On Time-Domain Transient Electromagnetic Soundings

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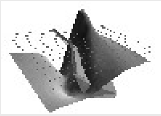
"Some issues in modelliing TEM responses and their relevance to real-world systems and geology"

TOPICS

- **Basic Principles**
- **Motivation**
- **Forward Modeling**
- **Inversion Techniques**
- **Case Study**
- **Conclusions**

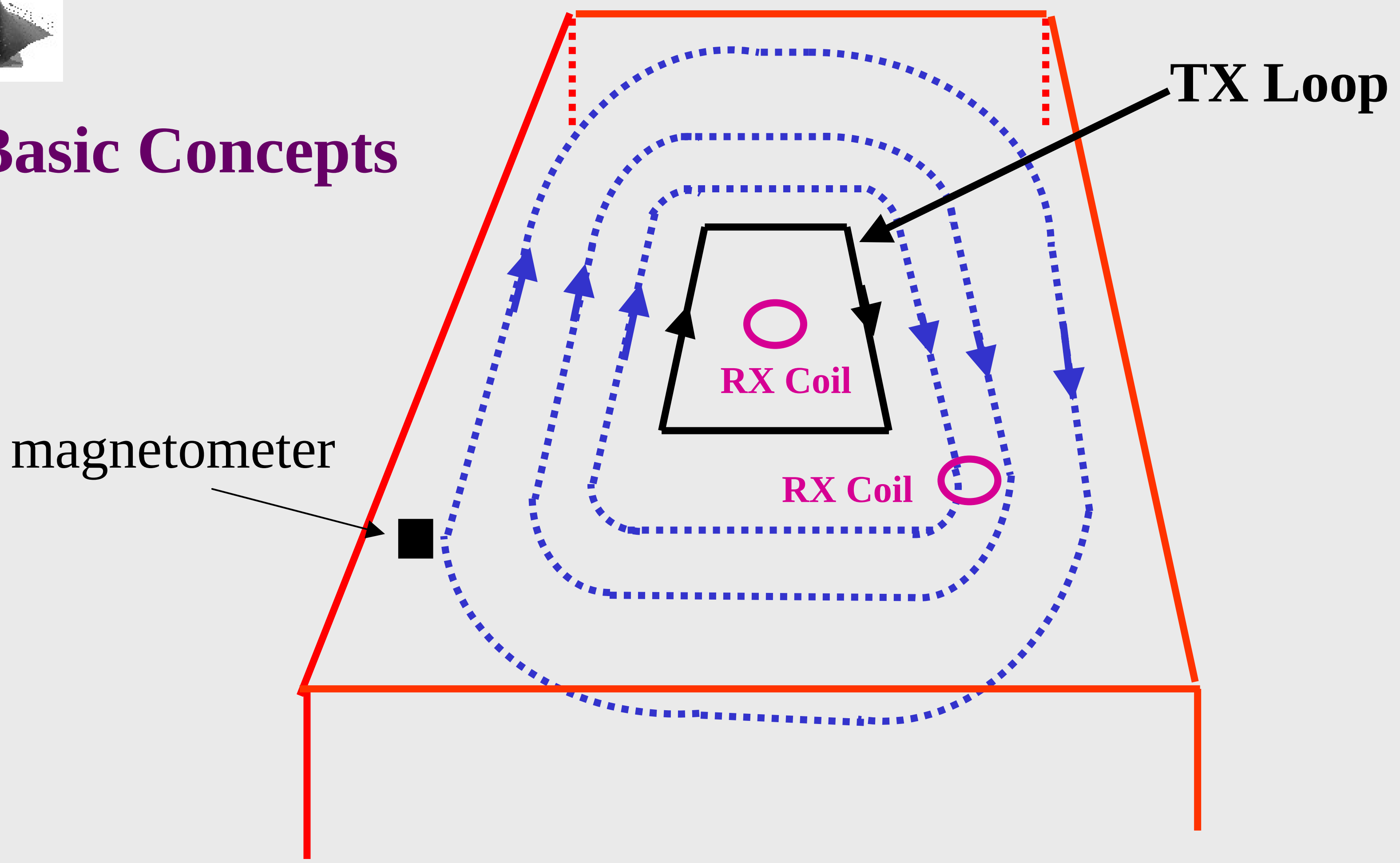
Petroseikon

Basic Principles



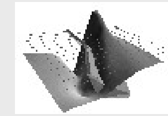
- Primary magnetic field is generated when a current passes through transmitter loop
- The current is varied, interrupting Primary magnetic field, currents are induced in the ground (Faraday's Law)
- The current system flowing in paths below transmitter, producing a secondary magnetic field or its time derivative
- Magnitude and distribiution of the induced current density depend on the electrical properties of ground
- Changes of secondary magnetic field with time induce a voltage in receiver coil (magnetometer)
- Measurment of the voltage induced in a receiver coil or magnetometer at various times can reveal the electrical resistivity of the earth

Basic Concepts



The locus of maximum amplitude of induced currents diffuses downward and outward with time - **“Smoke Rings”**

Motivation



Why not leave this problem to the academics?

- **software engineering issues**
- **tweak the code to see just how it works**
  or develop multiple techniques to verify results

- **Client request:**

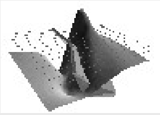
❑ extend to other components, configurations
❑ B field inversion
❑ polarization effects, magnetic effects
❑ on-time data
❑ airborne and borehole data
❑ determine background resistivities for 3D modelling
❑ periodic response

•**Implementation**

- utilize our forwards codes which have the generalizations

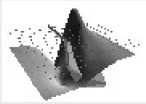
Forward Modeling- Approximate

(*Anderson's approach*)

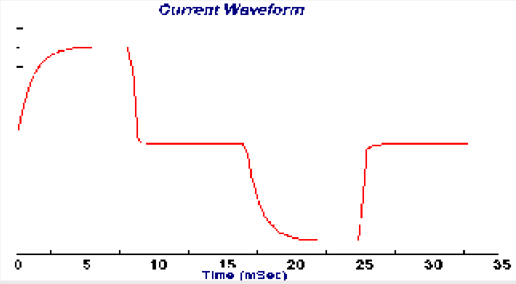


- Tx and Rx concentric
- Equivalent moment circular loop Tx
- Compute dBz/dt in the off-time
- *Causal* waveform with "infinite" bandwidth
  - Hankel transform filter for scattering in frequency domain
  - Transient response with a Fourier transform filter
  - Perfect impulse response with infinite off-time but correct impulse amplitude
- Only ground data – Tx and Rx on air-ground interface
- Some slight adaptions of Anderson's approach

Forward Modeling- General



- ✓In-loop and out-of-loop responses with arbitrary location and orientation of Rx
- ✓Loops with arbitrary shapes, dipole-like Tx's
- ✓Ground, airborne, borehole
- ✓Layers have resistivity, permeability, permittivity, Cole-Cole



Waveforms are periodic:

- ✓Transmitting Waveform is repeated many times and data are stacked
  - -A discrete spectrum at harmonics of the base-frequency
  - -Utilize variable frequency sampling with interpolation for harmonics
  - -Calculate spectrum of the waveform
  - -Convolve with layered earth impulse response and the low-pass filter in FD
    - ➔ transform to time-domain using appropriate harmonics
- ✓Utilization of various current waveforms
- ✓Finite bandwidth – electronic implementation, linearity of coils , high frequency noise

Effersǿ et al, 1999

Forward Modeling- Current Waveform

- ✓**50% duty cycle with linear ramp off:**
  Geonics, Zonge, Sirotem, Crone
- ✓**Half-sine current pulse:**
  Input waveform - Geotem, Megatem
- ✓ **Almost 50% duty cycle with sine on/off:**
  VTEM
- ✓ **Short Triangle current pulse:**
  AeroTem
- ✓**SawTooth Current with Coil - *step response*:**
  UTEM and Spectrem

