IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received June 18, 2019, accepted July 12, 2019, date of publication July 25, 2019, date of current version August 14, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2930961

The Development and Applications of the Semi-Airborne Electromagnetic System in China

XIN WU[1,2,3], GUOQIANG XUE[1,2,3], GUANGYOU FANG[4], XIU LI[5], AND YANJU JI[6]
[1]Key Laboratory of Mineral Resources, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[2]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
[3]Institutions of Earth Science, Chinese Academy of Sciences, Beijing 100029, China
[4]Institute of Electronics, Chinese Academy of Sciences, Beijing 100190, China
[5]School of Geology and Engineering, Chang'an University, Xi'an 710054, China
[6]College of Electrical Engineering and Instrumentation, Jilin University, Changchun 130026, China

Corresponding author: Guoqiang Xue (ppxueguoqiang@163.com)

This work was supported in part by the Major National Research Equipment Development Project under Grant ZDYZ2012-1-03, in part by the Key Technologies for Deep Resources Prospecting of Beijing Municipal Science and Technology Commission under Grant Z181100005718001, and in part by the Natural Science Foundation of China under Grant NSFC-41830101.

ABSTRACT Semi-airborne electromagnetic method (SAEM) is a geophysical electromagnetic detection method which places the transmitting subsystem on the ground and the receiver subsystem on the flight platform. This transceiver configuration has been found to be more efficient than that of the traditional ground electromagnetic methods while it can get much deeper penetration than the traditional airborne electromagnetic methods. Therefore, the SAEM has been widely used in mineral, groundwater, geothermal, and other resources exploration fields. In this paper, we would like to take the most key problems encountered in the SAEM system design and application as the starting point, and then we focus mainly on reviewing the progress of the transmitter, sensor, and receiver technology, as well as data processing, modeling, and imaging methods of the SAEM in China. In particular, the research progress of multi-source SAEMs will be introduced. Beyond that, two prospecting examples with different SAEM systems will be introduced. Finally, we will discuss the future of the SAEM in terms of equipment developing, data processing, modeling and inversion, to promote the research and application in this field to a higher level.

INDEX TERMS Semi-airborne, ground-air, electromagnetic, multi-source, exploration.

I. INTRODUCTION

Electromagnetic method acquires the electromagnetic transfer function of the earth system by observing the electromagnetic response excited by natural or artificial sources, and extracts the distribution information of the electrical parameters of the earth on this basis [1]. The traditional electromagnetic observation devices are located on the surface of the earth, and only a few constraints are imposed on the detection equipment, therefore the detection results obtained by the traditional electromagnetic methods will take into account both the large detection depth and the shallow high resolution. However, the work efficiency of the traditional methods has been found to be low, particularly in the desert, the Gobi, mountain, wetland and water network dense areas. With the intent of overcoming the limitations of various topographical and geomorphological conditions, the Airborne Electromagnetic Method (AEM) was proposed in the middle of the last century.

In AEM, all of the components of the observation system will be mounted on a flight platform. In accordance with the selected method, the AEM can be further divided into two types: Airborne Transient Electromagnetic (ATEM) and Airborne Frequency-domain Electromagnetic (AFEM). In the early stage of AEM technology, the helicopters had also been tried as a platform due to its obvious advantages of low-altitude and low-speed performance, but limited by its load capacity at that time, the flight platforms used in AEM were mainly fixed-wing aircraft from the late 20th century to 2000. In recent years, with the dramatic improvements in performance, the helicopter has become the main platform of AEM (Fig.1). However, due to the dual constraints of the power

The associate editor coordinating the review of this manuscript and approving it for publication was Giovanni Angiulli.

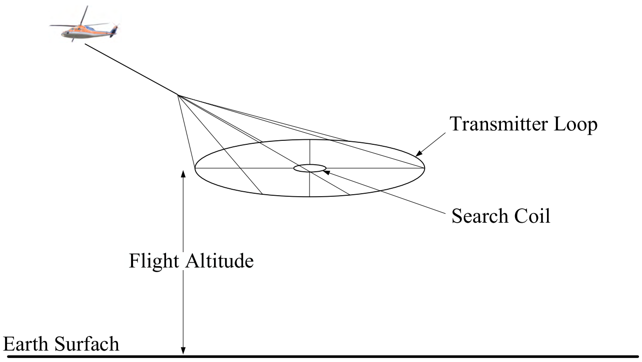


FIGURE 1. Helicopter-borne TEM.

supply and allowable carrying weight of the helicopters, the maximum detection depth which can be achieved by the existing AEM systems remains still relatively limited [2]–[4].

Semi-Airborne Electromagnetic Method (SAEM) is a method which combines the advantages of both ground and airborne method. SAEM usually deploys the high-power transmitting system (including transmitter and transmitting antenna) on the ground, and also uses a flight platform to carry sensors (induction magnetometer, or search coil) and acquisition system for aerial observations [1], so as to achieve a balance between detection depth and work efficiency. There are also two types of SAEM: Semi-airborne Transient electromagnetic (SATEM) and Semi-airborne frequency-domain electromagnetic (SAFEM). Both of these methods have been applied in mineral resources exploration, groundwater, geothermal resources exploration, geological mapping, environmental monitoring and other fields [5]–[8].

Compared with the traditional AEM, it has been found that, because the SAEM transmitting system is placed on the ground, the power and weight of the system are no longer limited by the power supply and carrying capacity of the flight platform. Therefore, higher power output can be realized, and thereby larger detection depths can be realized than that of the AEM methods, meanwhile the flight risk can be reduced. In addition, due to the miniaturization of sensors and acquisition systems, and the remarkable improvement in the performance of low-cost civil UAVs (Unmanned Aerial Vehicle) in recent years, it has become possible to use the low-cost civil UAVs to carry SAEM detection system. These developments will help to further reduce the application and maintenance costs of SAEM systems; in addition, multi-field and multi-component observation can be realized based on a UAV formation, in which each UAV carries different sensors and forms a tensor of sensors.

Based on the above analysis, Chinese researchers have basically reached the following consensus in the development direction of SAEM technology: using low-cost civil UAV as the carrier platform; using distributed transmitting array to enhance the total output power of the transmitting system, and reduce the difficulty of transportation and layout; developing more portable and flexible sensor and acquisition units; adopting composite processing methods to mine the data potential, and finally achieve efficient and reliable extraction of underground electrical parameter distribution information.

