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Sotoudeh, Saeed, Lantini, Livia ORCID logoORCID: https://orcid.org/0000-0002-0416-1077, Uzor, Stephen and Tosti, Fabio ORCID logoORCID: https://orcid.org/0000-0003-0291-9937 (2025) A Systematic review into the application of ground-based Interferometric Radar Systems for bridge monitoring. Remote Sensing, 17 (9). pp. 1-31.

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Review

A Systematic Review into the Application of Ground-Based Interferometric Radar Systems for Bridge Monitoring

Saeed Sotoudeh [1,2], Livia Lantini [1,2], Stephen Uzor [1,2] and Fabio Tosti [1,2,*]

[1] School of Computing and Engineering, University of West London (UWL), London W5 5RF, UK; saeed.sotoudeh@uwl.ac.uk (S.S.); livia.lantini@uwl.ac.uk (L.L.); stephen.uzor@uwl.ac.uk (S.U.)

[2] The Faringdon Research Centre for Non-Destructive Testing and Remote Sensing, University of West London, London W5 5RF, UK

* Correspondence: fabio.tosti@uwl.ac.uk; Tel.: +44-(0)-20-8231-2984

Abstract: Ground-based interferometric radar (GBIR) is a powerful remote sensing technique used for infrastructure monitoring, particularly in the field of bridge structural health monitoring (SHM). Despite its high resolution and rapid data acquisition and the availability of various commercial systems, GBIR has not yet been fully recognised or routinely adopted in standard bridge monitoring practices. This study presents a comprehensive review of GBIR technologies and methods historically applied in bridge SHM. A total of 104 peer-reviewed papers were selected through a systematic review process, encompassing 128 monitored bridges assessed using a wide range of GBIR systems. The applications of GBIR across different bridge materials and operational conditions are discussed in detail. The review shows that 76% of GBIR applications focus on roadway and railway bridges. In terms of materials, steel and concrete bridges dominate the dataset, accounting for 95% of the total, while masonry bridges represent only 5%. The GBIR system types examined in this study are categorised into six main groups based on their technical specifications, with their key characteristics and capabilities analysed. The review also investigates bridge feature extraction techniques, revealing a predominant focus on identifying natural frequencies, while fewer studies explore the extraction of damping ratios and structural mode shapes. Furthermore, the integration of GBIR with other sensing technologies—particularly accelerometers—is explored, highlighting opportunities for complementary sensor fusion. Overall, this study provides a comprehensive overview of the current state of practice and identifies key areas for future research and technological development.

Keywords: ground-based interferometric radar (GBIR); structural health monitoring (SHM); bridge monitoring; remote sensing; sensor integration; feature extraction

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1. Introduction

The study of bridges has increased due to their growing importance and essential function in modern urban life [1,2]. Ensuring the structural integrity and operational safety of these critical infrastructure require effective structural health monitoring (SHM) strategies. SHM plays a vital role in identifying damage caused by various factors including (i) climate change effects [3] (e.g., accelerated material degradation, increased flood frequency and intensity, scouring, and pavement damage), (ii) seismic activity [4], and (iii) the rising demands of industrial development such as higher axle loads and increased travel speeds [5].

To address these challenges, a range of SHM techniques has been developed and implemented as early warning systems. These include both satellite and ground-based monitoring methods. On a broader spatial scale, satellite remote sensing provides valuable data on surface variations that could pose risks to structural stability [6]. However, in-field monitoring offers more detailed real-time insights into a structure's condition of behaviour.

Various technologies used in SHM can measure parameters, such as deflections, accelerations, velocities and strains [2]. Conventional approaches—including direct current differential transducers (DCDT), linear variable differential transformers (LVDT), accelerometers, strain gauges and tiltmeters—require direct installation on the structure. While these methods are widely used for their accuracy, they are often costly and time-consuming due to the need for multiple sensors and complex installation procedures [7].

Alternatively, remote sensing techniques offer the advantage of collecting accurate data rapidly and without direct installation. Examples include videometry [8], terrestrial laser scanning (TLS) [9] and ground-based interferometric radar (GBIR) [10–12], amongst others. These techniques vary in terms of sampling frequency, spatial resolution, and accuracy, all of which must be carefully considered during sensor selection.

Among these technologies, GBIR is particularly effective for deflection measurements. Although not new to SHM, its application to civil infrastructure—especially bridges—dates back to 1999 [13]. Since then, GBIR has been used to monitor a wide range of structures, including dams, tunnels, bridges, towers, residential buildings, and heritage assets [14]. The system's ability to remotely acquire high-density data rapidly, regardless of lighting or weather conditions, has made it a reliable and versatile SHM tool.

Driven by the growing need to monitor diverse structural types in a rapidly evolving built environment, several types of GBIR systems have been developed. Nevertheless, challenges remain, particularly in 3D displacement tracking [15] and target detection [16]. Therefore, it is crucial to understand the historical evolution of GBIR technology, assess its current capabilities, and identify future opportunities.

This paper presents a systematic review of the application of various GBIR system types in bridge structural monitoring. The remainder of the paper is organised as follows: Section 2 outlines the methodology for the selection of reviewed papers; Section 3 analyses the research developments in bridge infrastructure monitoring; Section 4 explains the working principles of GBIR; Section 5 discusses advances in data acquisition and processing and provides an overview of the GBIR systems applied to bridge monitoring to date; and Section 6 concludes the study and outlines future research directions.

2. Methodology

The methodology for papers' selection in this study stems from standard approaches used in systematic literature reviews [17]. Figure 1 illustrates the chronological steps followed in the selection process, and Table 1 presents the main keywords used.

To structure the search, the logical operator "AND" was used to combine different keyword categories, while "OR" was used to include relevant synonyms for each keyword to ensure comprehensive coverage. During the search process, it was found that GBIR has been referred to in the literature using 45 different synonyms, all of which are listed in Table 1.

A comprehensive multi-stage filtering process was conducted to identify the most relevant studies. The Scopus database was selected as the primary search engine. An initial search using the selected keywords returned 220 records. These records were then filtered based on "Subject Area", "Document Type" (journal, conference, letter, workshop, etc.), "Language", and other keywords. The refined search retained only English-language papers within relevant subject areas, e.g., "Engineering, Earth and Planetary Sciences, etc.," and limited the results to journal publications.

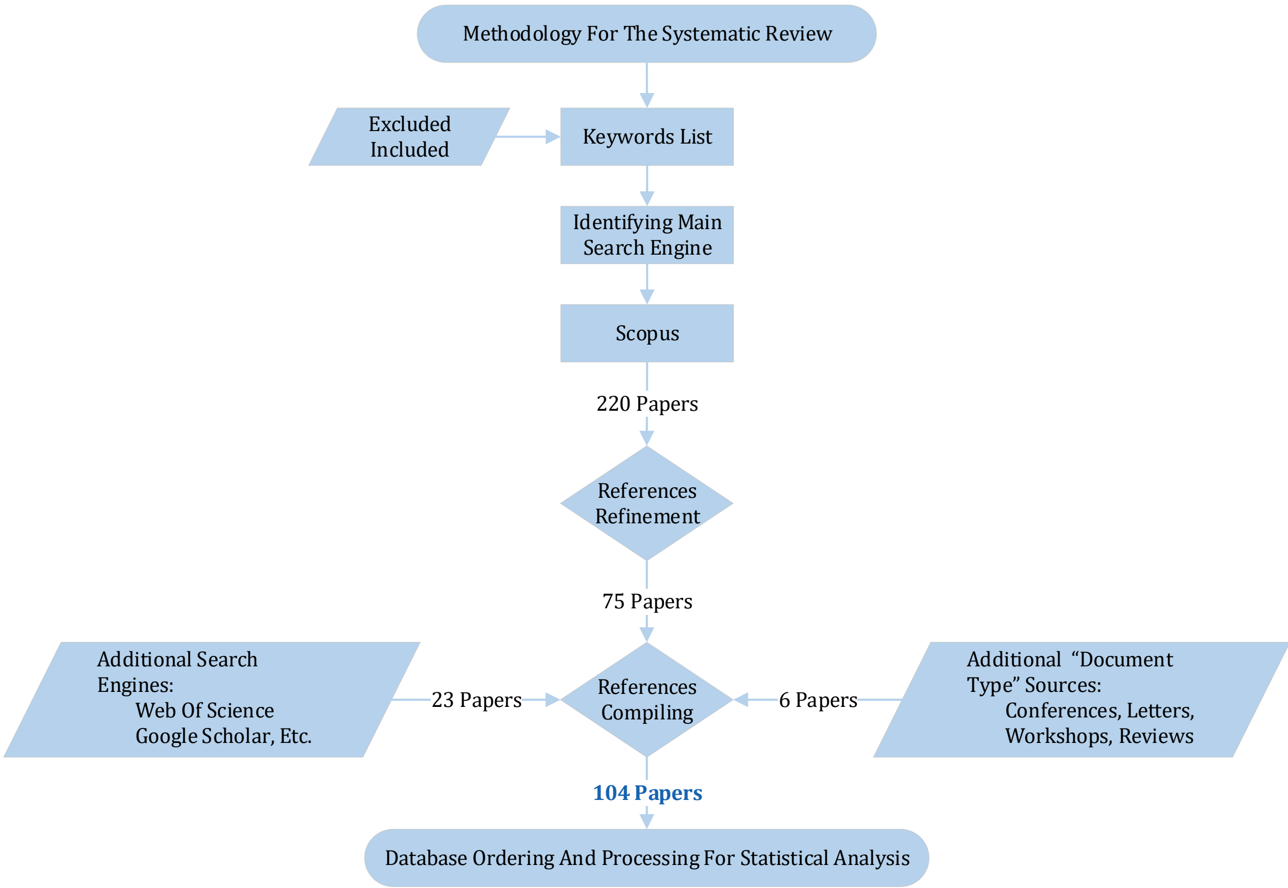

Figure 1. Research methodology for the database selection used in this study.

Table 1. Main keywords and their synonyms used in search engines Scopus and Web of Science.

"real aperture radar monitoring" OR "aperture radar interferometer" OR "radar-based monitoring" OR "radar-based measurement" OR "Radar remote sensing" OR "radar interferometry" OR "radar interferometric" OR "Radar -based displacement measurement" OR "no-Doa" OR "Multiple input multiple output" OR "MIMO" OR "MIMO radar" OR "microwave" OR "Microwave remote sensing" OR "microwave radar interferometry" OR "microwave interferometry" OR "microwave interferometry radar" OR "interferometry" OR "interferometric" OR "Interferometric synthetic radar" OR "interferometric real aperture radar" OR "interferometric radar" OR "interferometric radar sensor" OR "interferometer real aperture radar" OR "Ground-based SAR" OR "Ground-based synthetic aperture radar" OR "ground-based radar" OR "Ground-based radar interferometry" OR "ground-based radar interferometer" OR "ground-based microwave radar interferometry" OR "ground-based microwave interferometry" OR "ground-based microwave interferometer" OR "ground-based interferometry radar" OR "ground-based interferometric radar" OR "Ground based synthetic aperture radar" OR "Ground based interferometric SAR" OR "GB-SAR" OR "GBSAR" OR "GB-SAR interferometry" OR "GBRI" OR "FastGBSAR" OR "electromagnetic monitoring" OR "IBIS" OR "GB-InRAR" OR "GBMI"	Bridge	"monitoring" OR "health monitoring" OR "structural health monitoring" OR "structural monitoring" OR "structural health" OR "data collection" OR "displacement measurement" OR "vibration" OR "SHM"

To ensure that valuable studies were not excluded, each result was double-checked prior to final exclusion. Following this screening process, 75 papers remained in the database.

To expand the dataset and ensure comprehensiveness, additional searches were conducted using alternative databases, including Web of Science and Google Scholar. This resulted in 23 further relevant papers being identified and added to the database. Moreover, 6 additional documents, classified as "Conferences" or "Letters", were included from the earlier "Document Type" selection phase due to their high citation counts and substantial relevance to the research topic.

In total, 104 papers were selected to form the final dataset for analysis in this review.

3. Bridge Structural Health Monitoring Systems

Monitoring bridge structures can be categorised into two major streams of technology, i.e., satellite-based and ground-based systems. Satellite data provide valuable information about the long-term behaviour of structures. The accuracy of satellite-derived deflection measurement can reach millimetre or sub-millimetre levels [18]. However, satellite-based SHM suffers from a few limitations, as follows:

i. Temporal resolution: This refers to the "revisit time", i.e., the time interval between successive satellite observations of the same location on Earth [18]. Revisit times can span several days, making satellite monitoring unsuitable for real-time applications.
ii. Spatial resolution: This defines the smallest surface area observable by the satellite. With resolutions typically in the order of metres [18], the ability to detect localised damage free-standing and in full accuracy is limited, unless complemented by on-site reflectors [19].