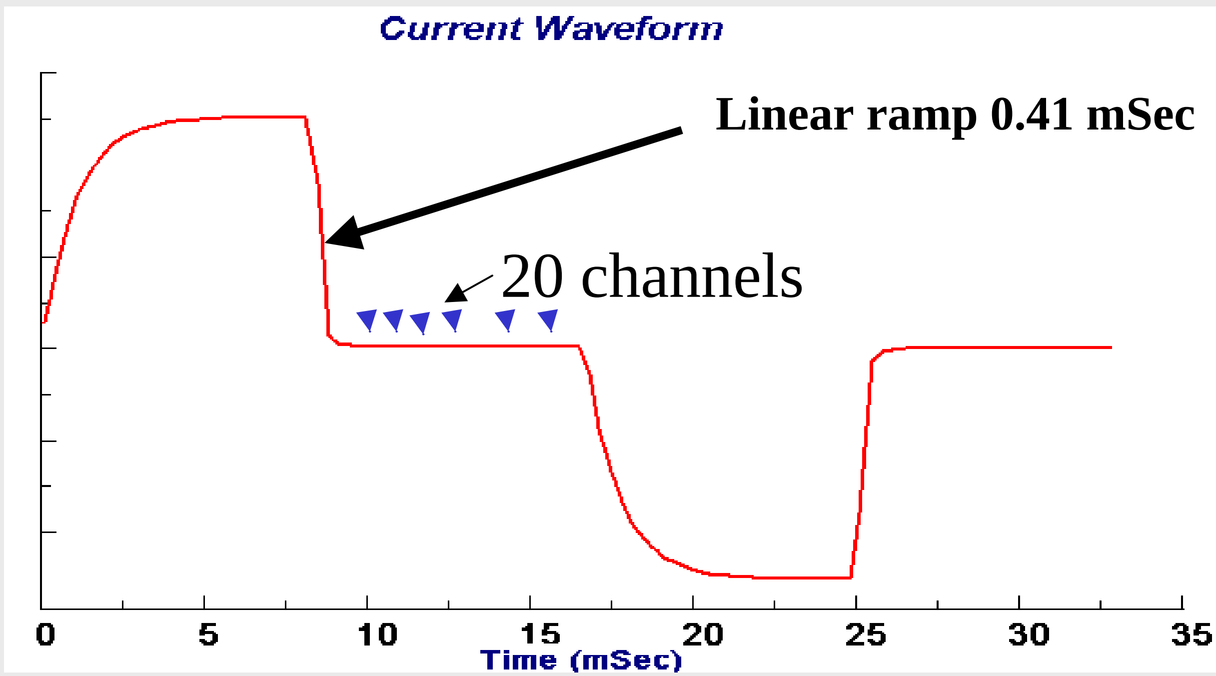
Approximate VS. General Modeling

	General	Approximate
Transmitter	Loop, Dipole	Loop
Receiver Location	Arbitrary	Center of loop
Current Waveform	Arbitrary	Impulse
Rx orientation	Arbitrary	Vertical
Time Channel	Off-Time On-Time	Off-Time
System Type	Airborne Ground Borehole	Ground

Forward Modeling- Example

Simulation of Geonics ground system

Bandwidth: from 30Hz to 190 KHz with lowpass



Forward Modeling- Examples

3-Layered Earth Model –large regional aquifer

from Fitterman and Stewart, 1986

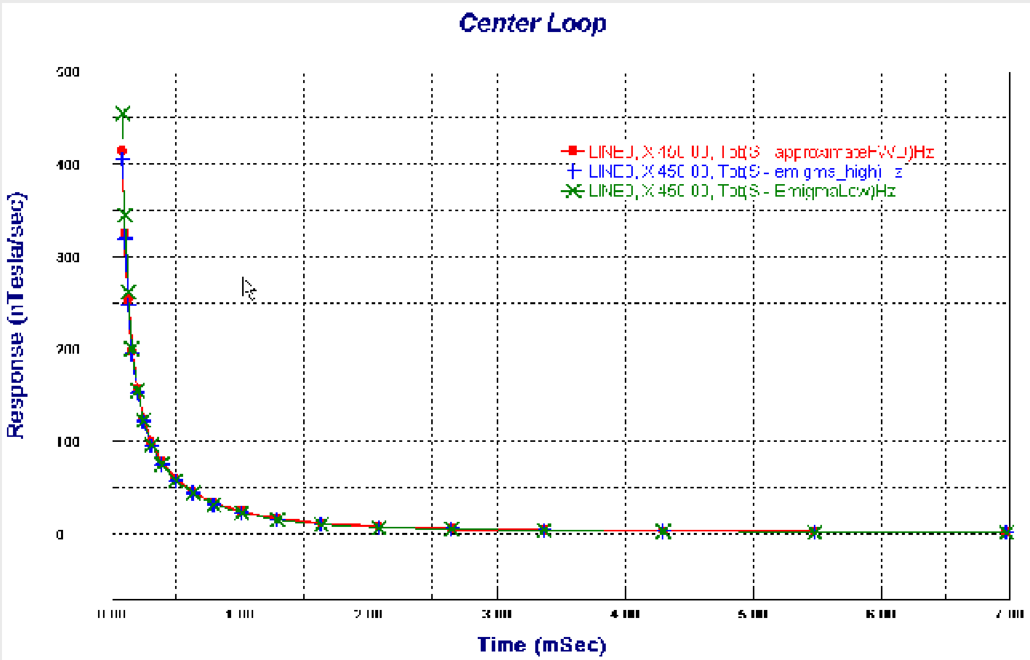
Basalt Cover: 1000 ohm*m — 400m

Sandstone aquifer: 100 ohm*m — 400m

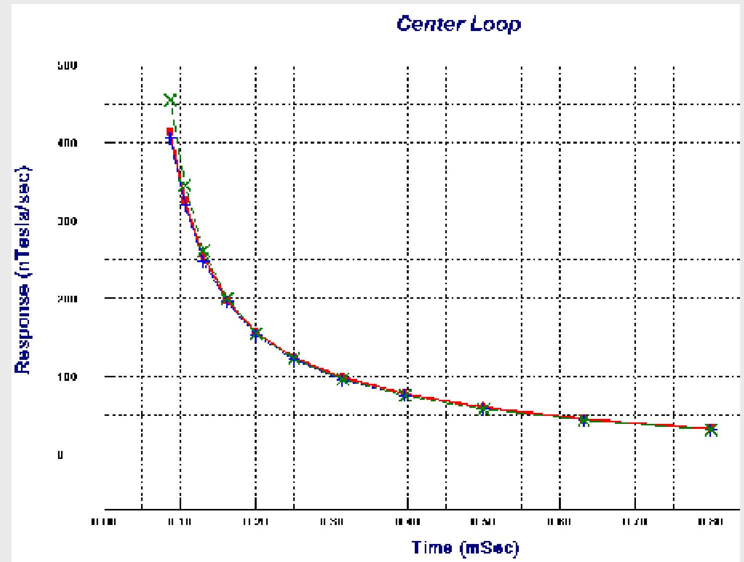
Sediments: 20 ohm*m

- **TX-RX Configuration**
  - **Transmitter: square loop 900m by 900m**
  - **2 stations: one inside loop, one outside loop**

