



Development of a UAV-based fully-airborne transient electromagnetic system

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Abstract. In order to meet the challenges of transient electromagnetic exploration in complex terrain, a lightweight, low-noise, three-component, fully-airborne transient electromagnetic system is designed based on an unmanned aerial vehicle platform. By receiving the three-component electromagnetic field, reliable detection of the normal component even in undulating terrain is enabled, while also offering a theoretical basis for correcting errors arising from receiver coil oscillation. Through a system-level optimization design, the system balances weight and transmission power, resulting in a lightweight (14.94 kg), large transmitting magnetic moment (2250 Am²), and extremely low system noise (1.7 nT/s) configuration. A series of performance verification experiments and field tests verify the stability and practical operability of the proposed system in field applications. Comparisons between the inversion results of the collected detection data and borehole logging data further confirm the reliability of the system. Therefore, this system can provide an effective technical approach and solid data support for the fine detection of subsurface interfaces within a depth of 50 meters.

1 Introduction

In recent years, Transient Electromagnetic (TEM) methods have become indispensable in geophysical studies including but not limited to mineral exploration (Steuer et al., 2020), hydrogeological mapping (Podgorski et al., 2013), fresh-water investigation (Siemon et al., 2011) due to the high sensitivity to conductive targets. Airborne Electromagnetic Method (AEM) was proposed to further increase the working efficiency early in the middle of 20th century (Wu et al., 2019). During the past few decades, flexed-wing aircraft and helicopter have become the mainstream platform due to their heavy-lift capability. Helicopter-based platform especially, outperformed due to its low-altitude performance. The VTEM series is a premier helicopter-borne TEM system utilizing a high-power, concentric-loop configuration. According to different dipole moment and loop diameter, this series consists of VTEM Plus, VTEM Max and VTEM ET (Laizer et al., 2025). The SkyTEM system developed by Hydro Geophysics is one of the most sophisticated helicopter-borne transient electromagnetic (HTEM) platform as well. This series has a rigid, dual-moment transmitter configuration that simultaneously maps high-resolution near-surface resistivity and deep geological conductors (Auken et al., 2009).

Although traditional helicopter-borne systems offer extensive coverage, their operational costs and logistical constraints in rugged terrains often limit their applicability. The emergence of unmanned aerial vehicles (UAV) has revolutionized this fields by providing a lower-altitude, terrain-following alternative. As a carrier platform of various types of sensors, UAV have



already become increasingly popular in other geophysical surveys including magnetic exploration (Kolster et al., 2022), ground-penetrating radar (López et al., 2022), LiDAR (Noviello et al., 2021) as well as integrated approaches e.g. photogrammetry-magnetometry (Martelet et al., 2021). In contrast, most of current UAV-based TEM implementations rely on semi-airborne configuration utilizing a ground stationary transmitter and a drone-towed receiver, which restricts mobility in inaccessible regions (Dadrass Javan et al., 2024).

Therefore, the pursuit of achieving a true fully-airborne drone TEM system, where both the transmitter and receiver are integrated into the flight platform, has never ceased. An UAV-based TEM system named SkyTEM21HR was successfully conducted for geotechnical ground investigation, whose data is proved to be useful, and the spatial sampling rate has been improved due to the drone platform. However, the system still weighs 150kg, therefore a heavy-lift drone is necessary for filed operation (Nyboe et al., 2024). Tang et al. (2026) developed Wukong system for goaf detection with 80000 Am² transmitting magnetic moment yet only 1 component, and the system has been proved to be efficient as its strong ability to identify anomalies. Apart from a unified transmission and receiver platform integrated on one drone, a dual drone configuration named NEXT system developed by Radai Ltd. revealed another option. In that case, the compact mobile transmission loop is carried by a drone while the response is detected with a receiver transported by another drone (Pirttijärvi et al., 2022). Despite its potential, such a fully-airborne system faces significant challenges, including the strict load limits of UAVs, the electromagnetic interference (EMI) generated by drone motors and the need for lightweight yet high-power transmission. That's the reason for various compromises existing in the aforementioned systems.

This paper presents a novel fully-airborne TEM system designed to address these challenges through developing a lightweight 3-component magnetic sensor to realize real terrain-following exploration problem by obtain vertical normal component of uneven terrain. Meanwhile, to enhance the operational capabilities in steep mountainous terrain, a lightweight structural design is implemented.

2 System design and development

The system is designed to be lighter than 15kg for an easily equipment with a lighter-lift UAV (e.g. DJI T60, DJI FC30). In that case, smaller work group is capable for deployment on complex terrain. Optimizations from equipment development to structural design are conducted to achieve the above-mentioned aims as the Fig.1 illustrated.

In this system, electromagnetic compatibility during each part is well considered at the design stage, therefore a separated structure of the electronic devices and the towed bird is applied. The TEM transceiver consists of transmitter and receiver as well as their high-density lithium battery power. Through the formed binding cable and the attached electrical cable, the transceiver is connected to the towed pod to ensure the simplicity and stability of the overall structure.