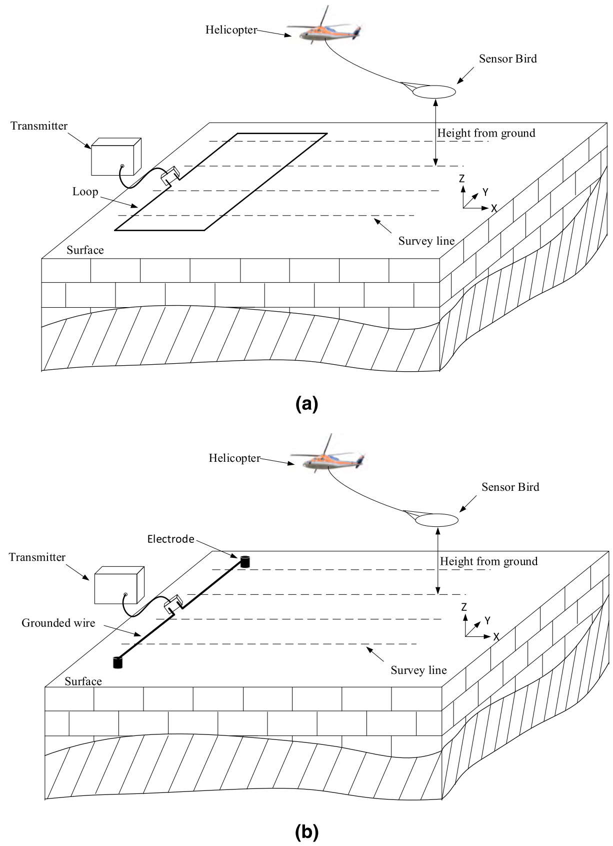
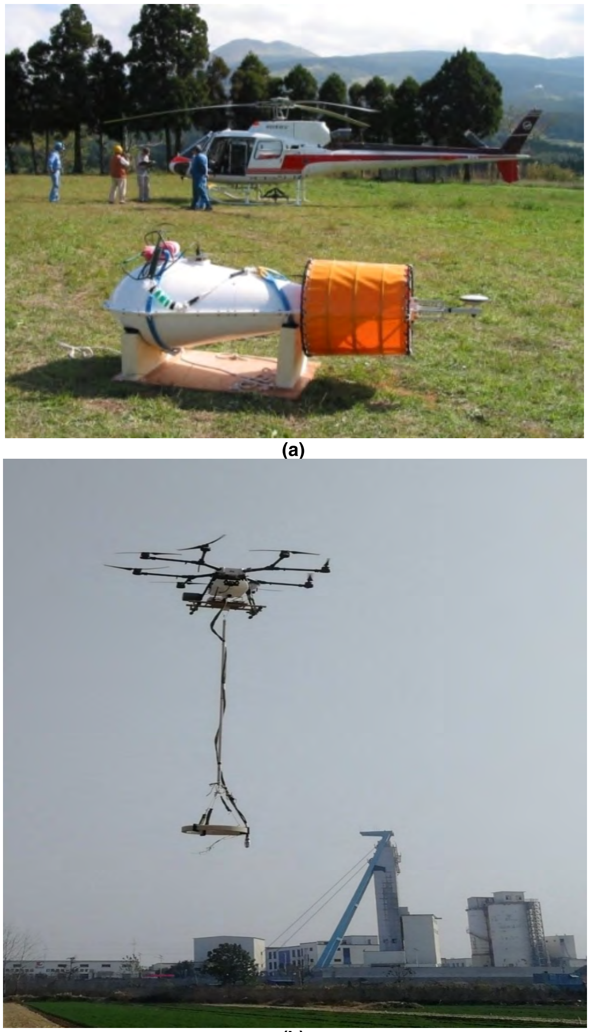


FIGURE 2. Configuration of traditional semi-airborne TEM systems (a) with loop source and (b) with grounded wire source.

In this paper, we will review the development of the international mainstream SAEM technology briefly, and then elaborate on the key technical difficulties faced by SAEM in regard to system design, application, and data processing. Then on this basis, the latest progress in the research and development of SAEM systems, data processing, and imaging methods in China during the past decade were carefully reviewed. Finally, we will discuss the future of SAEM in terms of equipment developing, data processing, modeling and inversion, to promote the research and application in this field to a higher level.

II. ORIGIN OF SAEM SYSTEMS

The world's first SAEM detection system, Turair, was introduced in the early 1970s [9], [10]. After 1990s, FlairTEM [6], [11], TerraAIR [12], GREATEM [7], [13], [14] appeared. In the early days of the SAEM method and technology development, closed loops had been used as the transmitting antenna (Fig.2a). Since the introduction of the GREATEM system, the long grounded wire source has also been used as the transmitting antenna (Fig.2b). The SAEM systems generally utilize the induction magnetometer as the sensor to observe the electromagnetic field of the earth's response. In the above-mentioned systems,



(a)

(b)

FIGURE 3. **Common SAEM systems: (a) with helicopter [15] and (b) with UAV (SAEM system of the Institute of Electrics, Chinese Academy of Sciences).**

because the sensors and acquisition units were still heavy, the manned helicopters were used as the carrying platforms (Fig.3a). During the subsequent development, with the increase in the UAV's carrying capacity, and the further optimization and weight reduction of the sensors and acquisition units, it was determined that the observation systems can also be carried by UAVs (Fig.3b).

The Turair System is considered to be a pioneer in the field of SAEM detection systems. The Turair system was developed by Scintrex Company, and carried out extensive exploration work in the 1970s and 1980s. The Turair is a SAFEM system, which utilized closed loops as transmitting antenna. The typical size of the loop was 2 km × 4 km (based on a special device which can feed out more than 20 km of wire continuously), and the base frequencies were 200 or 400 Hz (with other frequencies also adopted). It was generally powered by a 15 kW generator, and the transmitting current range was 4-10 A. The Sensor system consisted of two horizontal coplanar and/or two vertical coaxial air-core coils, which were rigidly mounted 2.2 m apart in the sensor pod (Bird). The Bird was connected to the aircraft using a pull cable, and was maintained 30 meters below the aircraft under normal operating conditions. The Turair's observation was the ratios of the field strength and the phase difference of the alternating magnetic field at the towed coils. The sensitivity of the system was 0.1% strength ratio and 0.1° phase difference, respectively.

The FlairTEM system was developed by the Elliott Geophysics International Pty Ltd., and was considered to be the time-domain version of Turair [16]. The FlairTEM System was based on Zonge's ground-based electrical equipment, and carried out aviation adaptability upgrades and improvements to meet the needs of SAEM detections. The FlairTEM system used the Zonge's transmitter to transmit the square wave in 1 to 32 Hz with a duty cycle of 50%. The maximum power which the system can reach was 25 kW. The size of the loop was generally in the kilometer class, such as 6km×2km. The receiver used the Zonge GDP 32, and the sensor was a coil with an iron core with an effective area of 10000 m^2. The Receiver typically used three channels, two of which received the Z and X components of the magnetic field, and the third one received the radar altimeter data. The bird was carried by helicopter, and a height of approximately 50 m from the surface was maintained during flight.

The TerraAir system was developed by Fugro and was a SATEM system which has adopted the EM-37 transmitter of Geonics and the receiving system of GEOTEM (Fugro). The TerraAir system also used closed loops as transmitter antenna, the typical size of the loop was 1km×1km. The typical transmitter current was 5.25 A with a corresponding turn-off time of 278 μs. The sampling rate of the receiver was more than 20 kHz, and the receiver worked continuously and did not synchronize with the transmitter.

The GREATEM (Grounded electrical-source airborne transient electromagnetic) proposed by Hokkaido University of Japan, and was considered to be an airborne version of the Long Offset Transient Electromagnetic (LOTEM) [13]. GREATEM utilized a generator (60KW, 440V) to supply power to the transmitter (Chiba electronics, maximum output 500V, 50A). The typical transmitting current was 24A. The transmitting waveform was a bipolar square wave with the duty cycle of 50%, and its transmitting base frequency was 0.625Hz. The GREATEM utilized two types of Bird: the Namazu-Type, which was suitable for deep exploration and was suspended by a manned helicopter; and the Unagi-Type, which was suitable for shallow observation and can be suspended by a heavy unmanned helicopter. In addition to a three-axis induction magnetometer, there were other devices installed in the bird. These included a fiber optic gyroscope for the observation and recording of the bird's attitude in the air; a magnetoresistance sensor for observation and recording flying direction of the bird; a GPS; and a battery. The data recording system (12.5 kHz, 16-bit ADC) was mounted on the flight platform, and included a data control PC, a high-precision synchronous clock and so on.

In addition, a three-axis loop was used to observe natural and human noise on the ground.

In recent years, with the support of the DESMEX project (Deep Electromagnetic Sounding for Mineral Exploration), a number of research institutions and enterprises in Germany have jointly developed a new SAEM system [17], [18]. Although the newly developed system has inherited some techniques of LOTEM, it is considered to be a SAFEM system. The reason for choosing frequency domain processing is that it is relatively easy to remove harmonic noise, and also has more flexibility in the selection of the signal frequencies which are least affected by system motion. As a result, a better signal-to-noise ratio can be obtained. The typical transmitter current is 20 A, and the base frequency is 10.41 Hz. A Metronix ADU-07 acquisition unit is used to record data with the bandwidth from 1 Hz to 10 kHz. The system also utilizes helicopters as the flight platforms and a tube-shaped bird to carry the sensors. There are two types of sensors, one is a combination of fluxgate and induction coil sensors (in-flight noise level of a few pT), and the other is SQUID-based magnetometer. The system adopts a high precision GPS synchronization strategy to realize synchronous observation and recording of the transmitter current and magnetic field response. An Inertial Navigation System (INS) is used to record the motion and attitude of the bird; and the Inertial Measurement Unit (IMU) of the INS is used to record the orientation angles and the angular velocity of the bird.