While satellite data are not ideal for real-time monitoring, they provide a valuable tool for assessing long-term structural behaviour. As infrastructure ages, the decay severity becomes more discernible in satellite imagery, offering insights that can inform the deployment of on-site sensors, including their number and location, for further investigation [18].

On the other hand, ground-based sensors provide higher spatial and temporal resolution, making them more effective for detailed and real-time structural assessments. Although their spatial coverage is more limited than satellite systems, ground-based approaches enable both static and dynamic investigations in real-time operational conditions.

In recent years, several ground-based SHM technologies have emerged, incorporating advanced sensors. These include sensors directly installed on the structure, such as the DCDT and the LVDT, accelerometers, and wireless sensor networks (WSNs) (Figure 2a–d). Additionally, GBIR (Figure 2e), while ground-based, can operate remotely from distances up to 1 km [20]. These systems' primary advantages and limitations are summarised in Figure 3.

A key advantage of using contact sensors is that the data collected can be precisely correlated with specific structural elements. This information can be later implemented in numerical models and associated with the relevant physical points in real life. DCDT and LVDT sensors are well-suited for measuring displacements. Their high accuracy and sampling frequency provide critical insights into dynamic behaviour [21]. However, these systems typically require external referencing, which may introduce errors, especially in field environments where ambient vibrations can affect the stability of the reference system. For example, installing a stable reference for LVDT sensors on river bridges can be logistically challenging, especially when scaffolding is needed. Accelerometers offer advantages in dynamic feature extraction due to their high sampling frequency (e.g., 600 Hz [9]) and capability to record acceleration responses effectively.

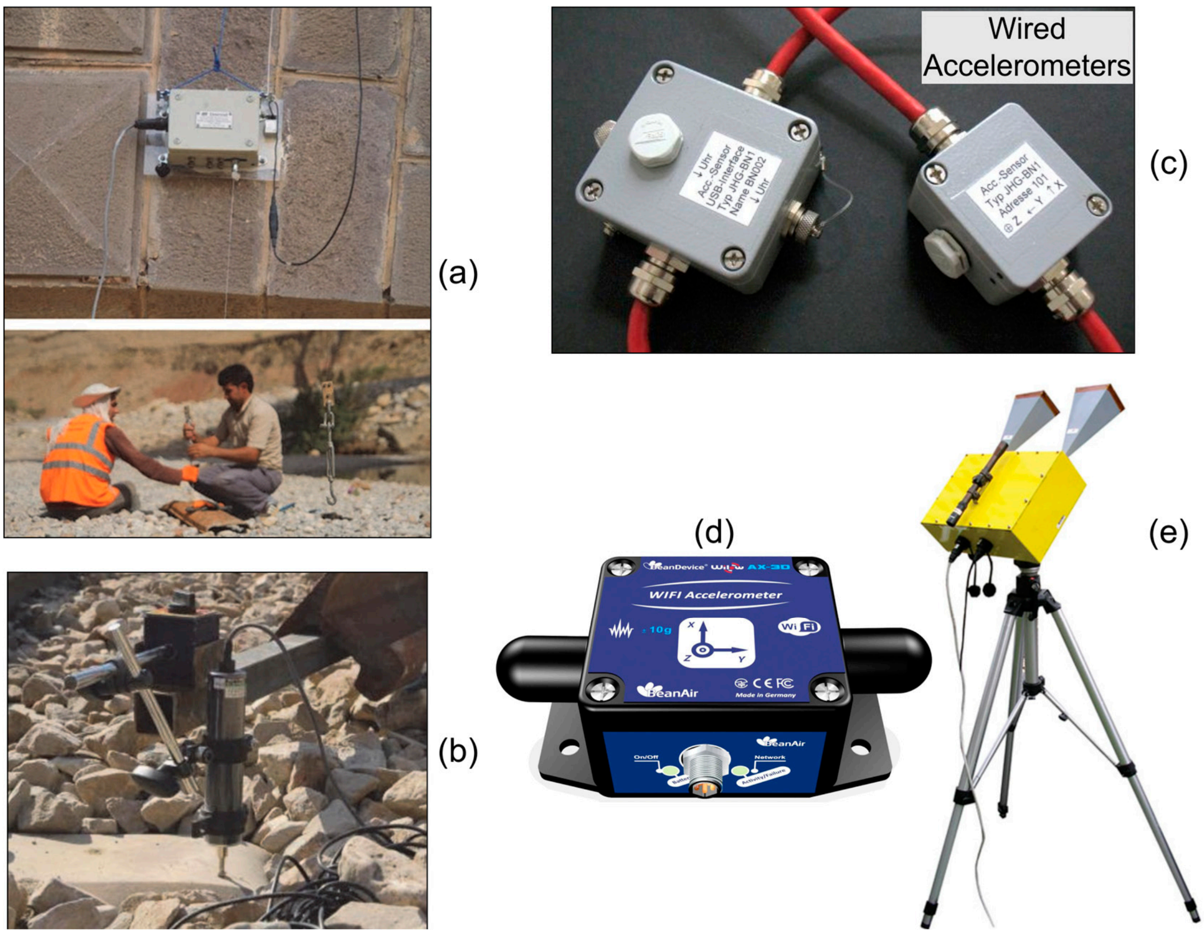

Figure 2. Ground-based sensors used in bridge SHM. (**a**) DCDT and referencing with weight suspended under the bridge [21], (**b**) LVDT mounted and referenced on a heavy rail fixture [21], (**c**) accelerometer, adapted from reference [9], (**d**) WSN [22], and (**e**) GBIR [10].

Still, as with displacement sensors, their reliance on physical installation and cabling poses logical challenges. To address this limitation, WSNs have been introduced. While they reduce the need for cabling, they still face practical issues such as power supply limitation and system synchronisation.

The use of GBIR systems has addressed many of the limitations associated with traditional contact sensors. GBIR operates primarily using frequency-modulated continuous-wave (FMCW) or stepped-frequency continuous-wave (SFCW) techniques, depending on the sensor model. These techniques enable the generation of range bins, which represent discrete distance intervals within the radar's line of sight. GBIR can therefore collect displacements separately at all the range bins and at the same time. This configuration allows GBIR to simultaneously collect displacement measurements across multiple points along a structure, each corresponding to a separate range bin. As such, the need to install multiple individual sensors, synchronise them, and manage complex on-site setups is eliminated. Moreover, GBIR can detect targets with fine precision, in some cases as small as 5 cm [23], and offers high sampling frequencies (up to 200 Hz [20]), making it highly suitable for both static and dynamic investigations.

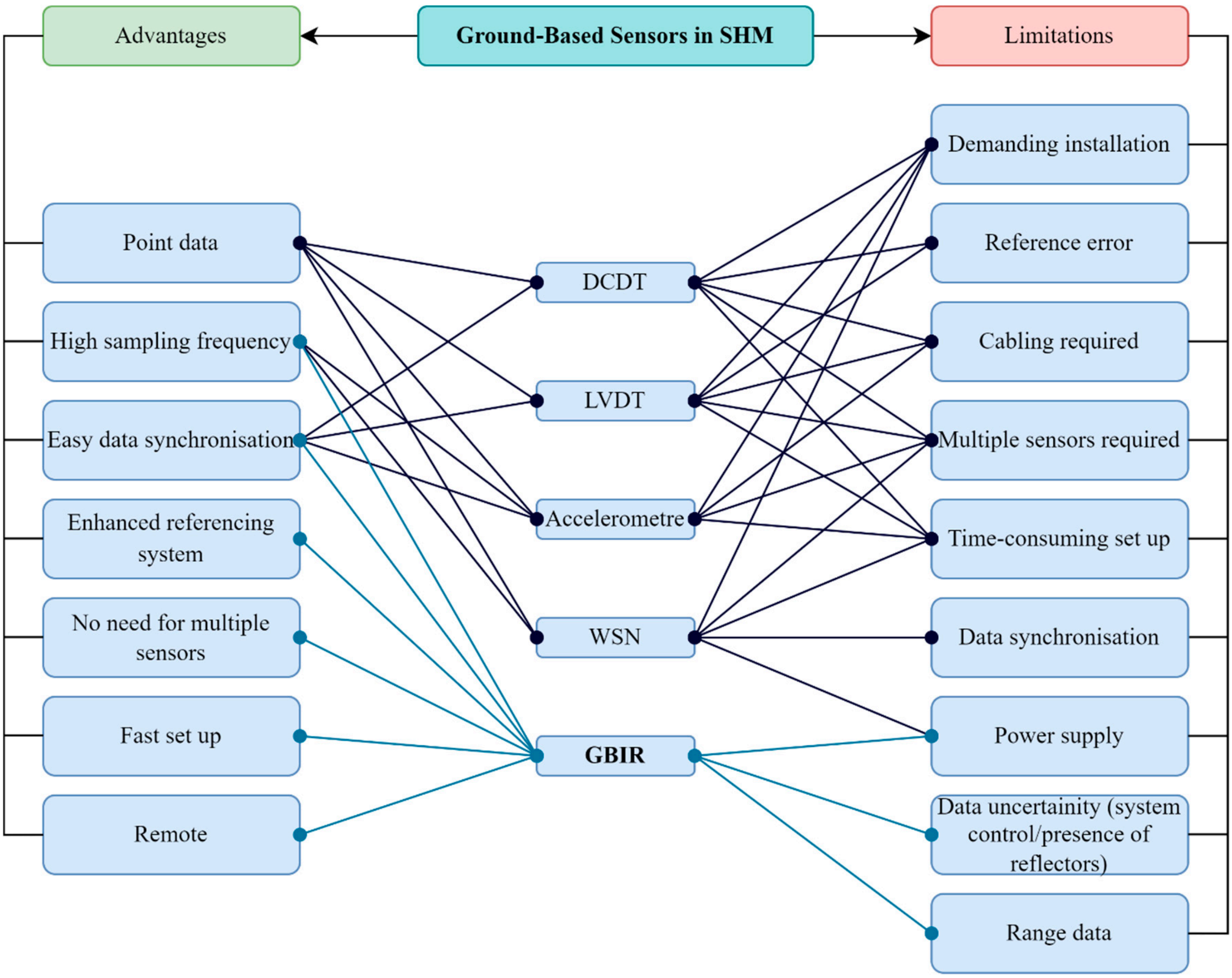

Figure 3. Advantages and limitations of ground-based sensors in bridge health monitoring.

An additional advantage of GBIR is its all-weather, day-and-night operability, due to its use of electromagnetic (EM) waves that are unaffected by lighting or atmospheric conditions. Recent technological improvements have further enhanced GBIR systems with embedded accelerometers, thereby improving the reliability and accuracy of the collected data [24].

Nevertheless, certain limitations remain. For instance, the detection of multiple targets within the same range bin can introduce signal interference and ambiguity. Furthermore, issues such as system control and power supply management, especially for long-term monitoring, still require ongoing optimisation.

Figure 3 shows that GBIR holds most of the advantages as opposed to ground-based sensor technologies while exhibiting relatively fewer drawbacks, making it a natural choice for comprehensive SHM applications.

4. GBIR Principles

GBIR operates by emitting a microwave signal towards a target and receiving the reflected signal. The distance to the target is calculated based on the speed of light (c) and the signal travel time (t). This system generates in-phase (I) and quadrature (Q) factors, from which the signal amplitude (A) and phase (φ) can be derived [25]. The key to displacement monitoring lies in detecting the phase shift between two consecutive acquisitions. This phase difference ($\Delta\varphi$) allows the computation of the displacement along the radar's line of sight (LOS) (d_{LOS}), according to Equation (1), where λ denotes the wavelength of the signal:

$$d_{LOS} = \frac{\lambda\, \Delta\varphi}{4\pi} \quad (1)$$

GBIR systems typically rely on microwave radar sensors that operate using either FMCW (Figure 4a) or SFCW (Figure 4b) techniques, allowing the radar to produce range profiles and locate targets across the LOS [26]. Both techniques function by sweeping the signal frequency up to a defined bandwidth (B) in increments of Δf over time intervals Δt. These sweeps repeat in cycles of duration T until the end of the acquisition phase. The main difference lies in how the frequency increases over time: SFCW systems perform this increment in discrete steps, whereas FMCW systems apply a continuous, linear increase. This occurrence is commonly known as chirp frequency modulation.

