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New technologies of TEM in China

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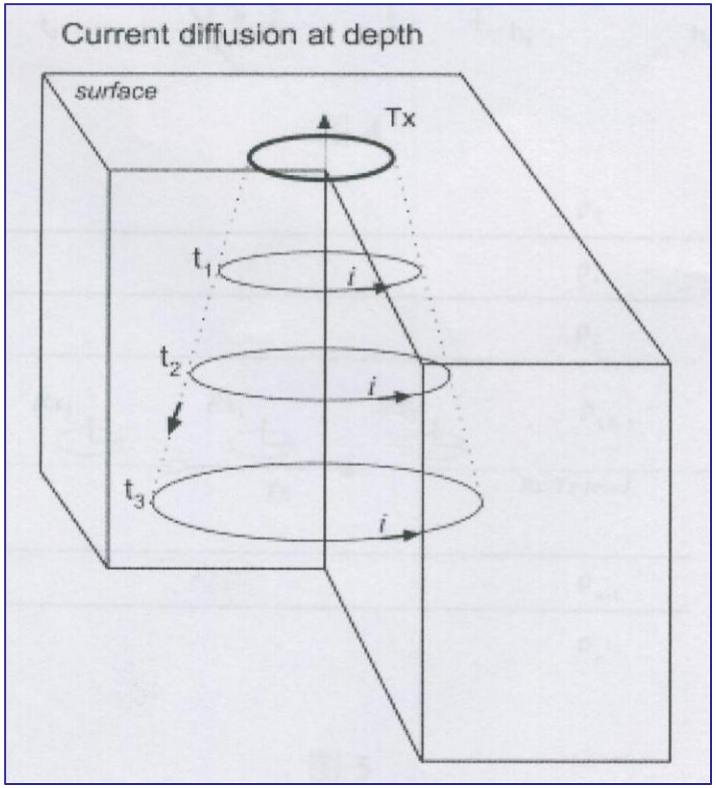
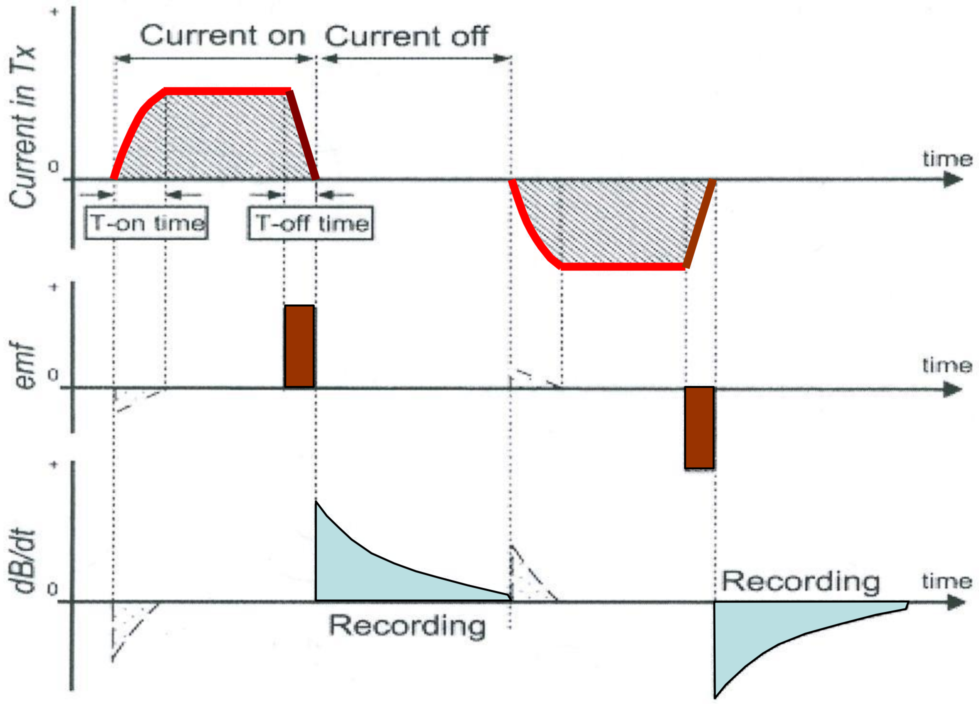
1. Introduction

1.1 TEM Introduction





Transient electromagnetic method（TEM）is a time domain method in electromagnetic exploration, which is sensitive to conductive targets and have been widely used in mineral source, coal, ground water, environment and engineering investigation(Nabighian,1991).

1. Introduction continued

1.2 Some vital issues in TEM exploration

1) Understand and calculate the TEM response base on its physical mechanism.
2) Greater investigation depth is needed to meet the need from deep mineral deposits and coal hydrogeology.
3) Higher precision and faster detection for both shallow and deep investigation.
4) Efficient processing method suitable to 2D and 3D data.

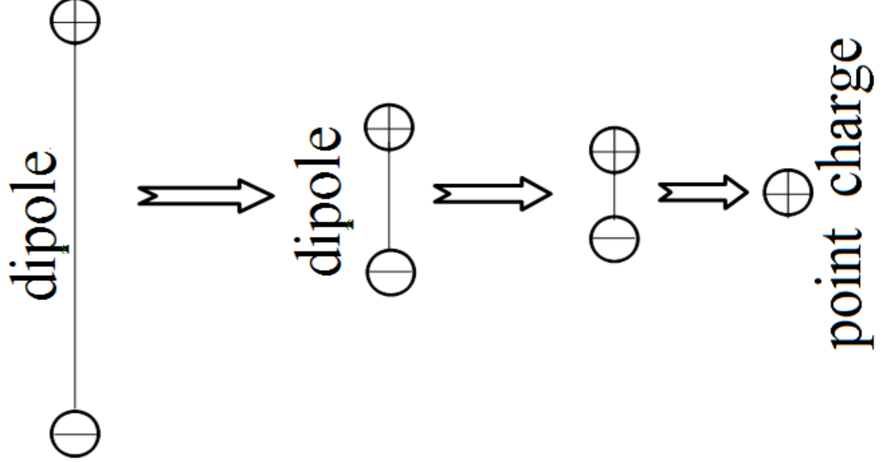
2. Infinitesimal Point Charge

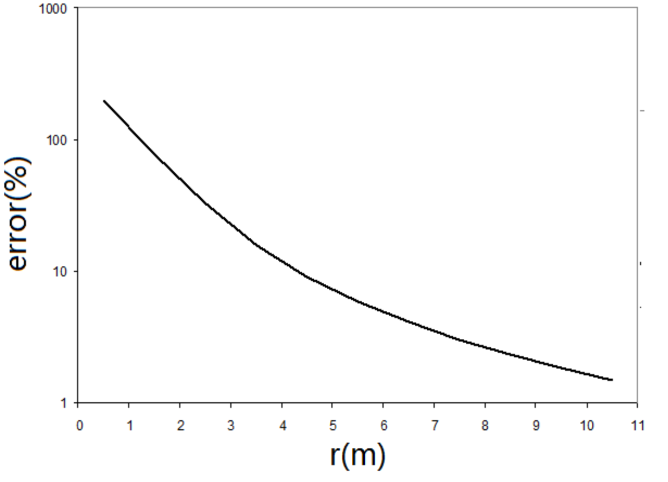
2.1 Traditional approach to calculate TEM response due to a finite source