III. ANALYSIS OF TECHNICAL DIFFICULT IN SAEM

Through the long-term tracking and analysis of the SAEM technology characteristics, Chinese researchers have come to widely believe that developing the SAEM method and technology is more suitable for China's national conditions.

Due to the aerial observation mode, the difficulties which have been encountered in the design and application of SAEM have been different from those of the traditional ground methods. In order to move forward, some of those problems need to be resolved at the hardware level, while other problems require method and processing solutions, as detailed in the next section:

(1) As an aerial observation method, the requirement of the carrying capacity of the onboard portion does not factor in the traditional ground method. The performance parameters of the inductive magnetometer (slope and linear bandwidth of the sensitivity curve, and output noise level) are directly related to the geometric parameters of the coil, material parameters, and the fabrication process. Therefore, if the performance of the sensor is to be optimized by adjusting the above parameters, the weight of the sensor will often increase at the same time. In addition, the realization of airborne carrying requires certain structural components, whose weight will occupy the available weight resources of the system, thereby counteracting the optimization of the system performance. These issues indicate that under the condition of limited available weight, the processes of improving the performance of the SAEM systems through correlation optimization based on geometric parameters, material parameters, and the fabrication process will be much more complex than those of the traditional ground system.

(2) During SAEM detection processes, the survey line often needs to cross the near zone, the transition zone, and the far zone, and the approximate boundary points of those zones on the survey line tend to vary for different signal frequencies. When the observation position is in the far zone for the entire signal bandwidth, then the Z component magnetic field sensor could be an ideal choice. However, when the observation position is continually approaching to the transmitting wire along the survey line, the observation signal will first increase, then weaken, and subsequently completely disappear when the system crosses over the transmitting wire (similar to Zero Position). Alternatively, if an X-component magnetic field is observed, the signals will increase as the transmitting wires are approached until the maximum is reached, at which point the system will leap over the cable. This phenomenon in which the wavefront vector of exciting electromagnetic field changes along the survey line has been found to be a major challenge for the SAEM detections, both in the frequency domain and time domain.

(3) In order to minimize the interference of the flight platforms during aerial observation, it is necessary to observe the disappearance distances of the electromagnetic noise of the flight platforms before carrying begins. This allows for the minimum distance between the sensor and the flight platform to be ascertained. Based on the existing tests, it is found that in order to minimize the interference of electromagnetic noise from the flight platforms, it is necessary to increase the distance between the sensor and the flight platform to several meters. However, under this condition, a certain size of the carrier structure of sensor is required to meet the requirement of disappearance distance of platform EM noise. In Helicopter-borne Transient electromagnetic systems (HTEM system, such as SkyTEM and VTEM), the transceiver structure is mounted under the platform in the form of soft connection to reduce the propagation of aircraft vibration to the transceiver structure. Taking VTEM-Plus as an example, the weight of its transceiver structure is about 500 kg, the diameter of transmitter loop is 28 meters, the main pull cable is Kevlar material, about 40 meters (considering the disappearance distance of platform EM noise). The speed of the helicopter is normally 90 km/h, when the system enters the working flight state, the huge inertia can ensure that the transceiver structure can be relatively stable. For the SAEM system using UAV, because the available load of the existing civil UAV is only about 10 kg, its maximum speed can only reach 10 km/h after the loading of the SAEM system. Under these conditions, if a soft connection structure is used like in HTEM systems (we have experimented), the sensor will be very susceptible to the near-surface turbulent, resulting in severe shaking, thus introducing additional motion-induced noise in the data. But if the carrier structure of the sensor is installed on the platform in the form of hard-links, a large and hard-linked carrier structure of the sensor will increase the

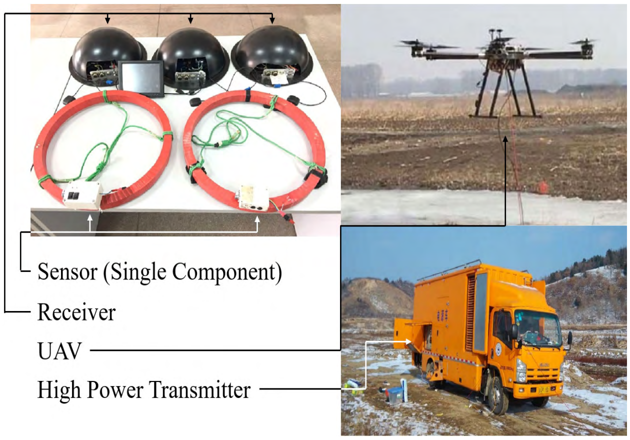


FIGURE 4. Composition of the SAEM system developed by Jilin University [22].

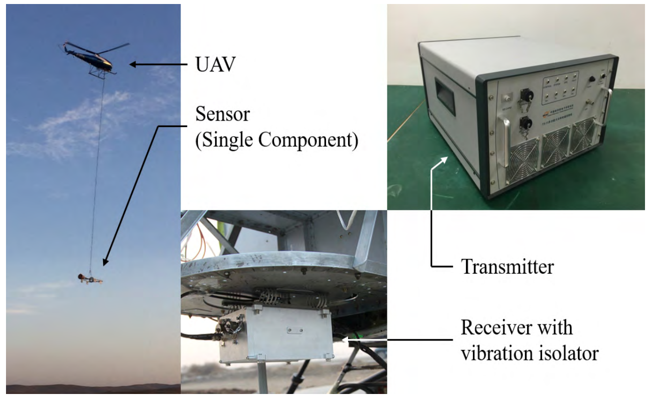


FIGURE 5. Composition of the SAEM system developed by the Chinese Academy of Sciences [19]. The UAV (Tianxiang V-750) showed in this figure was reconstructed from a two-seat helicopter.

difficulty of takeoff and landing for the system. Therefore, some new techniques are required in order to carry out more effective airborne system operations and optimize the noise performance of the entire system. This issue has become very important and urgently require solutions.

(4) One of the main advantages of the SAEM method is the use of the ground-based high-power transmitter. However, this has resulted in the size and weight of the transmitter system becoming very large, even requiring special vehicles to load and transport. In many underdeveloped areas, the observation area is complicated by difficult terrain conditions, which has resulted in poor traffic conditions, and the transmitter vehicles sometimes have difficulty in reaching the preset transmitting location. In addition, the deployment of transmitting cables still mainly relies on manual work. When a large transmitter electrode spacing is required, or the ground conditions are complex, the deployment efficiency of transmitting wire will become the bottleneck restricting the efficiency of the entire survey. This indicates that although SAEM transmitter can able follow the relevant technology of traditional ground method, the manner in which the transmitted signal is enhanced (by increasing the transmitter power and expanding the spacing of transmitter electrodes) may limit the applications of the SAEM systems under certain conditions.

IV. SAEM HARDWARE TECHNOLOGY IN CHINA

Tracing the above difficulties, since 2010, Jilin University [8], Chinese Academy of Sciences [19], Chengdu University of Technology [20], and Chang'an University [21] and other research institutions led the development of SAEM related technologies under the support of national and local projects. Jilin University has carried out research and development projects related to SAEM system (Fig.4), focusing on the optimization and development of sensors and transmitters, flight noise suppression and SAEM rapid imaging methods. Also, the Chinese Academy of Sciences has developed a SATEM system (Fig.5), focusing on the design and development of smart and low-noise sensors as well as high-stability transmitters. The Chengdu University of Technology has carried out SATEM system research and development and data processing research. Chang'an University proposed a new SATEM method based on distributed transmission technology (multi-source), and carried out research studies related to the fast-imaging method based on multi-source technology. These research efforts have greatly promoted the development of SAEM method and technology in China.

