On Recovering IP Information from EM Data

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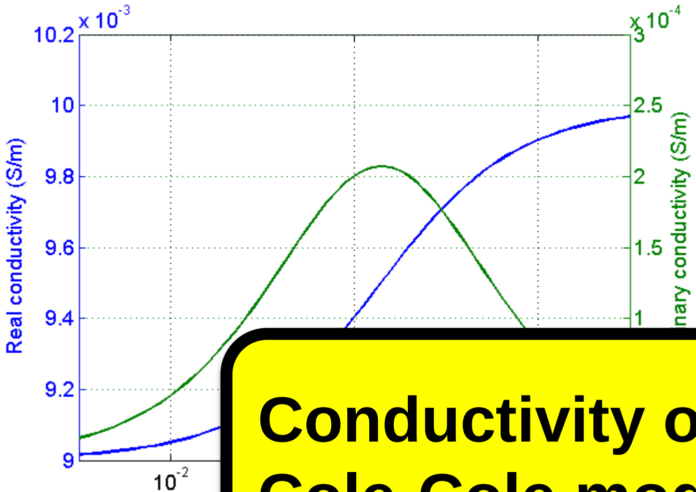
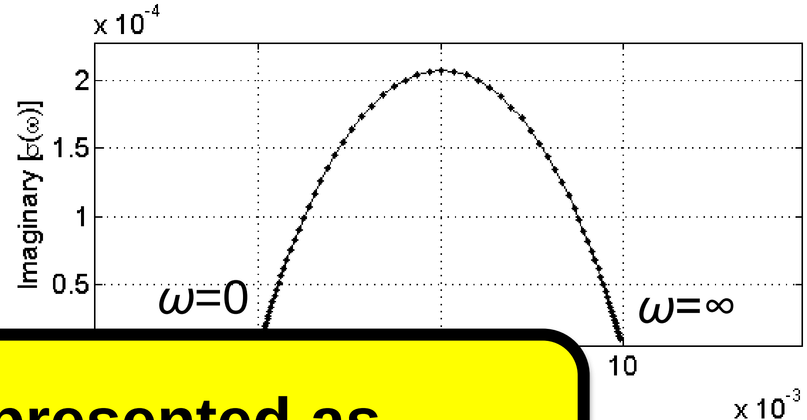
Outline

- Background for IP problem
- Forward problem in the time domain
- Inverse problem
- Field example Mt. Milligan
- Conclusions and the path ahead

Electrical conductivity is complex

$$\vec{J} = \sigma(\omega)\vec{E}$$





Conductivity often represented as Cole-Cole model but that is not crucial

Co

nductivity

$$\sigma(\omega) = \sigma_\infty \left[(1 - \frac{\eta}{1 + (1-\eta)(i\omega\tau)^c}) \right]$$

σ_o : Conducti at zero frequency

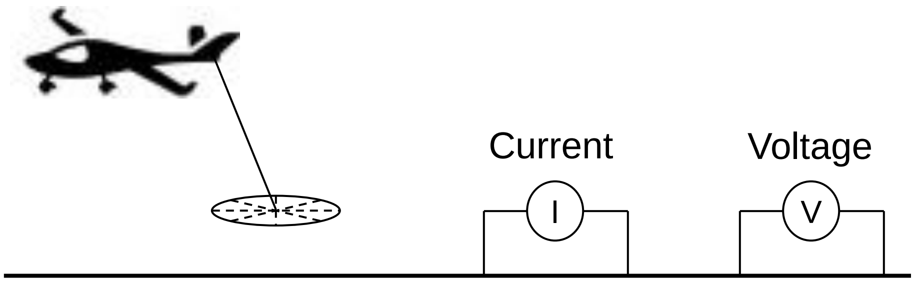
η : Chargeability

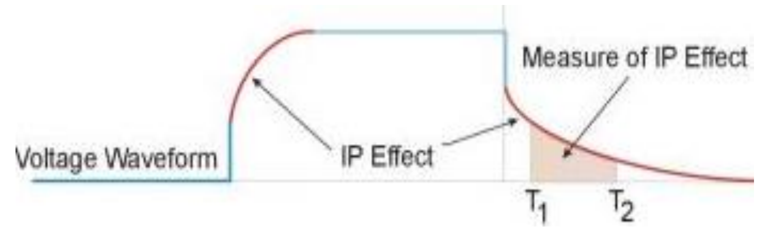
ω : Angular frequency

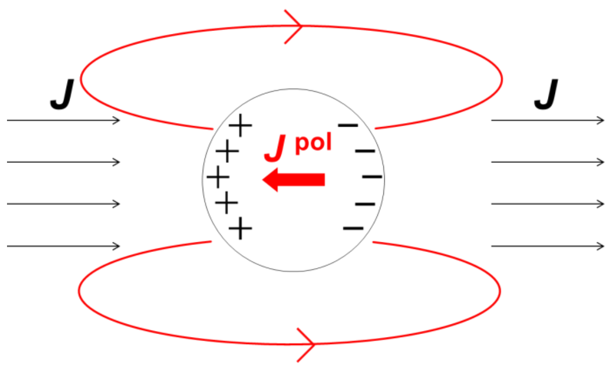
τ : Time constant

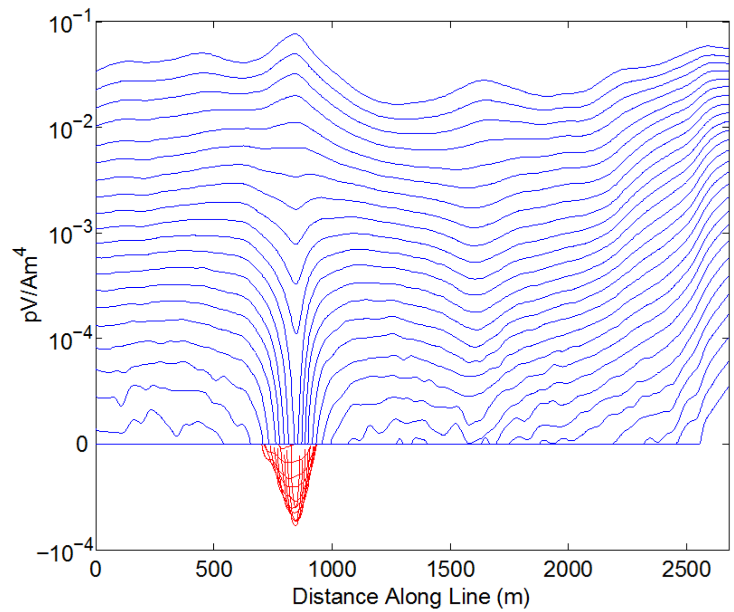
c : Frequency dependence

Different experiments









Inverse problem: **two** paths

1. **Directly** in time domain

2. **Linearized** inversion

Complex conductivity

$$\sigma(\omega) = \sigma_\infty \left[\left(1 - \frac{\eta}{1 + (1-\eta)(i\omega\tau)^c}\right) \right] = \sigma_\infty + \Delta\sigma(\omega)$$

$\sigma(\omega)$: Conductivity

σ_o : Conducti at zero frequency

η : Chargeability

ω : Angular frequency

τ : Time constant

c : Frequency dependence

- ***σ_∞*** is background conductivity
- Obtained **from early times** that are not contaminated with IP effects.
- The **IP effect is a perturbation**. This is a good approximation when ***η*** is small and has been traditionally used

IP data and EM coupling removal

- **Conductivity**

$$\sigma(\omega) = \sigma_\infty + \Delta\sigma(\omega) \qquad \tilde{\eta}(\omega) = \frac{\eta}{1+(1-\eta)(i\omega\tau)^c}$$

$$\Delta\sigma(\omega) = -\sigma_\infty \tilde{\eta}(\omega)$$

$$\ldots t)$$

✓ **Background conductivity**

✓ **Removing EM coupling**

$$\ldots + \frac{dF}{d\sigma}\Delta\sigma(t)$$

$$\boxed{F[\sigma_\infty + \Delta\sigma(t)] - F[\sigma_\infty]} = d^{IP}(t) = -\frac{dF(t)}{d\sigma}\sigma_\infty \eta(t)$$

$$d^{IP}(t) = G(t)\eta(t) \qquad G(t) = -\frac{dF(t)}{d\log(\sigma)}$$

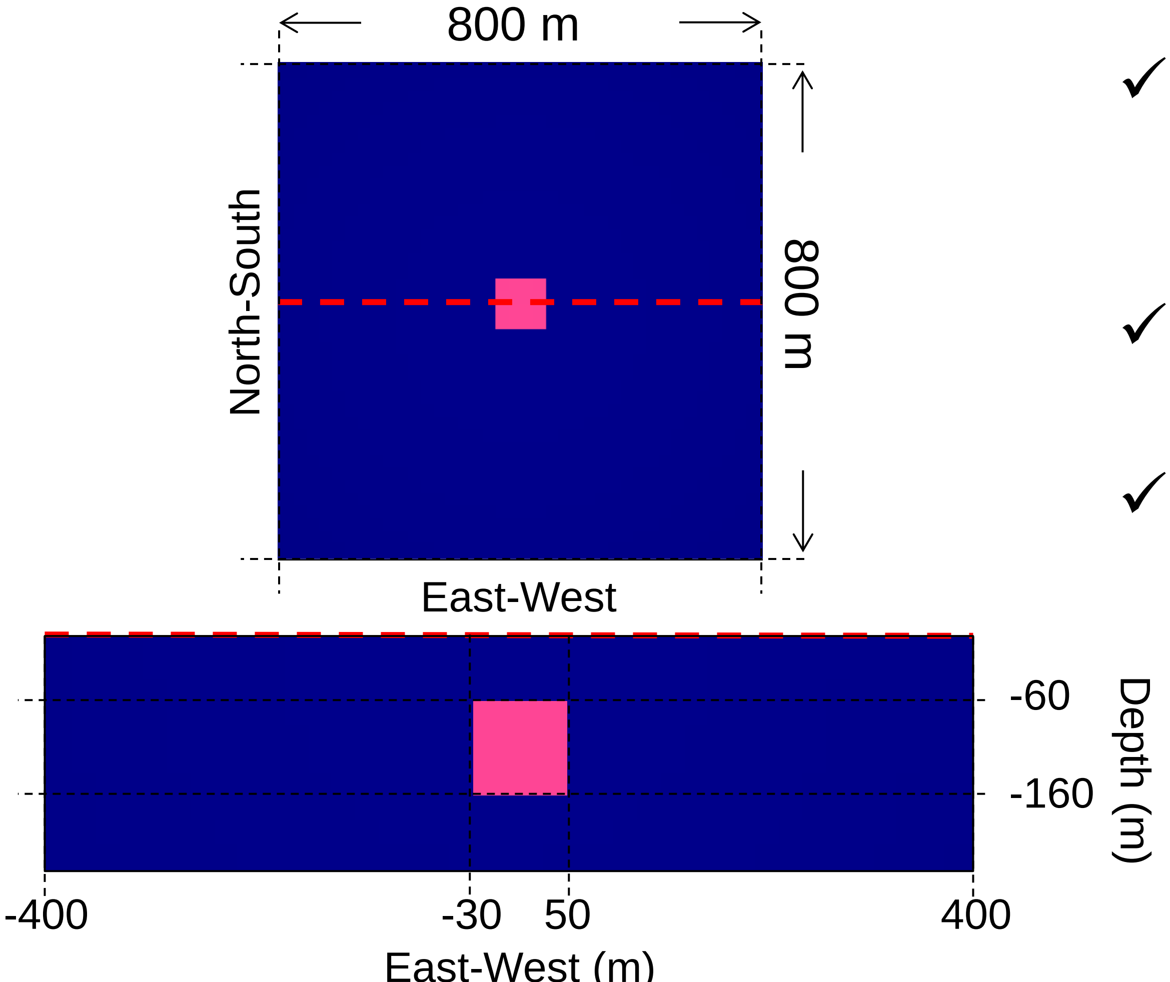
Routh and Oldenburg (2001)

Need background conductivity ($\boldsymbol{\sigma}_{\infty}$)

