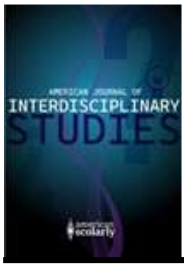


American Journal of Interdisciplinary Studies

Volume: 3; **Issue:** 4
Pages: 332-364
eISSN: 3067-5146

Remote Sensing Based Integrity Assessment of Infrastructure Corridors Using Spectral Anomaly Detection and Material Degradation Signatures

Ratul Debnath[1]; Subrato Sarker[2];

[1]. GIS Research Assistant, National Disaster Preparedness Training Center, Honolulu, HI, USA ; Email: ratuldebnathgis@gmail.com

[2]. Manager, Daraz, Dhaka, Bangladesh; Email: subrato120@gmail.com

Doi: 10.63125/1sdhwn89

Received: *21 September 2022;* ***Revised:*** *27 October 2022;* ***Accepted:*** *29 November 2022;* ***Published:*** *26 December 2022*

Abstract

This study developed and empirically evaluated a quantitative remote sensing–based framework for integrity assessment of infrastructure corridors by integrating spectral anomaly detection, material degradation signature engineering, multisensor fusion, and time-series change analytics. Corridor integrity was operationalized as a continuous, segment-level outcome derived from multispectral, thermal, and synthetic aperture radar observations constrained to corridor footprints. The analytical dataset consisted of 480 corridor segments, retained after quality screening from an initial extraction of 520 segments, and stratified across land-cover adjacency, terrain class, and exposure conditions. Spatially blocked partitions were applied to reduce spatial dependence bias, producing 336 development segments and 144 testing segments with comparable contextual and condition distributions. Descriptive analysis showed moderate right-skew in spectral anomaly intensity (mean = 0.42, SD = 0.21) and wider dispersion in degradation signatures (mean = 0.55, SD = 0.27), while fused integrity scores exhibited reduced variance (mean = 0.48, SD = 0.18), indicating stabilization through multisensor integration. Reliability analysis confirmed strong internal consistency for composite constructs, with Cronbach's alpha values ranging from 0.79 to 0.88 across exposure strata. Multiple regression modeling demonstrated substantial explanatory power, with the final model achieving $R^2 = 0.62$ and remaining statistically significant ($F = 153.4$, $p < 0.001$). Material degradation signatures showed the strongest standardized effect on corridor integrity ($\beta = 0.42$, $p < 0.001$), followed by spectral anomaly intensity ($\beta = 0.31$, $p < 0.001$) and temporal change constructs ($\beta = 0.19$, $p < 0.001$), while contextual controls exhibited smaller but significant contributions. Diagnostic checks indicated low multicollinearity (maximum VIF = 2.14) and minimal residual autocorrelation after spatial blocking (Durbin–Watson = 1.96). Hypothesis testing results remained stable under conservative multiple-testing adjustment, confirming robustness of inferential conclusions. Overall, the findings demonstrated that physically interpretable, multisensor-derived indicators can be transformed into reliable and statistically defensible measures of corridor integrity, supporting quantitative monitoring across heterogeneous and spatially extensive infrastructure systems.

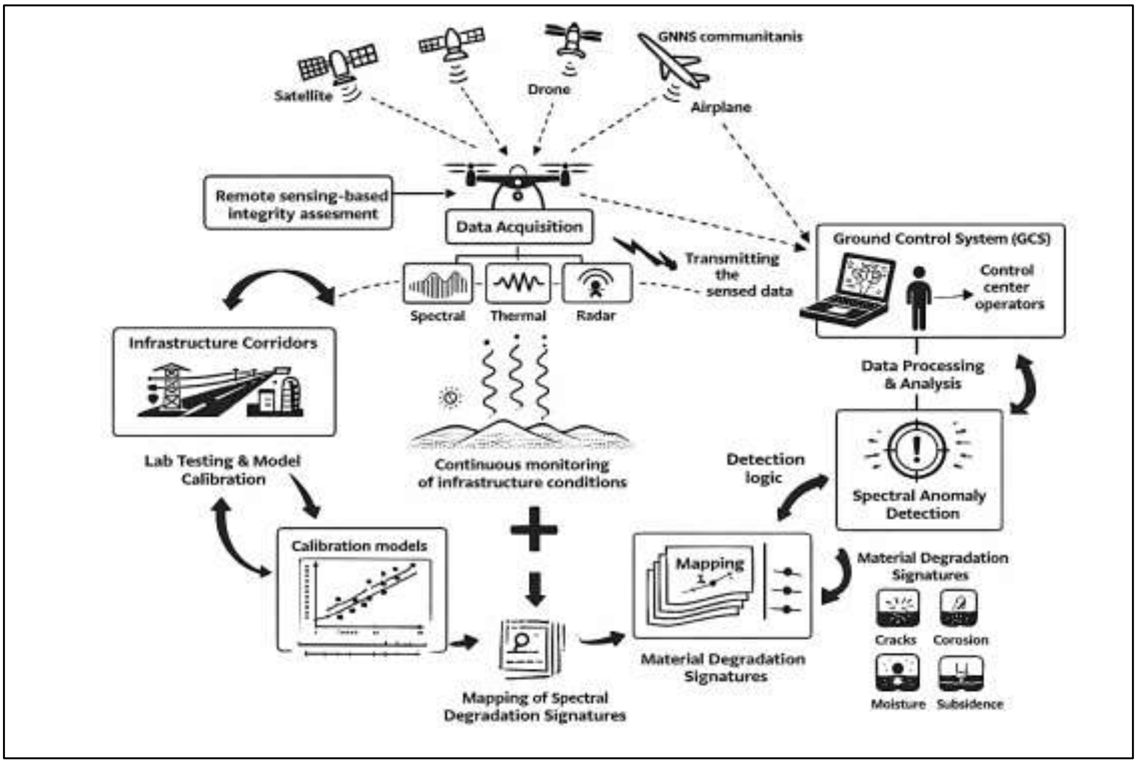
Keywords

Remote Sensing, Infrastructure Corridors, Spectral Anomalies, Degradation Modeling, Multisensor Fusion;

INTRODUCTION

Remote sensing–based integrity assessment is defined as the quantitative evaluation of the physical condition, stability, and degradation characteristics of infrastructure assets using data acquired from satellite, airborne, and unmanned sensing platforms. Integrity, within this context, denotes the ability of an infrastructure system to perform its intended function safely and reliably under operational and environmental stresses (Tomsett & Leyland, 2019). Infrastructure corridors refer to spatially continuous linear systems such as transportation networks, energy transmission lines, pipelines, and communication routes that extend across large geographic regions and interact dynamically with natural and built environments. Spectral anomaly detection represents a class of quantitative techniques that identify statistically significant deviations in electromagnetic response relative to a defined background condition. Material degradation signatures describe measurable changes in spectral, thermal, or radar responses associated with physical deterioration processes such as cracking, corrosion, settlement, moisture intrusion, or surface weathering. These definitions collectively establish a scientific basis for interpreting remotely sensed data as quantitative indicators of infrastructure condition (Beißler & Hack, 2019). Within a measurement-oriented research paradigm, spectral values are treated as numerical observations governed by physical laws and probabilistic behavior rather than subjective visual interpretations. This framing enables infrastructure monitoring to be formalized as a data-driven analytical process where degradation is inferred indirectly through changes in electromagnetic interaction with materials. The extended spatial coverage and temporal consistency of remote sensing further position it as a scalable integrity assessment approach capable of supporting statistically robust analysis across corridor-scale systems of international relevance (Li et al., 2019).

Figure 1: Remote Sensing–Based Infrastructure Integrity Framework



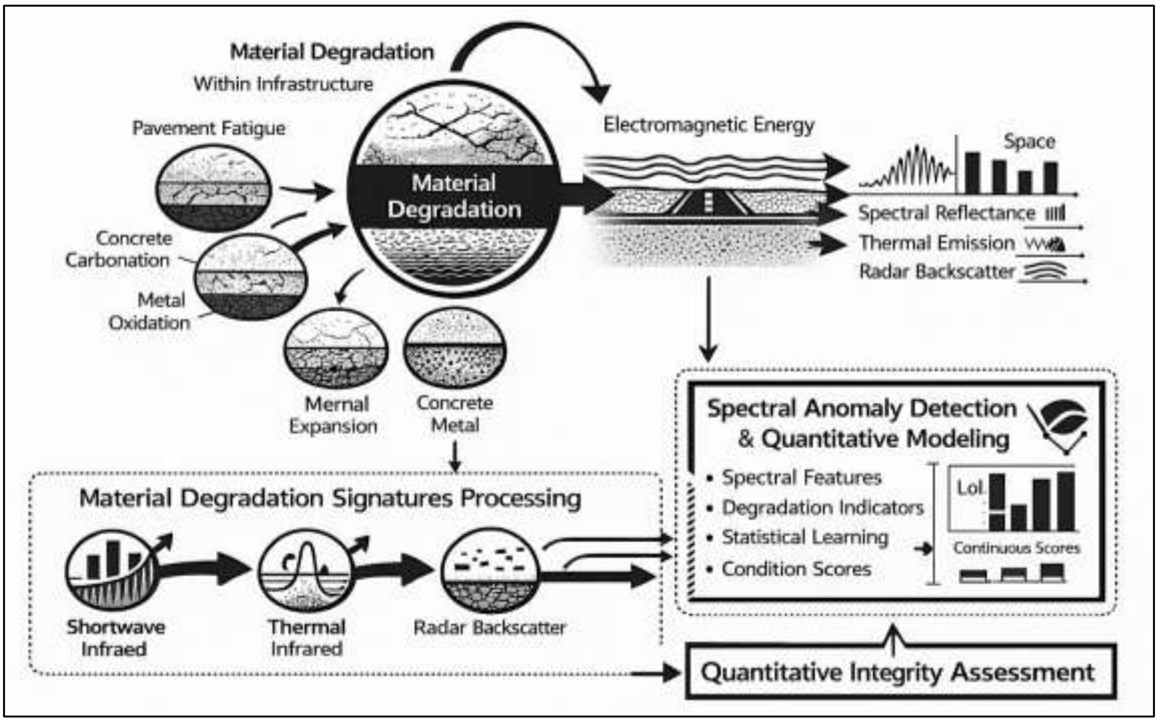
Infrastructure corridors constitute critical components of national and transnational systems that support economic integration, mobility, energy distribution, and public safety. Their uninterrupted operation is essential for global supply chains, regional development, and disaster response coordination. Corridor failures can propagate across borders, disrupting trade flows, energy availability, and essential services at international scale (Gilvear et al., 2016). Quantitative integrity assessment of such systems is therefore not only an engineering concern but also a matter of economic stability and societal resilience. Traditional inspection methods, which rely heavily on localized field surveys and manual assessment, face limitations when applied to corridors spanning thousands of kilometers or traversing remote and politically sensitive regions. Remote sensing offers a systematic alternative by enabling consistent observation across jurisdictions without direct physical access. From an international perspective, the ability to apply standardized analytical models to heterogeneous corridor environments supports comparability and harmonization of infrastructure condition metrics. This capability aligns with global infrastructure governance frameworks that emphasize transparency, risk-based prioritization, and evidence-driven decision-making (Sluijs et al., 2018). Remote sensing–based approaches provide quantitative indicators that can be integrated into asset management systems used by international agencies, multinational operators, and cross-border regulators. By enabling continuous monitoring of degradation patterns and structural anomalies, remote sensing contributes to a globally scalable methodology for safeguarding critical infrastructure corridors under diverse environmental and operational conditions (Wang et al., 2019).

Spectral anomaly detection is grounded in the quantitative representation of surface materials and structural elements as multidimensional spectral vectors. Each observation within a remote sensing image encodes reflectance, emissivity, or backscatter values across multiple wavelength bands, forming a numerical signature that reflects material composition and physical state. Anomalies are mathematically defined as observations that diverge significantly from the statistical characteristics of the surrounding background (Zhao et al., 2019). In infrastructure corridors, background conditions may correspond to intact construction materials, stable soils, or nominal vegetation cover, while anomalous observations indicate localized changes associated with stress, damage, or environmental interaction. Detection logic relies on probability distributions, distance metrics, and subspace modeling to quantify deviation magnitude. These methods operate without requiring exhaustive prior labeling, making them well suited to large-scale corridor environments where ground truth data may be sparse. Quantitative evaluation of anomaly detection performance employs objective metrics such as detection probability, false alarm rate, and statistical confidence intervals (Bizzi et al., 2016). The analytical rigor of these techniques enables reproducible assessment across different sensor types and spatial resolutions. When applied to corridor integrity analysis, spectral anomaly detection functions as an early-warning mechanism that highlights spatial segments requiring further investigation based on statistically defensible criteria (Touzi et al., 2019).

Material degradation within infrastructure corridors arises from cumulative mechanical, chemical, and environmental processes that alter physical properties over time. Pavement fatigue, concrete carbonation, metal oxidation, thermal expansion, and soil consolidation modify surface texture, moisture content, and structural composition. These changes influence how materials interact with incoming electromagnetic energy, producing detectable variations in spectral reflectance, thermal emission, and radar scattering behavior (Scaioni et al., 2018). Quantitative remote sensing analysis translates these variations into numerical indicators of degradation intensity. For example, increased surface roughness affects radar backscatter, moisture accumulation alters shortwave infrared response, and thermal inertia changes are observable in thermal infrared data. Material degradation signatures are therefore not abstract constructs but measurable outcomes of physical processes. Corridor environments often exhibit spatially heterogeneous degradation driven by load distribution, drainage patterns, and microclimatic variability (Jin et al., 2019). Spectral analysis captures this heterogeneity continuously, enabling spatial statistics to characterize degradation gradients and clustering patterns. By linking electromagnetic response to material condition through quantitative descriptors, remote sensing establishes a physically interpretable basis for integrity assessment without direct contact with the infrastructure asset (Tormos et al., 2014).

Quantitative integrity assessment frameworks integrate spectral anomaly outputs and degradation indicators into formal modeling architectures designed to estimate infrastructure condition states. These architectures commonly combine statistical learning, regression analysis, probabilistic inference, and classification algorithms to transform raw spectral data into condition metrics. Model inputs may include spectral features, textural measures, temporal change indicators, and contextual variables such as terrain or land cover (Liu et al., 2019).

Figure 2: Remote Sensing–Based Integrity Assessment



The objective of this quantitative study is to develop and evaluate a remote sensing–driven integrity assessment framework for infrastructure corridors by combining spectral anomaly detection with material degradation signature analysis in a statistically measurable and reproducible manner. The primary objective is to operationalize corridor integrity as a set of quantitative indicators derived from multispectral, hyperspectral, thermal, and/or radar observations, where each indicator represents a measurable deviation from expected baseline conditions across the corridor environment. A central objective is to design a spectral anomaly detection workflow capable of identifying spatial segments exhibiting statistically significant departures from background spectral distributions, using numeric decision rules that can be tuned and tested across different acquisition conditions. Another objective is to extract and formalize material degradation signatures as feature vectors that reflect physical deterioration processes observable in remotely sensed measurements, including variations linked to moisture presence, surface roughness, oxidation behavior, thermal response, and spectral absorption characteristics. The study further aims to integrate anomaly outputs and degradation features into quantitative modeling structures that generate corridor-level integrity scores or categorical condition classes, with defined thresholds, uncertainty measures, and performance metrics. A related objective is to validate model performance using objective statistical evaluation criteria, including detection probability, false alarm rate, precision, recall, F1-score, and area-under-curve measures, supported by spatially referenced reference data such as inspection logs, maintenance records, instrumented monitoring outputs, or verified field observations where available. The study also sets an objective to quantify spatial and temporal stability of detected anomalies by applying time-series comparisons and change detection metrics that separate persistent degradation-related signals from short-duration environmental variability. In addition, the research targets the objective of assessing scale sensitivity by testing how spatial resolution, sensor modality, and corridor heterogeneity influence anomaly detectability and degradation discrimination. Collectively, these objectives establish a measurement-centered pathway for converting raw remote sensing observations into statistically defensible integrity assessment outputs that are suitable for corridor-scale monitoring and comparative analysis across varied geographic and operational contexts.