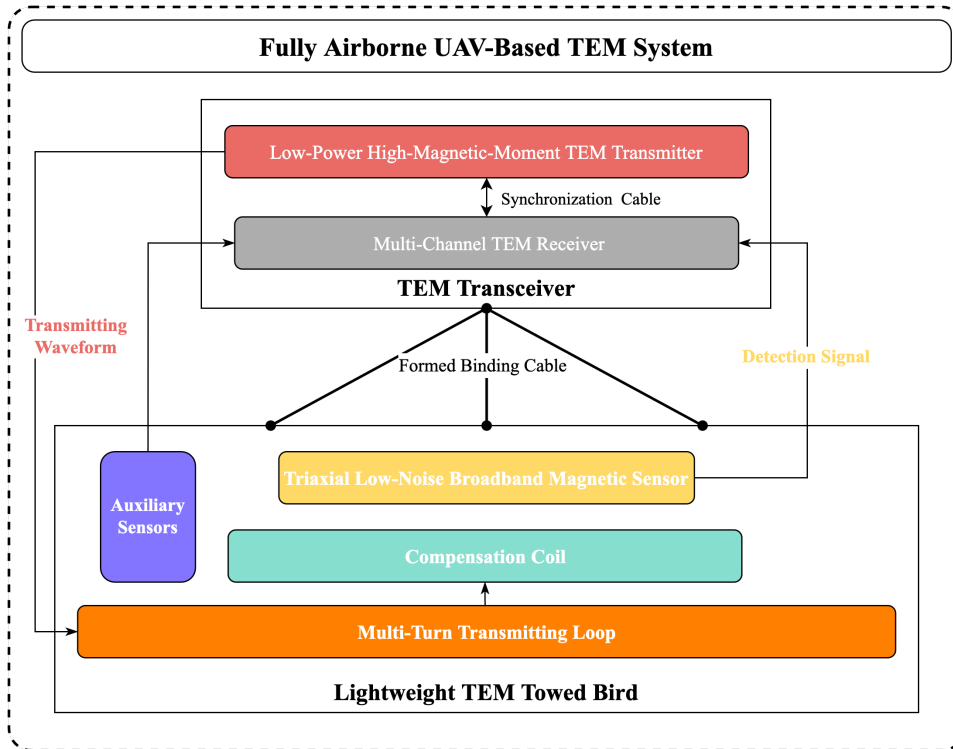


Figure 1 System structural design

2.1 Design and development of low-power high-magnetic-moment TEM transmitter

The research on high-frequency pulse fast shutdown technology was conducted to achieve TEM transmission with rapid shutdown, large magnetic moment, low power consumption, and compact size. Based on constant-voltage dual-clamp transmission technology, the power circuit of the transmission system employs segmented optimization techniques in the transmission current waveform. Dual clamping can simultaneously clamp the rising and falling edges of the current with high voltage, achieving a rapid and linear rise or fall of the edges, enabling the generation and high-precision control of high-quality electromagnetic pulse signals. The power switching and power inverter circuits transmit dual pulses, with both large and small magnetic moments to achieve blind zone suppression and high-precision detection in both deep and shallow areas. While increasing the peak transmission current, the transient electromagnetic pulse width is further compressed to reduce the power consumption.

A high-speed power switch design was conducted on the proposed TEM transmitter to achieve power inversion, rapid power supply switching, as well as dual clamping of active constant voltage which is segmented adjustable. It utilized three sets of isolated power supplies internally to eliminate crosstalk and enhance system control stability. The power components adopted a high-speed MOSFET full-bridge inverter circuit to achieve rapid shut-down and improve detection resolution.



Transmitter function and performance tests, as well as synchronous transmit/receive decoding tests were conducted. And Fig. 2 illustrates the test results of the actual transmitted pulse, which demonstrated that the TEM transmitter achieved alternating large and small current dual-pulse transmission, and that the transmitted current exhibited high stability both during the flat-top period and between repetitive periodic pulses. Under 24V power supply conditions, the dual-clamping constant voltage up to 500V could be reached, and the clamping voltage level remains stable during current shutdown, ensuring the linearity of shutdown current. Transmission capability experiments with an equivalent load proved that the transmitted current could reach up to 20A.

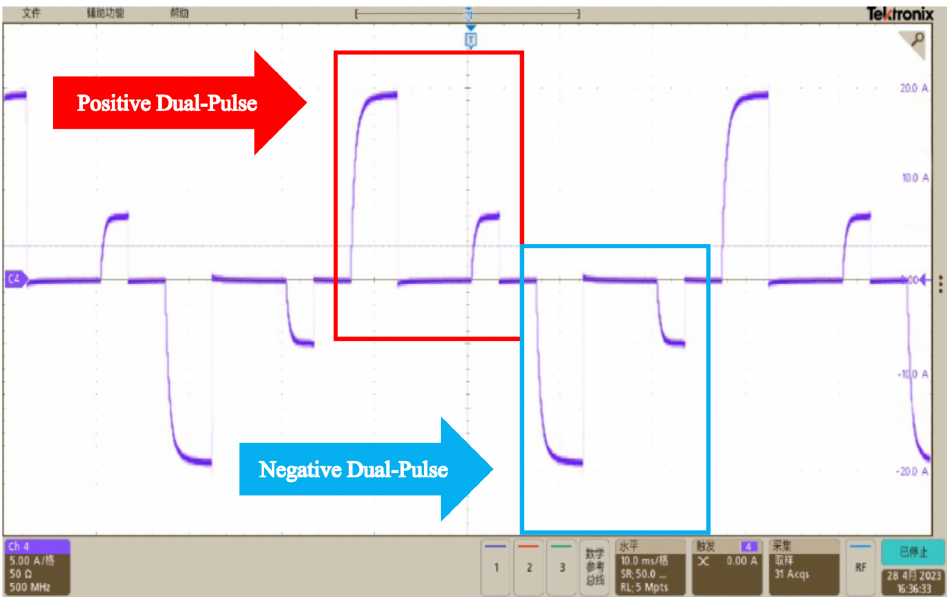


Figure 2 Test result of transmitted pulse current

2.2 Research on multi-channel signal acquisition technology

The multi-channel signal receiver mainly completes the signal acquisition and recording from the triaxial magnetic field sensor, including signal conditioning, analog-to-digital conversion, data storage, and data quality monitoring. The circuit design and internal structure is illustrated in Fig. 3.