- Carry out 3D inversion of the AEM data (leave out time channels that have **negative transients**)
- Methodology: Yang and Oldenburg [AGU, 2012, ASEG 2012]
- Local mesh for forward modelling and sensitivities
- Stochastic selection of transmitters

Synthetic example

- True model



✓ Discretization

- 20 m core cells
- 69 x 69 x 50 cells

✓ Background

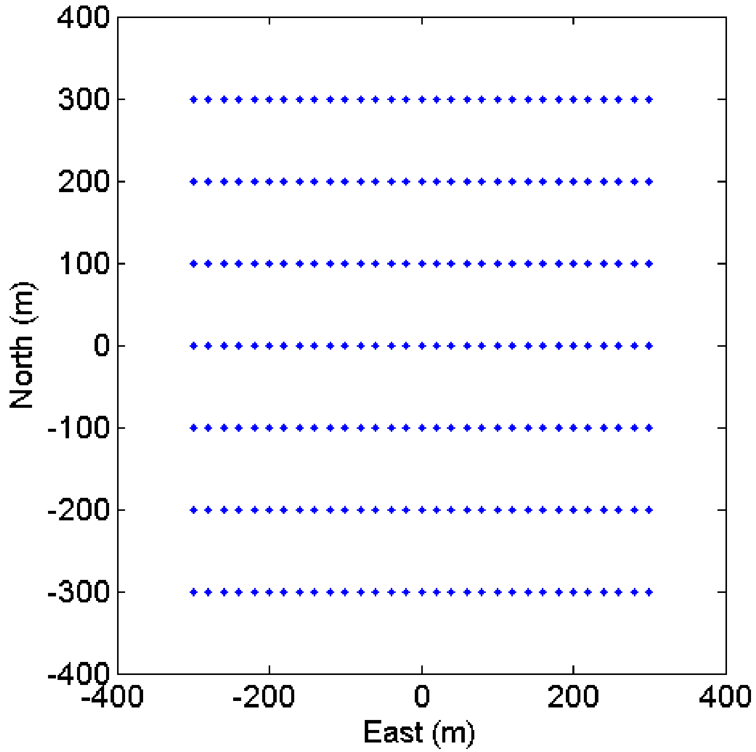
σ_{half} = 5e-4 S/m

✓ Target

- σ_∞ =6.25e-2 S/m
- η = 0.2
- τ = 0.01
- 80m x 80m x 80m
- 60m below surface

Synthetic example

- Geometry



✓ VMD source

30m above surface

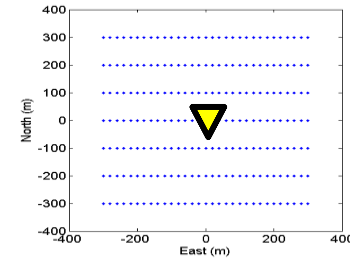
Collocated Rx

✓ 7×31 = 217 Txs

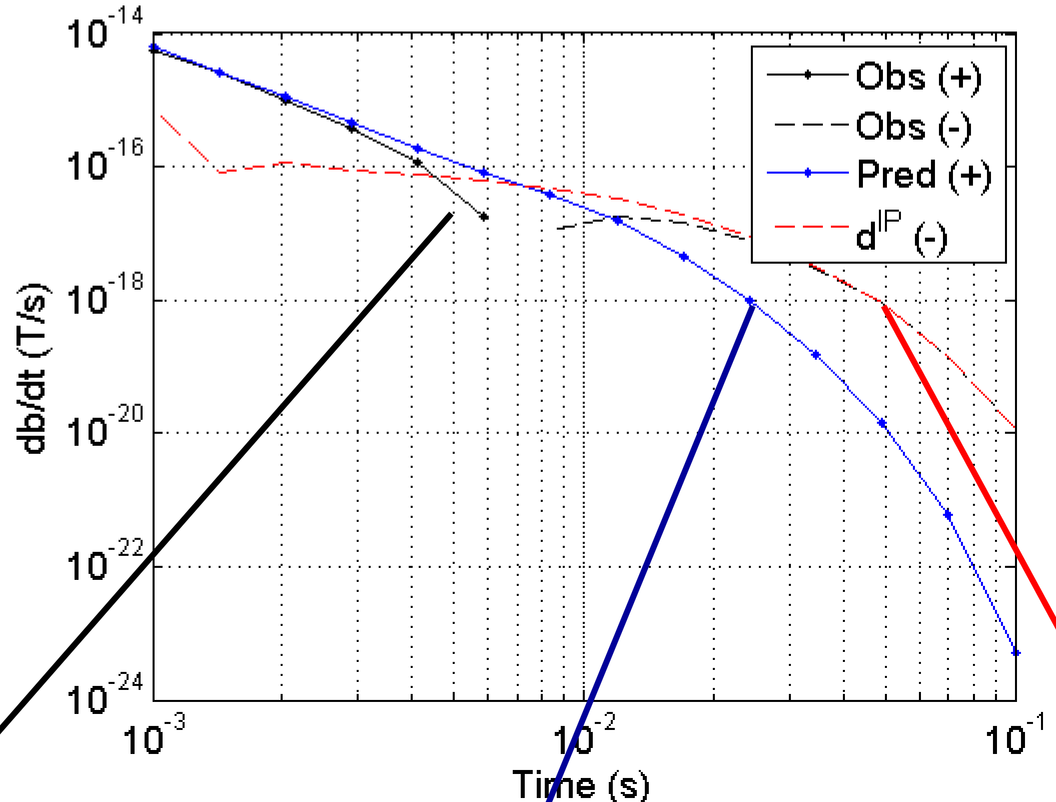
✓ Receivers

- Collocated with Tx
- Measuring db/dt
- 14 time channels
- 10^{-3} – 10^{-1} seconds

Synthetic Airborne EM data

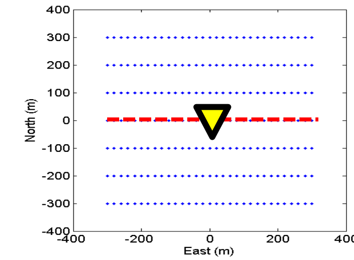


- At x = 0 m (EW) and y = 0 m (NS)

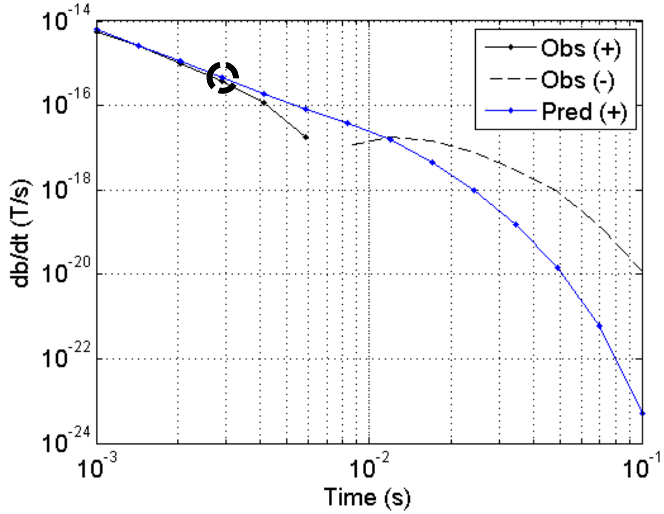


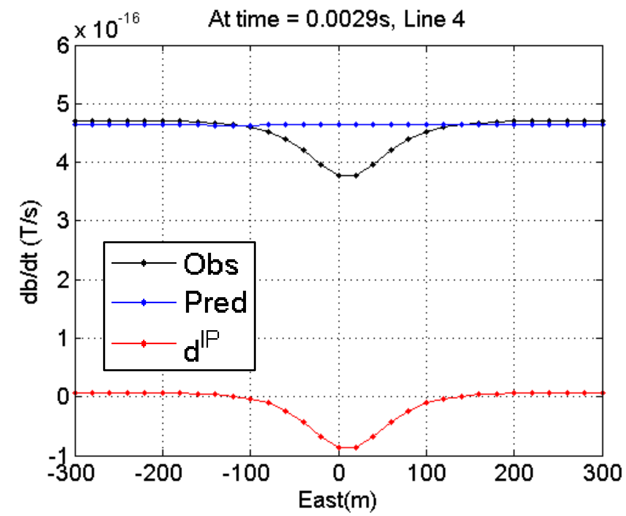
$$F[\sigma_\infty + \Delta\sigma(t)] - F[\sigma_\infty] = d^{IP}$$