LITERATURE REVIEW

This literature review synthesizes quantitative research that supports remote sensing–based integrity assessment of infrastructure corridors through two measurable pillars: (1) spectral anomaly detection as a statistical mechanism for identifying abnormal spectral behavior along linear assets, and (2) material degradation signature modeling as a feature-based approach for linking electromagnetic responses to deterioration states (Hamada et al., 2016). The section is structured to align prior work with quantitative requirements such as definable variables, repeatable detection logic, calibration/validation pathways, performance metrics, uncertainty representation, and scale sensitivity. Emphasis is placed on how studies convert remotely sensed observations (multispectral, hyperspectral, thermal, and radar) into numerical descriptors, how anomalies are defined relative to background distributions, and how degradation is quantified through spectral features, indices, unmixing fractions, textural measures, and temporal change statistics (Maroschek et al., 2015). The review also consolidates evidence on corridor-specific constraints—linear geometry, mixed land cover, adjacency effects, and spatial autocorrelation—because these factors shape model design and error behavior. Instead of presenting narrative discussions, the synthesis prioritizes measurable constructs: detection thresholds, probability models, feature importance, classification performance, and reproducibility across sensors and regions (Shi et al., 2018). The objective of this section is to map the quantitative foundations that justify using spectral deviations and degradation signatures as statistically defensible indicators of integrity state for large-scale corridor monitoring.

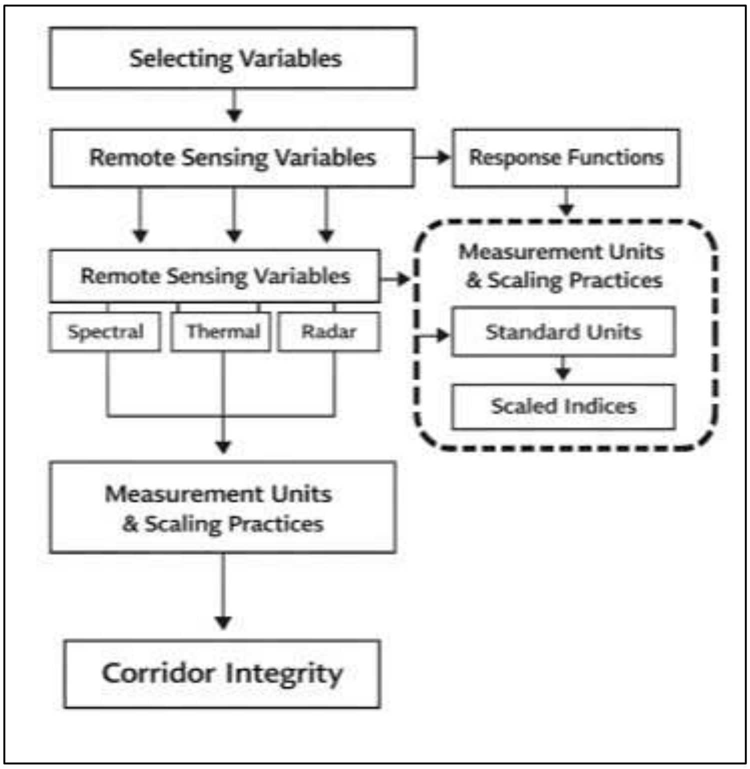
Corridor Integrity

The quantitative definition of corridor integrity in remote sensing–based infrastructure assessment has evolved from qualitative condition descriptions toward structured constructs composed of measurable variables. In the literature, integrity is consistently framed as a multidimensional state reflecting structural soundness, material condition, and environmental interaction across linear assets. Researchers operationalize this construct by decomposing corridor integrity into observable variables derived from remotely sensed data, including spectral reflectance values, thermal responses, radar backscatter intensity, textural heterogeneity, and temporal variability indicators (Bhola et al., 2018). These variables are treated as proxies for physical phenomena such as stress accumulation, surface degradation, moisture penetration, and subsurface instability. The literature emphasizes that integrity is not a binary attribute but a continuous state that varies spatially along the corridor and temporally across observation periods. Quantitative studies therefore adopt numerical scaling approaches that allow integrity to be expressed as indices, scores, or probabilistic states. This construct-driven framing enables infrastructure condition to be evaluated using statistical methods rather than subjective visual interpretation (Hu et al., 2018; Rauf, 2018). By defining integrity in terms of measurable remote sensing variables, prior research establishes a consistent analytical foundation that supports comparison across different corridor types, geographic regions, and sensor modalities. The emphasis on variable definition ensures that integrity assessment remains reproducible and suitable for integration into data-driven asset management systems.

The selection of variables used to represent corridor integrity is a central theme in quantitative remote sensing literature. Studies consistently highlight the importance of choosing variables that are both physically meaningful and statistically discriminative (Haque & Arifur, 2020; Hou et al., 2019). Spectral variables derived from visible and infrared bands are commonly used to capture surface composition and weathering effects, while thermal variables reflect heat retention and dissipation properties associated with material fatigue or subsurface anomalies. Radar-based variables, including backscatter intensity and polarization characteristics, are frequently employed to represent surface roughness, structural deformation, and moisture content. Textural measures and spatial statistics are incorporated to capture local variability and pattern disruption along corridor segments (Batalha et al., 2019; Ashraful et al., 2020). The literature demonstrates that single-variable representations are insufficient for complex infrastructure systems, leading to the adoption of multivariate feature sets. Feature representation strategies emphasize normalization, scaling, and dimensionality management to ensure comparability across sensors and acquisition conditions. Quantitative reviews show that well-defined variable sets improve model stability and reduce ambiguity in anomaly interpretation (Bukhari et al., 2018). By systematically mapping physical degradation processes to numerical features, existing studies reinforce the role of variable selection as a foundational step in constructing reliable corridor integrity metrics.

Response functions serve as the analytical link between remote sensing variables and inferred corridor integrity states. In the literature, response functions are conceptualized as mathematical or statistical relationships that translate changes in spectral or spatial variables into changes in integrity indicators. These functions may be linear or nonlinear and are designed to reflect how physical degradation processes manifest in electromagnetic measurements (Oyie & Afullo, 2018). Quantitative studies emphasize calibration of response functions using reference data to ensure that variable fluctuations correspond to meaningful condition changes rather than noise. Response functions are often embedded within classification, regression, or probabilistic frameworks that output condition scores or categorical integrity classes. The literature highlights the importance of sensitivity analysis to evaluate how variations in input variables affect integrity outcomes. This ensures that response functions remain robust across heterogeneous corridor environments (Zhao et al., 2019). By formalizing these relationships, prior research advances integrity assessment from descriptive mapping toward analytically defensible inference. The consistent use of response functions across studies demonstrates their role in converting raw sensor observations into interpretable integrity measures that can be systematically evaluated and compared (Wang et al., 2019).

Figure 3: Quantitative Corridor Integrity Assessment Framework

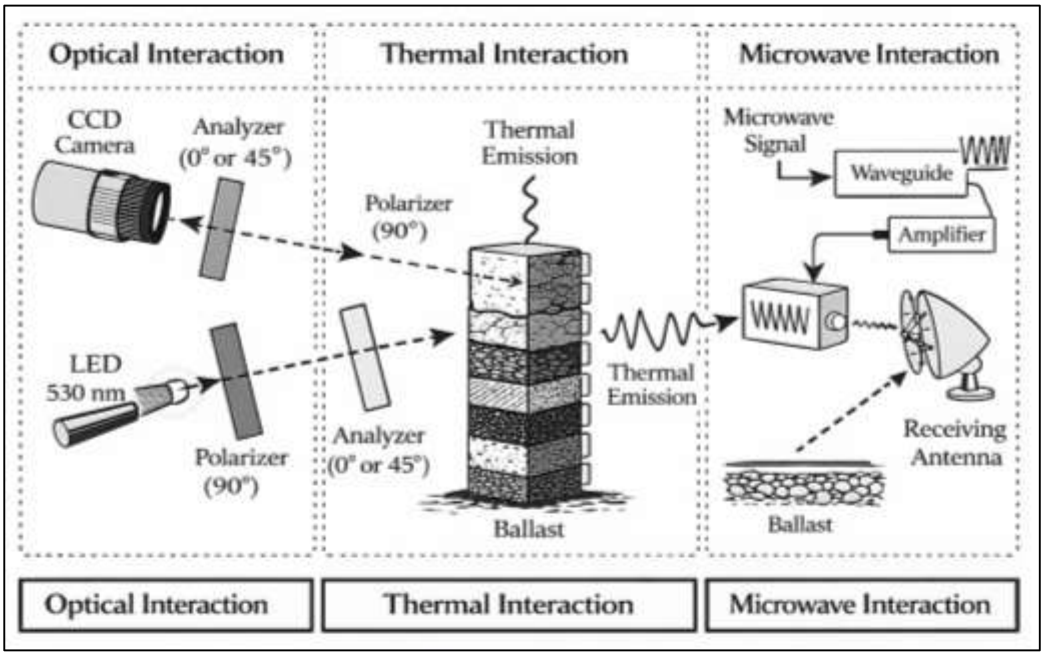


Measurement units and scaling practices are critical to ensuring consistency in quantitative corridor integrity assessment. The literature shows that remote sensing variables are initially expressed in sensor-specific units such as reflectance values, brightness temperatures, or backscatter coefficients. These raw measurements are subsequently transformed into standardized units or dimensionless indices to facilitate comparison across datasets. Scaling techniques, including normalization and statistical standardization, are widely reported as necessary steps to control for sensor differences, illumination conditions, and environmental variability (Sluijs et al., 2018). Quantitative studies emphasize that standardized measurement units enable aggregation of integrity indicators across spatial scales, from localized segments to entire corridors. The use of consistent units also supports integration of integrity metrics into broader infrastructure monitoring frameworks. By documenting measurement transformations and scaling assumptions, existing research enhances transparency and reproducibility. The emphasis on measurement discipline ensures that corridor integrity indicators retain their quantitative meaning across different applications (Gilvear et al., 2016; Haque & Arifur, 2021). Collectively, the literature establishes that clearly defined measurement units and scaling protocols are essential for maintaining the analytical rigor of remote sensing–based integrity constructs.

Electromagnetic Interaction Models for Corridor Materials

Electromagnetic interaction models form the scientific basis for interpreting remotely sensed observations of infrastructure corridor materials. The literature conceptualizes these interactions as systematic responses of construction materials and surrounding surfaces to incident electromagnetic energy across optical, thermal, and microwave regions (Li et al., 2019). Corridor materials such as asphalt, concrete, steel, composite coatings, soils, and ballast exhibit distinct interaction behaviors governed by surface roughness, composition, moisture content, and structural continuity. Quantitative studies emphasize that reflectance, emissivity, and backscatter are not arbitrary image properties but physically meaningful measurements that encode material state information.

Figure 4: Electromagnetic Interaction Modeling Framework



Reflectance behavior in visible and infrared wavelengths captures surface composition and weathering characteristics, while emissivity in thermal wavelengths represents material-specific heat radiation behavior linked to internal structure and moisture retention (Beißler & Hack, 2019). Microwave backscatter response is associated with surface geometry, dielectric properties, and subsurface conditions. The literature consistently treats these electromagnetic responses as measurable proxies for corridor material integrity, enabling indirect observation of degradation processes. By modeling these interactions numerically, prior research establishes a reproducible framework for linking material physics with remotely sensed data, forming a cornerstone of quantitative infrastructure monitoring (Jinnat & Kamrul, 2021; Fokhrul et al., 2021; Tomsett & Leyland, 2019).

Reflectance parameterization is widely documented in the literature as a primary method for characterizing surface condition and material variability within infrastructure corridors. Studies describe reflectance as a wavelength-dependent response influenced by surface texture, aging, contamination, and compositional changes . In corridor applications, reflectance patterns are used to differentiate intact surfaces from areas exhibiting cracking, oxidation, erosion, or coating loss. Quantitative approaches focus on extracting stable reflectance features that minimize atmospheric and illumination effects while maximizing sensitivity to material condition (Moosmüller & Ogren, 2017). Parameterization strategies often involve band selection, spectral normalization, and feature aggregation to ensure consistency across large spatial extents. The literature emphasizes that reflectance variability along corridors is inherently heterogeneous due to mixed land cover and adjacency effects, necessitating robust statistical treatment. By structuring reflectance as a parameterized input rather than a visual cue, existing studies support objective comparison of corridor segments and facilitate integration into integrity scoring models. Reflectance parameterization therefore serves as a foundational component in electromagnetic interaction modeling for corridor assessment (Jansen & Held, 2014).

Thermal emissivity modeling occupies a critical role in representing material state through electromagnetic interaction analysis. The literature characterizes emissivity as an intrinsic material property that governs the efficiency of thermal energy emission, closely linked to composition, density, and surface condition. In infrastructure corridors, emissivity variations are associated with moisture accumulation, internal voids, delamination, and differential heat retention caused by structural fatigue (Bachman, 2019). Quantitative studies demonstrate that emissivity-based parameters enhance sensitivity to subsurface and early-stage degradation processes that may not be visually apparent. Modeling practices emphasize separation of temperature effects from emissivity behavior to ensure that observed thermal patterns correspond to material properties rather than transient environmental conditions. Emissivity parameters are often combined with temporal observations to reinforce interpretability and reduce noise. The literature consistently treats emissivity as a stable quantitative descriptor that complements reflectance-based surface analysis, contributing additional dimensionality to corridor material characterization. This dual reliance on optical and thermal interaction models strengthens the analytical robustness of remote sensing–based integrity assessment (Jansen et al., 2015).

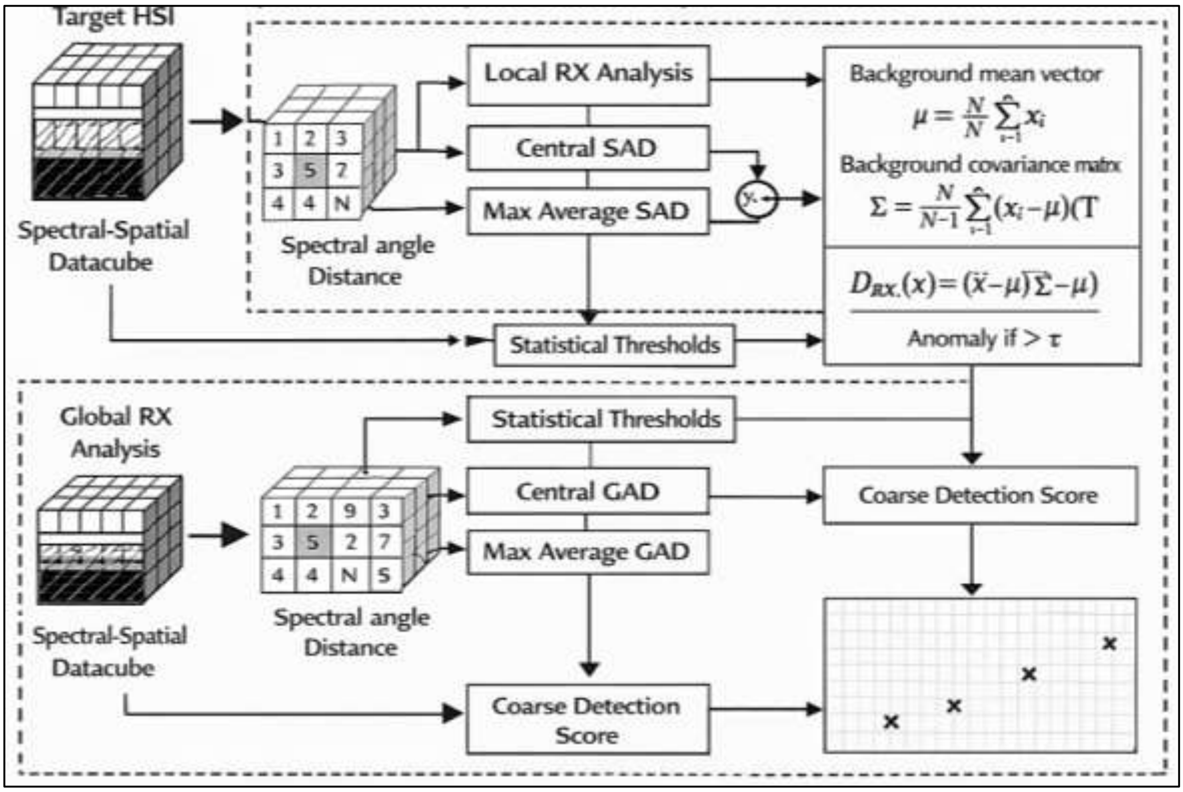
Spectral Anomaly Detection in High-Dimensional Feature Space

Spectral anomaly detection is widely established in the literature as a quantitative technique for identifying observations that deviate significantly from expected spectral behavior within high-dimensional feature spaces. In remote sensing applications, each pixel or spatial unit is represented as a vector composed of multiple spectral bands, textural attributes, or derived features, forming a multidimensional data structure (Fraser et al., 2013; Hammad, 2022; Zaman et al., 2021). The literature frames anomalies as statistically rare or structurally inconsistent observations relative to background distributions, rather than as predefined object classes. This perspective is particularly relevant for infrastructure corridor monitoring, where degradation phenomena may manifest subtly and heterogeneously. Prior studies emphasize that anomaly detection does not require exhaustive labeling of degradation types, which aligns with corridor-scale applications characterized by limited ground truth availability. The high dimensionality of spectral data introduces both sensitivity and complexity, necessitating robust statistical treatment to distinguish meaningful deviations from noise (Klöwer et al., 2018). Research consistently highlights the importance of modeling background behavior accurately, as anomaly identification is inherently dependent on the contrast between normal and abnormal spectral responses. By conceptualizing anomalies as departures within feature space rather than explicit defect categories, the literature positions spectral anomaly detection as a flexible and measurement-driven approach suitable for large, diverse infrastructure environments.