The triaxial magnetic field signal is processed by a protection circuit and impedance matching before being input to a low-noise differential amplifier circuit, where DC bias compensation is implemented. To meet the requirements of signal acquisition in large dynamic range, the subsequent stage is designed based on a programmable gain amplifier circuit with 1/4, 1, 4, 8, and 16 times gain adjustment to regulate the signal amplitude. Finally, after anti-aliasing filtering, the signal is input to an analog-to-digital converter (ADC) circuit for acquisition.

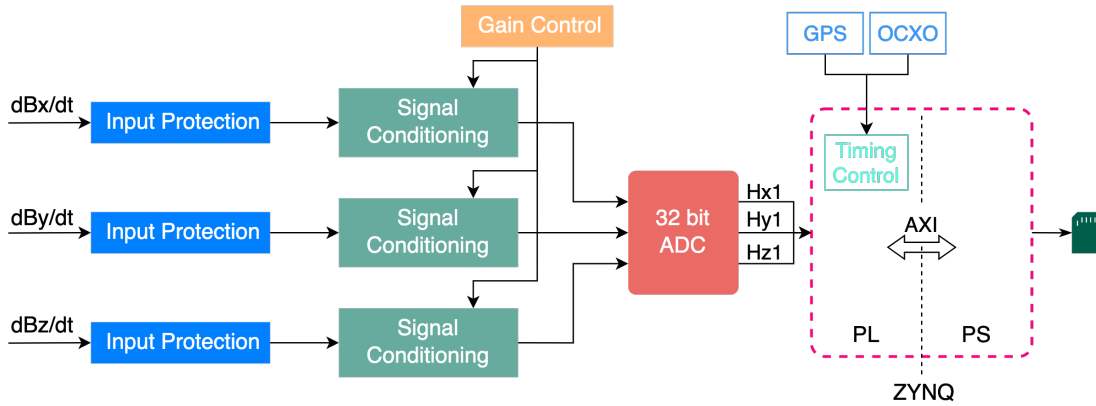


Figure 3 Block diagram of developed signal receiver

The system adopts the LTC2500 true 32-bit ADC to realize high-precision and high-speed signal acquisition with a maximum sampling rate of 1Msps. High-speed sampling is performed at the front end, followed by SSINC digital filtering to achieve low-sampling-rate data output, which significantly improved the dynamic range to approximately 138dB@1 Ksps ($FS=\pm 5V_{pp}$). The central controller of the receiving system is selected as ZYNQ7020. The PL end, which acts as the FPGA, handles the acquisition of the ADC-digitized data and FIR data filtering, sending it to the ARM processor at the PS end via the AXI bus. The ARM processor then caches the data in double data rate (DDR) memory.

The receiver also integrates a high-precision synchronous clock calibration circuit to provide the system with highly stabled local synchronous clock signal for time matching between the transmitter and receiver.

The noise level of receiver was tested, and the results are shown in Fig.4, from which the dynamic noise level of the signal receiver at the 1ms sampling window are shown as 0.145 μV (Z), 0.147 μV (X), and 0.16 μV (Y).

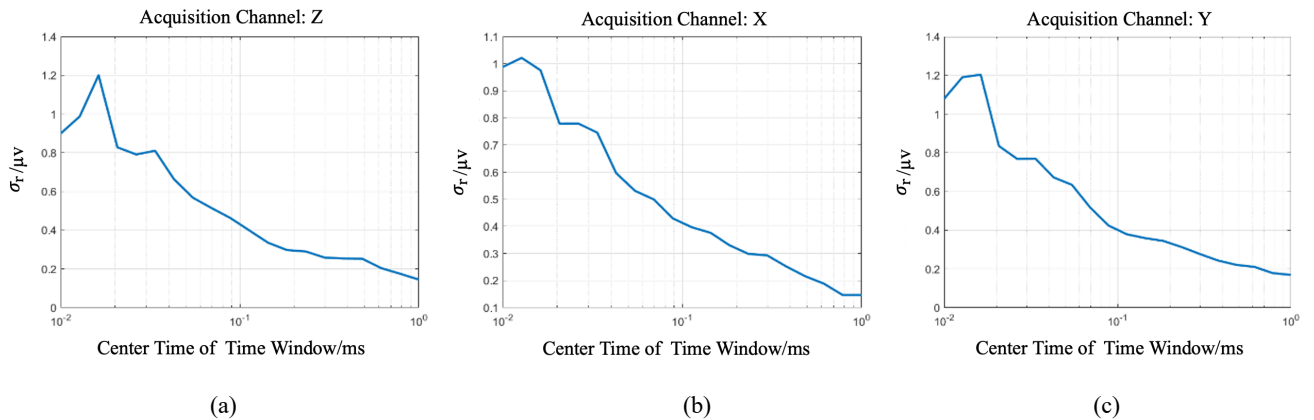
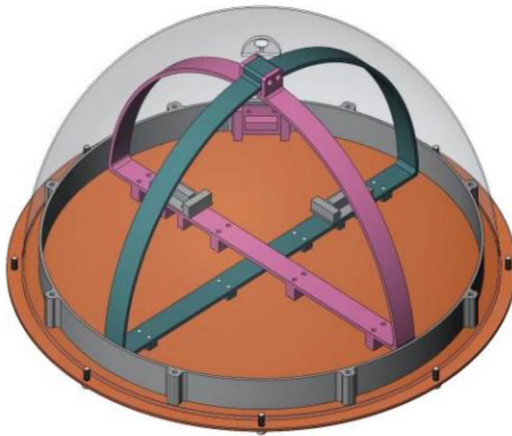


