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Advances in Magnetic Gradiometry for Aeromagnetic Surveys: Principles, Applications, and Future Directions – A Comprehensive Review

Ogunkoya Olubunmi Charles
Ajayi Crowther University, Oyo, Southwestern, Nigeria
co.ogunkoya@acu.edu.ng

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Abstract

Magnetic gradiometry has revolutionized aeromagnetic surveys, offering high-resolution mapping of subsurface structures and mineral deposits. This review explores the principles, instrumentation, data processing methods, and applications of the technique in geophysical exploration. Recent advancements in sensor technology, particularly the development of superconducting quantum interference devices (SQUIDs), have facilitated the implementation of full tensor magnetic gradiometry (FTMG), enabling higher-resolution subsurface characterization. The integration of these systems with unmanned aerial vehicles (UAVs) has significantly enhanced survey adaptability and spatial coverage. Furthermore, advanced data processing methodologies, such as multifractal singular value decomposition (MSVD) and optimized empirical mode decomposition (EMD) techniques, have substantially improved noise suppression and anomaly detection capabilities in geophysical datasets. Novel edge detection filters and 3D inversion algorithms have improved interpretation capabilities. Magnetic gradiometry has found applications in mineral exploration, hydrocarbon detection, geological mapping, and archaeological investigations. Its integration with other geophysical methods has proven effective for comprehensive subsurface characterization. While challenges persist in noise reduction and interpretation ambiguities, ongoing research in sensor technology, data processing, and integration with artificial intelligence promises to expand the capabilities of this powerful geophysical exploration technique.

Keywords: Magnetic Gradiometry, Aeromagnetic Surveys, Unmanned Aerial Vehicles (UAVs), Mineral Exploration, Geophysical Data Processing

Introduction

Aeromagnetic surveys have a rich history in geological exploration and mineral resource mapping. These surveys have played a pivotal role in delineating subsurface structural configurations, mineralized zones, and lithological characteristics across diverse geological terrains. In the early stages, aeromagnetic surveys were primarily used for regional exploration and mapping of large areas. For instance, a manned aeromagnetic system using a helicopter in the area of Pocheon, Korea, was employed for the exploration of iron ore mineral distribution (Kim et al., 2021). As technology advanced, unmanned aeromagnetic systems using multicopters were introduced for high-resolution exploration, allowing for more detailed and precise mapping of mineral resources (Kim et al., 2021). Interestingly, aeromagnetic surveys have found applications beyond mineral exploration. In the oil and gas industry, these surveys have been used to locate steel-cased wells, including abandoned ones, which is crucial for environmental and safety reasons (Saint-Vincent et al., 2020). This application has led to more accurate estimations of well counts in various regions, highlighting the discrepancies between database records and actual well numbers. In recent years, aeromagnetic surveys have evolved to incorporate advanced data processing techniques and integration with other geophysical methods. For example, the high-resolution aeromagnetic data from the Nanpanjiang-Youjiang metallogenic belt in southeast China were combined with gamma-ray spectrometry data to conduct comprehensive litho-structural mapping (Liao et al., 2023). This integration has significantly enhanced our understanding of geological structures and improved mineral exploration efforts.

Importance of magnetic gradiometry in geophysical exploration

Magnetic gradiometry has emerged as a crucial technique in geophysical exploration, particularly in aeromagnetic surveys, offering significant advantages over traditional magnetic field measurements. This method involves measuring the spatial gradient of the magnetic field, providing higher resolution and sensitivity to detect subtle geological features and mineral deposits (Jorgensen et al., 2023; Luoma & Zhou, 2020). The application of magnetic gradiometry in aeromagnetic surveys has revolutionized mineral exploration, geological mapping, and environmental monitoring by enabling the detection of weak magnetic anomalies and improving the accuracy of subsurface characterization (Ai et al., 2024; Eldougdoug et al., 2023). Recently, advancements in technology have significantly improved magnetic gradiometry capabilities. The development of quantum sensors utilizing spin defects in diamonds allows for detailed imaging of nanoscale magnetic patterns, achieving unmatched sensitivity and spatial resolution (Huxter et al., 2022). Moreover, the incorporation of unmanned aerial vehicles (UAVs) in magnetic gradiometry surveys has introduced new options for swift, flexible, and efficient data collection in tough terrains (Accomando & Florio, 2024; Porras et al., 2021). This technique has become vital in geophysical exploration, especially in aeromagnetic surveys, as it provides high-resolution data. Advances in sensor technology and data processing methods have significantly enhanced our understanding of subsurface structures and mineral deposits. Given the increasing demand for mineral resources, the role of magnetic gradiometry in directing exploration activities and optimizing resource extraction is poised to grow even more (Liao et al., 2023; Yin et al., 2025).

Aim and objectives of the review

This review work aims to critically analyze the principles, advancements, applications, and future directions of magnetic gradiometry in aeromagnetic surveys, emphasizing its role in enhancing subsurface characterization for geophysical exploration. The objectives include reviewing the fundamental principles of magnetic gradiometry and its advantages over traditional total field measurements; examining the evolution of instrumentation; evaluating advanced data processing techniques such as Multifractal Singular Value Decomposition (MSVD) for noise reduction and anomaly detection; assessing the integration of gradiometry with other geophysical methods for improved litho-structural mapping; exploring applications in mineral exploration, hydrocarbon detection, environmental studies, and archaeology; identifying challenges like noise interference and interpretation ambiguities; and discussing emerging technologies.