Forward Modeling- Comparison



early time

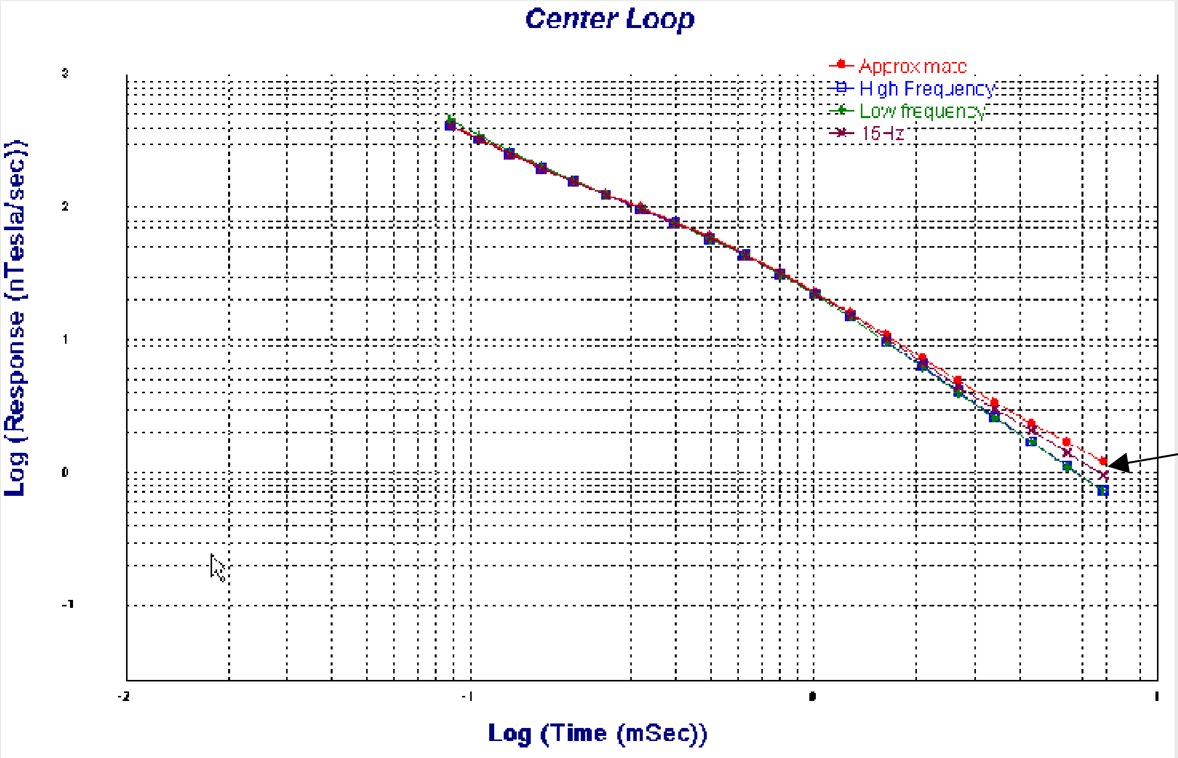


Red: Approximate **Blue: General up to 190KHz** **Green: General up to 19KHz.**

➢Increasing bandwidth with general method gives response at early time closer to response simulated by approximate method.

Effersø et al, 1999

Forward Modeling- Bandwidth



Energy at frequencies below system response?

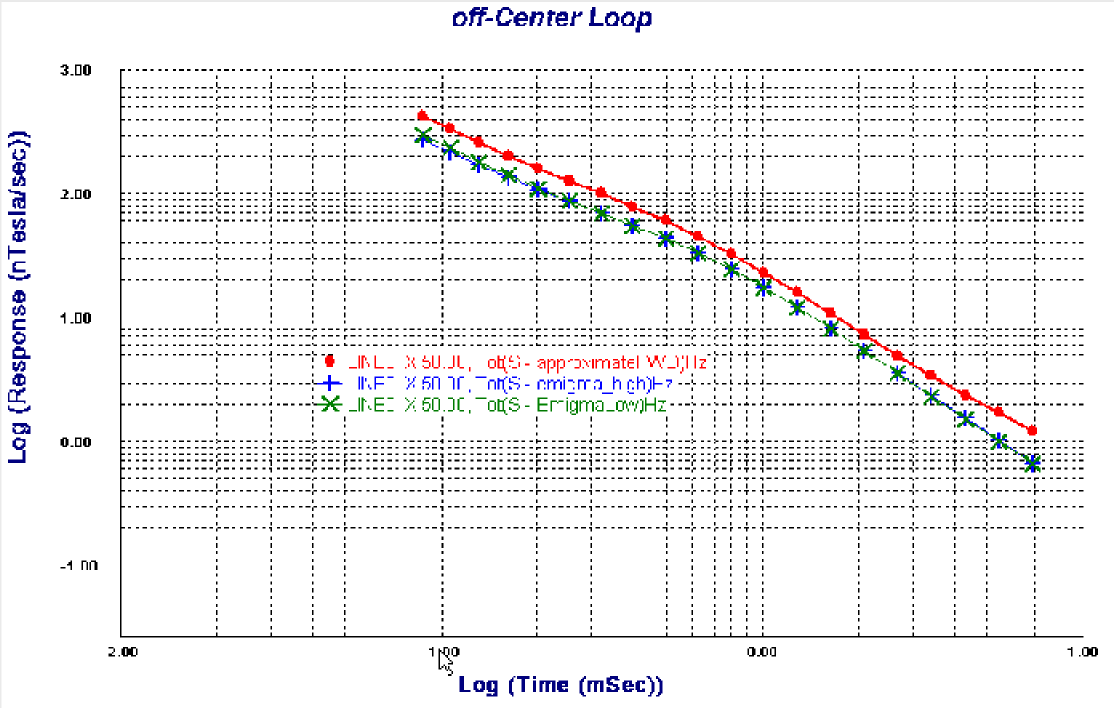
Red: approximate.

Blue: General up to 190KHz.

Green: General up to 19KHz.

Purple: 15Hz basefrequency

Forward Modeling- slightly off-centre



Red: approximate.

Blue: General up to 190KHz off center.

Green: General up to 19KHz off center

Inversion Techniques

Four methods encorporating Marquardt inversion and Occam's algorithm, and general/approximate forward simulation techniques

Method	Inversion Technique	Forward Modelling
1	Marquardt	General
2	Occam	General
3	Marquardt	Approximate
4	Occam	Approximate

- **Marquardt inversion: least-squares under parametrized**
- **Occam Inversion**
  - **Generates smooth resistivity function with respect to depth**
  - **can be over- parametrized**
  - **The resistivity is the inversion parameter – layer thickness constant**