1). Regard the source as a dipole(Kaufman,1987)

2). Regard the source as a superposition of many dipoles(Nabighian,1991)

The relative error drops with the decrease of dipole dimension. The smallest and intrinsic source should be point charge





2. Infinitesimal Point Charge continued

2.2 Basis

According to Maxwell equations so long as an electric charge varies with time it will excite electromagnetic wave .

$$\nabla \times H = j + \frac{\partial D}{\partial t}$$

2.3 Mathematics

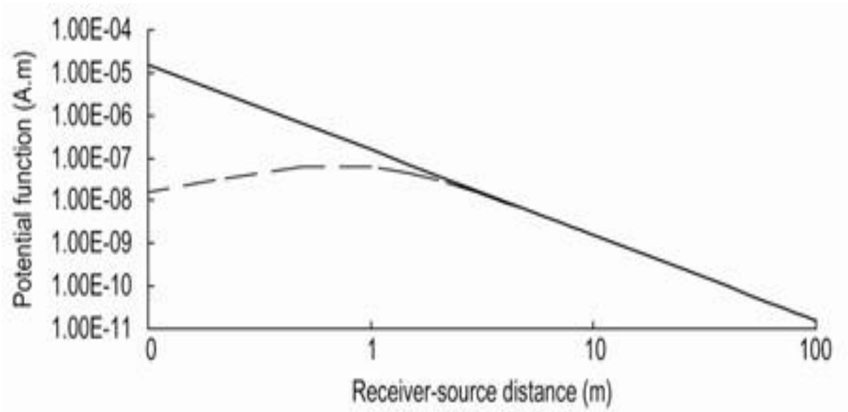
Based on point charge hypothesis, TEM field analytical solution has been derived by introducing time-domain Green function. Integral formula has been used to transform electromagnetic field damping wave equation into Green function integral form. Auxiliary path has been constructed for solving singularity problem. Four heavy generalized integral formula of time-domain electromagnetic field response has been arrived by using Jordan's lemma, the residue theorem and generalized function method. Direct-time-domain exact solution of D'Alembert equations firstly has been derived(Zhou,2013;Xue,2014).

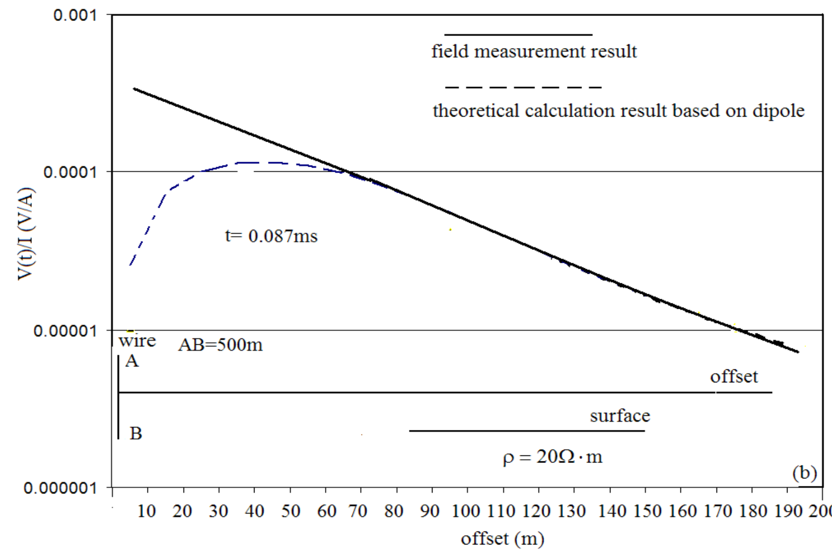
$$E(\mathrm{x},t) = -\int_0^t \int_D \left(\frac{1}{\sigma} \frac{\partial J(\mathrm{x}',\tau)}{\partial \tau} + \nabla \left(\frac{\rho(\mathrm{x}',\tau)}{\sigma\mu\varepsilon} \right) \right) T e^{-\frac{\sigma\mu|\mathrm{x}-\mathrm{x}'|^2}{4(t-\tau)}} d\mathrm{x}' d\tau$$

$$E(\mathrm{x},t) = -\int_0^t \int_D \left(\frac{1}{\sigma} \frac{\partial J(\mathrm{x}',\tau)}{\partial \tau} + \nabla \left(\frac{\rho(\mathrm{x}',\tau)}{\sigma\mu\varepsilon} \right) \right) T e^{-\frac{\sigma\mu|\mathrm{x}-\mathrm{x}'|^2}{4(t-\tau)}} d\mathrm{x}' d\tau$$

2. Infinitesimal Point Charge continued

2.4 Comparison with dipole



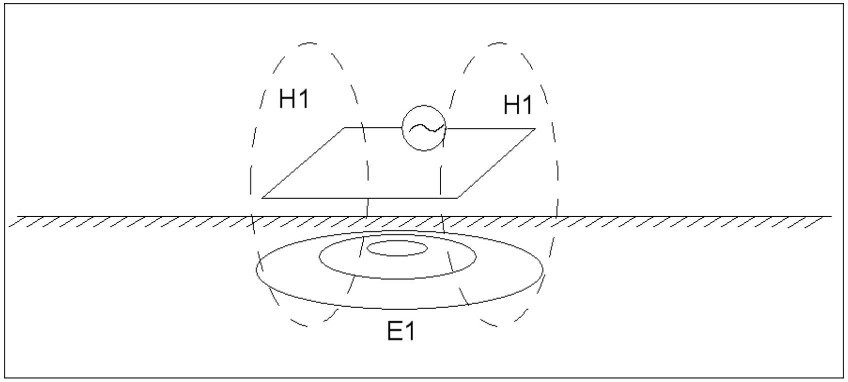


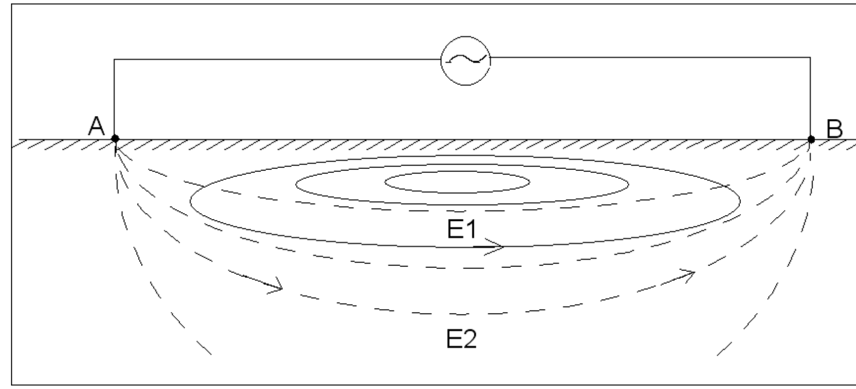
Solid line represents infinitesimal point charge (left figure) and measured data (right figure), dashed represents dipole (both figures)

It is shown that the field of the infinitesimal point charge in the near source zone is different from that of dipole, whereas the far-source zone fields of these two sources are identical. The comparison of real and simulated data shows that the infinitesimal point charge represents the real source better than dipole source.