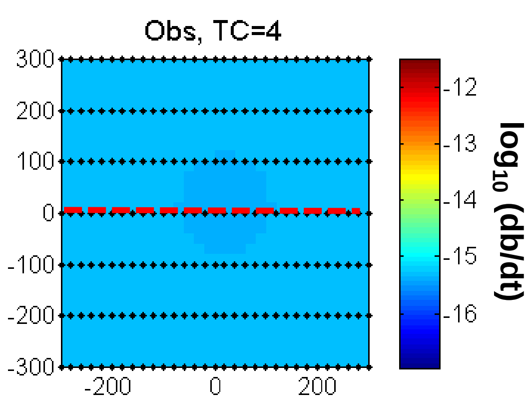
Synthetic Airborne EM data

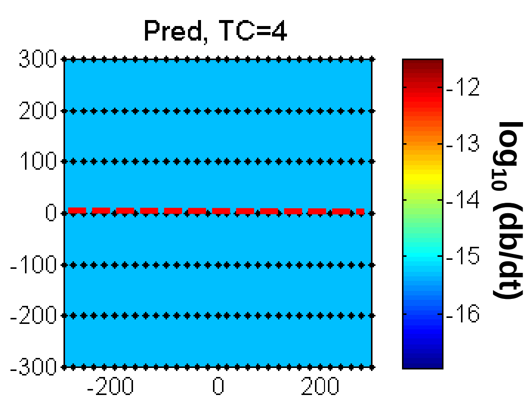


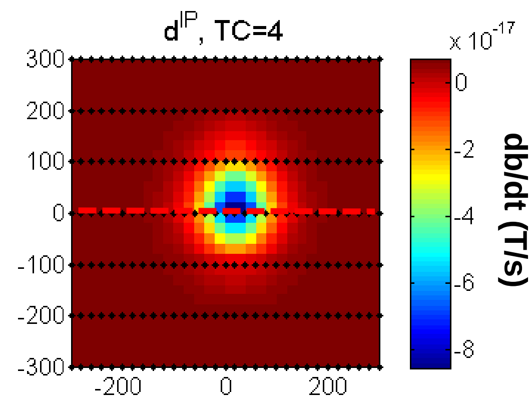
- db/dt data at time = 0.003s



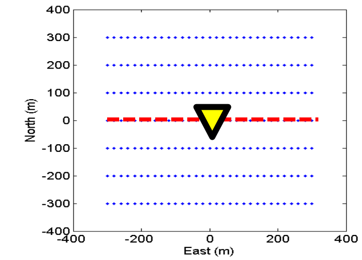




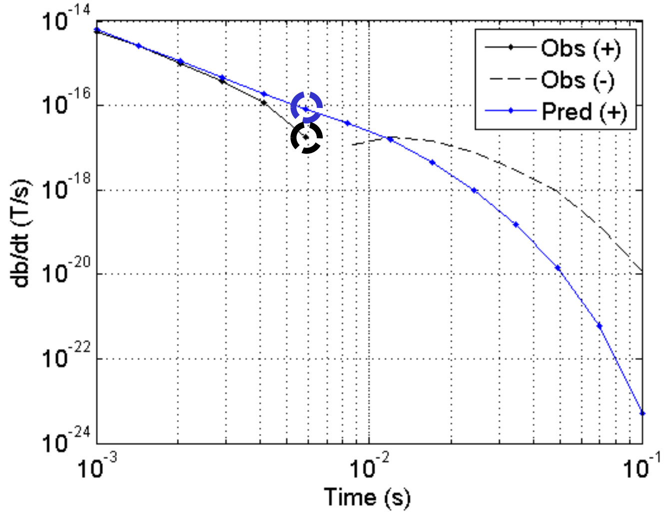


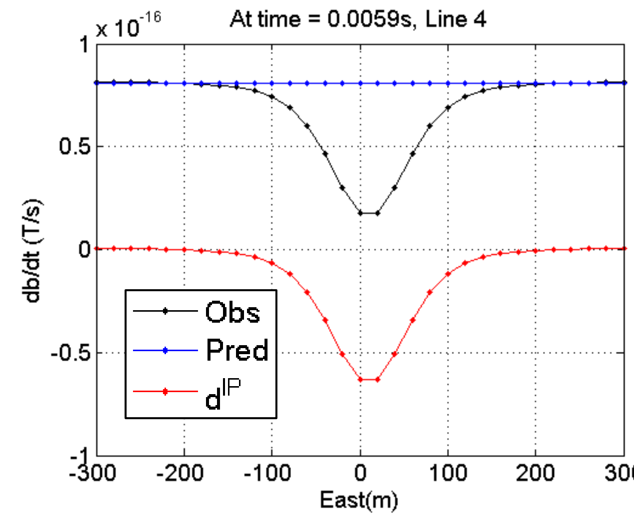


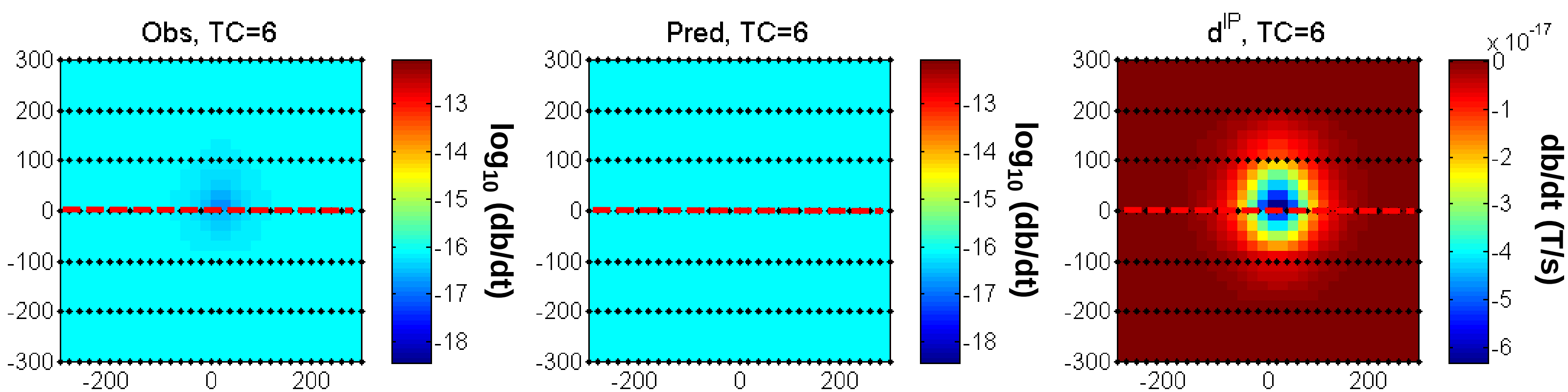
Synthetic Airborne EM data



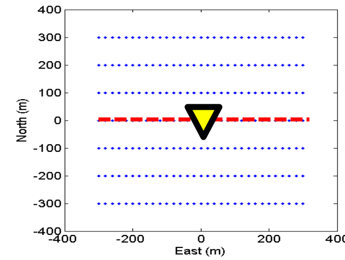
- db/dt data at time = 0.006s



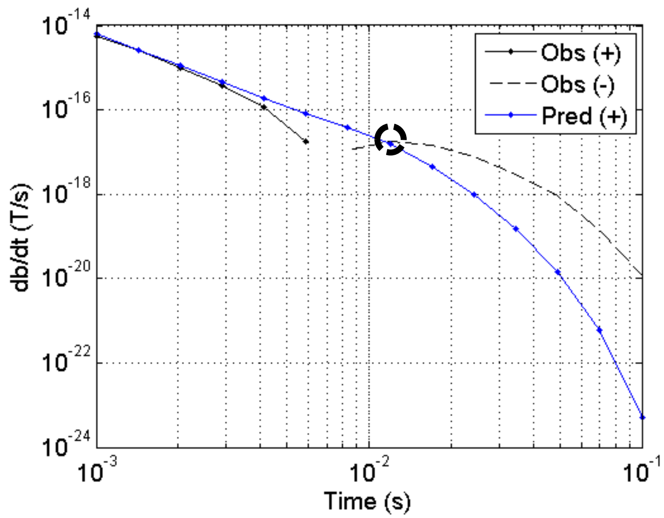


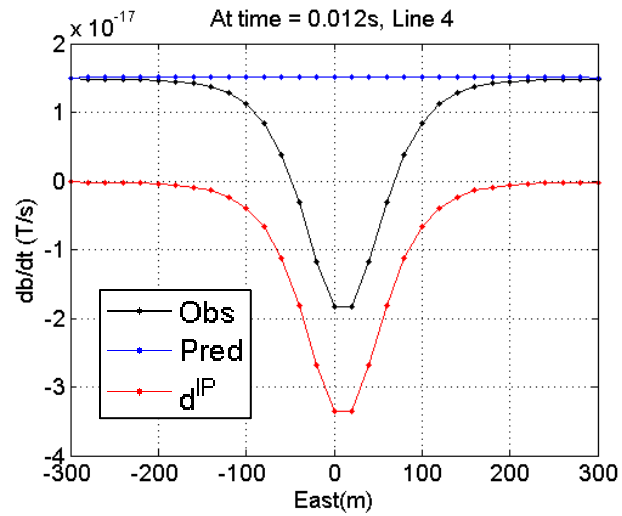


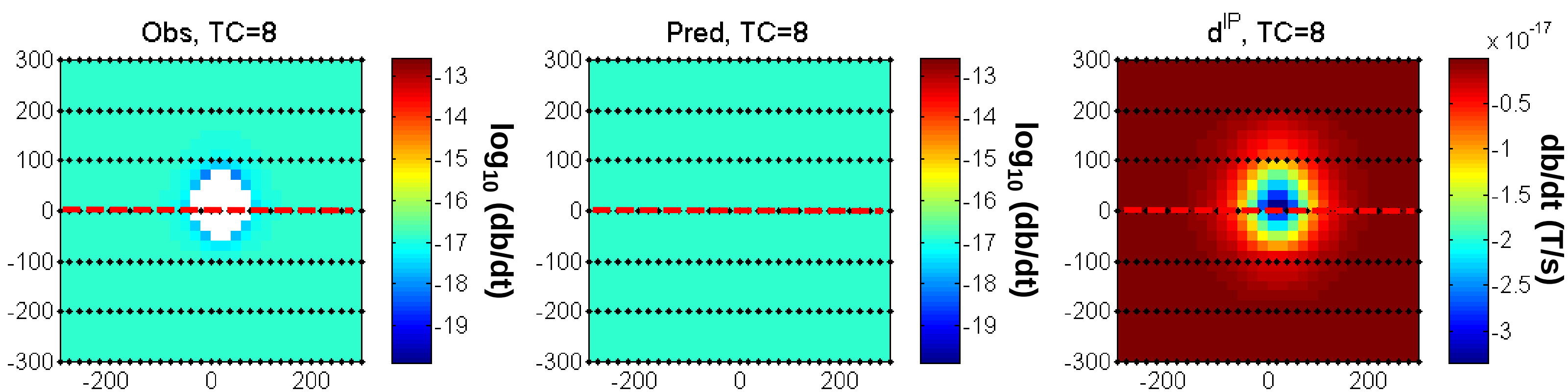
Synthetic Airborne EM data



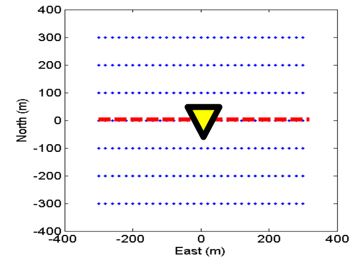
- db/dt data at time = 0.012s



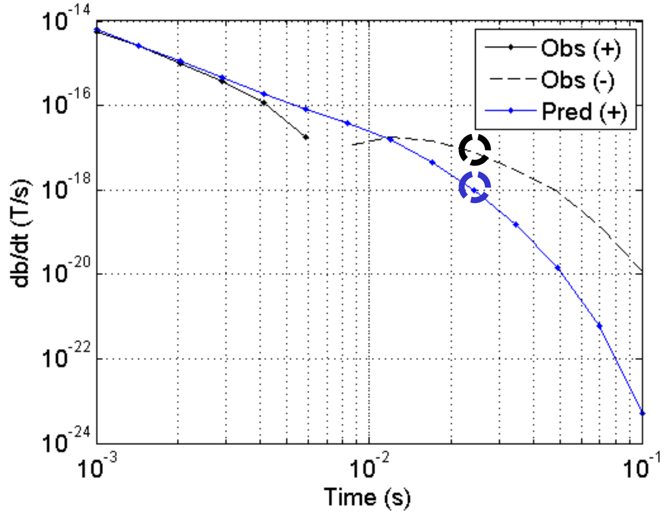


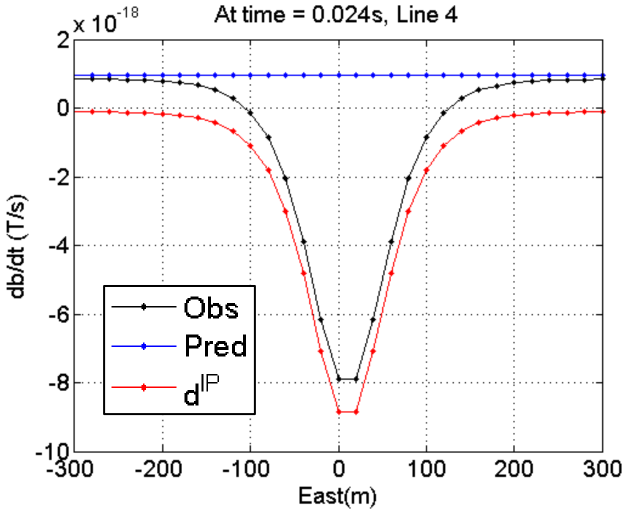


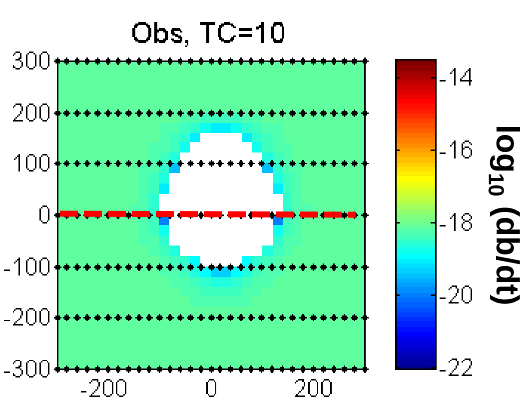
Synthetic Airborne EM data

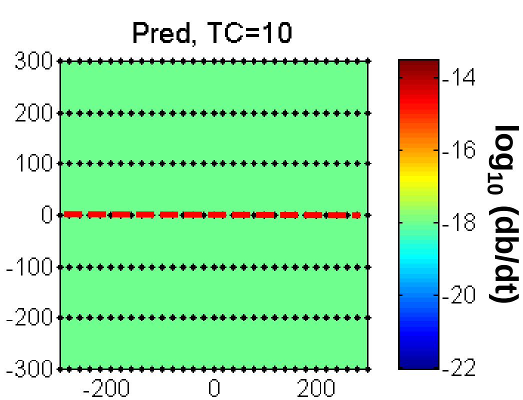


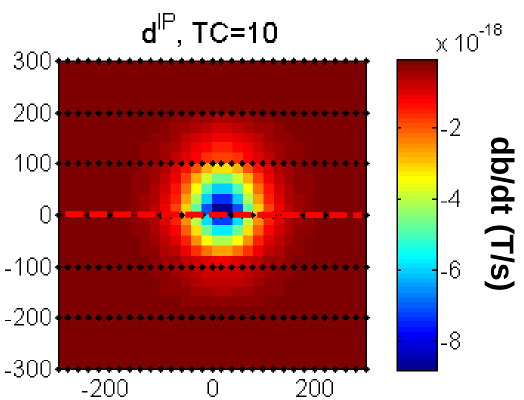
- db/dt data at time = 0.024s











Linear Inversion

- At each time

$$\min \quad \phi = \phi_d(\mathbf{m}) + \beta\phi_m(\mathbf{m})$$
$$\text{s.t. } 0 \leq \mathbf{m}$$

