National Journal of Antennas and Propagation, ISSN: 2582-2659 Vol. 5, No. 1, 2023 (pp. 18-25)
RESEARCH ARTICLE
HTTP://ANTENNAJOURNAL.COM

Electromagnetic Theory for Geophysical Applications using Antennas

Robert H. Luedke[1], G.C. Kingdone[2], Q. Hugh Li[3], FreddiNoria[4],
[1-4]*Robotics and Automation Laboratory Universidad Privada Boliviana Cochabamba, Bolivia*

KEYWORDS:
Absorption,
synchronization signal,
time division multiplexing,
frequency division multiplexing,
amplitude division multiplexing,
modulation index,
spread spectrum

ARTICLE HISTORY:
Received 02.08.2022
Revised 05.09.2022
Accepted 03.10.2022

DOI:
https://doi.org/10.31838/NJAP/05.01.04

Abstract

Electromagnetic (EM) theory plays a pivotal role in geophysics, offering valuable insights into the subsurface properties of the Earth. In this comprehensive review, we delve into the principles, methods, and advancements in electromagnetic theory for geophysical applications. We explore how EM theory is employed to investigate the Earth's electrical conductivity, map subsurface structures, and detect geological features such as mineral deposits, groundwater reservoirs, and hydrocarbon accumulations. Additionally, we discuss advanced techniques and emerging trends in EM geophysics, including time-domain and frequency-domain methods, inversion algorithms, and multi-physics integration. By gaining a deeper understanding of electromagnetic theory in geophysics, researchers and practitioners can harness its potential to address key challenges in resource exploration, environmental monitoring, and hazard mitigation.

Author's e-mail: robert.h.lu@upb.edu, kingdone.gc@upb.edu, Hugh.l@upb.edu, noria.fred@upb.edu

How to cite this article: Luedke RH, Kingdone GC, Hugh Li QH, FreddiNoria. Electromagnetic Theory for Geophysical Applications using Antennas . National Journal of Antennas and Propagation, Vol. 5, No. 1, 2023 (pp. 18-25).

Introduction to Electromagnetic Theory in Geophysics

Electromagnetic theory provides a powerful framework for studying the Earth's subsurface properties and structures. In geophysics, electromagnetic methods are employed to probe the electrical conductivity distribution of the Earth's interior, which is influenced by factors such as lithology, fluid content, and temperature.[1-17] By measuring electromagnetic signals emitted or induced in the Earth's surface, geophysicists can infer subsurface properties and delineate geological features of interest. Electromagnetic theory plays a pivotal role in geophysics, providing insights into the interactions between electromagnetic fields and the Earth's subsurface. In geophysical exploration, electromagnetic methods are widely employed to study the Earth's interior structure, detect subsurface features, and infer geological properties as shown in Fig. 1.

Maxwell's equations form the foundation of electromagnetic theory, describing how electric and magnetic fields interact and propagate in space. These equations govern the behavior of electromagnetic waves, guiding the design and interpretation of geophysical experiments.

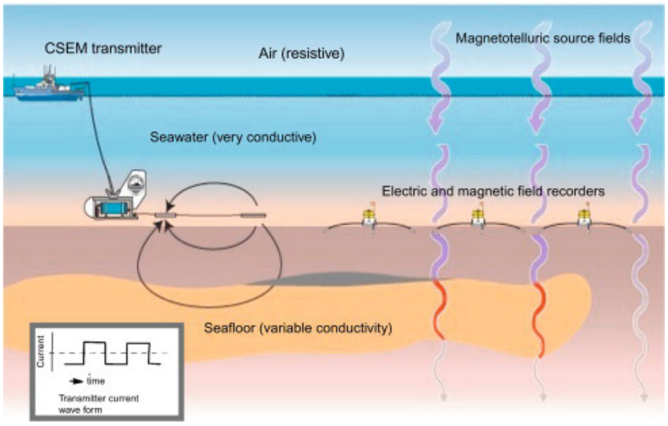

Fig.1: Electromagnetic Method

In geophysics, electromagnetic waves are generated by artificial sources such as electromagnetic transmitters or induced by natural phenomena like solar radiation. As these waves propagate through the Earth's subsurface, they interact with geological formations, causing reflections, refractions, and diffractions that carry valuable information about the Earth's composition and structure.