Principles of Magnetic Gradiometry

Fundamentals of magnetic fields

Magnetic gradiometry in aeromagnetic surveys is based on the core principles of magnetic fields and their spatial differences. This method measures the spatial gradients of the Earth's magnetic field, yielding more detailed insights into subsurface structures compared to standard total field assessments. The emphasis in magnetic gradiometry is on evaluating how the magnetic field changes across various spatial directions. This is particularly advantageous in aeromagnetic surveys, where gradient measurements can pinpoint magnetic anomalies linked to geological features. Gradiometer sensors typically assess the difference in magnetic field strength between two closely placed points, effectively canceling out the Earth's background field to highlight local irregularities (Jorgensen et al., 2023). A significant advancement in this area is full tensor magnetic gradiometry (FTMG), which has become more feasible due to enhancements in superconducting quantum interference device (SQUID) technology. FTMG measures all components of the magnetic field gradient tensor, presenting a thorough perspective of the spatial variations in the magnetic field. This method provides several benefits over traditional magnetic field measurements, such as enhanced sensitivity, improved spatial resolution, and reduced sensitivity to temporal changes in the Earth's magnetic field (Jorgensen et al., 2023). The principles of magnetic gradiometry have also extended beyond traditional geological surveys. For example, quantum sensors reliant on nitrogen-vacancy (N-V) centers in diamonds have allowed for detailed imaging of nanoscale magnetic patterns. These sensors can be applied in a gradiometry technique that greatly improves the measurement sensitivity of static fields, paving the way for the imaging of weakly magnetic systems. This approach entails mechanically oscillating a single N-V center at the end of a scanning diamond probe, which translates local spatial gradients into AC magnetic fields, thus enabling the use of sensitive AC quantum protocols (Huxter et al., 2022; Newman et al., 2024). Magnetic gradiometry in aeromagnetic surveys leverages the fundamental properties of magnetic fields to provide high-resolution data on subsurface structures. By measuring field gradients rather than absolute field strengths, this technique offers improved sensitivity and spatial resolution, making it a powerful tool for geological exploration and other applications requiring detailed magnetic field mapping.

Concept of magnetic gradients

Magnetic gradiometry in aeromagnetic surveys focuses on the measurement of spatial variations in the Earth's magnetic field, offering valuable insights for geological exploration and mineral detection. This principle is based on assessing the difference in magnetic field strength between multiple sensors positioned at a fixed distance apart, facilitating the identification of subtle magnetic anomalies connected to subsurface structures (Jorgensen et al., 2023; Ma et al., 2023). Gradiometry presents numerous advantages over traditional magnetic field measurements, such as enhanced sensitivity, sharper imaging, and minimization of field drifts (Huxter et al., 2022). This method is particularly beneficial in archaeology, where the sources of interest are often shallow, and in mineral exploration, where it aids in identifying mineralization-associated residual anomalies (Accomando & Florio, 2024; Ma et al., 2023). Recent innovations have led to the creation of full tensor magnetic gradiometry (FTMG) using superconducting quantum interference devices (SQUIDs), allowing for efficient 3D modeling and inversion of magnetic data (Jorgensen et al., 2023). Furthermore, the deployment of unmanned aerial vehicles (UAVs) in magnetic gradiometry has become more popular, providing consistent coverage across large areas while giving access to steep terrains and minimizing both time and risks (Accomando & Florio, 2024). However, challenges remain in UAV-based gradiometry, such as magnetic interference from onboard components and sensor oscillations, which require careful system design and data processing techniques to overcome (Accomando & Florio, 2024). Furthermore, magnetic gradiometry in aeromagnetic surveys has become an essential tool in various fields, including mineral exploration, archaeology, and geological mapping. Its ability to provide high-resolution magnetic anomaly data, coupled with advancements in sensor technology and data processing techniques, makes it a powerful method for understanding subsurface structures and properties.

Types of magnetic gradients (vertical, horizontal, total)

Magnetic gradiometry in aeromagnetic surveys employs various types of gradients to enhance the detection and interpretation of subsurface geological features. The three primary types of magnetic gradients used are vertical, horizontal, and total gradients. Vertical gradients measure the rate of change of the magnetic field in the vertical direction.

They are particularly effective in highlighting near-surface features and enhancing the resolution of magnetic anomalies. The vertical gradient is often used in conjunction with other methods to improve edge detection and delineate structural boundaries (Ai et al., 2024). For instance, the first vertical derivative of the total magnetic field has been shown to amplify superficial anomalies and separate them horizontally, making it useful for identifying shallow magnetic sources (Karimi et al., 2023). Horizontal gradients, including the total horizontal gradient (THG), are valuable for detecting lateral changes in magnetic properties. The enhanced horizontal gradient amplitude (EHGA) method has been demonstrated to position peaks over source borders and create sharp, clear edges for magnetic sources (Eldosouky et al., 2022). This approach is particularly useful for delineating structural lineaments and identifying subsurface faults and contacts. The total gradient, which combines both vertical and horizontal components, provides a comprehensive measure of the magnetic field's spatial variation. The logistic total horizontal gradient (LTHG) has been employed to delineate deep-seated and shallow magnetic signals related to peak and border magnetization, respectively (Karimi et al., 2023). This method is especially useful in complex geological settings where both deep and shallow structures are of interest. In conclusion, the choice of gradient type depends on the specific geological targets and survey objectives. Vertical gradients are often preferred for near-surface features, horizontal gradients for lateral changes, and total gradients for a more comprehensive analysis. The integration of these gradient techniques with other methods, such as the tilt depth method (TDM) and strike alignment (SA) analysis, can provide a more robust interpretation of aeromagnetic data (Eldosouky et al., 2022; Karimi et al., 2023).