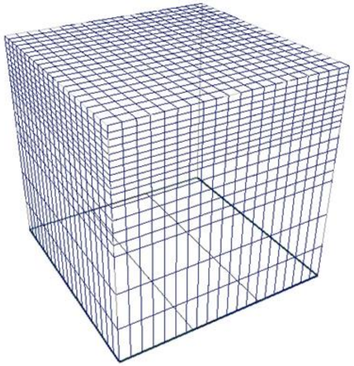
$$\phi_d = \sum_{i=1}^{N} \left(\frac{\vec{d}_i^{pred} - \vec{d}_i^{obs}}{\epsilon_i} \right)^2$$

$$\phi_m = ||\mathbf{W_m}(m - m_{ref})||_2^2$$

$$d^{IP}(t) = G(t)\tilde{\eta}(t)$$

$$G(t) = -\frac{dF(t)}{d\log(\sigma)}$$

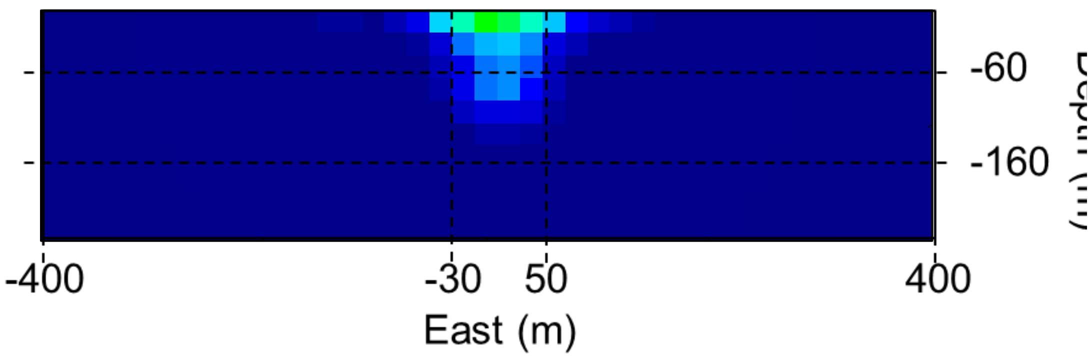
3D volume of $\tilde{\eta}(t)$



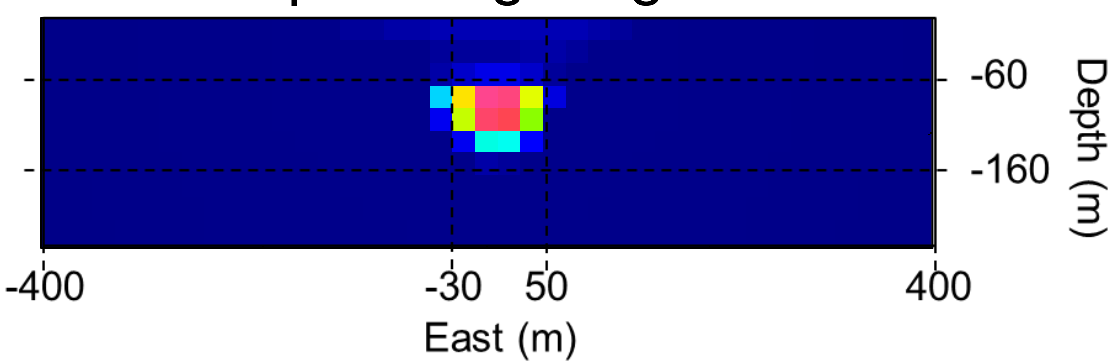
Recovered pseudo chargeability

<Cross section>

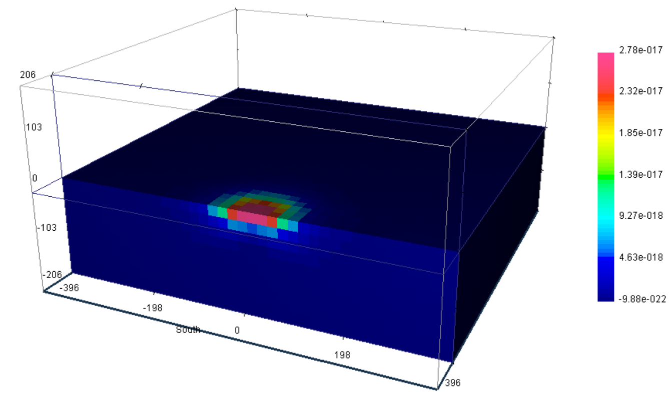
Without depth weighting



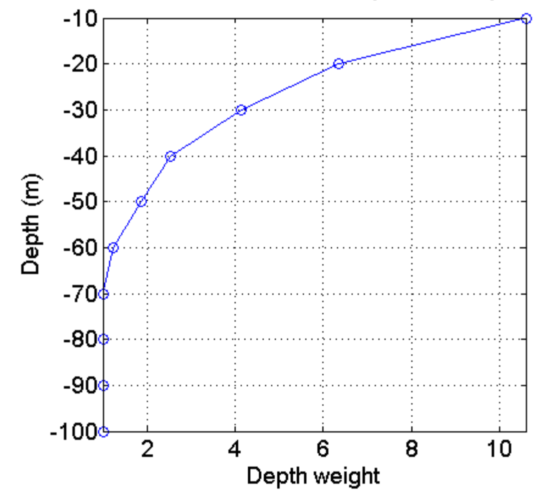
With depth weighting



Sensitivity volume

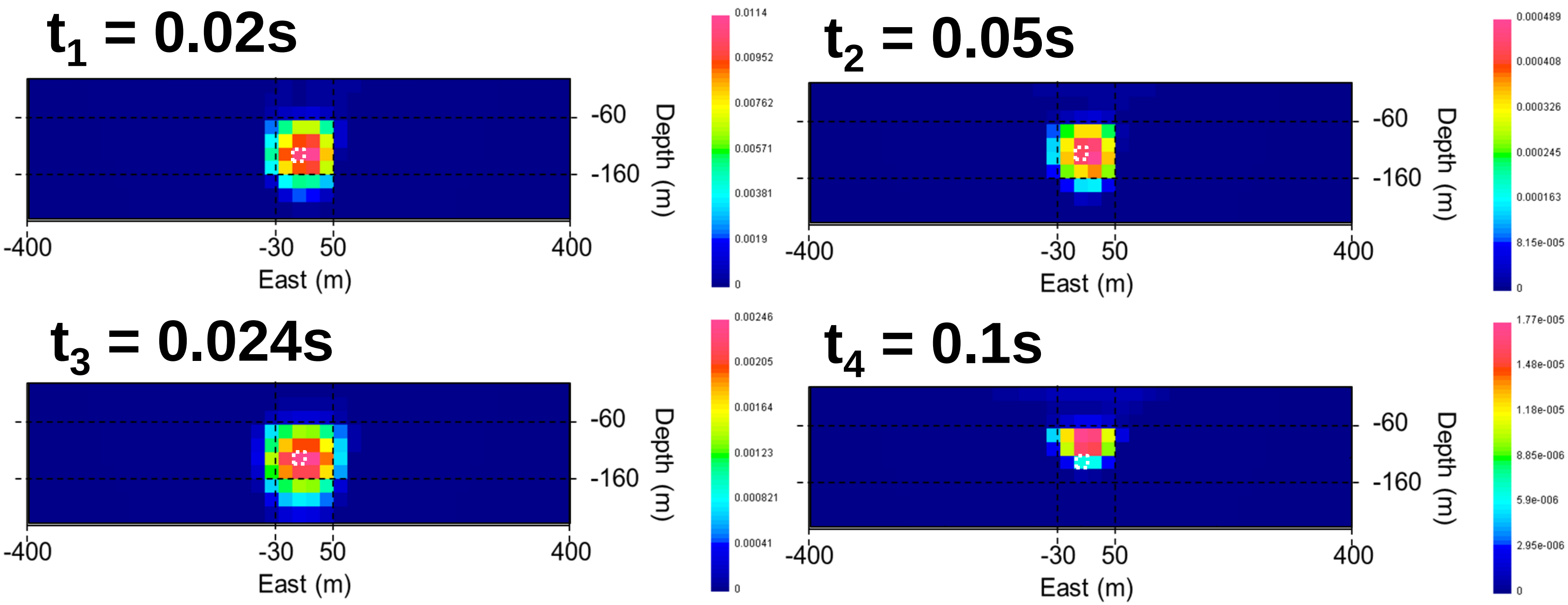


Depth weighting



Recovered pseudo chargeability

- At four different time channels

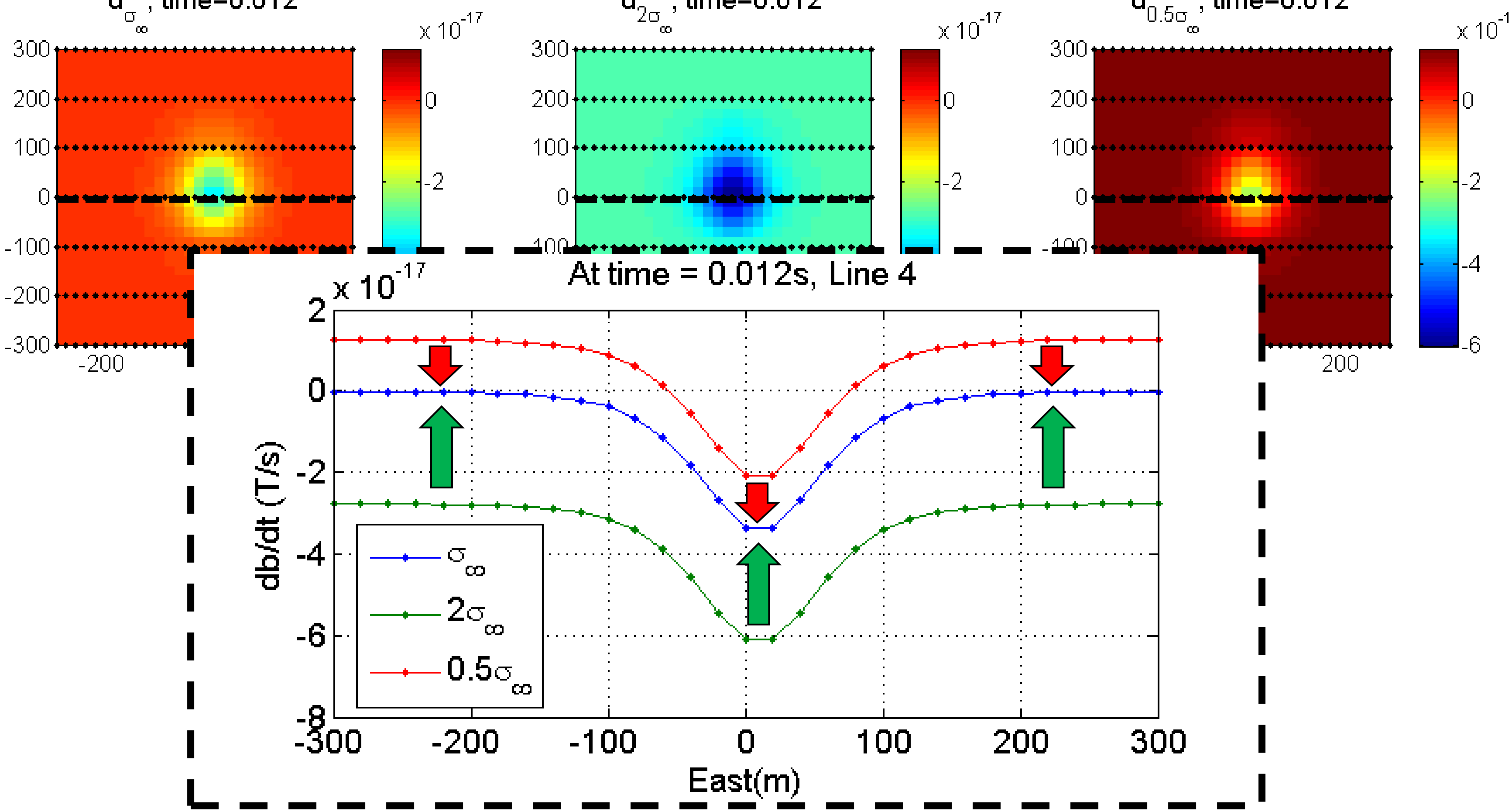


Effects of background conductivity

True background (σ_∞)