Geophysicists utilize various electromagnetic methods, including magnetotellurics, electromagnetic induction, and ground-penetrating radar, to probe subsurface properties. These methods exploit differences in electrical conductivity, magnetic susceptibility, and dielectric permittivity of geological materials to infer subsurface structures, detect mineral deposits, or monitor environmental changes.

Electromagnetic theory provides the framework for understanding the complex interactions between electromagnetic fields and geological materials. By analyzing the propagation and response of electromagnetic waves, geophysicists can interpret data collected from field measurements and derive valuable insights into subsurface properties.

Advancements in computational modeling, instrumentation, and signal processing techniques have enhanced the capabilities of electromagnetic methods in geophysics, enabling high-resolution imaging and deeper penetration into the Earth's subsurface. As a result, electromagnetic exploration techniques continue to play a crucial role in advancing our understanding of the Earth's structure, resource exploration, and environmental monitoring.

Principles of Electromagnetic Theory for Geophysical Applications

The principles of electromagnetic theory govern the interaction between electromagnetic fields and geological materials. Key concepts include Maxwell's equations, which describe the behavior of electric and magnetic fields in space, and Ohm's law, which relates electrical conductivity to the flow of electric current. In geophysics, electromagnetic waves propagate through the Earth's subsurface, where they are attenuated, reflected, or scattered by geological structures and material properties. Understanding the electromagnetic response of the Earth allows geophysicists to interpret field measurements and infer subsurface properties [18]-[37].Electromagnetic theory serves as a fundamental framework for understanding and interpreting geophysical phenomena through the study of electromagnetic fields and their interactions with geological structures. In geophysical applications, electromagnetic theory is applied to investigate subsurface properties, map geological structures, and explore natural resourcesas shown in Fig. 2.

Maxwell's equations form the cornerstone of electromagnetic theory, providing mathematical

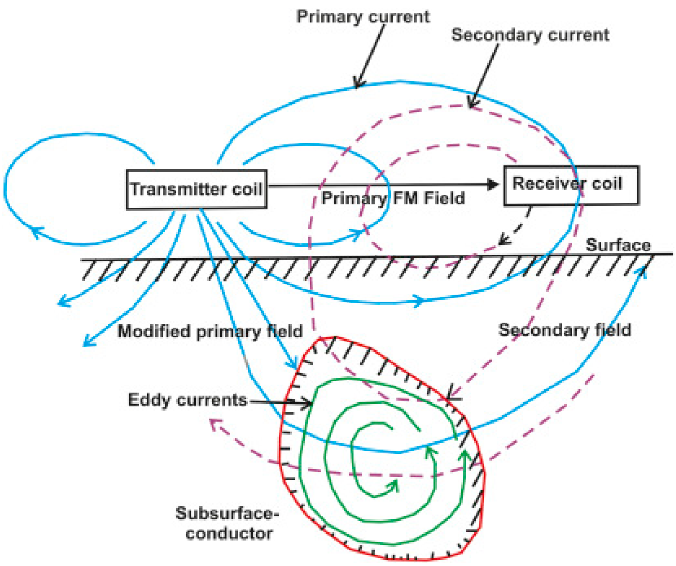

Fig. 2: Electromagnetic Survey

descriptions of how electric and magnetic fields interact and propagate. These equations govern the behavior of electromagnetic waves, guiding the design and interpretation of geophysical experiments. Understanding Maxwell's equations allows geophysicists to predict and analyze the behavior of electromagnetic fields in various geological settings.

One key principle of electromagnetic theory applied in geophysics is the relationship between electromagnetic properties and subsurface geological features. Geological materials exhibit different electrical conductivity, magnetic susceptibility, and dielectric permittivity, which influence how electromagnetic waves interact with them. By measuring the response of electromagnetic fields to geological structures, geophysicists can infer valuable information about subsurface properties such as lithology, fluid content, and structural heterogeneity.

