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Earth Sciences Division

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A new 3D parallel high resolution electromagnetic nonlinear inversion based on new global magnetic integral and local differential decomposition (GILD)

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Abstract

In this paper, a new Three-Dimensional (3D) electromagnetic (EM) modeling and nonlinear inversion algorithm is presented based on global integral and local differential equations decomposition (GILD). The GILD parallel nonlinear inversion algorithm consists of five parts: (1) The domain is decomposed into subdomain SI and subdomain SII. (2) A new global magnetic integral equation in SI and the local magnetic differential equations in SII will be used together to obtain the magnetic field in the modeling step. (3) The new global magnetic integral Jacobian equation in SI and the local magnetic differential Jacobian equations in SII will be used together to update the electric conductivity and permittivity from the magnetic field data in the inversion step. (4) The subdomain SII can naturally and uniformly be decomposed into 2^n smaller sub-cubic-domains; the sparse matrix in each sub-cubic-domain can be eliminated separately, in parallel. (5) A new parallel multiple hierarchy substructure algorithm will be used to solve the smaller full matrices in SI, in parallel. The new GILD parallel algorithm is of the very high parallel rate over 96%. Conventional nonlinear inversion often fails to interpret field data from environmental remediation and oil exploration due to its unstable, very low resolution, and very long computational time and enormous storage costs. The new GILD parallel inversion is a high performance parallel algorithm, consistently stable, and high resolution imaging algorithm which greatly improves the ill-posed condition of the conventional inversion algorithm, and reduces greatly its computational time and storage requirements. The applications of the new 3D parallel GILD EM modeling and nonlinear inversion algorithm and software are: (1) to create high resolution controlled-source electric conductivity and permittivity imaging for interpreting electromagnetic field data acquired from cross hole, surface to borehole, surface to surface, single hole, and multiple holes; (2) to create the magnetotelluric high resolution imaging from the surface impedance and field data. The new GILD parallel nonlinear inversion will be a 3D/2.5D powerful imaging tool for the oil geophysical exploration and environmental remediation and monitoring.

Introduction

The 3D subsurface electromagnetic (EM) imaging using full wave field nonlinear inversion will be an important and essential tool for environmental site remediation and monitoring of the ground water and vadose zone, geophysical oil and mining exploration, oil production, reservoir management, and environmental site characterization, because electrical conductivity has both direct or indirect relationship to pore fluid, porosity, saturation, and permeability, as well as to other rock properties.

There is some work to be done on electromagnetic inverse imaging and full wave velocity imaging. Lax (1967) and (1989) provided valuable insights and theoretical foundation for inverse scattering. Xie and Chen (1985) developed a modified pulse-spectrum technique for solving inverse problems of 2D elastic wave equation. Xie and Li (1986), (1988), (1989) developed a new integral geometry iterative method for controlled source wave velocity imaging. Oristaglio (1989) developed an inverse scattering formula that uses all the data. Xie and Zou (1991) developed 3D parallel inversion. Lee and Xie (1993) developed an electromagnetic crosshole imaging. Habashy, Groom, and Spies (1993) developed the static localized nonlinear approximation and localized nonlinear extended Born approximation. Pellerin et al. (1993) developed 3-D electromagnetic inversion. Nekut (1994) developed an electromagnetic ray-trace tomography. Mackie and Maden (1993) did 3D MT inversion using conjugate gradient. Chen and Kim (1995) developed a parallel algorithm for inverse scattering problems of Maxwell's equations on hypercubes. Li et al. (1995) developed a nonlinear three-dimensional inverse imaging for direct current data. Torres-Verdin and Habashy did 2D electromagnetic inversion by extended Born approximation. Newman (1995) developed a crosswell electromagnetic inversion using integral and differential equation, he used the staggering difference scheme for the forward modeling and the electric integral equation for inversion. Zhdanov (1996) developed a underground imaging by frequency-domain electromagnetic migration. In the past 3 years, we have developed two kinds of 3D nonlinear electromagnetic inversion, one using a new magnetic field integral equation, and another using the electric field integral equation (Xie et al., 1995a, 1995b; Xie and Lee 1995c).