A. TRANSMITTER TECHNOLOGY

How to ensure that (1) the amplitude of the transmitter current pulse is large and constant, (2) the waveform is stable and distortion-free, and (3) the transmitter is small and light, have become the central problem of high-performance transmission technology in recent years [23]. Xue *et al.* [24] designed a current stabilization controller based on the pulse width modulation circuit (PWM), which effectively suppressed the error of current stabilization control below 4%, and restrained the load change caused by grounding load capacitance. Shi *et al.* [25] introduced the transmission line model for the purpose of solving the problem of current waveform distortion during the early phase of the current turn-off for long grounded wire sources, which can be used as a theoretical guide for the design and implementation of the minimum current turn-off duration for transmitters. Also, in order to solve the problem of poor performance for the existing electrical source transmitters when outputting high frequency signals, Zhen and Di [26] proposed a dual transmitter system which had the ability to overcome the limitation of the parasitic inductance of the power supply lines, and also improved the high-frequency transmission capability of the transmitter using the parasitic inductance effect. In another related study, the high-frequency transmission capability of the transmitter was effectively improved by Li *et al.* [27], who had adopted a solution based on capacitive compensation technology in order to offset the inductive effects of loop conductors. Geng *et al.* [28] took the constant-current transmission converter as their research object, designed the circuit topology of the converter in detail, and then proposed a new model reference adaptive proportional integral (PI) control algorithm, which effectively eliminated the current rise overshoot and made the descent edge more linear. In addition, in order to solve the heat dissipation problem of high-power transmitters, Xue *et al*. [29] analyzed the characteristics of striped radiators and fan radiators, and obtained the engineering calculation expression of the Nusselt number and the design process of air-cooled heat dissipation. As a result, the rises in temperature of the 40 kW transmitter could be controlled within the range of 20°C∼40°C under general working conditions.

B. SENSOR TECHNOLOGY

Since the technology of non-contact electric field sensor (capacitive electrode) is not yet fully mature, the induction magnetometer (IM) is still mainly used in the existing SAEM system. Considering the need to carry the sensors on the air, the IM sensor technology for SAEM systems is mainly focused on achieving the characteristics of lightweight, miniaturization and low noise. Yan *et al*. [30] put forward two schemes for IM optimization as follows: 1) optimizing the coil parameters when the size of the core is known; 2) optimizing the parameters of the core and coil when only the maximum allowable size of the sensor is known. Duan and Luo [31] introduced the Backtracking search algorithm (BSA) into the optimization of IM, and proposed the adaptive BSA (ABSA), the probabilities of crossover and mutation are varied depending on the fitness values of the solutions to refine the convergence performance, and thereby the optimization problems are effectively solved. Liu *et al*. [32] designed and optimized the IM sensor ultralow noise preamplifier with linear bandwidth from 0.1 Hz to 10 kHz, and the optimized IM sensor noise level was 1pT/$\sqrt{}$Hz @ 1Hz and 1.5 fT/$\sqrt{}$Hz @ 2 kHz, with a total weight of only 1.5 kg. Also in the frequency range of 0.1 Hz ∼ 10 kHz, Shi *et al*. [33] perform IM sensor optimization under given noise equivalent magnetic induction and sensor size conditions, analyze the transducer model; the equivalent input voltage and current noise of the n-paralleled dual Junction Field-Effect Transistor (JFET) differential preamplifier used in sensor were calculated and optimized, and the optimal sensor configuration was obtained considering the minimum outer diameter limit of the sensor. Shi *et al*. [34] further optimized the weight of the sensor under specific noise constraints. Yuan *et al*. [35] designed a three-component IM sensor for the specific needs of the SAEM method, and proposed to reduce the signal distortion by using the underdamped matching mode; through the low noise design of the amplifier circuit, the noise level of the sensor was effectively reduced. The three-component IM sensor proposed in this study has a total weight of 3.2 kg and a working bandwidth of 0.1 Hz to 10 kHz, which has been used in practical observations. In addition, Qu *et al*. [36] carried out the theoretical study of the optically pumped magnetometer as the sensor of SAEM, which laid the foundation for the follow-up work.

C. RECEIVER TECHNOLOGY

The data acquisition technology which has applied to SAEM systems is relatively mature, and mainly emphasizes the large dynamic, low noise and light miniaturization. For the purpose of debugging and calibrating SAEM receiver, Gao *et al*. [20] first studied the characteristics of SAEM signals, using the field programmable gate array (FPGA) as the main controller. Then, based on the SOPC technology, referred to as the Niosll softcore, the simulation output of the SAEM signal was realized, and a test device dedicated to the SAEM receiver was developed in combination with the PC and the DA circuit in order to meet the requirements of the SAEM receiver test and calibration.

V. SAEM METHOD RESEARCH IN CHINA

When comparing with the hardware technology, which began in 2010, the research regarding the SAEM theory, method and data processing had begun in China in the 2000s [37]. In recent years, with the completion of many SAEM prototypes in China, a number of new research results have emerged under the impetus of a large amount of measured data.

A. DATA PROCESSING

Jilin University equipped the SAEM prototype on a small unmanned airship [8], in order to achieve low-cost, high-reliability testing and application. To overcome the baseline drift problem during flight, Wang *et al*. [38] introduced a wavelet analysis method based on the multiresolution analysis, in which a sym8 wavelet with 10 decomposition levels was used, and the approximation at level-10 as the baseline drift was obtained, so the corrected signal was then resulted by removing the estimated baseline drift from the original signal. To suppress the stationary noise and part of the non-stationary noise (such as sferics noise, aircraft engine noise and other human-related electromagnetic noises) entering the SAEM observation, Ji *et al*. [39] introduced a composite noise suppression method based on wavelet threshold method and exponential adaptive window width-fitting: the wavelet threshold method is used to remove the white noise in the data to the maximum extent, and then the data is segmented, and the decay curve features are picked up in each data segment, and the non-stationary noise is identified and eliminated. Based on this method, Li *et al*. [40] improved the processing details and applied them to the relevant detection tasks of Huaiyin-Shengshui fault. Motion noise is an important type of noise in airborne electromagnetic detection: the observation coil moves in the geomagnetic field, which leads to the change of the magnetic flux in the coil due to the inhomogeneity of the geomagnetic field, and the induced electromotive force (EMF) is considered to be the motion noise. In order to overcome the motion noise, amount of research have been done [41]–[43]. In order to eliminate the influence of motion noise in SAEM observation, Liu *et al*. [25] introduced the Ensemble Empirical Mode

Decomposition (EEMD) method to decompose the data into several Intrinsic Mode Functions (IMFs), and the motion noise will be separated from the useful signal at different levels of IMF. In another related study, Wu *et al.* [46] proposed a method based on the wavelet neural network in order to overcome the influence of high-frequency motion noise. This method was originally proposed for helicopter-borne TEM data, however, since SAEM observation data sometimes also contain the same phenomena, and the method has now also been introduced into the processing of SAEM data.

B. MODELING AND IMAGING

During the early stage of SAEM technology development, it was necessary to provide theoretical support for hardware system design, field methods, data processing and inversion through the forward modeling process. Ji *et al.* [47] carried out a one-dimensional SATEM forward modeling based on electrical sources, and used the research results to discuss the influence of the observation point elevation on the response results, and verified the discussion conclusions through field observations. Kang *et al.* [48] carried out one-dimensional forward research for SAFEM, which also used long grounded wire as the transmitter antenna. Through the forward modeling, the effects of parameters such as anomaly resistivity, anomaly burial depth and thickness, transmitting and receiving offset, the elevation of observation points on detection results were discussed, which laid a strong data foundation for the subsequent system design. Based on the above research, Liu *et al.* [49] developed a three-dimensional forward method based on combined mimetic finite volume and rational Krylov subspace, which is more efficient in discretization of Maxwell equations than the traditional method using the implicit time-stepping strategy, so these research results lay a good foundation for the SAEM three-dimensional inversion.

