Penetrating remote sensing: Next-generation remote sensing for transparent earth

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Building upon a unified theoretical framework (based on electromagnetic principles and considering interactions with the Earth's subsurface materials), we consider a synergistic blend of high-spectral, electromagnetic, and diverse multi-physics techniques to introduce a new concept of penetrating remote sensing. By seamlessly amalgamating the interplay between multiple physical fields, penetrating remote sensing allows us to understand the Earth from its surface to its interior, effectively uncovering information about the planet's internal composition. The outcome of this new concept encompasses detailed imagery and three-dimensional models, offering insights into the distribution, structure, properties, and dynamic behavior of materials residing within the Earth. It empowers us to delve into the profound layers of the Earth, unveiling its structural composition and evolutionary processes. This deeper understanding encompasses vital aspects concerning the Earth's crust, mantle, and core, comprehending temperature distributions, flow patterns, and other crucial information that enriches our knowledge of the planet's interior.

Our research addresses topics such as how to overcome technical challenges in achieving three-dimensional imaging and modeling of the Earth's surface, shallow subsurface, and deep-seated material structures and movements. We establish a unified physical mechanism of interaction between whole-spectrum electromagnetic fields and subsurface materials, which can alter the functional theory of conventional single-physical-field detecting methods (that are focused on their own distinct physical principles). Our new concept of penetrating remote sensing can reduce uncertainties, improve resolution, and enhance the accuracy of subsurface target detection.

CONCEPT OF PENETRATING REMOTE SENSING

Full-spectrum electromagnetic field refers to the whole range of electromagnetic radiation, including ultraviolet, visible light, infrared, microwave, and other low-frequency electromagnetic waves.[1] Penetrating remote sensing techniques involve static magnetic and gravity as classical potential fields. A unified numerical framework for describing the interaction mechanisms between the electromagnetic field and multi-physics media is the key and aim of penetrating remote sensing, which allows us to harness and manipulate these waves in order to achieve deep-Earth space sensing capabilities (Figure 1).

As shown in Figure 1, penetrating remote sensing relies on high-precision numerical simulation techniques for different frequencies of electromagnetic waves and potential fields. It involves the study of coupling mechanisms between electromagnetic and potential fields, the development of coupled inversion techniques for various kinds of data, and high-precision three-dimensional imaging of various media at different depths within the Earth's interior. Penetrating remote sensing explores the interaction between earth surface/subsurface physical properties with variant frequency electromagnetic waves, and it is a multidisciplinary area of research including hyperspectral imaging, electromagnetic, and potential field methods. The detecting depth, resolution, and physical properties of these methods are complementary.

The relationship between electromagnetic wave frequency and penetrating depth is inversely proportional.[2] Various detection technologies are employed in remote sensing to penetrate different depth ranges.[3,4] These detection technologies are categorized based on their electromagnetic frequencies, as outlined below. Hyperspectral sensors are primarily sensitive to surface reflectance, which

