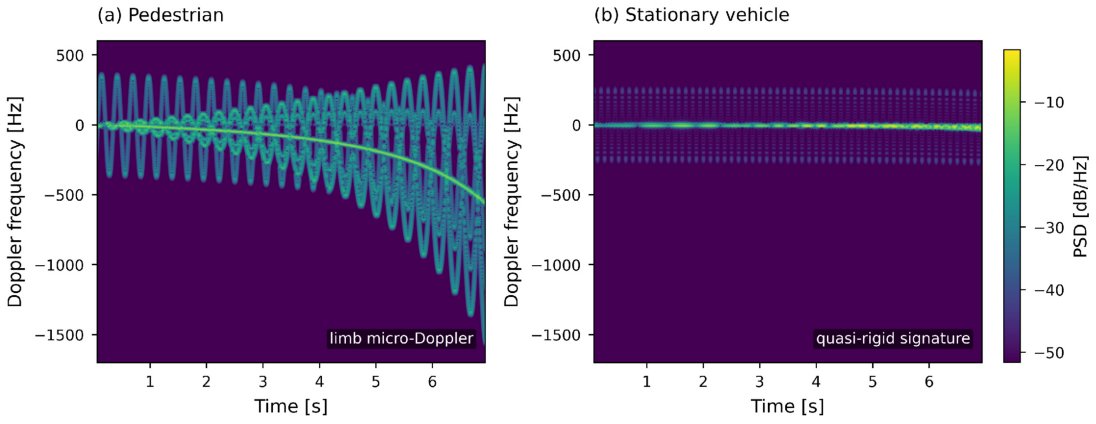


Fig. 4. Synthetic micro-Doppler spectrograms of a walking pedestrian (a) and a stationary vehicle (b).

example, detecting and classifying slow-moving targets at short range under favourable visibility. Replacement is defined here for individual functions, not for the whole surveillance role. The three modes impose different architectural requirements and are supported by different types of evidence.

Table 4 summarises their relative operational tendencies across seven mission-relevant dimensions, intended to capture qualitative trade-offs rather than universal performance rankings.

6.2. *Technical characteristics of optoelectronic scanners relevant for military applications*

Unlike GSRs, which mainly provide information about the target range, azimuth, and radial velocity, optoelectronic scanners allow direct measurement of an object geometry. In the case of LiDAR, this is done by measuring the time of flight (ToF) of a laser pulse or by frequency modulation (FMCW-LiDAR), while in passive sensors – by analysing the image in visible light or infrared.

From the point of view of battlefield applications, the most relevant comparison parameters are angular resolution or instantaneous field of view, spatial sampling density or point-cloud density, refresh rate or frame rate, usable detection and classification range, sensitivity to atmospheric obscurants (fog, rain, dust, smoke), dependence on thermal contrast or target reflectivity, and sensor signature during operation. These parameters should be interpreted differently for passive thermal imagers, visible-spectrum cameras, and active LiDAR systems, because they do not provide the same observables.

Studies on mobile 3D scanning indicate that the effectiveness of object detection and classification largely depends on data-processing algorithms, not only on sensor hardware parameters [19]. At the same time, passive thermal sensors and active LiDAR should not be treated as operationally equivalent: thermal imaging depends strongly on scene temperature contrast, whereas LiDAR performance additionally depends on laser wavelength, target reflectivity, atmospheric transmission, and constraints related to active emission. Consequently, the optoelectronic scanner should be seen as part of a larger "chain of perception", including data filtering, scene segmentation, and object classification.

6.3. *Analogies to perception systems in autonomous vehicles*

Significant progress in object detection and classification using LiDAR and optoelectronic cameras has been made in autonomous vehicles. In this domain, methods for detecting obstacles, pedestrians, vehicles, and road signs in complex road environments have been developed, which, in terms of geometry and statistics, show significant similarities to the ground battlefield environment.

