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The Interferographic TEM Method (ITEM)

Beamforming for EM Geophysics Resolution Improvement

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Goals & Outline

Goals:

- Introduce a new concept for TEM surveys and analysis inspired by techniques from adjacent technical fields
- Show processing results illustrating resolution achieved for 2 structural models
- Make clear Why to do this

Outline:

1) Introduction
2) Background on Array Processing in Wave Propagation Techniques
3) Interferographic TEM (ITEM) Methodology
4) Imaging & Synthetic Tests
5) Inversion Comparisons
6) Resolution
7) Discussion and Conclusions

Top Level Overview

- Multi-Source – Multi-Receiver Methods [aka synthetic aperture (SA) and/or beamforming] are established in numerous technical fields such as radar (SAR), RF signal direction finding, radio astronomy, and medical imaging (spatial processing only)
- Interferographic TEM processes data with a space-time beamforming transformation
- Main benefit of ITEM beamforming is that it achieves significant synthetic compaction of EM field structure in subsurface, improving spatial resolution for buried targets
- Data acquisition consists of H profiles repeated for each of ~ 10 source positions
- Best applied with drones in semi-airborne TEM surveys (sources on ground surface)
- Our system for terrestrial application is called

  Drone-enabled Interferographic Transient ElectroMagnetics (DITEM)
- Multiple-source – multi-receiver TEM data sets are quickly analyzed to generate 2D images of electrical resistivity variations at depth
- However, it is expected that the greatest resolution gains will result from internalizing ITEM processing within 2D [3D] EM optimization software

My Background

1978 – B.Sc. Geology, University of Florida

1986 – Ph.D. Geophysics, Colorado School of Mines

1984-87 – USGS Geophysics Branch, Golden, CO

1987-97 – Self-Employed Geophysicist, Lakewood, CO

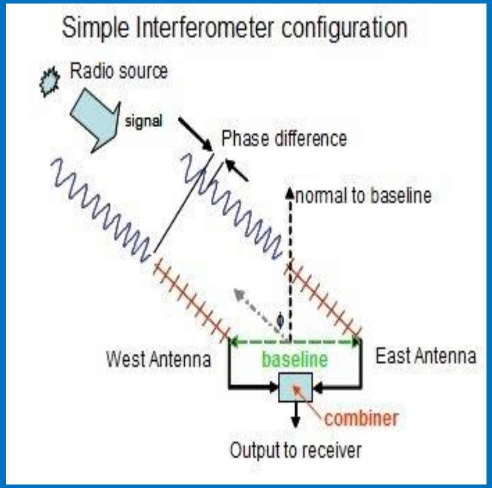
1997-2016 – In U.S. Defense industry

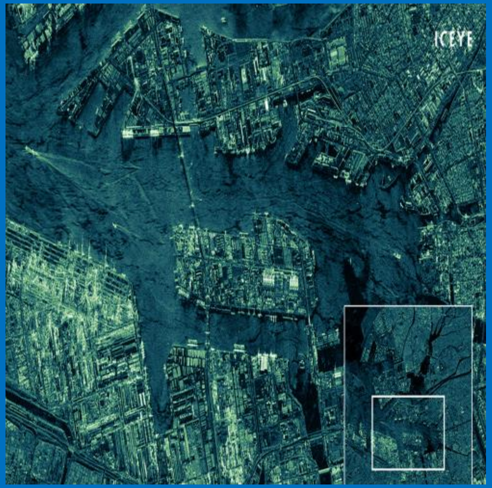
2016-Present – Semi-retired, return to EM geophysics (part-time)

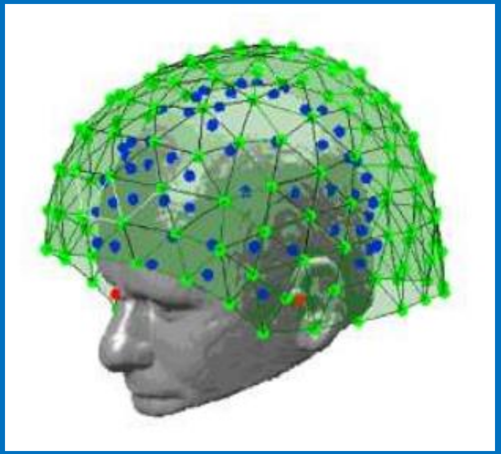
2020 – Formed Electromagnetic Geophysical Imaging Solutions, LLC