Inversion Techniques-Synthetic Example

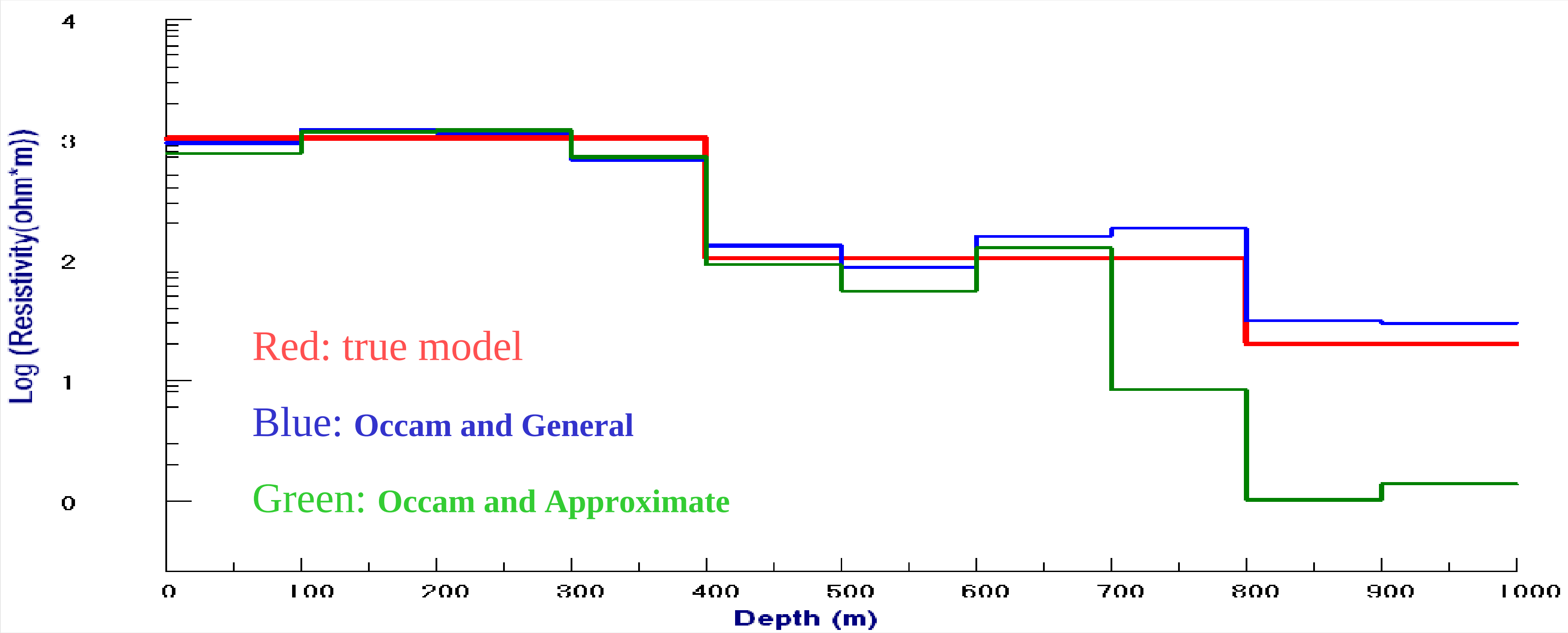
OCCAM Inversions to Synthetic data

- Occam +General and Occam+Approximate
- Synthetic data with bandwidth to 19KHz
- Gaussian random noise with 5% deviation added to data
- Invert 20 time off-time channels
- ½ space resistivity starting models

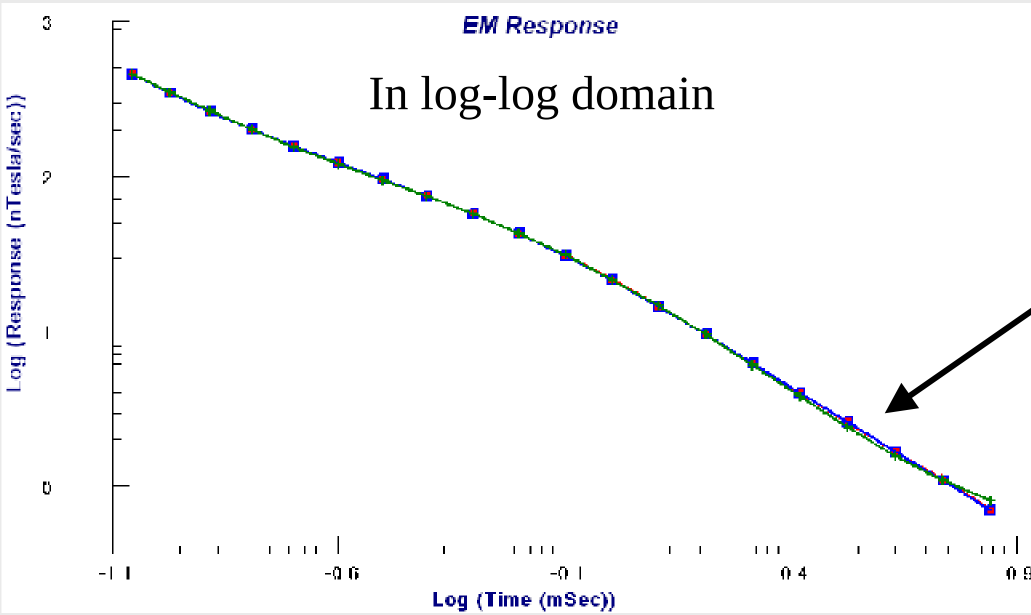
  with uniform layer thickness

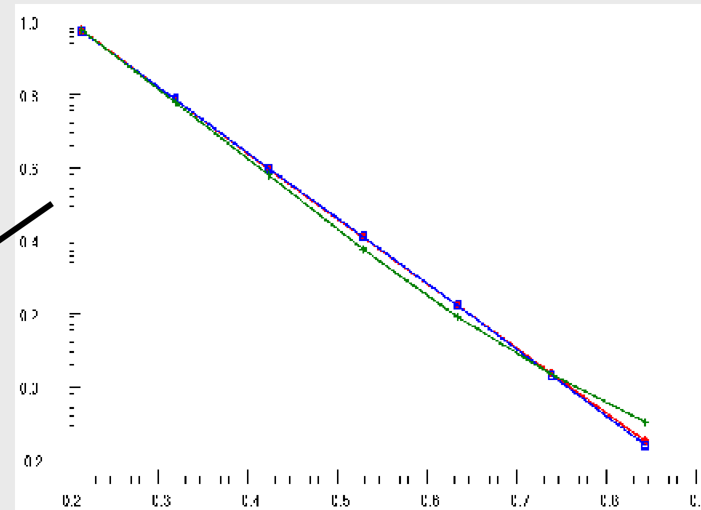
Inversion Techniques-in-loop

Method	Starting model			Constraint on	
	# Layers	**Resistivity** (ohm*m)	**Layer Thickness** (m)	**Resistivity** (ohm*m)	**Thickness** (m)
Occam and General	9 +base	100	100	1~2000	Fixed (100m)
Occam and Approximate	9 +base	100	100	1~2000	Fixed (100m)



Inversion Techniques-in-loop





Red: true data plus noise

Blue: Occam and General

Green: **Occam and Approximate**

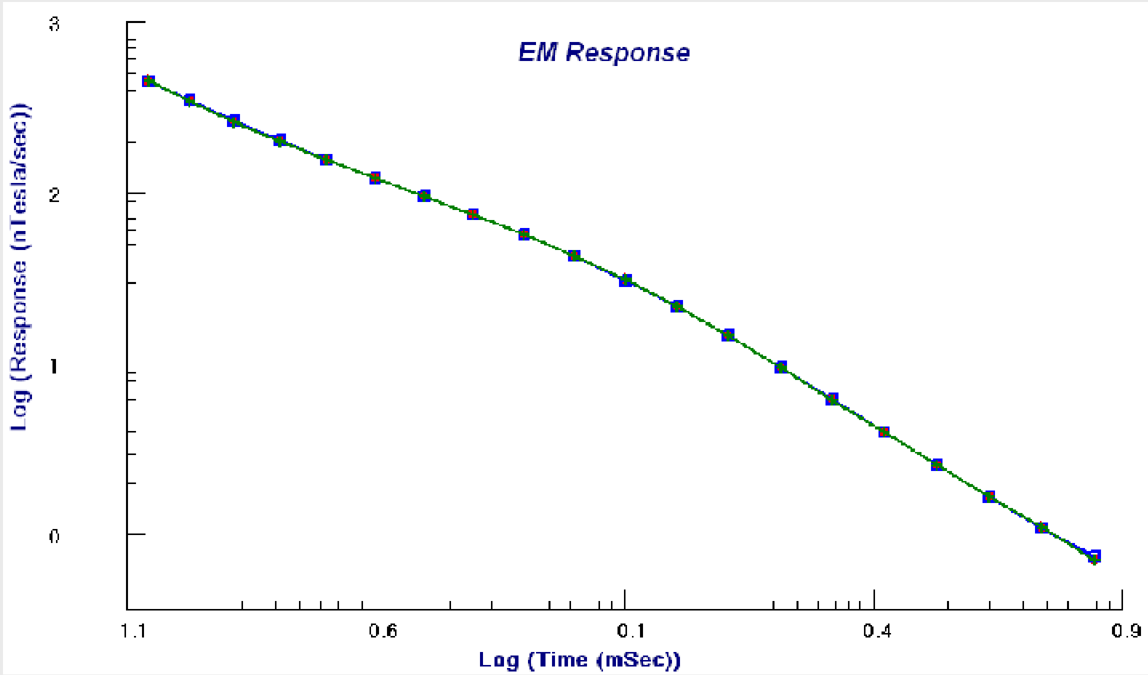
Blue fits depth to basement better than Green.