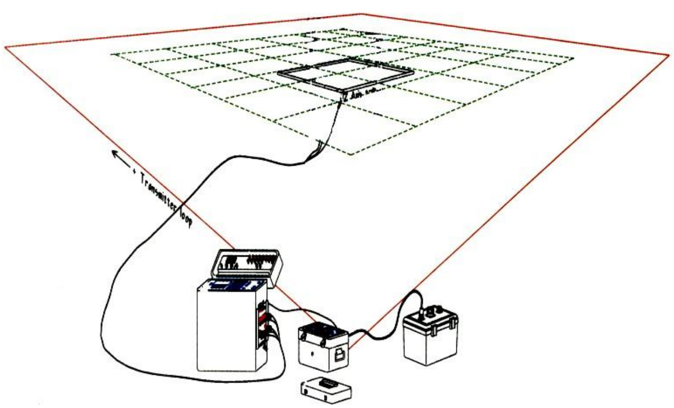
3. Electric Source Short-offset TEM

3.1 Background





1) Loop source excites only horizontal induction current, while grounded wire source has both horizontal and vertical induction current. This leads to loop source TEM only sensitive to conductive targets.

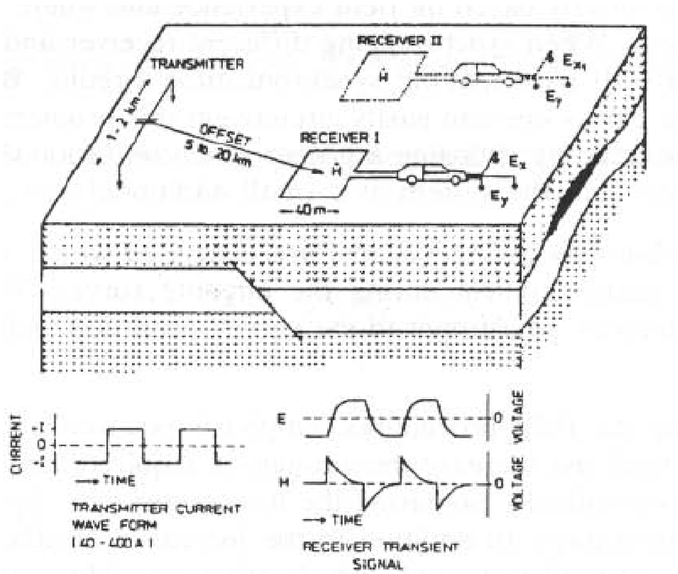


2) Detection depth of loop source TEM usually is shallower than 1km.

3) Difficult to lay the transmitting loop at mountain areas.

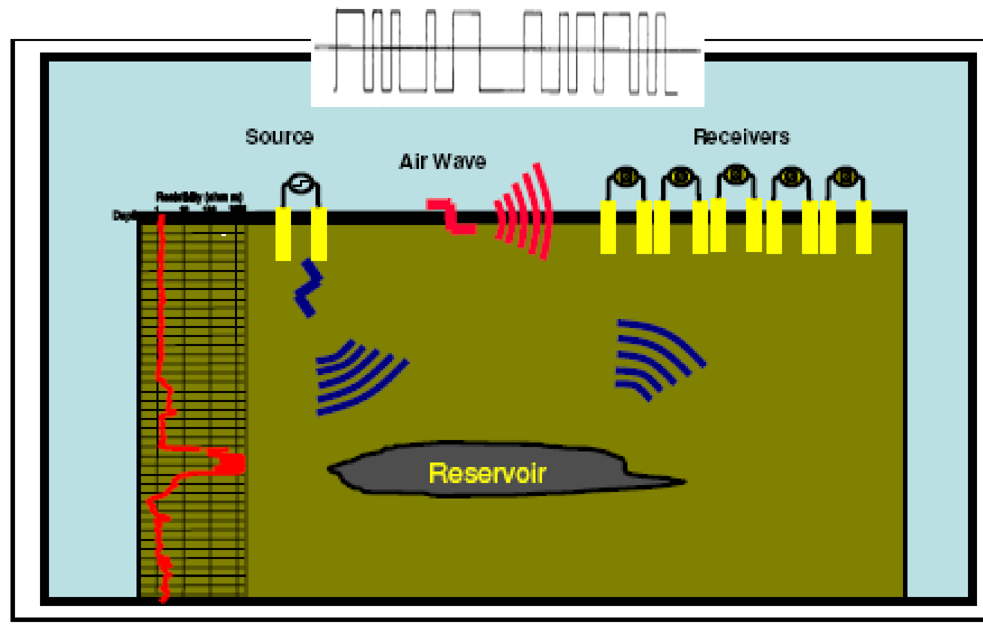
3. Electric Source Short-offset TEM continued

3.1 Background Continued



LOTEM(Strack,1992)

- **Advantage**: great detection depth (more than10km)
- **Disadvantages**: great source-receiver distance (2~20Km), weak signal, volume effect, poor precision,



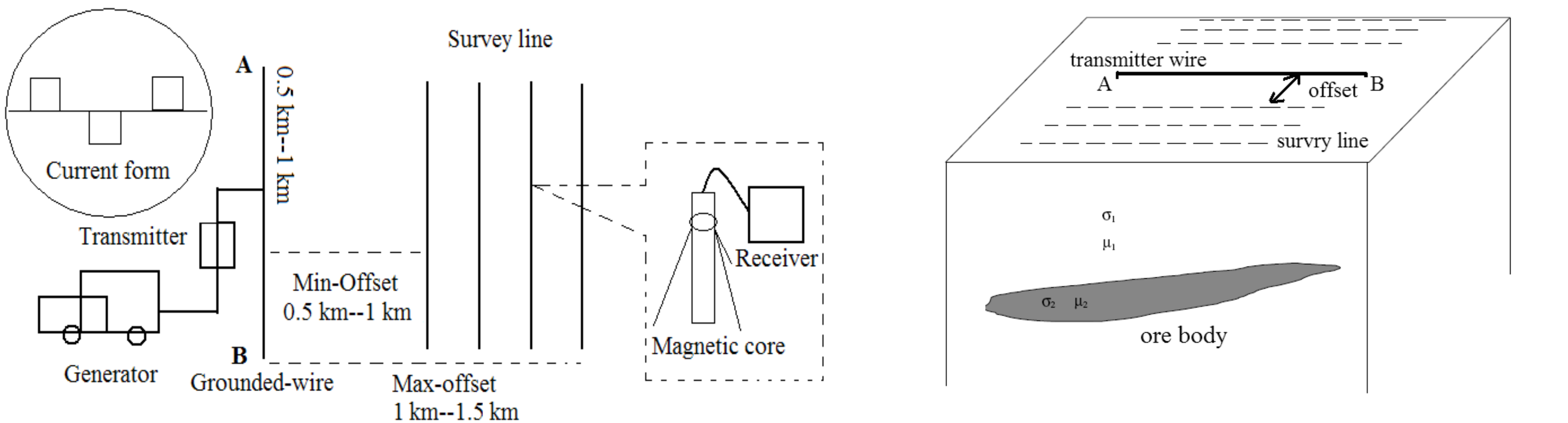
MTEM(Ziolkowski,2007)