Another principle is the concept of electromagnetic wave propagation and scattering. When electromagnetic waves encounter boundaries or interfaces between different geological formations, they undergo reflection, refraction, and diffraction, leading to changes in their amplitude, phase, and polarization. By analyzing these wave interactions, geophysicists can delineate subsurface boundaries, identify geological discontinuities, and characterize geological structures.

Furthermore, electromagnetic theory enables the design and optimization of geophysical survey methods and instrumentation. By applying principles such as antenna theory, signal processing, and electromagnetic modeling, geophysicists develop techniques for generating electromagnetic fields, measuring their responses, and interpreting acquired data. These methods include techniques such as magnetotellurics, electromagnetic induction, ground-penetrating radar, and controlled-source electromagnetic surveys.

In summary, the principles of electromagnetic theory form the foundation for geophysical exploration, providing a systematic framework for understanding the interactions between electromagnetic fields and geological structures. By leveraging these principles, geophysicists can extract valuable subsurface information, advancing our knowledge of Earth's composition, structure, and resources.

Methods and Techniques in EM Geophysics

Electromagnetic methods in geophysics encompass a variety of techniques for measuring and analyzing electromagnetic signals. These include:

- **Time-Domain Methods:** Time-domain electromagnetic (TDEM) methods involve transmitting transient electromagnetic pulses into the Earth's subsurface and measuring the transient responses. TDEM surveys are used to map subsurface conductivity variations and detect conductive targets such as mineral deposits and groundwater reservoirs. Time-domain methods in geophysics refer to a class of techniques used to analyze the response of geological materials to transient electromagnetic signals over time. Unlike frequency-domain methods, which examine the frequency content of electromagnetic signals, time-domain methods focus on the temporal behavior of electromagnetic fields and their interaction with subsurface structuresas shown in Fig. 3.

One common time-domain method is time-domain electromagnetic (TDEM) surveys, where a transient electromagnetic pulse is generated and its response is measured over a range of time intervals. By analyzing the decay of electromagnetic signals as they propagate through the Earth's subsurface, TDEM surveys provide

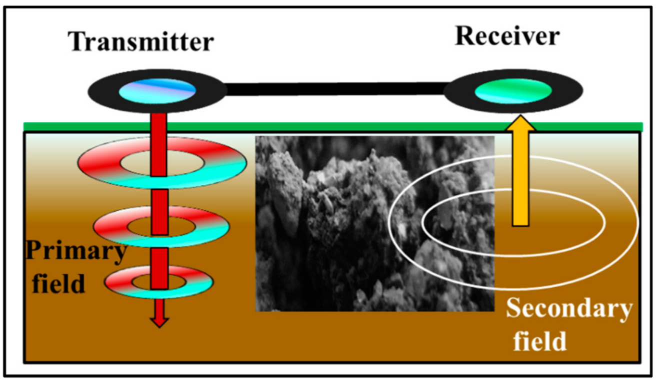

Fig. 3: Techniques in EM Geophysics

information about the electrical conductivity distribution of geological formations.[38-43].

Another time-domain method is ground-penetrating radar (GPR), which uses pulsed electromagnetic signals to image subsurface features such as soil layers, buried objects, and geological interfaces. By analyzing the reflection and scattering of electromagnetic waves, GPR provides high-resolution images of subsurface structures, making it valuable for archaeological studies, environmental assessments, and infrastructure inspections.

Time-domain methods offer several advantages, including the ability to resolve complex subsurface structures, detect small-scale features, and discriminate between different geological materials. Additionally, they are versatile and applicable to a wide range of geological settings, from shallow near-surface investigations to deep exploration targets. Overall, time-domain methods play a critical role in geophysical exploration, providing valuable insights into the Earth's subsurface properties and processes.

- **Frequency-Domain Methods:** Frequency-domain electromagnetic (FDEM) methods utilize continuous-wave electromagnetic signals at various frequencies to probe the Earth's subsurface. FDEM surveys provide information on subsurface conductivity distribution and depth of investigation, making them suitable for mineral exploration, hydrogeological studies, and environmental monitoring. Frequency-domain methods in geophysics are techniques used to analyze the frequency content of electromagnetic signals and their interaction with geological structures. These methods exploit the variation of electromagnetic properties with frequency to infer subsurface properties and map geological features.