Advantages of gradiometry over total field measurements

Gradiometry offers several advantages over total field measurements in aeromagnetic surveys, particularly in terms of sensitivity, resolution, and noise reduction. The use of magnetic gradiometry techniques has significantly enhanced the capabilities of geophysical exploration and imaging. Gradiometry provides an order-of-magnitude better sensitivity compared to static field imaging, allowing for the detection of weaker magnetic signals (Huxter et al., 2022). This increased sensitivity is crucial for identifying subtle geological features and mineral deposits that may not be detectable with conventional total field measurements. Additionally, gradiometry produces more localized and sharper images, enabling better delineation of geological boundaries and structures (Huxter et al., 2022).

This improved spatial resolution is imperative in complex geological settings where precise mapping is essential. One of the advantages of gradiometry is its effectiveness in suppressing field drifts and reducing noise (Accomando & Florio, 2024; Huxter et al., 2022). By measuring the spatial gradients of the field magnetic rather than the total magnetic field, gradiometry effectively eliminates the effects of temporal variations in the magnetic field of the Earth and reduces the regional magnetic anomalies' impact. This noise reduction is especially beneficial in aeromagnetic surveys, where the magnetic interference from the aircraft and other sources can be significant (Accomando & Florio, 2024). The implementation of vertical gradiometer systems on Unmanned Aerial Vehicles (UAVs) has further improved data acquisition in challenging terrains and large areas, although careful noise filtering is required to address oscillations of the suspended sensors (Accomando & Florio, 2024). In conclusion, magnetic gradiometry offers superior sensitivity, resolution, and noise reduction compared to total field measurements in aeromagnetic surveys. These advantages make gradiometry a powerful tool for geological exploration, enabling more accurate mapping of subsurface structures and mineral deposits, particularly in areas with complex geology or weak magnetic signatures.

Instrumentation and Data Acquisition

Evolution of magnetic gradiometers

Magnetic gradiometers have undergone substantial advancements, with multiple configurations now deployed in aeromagnetic surveys. The integration of unmanned aircraft systems (UASs) has facilitated highly flexible, rapid, and efficient survey operations while delivering exceptional spatial resolution. A recently developed magnetic gradiometer system, incorporating dual fluxgate magnetometers, two high-precision GPS receivers, and a microcontroller-based control and data-logging unit, has been optimized for UAS compatibility (Luoma & Zhou, 2020). This compact, low-cost system is particularly well-suited for high-resolution geophysical investigations of subsurface magnetic anomalies. Advancements in technologies like laser diodes and microfabrication have led to the development of compact, integrated optically pumped gradiometers. These improvements have enabled applications in magnetoencephalography, with potential for biomagnetic source detection without shielding (Dong et al., 2023). However, challenges remain in implementing vertical gradiometers for drone-borne measurements because of unstable systems and noise issues. To address these problems, a magnetic vertical gradiometer UAV system was developed, suspending the magnetometer 3m below the drone to reduce magnetic and electromagnetic noise (Accomando & Florio, 2024). In summary, the evolution of magnetic gradiometers has seen significant improvements in sensitivity, compactness, and integration with aerial platforms. Quantum sensors, including SQUIDs and optically pumped magnetometers, show promise for future geophysical exploration applications (Stolz et al., 2022). These advancements have facilitated the development of next-generation airborne vector magnetometers characterized by ultra-low noise floors and exceptional dynamic range capabilities, as well as airborne full tensor gradiometer instruments, which have already demonstrated successful commercial operations in aeromagnetic surveys.

Modern gradiometer systems for aeromagnetic surveys

Modern gradiometer systems for aeromagnetic surveys have significantly advanced the field of magnetic exploration, offering high-resolution data acquisition and improved noise reduction capabilities. These systems typically employ multiple magnetometers arranged in specific configurations to measure magnetic field gradients, providing more detailed information about subsurface structures and anomalies (Accomando & Florio, 2024; Luoma & Zhou, 2020). Unmanned Aerial Vehicles (UAVs have become a versatile effective platform for aeragnetic surveys, enabling rapid data acquisition extensive areas, even in difficult terrains. To reduce the magnetic interference caused by the UAV, magnetometers are commonly suspended below the aircraft using ropes or mounted on extended booms (Accomando & Florio, 2024; Le Maire et al., 2020). For example, a fluxgate three-component magnetometer has been successfully placed 42 cm in front of a UAV using a composite pipe for aeromagnetic investigations (Le Le Maire et al., 2020). Advanced gradiometer systems utilize a variety of sensor types, including fluxgate magnetometers, optically pumped magnetometers, and alkali vapor cells. These sensors are highly sensitive, with some achieving resolutions in the femtotesla range (Cook et al., 2024; Limes et al., 2020). Particularly, optically pumped magnetic gradiometers that rely on non-linear magneto-optical rotation have shown sensitivities of 18 fT cm−1Hz−1 and effectively eliminate common mode magnetic field noise (Cook et al., 2024). Techniques for data acquisition have also progressed to tackle issues like noise reduction and edge detection. The implementation of multifractal singular value decomposition (MSVD) and enhanced bi-dimensional empirical mode decomposition (BEMD) algorithms has proven effective in diminishing noise and extracting residual magnetic anomalies (Ma et al., 2023). Moreover, sophisticated filtering methods, such as the modified non-local means (MNLM) algorithm, have been utilized to reduce noise and enhance edge detection in potential field data (Ai et al., 2024). Modern gradiometer systems for aeromagnetic surveys combine advanced sensor technologies, innovative platform designs, and sophisticated data processing techniques to provide high-resolution magnetic field measurements. These advancements have significantly enhanced the capabilities of aeromagnetic surveys in various applications, including mineral exploration, archaeological investigations, and geological mapping (Accomando & Florio, 2024; Kim et al., 2021; Liao et al., 2023).