Advantage: great power, pseudorandom transmitting source; multi-channel array, multi component, 3D detection; Pseudo-seismic imaging of data
Disadvantage: heavy, hard to conduct at mountain area; mainly used in marine; systemic and robust equipment have not been introduce to china

3. Electric Source Short-offset TEM continued

3.2 Definition

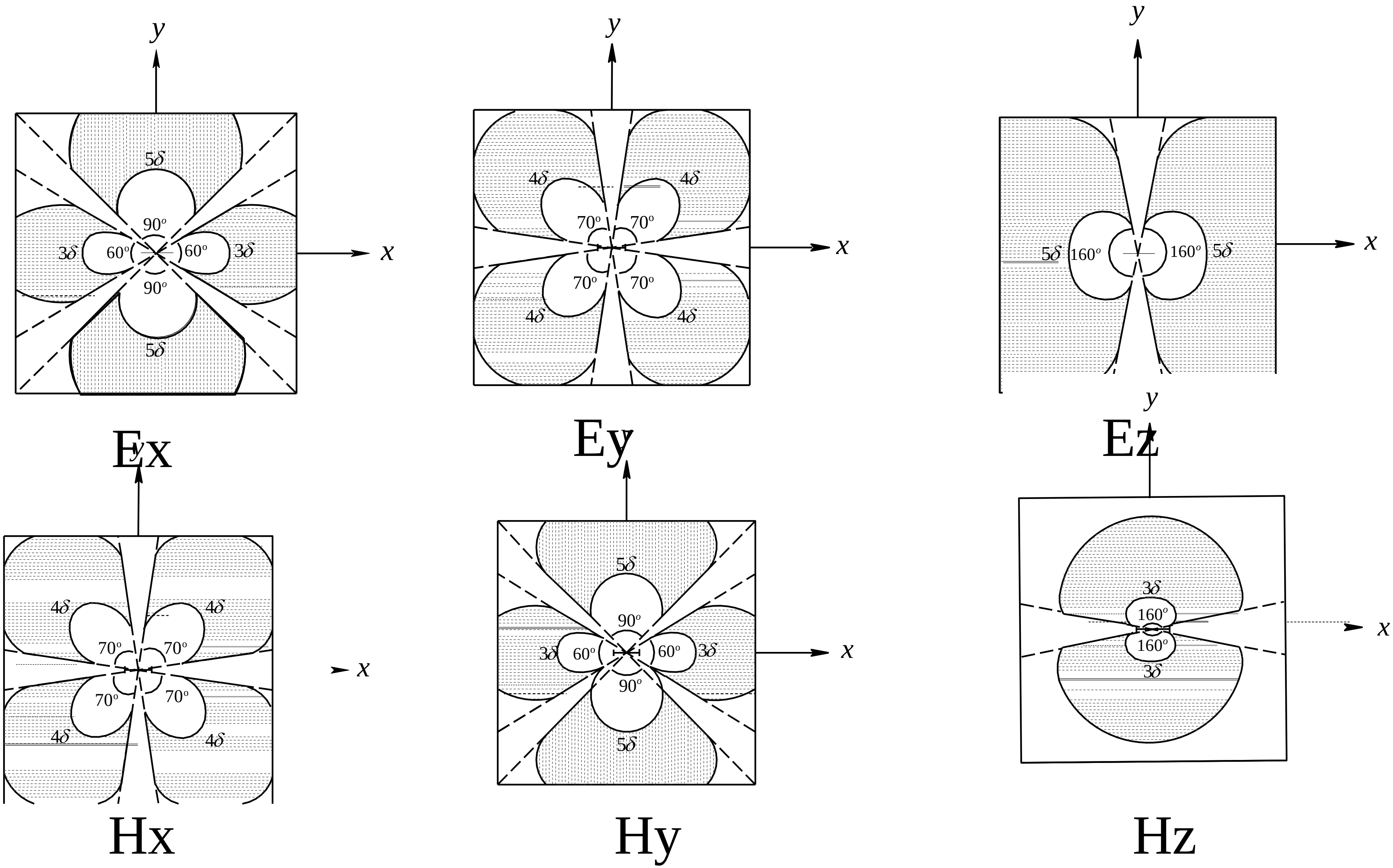
Short-offset TEM (abbreviated to SOTEM) means that the distance between transmitter and receiver is approximately equal to or less than the exploration depth(Xue,2013).



Typical SOTEM layout diagram

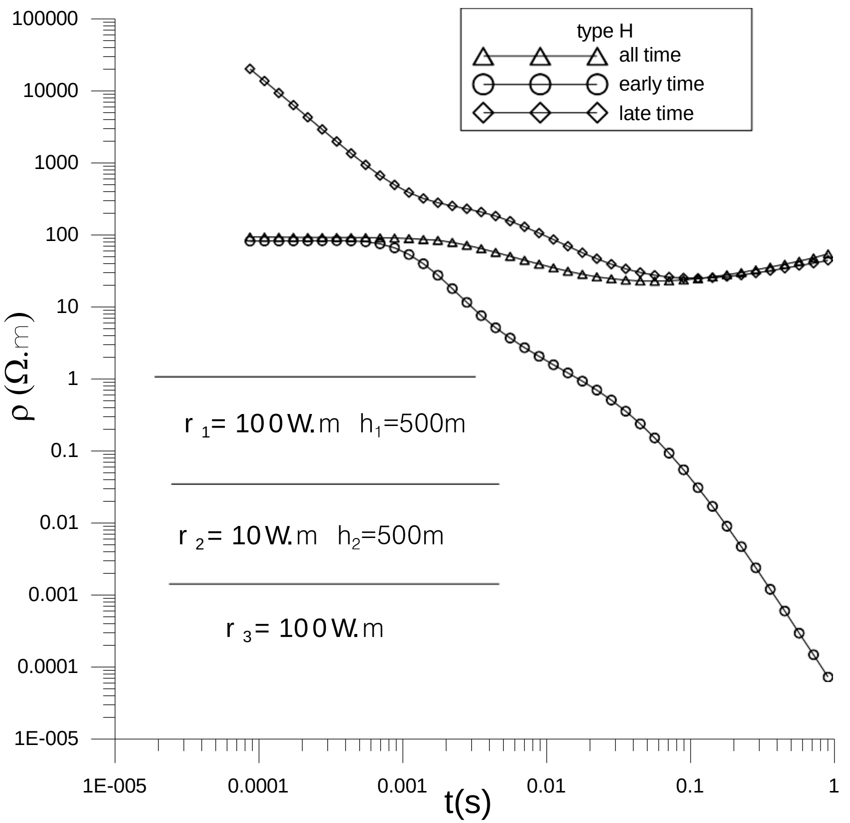
3. Electric Source Short-offset TEM continued