Wrong Background ($2\times\sigma_\infty$)

Wrong background ($0.5\times\sigma_\infty$)



Procedure

Invert TEM to recover a background 3D **σ** model

- ✓ Attempt to avoid soundings/times that have IP coupling effects
- ✓ Easy if there are **negative transients**

Compute d^{IP} data at multiple time channels

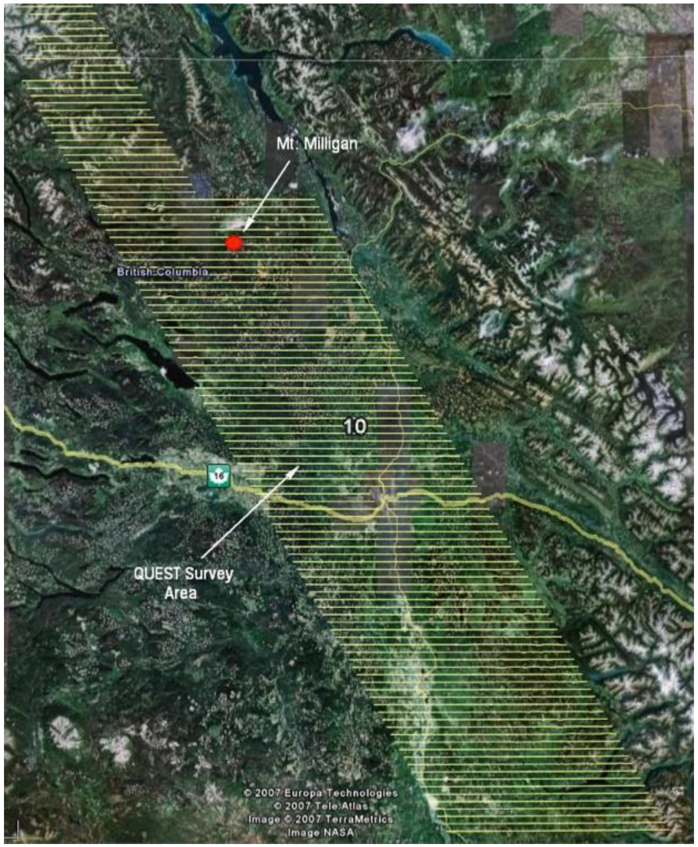
Estimate a regional field

- ✓ Assume IP data are composed of a **smoothly varying regional** plus true IP data
- ✓ Not easy; but this issue is confronted before

Subtract regional to obtain IP data

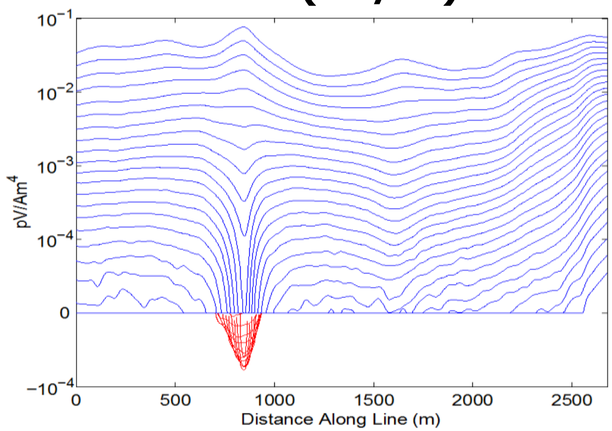
Invert individual time channels

Field example: Mt. Milligan VTEM

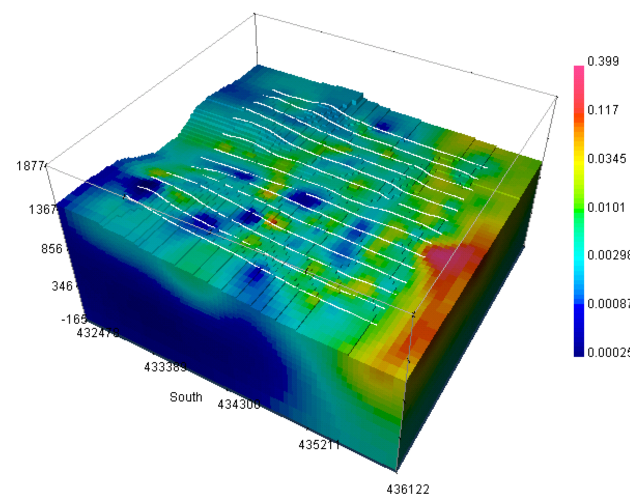


Geotech (2007)

