REMOTE SENSING IN MINING: A BRIEF OVERVIEW AND EXAMPLES

TELEDETEKCJA W GÓRNICTWIE: KRÓTKI PRZEGLĄD I PRZYKŁADY

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Abstract

Remote sensing (RS) has become an essential tool in the mining industry, offering efficient methods for data collection, processing and analysis. This paper provides a brief overview of RS applications in mining, focusing on techniques such as spectroscopy, Synthetic Aperture Radar (SAR), Light Detection and Ranging (LiDAR), and thermal imaging. These technologies support activities including mineral exploration, mine planning, operational monitoring, environmental assessment, and reclamation. RS enhances safety and risk management through techniques like InSAR and UAV photogrammetry, while also facilitating the management of mining waste and monitoring environmental impacts on vegetation, soil, water, and air quality. The integration of RS with Geographic Information Systems (GIS) and machine learning (ML) enables advanced predictive modeling and decision-making, driving sustainability and efficiency in mining operations. The paper highlights chosen case studies and emerging trends, underscoring the transformative potential of RS in the mining industry.

Keywords: *remote sensing, mining, mineral exploration, environmental monitoring, reclamation, UAV, hyperspectral imaging, InSAR, GIS, sustainability*

Streszczenie

Teledetekcja stała się kluczowym narzędziem w branży górniczej, oferując efektywne metody zbierania i przetwarzania i analizy danych. Niniejszy artykuł przedstawia krótki przegląd zastosowań teledetekcji w górnictwie, koncentrując się na technikach takich jak spektroskopia, dane radarowe (SAR), systemy LiDAR i dane termalne. Technologie te wspierają działania związane z eksploracją złóż, projektowaniem kopalń, monitoringiem operacyjnym, oceną środowiskową i rekultywacją. Teledetekcja poprawia bezpieczeństwo i zarządzanie ryzykiem dzięki technikom takim jak InSAR i fotogrametria, a także umożliwia lepsze zarządzanie odpadami górniczymi oraz monitorowanie wpływu działalności górniczej na roślinność, glebę, wodę i jakość powietrza. Integracja teledetekcji z systemami informacji geograficznej (GIS) i uczeniem maszynowym umożliwia zaawansowane modelowanie predykcyjne i podejmowanie decyzji, przyczyniając się do zrównoważonego rozwoju i efektywności operacji wydobywczych. Artykuł przytacza wybrane studia przypadków oraz nowe trendy, pokazując transformacyjny potencjał teledetekcji w przemyśle wydobywczym.

Słowa kluczowe*: teledetekcja, górnictwo, eksploracja, monitornig środowiskowy, rekultywacja, UAV, dane hiperspektralne, InSAR, GIS, zrównoważony rozwój*

Introduction

Remote sensing (RS) refers to the collection, processing and analysis of data about an object or area from a distance, primarily using satellites, aircrafts and drones (UAVs) equipped with various sensors. RS has become widely used in many industries and mining is no different. RS techniques allow for efficient, large-scale monitoring, surveys, projects and assessments. In recent years, RS techniques have emerged as powerful tools supporting various aspects of the mining industry, including mineral prospecting and exploration, mine planning, monitoring, environmental impact assessment, and reclamation. RS supports stakeholders, local authorities, environmental entities and mining professionals such as geologists and engineers with a level of detail and precision that was previously unattainable. The use of RS in mining offers numerous advantages, including the ability to cover large areas, access remote locations, and minimization of on-site interventions. It assists decision making on investment level as well as on operational level.

As technology advances, RS techniques become increasingly sophisticated and cost-effective, leading to a broader range of applications in mining. Techniques such as optical satellite imagery, Synthetic Aperture Radar (SAR), Light Detection and Ranging (LiDAR) or thermal imaging, among others, are now routinely used within and around mining industry. Furthermore, the integration of RS data with Geographic Information Systems (GIS) and machine learning techniques has opened new possibilities for data analysis and predictive modeling, enhancing decision-making processes across the mining lifecycle.

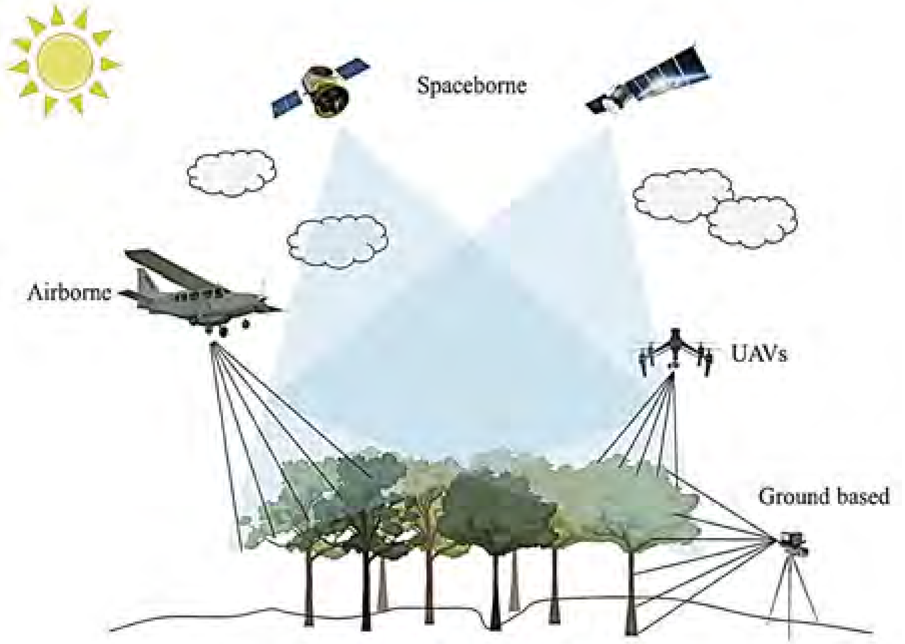


Fig. 1. Remote sensing categories regarding position of sensor (Tian et al., 2023)
Rys. 1. Typy teledetekcji w zależności od położenia sensora (Tian i in., 2023)

This paper aims to provide a general overview, including chosen applications of RS in the mining industry. It aims to explore different techniques available, their specific uses, and the challenges associated with their implementation. By examining current and emerging trends, we highlight the potential of RS to transform mining practices, contributing to a more sustainable and responsible approach to resource extraction.