One common frequency-domain method is frequency-domain electromagnetic (FDEM) surveys, where electromagnetic signals at specific frequencies are transmitted into the Earth's subsurface, and the response is measured. By analyzing the amplitude and phase of electromagnetic signals at different frequencies, FDEM surveys provide information about the electrical conductivity distribution of geological formationsas shown in Fig. 4.

Another frequency-domain method is magnetotellurics (MT), which measures natural electromagnetic signals generated by variations in the Earth's magnetic and electric fields over a range of frequencies. By analyzing the impedance tensor, which describes the relationship between electric and magnetic fields, MT surveys can

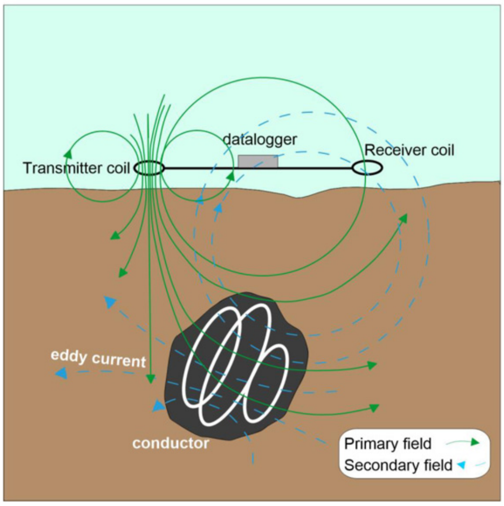

Fig. 4: Primary and secondary fields

infer the electrical resistivity structure of the Earth's subsurface.

Frequency-domain methods offer several advantages, including the ability to probe different depths and resolutions depending on the frequency range used. They are also sensitive to variations in geological properties such as mineral content, fluid saturation, and structural heterogeneity. Overall, frequency-domain methods are valuable tools for geophysical exploration, providing insights into the Earth's subsurface composition, structure, and dynamics.

- **Ground Penetrating Radar (GPR):** GPR is a high-resolution electromagnetic technique that uses radar pulses to image subsurface structures and geological features. GPR surveys are commonly used in archaeological studies, engineering investigations, and environmental assessments to detect buried objects, soil layers, and subsurface anomalies. Ground Penetrating Radar (GPR) is a geophysical technique used to non-invasively image subsurface features and structures. It operates by transmitting high-frequency electromagnetic pulses into the ground and measuring the reflected signals that bounce back from underground interfaces, such as soil layers, rock formations, or buried objects. GPR systems typically consist of a transmitter antenna that emits electromagnetic pulses, a receiver antenna that detects the reflected signals, and a control unit for data processing and display.

GPR is capable of providing detailed images of subsurface features with high spatial resolution, making it a valuable tool for various applications, including archaeological surveys, environmental assessments, geological mapping, and infrastructure inspections. The depth of penetration and resolution of GPR surveys depend on factors such as the frequency of the transmitted signals, the electrical properties of the subsurface materials, and the antenna configuration.

One of the key advantages of GPR is its ability to rapidly acquire data over large areas with minimal disturbance to the ground surface. It can be deployed in diverse terrain and environmental conditions, including urban areas, forests, deserts, and polar regions. However, GPR has limitations, such as limited penetration depth in highly conductive or attenuative materials, and challenges in interpreting complex subsurface structures. Nonetheless, ongoing advancements in GPR technology and data processing algorithms continue to enhance its capabilities and expand its range of applications in geophysics and beyond.

Applications of Electromagnetic Theory in Geophysics

Electromagnetic methods find diverse applications in geophysics across various fields, including:

- **Mineral Exploration:** Electromagnetic surveys are used to identify and delineate mineral deposits based on their electrical conductivity and magnetic susceptibility [44]-[48]. EM methods are particularly useful for detecting conductive ores such as base metals, precious metals, and graphite. Mineral exploration is the process of identifying and assessing areas of the Earth's crust that may contain valuable mineral deposits. It plays a crucial role in locating and extracting minerals essential for various industrial, commercial, and technological applications. Geophysical methods, including ground-based and airborne techniques, are widely used in mineral exploration to detect and characterize subsurface mineral depositsas shown in Fig. 5.