The main difficulties in developing the 3D electromagnetic nonlinear inversion algorithms and software are the very ill-posed, strongly nonlinear nature of the inverse problem and long computational time and large storage costs. In particular, the geological and hydrological structure and properties can be very complicated. The material is often anisotropic and the electric conductivity contrast of the targets is very large - on the order of 1:100 to 1:1000. Existing inverse techniques such as part field tomography, travelttime tomography, and Born approximation imaging can only be used for low resolution imaging of targets with low conductivity contrasts. The conventional nonlinear inversion also often fails to interpret field data collected for environmental remediation and oil exploration. The main reason is its inconsistent and unstable algorithm. The iteration of conventional nonlinear inversion includes two parts: (I) a finite element or finite difference scheme for differential equations used to obtain the electromagnetic field in the modeling step; (II) a discrete integral equation to update the electric conductivity in the inverse step. In part I, a troublesome artificial or absorption condition must be imposed on the boundary. Inaccurate reflection of this artificial boundary condition enters the inversion as numerical noise that will cause divergence and low resolution. In part II, the discrete integral equation produces an ill posed full matrix which is difficult to invert, due to the instability and nonlinearity of the problem, computational storage and timing requirements, and resolution accuracy concerns. In this paper, a new powerful parallel 3D EM modeling and nonlinear inversion algorithm is presented based on global integral and local differential equation decomposition (GILD) which addresses the shortcomings of the conventional inversion. The GILD parallel nonlinear inversion algorithm consists of five parts: (1) The domain is decomposed into subdomain SI and subdomain SII. (2) A new global magnetic integral equation in SI and the

local magnetic differential equations in SII will be used together to obtain the magnetic field in the modeling step. (3) The new global magnetic integral Jacobian equation in SI and the local magnetic differential Jacobian equations in SII will be used together to update the electric conductivity and permittivity from the magnetic field data in the inversion step. (4) The subdomain SII can naturally and uniformly be decomposed into 2^n smaller sub-cubic-domains; the sparse matrix in each sub-cubic-domain can be eliminated separately, in parallel. (5) A new parallel multiple hierarchy substructure algorithm will be used to solve the smaller full matrices in SI, in parallel. The advantages of the new GILD parallel EM modeling and inversion approaches are as follows. (1) It produces 2^n smaller sparse matrices and one small full matrix for both modeling and inversion which can be eliminated separately, in parallel, compared to conventional nonlinear inversion which used a sparse matrix equation for modeling but an ill posed full matrix equation for the inversion. This feature of the new method will greatly reduce the computational time and storage costs. (2) In the new method, No artificial boundary condition is required that reduces greatly numerical noises and is suitable for high resolution compared to the conventional inversion which needs a troublesome artificial boundary condition and its inaccurate reflection enters the inversion as numerical noise. (3) The numerical approaches are consistent in the new GILD parallel nonlinear inversion method, but numerical approaches are inconsistent in the conventional nonlinear inversion. (4) The 3D GILD parallel algorithm is very suitable for the massively parallel computer. (5) The strong regularizing is used in the SI and a new weak regularizing is used in the SII. These properties are important to obtain large scale high resolution subsurface images for seismic and electromagnetic imaging. Conductivity imaging using small scale synthetic data and field data show that the parallel 3D/2.5D GILD nonlinear inversion produces stable high resolution results and the computational speed is up 100 more times that of a conventional nonlinear inversion. The parallel rate of the new GILD is over 96%. The applications of the new 3D parallel GILD EM modeling and nonlinear inversion algorithm and software are: (1) to create high resolution controlled-source electric conductivity and permittivity imaging for interpreting electromagnetic field data acquired from cross hole, surface to borehole, surface to surface, single hole, and multiple holes; (2) to create the magnetotelluric high resolution imaging from the surface impedance and field data. The plan of this paper is as follows: the introduction has been presented in section 1. In section 2, we will present 3D EM modeling and nonlinear inversion using the new magnetic integral equation and finite element method. The 3D EM modeling and nonlinear inversion using a magnetic differential equation and finite element method will be described in section 3. In section 4, we will present a new 3D parallel EM modeling and nonlinear inversion based on global magnetic integral and local magnetic differential decomposition (GILD). The resistivity imaging will be shown in section 5. In section 6, we will describe conclusion.