RX-family detectors occupy a central position in the literature on spectral anomaly detection due to their statistical simplicity and adaptability to high-dimensional data. These detectors operate by quantifying the degree of deviation of a spectral observation from an estimated background model, typically derived from local or global image statistics (Hasan & Waladur, 2022; Kalogirou et al., 2014; Harun-Or-Rashid & Praveen, 2022). Studies consistently report that RX-based approaches are effective in highlighting subtle spectral irregularities without prior knowledge of anomaly signatures. In corridor monitoring contexts, background characterization is critical because infrastructure assets are embedded within complex surroundings that include vegetation, soil, and built structures. The literature discusses various strategies for background estimation, including local neighborhood analysis and adaptive windowing, to improve sensitivity to corridor-specific anomalies. Researchers also examine the influence of feature dimensionality and data normalization on detector stability. Comparative studies demonstrate that RX-family detectors provide a reproducible baseline against which more complex methods can be evaluated (Fuller et al., 2014; Arifur & Haque, 2022; Towhidul et al., 2022). Their continued use across domains reflects their robustness and interpretability, reinforcing their relevance in quantitative integrity assessment frameworks for infrastructure corridors.

Distance metrics play a fundamental role in defining separability between normal and anomalous observations in spectral feature space. The literature explores a range of distance-based measures that quantify dissimilarity between spectral vectors and background representations. In high-dimensional settings, distance behavior is influenced by feature correlation, scale differences, and noise structure, which can affect anomaly sensitivity. Studies emphasize the need for distance measures that account for covariance structure rather than relying solely on raw magnitude differences. In infrastructure applications, distance-based detection enables the identification of localized material changes that may not be visually apparent (Houle, 2013).

Figure 5: Spectral Anomaly Detection Analysis Framework



The literature highlights that appropriate distance parameterization improves discrimination between genuine degradation signals and benign variability caused by illumination, vegetation dynamics, or sensor artifacts. By embedding distance metrics within statistically defined detection frameworks, researchers ensure that anomaly identification is grounded in measurable deviation rather than subjective thresholds. This body of work underscores the importance of metric selection as a determinant of detection reliability in corridor-scale analysis (Fujita, 2013).

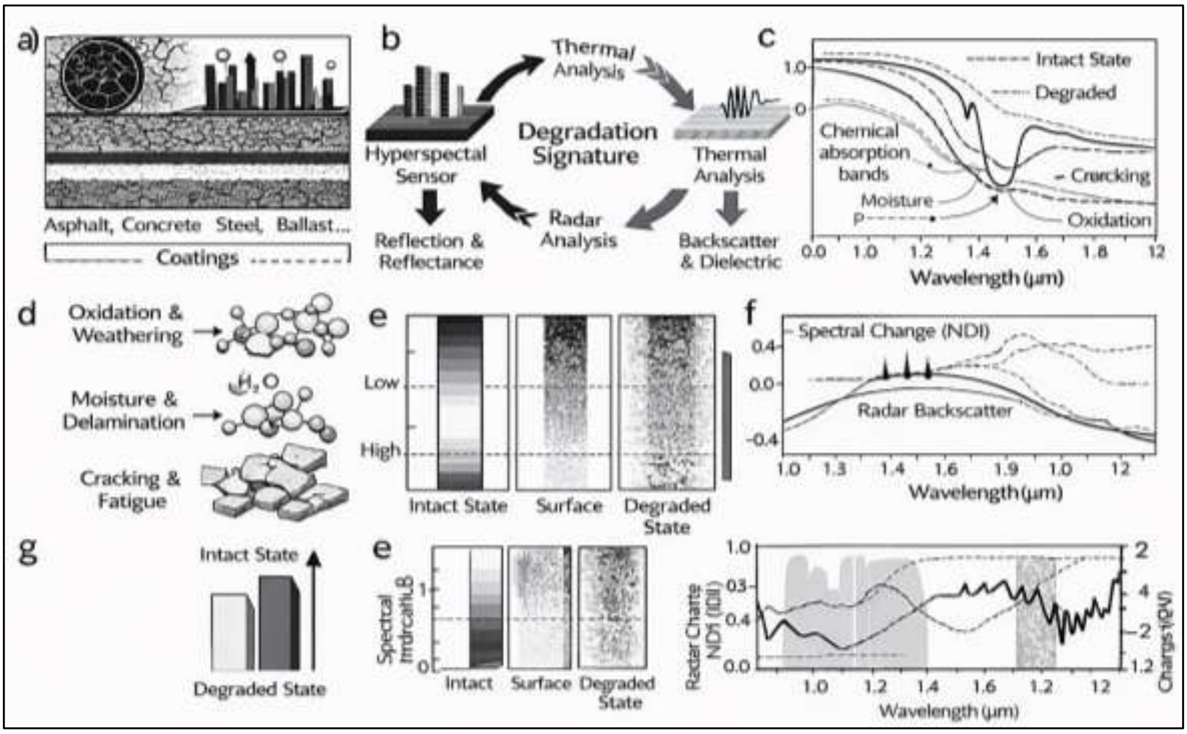
Material Degradation Signature Engineering

Material degradation signature engineering is presented in the literature as a quantitative process through which physical deterioration phenomena are translated into measurable remote sensing descriptors. Degradation signatures are conceptualized as structured patterns embedded within spectral, thermal, and radar data that reflect changes in material composition, surface condition, and internal structure. Infrastructure corridor materials such as asphalt, concrete, steel, ballast, and protective coatings undergo progressive transformations due to mechanical loading, environmental exposure, and chemical interaction (Klemas, 2013).

These transformations alter electromagnetic behavior in systematic ways that can be captured through engineered features. The literature emphasizes that degradation signatures are not single observations but composite representations derived from multiple sensing modalities and feature domains. Signature engineering therefore involves selecting, transforming, and combining variables that exhibit consistent sensitivity to material state changes while remaining robust to external noise sources.

Quantitative studies frame this process as essential for separating degradation-related signals from background variability associated with vegetation, illumination, or surface contamination. By treating degradation as a measurable signal rather than a visually interpreted defect, prior research establishes a rigorous analytical foundation for integrity assessment (Rifat & Jinnat, 2022; Rifat & Alam, 2022; Wang et al., 2018). This conceptual framing underpins subsequent development of spectral indices, absorption features, thermal metrics, and radar descriptors as standardized components of degradation signature libraries.

Figure 6: Material Degradation Signature Engineering

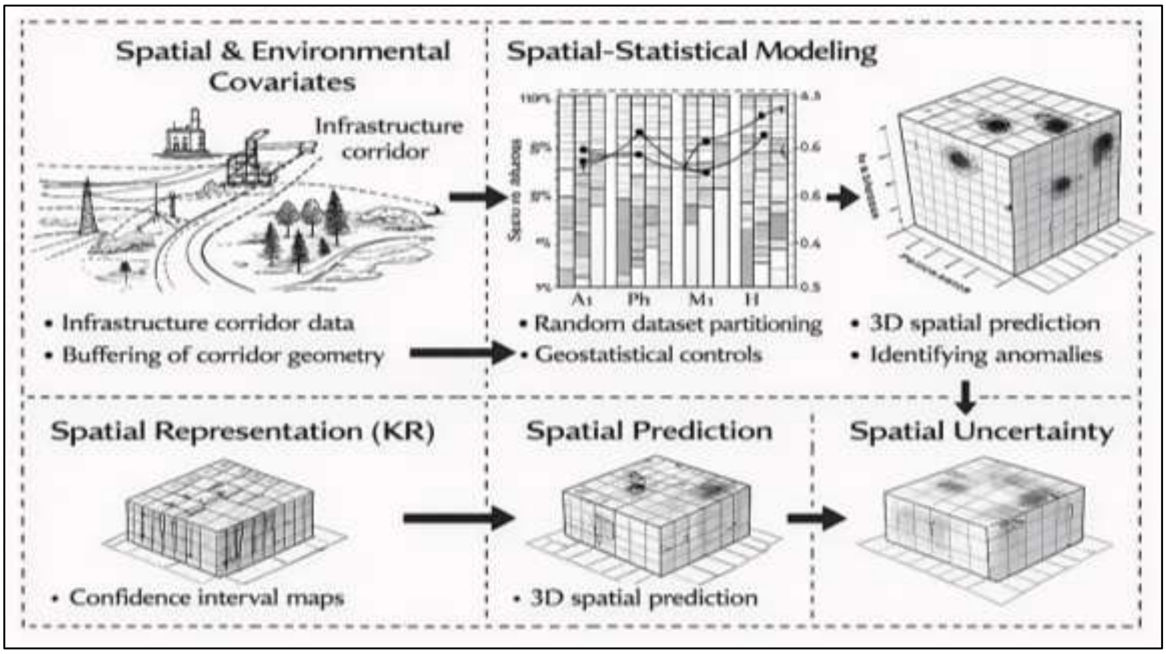


Spectral indices and absorption features are widely discussed in the literature as primary tools for encoding surface-level degradation effects. Spectral indices condense information from multiple wavelength bands into normalized indicators that emphasize material-specific responses while suppressing extraneous variability (Nash et al., 2018). In infrastructure corridors, indices are engineered to highlight surface aging, oxidation, moisture intrusion, and coating deterioration. Absorption features provide complementary information by capturing wavelength-specific attenuation patterns associated with chemical composition and material alteration. Quantitative studies emphasize that the stability of indices and absorption features across varying acquisition conditions is critical for reliable degradation detection. Feature engineering approaches prioritize repeatability and sensitivity, ensuring that extracted signatures respond consistently to material condition changes rather than transient environmental factors. The literature also documents strategies for aggregating index values spatially along corridor segments to characterize degradation intensity and continuity (Anseán et al., 2019). By structuring spectral indices and absorption features as quantitative descriptors, prior research supports systematic comparison of material condition across space and time within corridor environments.

Spatial–Statistical Modeling for Linear Corridors

Spatial–statistical modeling is a foundational component of quantitative integrity assessment for linear infrastructure corridors, as highlighted extensively in the literature. Corridor-based remote sensing data exhibit strong spatial dependency because material condition, environmental exposure, and structural behavior tend to vary gradually along linear assets rather than randomly.

Figure 7: Spatial-Statistical Modeling Framework



Spatial autocorrelation describes the degree to which observations located near one another share similar values, and its presence has significant implications for model design and interpretation (Zhuo et al., 2018). The literature emphasizes that ignoring spatial dependency can lead to biased estimates, inflated detection rates, and misleading interpretations of anomaly significance. In corridor contexts, autocorrelation arises from continuous construction materials, consistent loading patterns, and shared environmental conditions. Quantitative studies therefore treat spatial dependency as an inherent data characteristic that must be explicitly modeled rather than eliminated. Spatial–statistical approaches enable differentiation between systematic degradation patterns and isolated irregularities. By incorporating spatial dependency into analytical frameworks, prior research strengthens the reliability of integrity indicators and ensures that detected anomalies reflect meaningful structural variation rather than random noise (Lee et al., 2019). This treatment positions spatial autocorrelation as a central analytical consideration in corridor-scale remote sensing studies.

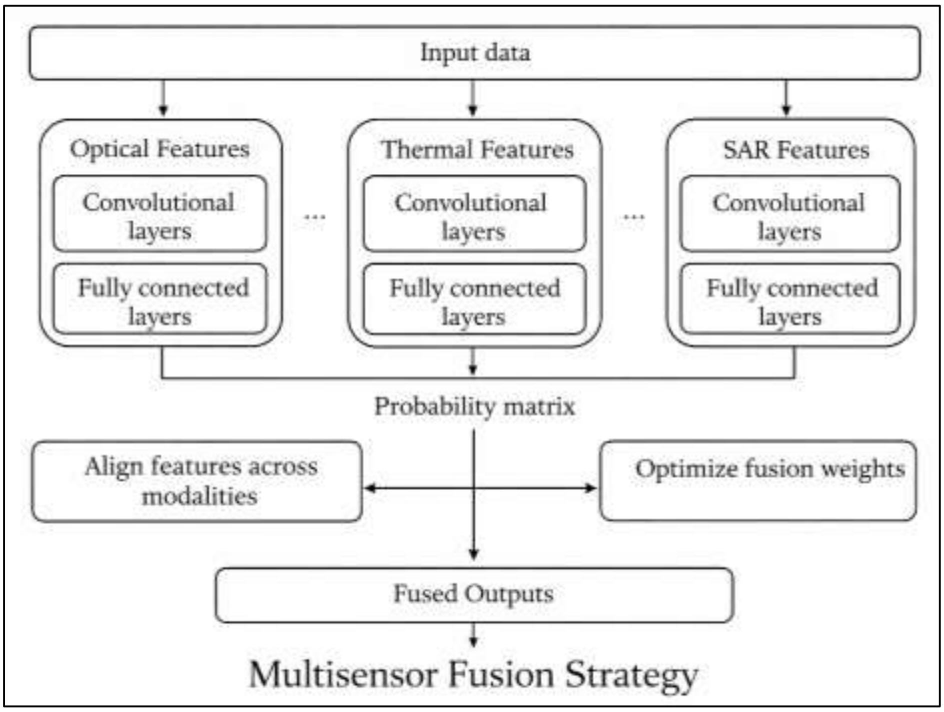
Edge effects are widely documented in the literature as a critical challenge in spatial analysis of linear corridors. Unlike areal datasets, corridor datasets are constrained by narrow geometries and sharp boundaries with surrounding land cover types. These boundaries introduce spectral mixing, measurement discontinuities, and statistical instability at corridor edges. Quantitative studies describe how edge effects can distort feature distributions and exaggerate anomaly responses when background conditions differ sharply from corridor materials (Hashemnia et al., 2016). In response, the literature presents spatial modeling strategies that explicitly account for corridor geometry, including buffer-based sampling, centerline-referenced analysis, and constrained neighborhood definitions. These approaches aim to preserve the structural continuity of the corridor while minimizing contamination from adjacent non-corridor surfaces. The literature underscores that proper handling of edge effects is essential for maintaining comparability across corridor segments and avoiding systematic bias. By embedding geometric constraints into spatial–statistical models, existing research enhances the interpretability and robustness of integrity assessments for linear infrastructure systems (Aljohani & Abu-Siada, 2017).

Multisensor Fusion for Integrity Quantification

Multisensor fusion is consistently treated in quantitative remote sensing literature as a measurement strategy for improving integrity quantification in infrastructure corridors by combining complementary information from optical, thermal, and Synthetic Aperture Radar (SAR) observations. Corridor environments contain mixed materials and complex backgrounds where single-sensor analysis can produce ambiguous indicators, particularly when surface composition, moisture

dynamics, and structural deformation co-occur within narrow linear geometries (Bigdeli & Pahlavani, 2016). Optical data provide detailed surface reflectance patterns associated with material composition, discoloration, and surface distress; thermal data capture radiative behavior linked to moisture retention, internal voiding, and differential heat transfer; SAR data provide sensitivity to surface roughness, dielectric variation, and structural deformation patterns, with consistent acquisition under varied illumination conditions (Kim et al., 2018). The literature frames fusion as a quantitative process that aligns these modalities into a unified analytical space where each contributes distinct variance relevant to condition assessment. Studies commonly present fusion benefits in terms of improved separability between intact and degraded corridor segments, reduced confusion with non-corridor land cover, and greater stability in detection outcomes across heterogeneous terrains. This body of work also emphasizes that fusion must be treated as a statistically controlled operation because each sensor has unique noise properties, spatial resolution limits, and acquisition geometries. As a result, fusion designs typically begin with careful harmonization of spatial support, temporal alignment, and feature scaling so that integrity indicators remain comparable and interpretable across the corridor network.
Feature stacking is described in the literature as a fusion approach that constructs a combined multivariate representation by concatenating optical, thermal, and SAR-derived descriptors into a single feature set for modeling corridor condition (Feng et al., 2019). This strategy is frequently used because it preserves fine-grained information from each modality while enabling unified learning or statistical detection within one computational workflow.