Remote Sensing and Spectroscopy

There are many definitions of RS, as the term encompasses a wide range of techniques, disciplines, and applications. RS is the science and technology of obtaining information about objects or areas from a distance, typically using sensors on satellites, aircrafts, UAVs, or even ground-based platforms, without direct physical contact (Graham, 1999). RS can be also described more specifically, as the study of the Earth's surface by gathering data and analyzing it to obtain information about a phenomenon or object without direct physical contact (Düzgün & Demirel, 2011).

RS can be classified based on various criteria, including the position of sensor (spaceborne, airborne, ground-based), the measurement equipment (satellite, aircraft, UAV, or ground-based sensors), and the technology used for data acquisition (passive or active sensors). Passive sensors measure reflected light or emmited energy, which comes from sunlight interacting with the Earth's surface or thermal infrared radiation. Active sensors on the other hand emit a microwave signal and measure its return after interacting with Earth's surface (Duzgun & Demirel, 2011).

This review primarily focuses on spaceborne and airborne RS, as these are particularly suited for capturing large-scale areas, such as mining sites, where extensive spatial coverage is required for effective analysis.

One of the key concepts in RS that concerns passive sensors is spectroscopy, which allows the analysis of light (electromagnetic wave) reflected or emitted by objects on the Earth's surface. Spectroscopy enables the clasification and characterisation of materials, such as land cover types, vegetation or rocks, due to specific absorption features that are unique to each material (Clark, 1999).

Specific parts of the electromagnetic spectrum include visible and near infrared (VNIR), shortwave infrared (SWIR), midwave infrared (MWIR) and longwave infrared (LWIR), also reffered as thermal infrared (TIR) (Fig. 2).

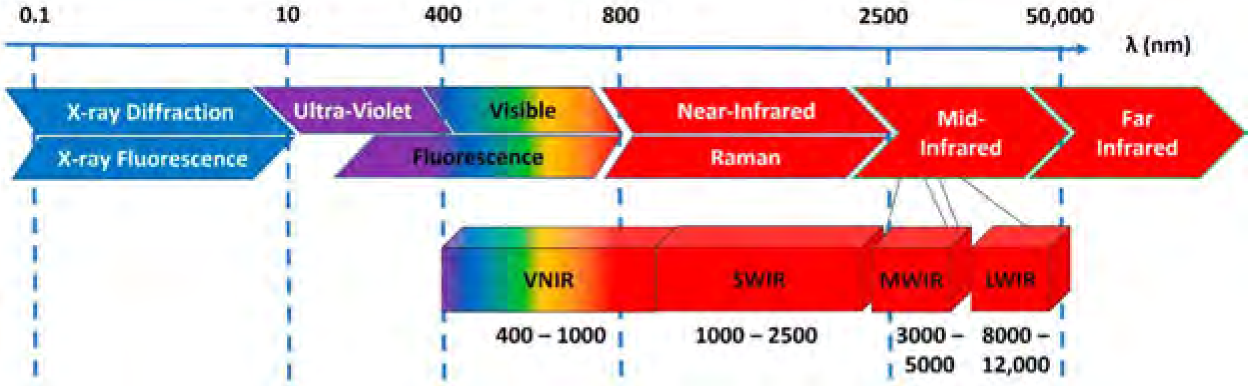


Fig. 2. Parts of electromagnetic spectrum (Jacq et al., 2022)
Rys. 2. Podział widma elektromagnetycznego (Jacq i in., 2022)

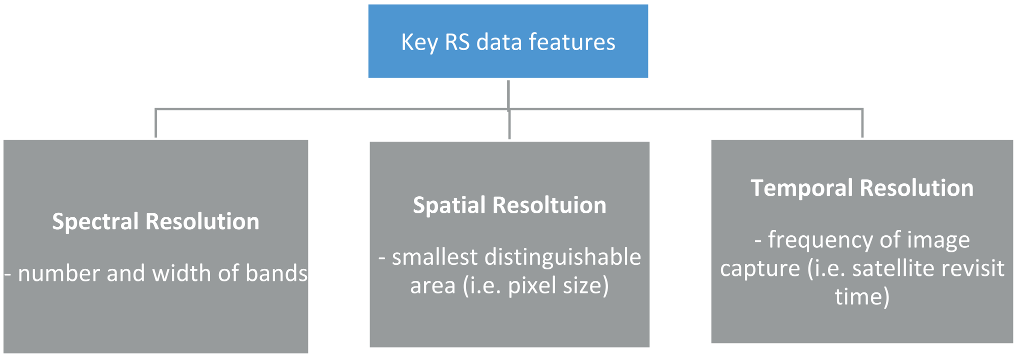


Fig. 3. The main features of remote sensing data
Rys. 3. Podstawowe cechy danych teledetekcyjnych

Characteristic absorption features of materials and objects in different parts of the electromagnetic spectrum enables their identification and characterization.

The most commonly used in spaceborne and airborne sensors are VNIR and SWIR. VNIR which spans wavelengths between approximately 400 to 1000 nm, overlapping with visible light and extending into the near-infrared. This range is useful for vegetation monitoring, sucha as detection of chlorophyll absorption features for instance (Jenal et al., 2019).

SWIR, on the other hand, covers wavelengths from approximately 1000 to 2500 nm. It provides additional spectral information, enabling the detection of water, minerals, and other materials with unique absorption features in this range (Hansen & Malchow, 2008; Jenal et al., 2019).

Combining VNIR and SWIR data enhances the detection of phenomena like vegetation stress or mineral composition, as their unique spectral properties complement each other (Jenal et al., 2019).

Key characteristics of spectral data

There are three main features of RS data: spectral resolution, spatial resolution and temporal resolution described in more detail in Figure 3.