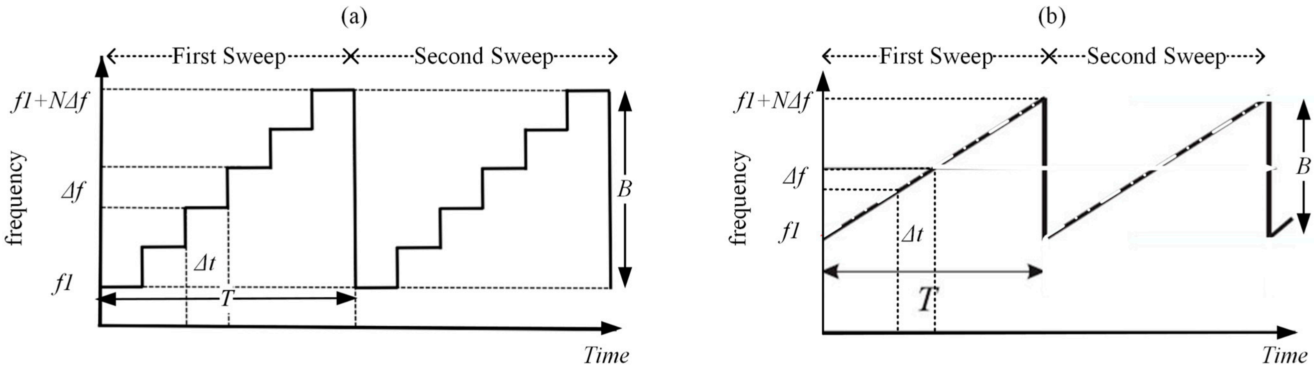

Figure 4. Working principles of (**a**) SFCW and (**b**) FMCW systems.

The outcome of this frequency sweep is the generation of a range profile, which maps the position of targets within the LOS by dividing the scene into discrete range bins. The resolution of this profile, expressed as ΔR, is governed by the radar bandwidth B and can be calculated based on Equation (2).

$$\Delta R = \frac{c}{2B} \quad (2)$$

A larger bandwidth leads to finer resolution ΔRs, enabling the radar to distinguish smaller movements and detect closely spaced targets more accurately [27]. In setups where the radar is positioned at an inclined angle θ, the vertical component of the displacement d_y must be derived from the LOS displacement by considering the radar-to-target geometry. Specifically, d_y depends on the LOS distance (R) and the vertical distance of the target to the radar H, as expressed by Equation (3).

$$d_y = \frac{R}{H} d_{LOS} \quad (3)$$

Figure 5 illustrates two typical monitoring configurations. In Scenario A, an ideal condition is presented where the displacement occurs exclusively in the vertical direction. Conversely, Scenario B depicts a more realistic situation involving complex displacements in both vertical and horizontal planes (2D) or in three dimensions (3D), including transverse components. In the latter case, a single radar cannot resolve all components of movement. Therefore, either multiple radars deployed at different angles [16,26,28,29] or a system equipped with multi-channel antennas [15,30,31] must be used. This approach enables the generation of multiple independent measurements, from which the full displacement vector can be reconstructed by solving a corresponding set of equations. The configuration and placement of the GBIR system are determined by the specific monitoring objectives. For example, installing the radar beneath the bridge is effective for capturing dynamic vibrations of the deck. In contrast, side-view configurations provide an optimal perspective for observing the displacement and bending of vertical structural elements such as piers.

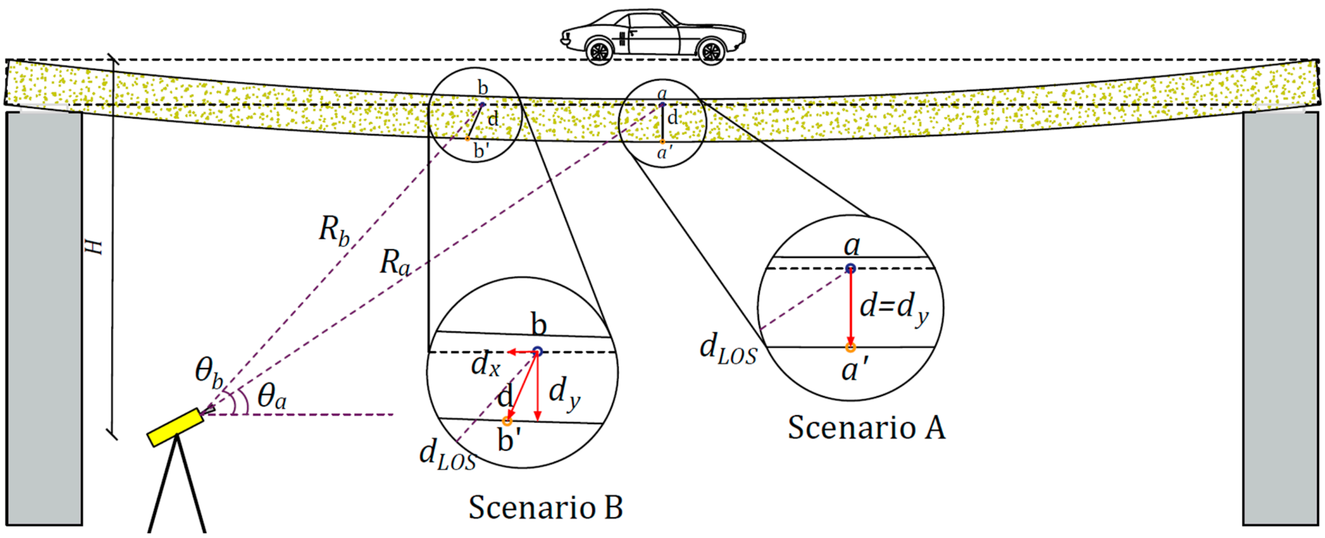

Figure 5. Deflection calculation framework with GBIR.

5. Statistics, Applications, and System Characteristics of GBIR for Bridge Monitoring

To analyse the current state of research on GBIR systems applied to bridge monitoring, key parameters were identified from the literature, considering both radar data acquisitions and structural characteristics. These parameters were categorised into three groups, i.e., (i) bridge function, (ii) bridge material, and (iii) GBIR system specifications. These parameters were statistically analysed using the finalised literature database, aiming to identify prevailing trends, gaps, and developments in the field.

Figures 6 and 7 illustrate the temporal evolution of publications and citations concerning the use of GBIR systems in bridge monitoring applications. The earliest identified study dates back to 1999, involving the monitoring of a mixed steel–concrete bridge using a prototype known as the Parabolic Dish Radar [13]. For approximately a decade following this pioneering work, publications remained limited in number, whereas they have grown faster in both the number of publications and citations throughout the years since 2010. In more detail, five publications published in 2010 were cited 385 times in total, while six publications in 2013 received 279 citations. By 2020, the number of relevant publications rose to 12 and collected 217 citations. This upward trend in the number of publications and citations confirms an increased level of interest in the use of GBIR systems for the SHM of bridge infrastructures, particularly over the last decade.

The following sections review key factors influencing the application of GBIR in bridge monitoring, focusing on bridge function, construction materials [30], and GBIR system types and specifications. These elements are key to the feasibility and effectiveness of GBIR data acquisition and interpretation in SHM.

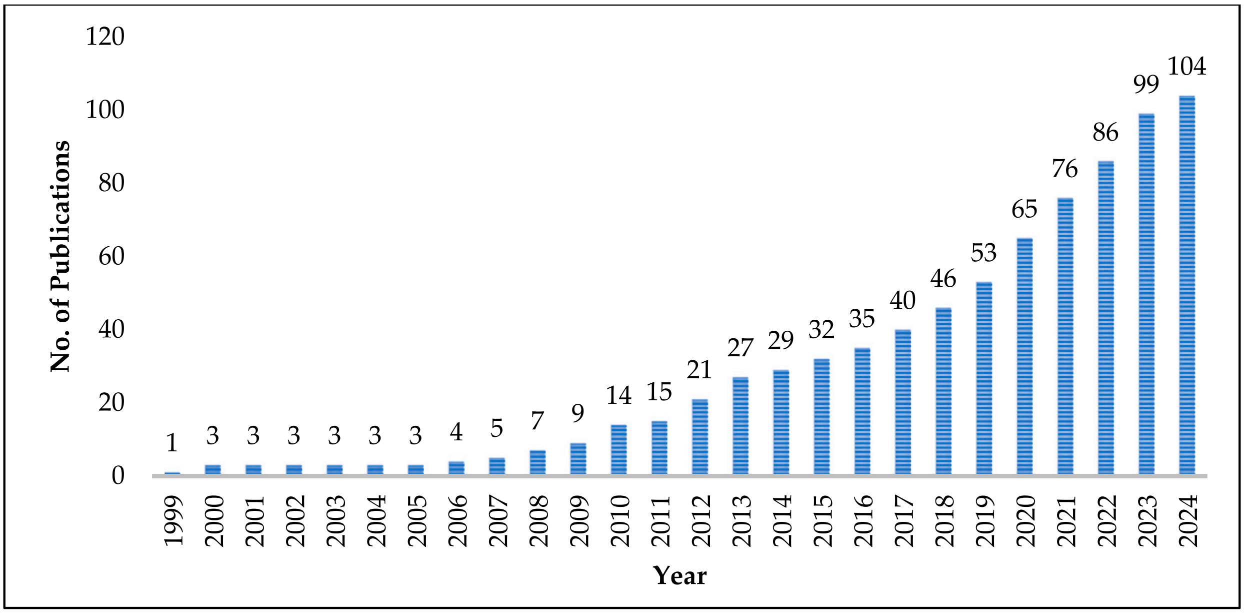

Figure 6. Number of publications from 1999 until 2024.

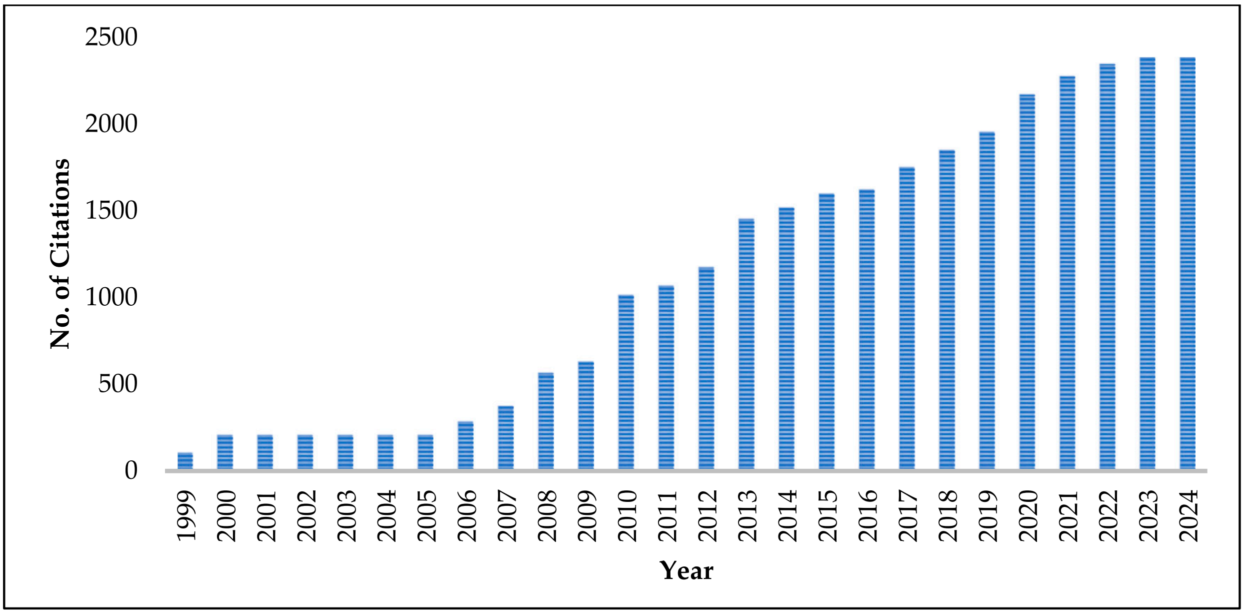

Figure 7. Number of citations since 1999 up to 2024.

5.1. Bridge Function

The function of a bridge fundamentally influences its loading pattern, which in turn affects structural responses detectable by GBIR systems. Functional categories like railway, roadway, or pedestrian bridges show different loading patterns, which can be identified from displacement data collected during monitoring.

For example, railway bridges typically experience periodic, high-intensity loading due to train passages, enabling a clearer distinction between different load types. Specific components, such as the locomotive (power car) and passenger cars, can be distinguished through their unique loading signatures [5,32]. These patterns support detailed assessments of vehicle–structure interaction and can inform further investigations into the impact of vehicle masses, axle spacing, and velocity on bridge dynamics.