- ✓ **Observed data (db/dt)**



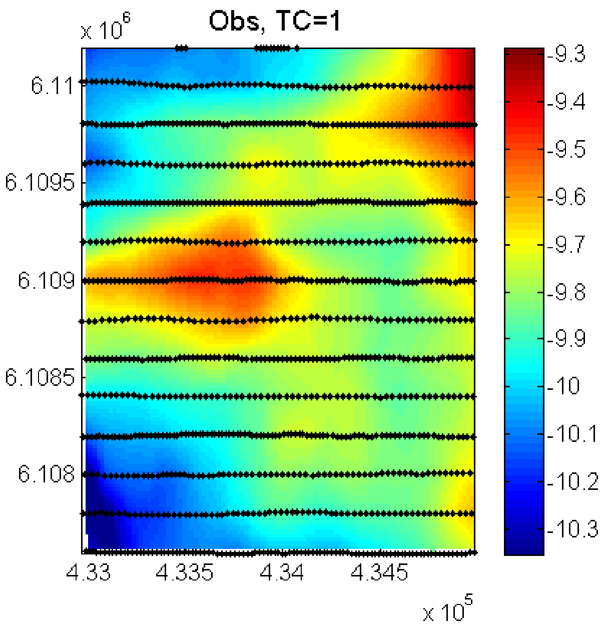
- ✓ **Recovered 3D conductivity model**



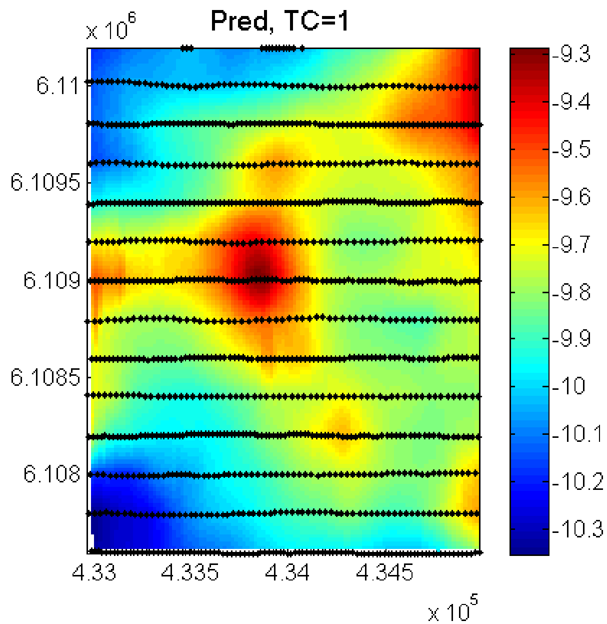
Mt. Milligan Airborne EM data

- db/dt data at time = 0.00463s

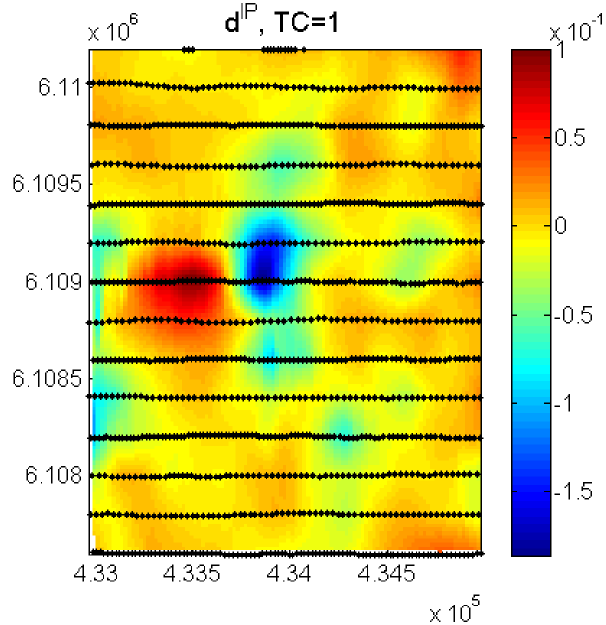
Observed



Predicted



d^{IP}

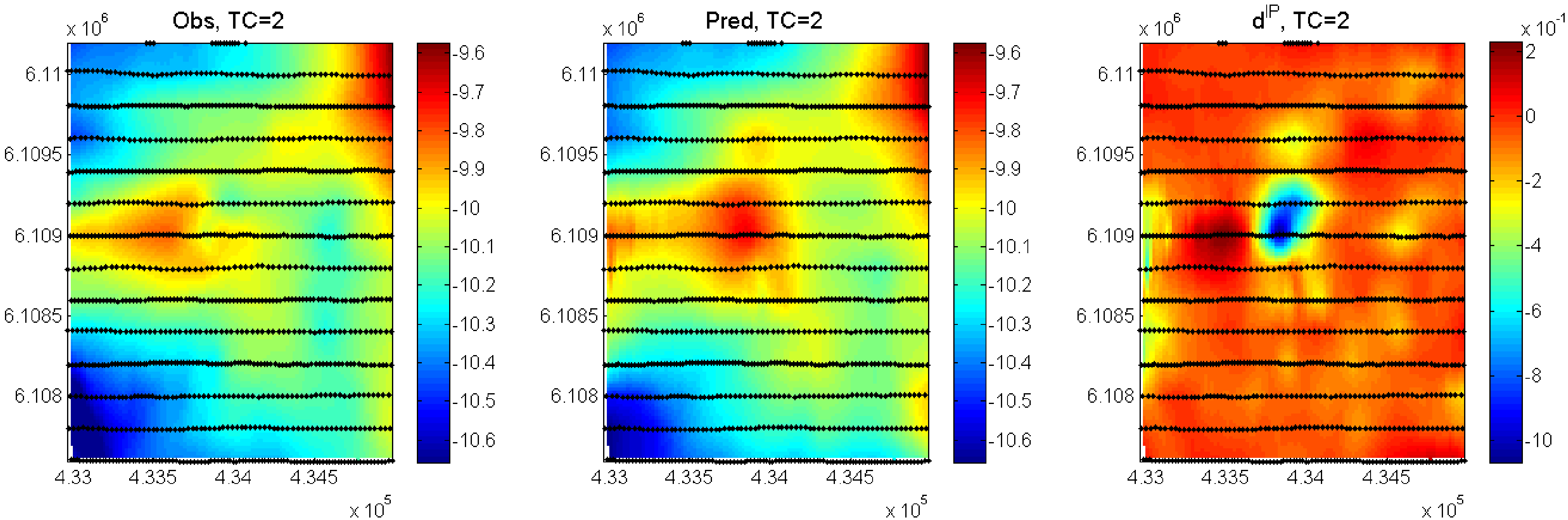


$$F[\sigma_\infty + \Delta\sigma(t)] - F[\sigma_\infty] = d^{IP}(t)$$

Mt. Milligan Airborne EM data

- db/dt data at time = 0.00473s

Observed **Predicted** **d^{IP}**

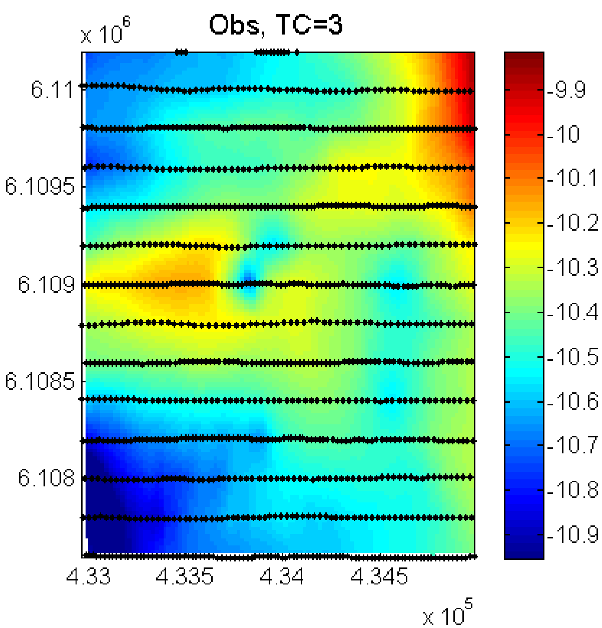


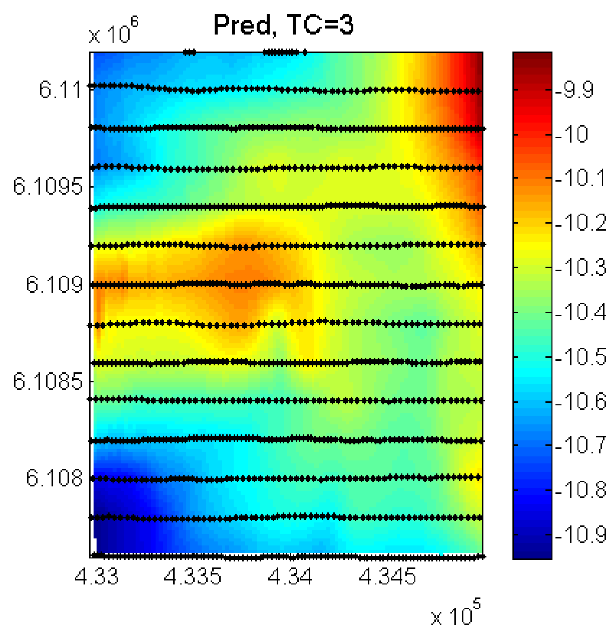
$$F[\sigma_\infty + \Delta\sigma(t)] \quad - \quad F[\sigma_\infty] \quad = \quad d^{IP}(t)$$