Survey design and flight parameters

Instrumentation and data acquisition play a crucial role in magnetic gradiometry for aeromagnetic surveys. The design of these surveys and the selection of appropriate flight parameters are essential for obtaining high-quality data and achieving the desired resolution and coverage. Full tensor magnetic gradiometry (FTMG) has become an effective technique for exploration, largely due to improvements in superconducting quantum interference device (SQUID) technology (Jorgensen et al., 2023). This method allows for the measurement of the second spatial derivatives of the magnetic potential, yielding more detailed insights into subsurface structures. In aeromagnetic surveys, selecting the appropriate platform is crucial. Both manned helicopters and UAVs have been efficiently utilized for regional and high-resolution studies, respectively (Kim et al., 2021). A primary challenge in aeromagnetic surveys is the electromagnetic interference produced by the survey platform. UAV-mounted systems necessitate careful integration of the magnetometer payload to maintain the integrity of total magnetic field measurements. Techniques such as magnetic shielding, filtering, compensation, and optimal sensor placement can help mitigate this issue (Walter et al., 2021). For instance, scalar magnetometers are often towed several meters beneath the UAV to reduce their magnetic influence, while fluxgate three-component magnetometers can be positioned closer to the vehicle with appropriate calibration and compensation techniques (Le Le Maire et al., 2020). The design of aeromagnetic surveys using magnetic gradiometry involves careful consideration of instrumentation, platform selection, and interference mitigation strategies. The choice of flight parameters, including altitude and survey line spacing, significantly impacts the resolution and scale of the observed magnetic anomalies (Le Le Maire et al., 2020). By optimizing these factors, researchers can obtain comprehensive and high-quality magnetic data for various applications, including litho-structural mapping and mineral exploration (Liao et al., 2023).

Data collection and quality control

Magnetic gradiometry in aeromagnetic surveys employs advanced instrumentation and data acquisition techniques to measure spatial differences in the Earth's magnetic field. Primary instrument used is the full tensor magnetic gradiometer (FTMG), which has become increasingly practical as a result of superconducting quantum interference device (SQUID) technology advancement (Jorgensen et al., 2023). This sophisticated equipment allows for the measurement of second derivatives of the magnetic potential, providing high-resolution data for subsurface mapping. Data collection in aeromagnetic surveys often involves helicopter-borne or fixed-wing aircraft equipped with FTMG sensors, as well as additional instruments such as gravimeters, laser altimeters, and GNSS systems for precise positioning (Cui et al., 2020). The Snow Eagle 601 platform, for instance, integrates multiple scientific instruments to conduct comprehensive surveys in challenging environments like Antarctica (Cui et al., 2020). Quality control measures are crucial to ensure data reliability, with techniques such as the modified non-local means (MNLM) algorithm being employed to reduce noise contamination in potential magnetic field data (Ai et al., 2024). Magnetic gradiometry in aeromagnetic surveys relies on cutting-edge instrumentation and rigorous data acquisition protocols. The integration of FTMG technology with other geophysical sensors, coupled with advanced noise reduction techniques, enables the collection of high-quality data for accurate subsurface mapping and interpretation. These advancements have significantly enhanced the capabilities of aeromagnetic surveys in various applications, including mineral exploration and geological mapping.

Data Processing and Interpretation

Noise reduction and filtering techniques

The processing and interpretation of data in magnetic gradiometry for aeromagnetic surveys involve various noise reduction and filtering methods that enhance the quality and accuracy of the collected data. These techniques are vital for extracting valuable insights from raw data and aiding in the interpretation of subsurface structures. One successful noise reduction method is the multifractal singular value decomposition (MSVD) approach, which effectively minimizes noise in aeromagnetic data (Ma et al., 2023). This technique, along with an enhanced bi-dimensional empirical mode decomposition (BEMD) algorithm, can efficiently isolate residual magnetic anomalies essential for mineral exploration. Another advanced noise reduction technique is the complete ensemble empirical mode decomposition with adaptive noise (CEEMDAN), which breaks down the original signal into intrinsic mode functions (IMFs) (Zheng et al., 2021). This method, combined with permutation entropy, correlation coefficient analysis, and wavelet threshold denoising, has demonstrated effectiveness in removing interference from UAV magnetic data. Notably, various filtering methods have been created to improve edge detection and boundary identification of causative sources in potential field data. The Balanced Horizontal Gradient (BHG) filter, which utilizes the arctangent function of horizontal gradient derivatives, has shown effectiveness in identifying source edges while avoiding false edges (Prasad et al., 2022). Similarly, an upgraded horizontal tilt angle filter has proven efficient at detecting source boundaries across different depths while minimizing the creation of false edges and enhancing resilience to noise (Ibraheem et al., 2023). Therefore, the application of these advanced noise reduction and filtering methods significantly elevates the quality and interpretability of magnetic gradiometry data in aeromagnetic surveys. These techniques facilitate more precise identification of subsurface structures, enhance the detection of mineralization-related anomalies, and provide vital insights for geological mapping and mineral exploration. Ongoing development of such methods is essential for advancing magnetic gradiometry and its applications in geophysical exploration.