Conversely, road and pedestrian bridges present more complex monitoring challenges. The heterogeneity in vehicle types, speeds, and spatial distribution introduces variability that makes load interpretation difficult. To overcome this, monitoring campaigns may incorporate controlled load testing or use camera-based sensors to classify vehicle types and estimate speed in real life [33,34].

Additionally, GBIR systems have been employed for dynamic analysis, such as the identification of modal parameters. These analyses typically assume the absence of external loading post event [35]. Such assumptions are more easily met on railway bridges due to scheduled train intervals, while road and pedestrian bridges often require traffic interruption to obtain undisturbed measurements [13]. Given these operational demands, effective GBIR deployment requires a high sampling rate and measurement precision, particularly for transient load events. GBIR systems lend themselves to be used for such applications, offering fast, remote data acquisition and adaptability across bridge typologies.

According to the reviewed literature, a total of 128 bridges have been monitored using various GBIR systems. As illustrated in Figure 8, roadway bridges constitute the largest share, representing 51% of the cases. Railway bridges follow with 25%, while pedestrian bridges account for 12%. Laboratory analogues make up 5%, and bridges with other or unspecified functions comprise the remaining 7%.

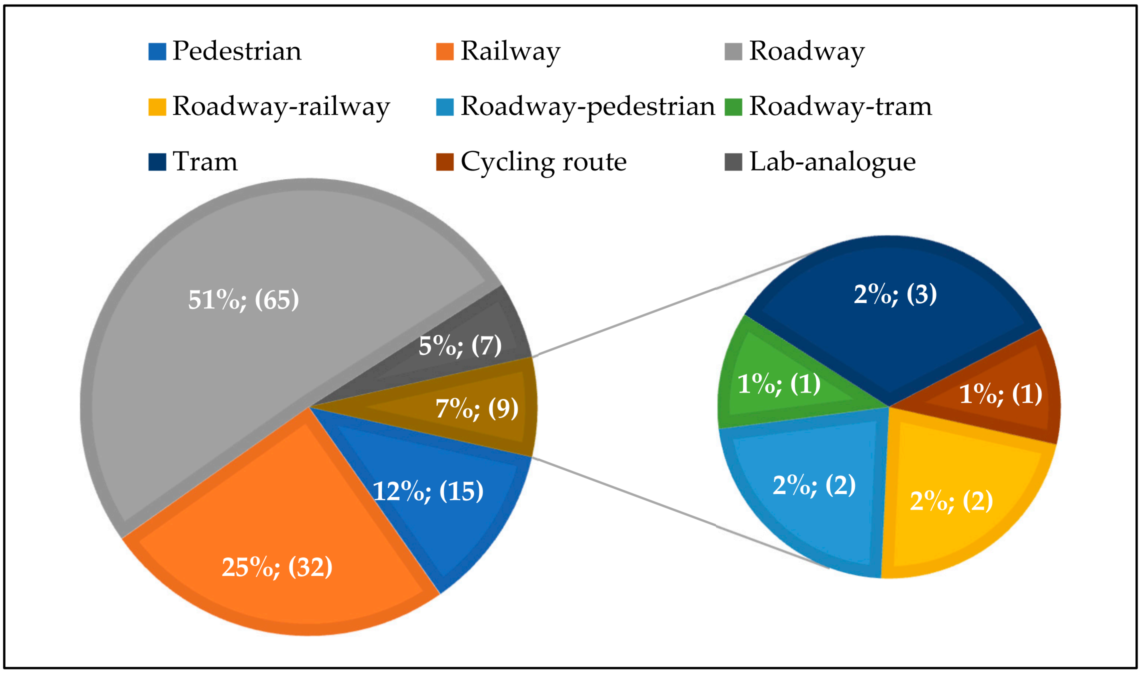

Figure 8. The distribution of publication records on the application of GBIR systems in bridge monitoring, classified by bridge function (percentage; absolute value—expressed in brackets).

5.2. Bridge Materials

Material properties play a critical role in the application of GBIR for bridge monitoring, particularly due to their interaction with electromagnetic (EM) waves. As GBIR operates by transmitting and receiving EM waves across space, the material composition and surface characteristics, such as roughness and transmission angle, significantly affect signal behaviour and data quality [36]. According to the EM wave propagation theory, as shown in Figure 9a, part of the transmitted signal is attenuated as it passes through a medium depending on the material's transparency, while the remaining part of the signal is reflected.

Amongst typical construction materials, concrete and masonry exhibit high EM transparency, whereas steel reflects most of the signal due to its low transparency. This makes steel highly suitable for signal reflection, although it can also result in multiple reflections within the same range bin, which may compromise data quality and interpretation. To enhance signal clarity and improve measurement accuracy, metal corner reflectors (CRs) are often installed on bridge structures, as shown in Figure 9b. These provide reliable reference points and help improve signal return, aiding in achieving a clear reference and obtaining a more significant dataset [11,12,26]. In reinforced concrete bridges, embedded steel bars can also contribute to signal reflection. However, due to the generally flat surfaces of concrete and the angle-dependent nature of reflection, signal mirroring may occur. To address this, Pieraccini et al. [37] proposed a mirror-mode measurement technique aimed at mitigating such an issue.

The nature of reflection is also influenced by surface roughness. Smooth surfaces tend to produce specular reflections, reflecting the signal back at consistent angles, typically perpendicular, whereas rough surfaces scatter the signal more diffusely [36]. Masonry structures, in particular, present additional challenges due to both their high EM transparency and typically rough surfaces. These conditions often require the use of CRs to obtain viable data. However, in the context of heritage structures, the installation of such equipment may be infeasible due to the risk of causing irreversible damage. Despite these constraints, successful acquisitions on masonry bridges without CRs have been reported by Pieraccini et al. [38] and Liu et al. [39] through the adoption of carefully controlled acquisition strategies.

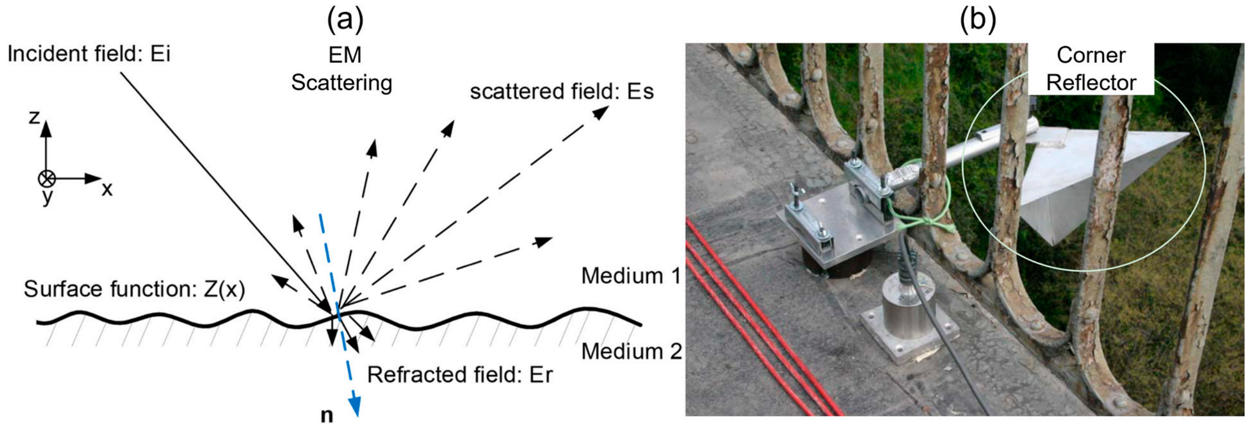

Figure 9. (**a**) A representation of the EM signal transmission and reflection, adapted from reference [36] and (**b**) trihedral CR installed on a bridge, adapted from reference [40].

The analysis of the selected publication database shows that GBIR has been employed across bridges constructed from a variety of materials, including concrete, steel, masonry, and mixed materials. The statistical distribution of material types from the reviewed literature database, depicted in Figure 10, indicates that concrete, steel, and mixed-design bridges form most of the investigated cases, i.e., 50%, 37% and 8%, respectively. However, masonry bridges represent only 5% of the total. This underrepresentation points to a significant gap in the literature and suggests an opportunity for expanding research into the application of GBIR on masonry bridges. Further investigations are needed to better understand the system's sensitivity to the physical and electromagnetic properties of masonry and to explore viable, non-invasive monitoring strategies for the implementation of GBIR on these assets [41].

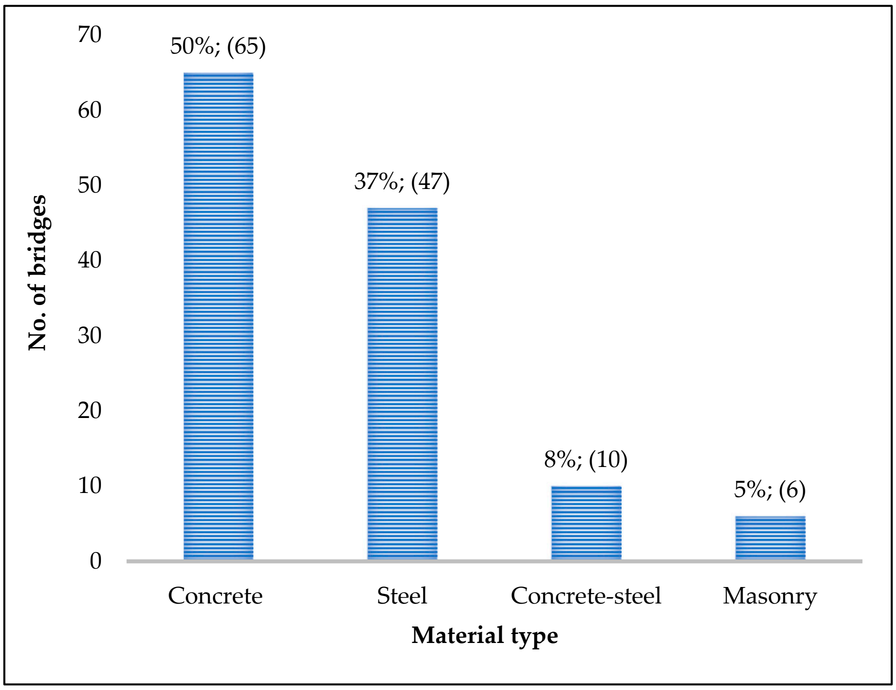

Figure 10. The distribution of publication records on the application of GBIR systems in bridge monitoring by material type (percentage; absolute value—expressed in brackets).

5.3. GBIR in Bridge Monitoring: Systems, Signals, and Synergies

5.3.1. GBIR System Categories in Bridge Monitoring

Several GBIR systems have been documented for bridge monitoring, incorporating various antenna types tailored to specific applications [14]. Caduff et al. [42] classified GBIR antennas into three main types: Dish Antenna Pencil Beam (Type I), Slotted-Waveguide Antenna Fan Beam (Type II) and Horn Antenna (Type III) (Figure 11). The selection of antenna significantly influences the radiation beam pattern, affecting the signal footprint over the monitored target. While the main lobe or main beam governs the primary reflection, side lobes may introduce noise from surrounding objects.

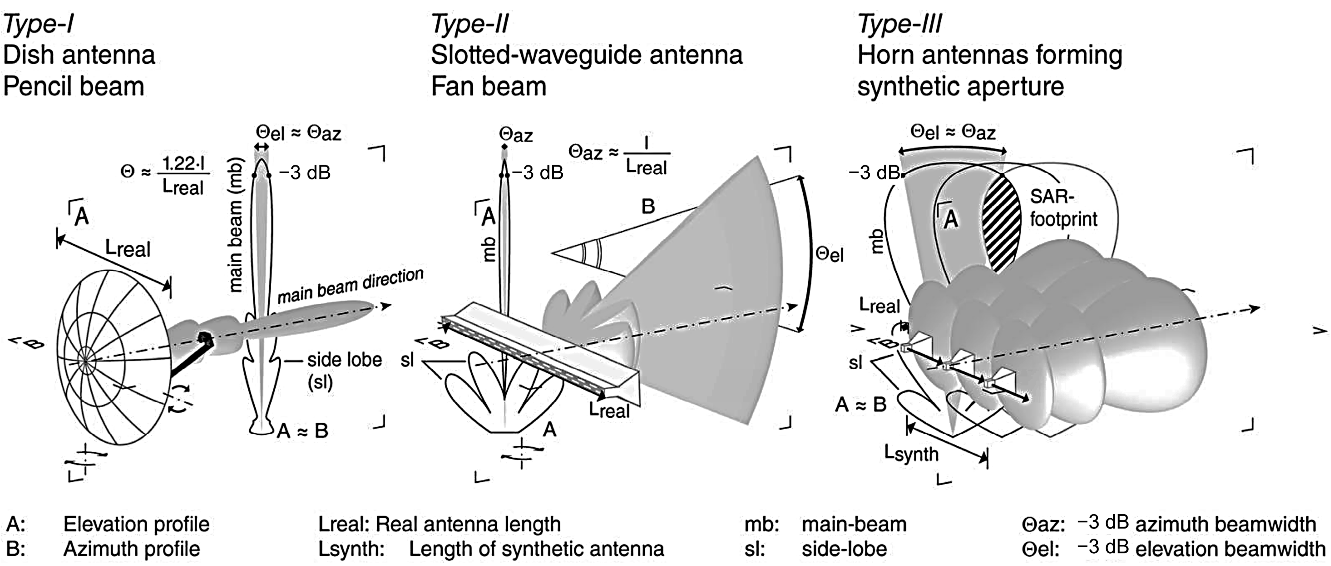

Figure 11. Antenna types for GBIR systems, adapted from reference [42].