3.3 Observation area for each EM component

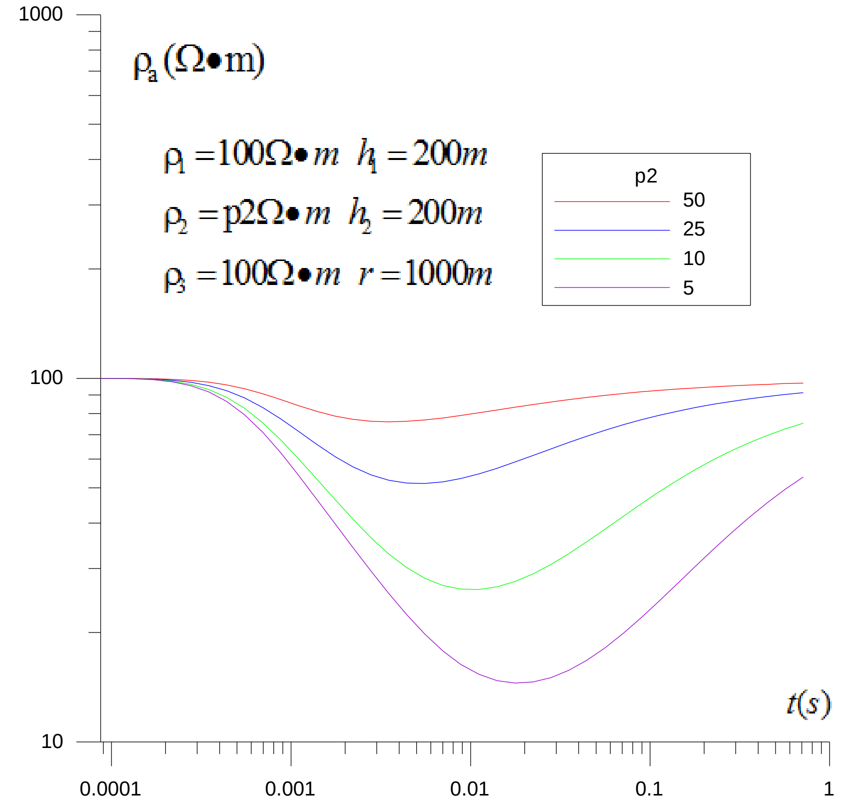


3. Electric Source Short-offset TEM continued

3.4 All-time apparent resistivity



Calculated by polynomial fitting method



Calculated by dichotomy method

3. Electric Source Short-offset TEM continued

3.5 Imaging

Electric field underneath the Tx

$$E_x(z,t)=\frac{Il\rho}{\pi z^3}[erf(\frac{u}{\sqrt{2}})-\frac{1}{2}+(\sqrt{\frac{2}{\pi}}u-\frac{1}{2})(1+\frac{u^2}{2})e^{-u^2/2}]$$

Time of maximum of Ex for a given depth

$$\left.\frac{dE_x(z,t)}{dt}\right|_{z=z_{image}}=0$$

Image depth

$$z^2(t)_{image}=\frac{4t}{\mu_0\sigma}$$

Hz from a current filament located at image depth

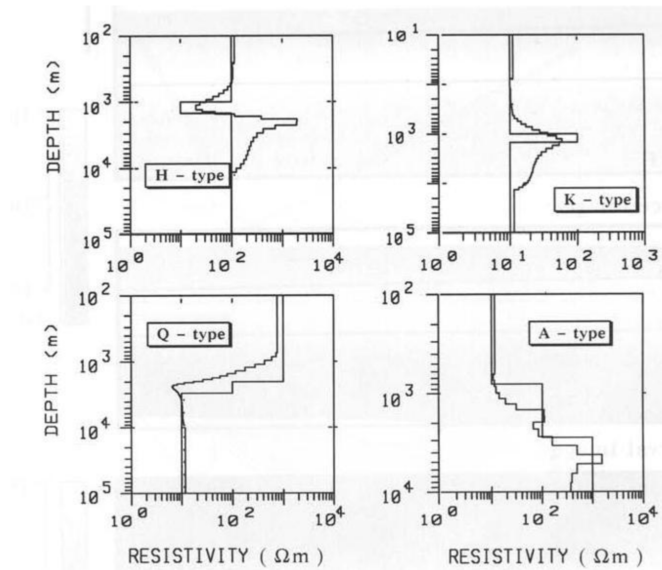
$$H_z=\frac{I}{4\pi}\frac{y}{y^2+z^2}\frac{x+L}{((x+1)^2+y^2+z^2)^{1/2}}\frac{x-L}{((x-1)^2+y^2+z^2)^{1/2}}$$