3D EM modeling and nonlinear inversion using the new magnetic integral equation and finite element method

We developed a 3D and 2.5D modeling and nonlinear inversion using a new magnetic integral equation in the paper by Xie et al. (1995a).

Modeling

The 3D finite element integral equation is used to calculate the magnetic field in an isotropic and isotropic modeling,

$$H^h(r) = \Theta \left(H^h(r'), H_b(r); (\sigma_{pq} + i\omega\epsilon_{pq})(r'), V_s \right), \quad (1)$$

definition of the operator Θ is

$$\begin{aligned} \Theta \left(H(r'), H_b(r); (\sigma_{pq} + i\omega\epsilon_{pq})(r'), V_s \right) = & H_b(r) - \\ & \int_{V_s} \nabla_{r'} g(r, r') \times \left[\mathbf{I} - \left[\mathbf{C} \left(\sigma_{pq} + i\omega\epsilon_{pq} \right) \right]^{-1} \left[\mathbf{C} \left(\sigma_b \delta_{pq} + i\omega\epsilon_b \delta_{pq} \right) \right] \right] \left(\nabla_{r'} \times H - J \right) dr' \\ & + \int_{V_s} \nabla_{r'} \times \bar{\bar{\mathbf{G}}}^E_s(r, r') \left[\mathbf{I} - \left[\mathbf{C} \left(\sigma_{pq} + i\omega\epsilon_{pq} \right) \right]^{-1} \left[\mathbf{C} \left(\sigma_b \delta_{pq} + i\omega\epsilon_b \delta_{pq} \right) \right] \right] \left(\nabla_{r'} \times H - J \right) dr'. \end{aligned} \quad (2)$$

Where $\mathbf{C}(\sigma_{pq} + i\omega\epsilon_{pq})$ is a 3×3 positive defined matrix, the entries, σ_{pq} and ϵ_{pq} , are anisotropic conductivity and permeability, $p=1,3, q=1,3$. $\mathbf{I}$ is the identifying matrix, The matrix

$$\mathbf{C} \left(\sigma_b \delta_{pq} + i\omega\epsilon_b \delta_{pq} \right) = \left(\sigma_b + i\omega\epsilon_b \right) \mathbf{I}, \quad (3)$$

σ_b, ϵ_b is the background conductivity and permittivity, and

$$\delta_{pq} = \begin{cases} 1, & \text{if } p = q \\ 0, & \text{if } p \neq q \end{cases} \quad (4)$$

H is the magnetic field, H_b is the background magnetic field, H^h is finite element magnetic field, σ is the electric conductivity, σ_b is the background electric conductivity, ϵ is the electric permittivity, ϵ_b is the background electric permittivity, point r and r' are in the V_s , V_s is scattering integral domain in which $(\sigma - \sigma_b) + i\omega(\epsilon - \epsilon_b) \neq 0$, $g_b(r, r')$ is the whole space Green's function, and $\bar{\bar{\mathbf{G}}}^E_s(r, r')$ is the background secondary electric Green's function, J is electric current source, and ω is angle frequency.

If the matrix in the equation (2)

$$\mathbf{C}(\sigma_{pq} + i\omega\epsilon_{pq}) = (\sigma + i\omega\epsilon)\mathbf{I}, \quad (5)$$

then the equation (1) reduces to a finite element magnetic integral equation in the isotropic media,

$$H^h(r) = \Theta(H^h(r'); H_b(r); \sigma + i\omega\epsilon; V_s), \quad (6)$$

where the operator Θ is

$$\begin{aligned} \Theta(H(r'); H_b(r); \sigma + i\omega\epsilon; V_s) = & H_b(r) - \\ & \int_{V_s} \nabla_{r'} g(r, r') \times \frac{(\sigma - \sigma_b) + i\omega(\epsilon - \epsilon_b)}{\sigma + i\omega\epsilon} (\nabla_{r'} \times H - J) dr' \\ & + \int_{V_s} \nabla_{r'} \times \bar{G}_s E(r, r') \frac{(\sigma - \sigma_b) + i\omega(\epsilon - \epsilon_b)}{\sigma + i\omega\epsilon} (\nabla_{r'} \times H - J) dr', \end{aligned} \quad (7)$$

the equation (6) has been presented in the paper by Xie et al.. (1995).