Figure 4 The test result of dynamic noise level of each acquisition channel. (a) Acquisition channel Z; (b) Acquisition channel X; (c) Acquisition channel Y

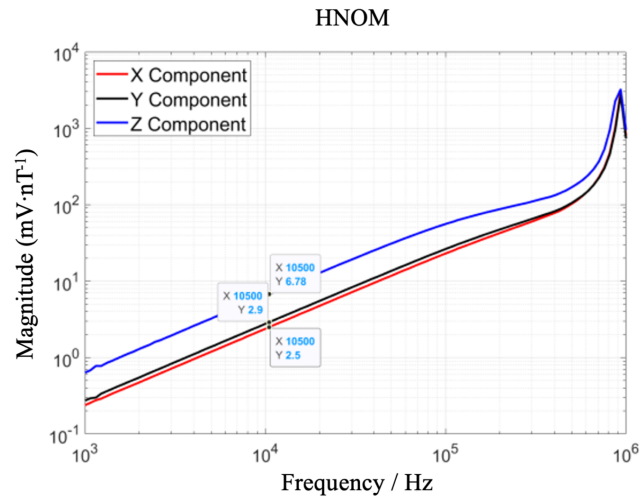


2.3 Design of triaxial low-noise broadband electromagnetic sensor

Through optimization methods study for the distributed impedance parameters of the sensor coil and impedance matching techniques, the bandwidth optimization design of the sensor coils was achieved. Capacitor compensation technology was employed, and a capacitor compensation network at the front end of the low-noise amplifier circuit was introduced to reduce the coil capacitance and increase the resonant frequency effectively. An optimized design of a hollow coil magnetic field sensor based on a ribbon cable structure was implemented. By setting the coils in the optimal damping state, effective acquisition of early-time high-frequency secondary field signals as well as weak late-time secondary field signals was enabled. The triaxial electromagnetic sensor was designed in a hemispherical structure shown in the Fig. 5(a). Apart from receiving coils, a low-noise signal amplification was also integrated using a bipolar transistor and a low-noise instrumentation amplifier, while impedance matching was also implemented. The sensitivity of the sensor was tested, and the measured frequency response results are shown in the Fig. 5(b). The receiving bandwidth of the electromagnetic field sensor is wider than 120kHz.



(a)



(b)

Figure 5 Developed electromagnetic field sensor. (a) Designed structure; (b) Measured frequency response

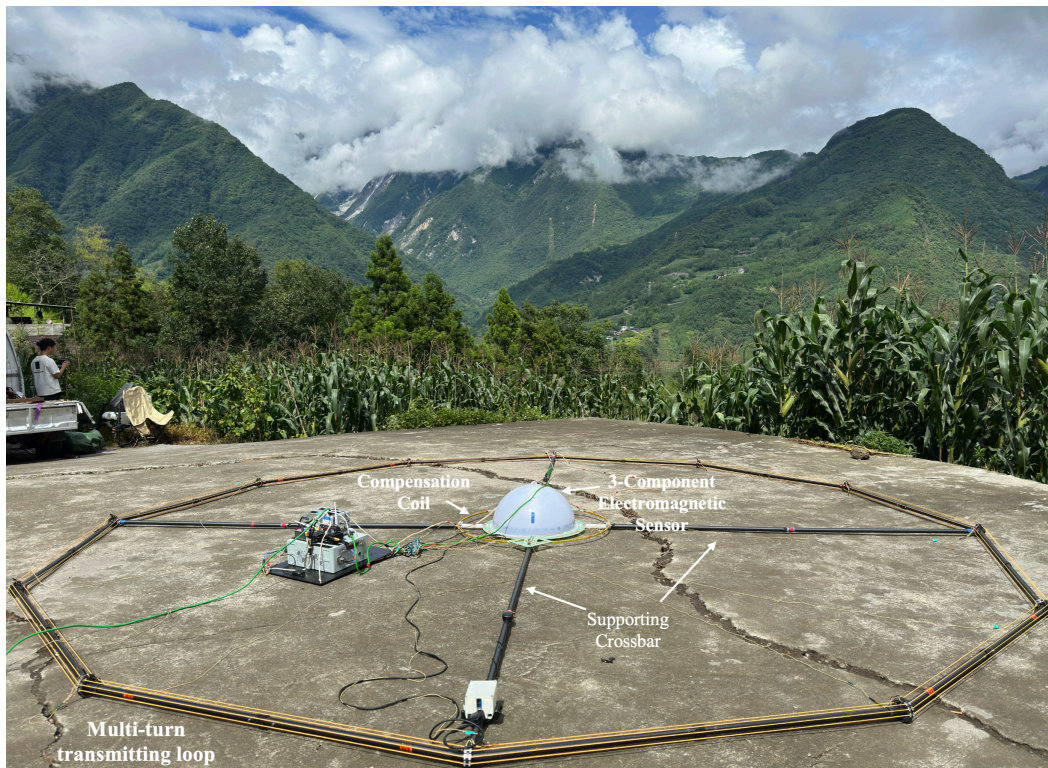
2.4 Design of lightweight TEM towed bird