Spectral resolution refers to the quantity and size of specific wavelength intervals, known as bands, within the electromagnetic spectrum that a RS instrument can detect (Jensen, 2014). Spectral sensors typically have spectral resolutions from 4 to more than 200 bands. Sensors with a smaller number of bands (typically ranging from 4 to 15) are referred to as multispectral sensors (MSI). Hyperspectral sensors (HSI), on the other hand, capture a significantly larger number of bands (usually more than 200) with very narrow and contiguous divisions across the electromagnetic spectrum, hence they enable to capture a greater number of characteristic absorbtion features of investigated areas or materials (Duzgun & Demirel, 2011). Figure 4 briefly explains the difference between MSI and HSI data. The spectral resolution is important for the type of surveys to be carried out, for example, when calculating RS indices such as vegetation indices (NDVi, SAVI, etc.), water presence (NDWI), MSI data is sufficient. Sometimes, however,

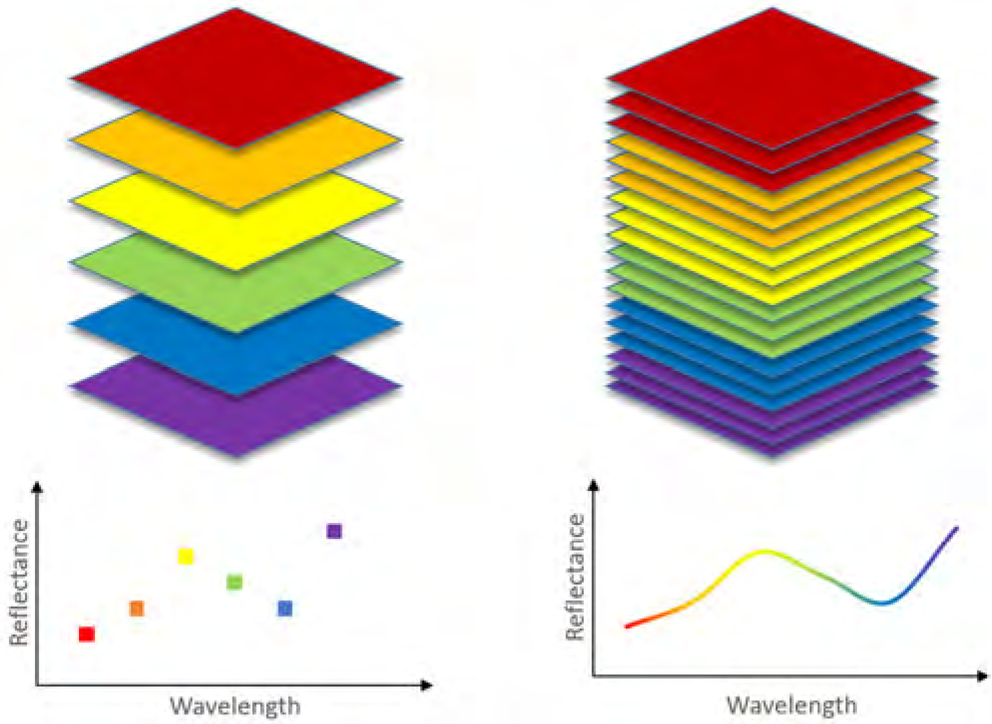


Fig. 4. General comparison between multispectral (left) and hyperspectral (right) data. Number of distinguishable spectral features on HSI data is significantly greater
Rys. 4. Ogólne porównanie danych multispektralnych (po lewej) i hiperspektralnych (po prawej). Liczba rozróżnialnych cech spektralnych na danych HSI jest znacząco większa

when surveys are carried out to map a specific mineral in mineral prospecting, or to detect a specific gas, amnong other, only the use of HSI data is sufficient.

Another term associated with spectral resolution is spectral range of a sensor, that simply represents the range of the electromagnetic spectrum that given sensor collects data i.e. VNIR+SWIR, or 400-2500 nm.

Spatial resolution measures the smallest angular or linear distance between two objects that a RS system can distinguish (Jensen, 2014). In spectral data it refers basically to the size of pixel. In the context of spatial RS, different spatial resolutions are used for different applications, depending on the detail requirements and the size of the observation area. Low-resolution (pixel size over 30 m) is suitable for large-scale analysis, such as tracking of regional scale trends, covering vast areas with limited detail. Medium-resolution (5-30 m pixel size) enables more detailed investigation or monitoring such as land cover mapping. High-resolution (pixel size below 5 m) and very high-resolution (VHR) data is necessary for precision tasks, and local scale analyses such as evaluating urban infrastructure or monitoring individual plants, supporting environmental protection, resource management, and urban planning efforts (https://eos.com/blog/spatial-resolution/).

Tab. 1. Chosen widely-applied satellite data characteristics
Tab. 1. Wybrane charakterystyki powszechnie stosowanych danych satelitarnych

Data provider*	Data type	Spectral range [nm]	Spectral resolution [nm]	Spatial resolution [m]	Temporal resolution [days]
PRISMA	HSI	400 - 2500	11 - 13	30	7
EnMAP	HSI	420 - 2450	6.5 - 10	30	4
EMIT	HSI	381 - 2493	7.4	60	1
Wyvern	HSI	445 - 880	13	5.3	2
Pixxel	HSI	470 - 900	3.5	5	1-4
AVIRIS**	HSI	360 - 2,500	9.5	5-20	airborne
ASTER	MSI	520 - 11650	60 - 700	15-90	archival
Sentinel-2	MSI	440 - 2200	15 - 175	10-60	10
Landsat 8-9	MSI	435 - 12510	16 - 1010	15-100	8
RADARSAT	Radar	n.a.	n.a.	8-100	24
TerraSAR-X	Radar	n.a.	n.a.	3	11
ICEYE	Radar	n.a.	n.a.	0.25-15	<1

*to simplify, we use commonly used names of either the provider, satellite constellation, satellite, mission or sensor. **airborne sensor installed on aircraft

Temporal resolution in a RS system typically refers to the spaceborne data and the frequency at which the sensor captures images of a specific area.

Table 1 presents typical data characteristics of popular open-acces and commercial satellite data providers.

Remote Sensing in Mining

RS adds significant value across all phases of the mining lifecycle, from mineral prospecting to mine reclamation. It equips geologists, field surveyors, environmental engineers and other specialists with critical data to produce outputs that enhance decision-making and operational efficiency. There are multiple aspects that RS data supports, for instance, it supports exploration in remote areas, help to detect outcropping rock layers. It allows to monitor vegetation. During operations, it allows tracking ground deformations, monitoring slope stability and assessing large-scale stockpile volumes, among others. Additionally, satellite data support monitoring of mining reclamation, including vegetation, soil and water condition monitoring (Borotkanych, 2024).