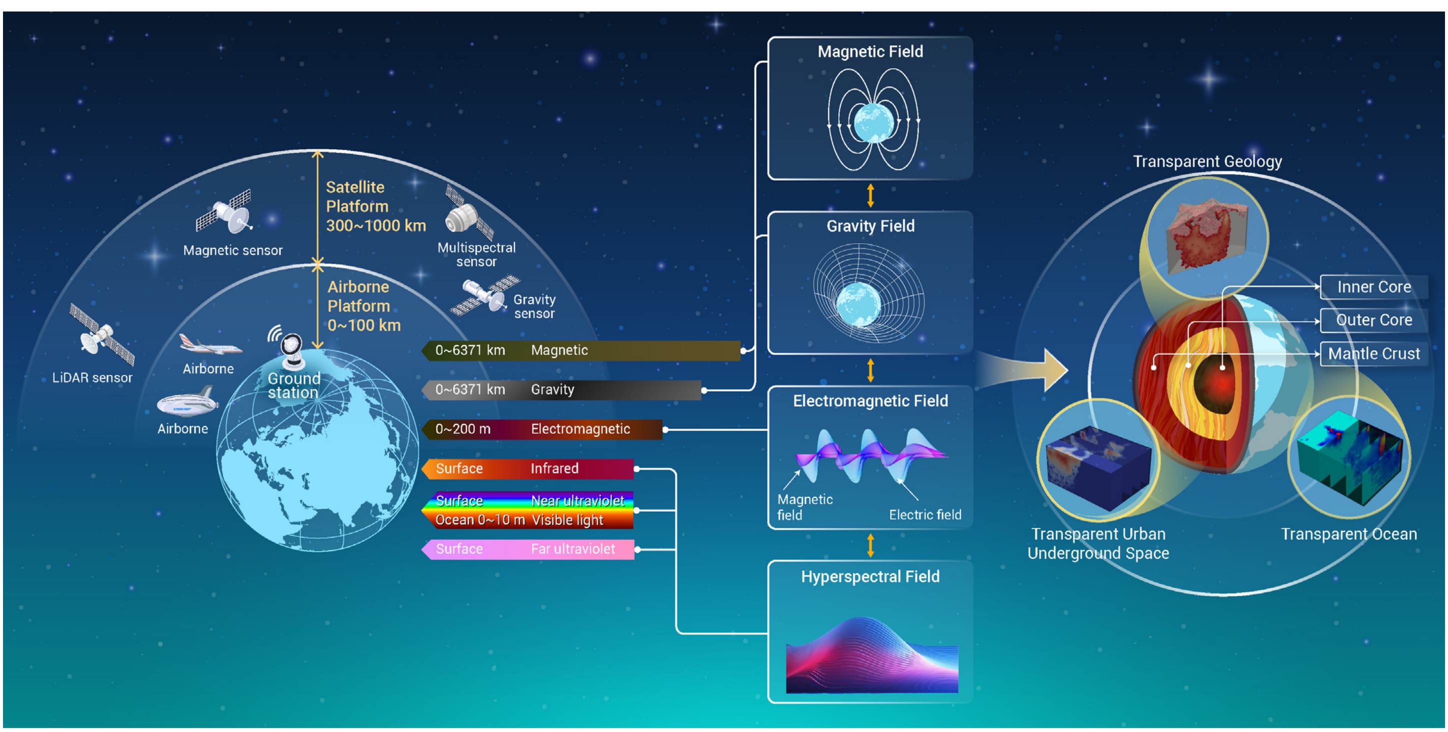

Figure 1. Concept of penetrating remote sensing

covers the interaction between incoming radiation and the top layer of the Earth's surface. Electromagnetic (EM) detection[3] is a geophysical method that uses EM fields to investigate the electrical conductivity of subsurface materials from an airborne or ground platform. Magnetometry[4] measures the secondary anomaly static magnetic field that is excited by the intense geomagnetic field. A geomagnetic field is generated by the flowing of molten iron fluids within the Earth's outer core. So, the physical property (i.e., the susceptibility of both near-surface targets—200 m deep—and the interior structure of the Earth) can be estimated according to surface-observed magnetic data. The gravity field is governed by the theory of general relativity. High-resolution gravity detection allows for detailed imaging interior density structures, and it can help to identify and sense different rock types, faults, mineral deposits, and groundwater reservoirs.

At present, quantitative interpretation of multi-physical fields is still a challenging task, mainly due to the fact that it its correlated with multiple disciplines. Consistency among the different datasets and their convergence toward a common subsurface model increases confidence in the interpretation and reduces potential risks, while it can also provide a means to validate interpretations by cross-validating results across multiple methods and datasets.

METHODOLOGY AND TECHNOLOGIES OF PENETRATING REMOTE SENSING

The availability of advanced remote sensing platforms brings the concept of penetrating remote sensing into a new era of multi-level, three-dimensional, multi-angle, all-round, and all-weather Earth observations. These platforms are divided into satellite, airborne, and ground-based, according to the vertical height from the Earth's surface. Our system for implementing the concept of penetrating remote sensing consists of the following components.

Multi-physics field-coupling simulation

Physically, the EM waves in each spectral band are essentially the same. So, it is possible to unify the simulation process of multi-source geophysical field simulations into a unified theory and numerical framework.