One of the key geophysical methods employed in mineral exploration is electromagnetic (EM) surveys. EM surveys

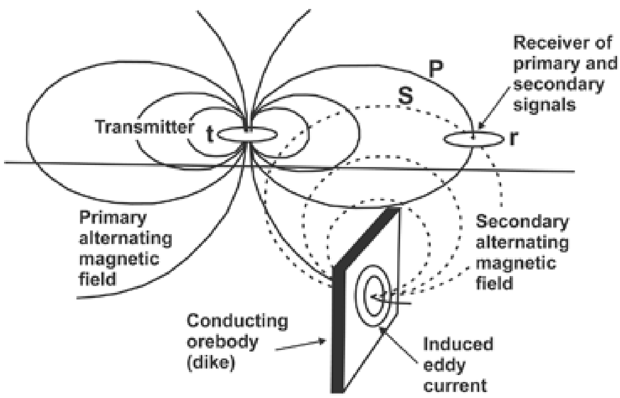

Fig. 5: FDEM

measure the electrical conductivity and magnetic susceptibility of the subsurface to identify potential mineralization zones. For example, frequency-domain electromagnetic (FDEM) surveys and time-domain electromagnetic (TDEM) surveys are commonly used to map conductive and resistive geological formations associated with mineral deposits.

Another important geophysical technique in mineral exploration is gravity and magnetic surveys. These surveys measure variations in the Earth's gravitational and magnetic fields caused by subsurface geological structures, such as ore bodies, faults, and mineralized zones. By analyzing gravity and magnetic anomalies, geophysicists can infer the presence and extent of mineral deposits.

Additionally, seismic surveys are utilized in mineral exploration to image subsurface geological structures and identify potential mineralization targets. Seismic waves are generated and recorded to map rock properties, fault structures, and stratigraphic layers that may host mineral deposits.

Overall, geophysical methods play a vital role in mineral exploration by providing valuable insights into subsurface geological structures, lithologies, and mineralization processes. By combining geophysical surveys with geological mapping, geochemical analysis, and drilling techniques, mineral explorers can efficiently and effectively locate and evaluate mineral deposits for economic exploitation.

- **Hydrogeological Studies:** Electromagnetic surveys provide valuable information on groundwater resources, aquifer properties, and hydrogeological structures. EM methods are employed to delineate groundwater flow paths, map saline intrusion, and locate fresh groundwater reservoirs. Hydrogeological studies involve the investigation of groundwater flow, distribution, and quality within the Earth's subsurface. These studies are essential for understanding the behavior of groundwater systems, managing water resources, and assessing potential environmental impacts. Geophysical methods play a crucial role in hydrogeological studies by providing non-invasive and high-resolution information about subsurface hydrological properties.

Electrical resistivity tomography (ERT) is commonly used in hydrogeological studies to map subsurface variations in electrical resistivity, which are indicative of changes in lithology, fluid content, and groundwater flow paths. By imaging subsurface resistivity distributions, ERT can delineate aquifer boundaries, characterize groundwater contamination plumes, and identify preferential flow pathways.

Seismic methods, such as seismic refraction and reflection surveys, are also employed in hydrogeological studies to map subsurface geological structures, assess aquifer properties, and locate potential groundwater resources. Seismic data can provide insights into subsurface lithology, porosity, and permeability, which are crucial for understanding groundwater flow dynamics and predicting groundwater availabilityas shown in Fig. 6.

Ground-penetrating radar (GPR) is another valuable geophysical tool in hydrogeological studies, particularly for investigating shallow groundwater systems and detecting subsurface features such as aquifer boundaries, bedrock fractures, and buried channels. GPR data can help delineate groundwater recharge zones, identify potential contamination sources, and assess the integrity of groundwater storage facilities.

Overall, geophysical methods are indispensable in hydrogeological studies, offering valuable information about subsurface hydrological properties and processes. By integrating geophysical surveys with hydrological modeling, groundwater monitoring, and field investigations, hydrogeologists can develop comprehensive understandings of groundwater systems and make informed decisions for sustainable water resource management and environmental protection.