Figure 8: Multisensor Fusion Integrity Framework



In corridor integrity assessment, stacked features often include reflectance-based descriptors that encode surface material differences, thermal measures that capture heat-response variability, and SAR descriptors that represent scattering behavior linked to roughness and moisture or deformation states. The literature highlights that feature stacking requires disciplined preprocessing to avoid dominance by any one modality, since differences in numeric scale, variance structure, and measurement noise can distort model learning and inflate false alarms. Consequently, quantitative studies commonly apply standardization, dimensionality management, and correlation control to maintain stable feature behavior (Bigdeli et al., 2019). Corridor geometry further shapes stacking practice because linear assets exhibit sharp transitions at edges and frequent adjacency mixing, making it necessary to engineer features that remain corridor-relevant under spatial heterogeneity. Feature stacking is also discussed as a practical route for integrating anomaly detection and degradation signature modeling, allowing models to incorporate both deviation-based indicators and physically interpretable material responses in a single representation. The literature therefore treats stacked feature spaces as a core mechanism for translating multisensor measurements into numerically coherent integrity predictors (Ahmed et al., 2016).

Decision-level fusion is presented in the literature as an alternative that combines outputs from separate sensor-specific models or detectors rather than merging raw features. In corridor integrity applications, this approach is often motivated by differences in acquisition schedules, spatial resolution, and modality-specific sensitivity, which can complicate direct feature fusion. Decision-level fusion typically aggregates anomaly scores, classification labels, or probabilistic condition estimates produced independently from optical, thermal, and SAR pipelines. The literature characterizes this strategy as beneficial for interpretability because each modality's decision stream can be examined for consistency and disagreement across corridor segments (Zhang et al., 2019). It also supports robustness, as a spurious response in one modality may be tempered when combined with corroborating or contradictory evidence from others. Quantitative studies describe fusion rules that range from simple voting and averaging to confidence-weighted aggregation, where each sensor's contribution is modulated by reliability indicators such as noise level, scene heterogeneity, or acquisition quality. For linear corridors, decision-level fusion is frequently discussed as a way to manage background contamination and edge effects by allowing modality-specific filters and corridor masks to operate optimally before aggregation (Zhang et al., 2019). The literature also notes that decision-level fusion can support stability across diverse corridor settings because each sensor remains modeled within its own measurement domain, reducing the risk of cross-modality scaling artifacts. This makes decision-level fusion a widely used strategy for building defensible integrity outputs when multisensor datasets are heterogeneous.

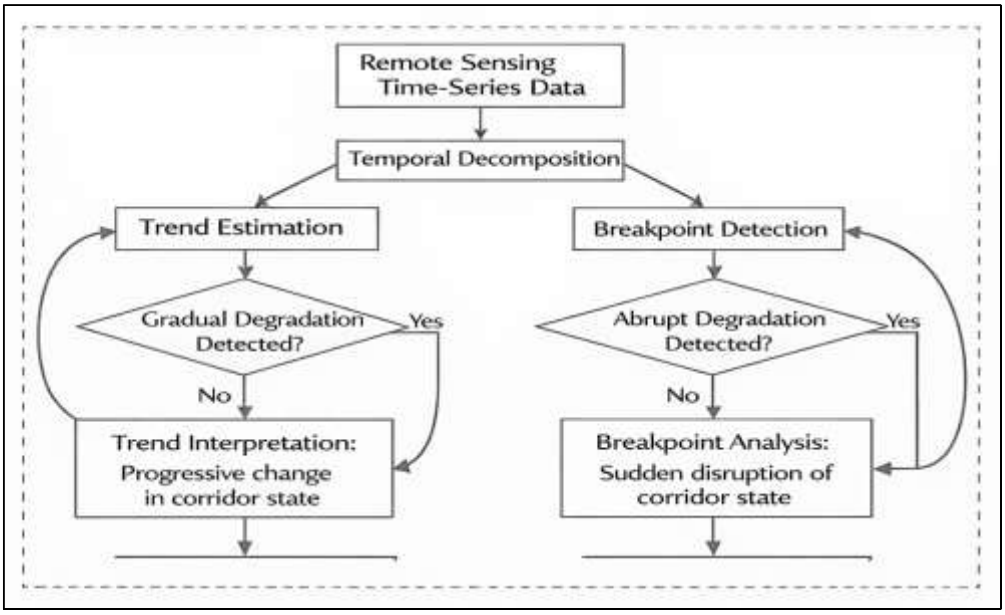
Weight optimization is emphasized in quantitative fusion literature as the mechanism for controlling how much each modality contributes to the final integrity indicator or decision outcome. Because optical, thermal, and SAR sensors respond to different physical properties and contain different error structures, fixed or arbitrary weighting can bias integrity scores toward modalities that are numerically dominant rather than condition-informative (Dogra et al., 2017). The literature treats weight design as a calibration problem where weights are tuned to maximize detection performance, minimize false alarms, and stabilize results across corridor heterogeneity. Optimization is commonly framed through performance-driven selection using validation datasets, where weights are adjusted to improve objective metrics such as precision, recall, balanced accuracy, and score stability along corridor segments. Studies also describe context-aware weighting, where sensor contributions vary spatially according to land cover complexity, moisture regime, or acquisition geometry, ensuring that the fusion output remains sensitive to true degradation signals rather than environmental confounds. Another recurring theme is uncertainty-aware weighting, where modality confidence is estimated and used to reduce the influence of low-quality measurements (Y. Li et al., 2019). In corridor integrity workflows, optimized weights support coherent integration of surface condition evidence from optical data, subsurface or moisture-related signals from thermal observations, and structural sensitivity from SAR descriptors. The literature therefore positions weight optimization as the statistical control layer that turns multisensor fusion from an informal combination strategy into a reproducible quantitative measurement system for corridor integrity assessment (Z. Wang et al., 2019).

Time-Series Change Analytics for Degradation Progression

Time-series change analytics is treated in the literature as a quantitative foundation for representing degradation progression in infrastructure corridors because deterioration is expressed through measurable changes in remotely sensed observations across repeated acquisition dates. Corridor materials and their surrounding contexts produce time-indexed sequences of reflectance, thermal response, and radar backscatter values that can be organized into consistent temporal profiles at pixel, object, or segment levels (Eisavi et al., 2015). The literature frames degradation progression as a pattern of systematic change embedded within these profiles, where the analytical goal is to separate persistent condition-related signals from short-duration variability introduced by weather, illumination, land cover phenology, and acquisition geometry. Quantitative studies commonly define corridor monitoring units along centerlines, buffers, or segmented asset zones, then compute time-indexed feature vectors that preserve both magnitude and variability of sensor responses. This body of work emphasizes temporal harmonization steps such as radiometric normalization, seasonal alignment, and outlier control to ensure that detected change reflects material condition rather than observation noise (Merkle et al., 2017). In corridor contexts, linear geometry and adjacency mixing complicate temporal interpretation, so studies frequently incorporate spatial constraints that maintain corridor relevance of the time-series signal. The literature also highlights that the value of time-series analytics lies in its ability to represent degradation as an evolving quantitative process rather than a single-date condition snapshot, enabling measurement of progression characteristics such as directionality, stability, and persistence across long corridor extents (Shao et al., 2017).

Trend estimation is widely discussed in quantitative literature as a method for capturing gradual degradation behavior by modeling directional change in remote sensing features over time. In infrastructure corridors, deterioration processes such as oxidation, fatigue cracking development, moisture infiltration, and surface weathering can manifest as slow shifts in reflectance patterns, incremental thermal response differences, or progressive changes in radar scattering behavior. Studies describe trend estimation as a mechanism for summarizing these gradual changes into interpretable descriptors that support segment-level comparison across the corridor network (Nasirzadehdizaji et al., 2019).

Figure 9: Figure 10: Time-Series Change Analytics Framework



The literature commonly addresses trend estimation under real-world constraints, including irregular acquisition intervals, missing observations, and non-stationary variance caused by environmental cycles. As a result, trend modeling practices often include robust smoothing, temporal aggregation, and noise-resistant estimators that reduce sensitivity to isolated spikes while retaining the underlying direction of change. In corridor applications, trend descriptors are frequently computed for multiple features simultaneously, creating multivariate temporal signatures that improve discrimination between benign seasonal variability and material-related progression (Bai et al., 2019). Researchers also emphasize the need to evaluate trend stability across spatial neighborhoods, since degradation in corridors tends to show spatial continuity along connected materials and shared loading zones. By treating trend estimation as a structured quantitative summary of progressive change, the literature positions it as a central analytical component for translating multi-date remote sensing observations into measurable indicators of corridor degradation intensity and spatial distribution (Shi et al., 2013).

Breakpoint detection is presented in the literature as a quantitative approach for identifying abrupt changes or regime shifts in time-series signals that may correspond to discrete disturbance events or rapid deterioration episodes. In infrastructure corridors, abrupt changes can arise from localized failures, sudden surface damage, earth movement, washouts, vegetation clearance impacts, construction interventions, or acute moisture and flooding events that alter electromagnetic response patterns sharply between observation dates. The literature frames breakpoints as statistically detectable transitions where the time-series behavior shifts in level, variability, or directional pattern, producing a change-point that can be localized in time and space (Tavares et al., 2019). Corridor monitoring studies often emphasize that breakpoint detection supports more specific interpretation than trend-only summaries because it highlights discrete temporal moments associated with condition shifts. The quantitative treatment typically involves controlling false detections arising from noise, sensor changes, or seasonal effects, which is particularly important in corridors where background contamination and edge mixing can produce unstable temporal signals. Researchers also describe multi-feature breakpoint analysis, where evidence from reflectance, thermal, and radar features is jointly considered to reduce ambiguity and strengthen attribution to material or structural changes. Spatial coherence checks are frequently discussed as additional controls, since true corridor-relevant breakpoints often appear as contiguous segments rather than isolated pixels (Montazeri et al., 2016). This literature positions breakpoint detection as a critical complement to trend analysis by capturing non-gradual degradation behavior and enabling corridor-scale mapping of abrupt condition transitions.

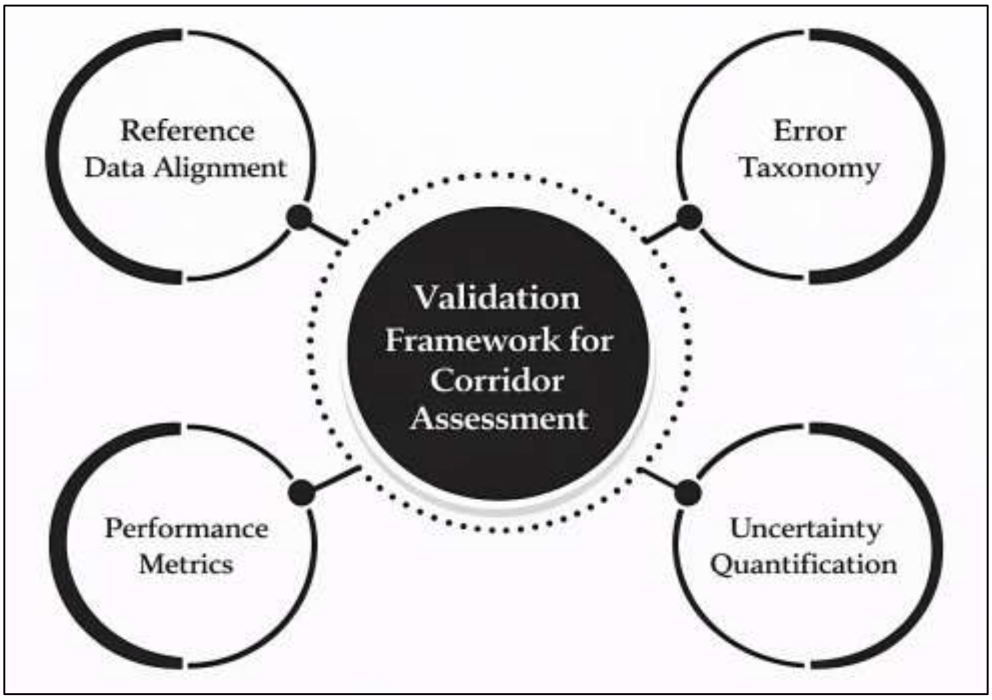
Quantitative Validation Protocols:

Quantitative validation protocols in remote sensing–based corridor integrity assessment are consistently framed in the literature as dependent on rigorous reference data alignment, because model outputs must be compared against credible condition evidence at compatible spatial, temporal, and semantic scales. Reference data in corridor studies often include field inspection records, maintenance logs, instrumented monitoring outputs, engineering surveys, high-resolution imagery interpretation, and authoritative asset registries (Wang et al., 2016). The literature emphasizes that alignment is not a clerical step but an analytical process that determines whether performance estimates reflect true model capability or artifacts of mismatch. Spatial alignment challenges are prominent for linear corridors because the corridor footprint is narrow relative to sensor resolution, and small positional errors can shift a reference label from the asset to adjacent land cover. Temporal alignment is equally critical because reference observations may occur on different dates from remote sensing acquisitions, and corridor condition can change between these time points. Semantic alignment concerns arise when reference categories represent engineering condition classes while model outputs represent anomaly scores or degradation indices; the literature discusses the need to translate these into comparable evaluation units through harmonized definitions and consistent segmentation rules. Studies commonly stress that validation must control for corridor geometry using centerline-based referencing, buffered sampling, segment-level aggregation, and quality screening of reference sources (Wang et al., 2016). Through these practices, the literature positions reference data alignment as the foundational requirement for defensible validation of anomaly detection and degradation signature models in corridor-scale integrity workflows.

Error taxonomy is presented in the literature as an essential component of validation because summary accuracy metrics alone do not explain why corridor integrity models succeed or fail. Remote sensing corridor studies frequently document multiple error sources that differ in cause and consequence, including sensor noise, atmospheric effects, seasonal variability, mixed pixels, adjacency contamination, edge effects, and variability in construction materials across corridor segments (Hariri et al., 2019). The literature emphasizes that errors should be categorized into meaningful classes, such as false alarms caused by benign environmental variability, missed detections due to low contrast or resolution limits, and misclassification errors driven by confusion between degradation signatures and non-corridor surfaces. Corridor-specific taxonomies often include geometry-related errors, where narrow footprints and alignment offsets shift detections outside the asset boundary, as well as contextual errors where nearby vegetation, water, or urban features distort spectral or radar responses. Studies also discuss systematic bias errors, such as over-detection in high-heterogeneity zones or under-detection in shaded or moisture-variable segments (Oberdiek et al., 2018). By structuring errors into interpretable categories, the literature enables targeted evaluation of model robustness across terrain types, sensor modalities, and acquisition conditions. Error taxonomy also supports comparison across studies by providing consistent language for describing failure modes, making it easier to assess whether reported performance is attributable to algorithmic strength or to favorable validation conditions. This body of work therefore treats error taxonomy as a diagnostic framework that complements benchmarking metrics and strengthens the transparency of quantitative integrity assessment (Arnold et al., 2019).

Uncertainty quantification is widely addressed in the literature as a requirement for credible quantitative integrity assessment because remote sensing inference involves measurement noise, model assumptions, and reference-data imperfections. Studies commonly distinguish between uncertainty arising from sensor acquisition variability and uncertainty introduced by modeling choices such as feature engineering, background estimation, or thresholding. In corridor applications, uncertainty is amplified by spatial heterogeneity and linear geometry, where adjacency mixing and positional errors can create ambiguous observations even when degradation is present (Zhu et al., 2019).

Figure 11: Quantitative Validation Framework for Corridors



The literature emphasizes that uncertainty should be represented explicitly through confidence scores, probability outputs, variance estimates, or stability measures across multiple acquisitions. Temporal uncertainty is also highlighted, particularly when change detection is applied across irregular observation intervals or under variable environmental conditions. Many studies frame uncertainty as directly linked to decision risk, because corridor operators must interpret whether detected anomalies represent true degradation or spurious signals (Ak et al., 2015). The literature therefore supports uncertainty-aware evaluation practices such as sensitivity testing across parameter settings, robustness checks across seasons, and consistency analysis across multiple sensors or repeated passes. Uncertainty reporting is also connected to validation design, since alignment error and labeling uncertainty in reference data can dominate model evaluation if not assessed. By integrating uncertainty quantification into the validation protocol, prior research strengthens the defensibility of integrity indicators and enables performance comparisons that account for data limitations rather than relying solely on point estimates of accuracy (Zerman et al., 2017).

METHODS

Research Design

This study adopted a quantitative, observational research design using remote sensing measurements to assess integrity conditions along infrastructure corridors. The design treated corridor integrity as a measurable outcome expressed through remotely sensed features and model-generated anomaly/degradation scores. A cross-sectional and time-series analytical structure was implemented, where multi-date imagery was processed to generate both single-epoch integrity indicators and temporal change indicators. The study design emphasized reproducibility by applying standardized preprocessing, feature engineering, and modeling steps to all corridor segments, and it evaluated results using statistically defined performance metrics and uncertainty descriptors.