Inversion Techniques- Marquardt Inversions

Marquardt Inversions

- Synthetic data with bandwidth to 19KHz
- Gaussian random noise with 5% deviation added to data
- Run inversion on all 20 time channels

Inversion Techniques-in-loop



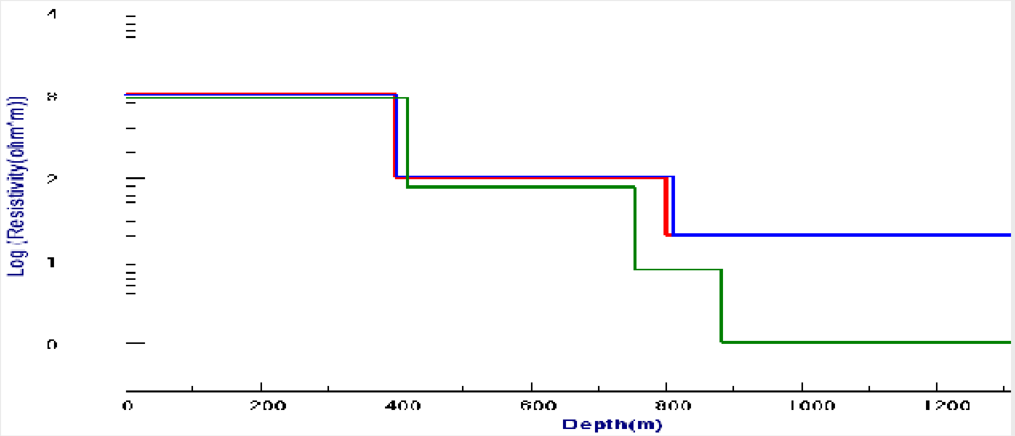
Red: true data plus noise

Blue: Marquardt and General

Green: Marquardt and Approximate

Inversion Techniques-in-loop

Method	Starting model			Constraint on	
	# Layers	**Resistivity** (ohm*m)	**Layer Thickness** (m)	**Resistivity** (ohm*m)	**Thickness** (m)
Marquardt and General	8	100	100	1~2000	1~1000
Marquardt **and Approximate**	8	100	100	1~2000	1~1000

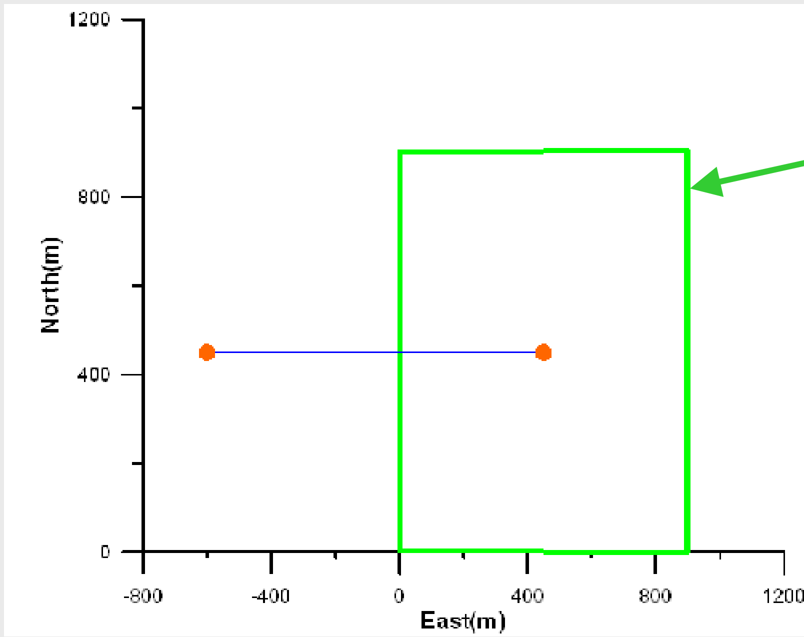


Red: true model

Blue: Inverted model using **Marquardt and General**

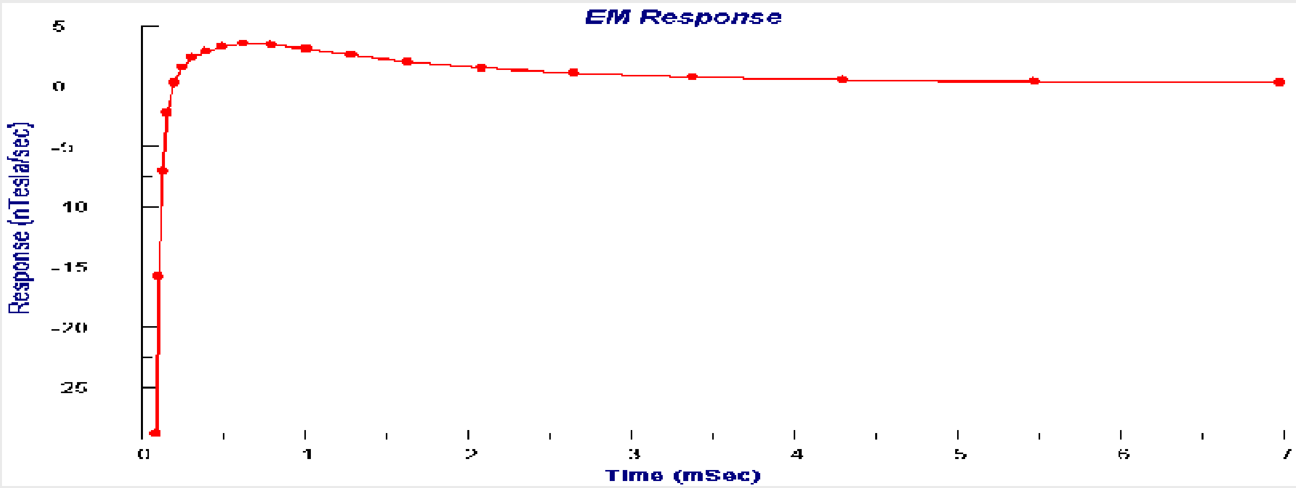
Green: Inverted model using **Occam and Approximate**

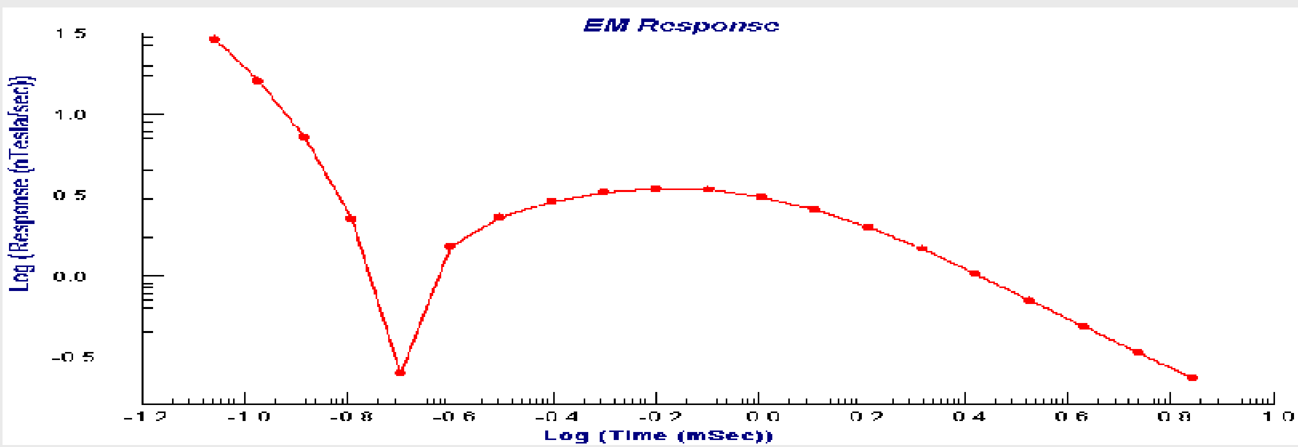
Inversion- Outside loop



TX Loop

Inversion- Outside loop





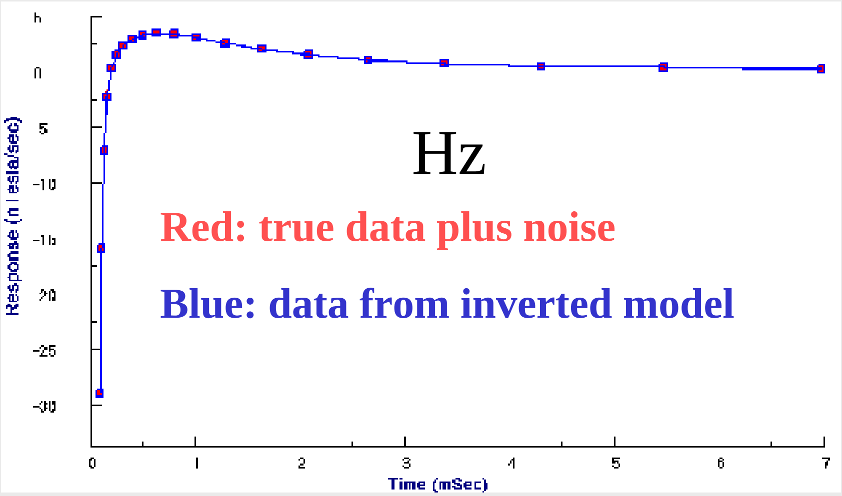
- ➢Hz at the station outside the loop
- ➢The response flips sign at early time