Gradient calculation methods

Gradient calculation techniques in magnetic gradiometry for aeromagnetic surveys are vital for improving the detection and understanding of subsurface geological features. These methodologies involve calculating the spatial derivatives of the magnetic field to highlight subtle variations and enhance the resolution of magnetic anomalies. A widely used method is the total horizontal gradient (THG) approach, which has been refined to deliver more accurate and cohesive edge results. A new filtering framework based on THG and its derivatives has been devised to yield more precise edge detection outcomes, free from misleading boundaries or artifacts (Ai et al., 2024). This revised method, validated with both synthetic and real datasets, has effectively reduced false artifacts while identifying edges with greater accuracy. Moreover, full tensor magnetic gradiometry (FTMG) has become a practical approach for exploration, driven by advancements in superconducting quantum interference device (SQUID) technology. The processing of FTMG data includes calculating the second spatial derivatives of the magnetic potential, facilitating more thorough 3D modeling and inversion (Jorgensen et al., 2023). This technique has been successfully applied to interpret helicopter-borne FTMG surveys, providing valuable insights into subsurface susceptibility and magnetization vector models. Gradient calculation methods in magnetic gradiometry have significantly improved the processing and interpretation of aeromagnetic data. These techniques, ranging from refined THG approaches to advanced FTMG processing, offer enhanced capabilities for detecting geological boundaries, suppressing noise, and extracting meaningful information from magnetic surveys. As demonstrated by their successful applications in various case studies, these methods continue to play a vital role in mineral exploration and geological mapping.

Integration with other geophysical data

Aeromagnetic surveys utilizing magnetic gradiometry can be effectively combined with other geophysical datasets to improve subsurface characterization and mineral exploration, offering a more comprehensive understanding of geological structures and mineralization zones. Integrating full tensor magnetic gradiometry (FTMG) with total magnetic intensity (TMI) data enhances subsurface modeling resolution and accuracy, as demonstrated by a study applying 3D regularized focusing inversion to helicopter-borne survey data over the Thompson Nickel Belt, enabling the recovery of magnetic susceptibility and magnetization vectors for detailed subsurface models (Jorgensen et al., 2023). Notably, combining aeromagnetic data with other methods, such as gamma-ray spectrometry in the Nanpanjiang-Youjiang metallogenic belt, can reveal complementary insights aeromagnetics identified concealed rocks and faults, while gamma-ray spectrometry differentiated carbonate from clastic rocks, enriching geological interpretations (Liao et al., 2023). Furthermore, machine learning techniques like Fuzzy C-Means clustering facilitate automated, objective-oriented integration of multiple datasets (Kumar et al., 2023), and deep learning methods, when constrained by domain knowledge, streamline subsurface characterization through efficient analysis of integrated geophysical data (Wu et al., 2023).

Applications in Various Fields

Mineral exploration

Aeromagnetic surveys employing magnetic gradiometry are highly effective for mineral exploration, providing critical insights into subsurface geological structures and potential mineralization zones by measuring variations in the Earth's magnetic field caused by geological features, including mineral deposits (Jorgensen et al., 2023; Kim et al., 2021). These surveys utilize both manned and unmanned aerial systems to acquire high-resolution magnetic data across extensive areas (Kim et al., 2021), with advanced processing techniques such as multifractal singular value decomposition (MSVD) and improved bi-dimensional empirical mode decomposition (BEMD) applied to reduce noise and extract residual magnetic anomalies for enhanced interpretation (Ma et al., 2023). The integration of aeromagnetic data with complementary geophysical methods like audio-frequency magnetotelluric (AMT) and gravimetric surveys has significantly improved mineral prospecting accuracy by providing a more comprehensive understanding of deep geological structures and mineralization features (Yin et al., 2025). Magnetic gradiometry has been successfully applied in identifying diverse mineral deposits, including iron ore (Kim et al., 2021), gold (Eldougdoug et al., 2023; Shebl et al., 2021), copper (Echogdali et al., 2021), and porphyry systems (Jorgensen et al., 2024; Mohamed et al., 2022), making it an indispensable tool for litho-structural mapping, mineral prospectivity analysis, and optimized resource allocation in exploration (Jorgensen et al., 2023; Liao et al., 2023).

Hydrocarbon exploration

Magnetic gradiometry in aeromagnetic surveys plays a crucial role in hydrocarbon exploration by providing detailed insights into subsurface structures and potential reservoirs through the measurement of spatial variations in the Earth's magnetic field. Conducted via aircraft, these surveys enable rapid, large-scale coverage, with unmanned aircraft systems (UASs) enhancing flexibility, efficiency, and cost-effectiveness while delivering high-resolution results (Luoma & Zhou, 2020). Although primarily linked to mineral exploration, magnetic gradiometry also aids in identifying hydrocarbon-related features such as structural traps, fault systems, and basement structures. Advanced processing techniques, including multifractal singular value decomposition (MSVD) and improved bi-dimensional empirical mode decomposition (BEMD), help reduce noise and isolate residual magnetic anomalies, improving data interpretation (Ma et al., 2023).