- **Hydrocarbon Exploration:** Electromagnetic surveys play a role in hydrocarbon exploration by detecting resistive hydrocarbon accumulations beneath

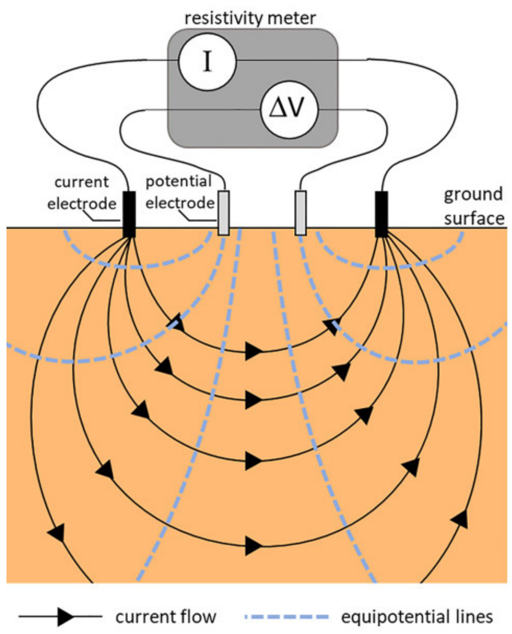

Fig. 6: Ground-penetrating radar

the Earth's surface. EM methods are used to map subsurface structures, identify potential oil and gas traps, and characterize reservoir properties. Hydrocarbon exploration is the process of identifying and assessing subsurface areas that may contain oil and gas deposits. It involves the systematic search for geological structures and formations conducive to hydrocarbon accumulation. Geophysical methods are instrumental in hydrocarbon exploration, providing valuable insights into the subsurface geology, fluid content, and potential hydrocarbon reservoirsas shown in Fig. 7.

Seismic surveys are the cornerstone of hydrocarbon exploration, utilizing sound waves to image subsurface geological structures and identify potential hydrocarbon traps. Seismic data help geoscientists map stratigraphic layers, faults, and anticlines that may indicate the presence of oil and gas reservoirs.

Electromagnetic (EM) surveys are also utilized in hydrocarbon exploration to detect subsurface hydrocarbon accumulations. EM methods measure variations in electrical conductivity caused by hydrocarbons and brines, enabling the delineation of potential reservoirs and the characterization of fluid properties.

Gravity and magnetic surveys complement seismic and EM methods by providing additional information about subsurface density variations and structural features. Gravity anomalies can indicate the presence of sedimentary basins or salt domes associated with hydrocarbon traps, while magnetic anomalies may reveal igneous intrusions or fault zones.

Overall, geophysical methods play a crucial role in hydrocarbon exploration by providing valuable information about subsurface structures, lithologies, and fluid properties. By integrating seismic, EM, gravity, and magnetic surveys, hydrocarbon explorers can efficiently and effectively locate and evaluate potential oil and gas reserves, contributing to the sustainable development of energy resources.

- **Environmental Monitoring:** Electromagnetic methods are employed in environmental studies to assess soil contamination, monitor groundwater quality, and detect subsurface pollution plumes. EM surveys help identify sources of contamination, track migration pathways, and evaluate remediation strategies. Environmental monitoring involves the systematic assessment and tracking of environmental parameters to evaluate changes over time, detect pollution sources, and safeguard ecosystems. Geophysical methods are valuable tools in environmental monitoring, providing non-invasive and high-resolution information about subsurface properties and processesas shown in Fig. 8.

Electrical resistivity tomography (ERT) is commonly used in environmental monitoring to map subsurface variations in electrical resistivity, which can indicate changes in soil moisture content, groundwater levels, and contaminant plumes. By imaging subsurface resistivity distributions, ERT can help identify contamination sources, delineate groundwater flow paths, and assess the effectiveness of remediation efforts.

Ground-penetrating radar (GPR) is another important geophysical technique in environmental monitoring, particularly for investigating shallow subsurface features such as buried utilities, landfill boundaries, and underground storage tanks. GPR data can provide detailed images of subsurface structures, facilitating the detection and characterization of environmental hazards.