Table 2 presents main categiores of RS data utilization in mining.

An additional categories of RS data utilization related to mining, but outside the mining lifecycle are:

- detection of illegal/ artisanal mining sites,
- due-dilligence on mining assets and projects.

Based on literature review, in the following sections, we present selected examples of RS data utilization in mining in the categories shown in Table 2.

Mineral prospecting and exploration

RS in mineral prospecting and exploration focuses on mapping lithological units and minerals, as well as faults and other lineaments aiding in identifying ore deposits. Unlike field surveys, RS is a more efficient, cost-effective method for gathering data, especially in hard-to-reach, rugged, or mountainous areas, common in arid and semi-arid regions (Girija & Mayappan, 2019).

Low and medium-resolution satellite data is usually used in the industry at the initial stages of prospecting and exploration for projects such as regional-scale targeting. It is usually combined with field validation and sampling. It can be also combined with other geological datasets for mineral prospectivity mapping (MPM) tasks. Successively high-

Tab. 2. Categories of remote sensing data utilization in mining
Tab. 2. Kategorie wykorzystania danych teledetekcyjnych w górnictwie

Usage category	**Keywords**
Mineral prospecting and exploration	*mineral mapping, alteration mapping, lithological mapping, outcrop detection, lineament detection*
Mine design / Land use planning	*land cover mapping, digital elevation model (DEM), land use classification*
Mining operation planning	*orthophotomaps, digital surface/terrain models (DSM/DTM), flow accumulation modeling, UAV photogrammetry, resource management, change detection*
Operational safety and risk management	*slope stability, displacement monitoring, Small Baseline Subset (SBAS), Interferometric Synthetic Aperture Radar (InSAR), conveyor belt monitoring*
Managment of mining waste	*contamination monitoring, TSF monitoring, environmental risk assessment*
Environmental assesment and monitoring	*vegetation condition indices (NDVI, WDI, VII), soil quality, water contamination, air quality monitoring, acid mine drainage*
Reclamation	*vegetation indices soil moisture, vegetation cover, soil quality assessment, landscape planning, reclamation success indices*

resolution satellite data and UAV data are utilized for local scale (deposit scale) exploration projects, to optimize geophysical campaigns and drillings.

For instance, in the Savitri River Basin, India the archival data from the Hyperion EO-1 mission enabled the identification of high-grade bauxite deposits across extensive areas. Utilizing spectral properties allowed for effective delineation of bauxite-rich regions, which would otherwise require extensive field sampling and geochemical analysis (Bedini, 2017).

Another interesting example is a case study at the Siilinjärvi apatite mine in Finland, where Unmanned Aerial Systems (UAS) were employed for geological and geophysical mapping of a carbonatite-hosting outcrop. This study utilized drones equipped with multispectral and hyperspectral cameras, along with magnetic sensors, to collect high-resolution data that allowed for precise lithological differentiation and mineral identification. By integrating multiple UAS sensors, the researchers created a comprehensive digital model of the outcrop, which included both surface and subsurface features. The hyperspectral data facilitated the discrimination of apatite-rich lithologies from waste rock, such as feldspar-pegmatite and syenitic fenite, while the magnetic data provided insight into the depth and orientation of ore-bearing carbonatite-glimmerite bodies. The study demonstrated that UAS-based mapping can improve traditional mineral exploration workflows by delivering accurate, data-driven geological interpretations in areas that are often difficult to access. The rapid UAS survey approach not only reduced the time and cost of data collection but also minimized field intervention by avoiding intrusive ground-based methods, showcasing the potential of UAS as a valuable tool for safer and more efficient resource exploration in the mining industry (Jackisch et al., 2020).

Another chosen example is a study conducted in the Central Iranian Terrane (CIT) that used multi-sensor satellite imagery from Landsat-8, Sentinel-2, ASTER, and WorldView-3 to explore carbonate-hosted Pb-Zn mineralization in the Kashmar-Kerman Tectonic Zone (KKTZ). The complex geological settings of this area, marked by extensive carbonate platforms and tectonic features, made traditional exploration challenging and costly. Researchers applied band ratio and Principal Component Analysis (PCA) techniques to identify hydrothermal alteration minerals, which are typically associated with Pb-Zn deposits, and used fuzzy logic modeling to combine these findings into mineral prospectivity maps (MPMs). The study mapped various minerals related to hydrothermal alteration, including iron oxides, hydroxyl-bearing minerals, and carbonates, by leveraging specific spectral bands in VNIR and SWIR regions from each satellite. This approach provided detailed information about the spatial distribution of potential ore mineralization. The findings were validated through field campaign and laboratory analyses, which confirmed the presence of alteration zones and highly prospective Pb-Zn mineralization sites (Sekandar et al, 2020)

Mine design / Land use planning

The use of RS data, such as Sentinel-2 has significantly advanced modern approaches to mine design and land use planning around mining sites. With 5-day revisit time and 10 m spatial resolution, Sentinel-2 provides precise land cover information, which aids in analyzing areas planned for mining projects (Phiri et al., 2020).

In the context of mine design, RS enables the identification of ranges and extents for mining investments, which is critical for evaluating locations in relation to existing infrastructure and high-value natural areas (Liping et al., 2018).

Digital Elevation Models (DEMs) and Digital Surface Models (DSMs) created with the use of RS are widely used by engineers at mine design projects. Additionally, it informs spatial planning around mines to promote a balance between economic interests and environmental conservation (Phiri et al., 2020; Liping et al., 2018).

Drones also facilitate flow accumulation modeling (FAM), which helps to identify water flow paths and erosion-prone areas. This capability supports the planning of drainage infrastructure and reduces environmental risks. Furthermore, drones are valuable for monitoring waste heaps and ensuring that extraction boundaries are respected; for example, unauthorized extraction was detected in the Pontils quarry using UAS systems.

Safety and risk management

UAVs are proved to be extremely useful for monitoring belt conveyor systems in mining. With high-resolution cameras and sensors, they can detect problems like roller wearing or misalignments quickly and efficiently. Analyzes with thermal sensors allow to monitor the risk of ignition. Ribeiro et al. (2019) highlight how combining UAV with smart route planning and well-placed charging stations makes it easier to cover even the longest conveyor systems. This means fewer people are needed to be sent into risky areas, and maintenance teams get the information they need faster to keep operations running smoothly (Ribeiro et al., 2019).