The Type I parabolic dish antenna radar, as employed by Farrar et al. [13], is one of the earliest radar technologies applied in bridge monitoring (Figure 12). In their study, a roadway bridge was dynamically loaded using a hydraulic shaker, and the resulting structural response was successfully captured using radar. The authors introduced four progressive levels of damage to the bridge's plate girder and monitored changes in dynamic parameters, such as natural frequency and damping ratio. The system identified the first six natural frequencies and associated damping ratios, with radar outputs closely matching accelerometer measurements (2.2% deviation), confirming the radar's reliability.

GBIR systems can be broadly classified based on their imaging capabilities. Ground-Based Real Aperture Radar (GB-RAR) which uses fixed transceivers, produces one-dimensional (1D) range profiles (Figure 13a). This system operates with a resolution ΔR and detect targets within a specified range. Conversely, the Ground-Based Synthetic Aperture Radar (GB-SAR) moves along a rail and generates azimuth or cross-range resolution (ΔCR) in addition to ΔR, thereby enabling two-dimensional (2D) displacement imaging. Cross-range resolution ΔCR is defined by Equation (4):

$$\Delta CR = \frac{\lambda}{2L} \quad (4)$$

Together, ΔR and ΔCR determine the pixel size of the 2D image, which increases with the distance from the radar (Figure 13b). Each pixel represents displacement data for a corresponding section of the structure. Compared to GB-RAR, GB-SAR systems offer superior spatial resolution, especially useful for distinguishing targets that lie at the same range but different azimuths. In Figure 13a, the GB-RAR system intercepts multiple targets within the same range bin, i.e., the coloured range, resulting in an averaged measurement with no differentiation between targets [26]. In contrast, Figure 13b demonstrates how GB-SAR can resolve these targets due to its azimuth resolution. However, GB-RAR offers significantly higher sampling frequencies, nearly ten times larger than GB-SAR [24,43], rendering GB-SAR not suitable for dynamic monitoring applications.

For comprehensive bridge health monitoring, both static and dynamic tests are essential, each requiring different sampling frequencies. GB-RAR is ideal for these tasks, due to its high sampling frequency rate, accommodating both static and dynamic behaviours. On the other hand, GB-SAR is primarily used for static acquisitions thanks to its high spatial resolution, and this is particularly effective in applications involving slow movements such as landslides or mining-induced subsidence. Since GB-RAR lacks cross-range resolution, precise positioning is critical to mitigate signal ambiguities from multiple targets overlapping in the same range. Recent studies have investigated this limitation by exploring radar signal characteristics [25], integrating augmented reality-based visualisation techniques [11], and employing multi-sensor integration strategies [16]. Examples of both commercial and custom-developed systems are shown in Figure 14.

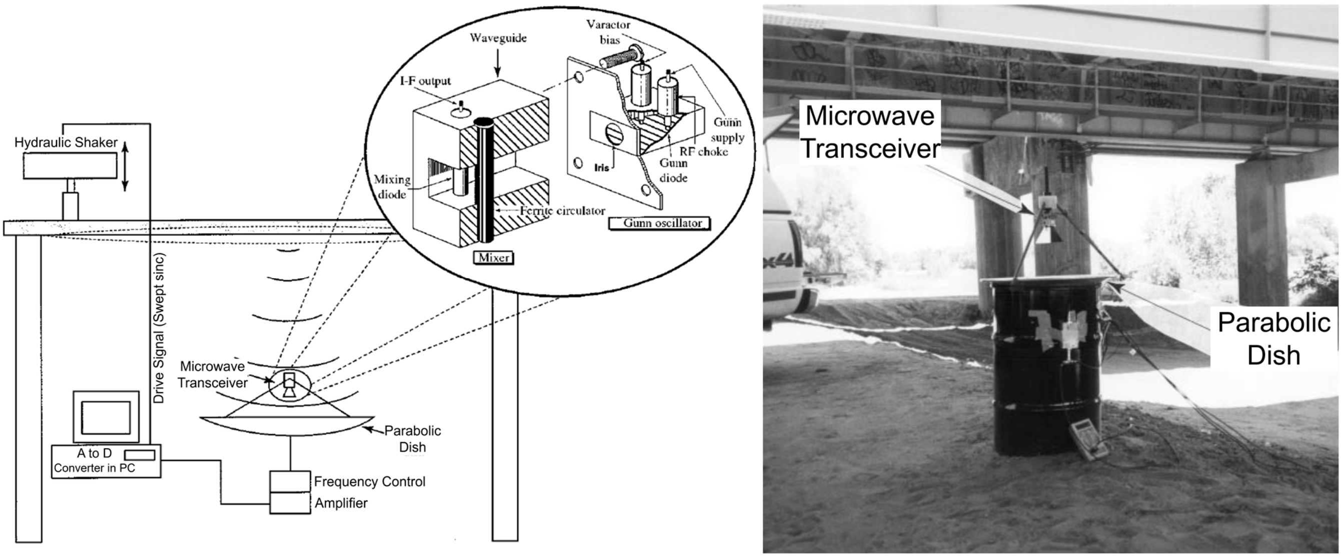

Figure 12. Type I parabolic dish antenna radar, adapted from reference [13].

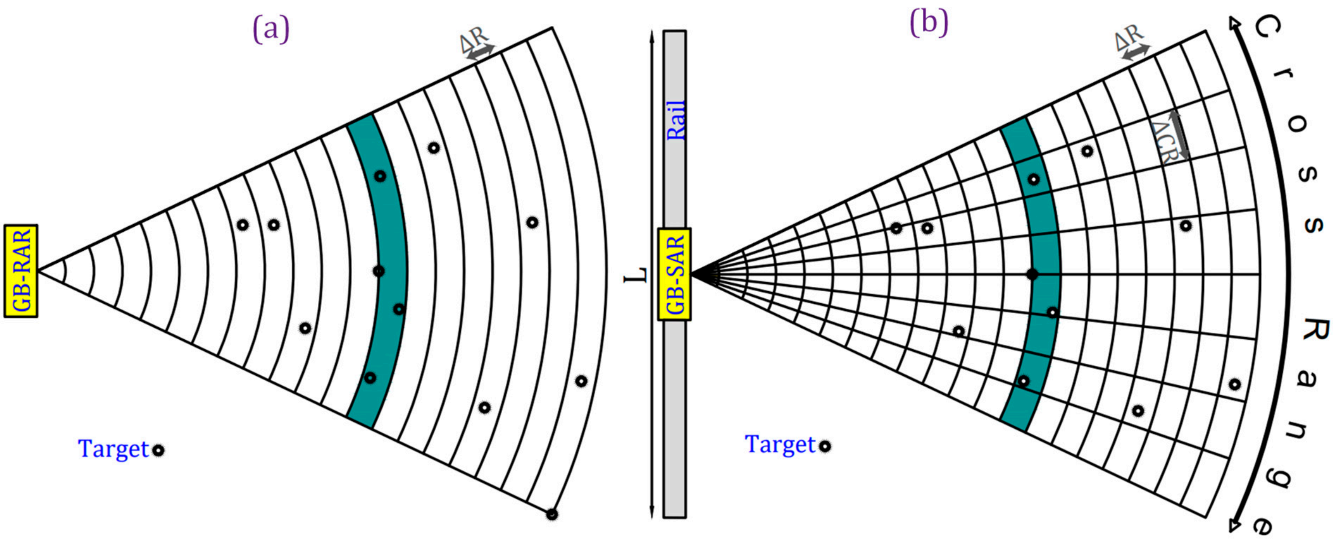

Figure 13. (**a**) GB-RAR 1D image data with ΔR resolution, and (**b**) GB-SAR 2D image data with ΔR and ΔCR resolution.

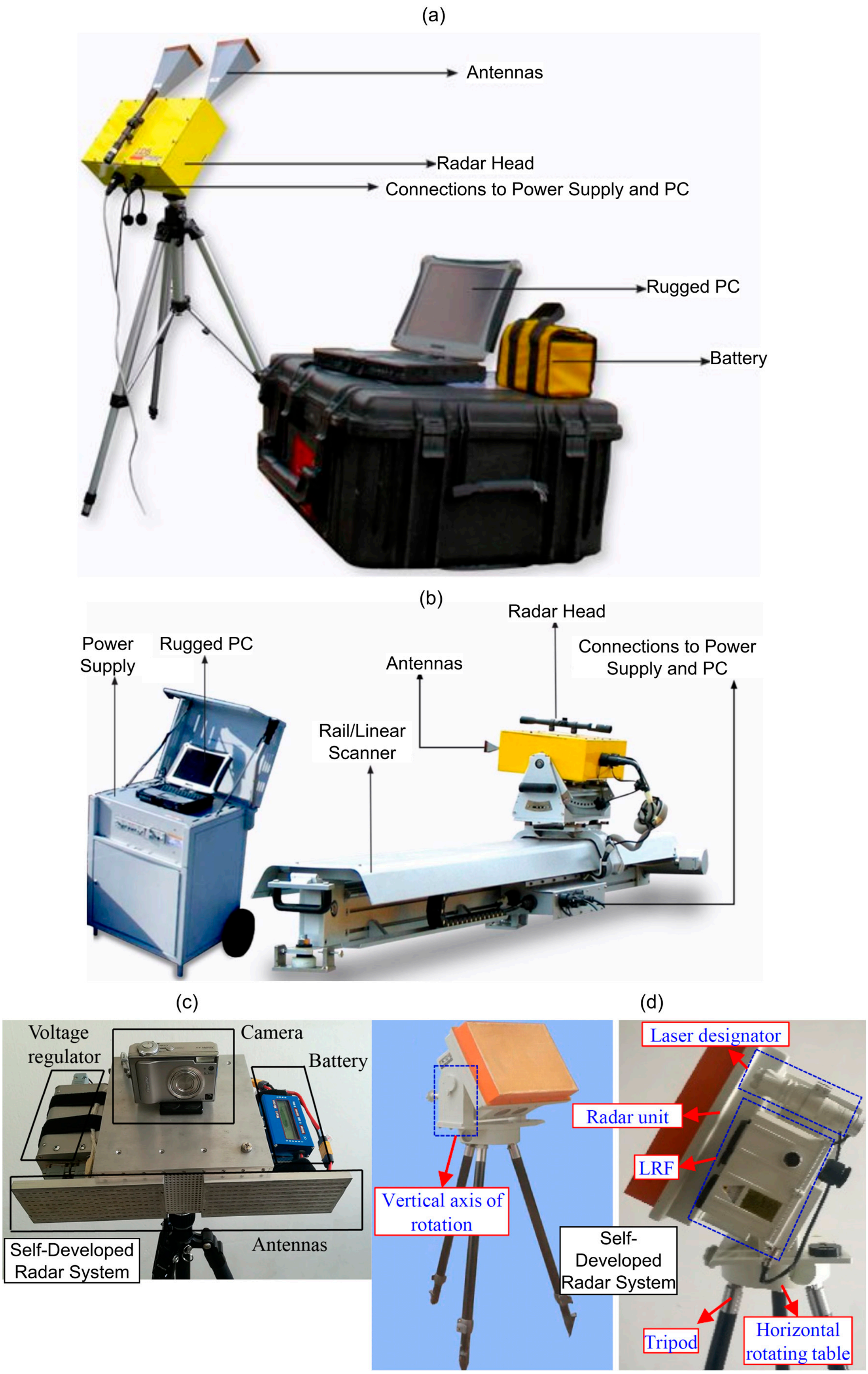

Figure 14. Interferometric radars (adopted from the corresponding references): (**a**) GB-RAR system IBIS-S [10,26], (**b**) GB-SAR system IBIS-FL [43], (**c**,**d**) samples of self-developed radars [34,44].