Nonlinear inversion

We used Gauss-Newton and finite element method to solve the regularizing nonlinear optimization of (1) for determining the electric conductivity and permittivity in the nonlinear inversion.

$$\begin{aligned} & \left(J^h{}^T J^h + \alpha R \right) \delta \left(\sigma_{pq} + i\omega\epsilon_{pq} \right) \\ & = N \left(H_d(r) - \Theta \left(H^h(r'), H_b(r); \left(\sigma_{pq}^{(n-1)} + i\omega\epsilon_{pq}^{(n-1)} \right) (r'), V_s \right); R(\sigma + i\omega\epsilon) \right), \end{aligned} \quad (8)$$

where J^h is the finite element Jacobian operator, $J^h{}^T$ is its transport matrix, the $R(\cdot)$ is a positive definite regularizing operator, α is regularizing parameter, $N(\cdot)$ is the Euler variation operator of the nonlinear optimization based on the integral equation

$$H_d(r) = \Theta \left(H(r'), H_b(r); \left(\sigma_{pq} + i\omega\epsilon_{pq} \right) (r'), V_s \right). \quad (9)$$

The equation (9) is a nonlinear integral equation of the first kind with respect to the parameters, $\sigma_{pq} + i\omega\epsilon_{pq}$, the r in (9) is the coordinate of location of the field data, H_d , r' in (9) is the coordinate of location of the model field, H , in domain V_s . The equation (1) is a linear integral equation of the second kind with respect to the magnetic field, H , the r and r' in (1) are in the domain V_s .

3D EM modeling and nonlinear inversion using a magnetic differential equation and finite element method

3D EM modeling using the magnetic differential equation has been developed by Xie et al. (1995c). A new 3D local nonlinear inversion using magnetic differential equation is presented in this section.

Modeling

The 3D finite element differential equation is used to calculate the magnetic field in the anisotropic and isotropic modeling.

$$\left\langle C^{-1} \left(\sigma_{pq} + i\omega \varepsilon_{pq} \right) \nabla \times H^h, \nabla \times \phi_i \right\rangle + i\omega \mu \left\langle H^h, \phi_i \right\rangle = \left\langle M_s^h, \phi_i \right\rangle \quad (10)$$

where ϕ_i is finite element base function, H^h is unknown discrete finite element magnetic field. $\langle \cdot, \cdot \rangle$ is the Galerkin inner production.

Nonlinear inversion

From the Galerkin approach of equation (10), we can obtain a local Jacobian differential equation with respect to $(\sigma + i\omega\varepsilon)$,

$$Q(J_l^h; \delta(\sigma + i\omega\varepsilon); \delta H^h) = 0, \quad (11)$$

where J_l^h is a local finite element Jacobian sparse matrix, Q is the Jacobian operator of (10). The global finite element integral equation (8) on SI and local differential equation (11) on SII construct a new GILD algorithm for nonlinear inversion. In the new 3D parallel GILD EM modeling, the 2ⁿ equations (10) and (11) will be solved on the 2ⁿ sub-cubic-domains of SII independently, in parallel.

New 3D parallel EM modeling and nonlinear inversion based on global magnetic integral and local magnetic differential decomposition (GILD)

NEW 3D GILD PARALLEL EM ALGORITHM

- The whole 3D cubic domain is decomposed into subdomain SI and subdomain SII.
- The new 3D global magnetic integral finite element equation (1) in SI and the local magnetic differential finite element equations (10) in SII will be used together to obtain the magnetic field in the forward modeling step.
- The new 3D global magnetic integral finite element Jacobian equation (8) in SI and the local magnetic differential finite element Jacobian equation (11) in SII will be used together to update the electric conductivity and permittivity in the inversion step.
- The subdomain SII can be naturally decomposed into 2ⁿ smaller sub-cubic-domains, the sparse matrix in each sub-cubic-domain can be eliminated separately, in parallel.