For example, Asvadi *et al*. proposed an obstacle-detection approach based on a LiDAR point cloud using voxelization and a multi-region ground-plane model, enabling the separation of static and dynamic objects [19]. Xie *et al*., on the other hand, presented a method for detecting and tracking obstacles in LiDAR data based on clustering and estimating object motion state [20]. These methods can be directly adapted to military applications, where the problem is to detect a person or a vehicle against the background of a complex structure.

6.4. *Detection and classification of objects in optoelectronic sensors using machine learning*

A key feature of optoelectronic sensors is the ability to use machine learning and deep learning algorithms for object detection and classification. Unlike classical radar algorithms, these methods operate on geometric or imaging features, which allows them to distinguish objects with similar motion signatures.

In this context, a relevant reference is a paper published in Sensors in 2021, in which the authors presented detection of people and small boats in thermal images using neural networks such as YOLO and Faster R-CNN [21]. The research shows high detection efficiency across a variety of environmental conditions, confirming that optoelectronic sensors, particularly thermal sensors, can play an important role in object classification and complement the information provided by the GSR. Although this work focuses on marine and river environments, its

Table 4.
Mission-driven comparison of radar and optoelectronic sensing modalities.

Parameter	GSR	Visible EO	Thermal IR	LiDAR
Practical surveillance range	high	low-medium	medium	low-medium
Weather / obscurant robustness	high	low	medium (condition-dependent)	low-medium
Classification / identification capability	low-medium	high	medium-high	medium-high
Dependence on contrast / reflectivity	low-medium	illumination-dependent	thermal-contrast-dependent	reflectivity/ transmission dependent
Operational emission signature	active RF	passive	passive	active optical
Spatial / geometric detail	low-medium	high image detail	medium (thermal image)	high 3D geometry
Clutter / false-alarm ambiguity	medium-high	medium	medium	medium

findings are only partially transferable to terrestrial scenarios, where background structure, obscuration, and thermal contrast may differ substantially.

6.5. *Cueing and fusion in hybrid GSR-optoelectronic architectures*

From a technical point of view, the most direct architecture is radar cueing, in which the GSR acts as a detection and pre-tracking sensor, while the optoelectronic scanner verifies and classifies targets. Such an arrangement allows:

1) reduction of false alarms by confirming radar indications in the optical domain,
2) improved target identification (human, vehicle, obstacle),
3) reduced operator response time with precise object indication.

Literature on LiDAR-radar [22] and radar-camera [23] data fusion in autonomous vehicles indicates the sensors complementarity: radar provides reliable radial-velocity information and retains utility under degraded visibility conditions, while optical sensors provide accurate object geometry and image detail. That evidence supports complementary sensing directly; its transfer to cueing architectures is plausible but not established, since the cited studies assume continuous, co-registered operation of both sensors rather than event-driven handover. An analogous mechanism may apply to battlefield reconnaissance systems, although its practical effectiveness will depend on environmental obscuration, target class, and deployment geometry.

6.6. *Limitations of optoelectronic systems*

It should be emphasised that optoelectronic systems are not free from limitations. Fog, heavy precipitation, smoke, dust, and battlefield aerosols can significantly degrade the range and quality of LiDAR measurements, sometimes reducing the practical detection range far below nominal clear-weather performance [24, 25]. Passive thermal imaging also depends on scene temperature contrast, which may vary with time of day, background heating, and target-background thermal equilibrium. Active LiDAR, in turn, introduces issues related to emitted optical power, eye-safety constraints, backscatter in obscurants, and the operational signature of an emitting sensor. In addition, ground obscurations create blind spots, similar to GSRs. For this reason, optoelectronic sensors should not be treated as universally interchangeable with radar; instead, the appropriate mode depends strongly on range, weather, obscuration, and classification requirements.