slowness

$$\frac{dt}{dz}=\frac{1}{2}z\mu_0\sigma$$

Conductivity of the image

$$\sigma=\frac{2}{\mu_0}\frac{d^2t}{dz^2}$$

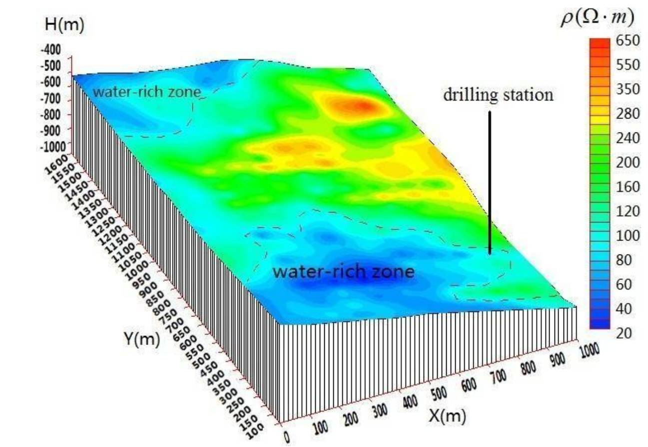


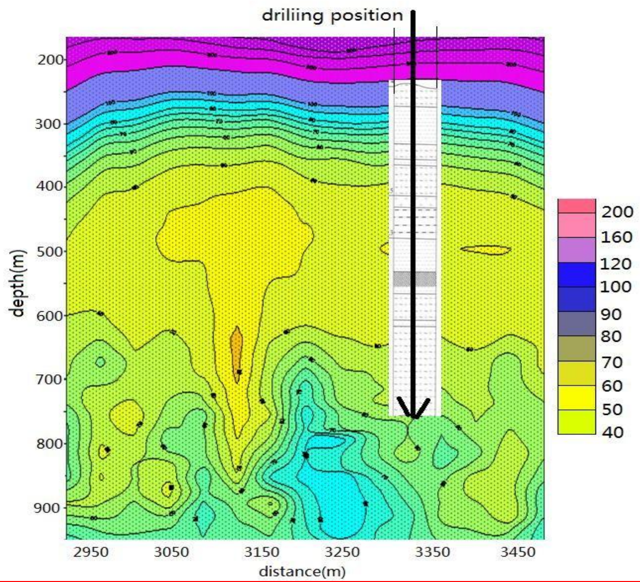
Source image for a three-layer model

3. Electric Source Short-offset TEM continued

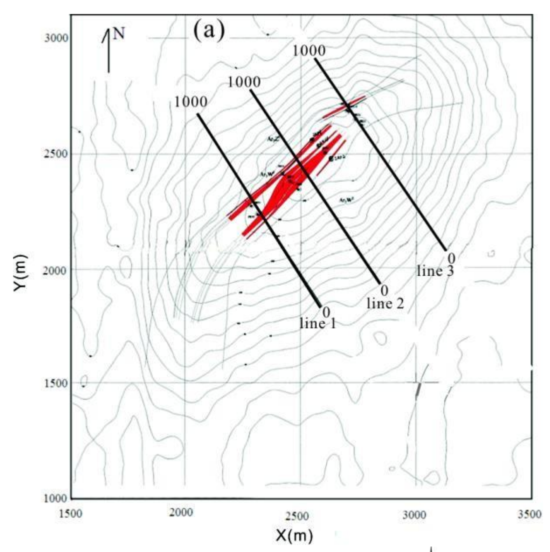
3.6 Case study

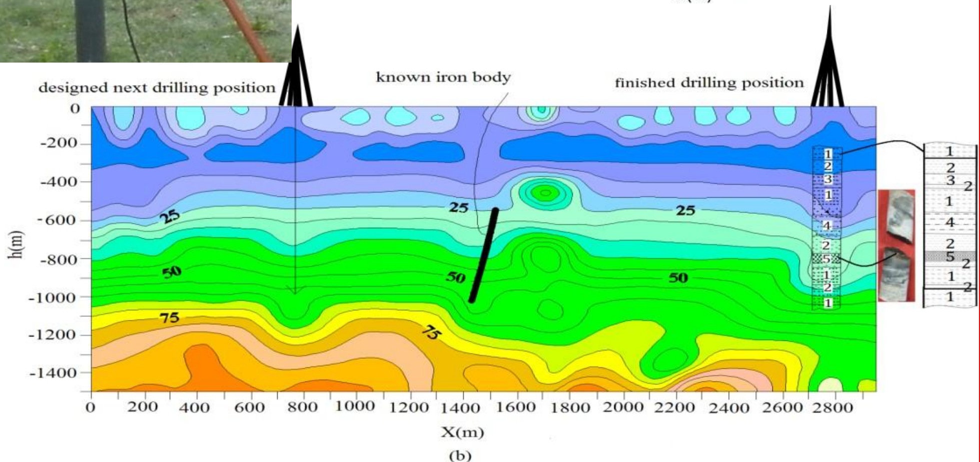
Investigation of hydrous coal mine in Shandong Province





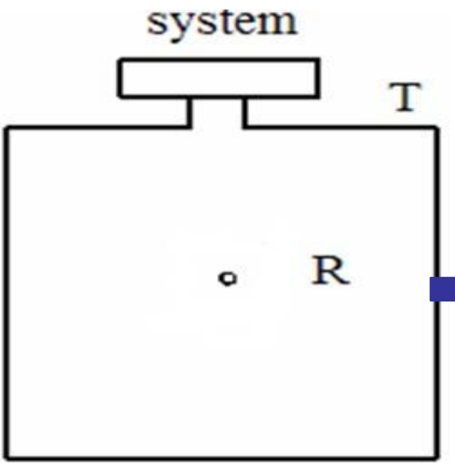
Discovery of Dawangzhuang Iron Ore in Anhui Province

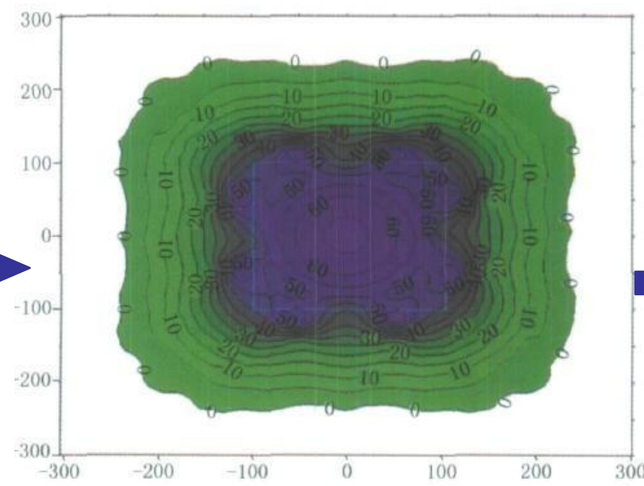


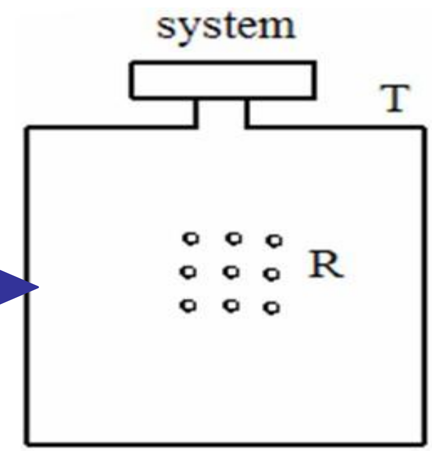


4. Modified Central Loop TEM

4.1 Reasons







Regular central loop TEM has only one survey point at once layout, which leads to energy waste and low work efficiency

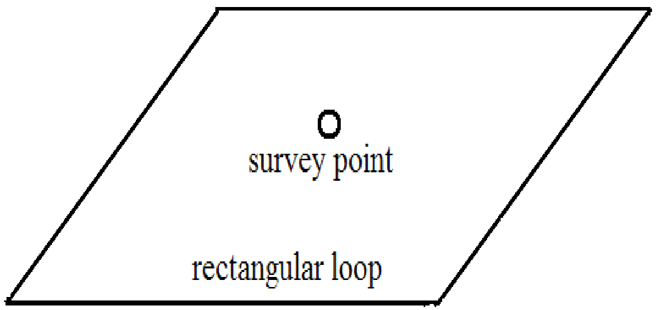
The vertical magnetic response in the central part of loop is Approximately equal (Xue,2012)

The modified device utilize the signal from a bigger central part which about 1/3 of loop area.

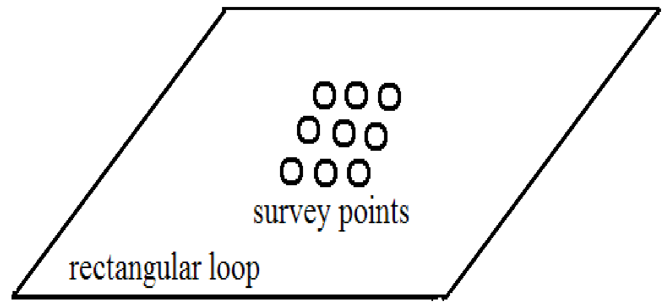
4. Modified Central Loop TEM continued

4.2 Modified theory

Central loop



Modified Central loop



$$H_z(\omega) = \frac{I_0}{k_1^2 a^3}[3 - (3 + 3k_1 a + k_1^2 a^2)e^{-k_1 a}]$$

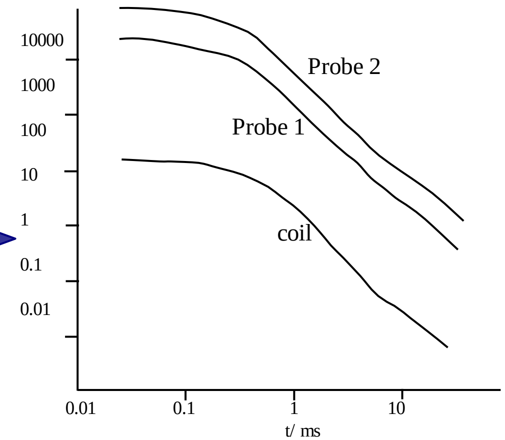
$$H_z(\omega) = \frac{I_0}{k_1^2 a^3}[Z_0(r) - (Z_1(r) + Z_2(r)k_1 a + Z_3(r)k_1^2 a^2)e^{-k_1 a}]$$

$$\rho_a^L(t) = \frac{\mu_0}{4\pi t}\left(\frac{2\pi I_0 a^2 \mu_0}{5t\,\frac{\partial B_z(t)}{\partial t}}\right)^{2/3}$$

$$\rho_a^L\left(\frac{\partial B_z(t)}{\partial t}\right) = \frac{u_0}{\pi t}\left[\frac{Z_1(r)\pi I_0 \mu_0}{60t\,\frac{\partial B(t)}{\partial t}}\right]^{\frac{2}{3}}$$