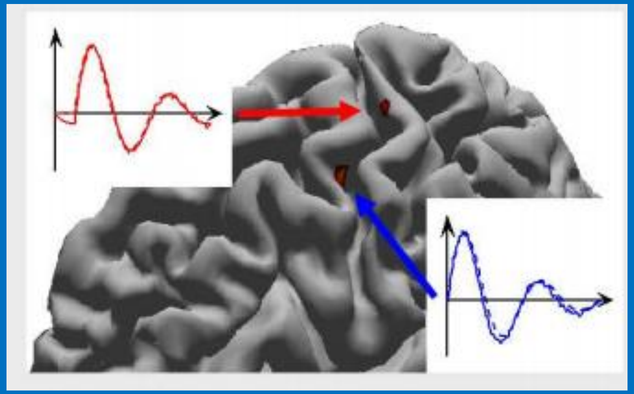
Background on Array Methods from Adjacent Technical Fields

- Interferometry used in defense industry SIGINT techniques & Radio Astronomy
- Synthetic apertures used in SAR, SIGINT, Sonar, GPR techniques
- Note that these are wave propagation problems
- Medical imaging – many varieties using host of robust techniques
- Specifically, brain imaging technique called Magnetoencephalogram (MEG) uses a beamforming approach that can be adapted for use in TEM geophysics



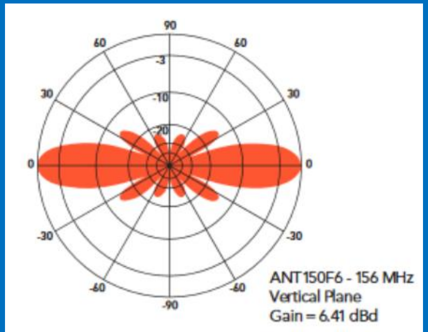






Synthetic Apertures: Wave Propagation

- Antenna Gain: increase or decrease in antenna radiation pattern compared to idealized isotropic antenna
  - Small antenna – low gain, wide beam
  - Large antenna – high gain, narrow beam



- Desired large antennas are often physically unrealizable

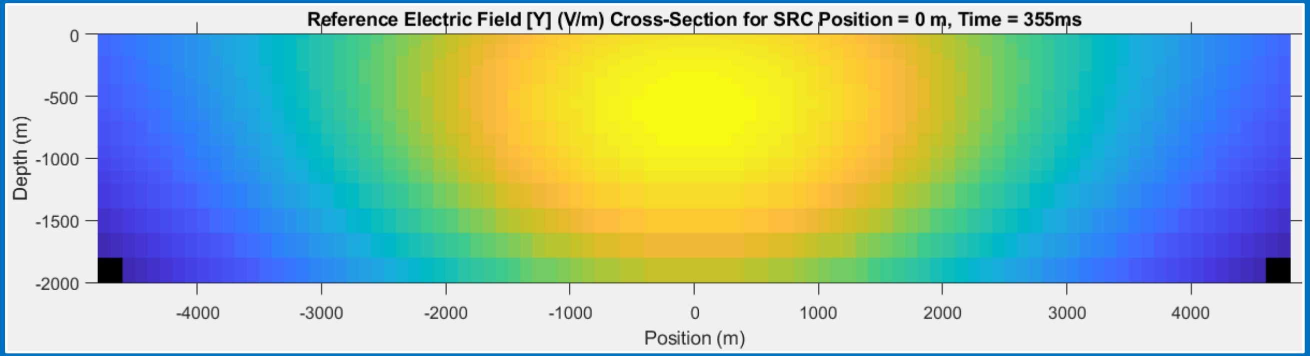
- The synthetic aperture concept uses multiple small antennas sequenced end-to-end; "combined" to form large antenna which provides effective beamforming

Prior Work with SAs in EM Geophysics

- Two PhDs (Fan,2011; Knaak, 2015) at Colorado School of Mines under Roel Snieder demonstrated that SAs can in fact be applied to EM geophysics
- They applied it in frequency domain marine CSEM context
- With use of a reference model, and frequency selection for a specific layer of interest, they showed signal enhancement achieved with SA for a potential pay zone
- Some antenna gain enhancement achieved, possibly slight narrowing of antenna beam pattern, not clearly specified
- Little to say on subject of spatial resolution
- Most recently improved and generalized by Tu and Zhdanov (2020); they do discuss spatial resolution, but mostly relative to original CSEM SA technique; use multiple frequencies for looking at different depth slices.