Seismic methods, such as seismic refraction and reflection surveys, are also employed in environmental monitoring to assess subsurface geology, detect subsurface voids, and monitor the stability of infrastructure such as dams and levees. Seismic data can help identify potential

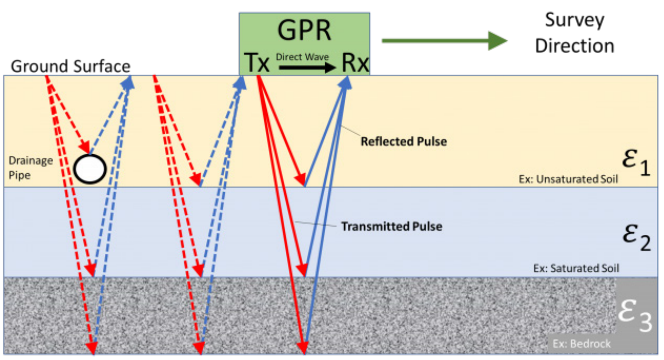

Fig. 7: Ground Penetrating Radar (GPR) flow

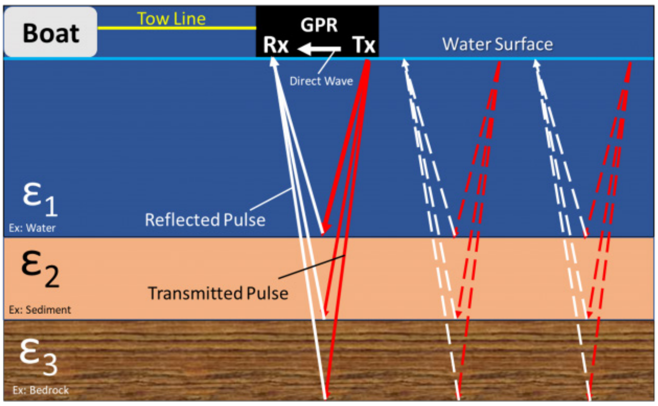

Fig. 8: Waterborne Ground Penetrating Radar -II

geohazards and inform mitigation strategies to protect the environment and public safety.

Overall, geophysical methods play a vital role in environmental monitoring by providing valuable information about subsurface conditions and processes. By integrating geophysical surveys with other monitoring techniques such as groundwater sampling, soil analysis, and remote sensing, environmental scientists can gain a comprehensive understanding of environmental dynamics and make informed decisions for sustainable management and protection of natural resources.

Advances in Electromagnetic Geophysics

Recent advancements in electromagnetic geophysics have led to improved measurement techniques, data processing algorithms, and interpretation methods.[26-32] These include:

- **Advanced Instrumentation:** Advances in electromagnetic instrumentation, such as multi-channel receivers, broadband transmitters, and vector sensors, enable high-resolution imaging and multi-parameter data acquisition in EM surveys.
- **Numerical Modeling:** Numerical modeling techniques, such as finite-difference, finite-element, and integral-equation methods, facilitate forward modeling and inversion of electromagnetic data, allowing geophysicists to reconstruct subsurface conductivity models with high accuracy and resolution.
- **Multi-Physics Integration:** Integration of electromagnetic data with other geophysical methods, such as seismic, gravity, and magnetic surveys, enhances subsurface imaging and interpretation by providing complementary information on geological structures and physical propertiesas shown in Fig. 9.

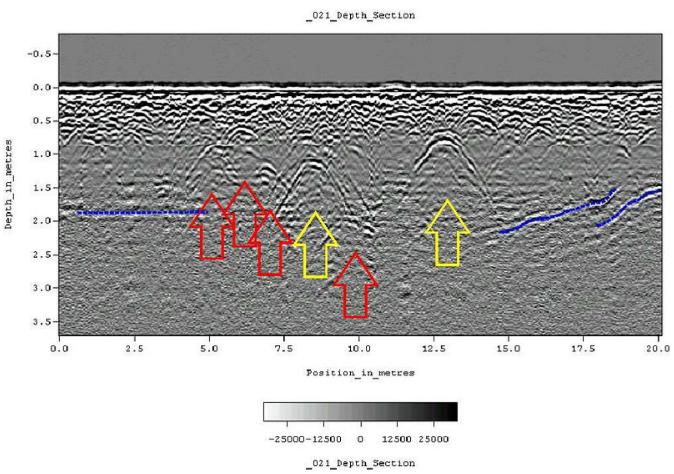

Fig. 9: Ground-penetrating radar - III

- Machine Learning and Data Analytics:Machine learning algorithms and data analytics techniques are increasingly being applied to analyze large-scale electromagnetic datasets and extract meaningful insights, enabling automated interpretation and decision-making in geophysical exploration.