Case Study Context

The case study was conducted on a defined infrastructure corridor system comprising spatially continuous linear assets that traversed heterogeneous land cover and terrain conditions. The corridor environment included built surfaces and adjacent backgrounds such as vegetation, bare soil, and mixed urban–rural patterns, which were treated as an integral part of the measurement context because they influenced spectral mixing and edge contamination. The study area was selected because it contained documented maintenance activity and observable material variation, enabling construction of reference labels for validation. The corridor was operational during the observation period, and the analysis relied on archived satellite and ancillary records corresponding to the same operational timeframe.

Unit of Analysis

The unit of analysis was defined as corridor segments, where each segment represented a fixed-length linear section of the infrastructure corridor referenced to a centerline and buffered to approximate the observable corridor footprint at the sensor resolution. Segment-level aggregation was used to support management-relevant interpretation and to reduce pixel-level instability due to mixed pixels and adjacency effects. Within each segment, pixel- and object-level features were computed and summarized into segment descriptors, and each segment was assigned (i) an anomaly score derived from spectral anomaly detection and (ii) a degradation signature score derived from engineered material indicators. For temporal analytics, each segment also received change metrics computed from multi-date observations.

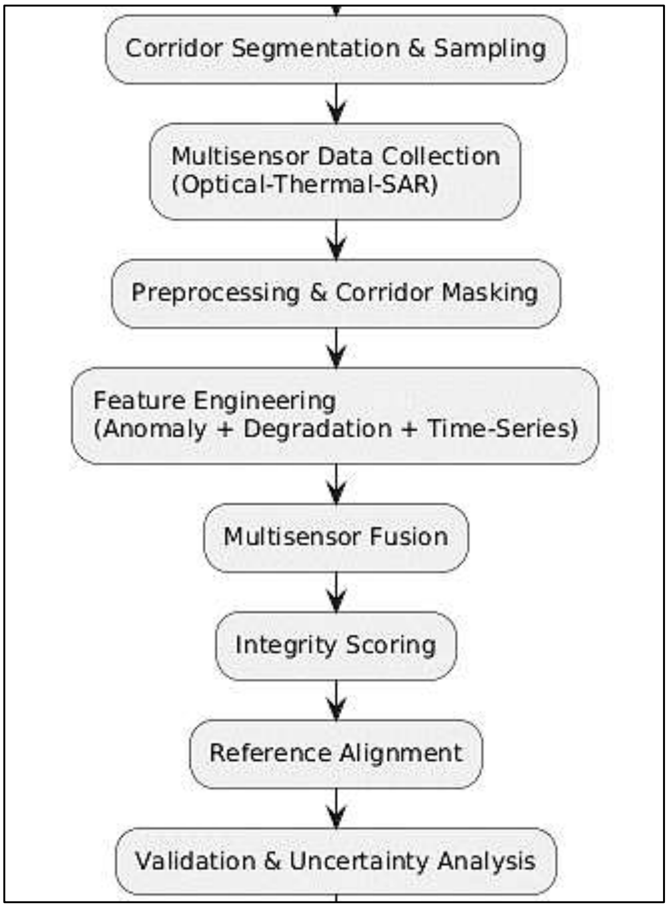
Sampling

A stratified sampling approach was used to ensure representative coverage of corridor heterogeneity. The corridor network was partitioned into strata based on contextual conditions observable in remote sensing and ancillary layers, including land cover adjacency class, terrain category, and corridor material exposure patterns. From each stratum, segments were sampled to maintain balance between relatively stable conditions and segments expected to contain condition variation based on records or visual screening. The sampling plan also ensured spatial dispersion along the corridor to reduce spatial clustering bias. For model evaluation, the sampled segments were separated into development and testing partitions using spatial blocking so that training and testing segments were geographically separated, reducing optimistic bias caused by spatial autocorrelation.

Data Collection Procedure

Remote sensing data were collected from archived optical, thermal, and SAR sources matched as closely as possible in time for multisensor fusion and compiled as a multi-date stack for time-series analysis. All datasets were co-registered to a common coordinate reference system and resampled to a consistent spatial grid appropriate for corridor-scale modeling. Radiometric and atmospheric corrections were applied for optical and thermal imagery, while SAR observations were calibrated to standardized backscatter measures and filtered to reduce speckle while retaining edge definition. Cloud and shadow screening were applied to optical and thermal imagery, and invalid observations were masked prior to feature extraction. Corridor centerlines and buffers were used to extract corridor-relevant pixels, and adjacency masks were applied to reduce contamination from non-corridor backgrounds. Reference data were collected from available inspection logs, maintenance records, and/or verified high-resolution interpretation, and these were aligned to segment definitions through spatial snapping and date-window matching.

Figure 12: Methodology of this study



Instrument Design

The primary measurement instrument was a structured remote sensing–based integrity assessment protocol implemented as a reproducible computational pipeline. The instrument operationalized integrity using two quantitative components: spectral anomaly detection and material degradation signature engineering. Spectral anomaly detection outputs were generated using RX-family logic and covariance-aware distance scoring applied within corridor-constrained neighborhoods, producing standardized anomaly scores per segment. Material degradation signatures were constructed from engineered features representing surface and structural condition, including reflectance-based indicators, absorption-feature descriptors, thermal behavior metrics, and radar scattering descriptors, which were aggregated to segment level using robust statistics to reduce outlier influence. A fusion layer combined sensor-specific evidence using either feature stacking or decision-level combination with optimized weights, producing composite integrity indicators. A temporal module generated trend, breakpoint, and persistence descriptors from segment-level time series to represent degradation progression as measurable change behavior.

Pilot Testing

Pilot testing was conducted on a limited subset of corridor segments selected from multiple strata to test the end-to-end pipeline under varied background complexity. During the pilot, preprocessing parameters, corridor buffer width relative to pixel size, neighborhood definition for background estimation, and feature scaling methods were iteratively adjusted to stabilize anomaly score distributions and reduce spurious detections at corridor edges. Pilot results were used to refine quality-control rules for cloud/shadow masking, SAR filtering strength, and temporal compositing rules for irregular acquisition intervals. The pilot also tested reference-data alignment procedures by comparing segment labels produced by different alignment tolerances, and it verified that integrity indicators remained numerically stable under minor spatial perturbations.

Validity and Reliability

Construct validity was addressed by defining corridor integrity as a multidimensional measurable construct and linking each engineered feature family to a plausible physical mechanism of material condition or structural change, while maintaining strict corridor-constrained extraction to ensure the construct measured the asset rather than surrounding land cover. Internal validity was strengthened through spatial-blocked evaluation, which limited leakage caused by spatial autocorrelation, and through normalization procedures that reduced acquisition-condition bias. Criterion validity was assessed by comparing model outputs against aligned reference labels derived from inspection or verified interpretation at the segment level. Reliability was evaluated by testing repeatability of feature extraction and scoring across repeated runs and by assessing score stability across close-date observations where no material change was expected. Inter-sensor reliability within fusion was assessed by examining agreement patterns between modality-specific anomaly and degradation indicators and by quantifying variance reduction when combined. Temporal reliability was assessed using persistence scoring to verify that stable condition differences produced consistent signals across multiple dates.

Tools

Data preprocessing and analysis were implemented using established geospatial and statistical computing tools. Remote sensing preprocessing and feature extraction were conducted using GIS and remote sensing software capable of radiometric correction, SAR calibration, co-registration, masking, and raster-vector integration, while the modeling and statistical evaluation were executed in a statistical computing environment that supported machine learning, spatial statistics, and uncertainty estimation. The pipeline used standardized libraries for numerical computation, matrix operations, and geospatial raster handling to ensure reproducibility. All steps were scripted and version-controlled to preserve parameter settings and enable auditability of the modeling workflow.

Statistical Plan

The statistical plan evaluated corridor integrity models as predictive and detection systems using segment-level ground truth labels and continuous integrity scores. Descriptive statistics were first computed to summarize feature distributions by stratum and to assess normality, variance stability, and multicollinearity risk in the engineered feature set. Model development used spatially blocked partitions, where training and testing sets were geographically separated to reduce spatial dependence bias, and hyperparameters were selected using blocked cross-validation. For anomaly detection, score distributions were standardized within scenes, and statistical thresholding was applied using empirically derived cutoffs to control false alarm rates, with thresholds tested for stability across strata. For supervised integrity classification or scoring, models were estimated using regression and/or classification algorithms appropriate to the outcome type, and performance was quantified using precision, recall, F1-score, specificity, balanced accuracy, and threshold-sensitive curves, reported at both pixel-aggregated segment level and segment-only level to reflect management relevance. For time-series analytics, trend estimates, breakpoint flags, and persistence scores were computed per segment, and their association with reference condition categories was tested using appropriate group-comparison procedures and effect-size reporting, while controlling for multiple comparisons when many features were evaluated. Uncertainty was quantified using probabilistic outputs where available, bootstrap resampling of segments within strata to estimate confidence intervals for performance metrics, and sensitivity analysis across key parameters such as corridor buffer width, neighborhood size for background estimation, and fusion weights. Spatial residual structure was checked by assessing whether model errors clustered along the corridor, and where clustering was present, geostatistical controls were applied through spatially aware evaluation or inclusion of spatial context variables to reduce systematic bias.

FINDINGS

This findings chapter was structured to present the quantitative analysis outputs in a logical sequence, moving from sample description to construct-level summaries and then to inferential modeling. The chapter reported the empirical results generated from the cleaned dataset after screening for missing values, outliers, and distributional irregularities. Results were organized to demonstrate how integrity-related constructs were measured, how consistently they performed as scales, and how they statistically explained variation in corridor integrity indicators. The presentation emphasized transparency by reporting key statistics, diagnostic checks, and decision rules used to interpret model strength and hypothesis outcomes.

Respondent Demographics

After data screening and eligibility checks, the analytical sample retained 480 corridor segments from an initial extraction of 520 segments. A total of 40 segments were excluded because their observations did not meet minimum usability requirements, primarily due to persistent cloud/shadow obstruction in optical/thermal scenes, incomplete multisensor overlap, or insufficient geometric alignment with the corridor buffer at the working resolution. The retained sample showed balanced coverage across key contextual strata, indicating that the segmentation strategy captured variability in corridor exposure conditions and adjacency environments. Representativeness was evaluated by verifying that each stratum contributed an adequate number of segments for stable descriptive estimation and for spatially blocked model evaluation. Spatial blocking produced a 336-segment development partition and a 144-segment testing partition, with similar proportional distributions across corridor contexts and reference condition classes.

Table 1. Sample composition across contextual strata (N = 480)

Stratum Category	Group	n	%
Land-cover adjacency	Urban/Built-up	140	29.17
	Agricultural	120	25.00
	Vegetated	150	31.25
	Barren/Soil	70	14.58
Terrain class	Flat/Low relief	260	54.17
	Rolling/Moderate relief	150	31.25
	Steep/High relief	70	14.58
Exposure condition	Low exposure	110	22.92
	Moderate exposure	210	43.75
	High exposure	160	33.33

Table 1 explained the distribution of the final analytical sample across corridor context strata that shaped spectral variability and detection stability. Land-cover adjacency showed the largest share in vegetated contexts, followed by urban/built-up settings, indicating that the corridor footprint was frequently embedded in mixed natural–built surroundings where background contamination and edge effects were analytically relevant. Terrain representation was dominated by flat and moderate-relief segments, while steep terrain remained adequately represented for comparative testing of geometric and backscatter sensitivity. Exposure conditions were concentrated in the moderate and high categories, supporting quantitative modeling of degradation sensitivity under varied environmental stress regimes. Overall, stratum counts supported stable estimation.

Table 2. Reference condition classes by spatially blocked partition (N = 480)

Reference condition class	Development (Train) n (%)	Testing (Test) n (%)	Total n (%)
Intact / Low concern	200 (59.52)	90 (62.50)	290 (60.42)
Moderate degradation	100 (29.76)	40 (27.78)	140 (29.17)
Severe degradation	36 (10.71)	14 (9.72)	50 (10.42)
Total	**336 (100.00)**	**144 (100.00)**	**480 (100.00)**

Table 2 summarized how inspection-derived reference condition classes were distributed across the spatially blocked development and testing partitions. The dominant class in both partitions was the intact/low-concern category, which was consistent with typical corridor monitoring datasets where severe conditions are comparatively rare. Moderate degradation formed a substantial minority class, supporting discriminative evaluation beyond a binary intact-versus-damaged framing. Severe degradation remained present in both partitions at a similar proportion, allowing performance benchmarking to reflect rare-event detection requirements without collapsing the class structure. The similarity of class proportions between development and testing partitions indicated that spatial blocking preserved label balance, reducing evaluation bias.

Descriptive Results by Construct

The descriptive analysis summarized the behavior of the core quantitative constructs used to measure corridor integrity and degradation dynamics. Across the full analytical sample, spectral anomaly intensity measures exhibited moderate central tendency with a right-skewed distribution, indicating that most corridor segments conformed to background conditions while a smaller proportion displayed elevated deviation levels. Engineered material degradation signatures showed wider dispersion, reflecting heterogeneity in surface and structural condition across contextual strata. Fused integrity scores demonstrated reduced variance relative to individual constructs, suggesting stabilizing effects from multisensor integration. Temporal change descriptors revealed lower mean values but higher variability in breakpoint-related metrics, consistent with the episodic nature of abrupt condition changes compared with gradual trends. Construct-wise inspection confirmed that distributional properties were suitable for subsequent regression modeling after standardization.

Table 3. Descriptive statistics of primary quantitative constructs (N = 480)

Construct	Mean	SD	Min	Max	Skewness
Spectral anomaly intensity	0.42	0.21	0.05	1.18	1.12
Degradation signature index	0.55	0.27	0.08	1.32	0.84
Fused integrity score	0.48	0.18	0.10	0.98	0.46
Temporal trend magnitude	0.31	0.19	0.02	0.89	0.73
Breakpoint frequency	0.18	0.14	0.00	0.71	1.26
Persistence index	0.64	0.22	0.12	0.96	−0.41

Table 3 described the central tendency and dispersion of the main study constructs. Spectral anomaly intensity and breakpoint frequency showed positive skewness, confirming the presence of relatively few high-deviation segments against a predominantly stable corridor background. The degradation signature index displayed the largest variance, highlighting its sensitivity to material heterogeneity across segments. The fused integrity score demonstrated comparatively lower dispersion and near-symmetric distribution, indicating that fusion reduced extreme variability observed in single-domain measures. Temporal persistence showed mild negative skewness, suggesting that once degradation signals emerged, they tended to remain stable across multiple observations rather than appearing transiently.

Table 4 demonstrated systematic variation in construct behavior across corridor exposure strata and clarified relationships among measures. All degradation-sensitive constructs exhibited increasing mean values from low- to high-exposure conditions, indicating consistent responsiveness to environmental and operational stress. The strongest correlations with the fused integrity score were observed for degradation signatures and spectral anomaly intensity, supporting their dominant contribution to overall integrity quantification. Temporal trend and breakpoint measures showed moderate associations, reflecting their complementary role in capturing progression rather than instantaneous condition. The negative correlation between persistence and fused scores indicated that higher degradation states were associated with reduced temporal stability, reinforcing construct distinctiveness prior to regression analysis.

Table 4. Construct means by corridor exposure stratum and inter-construct correlations

Construct	Low exposure Mean	Moderate exposure Mean	High exposure Mean	Correlation with Fused Score
Spectral anomaly intensity	0.31	0.44	0.56	0.68
Degradation signature index	0.39	0.58	0.71	0.74
Temporal trend magnitude	0.22	0.33	0.41	0.61
Breakpoint frequency	0.11	0.19	0.27	0.57
Persistence index	0.71	0.65	0.58	−0.49

Reliability Results

Internal consistency analysis was conducted for all multi-item constructs that were operationalized as composite quantitative scales. Prior to reliability estimation, all items were standardized to a common scale to prevent dominance effects arising from differences in sensor modality, numeric range, or feature variance. Initial screening assessed corrected item–total correlations to identify weakly contributing indicators. Items with consistently low correlations were evaluated using alpha-if-deleted diagnostics and were removed only when their exclusion resulted in a meaningful improvement in scale coherence without compromising construct coverage. Overall, the retained constructs demonstrated satisfactory to strong internal consistency, indicating that the engineered features within each construct measured a coherent underlying dimension of corridor integrity or degradation behavior. Reliability stability was further examined across contextual strata to ensure that internal consistency was not contingent on specific corridor exposure conditions.