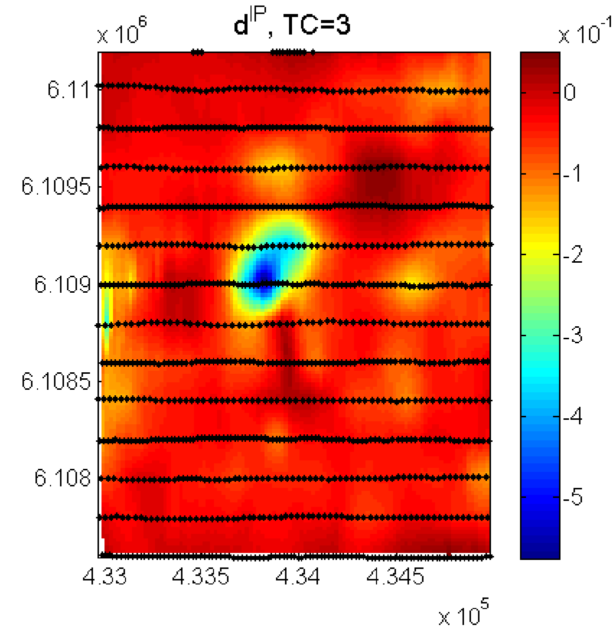
Mt. Milligan Airborne EM data

- db/dt data at time = 0.00488s

Observed **Predicted** **d^{IP}**





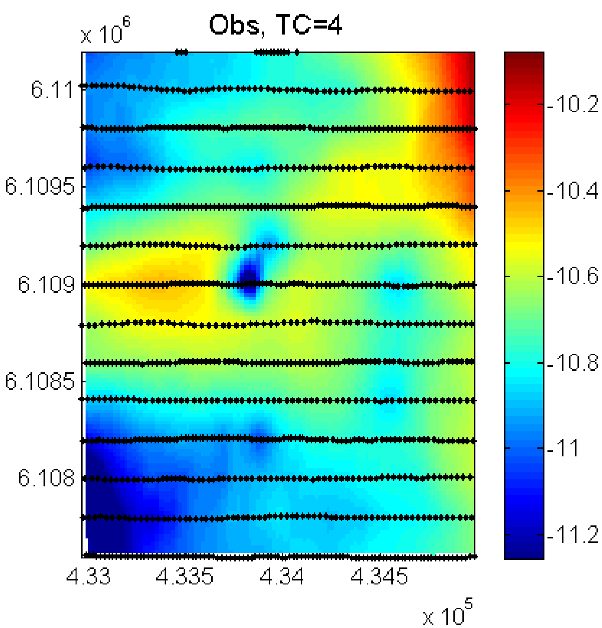


$$F[\sigma_\infty + \Delta\sigma(t)] - F[\sigma_\infty] = d^{IP}(t)$$

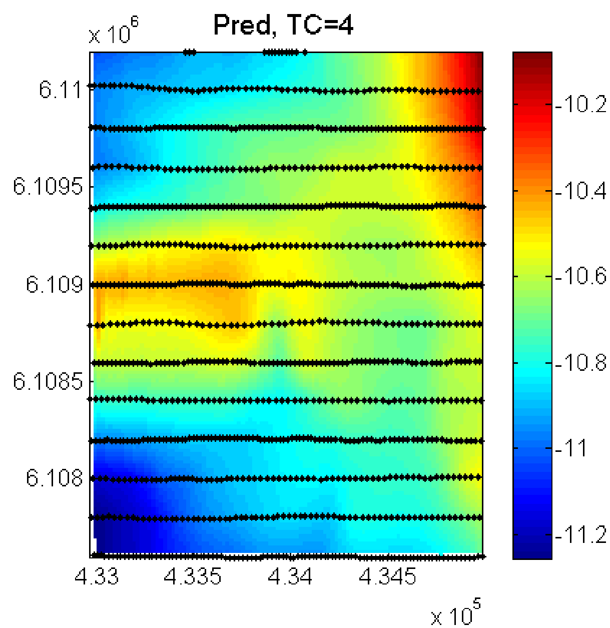
Mt. Milligan Airborne EM data

- db/dt data at time = 0.00508s

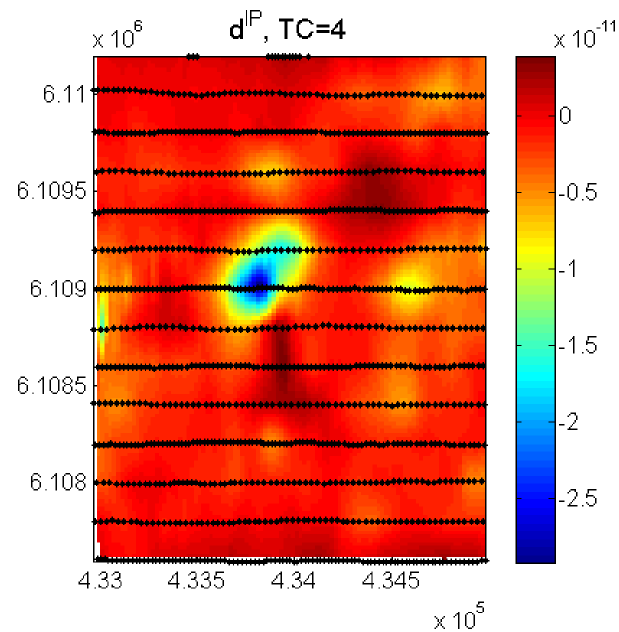
Observed



Predicted



d^{IP}

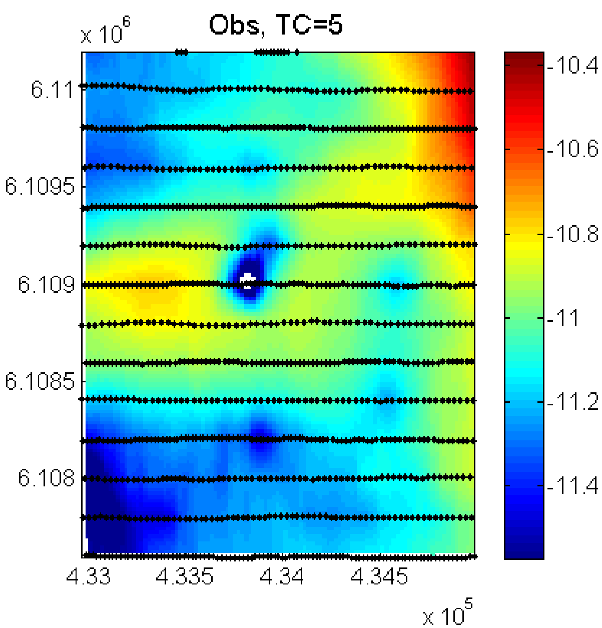


$$F[\sigma_\infty + \Delta\sigma(t)] - F[\sigma_\infty] = d^{IP}(t)$$

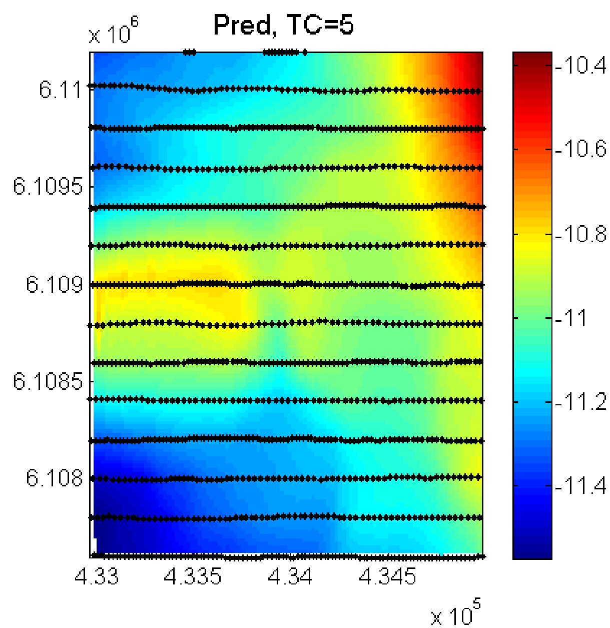
Mt. Milligan Airborne EM data

- db/dt data at time = 0.00537s

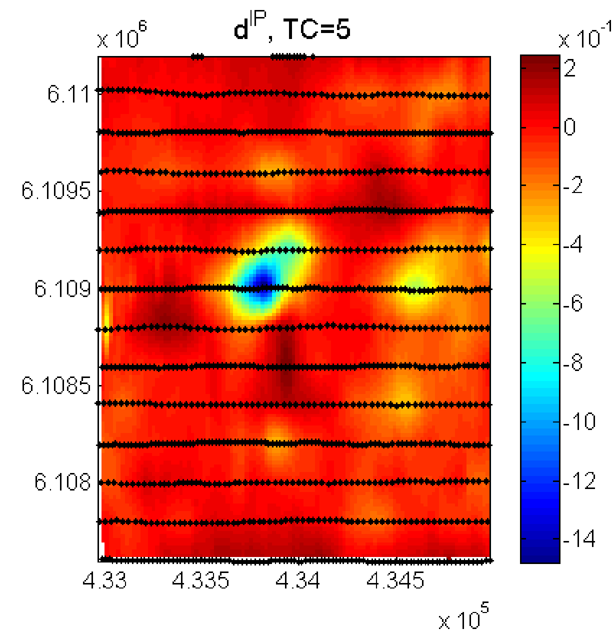
Observed



Predicted



d^{IP}

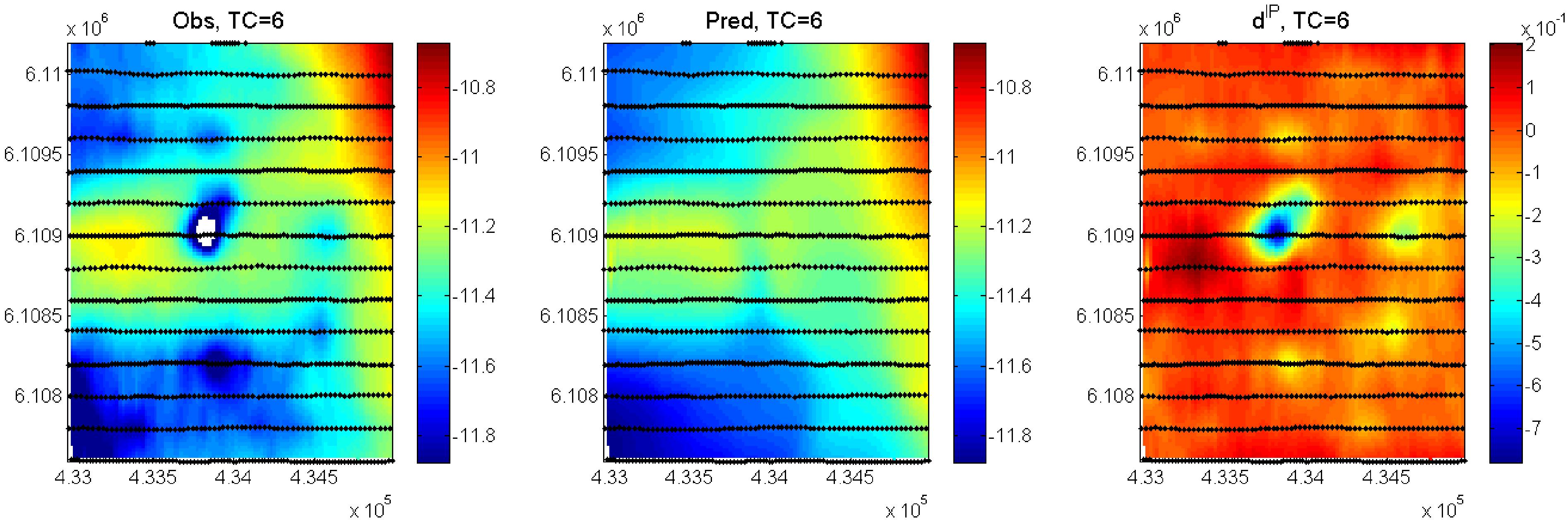


$$F[\sigma_\infty + \Delta\sigma(t)] \;-\; F[\sigma_\infty] \;=\; d^{IP}(t)$$

Mt. Milligan Airborne EM data

- db/dt data at time = 0.00577s

Observed **Predicted** **d^{IP}**

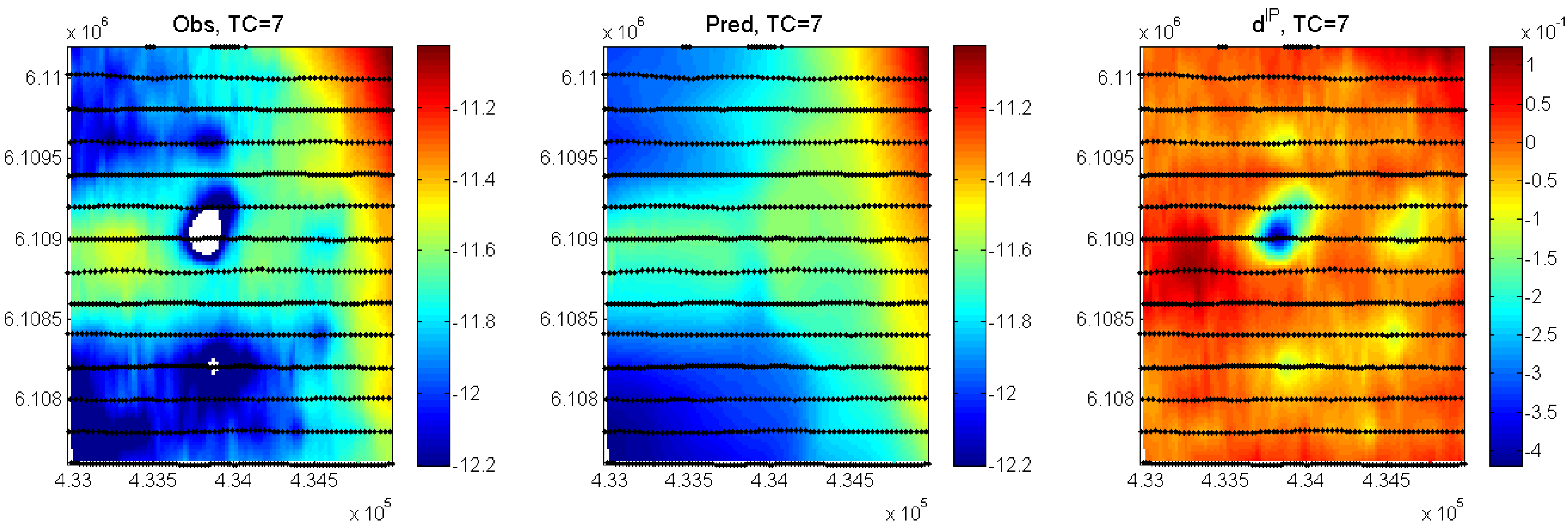


$$F[\sigma_\infty + \Delta\sigma(t)] - F[\sigma_\infty] = d^{IP}(t)$$

Mt. Milligan Airborne EM data

- db/dt data at time = 0.00635s

Observed **Predicted** **d^{IP}**

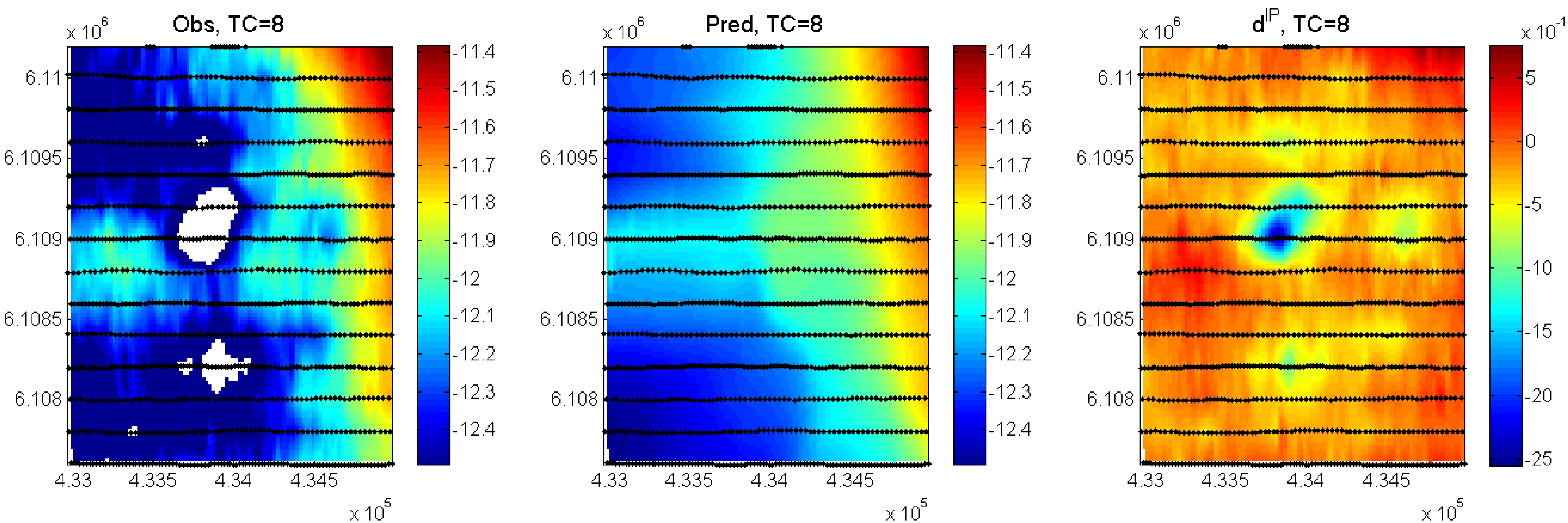


$$F[\sigma_\infty + \Delta\sigma(t)] \quad - \quad F[\sigma_\infty] \quad = \quad d^{IP}(t)$$