Furthermore, integrating magnetic gradiometry with advanced data processing and 3D imaging techniques (Jorgensen et al., 2023; Ma et al., 2023) enhances the accuracy of geological feature analysis relevant to hydrocarbon accumulation, ensuring the method remains a sophisticated and increasingly valuable tool in exploration geophysics.

Geological mapping and structural analysis

Aeromagnetic surveys utilizing magnetic gradiometry have proven to be invaluable tools for geological mapping and structural analysis across various fields. These surveys provide high-resolution data that can reveal concealed rocks, faults, and other geological structures, offering crucial support for interpretation and analysis (Liao et al., 2023). Aeromagnetic data in geological mapping can be used to generate total magnetic intensity (TMI), reduction to the pole or equator, and derivative maps, which efficiently identify hidden geological features. When combined with airborne gamma-ray spectrometry data, these surveys can differentiate between different rock types, such as carbonate and clastic rocks, refining structural interpretations (Liao et al., 2023). Additionally, advanced processing techniques like the enhanced horizontal gradient methods and tilt derivative method can reveal detailed structural lineaments and provide depth estimates for magnetic sources (Eldosouky et al., 2022). Interestingly, the applications of aeromagnetic surveys extend beyond traditional geological mapping. In the field of mineral exploration, surveys can be integrated with remote sensing data to generate maps indicating gold potential, thereby identifying promising zones for further investigation (Shebl et al., 2021). Furthermore, the advancement of unmanned aerial vehicles (UAVs) equipped with magnetometers has facilitated new opportunities for high-resolution magnetic field mapping in both outdoor and indoor environments. (Lipovský et al., 2021; Porras et al., 2021). In conclusion, magnetic gradiometry in aeromagnetic surveys has become an essential tool in geological mapping and structural analysis. Its applications range from identifying concealed geological features and mineral exploration to creating detailed 3D models of subsurface structures (Ghirotto et al., 2023; Ma et al., 2023). Ongoing development in advanced processing methods and integration with other geophysical methods continues to enhance the versatility and effectiveness of these surveys in various geological and geophysical applications.

Environmental and engineering studies

Magnetic gradiometry in aeromagnetic surveys has found significant applications in environmental and engineering studies, offering enhanced sensitivity and resolution compared to traditional magnetic field measurements. In environmental studies, aeromagnetic gradiometry has proven valuable for locating and mapping abandoned oil and gas wells. Research conducted in Pennsylvania and Wyoming demonstrated that aeromagnetic surveys could detect more wells than recorded in databases, estimating 395,000-466,000 wells in Pennsylvania and 181,000-182,000 in Wyoming (Saint-Vincent et al., 2020). The technique is useful for identifying steel-cased wells, including buried casings without aboveground markers, which is crucial for assessing potential environmental risks associated with abandoned wells. Interestingly, the application of magnetic gradiometry extends beyond traditional environmental studies. In engineering, it has been used to investigate salt structures in sedimentary basins. A study in the Nordkapp Basin utilized high-resolution aeromagnetic surveys to reconstruct salt diapirs, providing a 3-D model of the structures extending from 500-4,000 m below sea level (Paoletti et al., 2020). This application demonstrates the versatility of magnetic gradiometry in geological mapping and resource exploration. Magnetic gradiometry in aeromagnetic surveys offers significant advantages for environmental and engineering applications. Its ability to provide high-resolution imaging of subsurface structures, detect hidden wells, and map geological features makes it a valuable tool for various fields. The improvement of unmanned aerial vehicle (UAV) platforms for magnetic surveys further enhances the accessibility and efficiency of this technique, although challenges related to magnetic interference from the UAV itself need to be addressed (Zheng et al., 2021).

Archeological investigations

Magnetic gradiometry in aeromagnetic surveys has proven to be a valuable tool for archaeological investigations, offering high-resolution imaging of subsurface features and structures. This technique measures the spatial gradients in the Earth's magnetic field to detect and map archaeological remains. In archaeological applications, unmanned aircraft systems (UASs) equipped with magnetic gradiometers have emerged as flexible and effective tools for conducting high-resolution surveys (Luoma & Zhou, 2020). These systems typically employ two fluxgate magnetometers, a microcontroller-based data-logging system, and GPS receivers, allowing for quick and efficient mapping of large areas. The lightweight and inexpensive nature of these components makes them ideal for integration with UASs, enabling archaeologists to cover extensive sites with minimal ground disturbance. Interestingly, while magnetic gradiometry is commonly used in archaeology, it has also shown promise in other fields. For instance, high-resolution aeromagnetic surveys have been effectively employed in mapping salt diapirs in geological studies, demonstrating the versatility of this technique beyond archaeological applications (Paoletti et al., 2020). Additionally, advancements in edge detection techniques, such as the modified total horizontal gradient approach, have further enhanced the precision of identifying subsurface features in both archaeological and geological contexts (Ai et al., 2024). In conclusion, magnetic gradiometry in aeromagnetic surveys offers archaeologists a powerful, non-invasive method for site prospection and mapping. The integration of this technique with UAS technology has enhanced the efficiency and resolution of archaeological surveys, facilitating the detection of subtle magnetic anomalies associated with buried structures, hearths, and other anthropogenic features. As the technology continues to advance, we can anticipate even more precise and detailed mapping of archaeological sites, contributing to our understanding of past human activities and settlements.

Case Studies

To add value to the description of magnetic gradiometry in aeromagnetic surveys, the case history of Hashem and Richard (2024) and Karshakov et al. (2018) was presented.