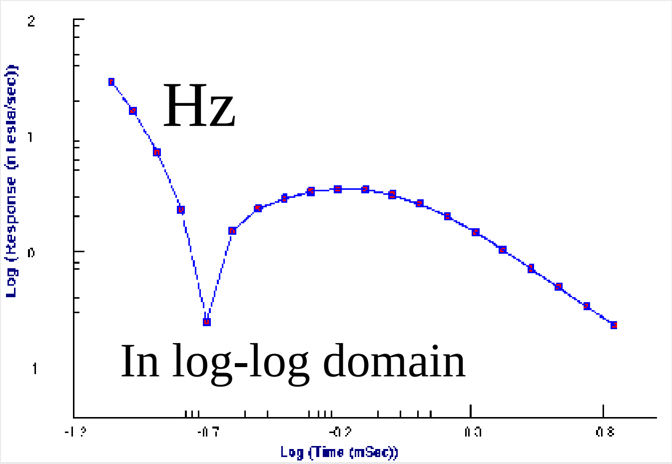
Inversion Techniques-Outside loop

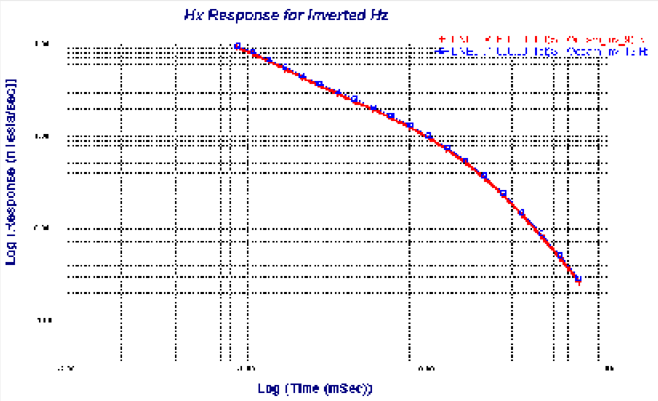
- Synthetic data by restricting the bandwidth within 19KHz
- Gaussian random noise with 5% deviation added to data
- Run inversion on all 20 time channels

Method	**Starting model**			**Constraint on**	
	# Layers	**Resistivity** (ohm*m)	**Layer Thickness** (m)	**Resistivity** (ohm*m)	**Thickness** (m)
Occam and General	9 +base	100	100	1~2000	Fixed

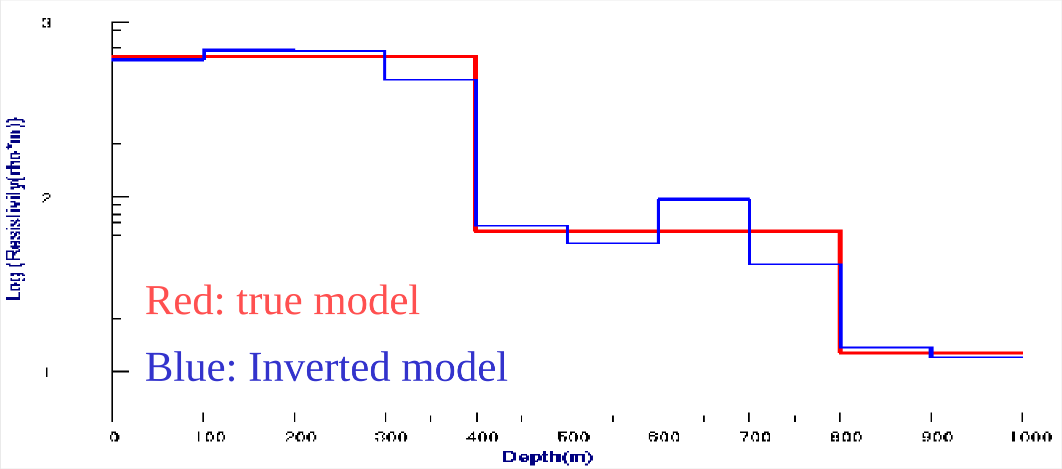
Inversion Techniques-Outside loop using Hz