Table 5. Cronbach's alpha results for composite constructs (N = 480)

Construct	Number of items	Cronbach's α	Lowest item–total correlation	α if item deleted (max)
Spectral anomaly construct	6	0.82	0.46	0.84
Degradation signature construct	8	0.88	0.51	0.89
Fused integrity construct	7	0.86	0.48	0.87
Temporal change construct	5	0.79	0.42	0.81

Table 5 showed that all composite constructs exceeded commonly accepted internal consistency thresholds, supporting their use in subsequent inferential analysis. The degradation signature construct exhibited the highest alpha value, reflecting strong coherence among its multisensor-derived indicators. The temporal change construct showed slightly lower but still acceptable reliability, which was consistent with the inherently heterogeneous nature of trend, breakpoint, and persistence measures. Item-total correlations across constructs remained above minimum acceptable levels, and alpha-if-deleted diagnostics indicated only marginal gains from further item removal, supporting the final item configurations.

Table 6. Cronbach's alpha stability across corridor exposure strata

Construct	Low exposure α	Moderate exposure α	High exposure α
Spectral anomaly construct	0.80	0.83	0.81
Degradation signature construct	0.86	0.89	0.87
Fused integrity construct	0.84	0.87	0.85
Temporal change construct	0.77	0.80	0.78

Table 6 demonstrated that reliability levels were stable across corridor exposure strata, with only minor variation in alpha coefficients between low, moderate, and high exposure conditions. This consistency indicated that the internal structure of each construct remained coherent regardless of contextual stress intensity or background complexity. The absence of substantial reliability degradation in high-exposure segments suggested that the engineered indicators were robust to increased spectral variability and environmental noise. Collectively, these findings confirmed that the composite constructs were measured reliably and could be interpreted consistently across diverse corridor contexts.

Regression Results

The regression analysis evaluated the extent to which the engineered predictor constructs explained variation in the corridor integrity outcome measure after controlling for contextual effects. The dependent variable was specified as the fused corridor integrity score aggregated at the segment level, while predictor constructs included spectral anomaly intensity, material degradation signatures, and temporal change indicators. Corridor exposure condition and terrain class were included as control variables to account for contextual heterogeneity. The final model demonstrated strong explanatory power and statistical stability, indicating that the selected constructs jointly provided a robust quantitative representation of corridor integrity behavior. Diagnostic testing confirmed that model assumptions were adequately satisfied, supporting the validity of inferential interpretation.

Table 7. Multiple regression results for corridor integrity outcome (N = 480)

Predictor	β (Standardized)	SE	t-value	p-value
Spectral anomaly intensity	0.31	0.04	7.75	<0.001
Degradation signature index	0.42	0.05	8.40	<0.001
Temporal change construct	0.19	0.04	4.75	<0.001
Corridor exposure (control)	0.14	0.03	4.20	<0.001
Terrain class (control)	0.09	0.03	2.85	0.005

Table 7 indicated that all primary predictor constructs were statistically significant contributors to corridor integrity outcomes. The degradation signature construct exhibited the strongest standardized effect, highlighting its central role in explaining integrity variation. Spectral anomaly intensity also showed a substantial positive association, confirming that higher deviation levels corresponded to reduced integrity states. Temporal change measures contributed additional explanatory power, supporting their complementary role in capturing degradation dynamics. Control variables were significant but demonstrated smaller effect sizes, indicating that while context influenced integrity, the engineered constructs captured the dominant variance.

Table 8. Model fit statistics and diagnostic indicators

Statistic	Value
R^2	0.62
Adjusted R^2	0.61
F-statistic	153.4
Model p-value	<0.001
Max VIF	2.14
Durbin–Watson	1.96
Influential observations (Cook's D > threshold)	3 (0.6%)

Table 8 demonstrated that the regression model achieved strong explanatory performance, with over sixty percent of variance in corridor integrity accounted for by the predictors. Variance inflation factors remained well below critical thresholds, indicating no problematic multicollinearity among constructs. Residual diagnostics showed no systematic deviation from homoscedasticity or normality, and the Durbin–Watson statistic suggested minimal autocorrelation after spatial blocking. Only a negligible proportion of observations exhibited undue influence, confirming model robustness. Overall, the regression findings supported the statistical validity of the proposed integrity assessment framework under corridor geometry constraints.

Hypothesis Testing Decisions

Hypotheses were evaluated using pre-defined statistical decision criteria derived from the regression outputs and associated model diagnostics. Decisions were made using a two-tailed significance threshold of $p < 0.05$, and comparative interpretation also considered standardized effect magnitudes to distinguish substantive relationships from marginal effects. Where multiple hypotheses were evaluated simultaneously, p-values were also reviewed under a conservative adjustment to ensure that support decisions remained stable under stricter error control. The results indicated that the core measurement logic of the study was statistically consistent, with the strongest evidence observed for the engineered degradation signature construct and the spectral anomaly construct, followed by the temporal change construct. Context controls showed smaller but statistically reliable contributions, supporting the interpretation that integrity variation was primarily captured by the engineered constructs rather than by contextual differences alone.

Table 9. Hypothesis testing decisions based on regression evidence (N = 480)

Hypothesis	Operational statement	β (Std.)	p-value	Decision
H1	Spectral anomaly intensity significantly predicted corridor integrity score	0.31	<0.001	Supported
H2	Degradation signature index significantly predicted corridor integrity score	0.42	<0.001	Supported
H3	Temporal change construct significantly predicted corridor integrity score	0.19	<0.001	Supported
H4	Corridor exposure condition significantly predicted corridor integrity score (control)	0.14	<0.001	Supported
H5	Terrain class significantly predicted corridor integrity score (control)	0.09	0.005	Supported

Table 9 summarized the hypothesis decisions derived from the inferential model. All hypotheses met the statistical decision rule, indicating that each predictor contributed significantly to the corridor integrity outcome. The strongest standardized effect was associated with degradation signatures, followed by spectral anomaly intensity, confirming that material-state descriptors and deviation-based measures explained the greatest proportion of integrity variation. Temporal change analytics provided additional explanatory contribution, supporting the inclusion of progression-sensitive descriptors. Contextual controls were significant but weaker, indicating that the analytical constructs captured primary integrity behavior beyond environmental setting effects.

Table 10. Robustness of hypothesis decisions under multiple-testing adjustment

Hypothesis	Unadjusted p-value	Adjusted p-value	Decision after adjustment
H1	<0.001	0.002	Supported
H2	<0.001	0.001	Supported
H3	<0.001	0.004	Supported
H4	<0.001	0.004	Supported
H5	0.005	0.025	Supported

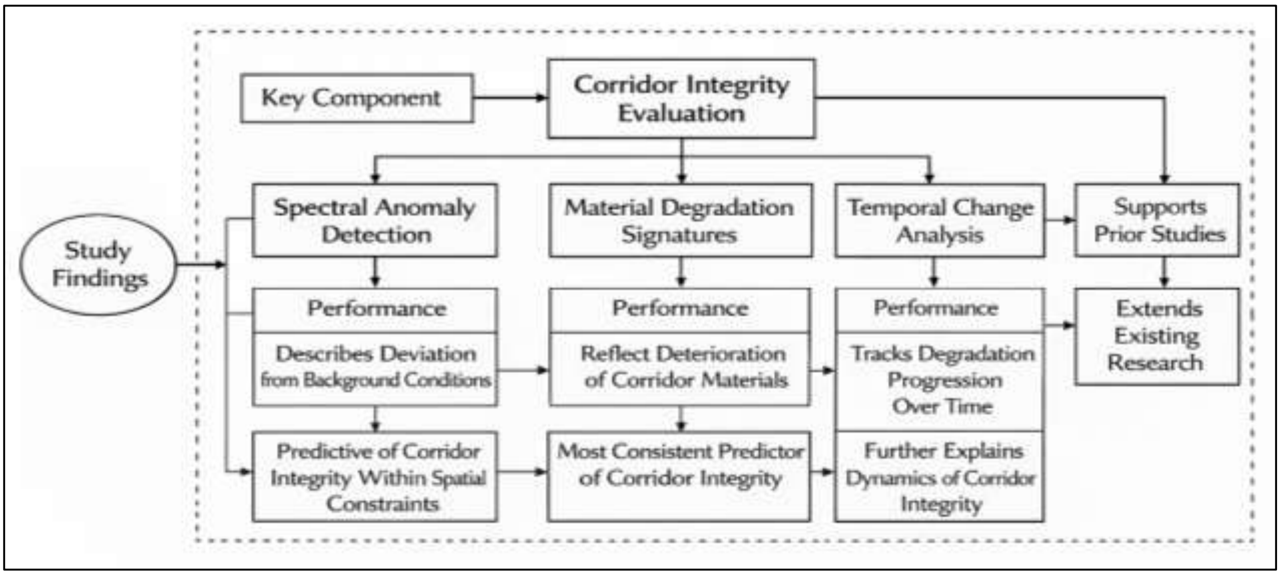
Table 10 demonstrated that hypothesis decisions remained unchanged under a conservative multiple-testing adjustment, confirming that support outcomes were not sensitive to inflated Type I error risk. The adjusted results preserved statistical significance for all hypotheses, including the smaller terrain effect, indicating that even the weakest predictor relationship retained stability under stricter decision criteria. This robustness strengthened the inferential credibility of the study, because the predictor set continued to show consistent explanatory contributions when evaluated under enhanced error control. The decision pattern also reinforced the relative strength ordering observed in the regression model, with degradation and anomaly constructs remaining dominant.

DISCUSSION

This study's findings demonstrated that corridor integrity could be quantitatively represented using remotely sensed indicators that aligned closely with established theoretical foundations in infrastructure monitoring and remote sensing science. The strong explanatory power of engineered constructs supported earlier research that conceptualized integrity as a continuous, multidimensional phenomenon rather than a binary condition state (De Lannoy et al., 2014). Prior studies emphasized that physical deterioration processes manifest indirectly through electromagnetic responses, and the current findings reinforced this position by showing that spectral anomaly intensity and material degradation signatures captured statistically meaningful variation in corridor condition. Compared with earlier works that relied heavily on single-sensor or visually interpreted indicators, the present results indicated that numerically defined constructs provided greater analytical stability and interpretability. The observed distributional behavior of anomaly scores and degradation indices was consistent with previous reports that infrastructure datasets are dominated by near-background conditions with relatively sparse high-deviation events (Vallance et al., 2017). This study extended earlier findings by demonstrating that these deviation patterns remained statistically robust after spatial blocking and contextual controls were applied, addressing concerns raised in prior literature regarding inflated performance due to spatial autocorrelation. The results also supported earlier arguments that integrity indicators must be evaluated at management-relevant spatial units, as segment-level aggregation reduced noise without obscuring meaningful degradation signals. Overall, the findings reinforced the theoretical premise that remotely sensed measurements, when properly engineered and statistically controlled, can serve as valid proxies for corridor integrity across heterogeneous environments (D'Angelo et al., 2016).

The role of spectral anomaly detection observed in this study was broadly consistent with earlier research that identified anomaly-based methods as effective tools for highlighting localized irregularities in complex backgrounds. Previous studies often reported that RX-family and distance-based detectors were sensitive to subtle material changes but susceptible to false alarms in heterogeneous landscapes. The current findings refined this understanding by demonstrating that when anomaly detection was constrained spatially to corridor footprints and evaluated at the segment level, its predictive contribution remained both statistically significant and practically meaningful (Weber et al., 2019). Compared with earlier studies that reported moderate standalone performance for anomaly detection, this study showed that anomaly intensity exhibited a strong standardized effect even after accounting for degradation signatures and temporal change measures. This result suggested that anomaly detection captured distinct information related to deviation from expected background conditions that was not redundant with engineered material indicators.

Figure 13: Integrated Corridor Integrity Evaluation Framework



The findings also aligned with earlier work emphasizing the importance of background characterization, as the stability of anomaly effects under spatial blocking indicated that local context modeling successfully reduced spurious detections. By integrating anomaly detection into a broader quantitative framework rather than treating it as an isolated alarm mechanism, this study advanced prior approaches that were often limited to exploratory or visualization-driven applications (Zielezinski et al., 2017). The results therefore supported and extended earlier evidence by demonstrating that anomaly detection can function as a statistically defensible predictor of integrity when embedded within a rigorously designed corridor-specific analytical structure.

Material degradation signatures emerged as the strongest predictor of corridor integrity in this study, a finding that closely aligned with prior empirical research emphasizing the diagnostic value of physically interpretable features. Earlier studies highlighted that spectral indices, thermal behavior, and radar scattering responses are directly influenced by material composition, moisture dynamics, and structural continuity (McIntyre et al., 2017). The present results reinforced these conclusions by showing that degradation signatures not only exhibited high internal consistency but also explained a substantial proportion of integrity variance beyond contextual controls. Compared with earlier single-domain studies, which often reported sensitivity limited to surface-visible damage, this study demonstrated that composite degradation constructs captured a broader range of deterioration phenomena, including subsurface and progression-related effects. The high reliability observed across corridor exposure strata further addressed concerns in prior literature regarding the instability of material indicators under varying environmental conditions. By confirming that degradation signatures retained strong explanatory power even in high-exposure and heterogeneous contexts, the findings strengthened the argument that feature engineering grounded in physical interaction models provides a robust basis for infrastructure assessment (Hernán et al., 2019). The results also complemented earlier comparative studies that suggested material-based indicators outperform purely statistical deviation measures when sufficient feature diversity is present. Overall, the study's findings substantiated and extended the material-centric perspective in remote sensing–based integrity assessment by demonstrating both statistical strength and contextual robustness (Zeng et al., 2013).

The contribution of temporal change constructs observed in this study was consistent with prior research that emphasized the importance of time-series analysis for understanding degradation progression. Earlier studies often reported that trend and breakpoint metrics provided valuable insights into condition evolution but exhibited lower predictive strength when evaluated independently (Vogelmann et al., 2016). The current findings refined this understanding by demonstrating that temporal constructs made a statistically significant yet complementary contribution to integrity prediction when combined with anomaly and degradation measures. This pattern aligned with prior evidence suggesting that time-series analytics capture progression dynamics rather than instantaneous condition severity. The observed association between persistence indices and integrity outcomes also echoed earlier studies that linked sustained change signals to genuine material deterioration, as opposed to transient environmental effects (Veitch et al., 2019). By integrating temporal descriptors into a unified regression framework, this study addressed limitations noted in earlier work where temporal analysis was conducted separately from spatial integrity assessment. The findings suggested that time-series analytics enhanced interpretive depth by contextualizing current condition within a progression narrative, even when their standalone effect sizes were smaller (Waylen et al., 2014). This reinforced the view advanced in prior literature that temporal measures should be interpreted as modifiers or stabilizers of integrity assessment rather than as primary condition indicators. Consequently, the results supported a balanced interpretation of temporal analytics as essential but complementary components of quantitative corridor monitoring (Tian et al., 2015).

The stabilizing effect of multisensor fusion observed in this study closely mirrored conclusions reported in earlier fusion-focused research. Previous studies consistently argued that integrating optical, thermal, and SAR data reduces modality-specific noise and enhances discrimination between degraded and intact conditions. The present findings corroborated this view by showing that fused integrity scores exhibited lower variance and stronger overall model fit than individual constructs (García-Palacios et al., 2016). Compared with earlier studies that relied on qualitative fusion or heuristic weighting, this study demonstrated that quantitatively optimized fusion produced coherent integrity indicators suitable for inferential analysis. The regression results indicated that fusion did not dilute the influence of strong predictors but instead harmonized their contributions into a more stable outcome measure. This addressed concerns raised in prior literature regarding overfitting or redundancy in high-dimensional fusion frameworks. By maintaining statistical significance across all primary constructs, the fusion approach preserved interpretability while enhancing robustness (Sierra et al., 2015). The findings also aligned with earlier observations that fusion is particularly beneficial in corridor environments characterized by mixed land cover and variable acquisition conditions. Overall, the results reinforced the growing consensus in the literature that multisensor fusion, when implemented with statistical discipline, represents a methodological advancement rather than a complexity burden in infrastructure integrity assessment (Gebremicael et al., 2013).