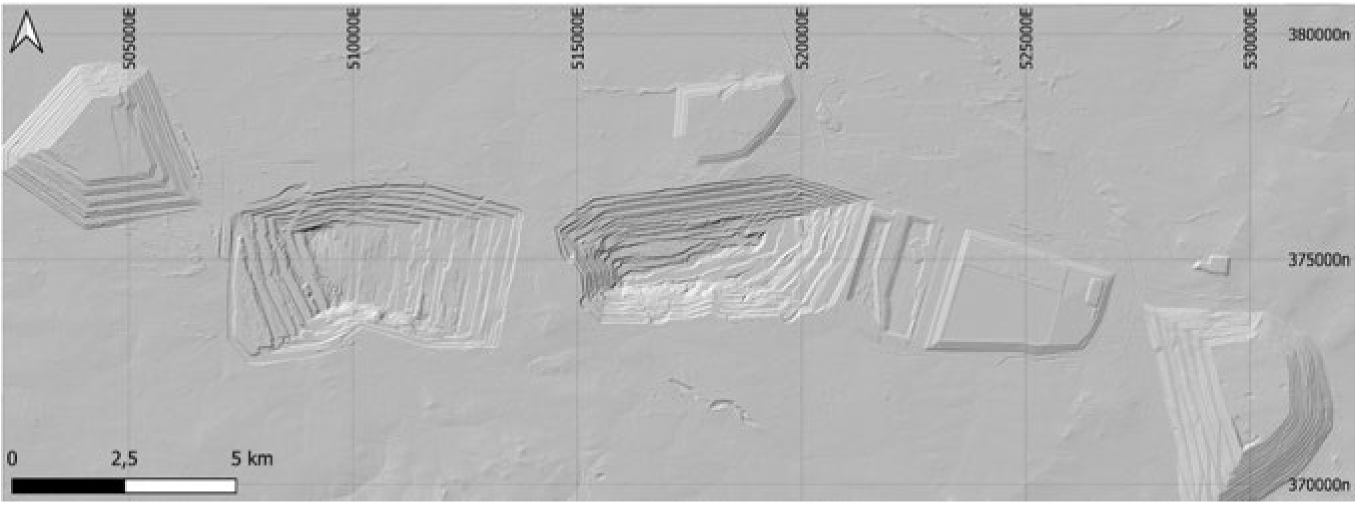


Fig. 5. Visualisation of DEM data on mining area of Belchatow Lignite Mine
Rys. 5. Wizualizacja danych DEM dla obszaru górniczego Kopalni Węgla Brunatnego Bełchatów

Mining operational planning & monitoring

In mining, the use of orthophoto maps and DEMs is essential for effective operational planning and monitoring. DEMs derived from satellite and airborne data are particularly valuable for large-scale analyses (Fig. 5), such as terrain modeling and identifying potential hazards like subsidence or erosion. For more detailed assessments, drone-based DEMs provide high-resolution insights into areas, enabling precise planning and resource management. Up-to-date DEMs are usually the input for mining production simulation software such as Haulsim (Maksymowicz, 2020).

An interesting example is outlined in the study by Carabassa et al. (2020), where using Differential Models (DMd) and the M3C2 method (Multiscale Model to Model Cloud Comparison) allowed for tracking changes in volume and material movement over time, demonstrated in the Falconera quarry.

Another interesting example is presented by Nikolakopoulos et al. (2015) emphasizes the use of UAV photogrammetry combined with GPS measurements, supporting mining operation planning in quarries. Drones equipped with high-resolution cameras allowed for the creation of accurate orthophotos and DSMs essential for detailed topographic mapping. This approach provided a 3D view of the quarry with centimeter-level accuracy, enabling precise volume calculations and terrain analysis. The study demonstrated that repeated surveys using the UAV-GPS combination can effectively monitor changes in material volumes and assess the progress of mining operations over time. The data collected allows for detailed mapping of excavation areas and supports planning by identifying how the exploitation will progress.

Another important aspect is the stability of dumping grounds and heaps which is critical, particularly in large open-pit mines. In the Xudonggou dump of the Anqian iron mine, a combination of RS techniques was utilized to monitor and assess stability, focusing on potential landslide hazards. The study integrated Small Baseline Subset (SBAS) analysis to map displacement patterns over time, supplemented by Infrared Thermography (IRT) to detect water-bearing layers that could contribute to instability (Wei et al., 2018).

In addition to ground-based RS monitoring tools like SBAS and IRT, satellite interferometry offers another layer of precision for observing large-scale surface deformations. Interferometric Synthetic Aperture Radar (InSAR) is particularly valuable due to its ability to detect millimeter-scale displacements over time, as demonstrated in a case study from a copper open-pit mine. This technique leverages radar signals from satellite missions, such as the Sentinel-1, to detect and monitor ground deformation with millimeter accuracy. By observing changes in ground displacement over time, InSAR can serve as an early warning system for slope failures, enhancing safety protocols and aiding in decision-making processes. With its six-day revisiting interval and high spatial resolution, Sentinel-1 allowed for detailed monitoring of surface deformations in the mine. The short revisiting period, coupled with a dense array of measurement points, enabled the identification of unstable areas and the detection of accelerating displacement trends, which are often precursors to slope failure. This forecasting capability is crucial in maintaining operational safety and minimizing economic losses (Intrieri et al., 2019).

While satellite technologies like InSAR excel in monitoring large open-pit mines with wide-area coverage, remotely piloted aircraft systems (RPAS) provide a solution for challenging terrains and more localized assessments. RPAS technology is gaining traction, particularly for minimizing risks to personnel and enhancing safety on mining sites. A notable example of the effective application of this technology is a study conducted in a closed marble quarry in the Apuan Alps, Italy, where RPAS were utilized to perform detailed structural analysis and risk assessment in preparation for the potential reopening of the mining site. Traditional geological methods would have been challenging or even impossible to implement due to the steep terrain and limited accessibility of certain sections of the quarry. By leveraging RPAS, researchers created an accurate three-dimensional model of the terrain, allowing for the identification of large rock blocks with potential instability. Data gathered through photogrammetry, specifically using structure-from-motion (SfM) techniques, enabled a detailed characterization of discontinuity patterns and geomechanical conditions. The identified rock blocks, which may pose hazards to future mining operations, underwent further stability analysis. The study findings indicated that the presence of rock bridges could significantly affect the stability of these blocks, underscoring the importance of monitoring this area as part of risk management in the context of planned mining activities (Salvini et al., 2017).