Challenges and Future Directions:

Despite the advancements in electromagnetic geophysics, several challenges and opportunities for future research exist:

- **Resolution and Depth Penetration:** Improving the resolution and depth penetration of electromagnetic surveys remains a challenge, particularly in environments with complex geological structures, heterogeneous properties, and cultural noise.
- **Quantitative Interpretation:** Developing robust inversion algorithms and quantitative interpretation techniques for electromagnetic data is essential for accurately characterizing subsurface conductivity distributions and extracting actionable information for resource exploration and environmental management.
- **Instrumentation and Field Deployment:** Enhancing the portability, reliability, and efficiency of electromagnetic instrumentation for field deployment in remote or challenging environments is critical for expanding the applicability and accessibility of EM geophysics.
- **Interdisciplinary Collaboration:** Fostering interdisciplinary collaboration between geophysicists, geologists, engineers, and data scientists is essential for advancing electromagnetic geophysics and addressing complex geological and environmental challenges.

Conclusion

Electromagnetic theory serves as a cornerstone in geophysics, providing essential tools and methodologies for investigating the Earth's subsurface properties and structures. By leveraging electromagnetic methods, researchers and practitioners can address key challenges in mineral exploration, hydrogeology, hydrocarbon exploration, and environmental monitoring. Continued advancements in instrumentation, numerical modeling, multi-physics integration, and data analytics hold promise for unlocking new insights into the Earth's subsurface and driving innovations in geophysical exploration and resource management. Through collaborative research efforts and interdisciplinary approaches, electromagnetic geophysics will continue to play a vital role in advancing our understanding of the Earth's complex dynamics and supporting sustainable development practices.

References

1. Keller, George Vernon, and Frank C. Frischknecht. "Electrical methods in geophysical prospecting." (1966).
2. Murphy, JOHN N., and HOWARD E. Parkinson. "Underground mine communications." Proceedings of the IEEE 66.1 (1978): 26-50.
3. Parkhomenko, Eleonora Ivanovna. Electrical properties of rocks. Springer Science & Business Media, 2012.
4. Bhattacharya, P. "Direct current geoelectric sounding: Principles and interpretation." (2012).
5. Laine, Edwin F., and R. Jeffrey Lytle. "A computer program for four probe resistivity measurements in a horizontally layered earth." IEEE Transactions on Geoscience Electronics 14.4 (1976): 232-235.
6. Koefoed, Otto, and Geosounding Principles. "1: Resistivity Sounding Measurements¤." (1979).
7. Gething, Phillip JD. Radio direction finding and superresolution. No. 33. IET, 1991.
8. Sunde, Erling Ditlef. "Earth conduction effects in transmission systems." (No Title) (1949).
9. Hill, David A., and James R. Wait. "Subsurface electromagnetic fields of a grounded cable of finite length." Canadian Journal of Physics 51.14 (1973): 1534-1540.
10. Wait, James R., and Kenneth P. Spies. "Subsurface electromagnetic fields of a line source on a conducting half-space." Radio Science 6.8-9 (1971): 781-786.
11. Jeon, Sungho, et al. "Universal Shift Register: QCA based Novel Technique for Memory Storage Modules." Journal of VLSI circuits and systems 5.02 (2023): 15-21.
12. Chakma, Kriti S., and Md Sarwar U. Chowdhury. "CSA Implementation Using Novel Methodology: RTL Development." Journal of VLSI circuits and systems 5.02 (2023): 22-28.
13. Shahrour, Isam, and Xiongyao Xie. "Role of Internet of Things (IoT) and crowdsourcing in smart city projects." Smart Cities 4.4 (2021): 1276-1292.
14. Nam, H., MGV Nunes, and N. Loukachevitch. "3D Printing: Next Generation Realization For Future Applications." International Journal of communication and computer Technologies 11.2 (2023): 19-24.