Multi-physics field feature library

The multi-physics field observation feature library contains a comprehensive collection of observed features or phenomena across full EM bands for detecting surface and subsurface targets. The library serves as a reference database for comparing observed geophysical features with known patterns and anomalies.

Multi-physics data compensation

Multi-physics field data need to be combined and integrated to create a unified dataset. This involves aligning and correlating the data points spatially and temporally, removing interferences, and ensuring that they are in a common coordinate system.

Multi-physics coupling inversion

The multi-physics field-coupling framework is formed based on the multi-physics field-coupling simulation. Each geophysical dataset can be simultaneously inverted to estimate subsurface three-dimensional models that are consistent with the observed dataset of other multiple methods.

Another typical utilization of penetrating remote sensing is oceanographic profiling exploration. By utilizing sensors for oceanographic profiling,[5] the existing capabilities of marine remote sensing can be extended from two dimensions to three dimensions, with applications encompassing biogeochemistry, ecology, ocean dynamics, and target detection. Three complex issues need be considered during the process.

The inherent optical properties (IOPs) of the water column. The absorption and scattering of various particles in the water column lead to a rapid attenuation of the laser energy. Therefore, the understanding of IOPs for the water column is critical for oceanographic profiling exploration.

The vertical stratification phenomenon in the water column. The vertical stratification of the water properties is related to the depth of the mixed layer and the different types of pycnoclines.

The forward simulation and the inversion of the models. The input parameters include the IOPs of the water column and the sensor system parameters. By performing simulations, the models calculate the change of energy and characteristics from the sensor data collection process.

APPLICATIONS OF PENETRATING REMOTE SENSING

Transparent geology

The Earth has a radius of 6,379 km, and it is composed by rock, magma, and molten iron fluids. Limited by the capabilities of current geophysical technologies, many scientific questions remain. Satellite-based magnetometry and gravimetry are among the very few geophysical methods that can penetrate the subsurface of the Earth several thousand kilometers to characterize its interior structure. At present, gravity and magnetic data interpretation lie on a single physical property model. Their resolution is below the application requirements. By integrating diverse datasets and multi-physics properties, the discrimination of subsurface deep structures can be enhanced, as well as the delineation of tectonics structures, predicting the motion of the mantle and the core system.

Transparent urban underground space

Urban areas can exhibit complex subsurface features, including multiple layers, voids, buried foundations, and anthropogenic disturbances. Distinguishing between different subsurface targets and accurately interpreting geophysical data are still challenging and largely depend on human expertise and additional supporting information. The performance of large-scale geophysical methods is very limited in coverage and resolution for urban data interpretation. One of the most promising solutions for urban underground detection is to integrate multiple data sources such as gravity, ground-penetrating radar, and EM methods by developing multi-physics coupling inverse technology to reconcile inconsistencies.

Transparent ocean

In natural ocean water, a maximum suspended layer of chlorophyll concentration would be generated due to the combined effects of nutrient gradients and natural lighting conditions, which is known as the chlorophyll scattering layer (CSL). As an important indicator in the ocean, the distribution of chlorophyll in the ocean subsurface layer is critical for many applications such as the estimation of ocean primary productivity and the quantization of global carbon cycle. One of the most promising solutions to detect the ocean chlorophyll profile is based on LiDAR technology (i.e., employing a blue or green laser to acquire information about the ocean subsurface profile).

CONCLUSION

We describe the concept of penetrating remote sensing, a new-generation detecting technology that integrates hyperspectral, EM, gravity, and magnetic data on satellite, airborne, and ground-based platforms. With the development of advanced remote sensing platforms, the concept of penetrating remote sensing brings a new era of multi-level, three-dimensional, multi-angle, all-round, and all-weather Earth observations. This concept has important applications in geophysics (for characterizing the actual interior structure of the Earth), mapping of urban areas, and better understanding of the ocean subsurface, which are not within reach of current remote sensing technologies.

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DECLARATION OF INTERESTS

The authors declare no competing interests.