In response to the limitations of conventional GBIR systems, several novel prototypes have emerged. A notable example is the Multiple-Input Multiple-Output (MIMO) radar developed by Pieraccini et al. [45], tested on a steel cable-stayed pedestrian bridge. This system comprises four parallel arrays of transceivers (Figure 15a), allowing data acquisition across multiple frequencies, positions and angles. This multi-dimensional configuration significantly enhances spatial and temporal resolution, producing a comprehensive 2D map of the acquisitions. The prototype successfully visualised individual transverse beams and resolved targets within the same range bin (Figure 15b,c), achieving an initial sampling frequency of 31.4 s per image, later optimised in subsequent iterations [46].

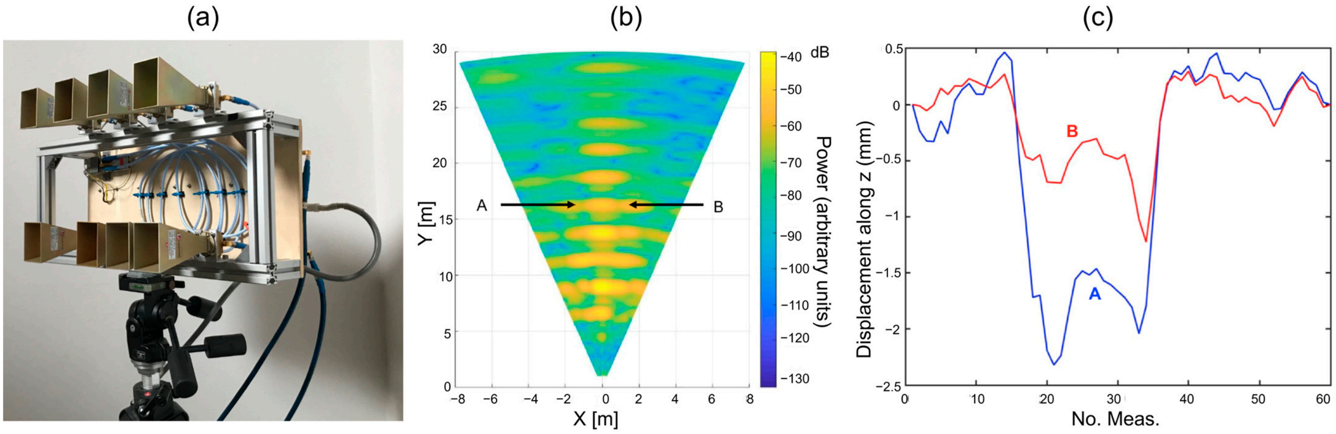

Figure 15. (**a**) MIMO radar, (**b**) 2D image data of the bridge deck, and (**c**) displacement data of different pixels and positions, adopted from reference [45].

To address the challenge of acquiring three-dimensional displacement data, the RotoSAR system [47] and later the Monostatic/Bistatic MIMO radar [15,30,31] were introduced. RotoSAR enabled the retrieval of all three displacement components with acceptable accuracy, while the Monostatic/Bistatic MIMO radar enabled 2D and 3D displacement monitoring, enhancing both spatial resolution and temporal performance. This was achieved by deploying fixed monostatic antennas alongside detachable bistatic antennas placed at various observation angles (Figure 16), allowing for angular decomposition and 3D displacement component extraction.

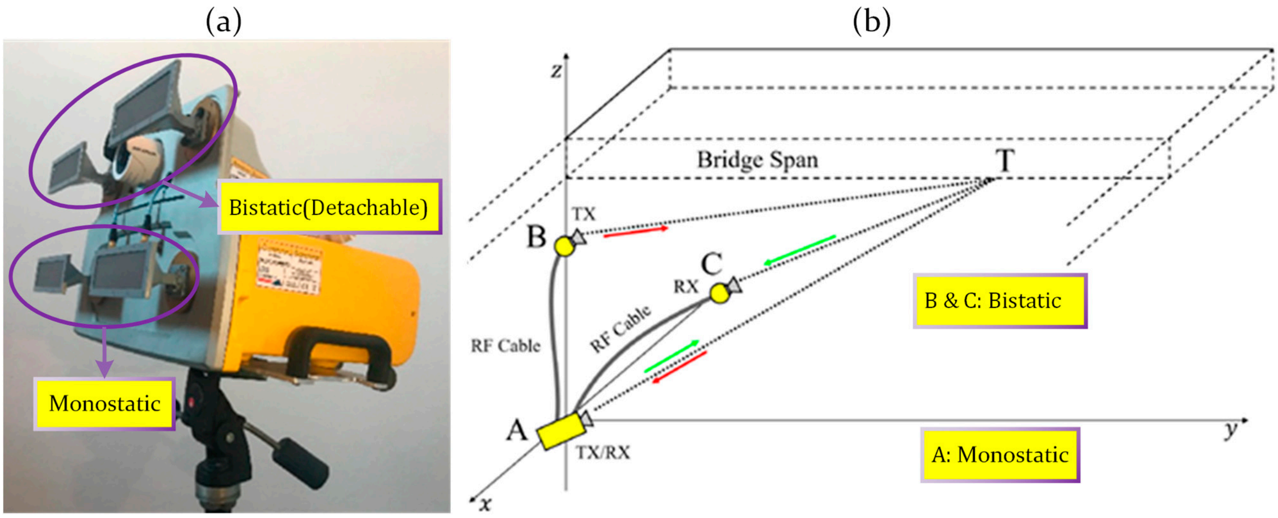

Figure 16. (**a**) Monostatic/Bistatic MIMO radar and (**b**) its working framework, adapted from reference [15].

Further developments in MIMO technology, incorporating multiple transmitters (N) and receivers (M), have expanded the number of observation channels to $N \times M$ and enhanced azimuth resolution (Figure 17). These systems employ wideband signals to improve range resolution (ΔR), offering highly accurate and detailed structural measurements [48].

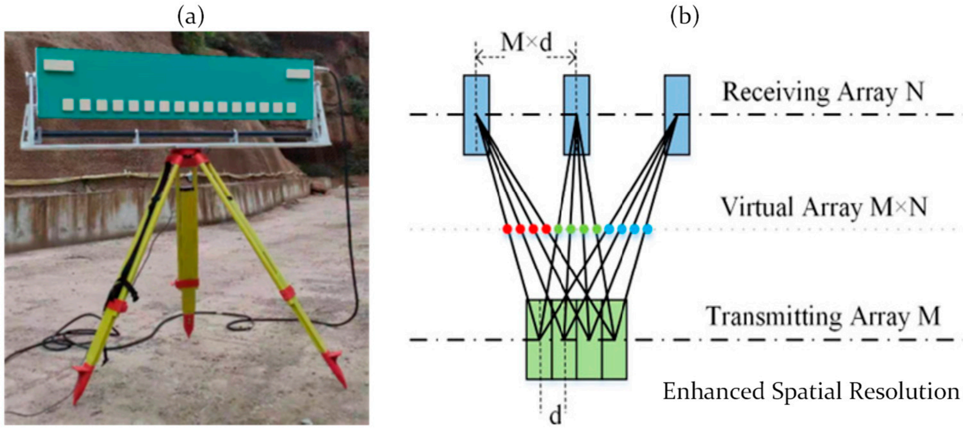

Figure 17. (**a**) The MIMO system and (**b**) framework indicating the number of observation channels, adapted from reference [49].

Another significant innovation is the GAMMA Portable Radar Interferometer (GPRI) developed by Gamma Remote Sensing [50]. Equipped with a slotted-waveguide antenna (Type II, Figure 11), the GPRI can function as either a GB-RAR or a GB-SAR system. It features two waveguide receivers and one transmitter, integrated with a Global Positioning System (GPS) for precise timing and positional coordination (Figure 18).

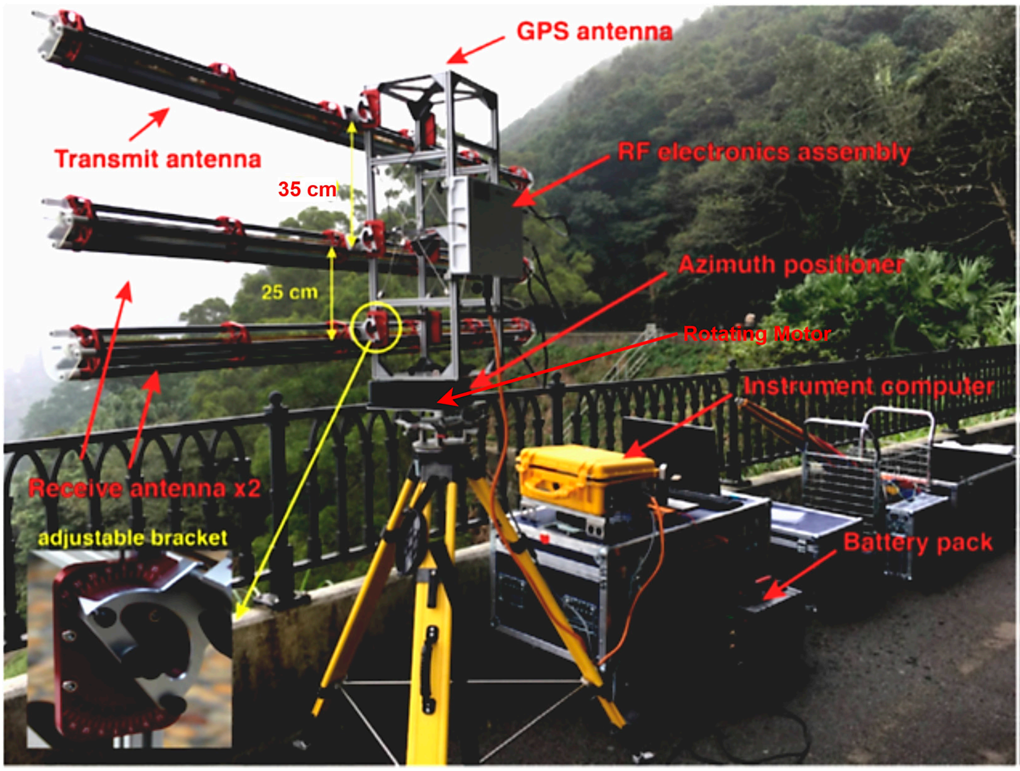

Figure 18. GPRI system components, adapted from reference [51].

5.3.2. GBIR Characteristics

Table 2 summarises the GBIR systems utilised in the 104 selected studies, detailing their key electronic and measurement characteristics.

A fundamental specification in radar design is the frequency band (*FB*), typically defined by the central frequency (*CF*) range. Most GBIR systems used for bridge monitoring operate within the Ku band, with CF ranges between 15.5 and 17.5 GHz. This band is widely adopted due to the cost efficiency it offers, as confirmed by Zhang et al. [34], who optimised their self-developed radar to a CF of 16 GHz to maximise affordability. However, the use of higher-frequency bands facilitates the design of faster and more lightweight radar systems [46], while also enhancing the measurement accuracy [47].

GBIR systems commonly implement frequency modulation (*FM*) techniques, such as FMCW and SFCW. These modulation types determine the system's range resolution (ΔR), which typically spans from 0.05 m to approximately 1.45 m, depending on the signal bandwidth B as defined in Equation (2). Most systems achieve ΔR values in the 0.5–0.75 m range, constrained by bandwidth limits, usually 300 to 400 MHz. In many regulatory environments, including the US and Europe, the maximum permitted bandwidth is 300 MHz, which restricts the achievable ΔR to approximately 0.75 m [24,43]. The cross-range resolution (ΔCR), relevant for GB-SAR systems, typically ranges from 4.4 and 50 mrad, affecting the spatial granularity of the 2D displacement images.

The sampling frequency (SF), defined as the number of acquisitions per second, is critical for dynamic monitoring, enabling the identification of modal parameters such as natural frequencies, mode shapes, and damping ratios. SF values in the reviewed systems range from 20 to 4000 Hz, with most systems operating around 200 Hz (Table 2). The importance of selecting an appropriate SF is underscored by Figure 19, which shows the first natural frequencies of railway bridges as a function of span length, based on Neitzel et al. [52], and Frŷba [53]. The wide variability in bridge behaviour necessitates a tailored selection of radar SF to match structural dynamics.