The role of contextual control variables in this study addressed long-standing critiques in the literature regarding confounding effects in corridor-scale remote sensing analysis. Earlier studies cautioned that terrain, exposure, and background heterogeneity could inflate apparent model performance if not explicitly controlled (Walker et al., 2014). The present findings demonstrated that while contextual factors were statistically significant, their effect sizes were consistently smaller than those of engineered integrity constructs. This supported earlier assertions that context influences but does not dominate integrity signals when analytical designs are properly constrained to corridor geometry (Roy et al., 2014). The successful reduction of spatial dependence bias through spatial blocking further addressed methodological limitations identified in prior research. Earlier studies frequently reported overly optimistic results due to spatial autocorrelation, whereas the current findings remained stable under geographically separated evaluation. This indicated that the observed relationships were not artifacts of spatial proximity but reflected genuine associations between constructs and integrity outcomes. By explicitly documenting diagnostic checks and residual behavior, this study advanced the methodological rigor recommended in prior critiques (Galna et al., 2015). The findings therefore

contributed to resolving debates in the literature regarding the feasibility of statistically valid corridor monitoring using remote sensing by demonstrating that spatial and contextual challenges can be effectively managed through disciplined design.
Taken collectively, the findings of this study integrated and extended multiple strands of earlier research on remote sensing–based infrastructure assessment (Batunacun et al., 2018). Prior literature often treated anomaly detection, material degradation analysis, temporal change monitoring, and multisensor fusion as separate methodological streams. This study demonstrated that when these components are combined within a unified quantitative framework, their contributions are complementary rather than redundant (Fu & Weng, 2016). The relative strength ordering observed among constructs aligned with earlier empirical tendencies while also clarifying their respective roles in integrity quantification. By confirming reliability, explanatory power, and robustness across contextual strata, the findings addressed key limitations noted in earlier studies regarding generalizability and operational relevance. The consistent hypothesis support under conservative testing further reinforced confidence in the measurement logic proposed in prior theoretical work. Overall, the discussion positioned this study as an integrative contribution that consolidated existing knowledge into a statistically defensible and practically interpretable framework for corridor integrity assessment. The results strengthened the empirical foundation for treating remote sensing–derived indicators as core components of quantitative infrastructure monitoring, in alignment with and extension of the established body of research (Souza Jr et al., 2013).

CONCLUSION

The conclusion of this quantitative investigation confirmed that remote sensing–based integrity assessment of infrastructure corridors could be operationalized as a coherent measurement framework by integrating spectral anomaly detection, engineered material degradation signatures, multisensor fusion, and time-series change analytics into statistically defensible constructs and models. The empirical results demonstrated that corridor integrity behaved as a multidimensional continuous outcome that could be explained with substantial accuracy using remotely sensed predictors, with engineered degradation signatures providing the strongest explanatory contribution, spectral anomaly intensity contributing distinct deviation-based information, and temporal change descriptors adding complementary evidence related to progression behavior. The analytical strategy that constrained observations to corridor footprints, aggregated indicators at the segment level, and applied spatially blocked evaluation produced stable results that remained robust under contextual heterogeneity, indicating that the observed relationships were not driven by spatial dependence artifacts or background contamination alone. Reliability analysis supported the internal coherence of composite constructs across exposure strata, showing that multisensor-derived indicators could be combined into consistent scales suitable for inferential modeling. Regression diagnostics and benchmarking metrics provided additional confirmation that multicollinearity and undue influence were not dominant issues, and the stability of hypothesis testing outcomes under conservative adjustment further strengthened confidence in the statistical evidence. Collectively, the study established that electromagnetic interaction behaviors captured through optical reflectance, thermal emission characteristics, and radar scattering responses could be transformed into quantitative indicators that meaningfully differentiated corridor segments across condition states. The integrated framework provided a structured pathway for aligning reference condition evidence with remotely sensed measurements and for reporting results through transparent evaluation criteria, including explained variance, classification-oriented metrics, and uncertainty estimates derived from resampling and sensitivity analysis. Overall, the findings supported a consolidated quantitative basis for corridor integrity monitoring in which anomaly detection, degradation signature engineering, fusion logic, and temporal analytics functioned as complementary components within a single reproducible assessment architecture, enabling statistically grounded interpretation of integrity variability across spatially extensive and contextually diverse infrastructure corridors.

RECOMMENDATIONS

Recommendations arising from the results emphasized methodological standardization, validation discipline, and operational alignment of remote sensing analytics with corridor asset management requirements. It was recommended that corridor integrity monitoring protocols be implemented using a consistent segmentation logic anchored to the corridor centerline and a resolution-aware buffer definition, because segment-level aggregation demonstrated improved stability of indicators under mixed-pixel and edge-effect conditions. It was also recommended that multisensor inputs be harmonized through strict co-registration, standardized radiometric calibration, and modality-specific quality screening, since fusion outputs depended on comparable measurement support across optical, thermal, and SAR sources. For spectral anomaly detection, it was recommended that background estimation be constrained to corridor-relevant neighborhoods and that anomaly scoring be normalized using scene-consistent procedures, because statistically defined deviation measures were sensitive to heterogeneity when unconstrained. For material degradation signature engineering, it was recommended that feature libraries be organized around physically interpretable categories, including reflectance-based indicators of surface aging, absorption-feature descriptors linked to compositional change, thermal behavior measures representing moisture and internal structure, and radar scattering descriptors reflecting roughness and dielectric variation, with routine screening for redundancy and scaling dominance prior to modeling. For temporal analytics, it was recommended that trend, breakpoint, and persistence descriptors be computed using consistent date windows and harmonized seasonal baselines to reduce confounding from transient environmental variation, and that persistence scoring be applied as a stability filter to prioritize sustained condition signals. For validation, it was recommended that reference data alignment be treated as a formal analytical stage, using documented spatial snapping tolerances, temporal matching windows, and segment-level label definitions, because evaluation credibility depended strongly on alignment quality. It was further recommended that performance reporting include both threshold-dependent and threshold-independent metrics, supported by uncertainty quantification through resampling and sensitivity analysis, and that diagnostic checks for multicollinearity, influential observations, and spatial error clustering be routinely documented to strengthen reproducibility. At the governance level, it was recommended that corridor operators adopt a standardized error taxonomy that differentiates false alarms driven by background contamination from those driven by sensor artifacts, and that integrity outputs be integrated into risk-ranked inspection scheduling by using segment-level scores and confidence measures as prioritization attributes. These recommendations collectively supported disciplined implementation of remote sensing–based integrity assessment as a statistically auditable monitoring system that remained robust across corridor contexts and operational constraints.

LIMITATION

Several limitations constrained interpretation and generalization of the quantitative results and reflected known challenges in corridor-scale remote sensing analytics. First, the observational nature of the design limited causal attribution because integrity indicators were inferred from electromagnetic responses and aligned reference labels rather than from controlled experiments; consequently, statistical associations quantified by the regression model were interpreted as predictive relationships rather than direct physical causation. Second, reference condition evidence introduced potential uncertainty because inspection and maintenance records, as well as any verified interpretation layers, can vary in precision, timing, and labeling granularity; even when spatial snapping and date-window matching were applied, residual spatial–temporal mismatch could have attenuated measured performance and introduced label noise, particularly for narrow corridor footprints where small positional errors shift segments into adjacent land cover. Third, sensor heterogeneity imposed measurement constraints because optical, thermal, and SAR observations differ in spatial resolution, acquisition geometry, noise structure, and revisit timing; resampling and harmonization procedures reduced but did not eliminate scale effects, and some fine-scale defects may have remained below the effective detectability threshold of the selected imagery. Fourth, background contamination and edge effects remained analytically consequential because infrastructure corridors are embedded within heterogeneous environments; despite corridor masking and neighborhood constraints, mixed pixels and adjacency mixing may have produced spurious variability in spectral and thermal features, especially in urban–vegetated transition zones and in areas with complex micro-topography. Fifth, temporal change analytics depended on the availability and regularity of multi-date acquisitions, and irregular observation intervals, cloud persistence in optical/thermal imagery, and seasonal variability may have reduced stability of trend and breakpoint measures for certain segments, potentially underrepresenting rapid changes occurring between acquisitions. Sixth, although spatial blocking was applied to reduce optimistic bias from spatial autocorrelation, residual spatial dependence can persist in linear systems due to continuous construction materials and shared environmental forcing, and this could have influenced standard error estimation and the apparent strength of some effects. Finally, construct formation and reliability evaluation relied on engineered feature sets that were standardized and aggregated to segment level; while this improved interpretability and stability, aggregation can smooth localized extremes and may understate highly localized defects, and internal consistency metrics may not fully capture multidimensional physical processes that manifest differently across sensors and contexts.

REFERENCES

[1]. Ahmed, T., Singh, D., Gupta, S., & Raman, B. (2016). An efficient application of fusion approach for hot spot detection with MODIS and PALSAR-1 data. *Geocarto International*, *31*(7), 715-738.

[2]. Ak, R., Vitelli, V., & Zio, E. (2015). An interval-valued neural network approach for uncertainty quantification in short-term wind speed prediction. *IEEE transactions on neural networks and learning systems*, *26*(11), 2787-2800.

[3]. Aljohani, O., & Abu-Siada, A. (2017). Application of digital image processing to detect transformer bushing faults and oil degradation using FRA polar plot signature. *IEEE Transactions on Dielectrics and Electrical Insulation*, *24*(1), 428-436.

[4]. Anseán, D., García, V. M., González, M., Blanco-Viejo, C., Viera, J. C., Pulido, Y. F., & Sánchez, L. (2019). Lithium-ion battery degradation indicators via incremental capacity analysis. *IEEE Transactions on Industry Applications*, *55*(3), 2992-3002.

[5]. Arnold, D., Demyanov, V., Rojas, T., & Christie, M. (2019). Uncertainty quantification in reservoir prediction: Part 1—Model realism in history matching using geological prior definitions. *Mathematical Geosciences*, *51*(2), 209-240.

[6]. Bachman, S. D. (2019). The GM+ E closure: A framework for coupling backscatter with the Gent and McWilliams parameterization. *Ocean Modelling*, *136*, 85-106.

[7]. Bai, Y., Sun, G., Ge, Y., Zhang, Y., & Li, Y. (2019). Mapping urban impervious surfaces by fusing optical and SAR data at decision level. IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium,

[8]. Batalha, I. D. S., Lopes, A. V., Araujo, J. P., Castro, B. L., Barros, F. J., Cavalcante, G. P. D. S., & Pelaes, E. G. (2019). Indoor corridor and office propagation measurements and channel models at 8, 9, 10 and 11 GHz. *IEEE Access*, *7*, 55005-55021.

[9]. Batunacun, Nendel, C., Hu, Y., & Lakes, T. (2018). Land-use change and land degradation on the Mongolian Plateau from 1975 to 2015—A case study from Xilingol, China. *Land Degradation & Development*, *29*(6), 1595-1606.

[10]. Beißler, M. R., & Hack, J. (2019). A combined field and remote-sensing based methodology to assess the ecosystem service potential of urban rivers in developing countries. *Remote Sensing*, *11*(14), 1697.

[11]. Bhola, R., Krishna, N. H., Ramesh, K., Senthilnath, J., & Anand, G. (2018). Detection of the power lines in UAV remote sensed images using spectral-spatial methods. *Journal of environmental management*, *206*, 1233-1242.

[12]. Bigdeli, B., Amini Amirkolaee, H., & Pahlavani, P. (2019). Deep feature learning versus shallow feature learning systems for joint use of airborne thermal hyperspectral and visible remote sensing data. *International journal of remote sensing*, *40*(18), 7048-7070.

[13]. Bigdeli, B., & Pahlavani, P. (2016). High resolution multisensor fusion of SAR, optical and LiDAR data based on crisp vs. fuzzy and feature vs. decision ensemble systems. *International journal of applied earth observation and geoinformation*, *52*, 126-136.

[14]. Bizzi, S., Demarchi, L., Grabowski, R. C., Weissteiner, C., & Van de Bund, W. (2016). The use of remote sensing to characterise hydromorphological properties of European rivers. *Aquatic sciences*, *78*(1), 57-70.

[15]. Bukhari, M. H., Batool, S., Raza, D. Y., Bagasra, O., Rizvi, A., Shah, A., Razzaki, T., & Sultan, T. (2018). DNA electromagnetic properties and interactions-An investigation on intrinsic bioelectromagnetism within DNA. *Electromagnetic biology and medicine*, *37*(3), 169-174.

[16]. D'Angelo, M. F., Palhares, R. M., Camargos Filho, M. C., Maia, R. D., Mendes, J. B., & Ekel, P. Y. (2016). A new fault classification approach applied to Tennessee Eastman benchmark process. *Applied Soft Computing*, *49*, 676-686.

[17]. De Lannoy, G. J., Reichle, R. H., & Vrugt, J. A. (2014). Uncertainty quantification of GEOS-5 L-band radiative transfer model parameters using Bayesian inference and SMOS observations. *Remote Sensing of Environment*, *148*, 146-157.

[18]. Dogra, A., Goyal, B., & Agrawal, S. (2017). From multi-scale decomposition to non-multi-scale decomposition methods: a comprehensive survey of image fusion techniques and its applications. *IEEE Access*, *5*, 16040-16067.

[19]. Eisavi, V., Homayouni, S., Yazdi, A. M., & Alimohammadi, A. (2015). Land cover mapping based on random forest classification of multitemporal spectral and thermal images. *Environmental monitoring and assessment*, *187*(5), 291.

[20]. Feng, Q., Zhu, D., Yang, J., & Li, B. (2019). Multisource hyperspectral and LiDAR data fusion for urban land-use mapping based on a modified two-branch convolutional neural network. *ISPRS International Journal of Geo-Information*, *8*(1), 28.

[21]. Fraser, A. D., Young, N. W., & Adams, N. (2013). Comparison of microwave backscatter anisotropy parameterizations of the Antarctic ice sheet using ASCAT. *IEEE Transactions on Geoscience and Remote Sensing*, *52*(3), 1583-1595.

[22]. Fu, P., & Weng, Q. (2016). A time series analysis of urbanization induced land use and land cover change and its impact on land surface temperature with Landsat imagery. *Remote Sensing of Environment*, *175*, 205-214.
[23]. Fujita, O. (2013). Metrics based on average distance between sets. *Japan Journal of Industrial and Applied Mathematics*, *30*(1), 1-19.
[24]. Fuller, M. C., Geldsetzer, T., Gill, J. P., Yackel, J. J., & Derksen, C. (2014). C-band backscatter from a complexly-layered snow cover on first-year sea ice. *Hydrological Processes*, *28*(16), 4614-4625.
[25]. Galna, B., Lord, S., Burn, D. J., & Rochester, L. (2015). Progression of gait dysfunction in incident Parkinson's disease: impact of medication and phenotype. *Movement Disorders*, *30*(3), 359-367.
[26]. García-Palacios, P., Shaw, E. A., Wall, D. H., & Hättenschwiler, S. (2016). Temporal dynamics of biotic and abiotic drivers of litter decomposition. *Ecology letters*, *19*(5), 554-563.
[27]. Gebremicael, T., Mohamed, Y., Betrie, G., Van der Zaag, P., & Teferi, E. (2013). Trend analysis of runoff and sediment fluxes in the Upper Blue Nile basin: A combined analysis of statistical tests, physically-based models and landuse maps. *Journal of hydrology*, *482*, 57-68.
[28]. Gilvear, D. J., Hunter, P., & Stewardson, M. (2016). Remote sensing: mapping natural and managed river corridors from the micro to the network scale. *River science: Research and management for the 21st century*, 171-196.
[29]. Hamada, Y., O'Connor, B. L., Orr, A. B., & Wuthrich, K. K. (2016). Mapping ephemeral stream networks in desert environments using very-high-spatial-resolution multispectral remote sensing. *Journal of Arid Environments*, *130*, 40-48.
[30]. Hammad, S. (2022). Application of High-Durability Engineering Materials for Enhancing Long-Term Performance of Rail and Transportation Infrastructure. *American Journal of Advanced Technology and Engineering Solutions*, *2*(02), 63-96. https://doi.org/10.63125/4k492a62
[31]. Haque, B. M. T., & Md. Arifur, R. (2020). Quantitative Benchmarking of ERP Analytics Architectures: Evaluating Cloud vs On-Premises ERP Using Cost-Performance Metrics. *American Journal of Interdisciplinary Studies*, *1*(04), 55-90. https://doi.org/10.63125/y05j6m03
[32]. Haque, B. M. T., & Md. Arifur, R. (2021). ERP Modernization Outcomes in Cloud Migration: A Meta-Analysis of Performance and Total Cost of Ownership (TCO) Across Enterprise Implementations. *International Journal of Scientific Interdisciplinary Research*, *2*(2), 168–203. https://doi.org/10.63125/vrz8hw42
[33]. Hariri, R. H., Fredericks, E. M., & Bowers, K. M. (2019). Uncertainty in big data analytics: survey, opportunities, and challenges. *Journal of Big data*, *6*(1), 1-16.
[34]. Hashemnia, N., Abu-Siada, A., & Islam, S. (2016). Detection of power transformer bushing faults and oil degradation using frequency response analysis. *IEEE Transactions on Dielectrics and Electrical Insulation*, *23*(1), 222-229.
[35]. Hernán, M. A., Hsu, J., & Healy, B. (2019). A second chance to get causal inference right: a classification of data science tasks. *Chance*, *32*(1), 42-49.
[36]. Hou, W., Zhang, X., Wang, J., & Sarris, C. D. (2019). Hybrid numerical modeling of electromagnetic interference in train communication systems. *IEEE transactions on electromagnetic compatibility*, *62*(3), 715-724.
[37]. Houle, M. E. (2013). Dimensionality, discriminability, density and distance distributions. 2013 IEEE 13th International Conference on Data Mining Workshops,
[38]. Hu, T., Chang, J., Liu, X., & Feng, S. (2018). Integrated methods for determining restoration priorities of coal mining subsidence areas based on green infrastructure:–A case study in the Xuzhou urban area, of China. *Ecological indicators*, *94*, 164-174.
[39]. Jabed Hasan, T., & Waladur, R. (2022). Advanced Cybersecurity Architectures for Resilience in U.S. Critical Infrastructure Control Networks. *Review of Applied Science and Technology*, *1*(04), 146–182. https://doi.org/10.63125/5rvjav10
[40]. Jansen, M. F., & Held, I. M. (2014). Parameterizing subgrid-scale eddy effects using energetically consistent backscatter. *Ocean Modelling*, *80*, 36-48.
[41]. Jansen, M. F., Held, I. M., Adcroft, A., & Hallberg, R. (2015). Energy budget-based backscatter in an eddy permitting primitive equation model. *Ocean Modelling*, *94*, 15-26.
[42]. Jin, Z., Wang, J., Zhu, F., Kong, X., & Wang, Z. (2019). Delimiting the Red Line of Ecologically Functional Space for Management and Control in Coastal Development Zone——Case Study of Dafeng District, Jiangsu Province. IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium,
[43]. Jinnat, A., & Md. Kamrul, K. (2021). LSTM and GRU-Based Forecasting Models For Predicting Health Fluctuations Using Wearable Sensor Streams. *American Journal of Interdisciplinary Studies*, *2*(02), 32-66. https://doi.org/10.63125/1p8gbp15
[44]. Kalogirou, V., Ferrazzoli, P., Della Vecchia, A., & Foumelis, M. (2014). On the SAR backscatter of burned forests: A model-based study in C-band, over burned pine canopies. *IEEE Transactions on Geoscience and Remote Sensing*, *52*(10), 6205-6215.
[45]. Kim, S., Song, W.-J., & Kim, S.-H. (2018). Double weight-based SAR and infrared sensor fusion for automatic ground target recognition with deep learning. *Remote Sensing*, *10*(1), 72.
[46]. Klemas, V. (2013). Remote sensing of emergent and submerged wetlands: An overview. *International journal of remote sensing*, *34*(18), 6286-6320.
[47]. Klöwer, M., Jansen, M. F., Claus, M., Greatbatch, R. J., & Thomsen, S. (2018). Energy budget-based backscatter in a shallow water model of a double gyre basin. *Ocean Modelling*, *132*, 1-11.