Mt. Milligan Airborne EM data

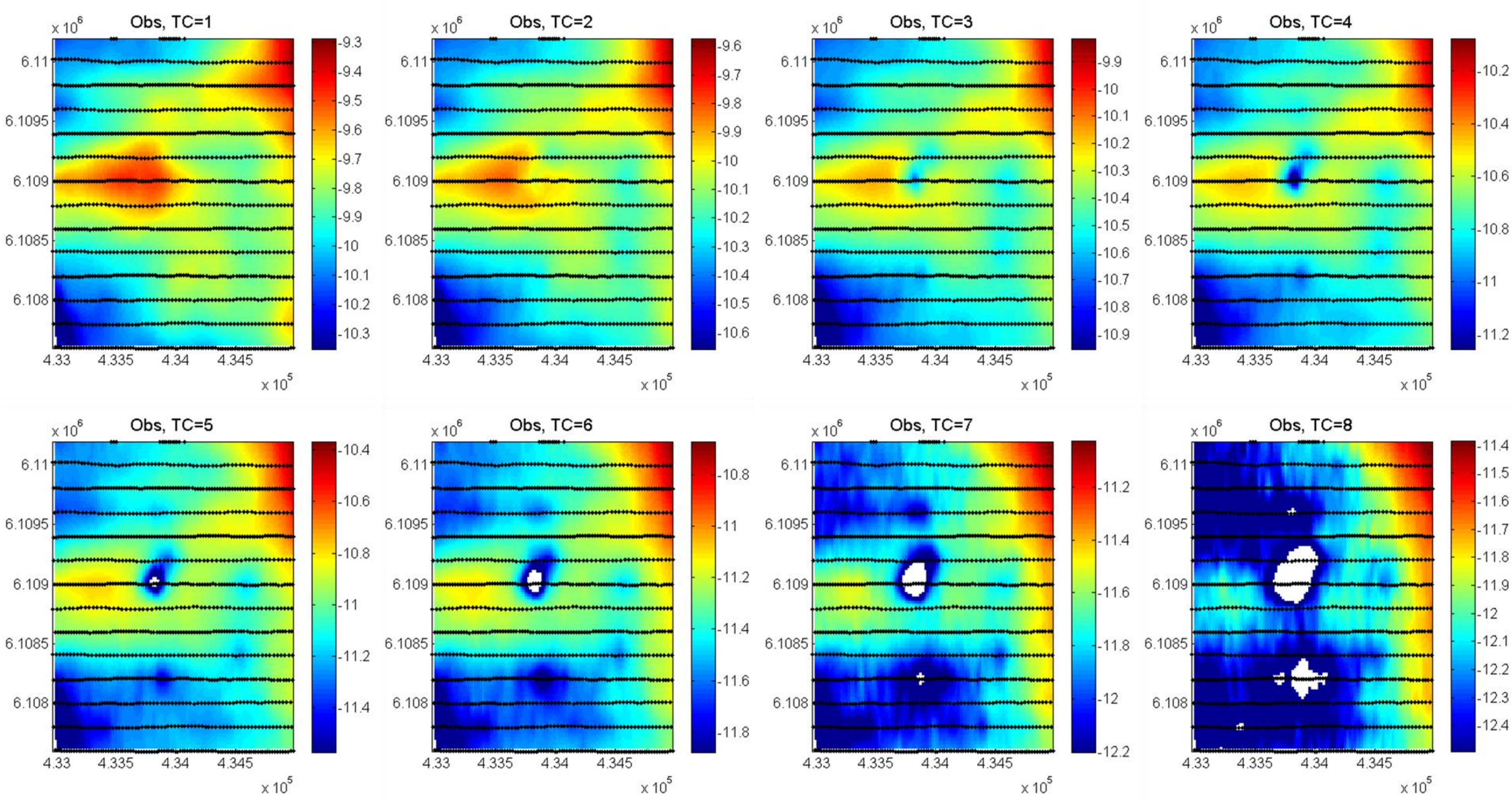
- db/dt data at time = 0.00715s

Observed | **Predicted** | **d^{IP}**

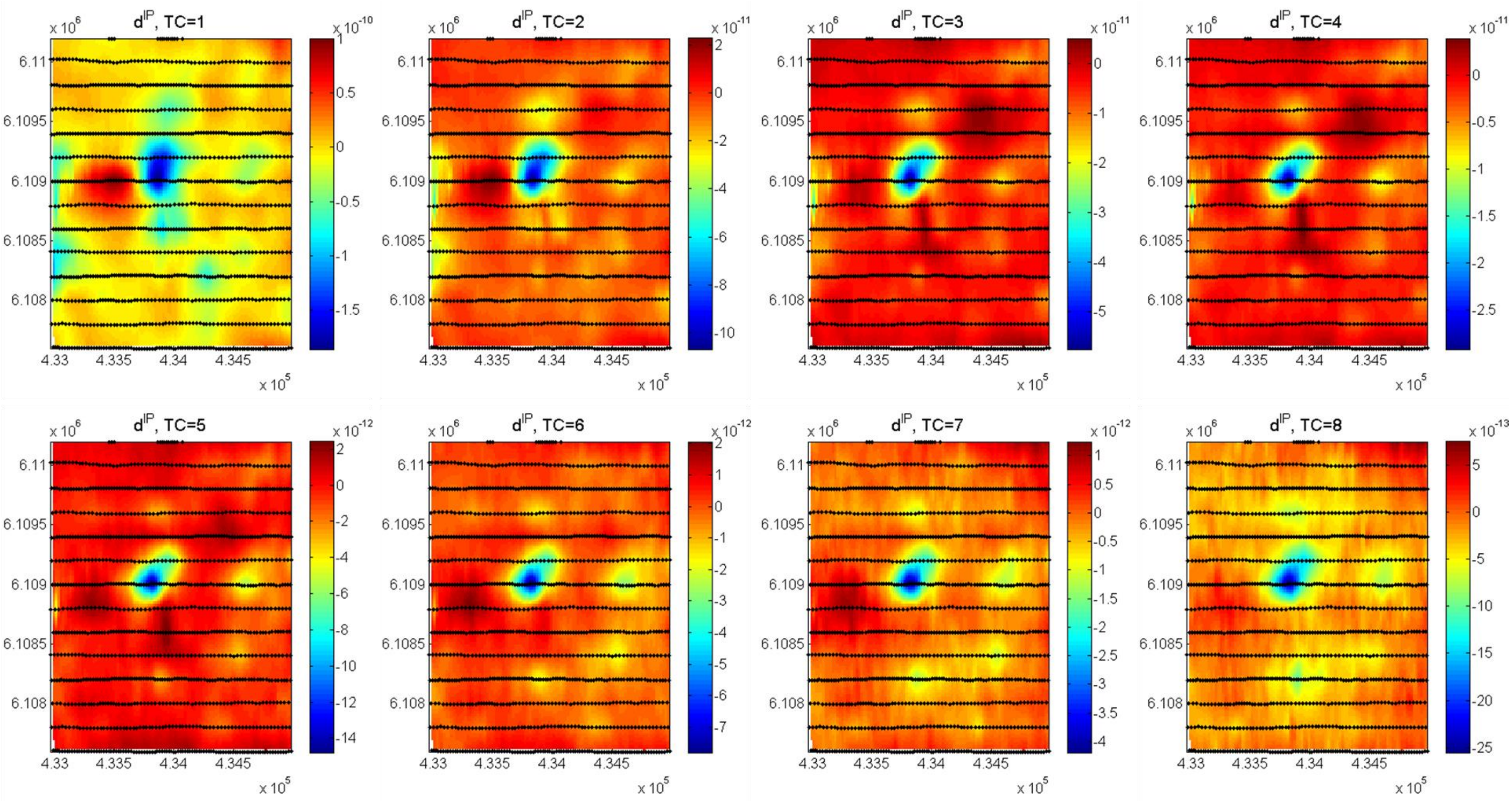


$$F[\sigma_\infty + \Delta\sigma(t)] - F[\sigma_\infty] = d^{IP}(t)$$

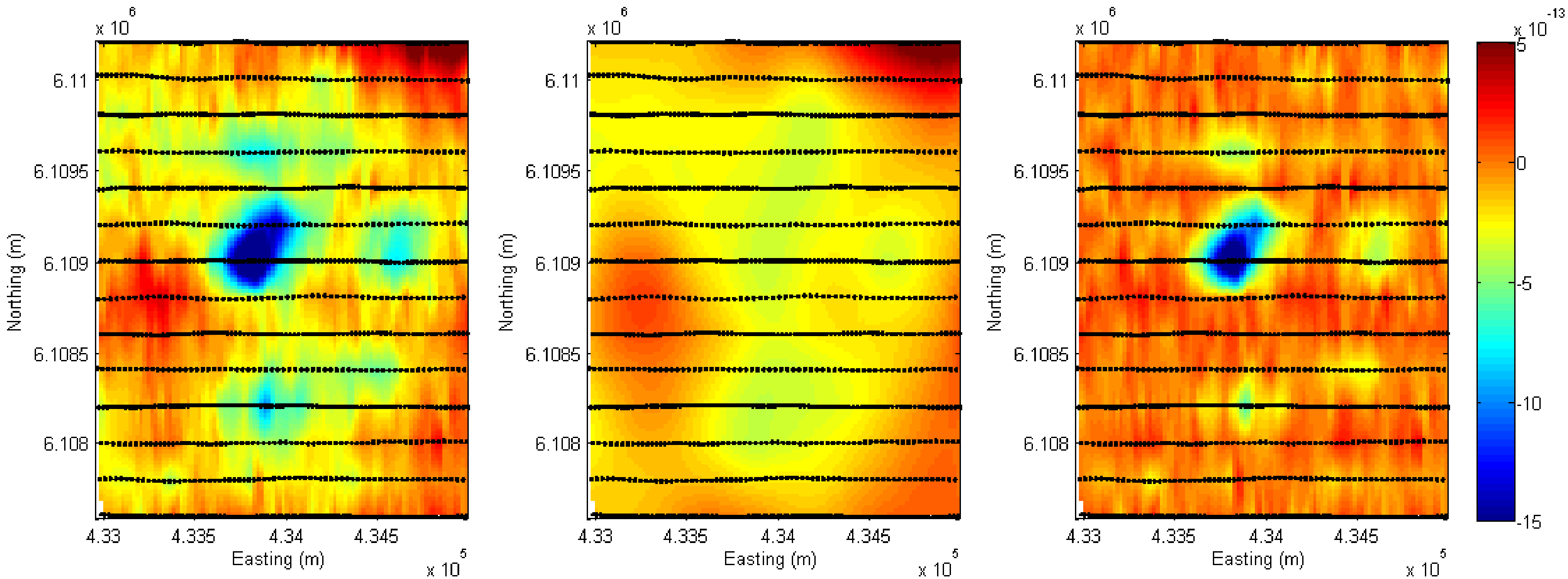
Observed data for all channels



d^{IP} data for all channels

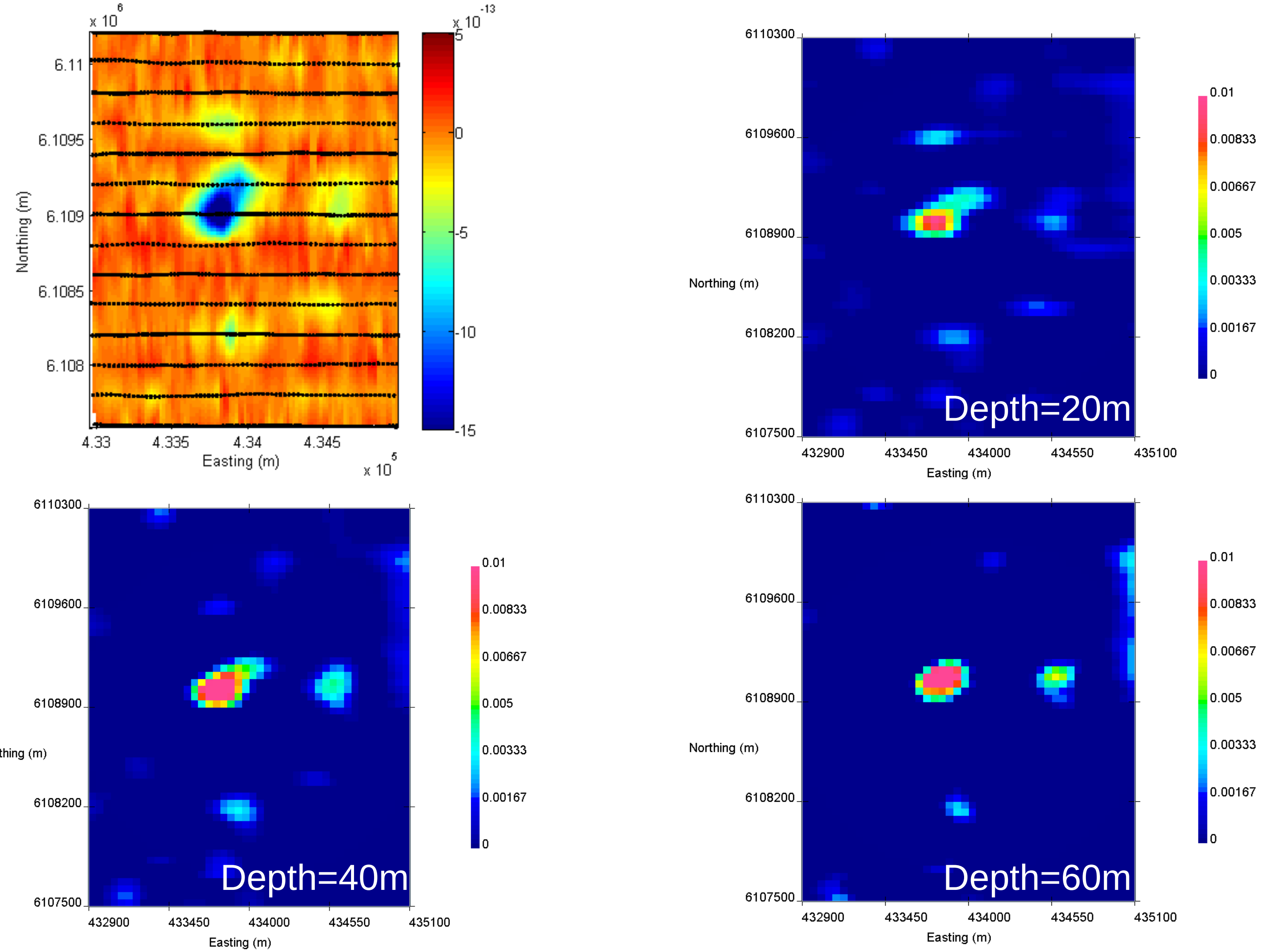


Removal of a regional



d^{IP} regional data for inversion

Inversion Results



Summary and path forward

- Estimating $\boldsymbol{\sigma}_{\infty}$, 3D background conductivity. (be mindful of IP coupling)
- $\mathbf{d}^{IP} = \mathbf{d}^{obs} - \mathbf{F}[\boldsymbol{\sigma}_{\infty}]$
- For each time channel:
  - ✓ Assume: $\mathbf{d}^{IP} = \mathbf{d}^{IP}(\text{true}) + \text{smooth background signal}$
- Estimate background signal (challenge)
- Individual inversions and then attempt to extract spectral information

Summary and path forward

- More advanced inversions to work with all time channels at once.

- Current progress provides **optimism** that we can invert the data if it is sufficiently high quality

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