Managment of mining waste

Effective management of mining waste is essential for minimizing environmental contamination and safeguarding public health. Mining activities generate large amounts of waste materials, often containing toxic elements that can leach into surrounding soil and water, posing long-term risks. RS has emerged as a valuable tool in identifying, monitoring, and assessing these waste sites, especially in regions with limited accessibility. By using advanced imaging and classification techniques, stakeholders can prioritize remediation efforts and implement strategies to mitigate the adverse effects of mining residues on ecosystems and communities.

In the El Triunfo region of Baja California Sur, Mexico, historical mining activities have left behind substantial waste containing high levels of heavy metals such as arsenic, cadmium, copper, lead, and antimony. These residues pose significant environmental and health risks due to their potential for erosion and dispersal by wind and water. Utilizing RS techniques combined with machine learning (ML), specifically supervised classification with the maximum likelihood algorithm on high-resolution satellite imagery, researchers have effectively identified and georeferenced 32 sites of mining waste, of which 26 were confirmed through field verification. The study demonstrated that RS is a powerful tool for mapping and managing mining waste in semi-arid environments, offering a cost-effective method to monitor and assess contamination in regions with challenging accessibility. The identified mining waste sites consisted of loose, fine-grained materials that are highly susceptible to weathering and mobilization, which exacerbate the spread of contaminants (Ahumada-Mexía et al., 2021).

Regarding mining waste, RS techniques are playing an important role in monitoring tailings storage facilities (TSFs). The use of satellite data, drones and terrestrial measurement systems enables regular, precise and remote collection of information on the technical condition of infrastructure and their impact on the environment. It is possible to analyze land displacements, detect presence of cracks or pipeline leakages. In addition, MSI and HSI data enable the assessment of water quality in waterbodies and neighboring ecosystems. A comprehensive spaceborne monitoring has been implemented, among others, at one of the large TSFs in Mexico (Schmidt et al., 2015).

Environmental assesment and monitoring

Mining activities significantly impact the environment, leading to land cover changes, soil degradation, water contamination, air quality decline, and loss of biodiversity, especially in highly diverse areas such as the Amazon (Nascimento et al., 2020; Rudke et al., 2020). RS is increasingly used to monitor these changes in near real-time, providing precise data for impact analysis and mitigation assessment. By employing multispectral and hyperspectral imaging, remote sensing facilitates environmental monitoring, covering aspects such as vegetation health, soil quality, water quality, and atmospheric pollution, which are crucial for comprehensive environmental assessments (Song et al., 2020).

Vegetation health in mining areas reflects overall environmental conditions, as plants are directly exposed to pollution, including heavy metals and particulate matter. Studies conducted in the Dexing copper mine in China and the Mount Lyell mining area in Australia have shown that hyperspectral vegetation indices, such as the Vegetation

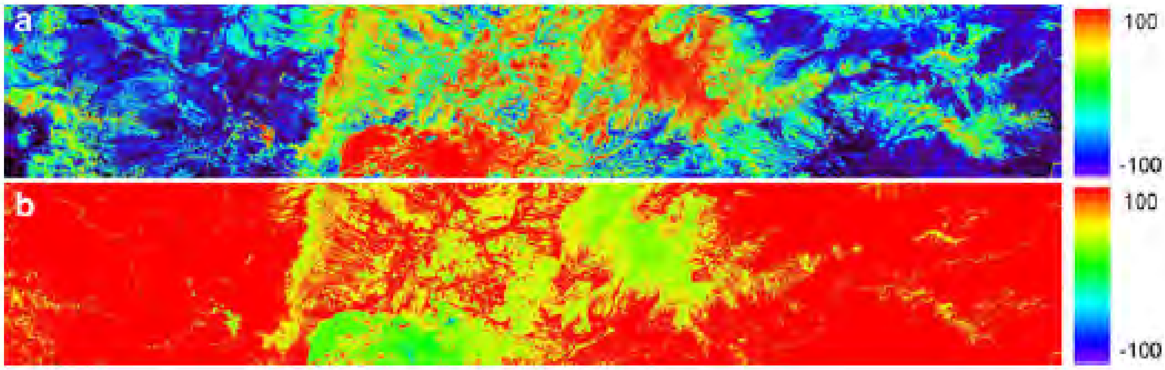


Fig. 6. Comparison in the form of spatial imaging for two remote sensing indicators VII (a) and NDVI (b). It can be clearly seen that the accuracy of vegetation growth is higher for VII (Zhang et al., 2011)

Rys. 6. Porównanie w formie obrazowania przestrzennego dla dwóch wskaźników teledetekcyjnych VII (a) i NDVI (b). Wyraźnie widać, że dokładność oceny wzrostu roślinności jest wyższa dla wskaźnika VII (Zhang i in., 2011)

Inferiority Index (VII) and the Water Disrelated Index (WDI), are more accurate in detecting vegetation stress than traditional indices like Normalized Difference Vegetation Index (NDVI) (Fig. 6) (Zhang et al., 2011). The VII is particularly sensitive to changes in vegetation health, making it a valuable tool for identifying areas under environmental stress from mining activities. Additionally, WDI can detect vegetation affected by metal pollutants, that are especially harmful to plants (Bing et al., 2011).