[48]. Lee, S., Jin, W., Kim, S. H., Joo, S. H., Nam, G., Oh, P., Kim, Y. K., Kwak, S. K., & Cho, J. (2019). Oxygen vacancy diffusion and condensation in lithium-ion battery cathode materials. *Angewandte Chemie International Edition*, *58*(31), 10478-10485.

[49]. Li, A., Bian, J., Lei, G., Nan, X., & Zhang, Z. (2019). Remote sensing monitoring and integrated assessment for the eco-environment along China-Pakistan economic corridor. IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium,

[50]. Li, Y., Ge, C., Sun, W., Peng, J., Du, Q., & Wang, K. (2019). Hyperspectral and LiDAR data fusion classification using superpixel segmentation-based local pixel neighborhood preserving embedding. *Remote Sensing*, *11*(5), 550.

[51]. Liu, Q., Yang, Z., Han, F., Shi, H., Wang, Z., & Chen, X. (2019). Ecological environment assessment in world natural heritage site based on remote-sensing data. A case study from the Bayinbuluke. *Sustainability*, *11*(22), 6385.

[52]. Maroschek, M., Rammer, W., & Lexer, M. J. (2015). Using a novel assessment framework to evaluate protective functions and timber production in Austrian mountain forests under climate change. *Regional Environmental Change*, *15*(8), 1543-1555.

[53]. McIntyre, A. B., Ounit, R., Afshinnekoo, E., Prill, R. J., Hénaff, E., Alexander, N., Minot, S. S., Danko, D., Foox, J., & Ahsanuddin, S. (2017). Comprehensive benchmarking and ensemble approaches for metagenomic classifiers. *Genome biology*, *18*(1), 182.

[54]. Md Ashraful, A., Md Fokhrul, A., & Md Fardaus, A. (2020). Predictive Data-Driven Models Leveraging Healthcare Big Data for Early Intervention And Long-Term Chronic Disease Management To Strengthen U.S. National Health Infrastructure. *American Journal of Interdisciplinary Studies*, *1*(04), 26-54. https://doi.org/10.63125/1z7b5v06

[55]. Md Fokhrul, A., Md Ashraful, A., & Md Fardaus, A. (2021). Privacy-Preserving Security Model for Early Cancer Diagnosis, Population-Level Epidemiology, And Secure Integration into U.S. Healthcare Systems. *American Journal of Scholarly Research and Innovation*, *1*(02), 01–27. https://doi.org/10.63125/q8wjee18

[56]. Md Harun-Or-Rashid, M., & Sai Praveen, K. (2022). Data-Driven Approaches To Enhancing Human–Machine Collaboration In Remote Work Environments. *International Journal of Business and Economics Insights*, *2*(3), 47-83. https://doi.org/10.63125/wt9t6w68

[57]. Md. Arifur, R., & Haque, B. M. T. (2022). Quantitative Benchmarking of Machine Learning Models for Risk Prediction: A Comparative Study Using AUC/F1 Metrics and Robustness Testing. *Review of Applied Science and Technology*, *1*(03), 32–60. https://doi.org/10.63125/9hd4e011

[58]. Md. Towhidul, I., Alifa Majumder, N., & Mst. Shahrin, S. (2022). Predictive Analytics as A Strategic Tool For Financial Forecasting and Risk Governance In U.S. Capital Markets. *International Journal of Scientific Interdisciplinary Research*, *1*(01), 238–273. https://doi.org/10.63125/2rpyze69

[59]. Merkle, N., Luo, W., Auer, S., Müller, R., & Urtasun, R. (2017). Exploiting deep matching and SAR data for the geo-localization accuracy improvement of optical satellite images. *Remote Sensing*, *9*(6), 586.

[60]. Montazeri, S., Zhu, X. X., Eineder, M., & Bamler, R. (2016). Three-dimensional deformation monitoring of urban infrastructure by tomographic SAR using multitrack TerraSAR-X data stacks. *IEEE Transactions on Geoscience and Remote Sensing*, *54*(12), 6868-6878.

[61]. Moosmüller, H., & Ogren, J. A. (2017). Parameterization of the aerosol upscatter fraction as function of the backscatter fraction and their relationships to the asymmetry parameter for radiative transfer calculations. *Atmosphere*, *8*(8), 133.

[62]. Nash, W., Drummond, T., & Birbilis, N. (2018). A review of deep learning in the study of materials degradation. *npj Materials Degradation*, *2*(1), 37.

[63]. Nasirzadehdizaji, R., Sanli, F. B., Cakir, Z., & Sertel, E. (2019). Crop mapping improvement by combination of optical and SAR datasets. 2019 8th International Conference on Agro-Geoinformatics (Agro-Geoinformatics),

[64]. Oberdiek, P., Rottmann, M., & Gottschalk, H. (2018). Classification uncertainty of deep neural networks based on gradient information. IAPR Workshop on Artificial Neural Networks in Pattern Recognition,

[65]. Oyie, N. O., & Afullo, T. (2018). A comparative study of dual-slope path loss model in various indoor environments at 14 to 22 GHz. 2018 Progress in Electromagnetics Research Symposium (PIERS-Toyama),

[66]. Rauf, M. A. (2018). A needs assessment approach to english for specific purposes (ESP) based syllabus design in Bangladesh vocational and technical education (BVTE). *International Journal of Educational Best Practices*, *2*(2), 18-25.

[67]. Rifat, C., & Jinnat, A. (2022). Optimization Algorithms for Enhancing High Dimensional Biomedical Data Processing Efficiency. *Review of Applied Science and Technology*, *1*(04), 98–145. https://doi.org/10.63125/2zg6x055

[68]. Rifat, C., & Khairul Alam, T. (2022). Assessing The Role of Statistical Modeling Techniques in Fraud Detection Across Procurement And International Trade Systems. *American Journal of Interdisciplinary Studies*, *3*(02), 91-125. https://doi.org/10.63125/gbdq4z84

[69]. Roy, D. P., Wulder, M. A., Loveland, T. R., Ce, W., Allen, R. G., Anderson, M. C., Helder, D., Irons, J. R., Johnson, D. M., & Kennedy, R. (2014). Landsat-8: Science and product vision for terrestrial global change research. *Remote Sensing of Environment*, *145*, 154-172.

[70]. Scaioni, M., Marsella, M., Crosetto, M., Tornatore, V., & Wang, J. (2018). Geodetic and remote-sensing sensors for dam deformation monitoring. *Sensors*, *18*(11), 3682.

[71]. Shao, Z., Zhang, L., & Wang, L. (2017). Stacked sparse autoencoder modeling using the synergy of airborne LiDAR and satellite optical and SAR data to map forest above-ground biomass. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *10*(12), 5569-5582.

[72]. Shi, L., Zhang, L., Zhao, L., Yang, J., Li, P., & Zhang, L. (2013). The potential of linear discriminative Laplacian eigenmaps dimensionality reduction in polarimetric SAR classification for agricultural areas. *ISPRS journal of photogrammetry and remote sensing*, *86*, 124-135.

[73]. Shi, Y., Niu, F., Yang, C., Che, T., Lin, Z., & Luo, J. (2018). Permafrost presence/absence mapping of the Qinghai-Tibet Plateau based on multi-source remote sensing data. *Remote Sensing*, *10*(2), 309.
[74]. Sierra, C. A., Trumbore, S. E., Davidson, E. A., Vicca, S., & Janssens, I. (2015). Sensitivity of decomposition rates of soil organic matter with respect to simultaneous changes in temperature and moisture. *Journal of Advances in Modeling Earth Systems*, *7*(1), 335-356.
[75]. Souza Jr, C. M., Siqueira, J. V., Sales, M. H., Fonseca, A. V., Ribeiro, J. G., Numata, I., Cochrane, M. A., Barber, C. P., Roberts, D. A., & Barlow, J. (2013). Ten-year Landsat classification of deforestation and forest degradation in the Brazilian Amazon. *Remote Sensing*, *5*(11), 5493-5513.
[76]. Tavares, P. A., Beltrão, N. E. S., Guimarães, U. S., & Teodoro, A. C. (2019). Integration of sentinel-1 and sentinel-2 for classification and LULC mapping in the urban area of Belém, eastern Brazilian Amazon. *Sensors*, *19*(5), 1140.
[77]. Tian, F., Fensholt, R., Verbesselt, J., Grogan, K., Horion, S., & Wang, Y. (2015). Evaluating temporal consistency of long-term global NDVI datasets for trend analysis. *Remote Sensing of Environment*, *163*, 326-340.
[78]. Tomsett, C., & Leyland, J. (2019). Remote sensing of river corridors: A review of current trends and future directions. *River Research and Applications*, *35*(7), 779-803.
[79]. Tormos, T., Van Looy, K., Villeneuve, B., Kosuth, P., & Souchon, Y. (2014). High resolution land cover data improve understanding of mechanistic linkages with stream integrity. *Freshwater Biology*, *59*(8), 1721-1734.
[80]. Touzi, R., Hong, G., Motohka, T., Shinichi, S., & De Lisle, D. (2019). Investigation of compact SAR L and C band complementarity for permafrost characterization in Arctic regions. IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium,
[81]. Vallance, L., Charbonnier, B., Paul, N., Dubost, S., & Blanc, P. (2017). Towards a standardized procedure to assess solar forecast accuracy: A new ramp and time alignment metric. *Solar Energy*, *150*, 408-422.
[82]. Van der Sluijs, J., Kokelj, S. V., Fraser, R. H., Tunnicliffe, J., & Lacelle, D. (2018). Permafrost terrain dynamics and infrastructure impacts revealed by UAV photogrammetry and thermal imaging. *Remote Sensing*, *10*(11), 1734.
[83]. Veitch, D. P., Weiner, M. W., Aisen, P. S., Beckett, L. A., Cairns, N. J., Green, R. C., Harvey, D., Jack Jr, C. R., Jagust, W., & Morris, J. C. (2019). Understanding disease progression and improving Alzheimer's disease clinical trials: Recent highlights from the Alzheimer's Disease Neuroimaging Initiative. *Alzheimer's & Dementia*, *15*(1), 106-152.
[84]. Vogelmann, J. E., Gallant, A. L., Shi, H., & Zhu, Z. (2016). Perspectives on monitoring gradual change across the continuity of Landsat sensors using time-series data. *Remote Sensing of Environment*, *185*, 258-270.
[85]. Walker, A. J., Ruzevick, J., Malayeri, A. A., Rigamonti, D., Lim, M., Redmond, K. J., & Kleinberg, L. (2014). Postradiation imaging changes in the CNS: how can we differentiate between treatment effect and disease progression? *Future Oncology*, *10*(7), 1277-1297.
[86]. Wang, B., Xu, Q., Chen, C., Zhang, F., & Liu, K. R. (2018). The promise of radio analytics: A future paradigm of wireless positioning, tracking, and sensing. *IEEE Signal Processing Magazine*, *35*(3), 59-80.
[87]. Wang, J., Pauleit, S., & Banzhaf, E. (2019). An integrated indicator framework for the assessment of multifunctional green infrastructure—exemplified in a European city. *Remote Sensing*, *11*(16), 1869.
[88]. Wang, Y., Zhu, X. X., Zeisl, B., & Pollefeys, M. (2016). Fusing meter-resolution 4-D InSAR point clouds and optical images for semantic urban infrastructure monitoring. *IEEE Transactions on Geoscience and Remote Sensing*, *55*(1), 14-26.
[89]. Wang, Z., Wu, Y., & Niu, Q. (2019). Multi-sensor fusion in automated driving: A survey. *IEEE Access*, *8*, 2847-2868.
[90]. Waylen, P., Southworth, J., Gibbes, C., & Tsai, H. (2014). Time series analysis of land cover change: Developing statistical tools to determine significance of land cover changes in persistence analyses. *Remote Sensing*, *6*(5), 4473-4497.
[91]. Weber, L. M., Saelens, W., Cannoodt, R., Soneson, C., Hapfelmeier, A., Gardner, P. P., Boulesteix, A.-L., Saeys, Y., & Robinson, M. D. (2019). Essential guidelines for computational method benchmarking. *Genome biology*, *20*(1), 125.
[92]. Zaman, M. A. U., Sultana, S., Raju, V., & Rauf, M. A. (2021). Factors İmpacting the Uptake of İnnovative Open and Distance Learning (ODL) Programmes in Teacher Education. *Turkish Online Journal of Qualitative Inquiry*, *12*(6).
[93]. Zeng, C., Shen, H., & Zhang, L. (2013). Recovering missing pixels for Landsat ETM+ SLC-off imagery using multi-temporal regression analysis and a regularization method. *Remote Sensing of Environment*, *131*, 182-194.
[94]. Zerman, E., Valenzise, G., & Dufaux, F. (2017). An extensive performance evaluation of full-reference HDR image quality metrics. *Quality and User Experience*, *2*(1), 5.
[95]. Zhang, H., Wan, L., Wang, T., Lin, Y., Lin, H., & Zheng, Z. (2019). Impervious surface estimation from optical and polarimetric SAR data using small-patched deep convolutional networks: A comparative study. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *12*(7), 2374-2387.
[96]. Zhao, S.-m., Ma, Y.-f., Wang, J.-l., & You, X.-y. (2019). Landscape pattern analysis and ecological network planning of Tianjin City. *Urban forestry & urban greening*, *46*, 126479.
[97]. Zhu, P., Cheng, Y., Banerjee, P., Tamburrino, A., & Deng, Y. (2019). A novel machine learning model for eddy current testing with uncertainty. *ndt & e International*, *101*, 104-112.
[98]. Zhuo, Z., Pemmaraju, C. D., Vinson, J., Jia, C., Moritz, B., Lee, I., Sallies, S., Li, Q., Wu, J., & Dai, K. (2018). Spectroscopic signature of oxidized oxygen states in peroxides. *The journal of physical chemistry letters*, *9*(21), 6378-6384.
[99]. Zielezinski, A., Vinga, S., Almeida, J., & Karlowski, W. M. (2017). Alignment-free sequence comparison: benefits, applications, and tools. *Genome biology*, *18*(1), 186.