The fully-airborne TEM detection towed bird, illustrated in Fig. 6, carries the transmitting coil, compensation coil, and triaxial electromagnetic sensor, making it a unified transceiver detection device with common-center transmission and reception, stable primary field compensation, and orthogonal three-component sensors. The towed bird adopted a regular dodecagon structure, on which the transmitting loop is carried. The equation for calculating the transmitting magnetic moment is as follows:

$$M = N * I * n \frac{r^2}{2} \sin\left(\frac{2\pi}{n}\right), \quad (1)$$



- 130 Where n is the number of sides of the polygon, here $n=12$; r is the radius of the circumscribed circle, which is 2.5m; N is the number of turns of the transmitting coil; and I is the peak transmitting current. The transmitting module is designed with a peak transmitting current of 10A-20A and 6 turns, therefore the transmitting magnetic moment is calculated as 1125 Am^2 - 2250 Am^2 .



135 **Figure 6 Design of lightweight TEM towed-bird**

3 System integration and evaluation

To achieve a fully airborne TEM system, the integration method also has a significant impact on the final performance. The proposed device employed a non-electrical connection design with the UAV, which improved the compatibility with the flight platform. This design also enhanced the system's electromagnetic compatibility, resulting in a better signal-to-noise ratio.

- 140 Simultaneously, the auxiliary radar altimeter and Inertial Measurement Unit (IMU) were mounted on the supporting crossbar to acquire the position and altitude of the towed bird, facilitating correction and analysis during data processing. From Fig. 7, the system integration result is given.

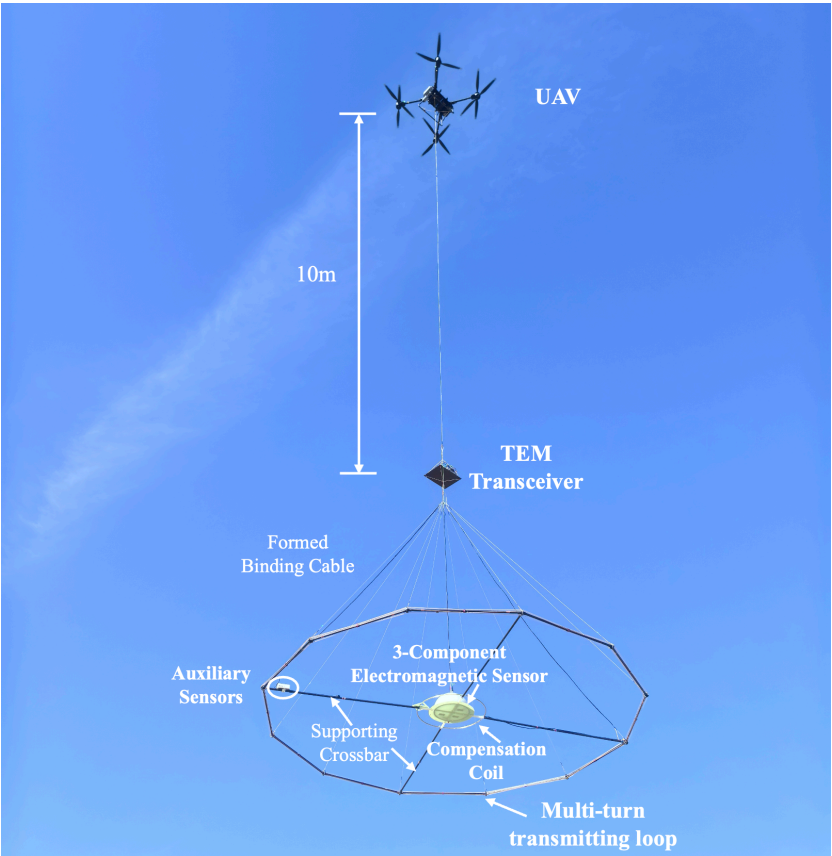


Figure 7 System integration

145 After system integration, evaluation tests and experiments were conducted on various performance indicators of the system,
and the key technical indicators are listed as Tab. 1. Compared with current state-of-art UAV fully-airborne TEM systems
(Wang et al., 2021; Nicklas et al., 2023), the UAV-HTeM-5M proposed in this paper achieved a better balance between system
weight and transmitting magnetic moment, while the other indicators are also at an advanced level. It is worth noting that this
system has significant advantages in receiving all electromagnetic field components (three components) and noise level
150 indicators, and its practical application results will be discussed in following section.

Table 1 Comparison of state-of-art systems with proposed system

Affiliation	SkyTEM Surveys	Chongqing Uni.	Jilin Uni.	Aerospace CAS
System	SkyTEM21HR	Wukong100-1	TEM-31	UAV-HTeM-5M
Sensor Component	1C	1C	1C	3C
Towed-Bird Dimension	——	Ø 12 m	2 m×2 m	Ø 5 m
Transmitting Moment	3480 Am ²	80000 Am ²	360 Am ²	2250 Am ²



Acquisition Bandwidth	900 kHz	——	≈ 60 kHz	120 kHz
Noise Level	——	——	≈ 10 nT/s	1.7 nT/s
System Weight	150 kg	——	8 kg	14.94 kg

4 Calibration of the vertical component using 3-component electromagnetic field data

In current TEM studies and applications, usually only the vertical component of electromagnetic field is recorded rather than all three components, which mainly attributes to the complexity of instrument system and the difficulty of data processing.