At the present time, a large amount of data and low computational efficiency are the main causes of the restriction in the development of SAEM three-dimensional inversion. In regard to the field data, the imaging and one-dimensional inversion are mainly used to extract the distribution information of the underground electrical parameters. Based on the horizontally layered model, Zhang *et al.* [50] carried out the SATEM response forward modeling, and the definition of the full zone apparent resistivity for the SATEM method was proposed and then tested on two typical geoelectric models. Based on the above-mentioned research, Qi *et al.* [51] further proposed the definition of the Y-component full zone apparent resistivity for SATEM. The long grounding wire source is also used here, and the grounding wire direction is defined as the X direction, and the direction perpendicular to X on the horizontal plane is defined as Y direction in their research. The definition of the apparent resistivity of the whole region proposed in this study is not limited by the early and late decay curves, nor is it related to the transceiver offset, and the reliability of the proposed definition was confirmed using field data. Differing from the above-mentioned apparent resistivity-based imaging methods, Li *et al.* [21], carried out the inverse-synthetic aperture imaging for SATEM, proposed a Kirchhoff migration imaging method suitable for SATEM virtual wave field and used the correlation superposition technology to achieve the synthesis of multi-point data in the aperture. On this basis, an inverse-synthetic aperture processing method with multiple point-by-point coverages was developed, and has been confirmed that this method had the ability to achieve higher anomaly resolution using field data.

C. MULTI-SOURCE SAEM

In the previous discussion, we have seen that the existing SAEM system generally uses a high-power transmitter. There are compromises between the design and application: in order to achieve a deep detection, it is necessary to increase the transmission power as much as possible. However, the high transmission power will lead to a large increase in the volume and weight of the transmitter, which results in great difficulties in transportation and deployment, even impossible in some region. To solve this problem, Zhang *et al.* [52] proposed a SATEM method based on multi-source that is, using small- or medium-sized transmitters to form a distributed transmitting array, so as to realize large-area and large-depth detection on the basis of miniaturization of equipment, and a multi-component full zone apparent resistivity definition for multi-source SAEM is further proposed. On this basis, Zhang *et al.* [53] derived the formulas for calculating the vertical apparent conductance and apparent depth of multi-source SATEM, thus established a fast imaging algorithm for multi-source SATEM. Based on the imaging algorithm, Zhao *et al.* [54] further developed a one-dimensional Occam inversion study of multi-source SATEM. Compared with the above multi-source SATEM research, Zhou *et al.* [55], [56] they proposed a multi-source SAFEM method. By studying the interaction between adjacent sources, they focused on solving the problem of field installation of multi-source transmitter system, and verified the feasibility of the multi-source SAFEM method through experiments. On this basis, Zhou *et al.* [57] proposed a tensor-tipper real induction vector divergence detection method to improve the detection accuracy of the SAFEM system for three-dimensional objects based on a pair of orthogonal electrical sources, and the advantages and feasibility of this method have been proved by field experiments.

VI. SAEM APPLICATION IN CHINA

The earliest SAEM application report in China was in 2013, two applications were carried out by Ji *et al.* [8] from Jilin University using the SATEM system developed by their team. In early 2012, the seawater intrusion detection was carried out in Rudong County, Jiangsu Province. A long grounded wire source with a pole distance of 1.5 km was used with the transmitter current of 14A. The Z component magnetic field response was observed using an unmanned airship as the carrying platform. The coil effective area

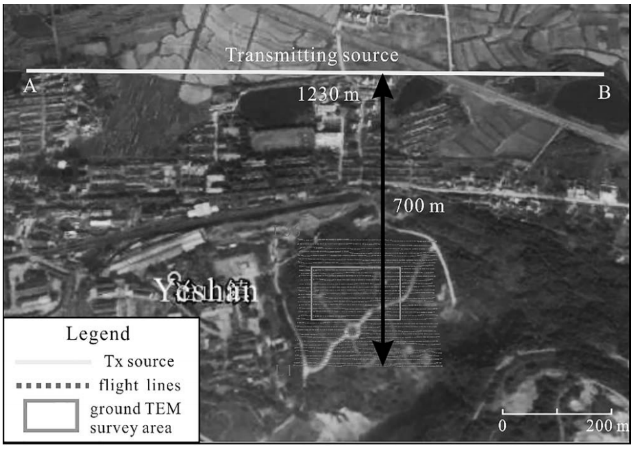


FIGURE 6. The layout of the transmitting source and survey lines.

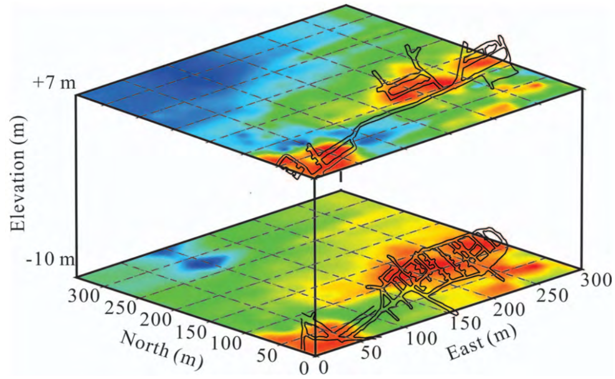


FIGURE 7. Slice maps of inversion result at 7 m and -10 m above the sea level and the tunnel networks.

was 20,000 m^2, the bandwidth was 2 kHz, and the cruising height of the system was 30 m. The resistivity profile is obtained by processing the detected data. The trend and path of seawater intrusion are judged by analyzing the resistivity variation of the profile. The results are in good agreement with the existing hydrogeological data. In addition, in September 2012, the system carried out groundwater resources exploration work in Bayanbaolig Basin of Xilingol League, Inner Mongolia, to clearly outline the basic form of the aquifer.

After several years of development, the system was able to support both time domain and frequency domain methods. The time domain transmitting base frequency includes: 3.125Hz, 6.25Hz, 12.5Hz, 25Hz, etc., and the frequency output frequency range is 0.01~8192Hz. The maximum output power of the transmitter is 100 kW and the maximum output current is 68 A. The multi-rotor UAV is used as the carrier platform, and the flight duration is more than 30 minutes. The Z-component magnetic field response is observed by the inductive magnetometer. The coil is 10-20 m below the UAV, weighing 3 kg, and the effective bandwidth is 0.1 Hz-10 kHz. At present, the system has been applied successfully, such as Xue *et al*. [58] applied the system to carry out the investigation and detection of goaf and underground cavities. The investigation area is located in Yeshan County, Jiangsu Province, with the aim of detecting abandoned underground mining tunnel network. The average elevation of the local surface is 100 m above sea level, and the buried depth of the goaf and underground tunnel is between 70 m and 150 m. As shown in Fig.6, 36 surveying lines were designed with the line length of 350 m and line spacing of 10 m. A long grounded wire was used as the transmitter antenna with a pole distance of 1230 m. The results are shown in Fig.7: two 1-D inversion slice maps at 7 m and -10 m above sea level, which is the approximate depth of the known underground tunnel. The inversion slices show that there is a high correlation between the high resistance area and the tunnel network, which proves the effectiveness of this method in detecting underground goaf.