6.7. *ICEYE and the importance of ISR multi-sensor architecture*

In recent years, the importance of satellite sensors in intelligence, surveillance, and reconnaissance (ISR) systems has been growing. For example, the ICEYE system offers high-resolution synthetic aperture radar (SAR) imaging, independent of weather conditions and time of day. Publicly available information on the use of ICEYE data in armed conflicts shows that effective reconnaissance of the modern battlefield relies on integrating multiple sources of information, from satellite SAR radars through tactical GSRs to local optoelectronic sensors. Although ICEYE is not an optoelectronic system, its use supports the broader argument for a multi-sensor reconnaissance architecture, in which individual sensing modalities compensate, at least in part, for the limitations of the others.

7. Conclusions

This review examined a contemporary battlefield GSR in terms of operational capabilities, architectural diversity, and fundamental technical limitations. While modern GSR systems remain a cornerstone of wide-area surveillance – particularly under adverse weather and illumination conditions – the analysis shows that their performance in detecting and identifying slow-moving ground targets is inherently constrained by near-ground propagation effects, clutter non-stationarity, Doppler-related ambiguities, and the trade-offs imposed by scanning strategies and adaptive detection thresholds.

A key outcome of the presented comparison is the observation that many limitations affecting GSR are not merely implementation-specific, but structural, arising from the physics of microwave sensing in cluttered terrestrial environments. Incremental improvements in waveform design, antenna technology, or detection algorithms can mitigate these effects only to a limited extent, often at the cost of increased system complexity, energy demand, or false-alarm sensitivity. Consequently, the effectiveness of classical GSR architectures reaches a point of diminishing returns, particularly in scenarios dominated by low-signature, slow-moving targets, and complex terrain.

In contrast, the review indicates that optoelectronic sensing systems, most notably laser scanners (LiDAR) and thermal imaging sensors, operate under a fundamentally different set of physical principles and therefore exhibit a complementary performance profile relative to GSR and, in selected operational contexts, may provide a competitive sensing option in the replacement sense defined in section 6. By directly measuring scene geometry or thermal contrast, optoelectronic systems bypass several radar-specific limitations, such as Doppler blind speeds and clutter-driven detection ambiguity. Advances in three-dimensional perception, driven largely by autonomous vehicle research and recent progress in deep learning-based object detection in thermal imagery indicate that optoelectronic systems can reliably detect and classify personnel and vehicles in complex natural environments.

Importantly, the analysis suggests that optoelectronic systems should not be viewed solely as auxiliary sensors for radar cueing. For short- to medium-range surveillance tasks, particularly where high spatial resolution and object discrimination are critical, LiDAR-based or thermal optoelectronic systems may, in some cases, provide sensing performance comparable to selected GSR functions; this remains a hypothesis and requires experimental verification. This observation provides a technical basis for considering optoelectronic scanners as standalone battlefield surveillance sensors only in selected mission profiles and under operational conditions compatible with their sensing physics.

The discussion of hybrid sensing architectures further indicates that robust surveillance concepts emerge from a system-level perspective, in which sensing modalities are selected and combined according to their physical strengths rather than according to legacy architecture alone. The growing operational role of spaceborne SAR systems, such as ICEYE, reinforces this trend by illustrating how radar-based and non-radar-based sensors coexist within hierarchical ISR frameworks. At the tactical level, a similar evolution can be expected, with optoelectronic scanning systems assuming an increasing role alongside traditional GSR and, in narrowly defined operational contexts, potentially replacing selected GSR functions.

In conclusion, this review findings support the strategic relevance of continued research into optoelectronic battlefield surveillance systems, including LiDAR-based solutions primarily in complementary and cueing modes and, in specific operational contexts, as potentially viable alternatives to selected classical GSR functions. Future work should focus on quantitative performance evaluation of optoelectronic surveillance under realistic battlefield conditions, assessment of robustness against environmental degradation, and developing sensor management and data fusion strategies that enable optoelectronic systems to operate as primary surveillance assets within modern ISR architectures.

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