155 However, former studies have proved that all-component interpretation takes more advantages in determining the range of anomalies and improving vertical and horizontal resolution (Chen et al., 2008). Yu et al. (2021) demonstrated that the 3-component TEM measurement has the potential of giving access to conductor information and the extension direction of anomalous body by numerical simulation.

For a better support of 3-component TEM data processing, a simultaneous 3-component TEM sensing and acquisition 160 technology was studied and developed in this paper. The increase of system complexity, however, brought higher noise level, which should be considered from the system design.

To better eliminate measurement errors caused by changes in sensor attitude, IMU (Inertial Measurement Unit) information was introduced, and a more complete attitude correction model can be constructed, providing data foundation for accurate inversion and modeling of complex underground geological bodies.

165 The coordinate of IMU (coil attitude) and the standard geographical system could be transformed using a rotation matrix. Under this circumstance, a cartesian coordinate system with the x-axis pointing east, the y-axis pointing north, and the z-axis pointing upwards was established. Define $\phi(t)$, $\theta(t)$, and $\psi(t)$ as the time-varying roll angle, pitch angle, and yaw angle, respectively. On this basis, the rotation matrix is formulated as follows:

$$R = R_{\psi}R_{\theta}R_{\phi} = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix}, \quad (2)$$

170 Based on the rotation matrix, the normal vector of the coil could be expressed as follows:

$$\vec{n}_{coil} = R(t)\vec{i} + R(t)\vec{j} + R(t)\vec{k}, \quad (3)$$

A transformation relationship between IMU coordinate (B') and geographic coordinate (B) was established as follows:

$$B = R \cdot B', \quad (4)$$

Therefore, we have:

$$\begin{aligned} B_x &= R_{11}B'_x + R_{12}B'_y + R_{13}B'_z, \\ B_y &= R_{21}B'_x + R_{22}B'_y + R_{23}B'_z, \\ B_z &= R_{31}B'_x + R_{32}B'_y + R_{33}B'_z, \end{aligned} \quad (5)$$



For each acquisition point, the rotation matrix could be expressed by real time measurement of IMU, and the calibrated response could be calculated using the aforementioned equations (2-5) and the pre-known system HNOM (Nominal
 180 Magnetic Field Transfer Coefficient).

The vertical component calibration of the electromagnetic response effectively suppresses interference caused by attitude variations and surface or near-surface inhomogeneities, yielding a more accurate reflection of deep-seated targets. To quantitatively evaluate the effectiveness of the attitude compensation algorithm, Pearson correlation coefficients between the coil response and inertial navigation attitude data were calculated before and after correction. The overall correlation
 185 coefficients corresponding to the x- and y-axis components decrease markedly. Meanwhile, the correlation between coil outputs and roll/pitch angles becomes insignificant, which demonstrates that the attitude-dependent interference is effectively suppressed. Improvements are also observed in the vertical-component electromagnetic responses, where the average relative correlation coefficient decreases by 10.9% with respect to pitch angle and 26.8% with respect to roll angle. The attitude-corrected three-component electromagnetic responses are illustrated in Fig. 8. Motion noise caused by attitude
 190 variations in the x- and y-axis components has been substantially suppressed. In contrast, the intrinsic signal strength of the z-axis component is significantly higher than that of the x- and y-axis components (typically by one to two orders of magnitude). When noise of the same magnitude level is suppressed, the relative improvement in the corrected signal is less pronounced than that observed in the horizontal components.

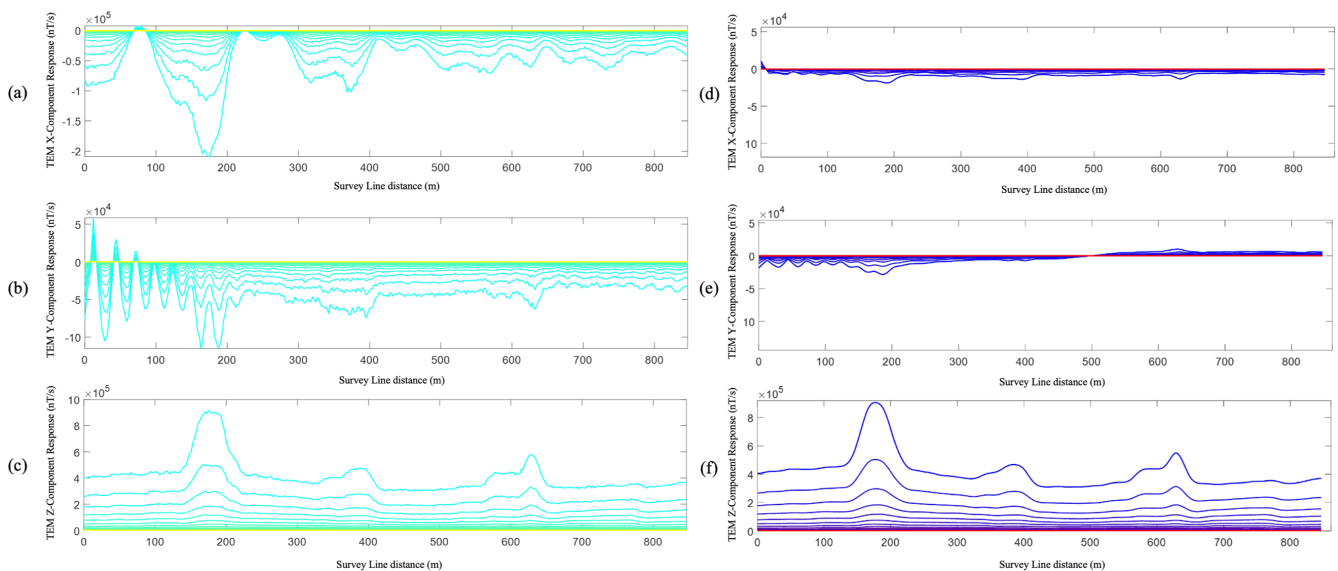


Figure 8 3-Component TEM Response. (a) TEM response of X-Component before calibration; (b) TEM response of Y-Component before calibration; (c) TEM response of Z-Component before calibration; (d) TEM response of X-Component after calibration; (e) TEM response of Y-Component after calibration; (f) TEM response of Z-Component after calibration;