The Chinese Academy of Sciences has carried out SATEM system research and development since 2013 with the support of national projects, and carried out exploration in 2017 at the Lianhuashan Iron Mine in the Changyi-Anqiu metallogenic belt in Shandong Province [19]. In this survey, 12 surveying lines were deployed, with a line length of 3 km, line spacing of 200 m, and the total survey area of 6.6 km^2. A grounded wire source was used with the pole distance is 2.7 km, the transmitter current is 20 A, and the base frequency is 6.25 Hz. The inductive magnetometer was used for three components observation. The Z component coil resonance frequency was 9.7 kHz, and the resonance frequencies of the X and Y component coil were both 29.5 kHz. The receiver sampling rate is 48 kHz, dynamic range > 120 dB. A large single-rotor UAV modified using a small manned helicopter equipped with receivers and sensors, cruising altitude is about 100 m (limited by surface conditions), and the cruising speed is about 15 m/s. The data was processed and the one-dimensional inversion was carried out to obtain the inversion profile of each profile. Taking the 500-meter section in the middle of line 6 as an example (corresponding to the known geological area), as shown in Fig.8(a), the underground structure of the section is approximately layered: the first layer is a Quaternary overburden with a thickness of about 50 m, and the main components are clay and gravel-bearing clay. The second layer is biotite granulite and garnet-bearing biotite granulite, this layer is slightly inclined, the thickness of this near the borehole ZK57 is about 160 m, and near the borehole ZK54 is about 210 m. There are many layers of ore bodies interpenetrating at the bottom of this layer. The third layer is a granite body. The boundary between the third and the second layer is clear, and the rock mass generally presents the trend of high in the north and low in the south. Fig.8(b) is a one-dimensional inversion profile, in which the resistivity changes show a four-layer structure. The layer interfaces are approximately 50 m, 130-150 m and 200-250m, which are in good agreement with the geological data shown in Fig.8(a). In recent years, the R&D team has been upgrading the system focusing on solving the problem of light and miniaturization. At present, the system can be also carried by a small multi-rotor UAV to carry out engineering exploration tasks.

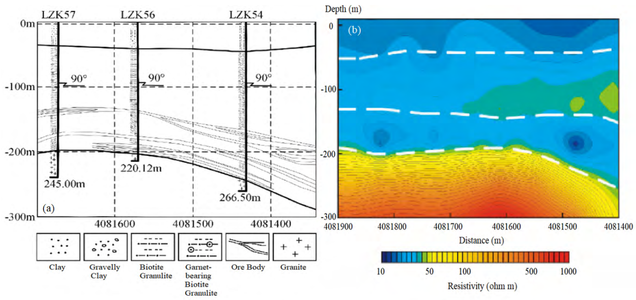


FIGURE 8. Geological and resistivity section along the exploration line 6: (a) Geological section and (b) resistivity profile.

VII. PROSPECTS FOR SAEM IN CHINA

With the development of application requirements, the research regarding SAEM method technology has become more in-depth, and now reflects the following development trends:

A. HIGH-FREQUENCY SAEM METHOD AND TECHNOLOGY

Due to the current demands, the SAEM method has been introduced into the development and construction of urban underground space, monitoring and maintenance of underground facilities, soil pollution detection, disaster prevention and mitigation and other fields. These types of requirements have mainly involved the underground space from 0 m to 100 m, and have emphasized high-resolution in the detection results. Therefore, it has become necessary to expand the frequency range of the traditional SAEM, for example, to 1 kHz $\sim$ 1 MHz. Obviously, when the frequency range is raised to such high levels, the response law of the electromagnetic field will not completely satisfy the assumption of the diffusion equation, but enter the transition section between diffusion equation and wave equation [59]. How to solve the problem of electromagnetic detection considering the effect of displacement current, break through the limitation of the existing theoretical framework, and realize the fine detection at the depth range of 0 m to 100 m without any blind zone, so as to better meet the needs of engineering detection, especially within urban areas, is one of the important directions of SAEM technology development.

B. MULTIDIMENSIONAL INVERSION BASED ON DEEP LEARNING

At the present time, some difficulties still exist in the multi-dimensional inversion of airborne electromagnetic sounding data by traditional methods. The main reasons are as follows: (1) the calculation time is long; and (2) the subjective regularization problem exists [60].

For these reasons, some researchers have begun to try to introduce the deep learning methods mainly based on the following considerations: (1) comparing with other methods which take the time of data acquisition completion as the starting time point of the processing, while the deep learning methods move the main working time to the network training process at ordinary times. After completing the training, the well-trained networks can be used to data processing (predict), which requires only one forward propagation, so the processing speed will be very fast. (2) since the deep learning approaches are end-to-end, data-driven approaches which minimize human assumptions and process interventions, the objectivity of the process will be significantly improved. (3) Based on the memory of the network, the data collected from multiple sources can be introduced to train the network, and makes the network more "savvy" (better generalization performance), and the applicability and reliability of the results can be continuously improved. Building suitable neural network structures for solving SAEM multi-dimensional inversion problems has attracted a lot of academic attention and become another important direction for the development of SAEM technology in China.

VIII. CONCLUSION

The SAEM method utilizes the high-power transmitter to improve the detection depth, and the aerial receiving to improve the detection efficiency. The SAEM method is an efficient and large-depth electromagnetic detecting method which combines the advantages of both ground and airborne methods, and is widely used in the field of resource detection, such as minerals, groundwater and geothermal.

The research regarding SAEM methodology and technology in China started late and lagged behind the international advanced level for some time. In recent years, although remarkable progress has been made in the fields of SAEM system design, hardware development, and data processing and imaging methods, a large number of problems remain unsolved, therefore, the degree of marketization of the developed systems still remains low. In the future, with increased demand, new methods and technologies (such as high-frequency SAEM) will be studied, and the deep learning method will be introduced into the three-dimensional inversion of data to achieve the fast, objective and strong generalization extraction of underground information. It is hoped that the introduction of this paper will further promote the research and application of SAEM technology, which could potentially provide more powerful technical means for mineral resource exploration and engineering construction.

REFERENCES

[1] M. N. Nabighian, *Electromagnetic Methods in Applied Geophysics–Theory*. Tulsa, OK, USA: Society Exploration Geophysicists, 1987, pp. 217–231.

[2] J. M. Legault, A. Prikhodko, C. Izarra, S. K. Zhao, and E. M. Saadawi, "Helicopter EM (ZTEM-VTEM) survey results over the Nuqrah Cu-Pb-Zn-Au Sedex massive sulphide deposit in the western arabian shield," in *Proc. 23rd Int. Geophys. Conf. Exhibit.*, Melbourne, VIC, Australia, Aug. 2013, pp. 1–4.

[3] G. Hodges, T. Y. Chen, and R. V. Buren, "HELITEM detects the Lalor VMS deposit," *Explor. Geophys.*, vol. 47, no. 4, pp. 285–289, Dec. 2016.

[4] F. Effersoe and B. Brown, "Application of helicopter time-domain EM for mine operations," in *Proc. 2nd Eur. Airborne Electromagn. Conf.*, Sep. 2017, pp. 1–4.

[5] R. O. Crosby and J. P. Steele, "Report on airborne geophysical surveys anyox area, British Columbia on behalf of Hogan mines limited," Dept. Mines Petroleum, Perth, WA, Australia, Assessment Rep. 3348, Aug. 1971.