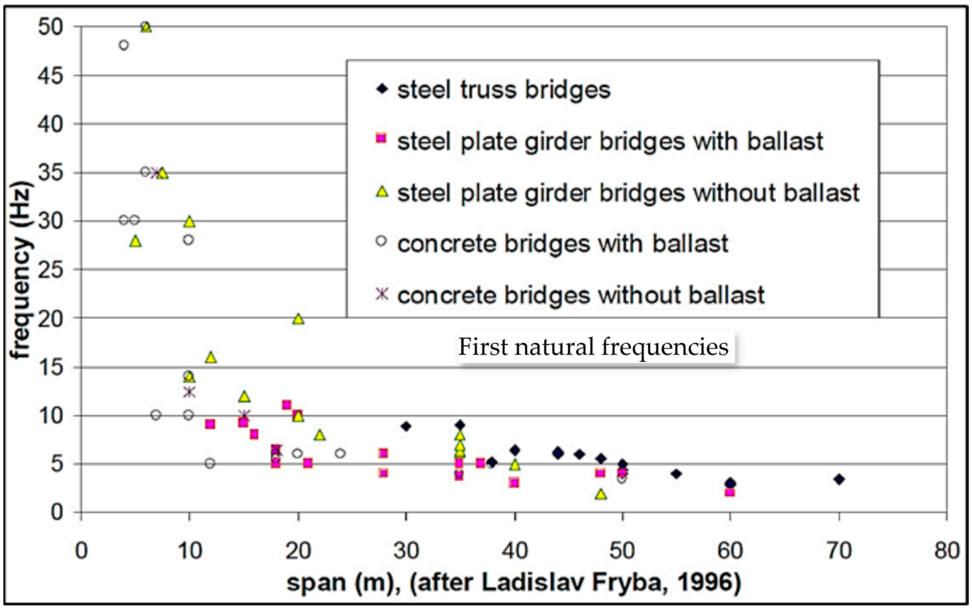

Figure 19. First natural frequencies of railway bridges according to bridge type and span length, adapted from references [52,53].

Table 2. Key characteristics of GBIR system types applied in bridge monitoring.

GBIR Type	No.	BF	CF (GHz)	B (MHz)	FM	ΔR (m)	ΔCR (mrad)	Image	SF (Hz)	D_{max} (m)	Accuracy (mm)	Developer	References
IBIS	65	Ku	16.9–17.3	300	FMCW SFCW	0.5–0.71	4.4	1D/2D	200	500–1000	0.01–0.1	IDS	[8,9,16,20,23,28,29,37,39,40,54–108]
FastGBSAR	3	Ku	17.2–17.5	300	FMCW	0.5	4.8	1D/2D	4000	4000	0.01–0.1	MetaSensing	[35,109,110]
SD [1] Parabolic dish radar	21	X or K	-	-	SFCW	-	NON	1D	-	-	-	LANL [2]	[13]
SD radar		Ku	16	300	FMCW	0.5	NON	1D	-	580	-	Southeast University	[25,33,34,111]
		Ku	16.75	350–380	SFCW	0.4	NON	1D	30	-	<0.1	University of Florence	[38,112–115]
		K	24	3000	FMCW	0.05	NON	1D	50	70	<0.02	CTTC [3]	[23]
		K	-	1000	FMCW	0.15	NON	1D	-	70	-	SKLHSBS [4] NUDT [5]	[116]
SD mm-wave radar		Ka	36.05	300	FMCW	0.5	NON	1D	-	-	sub-mm	HRBEU [6]	[44,117,118]
		V	77	4000	FMCW	0.0489	NON	1D	-	12	-	CAS [7]	[119,120]
SD radar SAR		Ku	15.5	1000	SFCW	0.15	4.75	2D	-	-	-	University of Florence	[121–123]
SD lightweight radar		V	60.25	3250	FMCW	0.05	NON	1D	20	-	-	Southeast University	[124]
SD-CW		S	-	-	CW	-	NON	-	-	-	-	University of Florence	[113]
MIMO (IBIS-FM)	11	Ku	17.2	400	SFCW	-	-	-	132	-	-	IDS	[15,30,31,125]
MIMO (FastGBSAR)		Ku	17.2	-	FMCW	0.5	-	2D	-	4000	0.01	MetaSensing	[106,126]
SD MIMO (CS)		-	-	-	SFCW	0.47	50	2D	31.4	-	0.1	University of Florence	[45]
SD MIMO		Ku	16.2	400–1000	FMCW	0.375	6.8–7.4	2D	-	50–500	-	Beijing Institute of Technology	[48,49]
		K	24	150	FMCW	-	-	2D	-	80	0.13	Telkom University	[127]
		W	77	103	FMCW	1.45	30.5	2D	-	-	0.04	University of Florence	[46]
GPRI	3	Ku	17.1–17.3	200	FMCW	0.75	6.8	1D–2D	4000	5–10,000	0.02~4	Gamma [8]	[51,128,129]
SD RotoSAR	1	X	10	160	SFCW	0.94	-	2D	-	-	-	University of Florence	[47]

Self-developed [1], Los Alamos National Laboratory [2], Centre Tecnològic de Telecomunicacions de Catalunya [3], State Key Laboratory for Health and Safety of Bridge Structures [4], National University of Defense Technology [5], Harbin Engineering University [6], Chinese Academy of Sciences [7], Gamma Remote Sensing [8].

Radar accuracy also varies by radar type. GB-RAR systems typically achieve sub-millimetre accuracy (~0.01 mm), while GB-SAR systems offer ~0.1 mm accuracy. These values depend not only on system types but also on the measurement context, such as whether the acquisition is static or dynamic, and the maximum distance to the target (D_{max}).

Figure 20 illustrates the distribution of radar types across the selected literature database. GB-RAR systems, such as IBIS-S and other custom-built models, are the most utilised. MIMO systems represent the second most used category, whereas RotoSAR has only appeared in a single study. According to Table 2, the University of Florence emerges as a key contributor to GBIR development, with extensive work across several radar types.

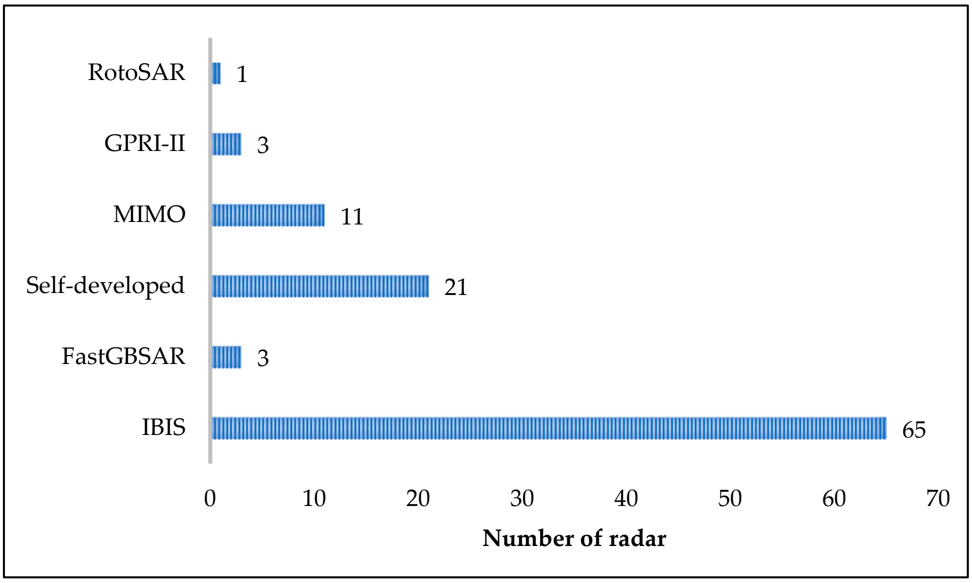

Figure 20. Implementation of interferometric radar types in bridge monitoring.

It is important to note that each GBIR architecture is uniquely suited to specific structural monitoring objectives.

GB-RAR systems, such as IBIS-S and FastGBSAR, are ideal for dynamic testing, thanks to their high SF (up to 4000 Hz), enabling accurate identification of modal parameters under real-time loads. GB-SAR systems, while limited in temporal resolution, deliver high spatial resolution, making them well suited for static deformation monitoring, especially over long-span or geometrically complex bridges. GPRI systems provide hybrid capabilities, operating in both real and synthetic aperture modes. Equipped with integrated GPS for time-synchronised acquisitions, they support mid-range applications, including static and quasi-dynamic monitoring with sub-millimetre accuracy. MIMO systems, offering multi-angle acquisition, enhance spatial resolution and enable the separation of displacement components, a critical feature for complex geometries or full-field 3D monitoring. RotoSAR, designed for full 3D displacement detection, addresses multi-directional motion but is limited by low spatial resolution and remains in early development. Ultimately, selecting an appropriate GBIR system depends on the specific monitoring goals—whether targeting high-frequency dynamic behaviour, high-resolution static deformations, or a multi-directional displacement tracking.

While systems such as IBIS-L and GPRI have been successfully employed in the long-term monitoring of dams, landslides, and slopes, their application in long-term bridge structural health monitoring remains very limited in the current literature. No journal studies reviewed in this paper reported the use of GBIR for long-term bridge structural health monitoring. This represents a critical research gap, highlighting the need for further studies on the feasibility and potential of GBIR in long-duration bridge monitoring. In contrast, short-term and dynamic monitoring, particularly using GB-RAR systems, has been widely demonstrated and forms the current core of GBIR-based bridge monitoring research.

5.3.3. GBIR Signal Analysis and Processing Techniques for Bridge Monitoring

Displacement over time is the primary output of GBIR sensors and can be acquired at different sampling frequencies, depending on whether the acquisition is static or dynamic. Various signal processing techniques are available in the literature to analyse these outputs in both the time and frequency domains [130].

Time domain methods typically employ statistical time-series techniques to estimate structural behaviour, often through the random extraction of signal segments to track condition variations over time. In contrast, frequency domain methods focus on extracting modal parameters, such as natural frequencies, mode shapes, and damping ratios, that are sensitive indicators of structural integrity. As a result, frequency domain techniques are particularly well suited for early damage detection [130].

A key advantage of GBIR systems over accelerometer sensors is their ability to directly measure displacements, allowing for the derivation of velocity and acceleration through first and second derivatives, respectively. Conversely, accelerometer data requires integration to derive these parameters, introducing random noise with each integration step. This noise often necessitates advanced filtering techniques such as the Kalman filter for noise removal and signal correction [131]. Nevertheless, GBIR outputs are not entirely immune to noise. Factors such as electromagnetic clutter, environmental conditions and the geometry of the monitored scene can introduce significant distortions, especially during long-term monitoring [26]. Amongst the environmental influences, humidity, temperature, and atmospheric pressure exert the most prominent effects, as shown in Figure 21 [26,132]. Seven papers in the reviewed literature address atmospheric phase correction and signal denoising in GBIR-based monitoring [16,57,58,73,80,81,128].

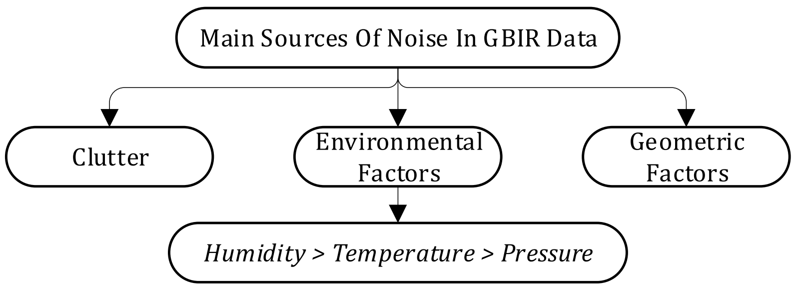

Figure 21. Main sources of noise in GBIR signals.

The importance of noise removal for accurate signal interpretation is critical, particularly for extracting damping-related parameters, which are especially sensitive to noise. Inaccurate feature extraction due to uncorrected noise may compromise structural assessment. Modal parameters remain the most extensively studied indicators in GBIR-based bridge monitoring. As shown in Figure 22, 63% of the selected papers examine the natural frequency of bridges. In comparison, damping ratios and mode shapes are analysed in only 13% and 11% of the studies, respectively. The remaining 13% of the literature does not report any investigation of modal parameters.