4. Modified Central Loop TEM continued

4.3 Modified instruments



Air coil:

heavy

and with small

receivearea(100m^2)

Magnetic probe:

portable and with

great receive area

(10000m^2, 20000m^2)

Significantly increase the signal strength

5. TEM Pseudo-seismic Imaging

5.1 Basic theory(Xue,2013)

Background

1). The precision in TEM prospecting is relative low compare with seismic method
2). Interpretation and judgment always be made based on experience of interpreter
3). 2D and 3D TEM inversion are time-consuming and expensive.
For the aim to improve the precision, can we interpret TEM data similar to seismic method?

Basic equation construction

Diffusion equations for TEM

$$\nabla\times\nabla\times\mathbf{H}_m(\mathbf{r},t)+\mu\sigma(\mathbf{r})\frac{\partial}{\partial t}\mathbf{H}_m(\mathbf{r},t)=0$$

Diffusion equations for seismic

$$\nabla\times\nabla\times\mathbf{U}(\mathbf{r},\tau)+\mu\sigma(\mathbf{r})\frac{\partial^2}{\partial\tau^2}\mathbf{U}(\mathbf{r},\tau)=0$$

$$\hat{\mathbf{H}}(\mathbf{r},p^2)=\hat{\mathbf{U}}(\mathbf{r},p)$$

Inverse Laplace transform

$$H_m(t)=\frac{1}{2\sqrt{\pi t^3}}\int_0^\infty \tau e^{-\tau^2/4t}U(\tau)d\tau$$

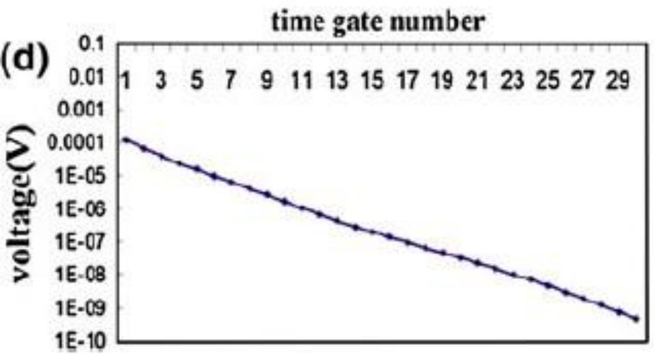
Discrete

$$H_i=\frac{1}{2\sqrt{\pi t^3}}(\tau_1 e\frac{-q_1^2}{t_i}(\tau_2-\tau_1)U_1+2\sum_{j=2}^{n-1}\tau_j e\frac{-q_j^2}{4t_i}(\tau_{j+1}-\tau_{j-1})U_j+\tau_n e\frac{-q_n^2}{4t_i}(\tau_n-\tau_{n-1})U_m)$$

5. TEM Pseudo-seismic Imaging continued

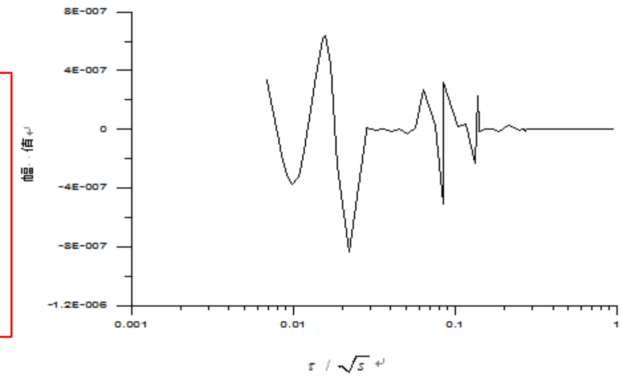
5.2 Key techniques

Wavelet extraction

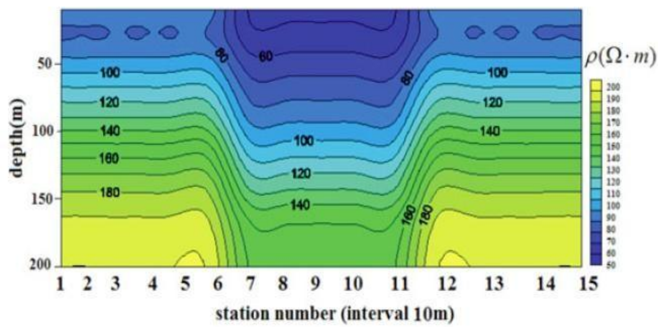


$$(\mathbf{A}^T\mathbf{A} + \alpha(\delta)\mathbf{I}) \cdot \mathbf{U} = \mathbf{A}^T\mathbf{F}$$

----main idea of calculation
1). normalize method has been adopted,
2). optimizing normalizing parameter have been selected by deviation theory
3).Newton iterative form to be used to make the transformed wave field stable and reliable.

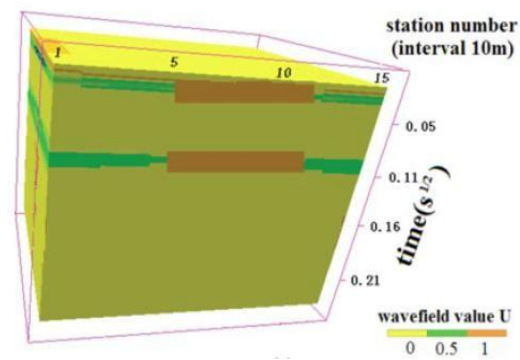


Migration imaging



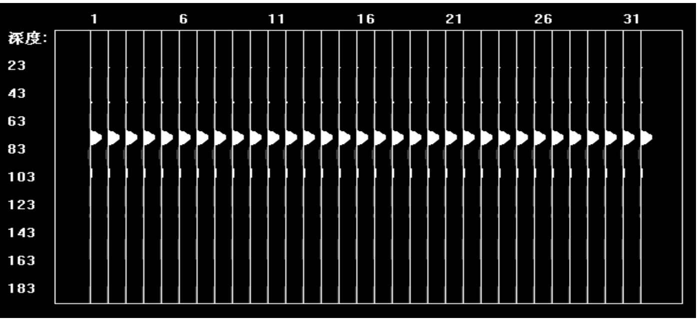
Kirchhoff integral function

$$u(x,y,z,t) = -\frac{1}{4\pi}\iint_Q \left\{[u]\frac{\partial}{\partial n}\left(\frac{1}{r}\right) - \frac{1}{r}\left[\frac{\partial u}{\partial n}\right] - \frac{1}{vr}\frac{\partial r}{\partial n}\left[\frac{\partial u}{\partial t}\right]\right\} dQ + \frac{F}{r_0}$$