5 Application

To evaluate the performance of proposed system, a TEM survey was conducted in a geologically hazardous area in Ordos, Inner Mongolia Autonomous Region. This area is a landslide zone overlying fragmented sandstone and loess. Figure 9(a) shows the planned survey line and the actual flight trajectory of this survey.

The system parameters used in this survey were:

- (1) Transmission current: 20A;
- (2) Transmission frequency: 25Hz;
- (3) Duty cycle: 25%;
- (4) Sampling rate: 1Mbps;
- (5) Flight speed: 2-4 m/s;
- (6) UAV platform: DJI T100.

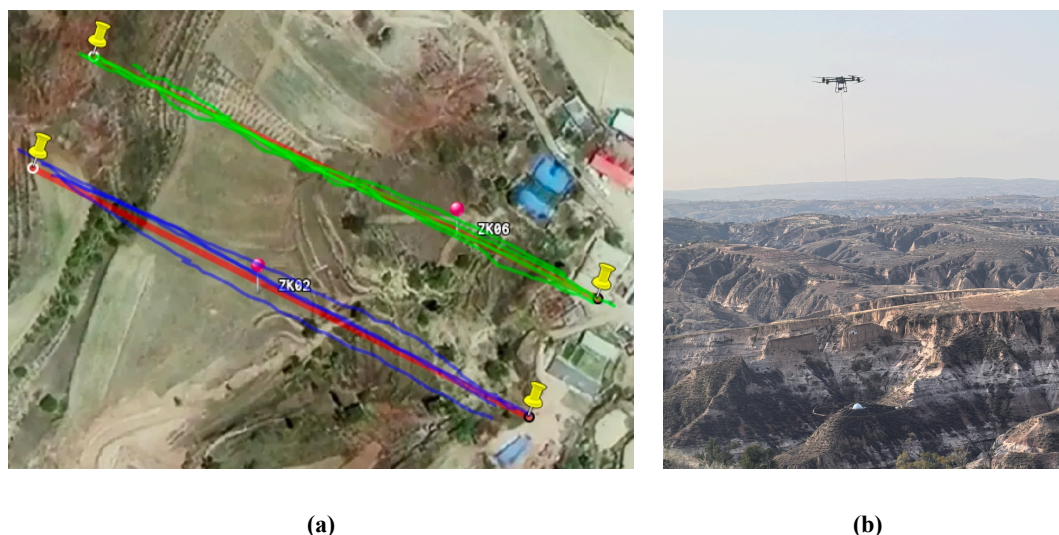


Figure 9 Proposed system in application. (a) Planned survey line and actual flight trajectory; (b) Picture of system in exploration

The inversion result of resistivity profile is shown in Fig. 10. According to the geological data, the upper layer is mainly Quaternary (Q3) loess-like silt and loess-like clay, while the lower layer primarily consists of fractured and strongly weathered Triassic (T2e) mudstone and sandstone. Water infiltration along the fractures on slip surface leads to lower resistivity at depth. The low-resistivity boundary of the slip surface is clear for the identification of landslide surface. However, to obtain an accurate stratigraphic interface, the relationship between resistivity and lithology was constructed (Ruffet et al., 1995; Jin et al., 2024; Auken et al., 2017), resulting in the predicted landslide surface boundary shown by the dashed line in Fig. 10(a) & (b). Comparison results with borehole data, which is located on the survey line, is shown in Tab. 2. The error between the landslide surface depth obtained through inversion from measured data and that from actual drilling data is approximately 1 m, which indicates a well correspondence to the actual situation.