[6] P. J. Elliott, "New airborne electromagnetic method provides fast deep-target data turnaround," *Lead. Edge*, vol. 16, no. 4, pp. 309–310, Apr. 1996.
[7] T. Mogi, T. Mogi, K. Kusunoki, H. Kaieda, H. Ito, A. Jomori, N. Jomori, and Y. Yuuki, "Grounded electrical-source airborne transient electromagnetic (GREATEM) survey of Mount Bandai, North-Eastern Japan," *Explor. Geophys.*, vol. 40, no. 1, pp. 1–7, 2009.
[8] Y.-J. Ji, Y.-J. Ji, Y. Wang, J. Xu, F.-D. Zhou, S.-Y. Li, Y.-P. Zhao, and J. Lin, "Development and application of the grounded long wire source airborne electromagnetic exploration system based on an unmanned airship," (in Chinese), *Chin. J. Geophys.*, vol. 56, no. 11, pp. 3640–3650, 2013.
[9] R. A. Bosschart and H. O. Seigel, "Advances in deep penetration airborne electromagnetic methods," in *Proc. 24th Int. Conf. Geological Congr.*, vol. 9, 1972, pp. 37–48.
[10] A. Becker, "Airborne electromagnetic methods," in *Geophysics Geochemistry Search for Metallic Ores*, vol. 31, P. J. Hood, Ed., Ottawa, ON, Canada: Geological Survey of Canada, 1979, pp. 33–43.
[11] P. Elliott, "The principles and practice of FLAIRTEM," *Explor. Geophys.*, vol. 29, nos. 1–2, pp. 58–60, 1998.
[12] R. S. Smith, A. P. Annan, and P. D. McGowan, "A comparison of data from airborne, semi-airborne, and ground electromagnetic systems," *Geophysics*, vol. 66, no. 5, pp. 1379–1385, 2001.
[13] T. Mogi, Y. Tanaka, K. Kusunoki, T. Morikawa, and N. Jomori, "Development of grounded electrical source airborne transient EM (GREATEM)," *Exploration Geophys.*, vol. 29, nos. 1–2, pp. 61–64, 1998.
[14] H. Ito, T. Mogi, A. Jomori, Y. Yuuki, K. Kiho, H. Kaieda, K. Suzuki, K. Tsukuda, and S. A. Allah, "Further investigations of underground resistivity structures in coastal areas using grounded-source airborne electromagnetics," *Earth Planets Space*, vol. 63, no. 8, pp. e9–e12, Aug. 2011.
[15] H. Ito, "Development of an integrated airborne geophysical survey system using helicopter—Improvement of airborne survey methods of electromagnetic, magnetic, gamma-ray spectrometry and infrared image," *Central Res. Inst. Electr. Power Ind.*, vol. 21, 2007, Art. no. 6011.
[16] D. Fountain, "Airborne electromagnetic systems-50 years of development," *Explor. Geophys.*, vol. 29, no. 2, pp. 1–11, 1998.
[17] C. Nittinger, "A novel semi-airborne EM system for mineral exploration-first results from combined fluxgate and induction coil data," in *Proc. Near Surf. Geosci. Conf. Exhibit.*, Sep. 2017, pp. 1–4.
[18] M. Cherevatova, C. Nittinger, M. Becken, P. Yogeshwar, W. Moerbe, B. Tezkan, R. Rochlitz, T. Guenther, H. Petersen, and U. Meyer, "Three-dimensional inversion of the semi-airborne data collected over ancient antimony mine in eastern Germany," in *Proc. 20th EGU Gen. Assem.*, vol. 20, Apr. 2018, Art. no. 12143.
[19] F.-B. Liu, L. Huang, L. Liu, J. Li, Z. Geng, Q. Zhang, and G. Fang, "Development and application of a new semi-airborne transient electromagnetic system with UAV platform," *Progr. Geophys.*, vol. 32, pp. 2222–2229, Aug. 2017.
[20] S. Gao, J.-M. Wang, L. Zhang, B. Cao, and C. Li, "Development of test device for semi-airborne transient electromagnetic receiver," *Prog. Geophys.*, vol. 32, pp. 1339–1345, Jul. 2017.
[21] X. Li, Y.-Y. Zhang, X.-S. Lu, and W.-H. Yao, "Inverse synthetic aperture imaging of the ground-airborne transient electromagnetic method with a galvanic source," *Chin. J. Geophys.*, vol. 58, no. 2, pp. 277–288, Mar. 2015.
[22] H. Zhou, "Research on ground-airborne frequency-domain electromagnetic methods with multiple sources," Ph.D. dissertation, College Instrum. Elect. Eng., Jilin Univ., Changchun, China, 2017.
[23] W.-Y. Chen, G.-Q. Xue, and J.-W. Cui, "Analysis on the influence from the shape of electric source TEM transmitter," *Prog. Geophys.*, vol. 30, pp. 126–132, Jul. 2015.
[24] K.-C. Xue, H.-G. Zhou, S. Wang, and J. Lin, "Constant-current control method of multi-function electromagnetic transmitter," *Rev. Sci. Instrum.*, vol. 86, no. 2, 2015, Art. no. 024501.
[25] Z.-Y. Shi, L.-H. Liu, P. Xiao, Z. Geng, and G.-Y. Fang, "Applying transmission line theory to study the transmitting turn-off current in a long grounded wire," *IEEE Trans. Antennas Propag.*, vol. 65, no. 10, pp. 5112–5122, Oct. 2017.
[26] Q.-H. Zhen and Q.-Y. Di, "High-frequency high-power CSAMT transmitting technology research," *Chin. J. Geophys.*, vol. 60, pp. 4160–4164, Nov. 2017.
[27] D. Li, C.-J. Zheng, P.-R. Lin, J.-L. Wang, J.-H. Li, and Y. Li, "A study of electrical source CSAMT high frequency transmitting based on Capacitor Compensation technology," *Geophys. Geochem. Explor.*, vol. 42, pp. 1253–1258, May 2018.
[28] Z. Geng, L. Liu, J. Li, F. Liu, Q. Zhang, X. Liu, and G. Fang, "A constant-current transmission converter for semi-airborne transient electromagnetic surveying," *IEEE Trans. Ind. Electron.*, to be published.
[29] K.-C. Xue, S. Wang, J. Lin, G. Li, and F.-D. Zhou, "Loss analysis and air-cooled design for a cascaded electrical source transmitter," *J. Power Electron.*, vol. 15, no. 2, pp. 530–543, Mar. 2015.
[30] B. Yan, W. Zhu, L. Liu, K. Liu, and G. Fang, "An optimization method for induction magnetometer of 0.1 mHz to 1 kHz," *IEEE Trans. Magn.*, vol. 49, no. 10, pp. 5294–5300, Oct. 2013.
[31] H. Duan and Q. Luo, "Adaptive backtracking Search algorithm for induction magnetometer optimization," *IEEE Trans. Magn.*, vol. 50, no. 12, pp. 1–5, Dec. 2014.
[32] K. Liu, W. Zhu, B. Yan, L. Liu, and G. Fang, "Ultralow noise preamplifier and optimization method for induction magnetometers," *IEEE Sensors J.*, vol. 15, no. 6, pp. 3293–3300, Jun. 2015.
[33] H. Shi, Y. Wang, and J. Lin, "Optimal design of low-noise induction magnetometer in 1 mHz–10 kHz utilizing paralleled dual-JFET differential pre-amplifier," *IEEE Sensors J.*, vol. 16, no. 10, pp. 3580–3586, May 2016.
[34] H.-Y. Shi, Y.-Z. Wang, J. Lin, and J. Li, "Numerical optimization of the tube-cored induction magnetometer Weight under specific noise constraints," *IEEE Sensors J.*, vol. 17, no. 11, pp. 3302–3308, Jan. 2017.
[35] S.-Y. Yuan, J. Lin, S. Song, D.-L. Sun, and F. Teng, "Design of ground-airborne TEM three-component air-core coil sensor," *J. Meas. Sci. Instrum.*, vol. 10, pp. 28–37, Jan. 2019.
[36] X. Qu, Z. Shi, G. Fang, and H. Yin, "Semi-airborne model for radiation from large grounded wire antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1800–1803, 2017.
[37] Y.-J. Ji, J. Lin, and Y.-C. Xu, "Theoretical study on semi-airborne transient electromagnetic exploration with large fixed source," in *Proc. 9th Int. China Geo-Electromagn. Workshop*, Guilin, China, 2009, pp. 121–126.
[38] Y. Wang, Y. Ji, S. Li, J. Lin, F. Zhou, and G. Yang, "A wavelet-based baseline drift correction method for grounded electrical source airborne transient electromagnetic signals," *Explor. Geophys.*, vol. 44, no. 4, pp. 229–237, Dec. 2013.
[39] Y. Ji, D. Li, M. Yu, Y. Wang, Q. Wu, and J. Lin, "A de-noising algorithm based on wavelet threshold-exponential adaptive window width-fitting for ground electrical source airborne transient electromagnetic signal," *J. Appl. Geophys.*, vol. 128, pp. 1–7, May 2016.
[40] D.-S. Li, Y. Wang, J. Lin, S. Yu, and Y. Ji, "Electromagnetic noise reduction in grounded electrical-source airborne transient electromagnetic signal using a stationarywavelet-based denoising algorithm," *Near Surf. Geophys.*, vol. 15, no. 2, pp. 1–11, Apr. 2017.
[41] M. S. Munkholm, "Motion-induced noise from vibration of a moving TEM detector coil: Characterization and suppression," *J. Appl. Geophys.*, vol. 37, pp. 21–29, Apr. 1997.
[42] G. Buselli, H. S. Hwang, and J. P. Pik, "AEM noise reduction with remote referencing," *Explor. Geophys.*, vol. 29, no. 2, pp. 71–76, 1998.
[43] T. Kratzer and J. Vrbancich, "Real-time kinematic tracking of towed AEM birds," *Explor. Geophys.*, vol. 38, no. 2, pp. 132–143, Dec. 2007.
[44] Y.-Z. Wang, R. Smith, K.-G. Zhu, and B. Chen, "HTEM noise frequency characteristics simulation and influencing analysis," in *Proc. Int. Workshop Gravity, Electr. Magn. Methods Appl.*, Apr. 2015, pp. 398–401.
[45] F.-B. Liu, J.-T. Li, L.-H. Liu, H. Ling, and G. Fang, "Application of the EEMD method for distinction and suppression of motion-induced noise in grounded electrical source airborne TEM system," *J. Appl. Geophys.*, vol. 129, pp. 109–116, Apr. 2017.
[46] X. Wu, G. Xue, X. Pan, J. Li, L. Liu, and G. Fang, "The removal of the high-frequency motion-induced noise in helicopter-borne transient electromagnetic data based on wavelet neural network," *Geophysics*, vol. 84, pp. K1–K9, Dec. 2019.
[47] Y. Ji, G. Yang, S. Guan, X. Zhang, and P. Tian, "Interpretation research on electrical source of time domain ground-airborne electromagnetic data," in *Proc. World Automat. Congr.*, Jun. 2012, pp. 1537–1540.
[48] L. Kang, L. Liu, C. Liu, F. Zhou, and Z. Shi, "Forward modeling and analyzing for frequency domain semi-airborne EM method," in *Proc. Int. Workshop Gravity, Electr. Magn. Methods Appl.*, Apr. 2015, pp. 366–369.
[49] W.-T. Liu, J.-M. Zhou, X. Li, and C. G. Farquhason, "3D modeling of grounded electric-source airborne time-domain electromagnetic data using rational Krylov subspace method," in *Proc. Int. SEG Exposit. 88th Annu. Meeting*, Aug. 2018, pp. 919–922.