Hashem and Richard (2024) demonstrated the effectiveness of UAV-based aeromagnetic gradiometry in a iron ore deposit in Western Iran. Using lightweight magneto-inductive sensors mounted on a hexacopter UAV, they detected magnetic anomalies associated with iron ore mineralization. The study revealed steep magnetic anomaly margins with gradients up to 10 nT/m, significantly higher than conventional single-sensor measurements. This approach proved particularly advantageous for small-scale, high-resolution surveys in accessible terrain. The UAV-based gradiometry system by Hashem and Richard (2024) offered advantages over conventional aeromagnetic surveys. It achieved higher resolution by flying closer to the ground (6 m) and using lightweight, low-power sensors. The gradiometry setup provided sharper anomaly delineation compared to single-sensor data derivatives. Hashem and Richard (2024) suggested integrating UAV-based aeromagnetic gradiometry with terrestrial magnetometry for enhanced mineral exploration. This multiscale approach allowed for comprehensive coverage, with UAVs providing regional data and ground methods offering detailed local insights.

Karshakov et al. (2018) explored the broader applications of aeromagnetic gradiometry in navigation and geophysical exploration. They emphasized the stability of magnetic field gradients over time, making them reliable for long-term applications. The study showcased the method's adaptability to various settings, including mineral exploration and unexploded ordnance detection. Karshakov et al. (2018) highlighted the limitations of conventional magnetic surveys, particularly their susceptibility to temporal variations in the geomagnetic field. Gradiometry's focus on local anomalies provided more stable and reliable measurements for repeat surveys and long-term monitoring. The study also noted the superior sensitivity and noise immunity of gradiometry systems, especially those using quantum sensors. Karshakov et al. (2018) explored integrating aeromagnetic gradiometry with inertial navigation systems and correlation-extremal navigation systems. This integration improved positioning accuracy and enhanced the spatial accuracy of geophysical surveys. The study suggested extending this integration to other geophysical methods for improved subsurface characterization.

Challenges and Limitations

Technical challenges in data acquisition and processing

Aeromagnetic surveys utilizing magnetic gradiometry encounter several technical challenges in data acquisition and processing, primarily centered on improving the detection accuracy of subsurface geological feature edges. While directional gradients of magnetic fields are commonly employed, these methods often produce low-resolution results and remain highly susceptible to noise interference, particularly in edge detection filters due to their reliance on directional derivatives (Ai et al., 2024). To mitigate these limitations, innovative filtering frameworks and noise suppression strategies have been developed, including a modified total horizontal gradient approach that enhances edge clarity by eliminating false boundaries and artifacts (Ai et al., 2024), alongside the application of the modified non-local means algorithm to reduce noise in synthetic and real datasets. Further challenges involve aeromagnetic noise suppression and the isolation of mineralization-related residual anomalies, addressed through advanced techniques like multifractal singular value decomposition (MSVD) and enhanced bi-dimensional empirical mode decomposition

(BEMD), which improve noise reduction and anomaly extraction (Ma et al., 2023). Additionally, 3D modeling and inversion of full tensor magnetic gradiometry (FTMG) data present complexities, necessitating efficient solutions such as single-point Gaussian integration with pulse basis functions for forward modeling and regularized focusing inversion to recover both magnetic susceptibility and magnetization vectors (Jorgensen et al., 2023). While magnetic gradiometry in aeromagnetic surveys faces challenges in noise reduction, edge detection, and data inversion, ongoing research and technological advancements are continually improving the accuracy and reliability of these techniques. The development of novel filtering frameworks, noise reduction algorithms, and efficient 3D modeling and inversion methods are contributing to overcoming these challenges and enhancing the capabilities of magnetic gradiometry in geophysical exploration.

Interpretation ambiguities and Cost considerations

Magnetic gradiometry in aeromagnetic surveys faces several challenges and limitations, particularly in terms of interpretation ambiguities and cost considerations. Interpretation ambiguities emerge as a result of the complexity of sub-surface structures and the inherent limitations associated with magnetic data. For instance, the study on full tensor magnetic gradiometry (FTMG) highlights the difficulty in separating induced and remanent magnetization, which can lead to misinterpretation of geological features (Jorgensen et al., 2023). Additionally, the presence of noise in aeromagnetic data can obscure subtle magnetic anomalies, making it challenging to accurately identify geological structures or mineral deposits (Ma et al., 2023). The multiscale analysis of aeromagneticc data in the Nordkapp Basin demonstrates that while effective in mapping salt diapirs, the method is limited by the low magnetization contrast, which may not exceed -0.08 A/m (Paoletti et al., 2020). Cost considerations play a significant role in the application of magnetic gradiometry within aeromagnetic surveys. While high-resolution aeromagnetic surveys can be effective for mapping diapirism and other geological features, they are rarely employed in salt structure research due to their high cost (Paoletti et al., 2020). The advancement of unmanned aerial vehicle (UAV) mounted aeromagnetic systems presents a potential solution to fill the gap between ground and airborne magnetic surveying, potentially reducing costs. However, these systems face challenges in compensating for the magnetic effects of the UAV itself and require careful integration of magnetometer payloads to preserve measurement integrity (Le Maire et al., 2020; Walter et al., 2021). While magnetic gradiometry in aeromagnetic surveys provides valuable insights into subsurface structures, it faces challenges in interpretation due to complex geological settings and data noise. The high cost of high-resolution surveys remains a limiting factor, although emerging technologies like UAV-based systems may offer more cost-effective alternatives in the future. Overcoming these challenges will require continued advancements in data processing techniques and survey methodologies.