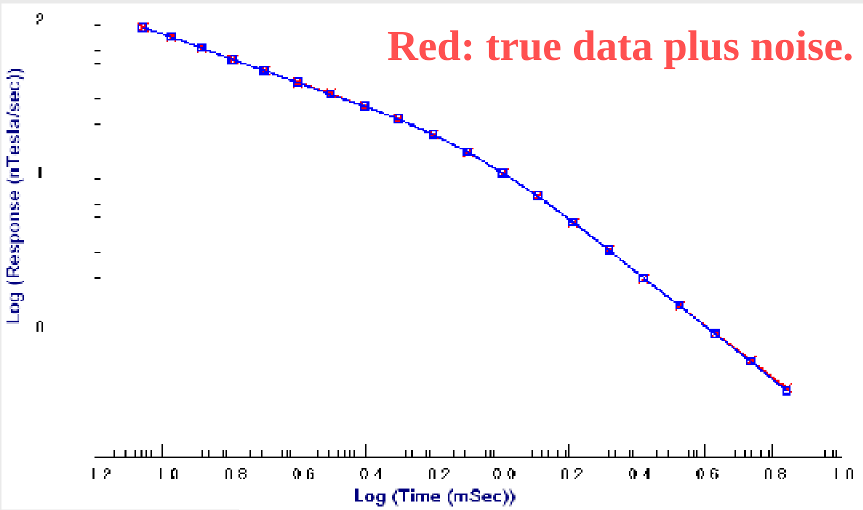


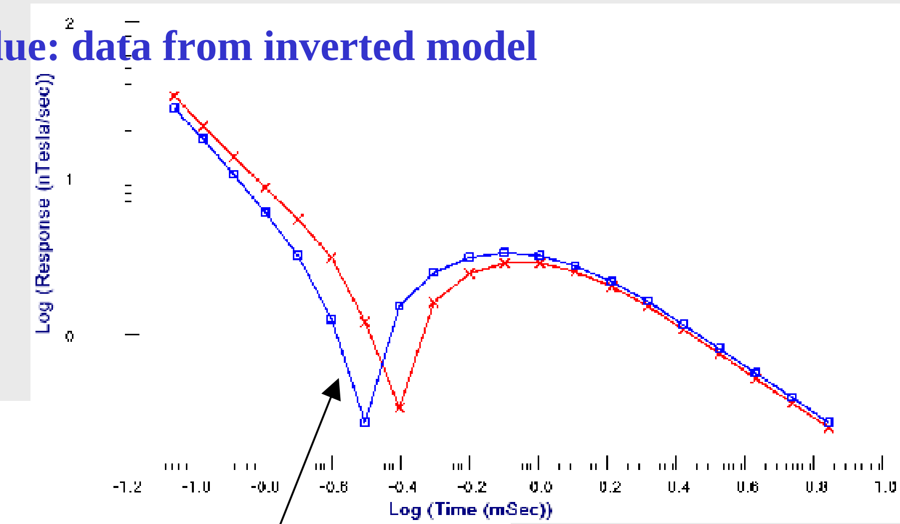
Hx fits to Hz model



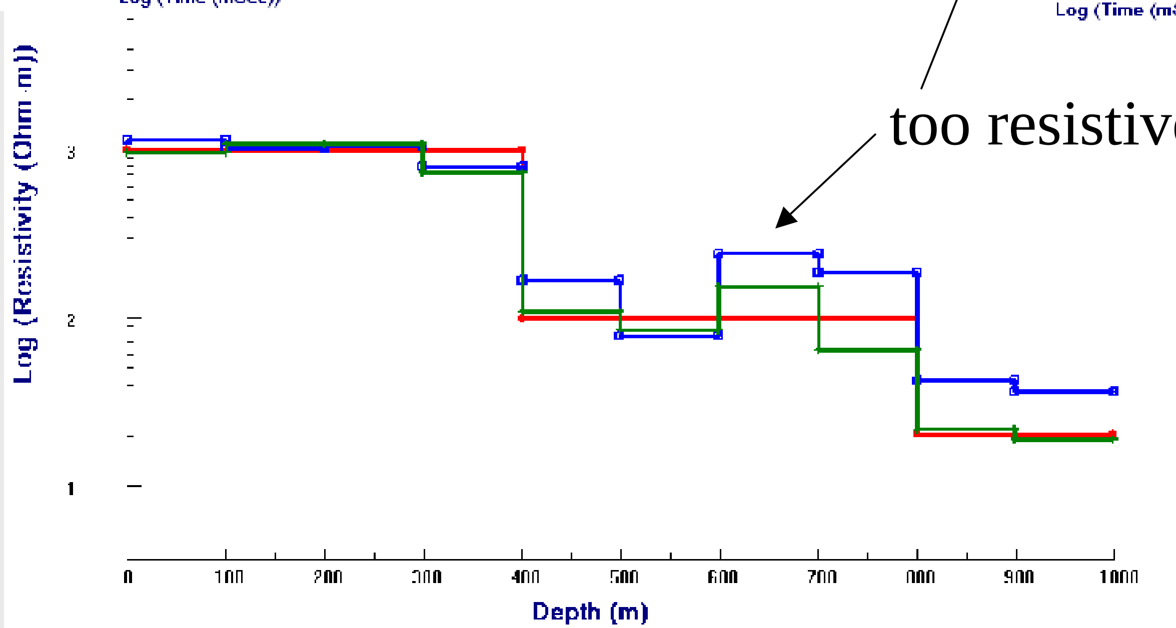
Inversion Techniques-Outside loop using Hx

Red: true data plus noise. Blue: data from inverted model





too resistive



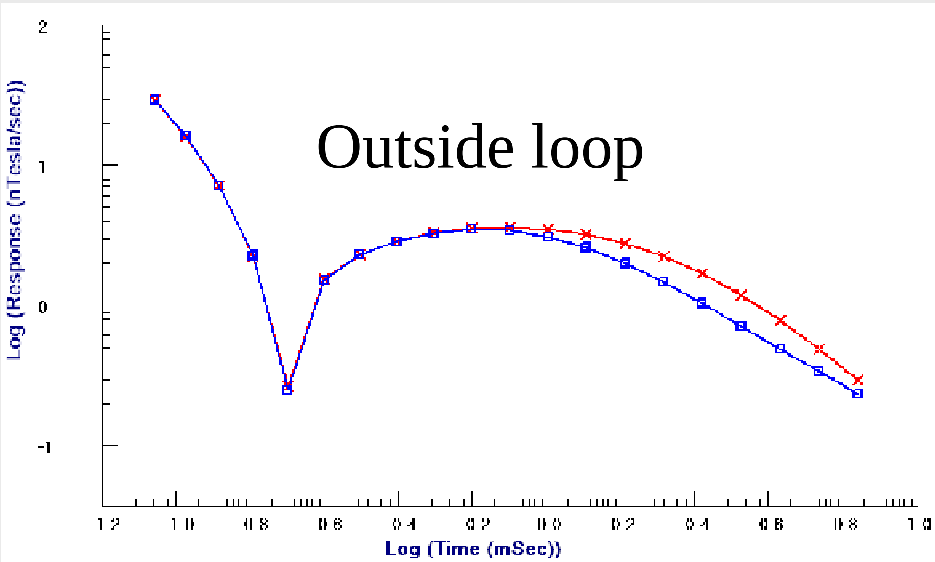
Red: True model. Blue: Inverted Hx . Green: Inverted Hz