[50] Y.-Y. Zhang, X. Li, and Z.-P. Qi, "Full zone apparent resistivity definition of semi-airborne transient electromagnetic method," in *Proc. Near-Surface Geophys. Asia Pacific Conf.*, Jul. 2013, pp. 1–4.

[51] Z. Qi, X. Li, J. Zhang, N. Sun, and W. Guo, "Full field apparent resistivity definition for the y-component of semi-airborne transient electromagnetics with a long wire source," in *Proc. Near-Surf. Asia–Pacific Conf.*, Honolulu, HI, USA, Jul. 2015, pp. 1–4.

[52] Y.-Y. Zhang, X. Li, W.-H. Yao, Q.-Q. Zhi, and J. Li, "Multi component full field apparent resistivity definition of multi-source ground-airborne transient electromagnetic method with galvanic sources," *Chin. J. Geophys.*, vol. 58, pp. 2745–2758, Apr. 2015.

[53] Y. Zhang, X. Li, J. Li, Y. Zhao, and W.-H. Yao, "Fast imaging technique of multi-source ground-airborne transient electromagnetic method," *Prog. Geophys.*, vol. 31, pp. 869–876, Feb. 2016.

[54] H. Zhao, X. Jing, X. Li, and W.-T. Liu, "A study of 1D inversion of multi-source grounded-airborne transient electromagnetic method: Geophysical and geochemical exploration," *Geophys. Geochem. Explor.*, vol. 43, pp. 132–142, Apr. 2019.

[55] H.-G. Zhou, Y. Yao, C. Liu, J. Lin, L. Kang, G. Li, and X. Zeng, "Feasibility of signal enhancement with multiple grounded-wire sources for a frequency-domain electromagnetic survey," *Geophys. Prospecting*, vol. 66, no. 4, pp. 818–832, May 2016.

[56] H. Zhou, J. Lin, C. Liu, L. Kang, G. Li, and X. Zeng, "Interaction between two adjacent grounded sources in frequency domain semi-airborne electromagnetic survey," *Rev. Sci. Instrum.*, vol. 87, no. 3, 2016, Art. no. 034503.

[57] H. Zhou, M. Zhang, C. Liu, J. Lin, and L. Kang, "Divergence of tipper real induction vector in tensor frequency-domain ground-airborne electromagnetic method," in *Proc. SEG Tech. Program*, Aug. 2018, pp. 998–1002.

[58] G. Xue, X. Li, S. Yu, W. Chen, and Y. Ji, "The application of ground-airborne TEM systems for underground cavity detection in China," *J. Environ. Eng. Geophys.*, vol. 23, no. 1, pp. 103–113, Mar. 2018.

[59] H.-Q. Zhang, Y. Chen, C.-X. Guo, and K. Zheng, "Influence analysis of displacement currents in geoelectromagnetic methods," *Int. J. Res. Eng. Adv. Technol.*, vol. 2, pp. 1–5, Apr. 2014.

[60] A. Ray and K. Key, "Bayesian inversion of marine CSEM data with a trans-dimensional self parametrizing algorithm," *Geophys. J. Int.*, vol. 191, pp. 1135–1151, Dec. 2012.

XIN WU received the Ph.D. degree in geophysics from the University of Chinese Academy of Sciences, in 2018. He is currently a Postdoctoral Researcher with the Key Laboratory of Mineral Resources, Institute of Geology and Geophysics (subordinate to the Institutions of Earth Science of the Chinese Academy of Sciences), and the University of Chinese Academy of Sciences, with an emphasis in theory, technology and application of the transient electromagnetic method.

GUOQIANG XUE is currently a Researcher with the Key Laboratory of Mineral Resources, Institute of Geology and Geophysics (subordinate to the Institutions of Earth Science of the Chinese Academy of Sciences), and a Professor with the College of Earth and Planetary Sciences, University of the Chinese Academy of Sciences, with an emphasis in transient electromagnetic exploration and applications. His research interests include TEM pseudo-seismic interpretation methods, TEM tunnel predication studies, large loop TEM exploration technology, the TEM response of short-offset excited by grounded electric sources, and analysis of time-varying point charge infinitesimal assumptions in the TEM field.

GUANGYOU FANG is currently a Researcher with the Key Laboratory of Electro-magnetic Radiation and Detection Technology, Chinese Academy of Sciences. He is mainly involved in the research of UWB radar imaging theory and technology, ground penetrating radar technology, geophysical electromagnetic exploration technology, lunar/Mars detection radar technology, UWB antenna theory and technology, and THz imaging technology.

XIU LI is currently a Professor with Chang'an University, with an emphasis in transient electromagnetic theory and applications. His research interests include TEM virtual wave-field inverse transformation, TEM virtual wave-field migration imaging, and semi-airborne TEM 3D migration imaging interpretation.

YANJU JI received the Ph.D. degree from Jilin University, Changchun, China, in 2004, where she is currently a Professor with the College of Instrumentation and Electrical Engineering. Her research interests include transient electromagnetic theory and exploration applications. She has more than 30 publications about transient electromagnetic theory and method. In 2010, she acquired the Second Award from China National Technology Invention, which is about the double wave field imaging of the groundwater combining nuclear magnetic resonance (NMR) with transient electromagnetic method.