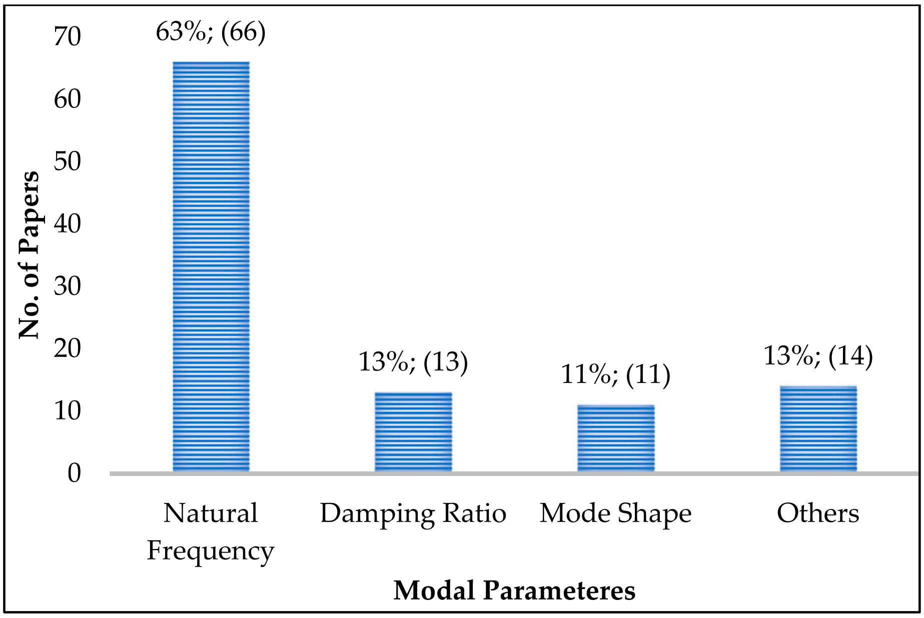

Figure 22. Distribution of main features investigated in bridge monitoring using GBIR systems (percentage; absolute value—expressed in brackets).

While artificial intelligence (AI) techniques, including machine learning (ML) and deep learning (DL), have not yet been widely applied to the structural monitoring of bridges using GBIR data, recent work highlights their potential. For example, Arnold et al. [98,133] demonstrated the feasibility of using ML approaches to detect and classify bridge crossing events with GBIR data. The integration of AI into GBIR processing workflows represents a promising research direction that remains largely unexplored for bridge structural monitoring scenarios. This may support tasks such as feature extraction, damage detection, automated pattern recognition, noise reduction and removal in radar signal processing. In addition, advancing research on long-term bridge monitoring using GBIR will make the relevance and necessity of AI-based solutions increasingly important.

5.3.4. GBIR and Integrated Technologies

The integration of GBIR systems with complementary technologies has been widely examined in the literature, highlighting their enhanced capability and versatility compared to standalone methods. Comparative studies have consistently demonstrated that GBIR provides reliable and accurate results for SHM, validating its use as a dependable tool in both short and long-term monitoring scenarios [13].

Amongst the 104 selected papers, 63 explored the integration of GBIR with other systems, resulting in 20 different technological combinations. As illustrated in Figure 23, accelerometers are the most frequently integrated devices with GBIR, offering complementary data on vibrational behaviour and modal parameters. Table 3 summarises the ten most common integrated systems from Figure 23, providing details on the nature and objectives of each integration.

The integration of GBIR with these complementary technologies enhances the overall resolution, validation capacity, and multidimensional insight in SHM. Besides increasing confidence in the measurements, such integrations also expand the range of applications where GBIR can play a central role in monitoring critical infrastructure.

Table 3. Overview of sensor technologies integrated with GBIR for static and dynamic bridge monitoring.

SHM Sensors	Description	References
Accelerometer	Accelerometers are frequently paired with GBIR systems due to their high sampling rates, making them ideal for dynamic analysis. Deflection data can be obtained via double integration, particularly with DC response accelerometers, allowing for an effective comparison and validation of GBIR-derived displacement outputs.	[9,13,23,33–35,40,54,55,63,64,72,82,83,87,90–95,100,102,105,114,119,120]
Camera	High-resolution digital cameras, including systems developed by Imetrum Ltd., have been used for dynamic displacement monitoring and mode shape identification. While their sampling frequencies are generally lower than GBIR, they can exceed 100 Hz, offering reliable visual data for structural dynamic investigations.	[8,33,34,55,80,86,88,107,111,124,134]
TLS	TLS systems provide a high-resolution 3D geometry of structures and have been employed in dynamic tests with sufficiently high acquisition rates. TLS outputs have been benchmarked against both GBIR and accelerometer data for validation in SHM applications.	[9,64,97,104,108,110]
Levelling	Levelling systems, including barcode and hydrostatic levelling, are used alongside GBIR for static deformation tracking. These systems are particularly suited for scenarios requiring high sensitivity in long-term monitoring.	[37,56,68,74,86,97]
Strain Measurements	Strain measurement systems, including traditional strain gauges and advanced Fibre Bragg Grating (FBG) sensors, help assess relative displacements and strain fields. Their data have been cross-validated with GBIR in various studies focusing on bridge monitoring.	[25,29,34,59,60]
LVDT	LVDT sensors are used to acquire accurate deflection data during dynamic testing, such as modal analysis. However, their accuracy may be affected by referring errors, which must be accounted for during interpretation.	[40,85,92,93,95]
GPS	Global Positioning System (GPS) modules integrated with GBIR can enhance geospatial accuracy by updating global position and time references. Structural-mounted GPS sensors operating at around 50 Hz have also been used to directly measure dynamic displacements for comparison with GBIR outputs.	[51,72,97,128,129]
Laser Tracker	Laser trackers are used alongside GBIR systems for displacement measurements, with sampling frequencies ranging from 100 to 1000 Hz. This makes them effective not only for geometry acquisition but also for dynamic monitoring when used alongside GBIR systems.	[60,86,119,120]
Inductive Gauge	Inductive gauges serve as a reliable reference for displacement monitoring and natural frequency estimation. Their suitable sampling frequencies and high sensitivity make them effective in validating GBIR measurements.	[79,89,99]
Ground Penetrating Radar (GPR)	GPR systems detect internal features like rebar, cracks, or moisture within structures. They are especially useful for identifying internal anomalies in sections where GBIR data indicate discrepancies.	[83,84]

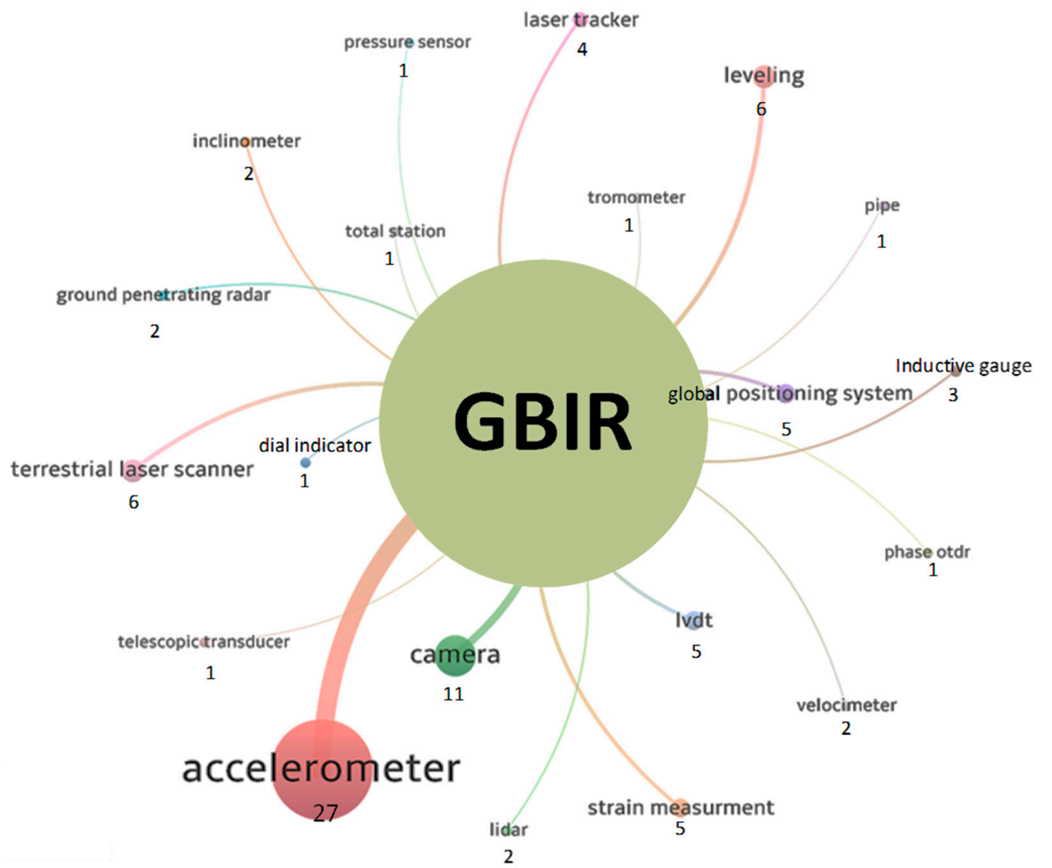

Figure 23. VOSviewer output representing the GBIR integration with other SHM systems and the number of occurrences.

6. Conclusions and Future Trends

Ground-based interferometric radar (GBIR) has emerged as a powerful tool for monitoring a wide range of civil infrastructure, including dams, landslides, mines, historical structures, residential buildings, and, most notably, bridges [14]. Given the crucial role of bridges in transportation networks and urban safety, their effective monitoring is of paramount importance. Numerous GBIR systems have been applied to different bridge types, often in combination with complementary sensors, to validate their accuracy and enhance data interpretation.

In this study, an in-depth analysis of the advantages and limitations of GBIR systems has been provided, particularly in the context of structural health monitoring (SHM). A key strength of GBIR lies in its capacity for remote, rapid data acquisition, often outperforming other ground-based monitoring technologies in terms of efficiency and coverage. The main conclusions of the present review are summarised below:

i. GBIR has demonstrated significant potential to lead future advancements in bridge monitoring. The growing number of publications indicates increasing interest in applying GBIR to bridge monitoring over the past two decades. However, further research is required to deal with its limitations.
ii. Most studies focus on roadway and railway bridges, which collectively represent 76% of all monitored cases. Other bridge types, such as pedestrian and heritage structures, are rarely investigated with GBIR.
iii. GBIR performance is sensitive to the material type of the monitored structure. This is particularly relevant in masonry bridges, which often require the installation of external corner reflectors. To date, only 5% of studies have addressed masonry structures, whereas steel and concrete are predominant in the literature.

iv. GBIR systems can be classified by their working principles and goals. Ground-Based Real Aperture Radar (GB-RAR) systems (e.g., IBIS-S) are ideal for dynamic bridge monitoring but lack cross-range resolution (ΔCR), limiting multiple-target distinction within the same range bin.

v. A lack of studies implementing different signal processing techniques for damage detection and structural state estimation is observed. This represents a critical gap.

vi. GBIR has been used in conjunction with at least 20 other sensor technologies to enhance accuracy and validation. Amongst these, accelerometers are the most frequently employed, supporting the validation of GBIR displacement measurements.

vii. Nearly all existing GBIR studies focus on short-term monitoring campaigns. Long-term applications, though common for other infrastructure such as dams or landslides using Ground-Based Synthetic Aperture Radar (GB-SAR) systems (e.g., IBIS-L and GPRI), remain virtually absent for bridges in the peer-reviewed literature. This represents a significant research gap.

Based on the review, the following areas are identified as key directions for future research:

i. Target Detection: Current GBIR systems lacking cross-range resolution (ΔCR) face difficulties in distinguishing multiple targets within the same range. Research into signal footprint visualisation techniques could help improve acquisition control and focus on areas of interest [10,11]. In addition, further research on advanced signal processing techniques is required to enhance target resolution [25].

ii. Material Sensitivity: The high sensitivity of electromagnetic waves towards different types of materials suggests that further studies are required in the future for both steel and masonry or concrete materials. For steel structures, it is suggested to apply methods to control the acquisition and range confinement. For masonry bridges, the evidence from the selected literature database shows that more in-depth investigations are required to better understand radar interaction.

iii. 3-D Displacement Monitoring: Single transceiver GBIR systems cannot resolve full 3D displacement components. Potential solutions to this issue include deploying multiple synchronised GBIR units [16] or integrating radars with complementary technologies, such as high-resolution cameras and triaxial accelerometers.

iv. Feature Extraction and Artificial Intelligence (AI) Interaction: Most current studies rely on frequency domain analysis for extracting modal parameters. Future research should expand to time domain and time–frequency techniques for more robust feature extraction, including capturing damping ratios and mode shapes. The integration of AI techniques, such as machine learning and deep learning, holds significant potential to enhance GBIR automation, diagnostic capabilities, and the real-time analysis of structural responses.

v. Long-Term Monitoring: A critical research gap lies in the long-term application of GBIR for bridge monitoring. Developing robust GB-RAR systems tailored to dynamic, continuous acquisition over extended periods is essential. Key research directions include improving hardware durability, optimising power supply systems, and implementing advanced noise reduction algorithms to mitigate environmental interferences (e.g., temperature, humidity, pressure, and clutter), which are especially impactful in long-term campaigns [26,132].

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