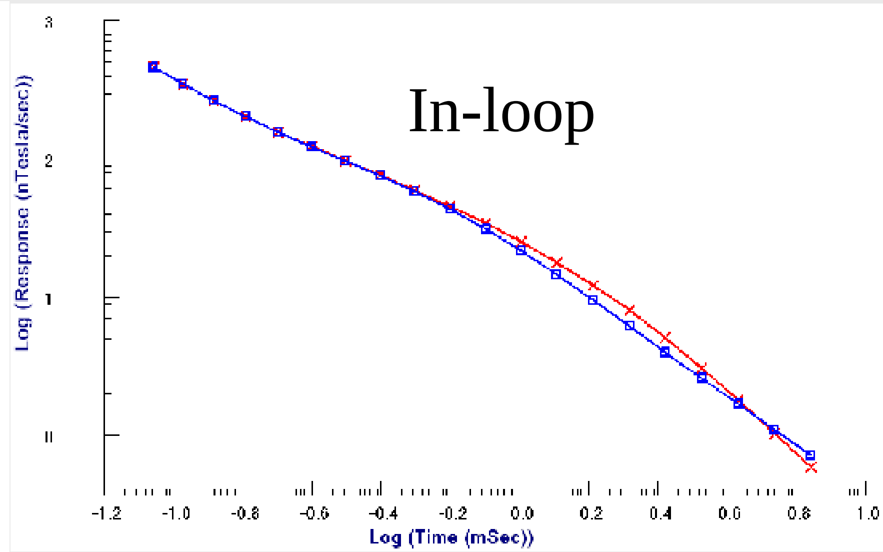
Inversion Techniques-Outside loop

3-Layered Earth Model

- Modification of previous model
- Mid-layer thicker

Inversion Techniques-Outside loop VS. in-loop

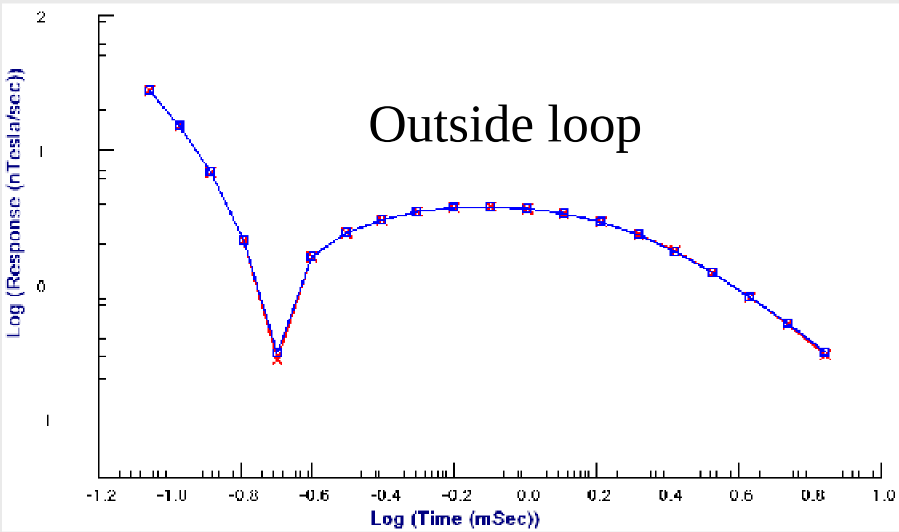


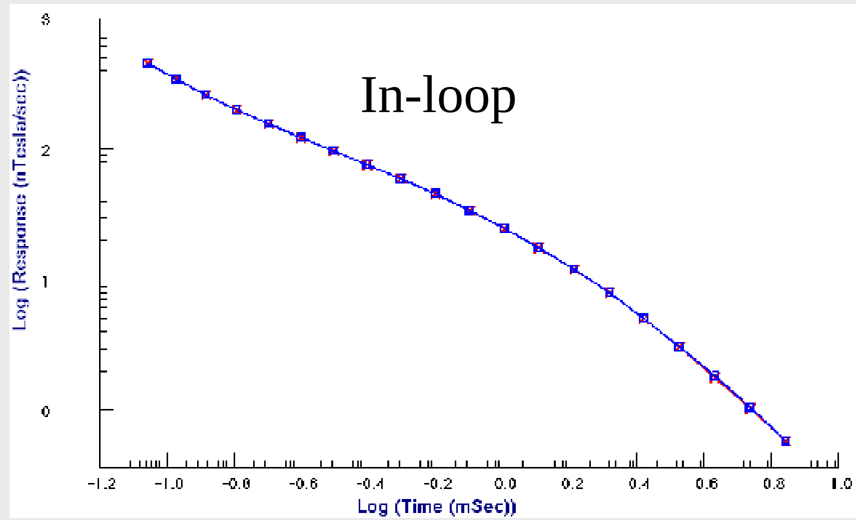


Red: thin mid-layer vs Blue: thick mid-layer

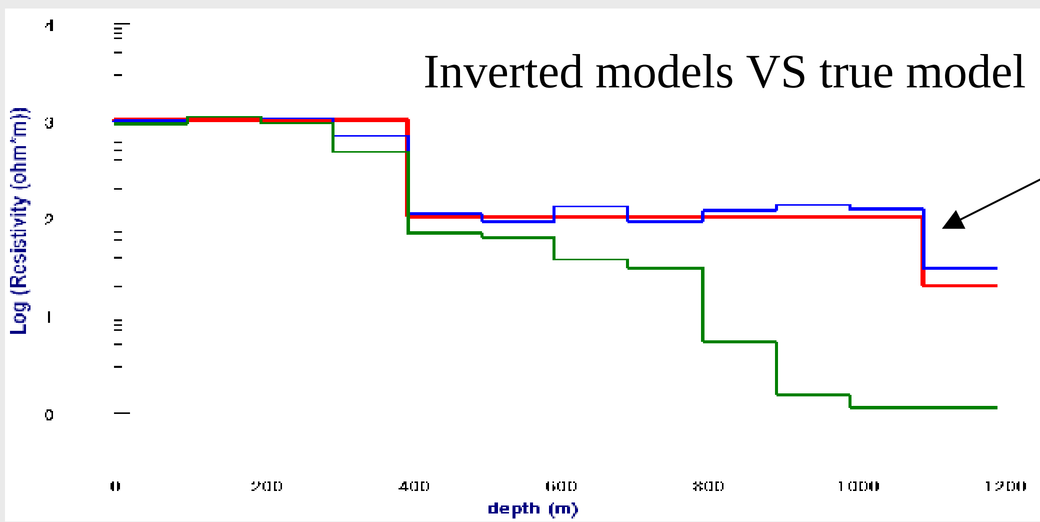
Method	**Starting model**			**Constraint on**	
	# Layers	**Resistivity** (ohm*m)	**Layer Thickness** (m)	**Resistivity** (ohm*m)	**Thickness** (m)
Occam and General	11 +BASE	100	100	1~2000	Fixed

Inversion Techniques-Outside loop





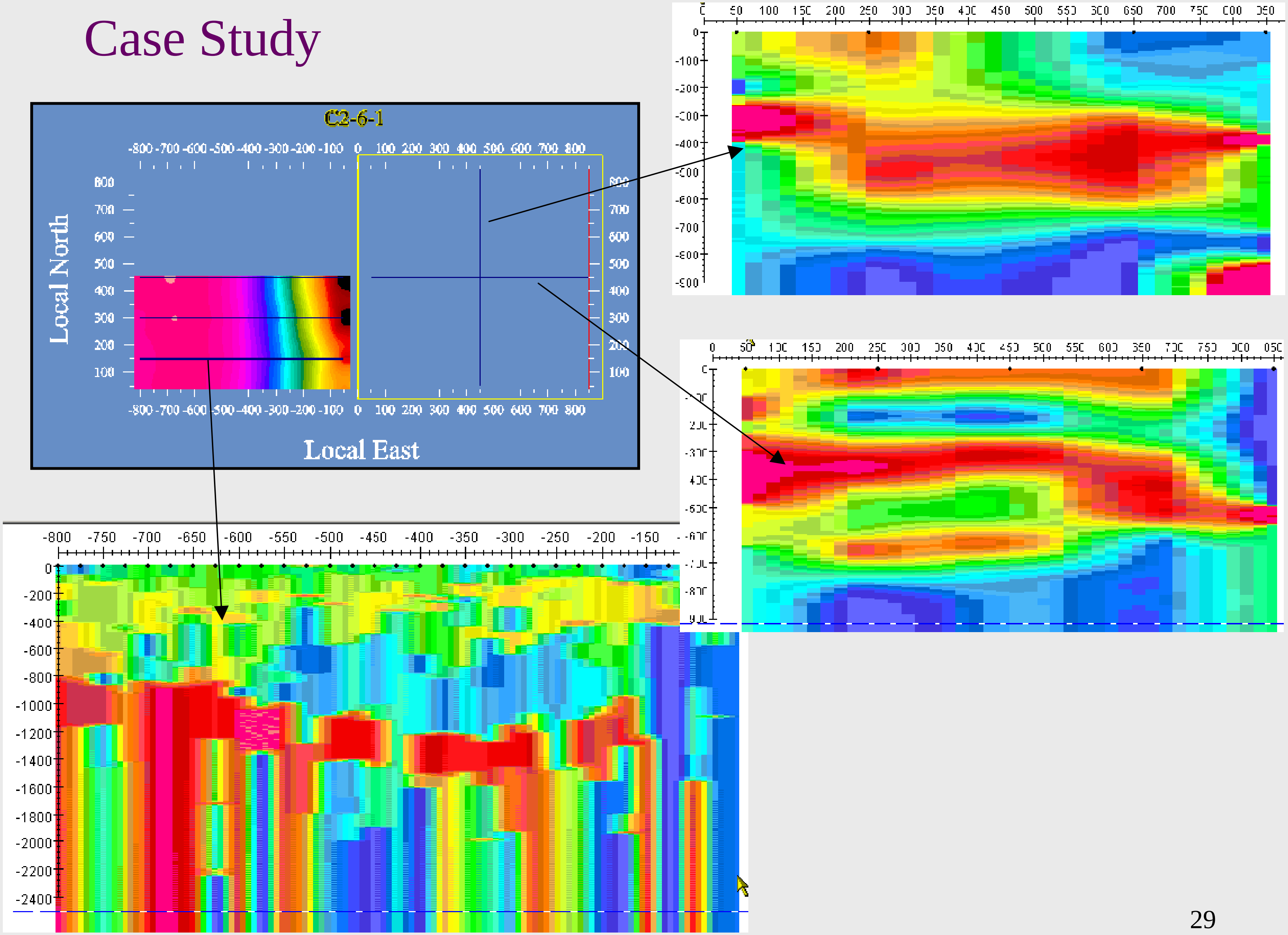
Red: true data plus noise. Blue: data from inverted model



Increased deep resolution

Red: true model. Blue: outside loop. Green: in-loop

Case Study



Conclusions

❖The use of a “general” technique for forward modeling allows the utilization of the complete range of layered forward modeling models and system waveforms

❖Reproducing all aspects of the data measuring system should be critically considered

❖Two inversion techniques utilizing general forward modelling can invert data collected by systems with various current waveforms and survey configurations with both on- and off-time data

❖The other two inversion techniques utilizing an approximate forward modeling tehcnique process only off-time vertical components of the coincident loop configuration
 - but are faster

Direction:

❖Inversion utilizing multiple components of data
❖Joint inversion of in-loop out-of-loop data
❖Joint inversion of resistivity and Cole-Cole parameters