- A new parallel multiple hierarchy substructure algorithm will be used to solve the smaller full matrices in SI.
- Strong regularizing is used in SI and a new weak regularizing is used in SII.
- A new adaptive mesh approach will be used in the inversion iteration.

The new 3D GILD parallel algorithm is presented graphically (Fig. 1), the new magnetic integral equation (New IE) is solved in subdomain (SI) which looks like a wall, and local differential equations (DE) are solved in subdomain SII which looks like rooms. For simplicity, we will use a 2D figure to replace the 3D figure topologically (see Fig. 2-5).

1. Parallel domain and electric parameters decomposition for inversion

Cells in the whole domain (Fig. 2) are decomposed into a subdomain SI (Fig. 4) and subdomain SII (Fig. 3). The subdomain SI is set of cells ■ (Fig. 4), the subdomain SII is set of cells ■ (Fig. 3). The electric conductivity and permittivity increment vector $(\delta\sigma, \delta\epsilon)$ is decomposed into two sub vectors, $(\delta\sigma_I, \delta\epsilon_I)$ and $(\delta\sigma_{II}, \delta\epsilon_{II})$, the $(\delta\sigma_I, \delta\epsilon_I)$ is electric conductivity and permittivity vector defined on cells ■ of the subdomain SI, the sub vector $(\delta\sigma_{II}, \delta\epsilon_{II})$ is electric conductivity and permittivity value defined on cells ■ of the subdomain SII.

Fig. 1, New 3D GILD parallel algorithm

2. A global magnetic integral finite element equation on cells ■ of the subdomain SI for inversion

Using the finite element method for solving regularizing nonlinear optimization of the new magnetic integral equation (9), a new global magnetic integral finite element Jacobian equation (8) on cells ■ of the SI for inversion will be

$$\Gamma \begin{pmatrix} \begin{bmatrix} \delta\sigma_I \\ \delta\epsilon_I \end{bmatrix}, \begin{bmatrix} \delta\sigma_{II} \\ \delta\epsilon_{II} \end{bmatrix}, H_D \end{pmatrix} = 0, \quad (12)$$

where H_D is the magnetic field data. Γ is a matrix.

3 A local magnetic differential finite element equation on cells ■ of the subdomain SII for inversion

In Fig. 3, the subdomain II can be decomposed into the 2^n same size sub cubic domains, each sub cubic domain has internal cells ■ and boundary cells ■. In each sub cubic domain, a local magnetic Jacobian differential finite element equation for inversion (11) in section 3 is used to present $(\delta\sigma_{II(l)}, \delta\epsilon_{II(l)})$. The 2^n sparse matrix equations are independent of each other and they have the same size and structure.

$$\Lambda_{(l)} \begin{pmatrix} \delta\sigma_{II(l)} \\ \delta\epsilon_{II(l)} \end{pmatrix} = P_{(l)} \begin{pmatrix} \begin{bmatrix} \delta\sigma_{I(l)} \\ \delta\epsilon_{I(l)} \end{bmatrix}, H_{D(l)} \end{pmatrix}, l = 1, 2, 3, \dots, 2^n \quad (13)$$

where $\Lambda_{(l)}$ and $P_{(l)}$ are sparse matrices, $H_{D(l)}$ is field data term.

We use 2^n processor elements in the Massively Parallel computer to solve equations (13) and obtain the 2^n local electric conductivity and permittivity increment vector simultaneously.