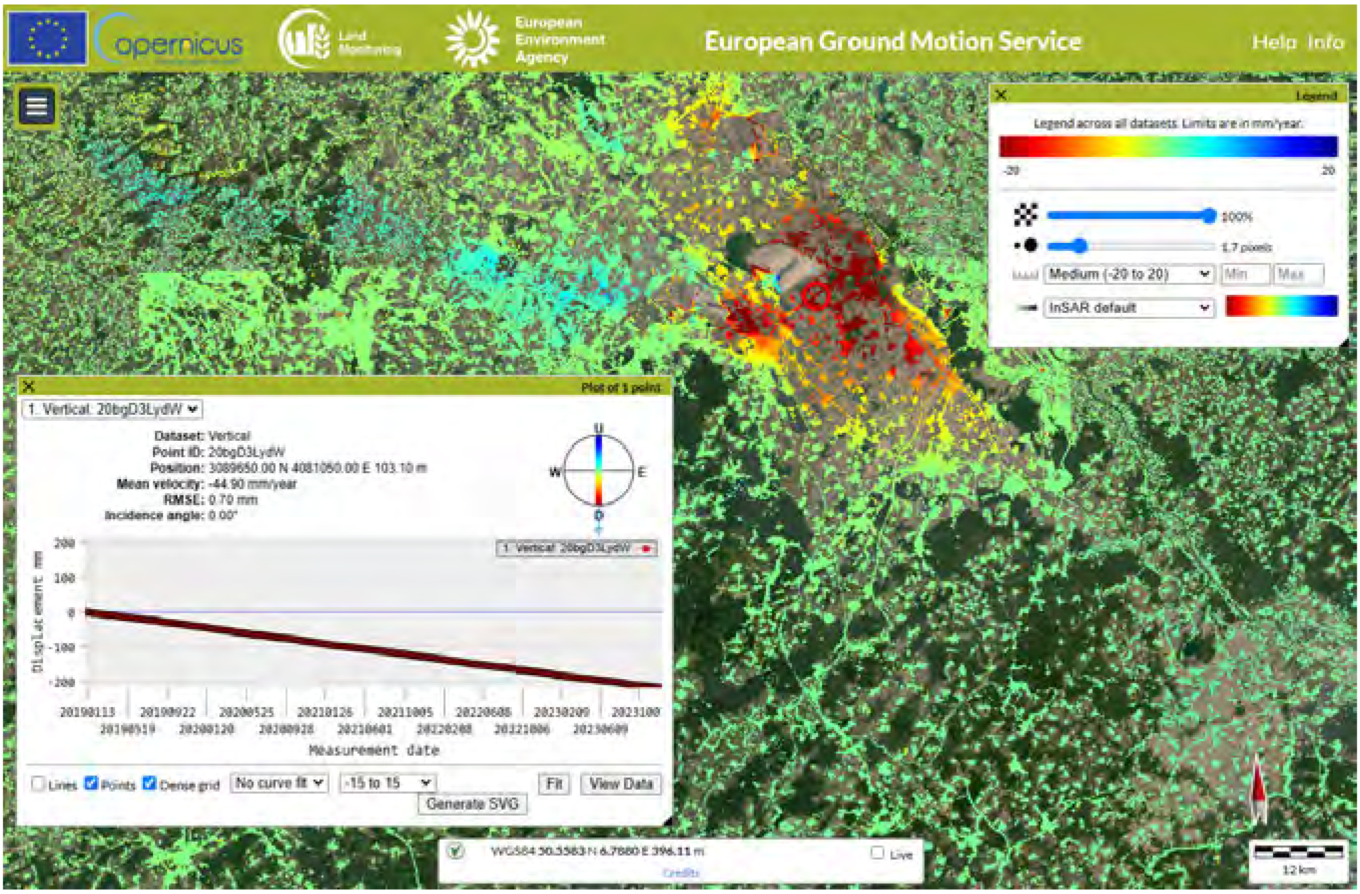
Mining also impacts water quality, primarily through acid mine drainage, which can pollute rivers and groundwater with heavy metals and acids (Rudke et al., 2020). In a study of mining's impact on protected areas in the western Amazon, researchers found that mining activities, particularly illegal operations, significantly contributed to water degradation in the region. By using satellite data from Landsat and Sentinel missions, they were able to track water quality changes and identify highly polluted areas, allowing for swift identification of regions in need of intervention (Nascimento et al., 2020).

The atmosphere is also affected by mining activities, which lead to increased concentrations of pollutants such as SO_2, NO_x, and particulate matter from emissions and mining dust (Haghighizadeh et al., 2024). For example, in mining area in China, a LiDAR and infrared satellite imaging have been used to monitor the spread of these pollutants and their impact on air quality (Zhang et al., 2011). This data is particularly valuable for assessing health risks and planning emission reduction strategies, which are crucial for protecting public health. Remote sensing technologies also provide insights needed to identify areas of greatest impact, facilitating the development of strategies to reduce emissions and minimize exposure for local communities.

Remote sensing techniques such as GIS, hyperspectral analysis, LiDAR, and satellite imagery play a critical role in monitoring and managing the environment affected by mining areas. They enable precise assessments of vegetation health, soil, water, and air quality, supporting more sustainable development of mining activities. The incorporation of these technologies into standard environmental assessments can help minimize mining's environmental footprint and improve natural resource management (Silveira Nascimento et al., 2020; Zhang et al., 2011; Haghighizadeh et al., 2024).

European Ground Motion Service (EGMS) is an interesting open access tool for assessing large-scale ground displacements in Europe. It is a part of Copernicus program, managed by the European Environment Agency (EEA), EGMS provides a comprehensive platform for visualizing and interpreting surface deformation trends. By leveraging radar data from Sentinel-1 satellites and advanced Interferometric Synthetic Aperture Radar (InSAR) technology, the service enables the detection of ground movement with millimeter-level precision.

It is useful for general monitoring of mining influence on land deformations. The platform's user-friendly interface allows for easy visualization of displacement data, offering insights into both large-scale trends and more local changes. Figure 7 showcases the use of EGMS data, demonstrating its application in identifying ground deformation patterns associated with cone of depression.