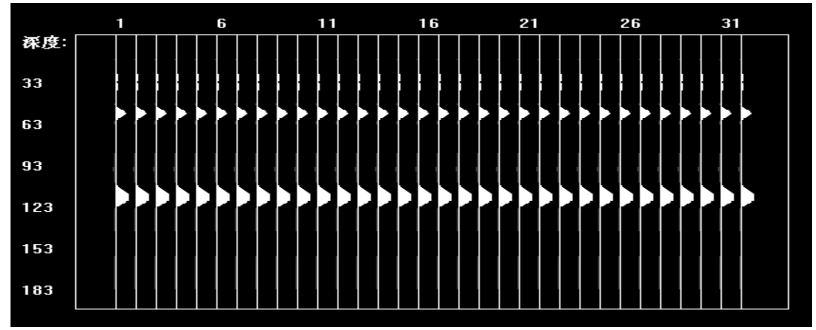
5. TEM Pseudo-seismic Imaging continued

5.3 Models simulation



$$\rho_1 = 5\Omega \cdot m, \quad h_1 = 80m$$

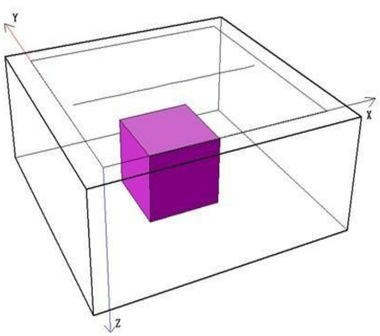
$$\rho_2 = 500\Omega \cdot m$$

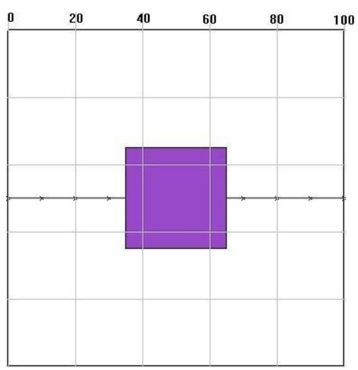


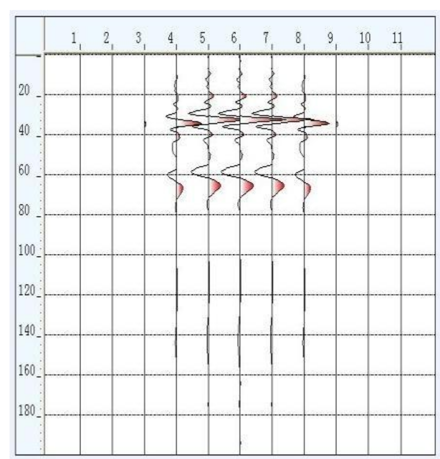
$$\rho_1 = 1\Omega \cdot m, \quad h_1 = 60m$$

$$\rho_2 = 10\Omega \cdot m, \quad h_2 = 60m$$

$$\rho_3 = 100\Omega \cdot m$$







$$\rho_1 = 10\Omega \cdot m$$

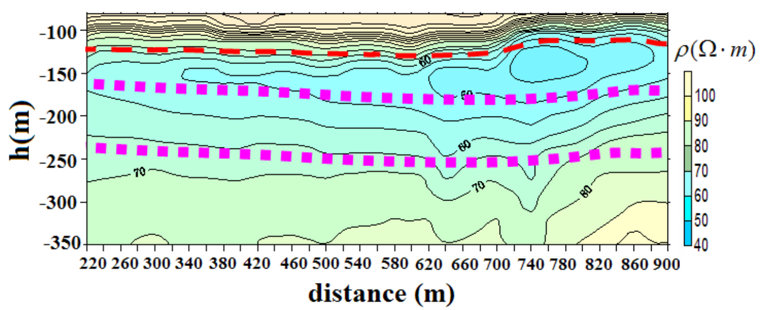
$$\rho_2 = 300\Omega \cdot m$$

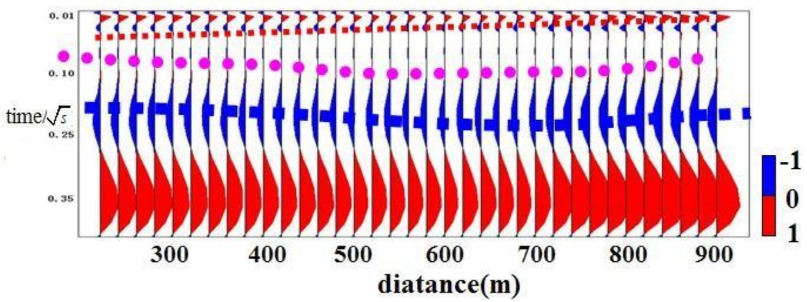
$$h = 70m$$

5. TEM Pseudo-seismic Imaging continued

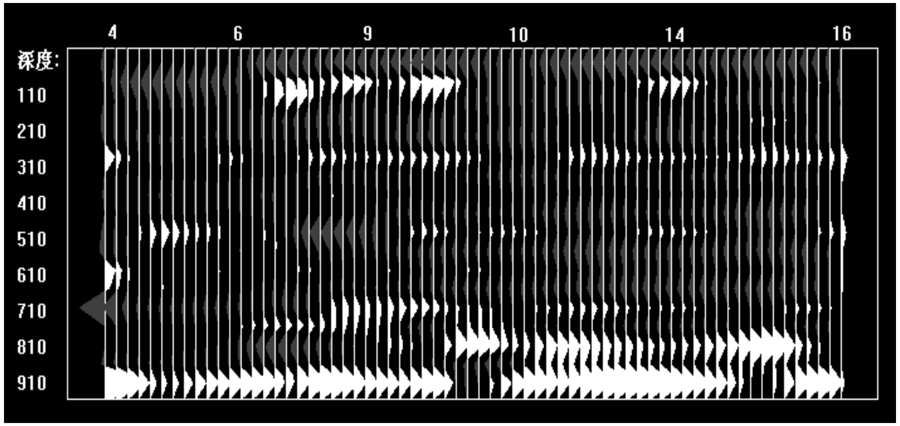
5.4 Case study

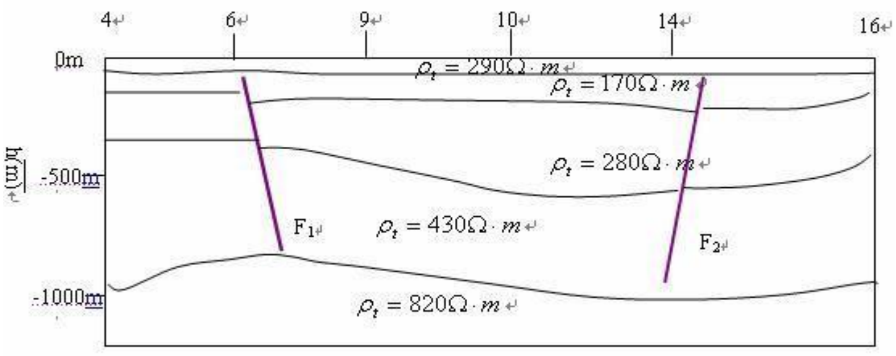
Recognizing electrical interface in Shanxi province





Detecting deep electric structure and distribution in Guangdong province





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