4 A reduced magnetic finite element integral equation on cells ■ of the subdomain SI for inversion

Upon substituting the parallel direct summation

$$\begin{pmatrix} \delta\sigma_{II} \\ \delta\epsilon_{II} \end{pmatrix} = \bigcup_{l=1}^{2^n} \oplus \begin{pmatrix} \delta\sigma_{II(l)} \\ \delta\epsilon_{II(l)} \end{pmatrix} \quad (14)$$

into the (12) in step 2, we have a reduced magnetic finite element equation for inversion on cells ■ of the subdomain SI (Fig. 4),

$$\Pi \begin{pmatrix} \delta\sigma_I \\ \delta\epsilon_I \end{pmatrix} = TH_D, \quad (15)$$

where Π and T are small full matrices. Using a parallel multiple hierarchy substructure algorithm, the 2^{n-1} parallel processors will be used to solve the reduced equation (15), in parallel.

Finally, the reduced 3D EM inversion equation small over the cells $\blacksquare$ of the 12 edges of the 3D large whole cubic domain in Fig. 5.

Fig. 2, Domain and its decomposition

Fig. 3, 2^n sub cubic domains in the subdomain SII

5. Strong and weak regularizing methods

The strong Tikhnov regularizing method will be used for the integral inversion on cells $\blacksquare$ of the subdomain SI in Fig. 4. A weak regularizing will be used on cell $\blacksquare$ of the subdomain SII in Fig. 3.

6. A new adaptive mesh approach

A new adaptive mesh approach for nonlinear inversion presented here is important for high resolution imaging.

- The uniform mesh is used for the starting model.
- A finer mesh is used in locations where the grad of the conductivity and the permittivity are large.
- A rougher mesh is used in locations where the grad of the conductivity and the permittivity are small.
- The adaptive mesh approach is performed step by step for nonlinear iteration.

Fig. 4, Subdomain SI

Fig. 5 Edge subdomain of the whole domain

Resistivity imaging

The new 3D parallel GILD nonlinear inversion has been tested using surface synthetic and crosshole field data. The model is a (90m x 90m x 80m) cubic frame conductor of 0.1 S/m conductivity that includes (30m x 30m x 50m) cubic conductor of 0.25 S/m conductivity shown in (A) of Fig.8. Sixteen frequencies, 64 vertical magnetic dipole (VMD) surface sources and 768 surface receivers were used. At each receiver point, the three magnetic components are computed. In testing of the parallel 3D GILD inversion, the above model was imbedded in a large cubic domain [-90m, 90m; -90m, 90m; 0, 120m] with initial conductivity 0.05 S/m. The domain is decomposed into the SI and SII. The SII is decomposed 16 sub cubic domains. The 16 processors of CRAY C90 were used for 16 sparse matrices equation in SII, in parallel. Then 8 processors were used for SI. The initial mesh is uniform. The new adaptive mesh technique is performed in parallel. After 18 iterations, the conductivity imaging was obtained. The resistivity imaging of model is shown in (B) of Fig. 8. The imaging on the subdomain SII is shown in (D) of Fig. 8 and imaging on the subdomain SI is shown in (C) of the Fig. 8. The imaging in (C) and (D) are assembled into the imaging in (B) in whole domain which is high resolution compare to the traditional imaging in Fig. 7. Figure 9 presents the high resolution resistivity imaging of the new 3D parallel GILD EM nonlinear inversion in T3D using the crosshole magnetic field data from the steam injection experiment in the California Bakersfield oil field. The imaging before injection is shown in (B) of Fig. 9, its sub imaging in subdomain SI is shown in (A) of Fig.9 and sub imaging in subdomain SII is shown in (C) of Fig. 9. The imaging in (A) and (C) or (d) and (F) are assembled into imaging in (B) or (E) in whole domain. Based on the difference in the imaging before (B) and after (E) the steam injection, how and where the steam was moving that can be shown clearly.

Conclusion

The resistivity imaging using surface synthetic data and crosshole field data show that the new 3D GILD parallel EM nonlinear inversion method is a powerful and robust stable high resolution imaging approach.