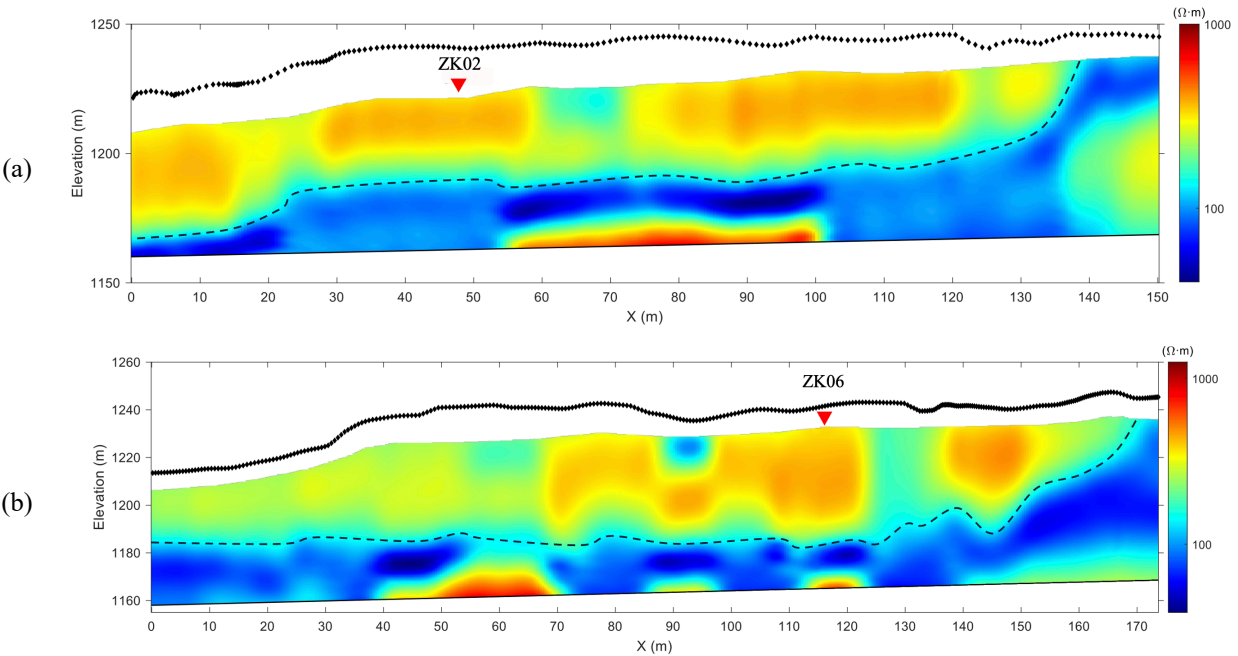


Figure 10 Inversion result as resistivity profile. (a) F6-2 resistivity profile; (b) F4-1 resistivity profile.

Table 2 Comparison of exploration result from measured data with borehole data

Observation data profile name	Borehole	Landslide Surface Depth		Error
		Drilling Data	Measured Data	
F6-2	ZK02	30.90m	31.94m	1.04m
F4-1	ZK06	47.60m	46.62m	0.98m

5 Discussion

The successful development of the proposed system marks a breakthrough in the field of lightweight and high-efficiency UAV-based fully-airborne TEM detection technology. From the application survey example and interpreted data, the proposed system is proved to be reliable.

Previous studies have demonstrated that various approaches have been developed for near-surface airborne geophysical exploration, yet each with distinct advantages and limitations. Eppelbaum and Mishne (2011) proposed the UAV-borne magnetic and VLF-EM measurements, providing a high mobility and ground-following flight capability for geophysical exploration over mountainous and complex terrain. The proposed method, however, utilized an active time-domain electromagnetic technique, can reconstruct vertical electrical structures and detect conductive targets such as water-bearing fractures even for non-magnetic subsurface media. For manned airborne electromagnetic surveys, Siemon (2012) developed precise 1-D forward and inverse algorithms for helicopter-borne high-frequency EM data, which mainly resolve shallow subsurface structures and rely on costly manned helicopter platforms with limited accessibility in rugged terrain.



Compared with similar technologies, the existing UAV-based TEM detection mainly uses a semi-airborne configuration, which has a ground stationary transmitter and a drone-towed receiver. The proposed system pioneered the “air-transmitted and air-received” operation mode, achieving a breakthrough in both exploration efficiency and terrain adaptability.

To achieve the above-mentioned results, innovations are made as follows: 1) An innovative segmented dual-clamping high-current transmission scheme was adopted, achieving narrow-pulse, high-magnetic-moment signal transmission while significantly reducing average power consumption. This fundamentally solves the problems of heavy load and high power-consumption in traditional helicopter-borne systems. 2) A high-performance three-component electromagnetic field sensor was developed (noise level: 1.7 nT/s), improving the sensitivity and signal-to-noise ratio of data acquisition significantly. 3) Integrated flight towed bird and compensation technology were optimized. A lightweight, transceiver-integrated towed bird was designed, making the system more suitable for complex field application scenarios, which improved the stability and reliability of exploration significantly.

Apart from above mentioned advantages, UAV-based fully-airborne TEM systems still suffer from a transmitter turn-off dead-time, which may degrade the detectability of extremely shallow targets. Furthermore, the payload, power consumption and flight-time constraints of UAV platform limit the overall system scale, restricting the achievable transmitting magnetic moment and deep-signal excitation capability. In practical field surveys, multi-depth joint exploration integrating complementary geophysical methods is therefore required. UAV-borne magnetic surveys and ground-penetrating radar can be adopted to fill the gap in ultra-shallow detection, while semi-airborne TEM approaches can compensate for the insufficient deeper performance of fully UAV-borne TEM.

Code and data availability

We express our sincere gratitude for the editor's diligent attention and acknowledgment of our research endeavours. We fully acknowledge the significance of data sharing as stipulated by the journal. Figure reconstruction data of inversion results are accessible to editors and reviewers for peer review purposes undersigned confidentiality obligations (Excel datasets, DOI: <https://doi.org/10.57760/sciencedb.43791>). Should the esteemed editor and reviewers require further elucidation or specific inquiries pertaining to the data, we pledge our utmost commitment to providing detailed explanations and clarifications.



Author contributions

260 **Feng Guo**: Writing-original draft preparation; Resources. **Ling Huang**: Investigation; Methodology; Writing-review and editing. **Jiankai Li**: Software; Visualization. **Guangyou Fang**: Supervision. **Lihua Liu**: Project Administration. **Xiaojun Liu**: Funding acquisition

Competing interests

The authors declare that they have no conflict of interest.

265

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