Dataset: Vertical
Point ID: 20bgD3LydW
Position: 3089650.00 N 4081050.00 E 103.10 m
Mean velocity: -44.90 mm/year
RMSE: 0.70 mm
Incidence angle: 0.00°

WGS84 50.5583 N 6.7880 E 396.11 m

Fig. 7. A view from the EGMS application of the Hambach lignite mining area in western Germany. The window in the lower left corner shows the displacement rate over time for the point marked by the red circle

Rys. 7. Widok z aplikacji EGMS dla obszaru górniczego węgla brunatnego Hambach w zachodnich Niemczech. Okno w lewym dolnym rogu pokazuje tempo przemieszczeń w czasie dla punktu oznaczonego czerwonym okręgiem

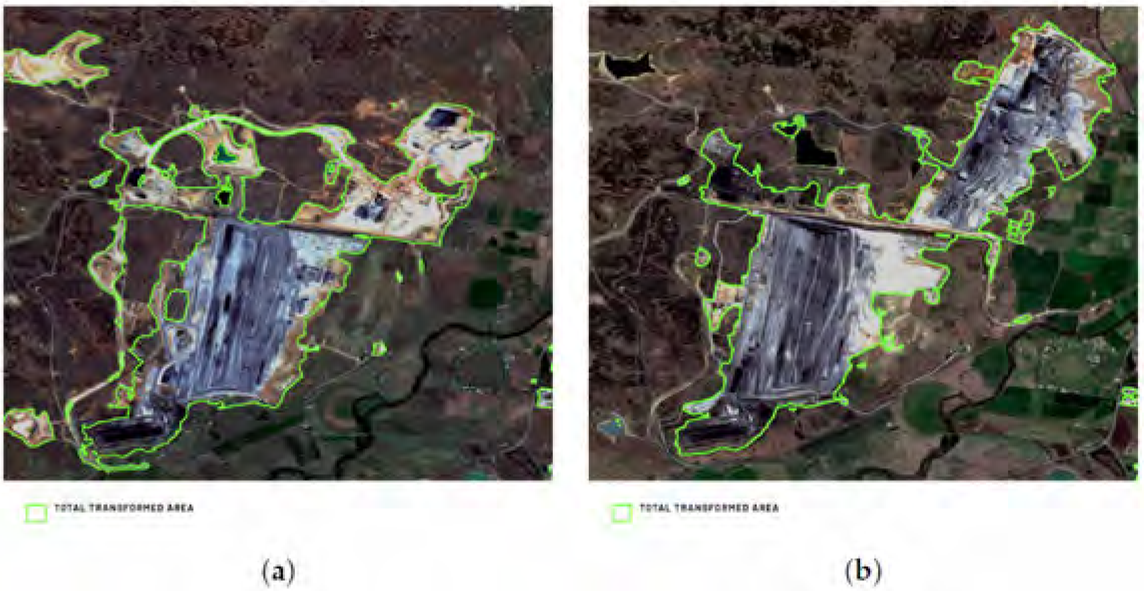


Fig. 8. Mining land use in Bengala Coal Mine (Australia). Comparison between 2019 (left) and 2021 (right) (Jabłońska et al., 2024)
Rys. 8. Wykorzystanie terenu górniczego w Kopalni Węgla Bengala (Australia). Porównanie między rokiem 2019 (po lewej) a 2021 (po prawej) (Jabłońska i in., 2024)

Land use is one of the biggest environmental impacts of mining, especially surface mining. Surface mining leads to land use that remains significant for a very long period, which underscores the significance of remote sensing methods for effective environmental monitoring. By combining RS with ML, it is possible to create tools for automated, near-real-time monitoring of surface mining activities. For example, Jabłońska et al., 2024 proposed an automated tool for mining areas monitoring by utilizing Sentinel-2 data and ML algorithms for segmentation and change detection.

Reclamation

Reclamation of mining areas is a crucial process aimed at restoring the environmental and economic value of degraded lands. This process encompasses activities such as improving soil quality, restoring water resources, and re-establishing vegetation. The application of RS and GIS enables detailed monitoring of reclamation efforts over time, providing more precise environmental management of post-mining sites (Buczyńska, 2020). To monitor reclamation success, indices like the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Moisture Index (NDMI) are widely used. For example, in the Salt Range coal mining region in Pakistan, NDVI values indicated improved vegetation health on reclaimed land compared to active mining areas (Ali et al., 2022).

Another example is from India's Jharia coal fields, researchers used a combination of NDVI and NDMI to assess vegetation and soil moisture. The study found a strong correlation between vegetation health and soil moisture, crucial for sustaining plant growth on reclaimed sites. RS data from Landsat images between 2000 and 2015 showed a 21% increase in vegetation cover, indicating substantial reclamation success in this open-cast mine area (Karan et al., 2016)

A study at coal mines in Henan Province, China, assessed reclamation quality using a system of indicators, including soil moisture and organic matter content. This study WorldView-2 satellite images to evaluate soil and vegetation parameters. The findings confirmed that soil quality on reclaimed land met necessary standards, with remote sensing data aligning well with on-site field surveys (Wang et al., 2023).

RS can be also applied to monitor the process of final pit flooding and water quality, when an anthropogenic waterbody is created as part of reclamation process.

Conclusions

Remote sensing (RS) provides a powerfull set of tools for the mining industry, enabling efficient data collection and analysis across large and remote areas with minimal on-site interventions. Utilizing sensors on satellites, aircraft, and UAVs, RS supports a wide range of applications, from mineral prospecting and mine planning to environmental monitoring and reclamation. Techniques such as spectroscopy, Synthetic Aperture Radar (SAR), Light Detection and Ranging (LiDAR), and thermal imaging provide detailed and actionable insights, especially when integrated with Geographic Information Systems (GIS) and machine learning for advanced analysis.

RS plays a pivotal role in mineral exploration by enabling lithological and alteration mapping, often in inaccessible or challenging terrains. For example, it supports large-scale targeting using medium-resolution data, while UAV-based hyperspectral and geophysical mapping enhances deposit-level exploration. Additionally, RS aids in mine design by generating Digital Elevation Models (DEMs), facilitating land-use planning, and balancing environmental and economic priorities.

During operations, RS supports safety and risk management, including slope stability monitoring through InSAR and UAV-based photogrammetry. It also enhances waste management by assessing TSFs and identifying contamination hotspots. RS contributes to environmental monitoring by tracking vegetation health, water and soil condition, and air pollution, utilizing indices like NDVI, VII, NDMI any many others for precise assessments. Furthermore, RS facilitates reclamation by evaluating the success of vegetation regrowth, soil rehabilitation, and water quality in final pits.

Emerging trends such as open-access platforms like the European Ground Motion Service (EGMS) and automated tools for real-time monitoring underscore the growing accessibility and utility of RS in mining. By reducing environmental impacts and improving operational efficiency, RS is transforming the mining industry into a more sustainable and responsible sector.

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