Future Directions and Emerging Technologies

Improvements in sensor technology and Integration with unmanned aerial vehicles (UAVs)

Advances in sensor technology and their integration with unmanned aerial vehicles (UAVs) are significantly enhancing magnetic gradiometry in aeromagnetic surveys, improving the efficiency, accuracy, and applicability of geophysical exploration techniques by enabling precision data collection through advanced multispectral, hyperspectral, and thermal sensors mounted on drones, coupled with AI-driven algorithms for real-time data acquisition and analysis (Agrawal & Arafat, 2024). This integration facilitates more detailed and accurate magnetic gradiometry measurements, improving the identification of geological structures and mineral deposits, despite challenges such as limited battery life and payload capacity that UAVs face, even as they offer advantages like low cost, flexibility, and access to remote areas (Mohsan et al., 2022). These limitations could potentially affect the duration and quality of aeromagnetic surveys. However, ongoing research is addressing these issues through the development of energy-efficient AI models and improvements in battery technology (Agrawal & Arafat, 2024). In addition, the future of magnetic gradiometry in aeromagnetic surveys looks promising with the convergence of improved sensor technology and UAV integration. Emerging technologies (artificial intelligence and computer vision) are likely to further enhance the capabilities of UAV-based magnetic gradiometry systems (Arafat et al., 2023). As these technologies continue to evolve, we can expect more precise, efficient, and cost-effective aeromagnetic surveys, leading to significant advancements in geophysical exploration techniques.

Advanced data processing and interpretation techniques

Advanced data processing and interpretation techniques for magnetic gradiometry in aeromagnetic surveys are rapidly evolving, with several emerging technologies showing promise for future applications, including full tensor magnetic gradiometry (FTMG), which is becoming increasingly practical for exploration due to advancements in superconducting quantum interference device (SQUID) technology, alongside the development of a new 3D regularized focusing inversion technique that utilizes Gramian regularization and a moving sensitivity domain approach to recover both magnetic susceptibility and magnetization vectors (Jorgensen et al., 2023). This method has been successfully applied to interpret helicopter-borne FTMG surveys, demonstrating its potential for improved subsurface imaging. Edge detection techniques are also advancing, with new filters like the Balanced Horizontal Gradient (BHG) filter overcoming limitations of conventional filters. The BHG filter effectively detects source edges without generating false edges and balances the detection of shallow and deep-seated sources (Prasad et al., 2022). Similarly, the improved horizontal tilt angle (impTDX) filter has shown high efficiency in detecting boundaries of sources at different depth levels while minimizing noise sensitivity and false edge creation (Ibraheem et al., 2023). Emerging technologies such as deep learning (DL) and machine learning (ML) are increasingly being applied to remote sensing data interpretation, including aeromagnetic surveys, demonstrating potential in handling large volumes of modern sensor data while improving processing times and interpretation accuracy (Haut et al., 2021). The integration of DL and ML with cloud computing systems offers a powerful architecture for managing vast remotely sensed datasets, providing implementation simplicity, cost efficiency, and high performance compared to traditional parallel and distributed architectures. The future of magnetic gradiometry in aeromagnetic surveys hinges on combining advanced data processing techniques such as 3D inversion and enhanced edge detection filters with emerging technologies like deep learning and cloud computing, which are expected to improve subsurface imaging accuracy and efficiency, opening new possibilities in mineral exploration, geological mapping, and environmental monitoring.

Conclusion

Magnetic gradiometry has emerged as a powerful and versatile technique in aeromagnetic surveys, offering significant advancements in geophysical exploration across various fields. The evolution of instrumentation, from traditional magnetometers to full tensor magnetic gradiometers (FTMG) utilizing superconducting quantum interference device (SQUID) technology, has greatly enhanced the sensitivity and resolution of magnetic field measurements. The integration of these advanced sensors with unmanned aerial vehicles (UAVs) has revolutionized data acquisition, allowing for rapid, high-resolution surveys in challenging terrains while minimizing costs and environmental impact.

The application of sophisticated data processing and interpretation techniques has further amplified the capabilities of magnetic gradiometry. Advanced noise reduction methods, such as multifractal singular value decomposition (MSVD) and enhanced bi-dimensional empirical mode decomposition (BEMD), have significantly improved the quality of aeromagnetic data. Novel edge detection algorithms, including the Balanced Horizontal Gradient (BHG) filter and improved horizontal tilt angle (impTDX) filter, have enhanced the delineation of geological structures and boundaries. Moreover, the integration of magnetic gradiometry data with other geophysical methods, such as gamma-ray spectrometry and gravimetry, has provided a more comprehensive understanding of subsurface features.

Looking ahead, the future of magnetic gradiometry in aeromagnetic surveys appears promising, with emerging technologies poised to further enhance its capabilities. The application of artificial intelligence and machine learning algorithms for real-time data analysis and interpretation is expected to revolutionize the field. Additionally, ongoing improvements in sensor technology, UAV capabilities, and data processing techniques will likely lead to even more precise and efficient aeromagnetic surveys. These advancements will continue to expand the applications of magnetic gradiometry across various domains, including mineral exploration, hydrocarbon detection, environmental monitoring, and archaeological investigations, solidifying its position as an indispensable tool in geophysical exploration and Earth sciences.

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