Its main advantages are as follows:

- The new 3D GILD parallel inversion reduced an enormous full matrix into 2^n smaller sparse matrices and one small full matrix which can be eliminated separately, in parallel, greatly reducing computational time and storage costs.
- A natural high performance parallel algorithm with very high parallel rate over 96%.
- No artificial boundary condition is needed that reduces greatly numerical noises and is suitable for high resolution imaging.
- The best combination of the strong regularizing in SI and new weak regularizing in SII is used to improve greatly the very ill -posed condition and obtain high resolution imaging.
- It is convenient to extended development of the 3D/2.5D new elastic velocity imaging (Li and Xie, 1997), DC resistivity imaging, and hydrological permeability imaging in the large scale anisotropic or isotropic media.
- The 3D GILD parallel algorithm is an optimal combination of the semi-analytic approach and finite element method.
- A new adaptive mesh approach is used for high resolution imaging.
- The applications of the new 3D parallel GILD EM modeling and nonlinear inversion algorithm and software are: (1) to create high resolution controlled-source electric conductivity and permittivity imaging for interpreting electromagnetic field data acquired from cross hole, surface to borehole, surface to surface, single hole, and multiple holes; (2) to create the magnetotelluric high resolution imaging from the surface impedance and field data.

A comparison of the advantages of the new 3D GILD parallel nonlinear inversion and the shortcomings of the conventional nonlinear inversion is given in the table 1.

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Table 1

Advantages of the new 3D GILD inversion	The shortcomings of the conventional inversion
<ul style="list-style-type: none"> • 2ⁿ smaller sparse matrices and one small full matrix which can be eliminated separately, in parallel, greatly reducing computational time and storage costs 	<ul style="list-style-type: none"> • Large full matrix and enormous computational time and storage costs
<ul style="list-style-type: none"> • A natural high performance parallel algorithm with very high parallel rate over 96% 	<ul style="list-style-type: none"> • Series algorithm which needs a partial parallelization manually
<ul style="list-style-type: none"> • Non artificial boundary condition is needed that reduces greatly numerical noises and is suitable for high resolution imaging 	<ul style="list-style-type: none"> • Inaccurate reflection of the artificial boundary condition enters the inversion as numerical noise that will cause divergence and low resolution
<ul style="list-style-type: none"> • Small numerical noise 	<ul style="list-style-type: none"> • Large numerical noise
<ul style="list-style-type: none"> • Consistent algorithm structure 	<ul style="list-style-type: none"> • Inconsistent algorithm structure
<ul style="list-style-type: none"> • The best combination of the strong regularizing in SI and new weaker regularizing in SII is used to improve greatly the very ill -posed condition and obtain high resolution imaging 	<ul style="list-style-type: none"> • Only strong regularizing is used in whole domain and it is difficult to adjust the regularizing degree.
<ul style="list-style-type: none"> • It is convenient to extended development of the 3D new elastic velocity imaging, DC resistivity imaging, and hydrological permeability imaging in the anisotropic or isotropic media. 	<ul style="list-style-type: none"> • It is inconvenient to extended development of the 3D new elastic velocity imaging, DC resistivity imaging, and hydrological permeability imaging in the anisotropic or isotropic media.
<ul style="list-style-type: none"> • Large scale domain 	<ul style="list-style-type: none"> • Small scale domain
<ul style="list-style-type: none"> • High resolution imaging New 3D nonlinear EM Inversion	<ul style="list-style-type: none"> • Low resolution imaging with pseudo umbra Old 3D nonlinear EM Inversion
<p>Fig. 6. High resolution imaging using new 3D parallel GILD EM nonlinear inversion</p>	<p>Fig. 7. Low resolution imaging with pseudo umbra using conventional 3D EM nonlinear inversion</p>

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Fig. 8 Resistivity imaging using new 3D GILD EM nonlinear inversion and surface synthetic data.

Resistivity imaging of the new 3D parallel GILD nonlinear inversion

Imaging before injection

(A) Sub-imaging in SI

(B) Assembled imaging

(C) Sub-imaging in SII

Imaging after injection

(D) Sub-imaging in SI

(E) Assembled imaging

(F) Sub-imaging in SII

Fig.9. The high resolution resistivity imaging using field data from the steam injection experiment in the Bakerfield oil field in California. Based on the difference in the imaging before and after the injection, how and where the steam was moving that can be shown very clearly.