Synthetic Apertures: Diffusion

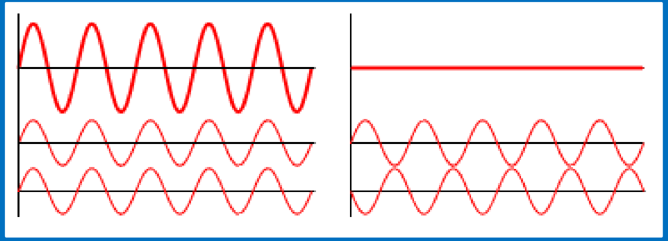
- The issue with applying SAs to TEM diffusion:
  - Signal sources are everywhere – there is no clear wavefront for time separation of returns from different parts of the medium
  - Only steady variation of signal sources vs. time that smears out response for a given location over a substantial time range, greatly overlapped with signal sources at other locations
  - In other words, highly mixed and overlapped information



- Can TEM data be unmixed, before analysis, and to what degree?
- SAR and Reflection Seismology processing do this unmixing well. TEM? Has received very little attention

Beamforming: A Different Focusing Concept

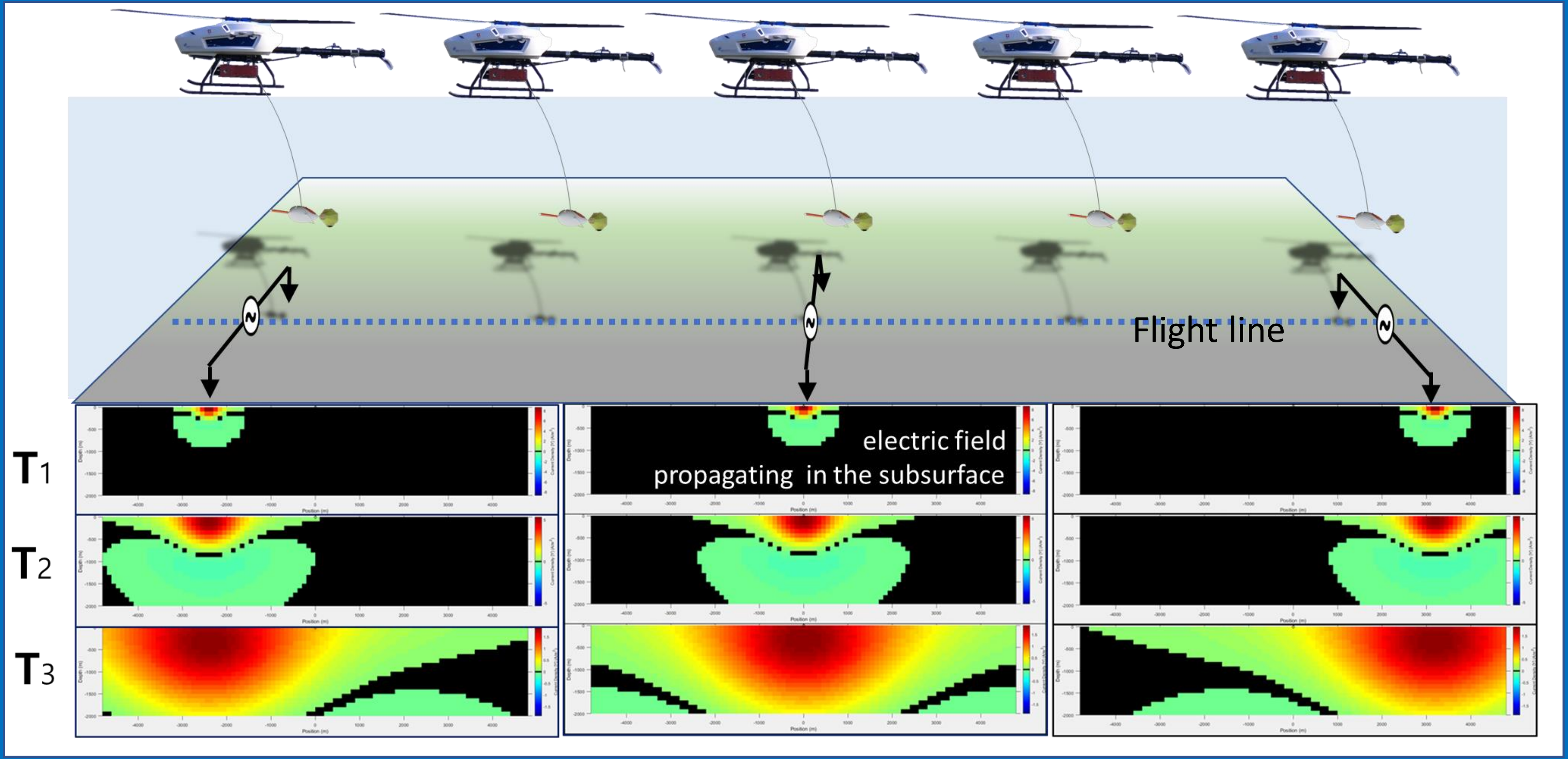
- In wave propagation, beamforming is specifically accomplished with SAs
- ➡ **Use Beamforming as the central focus for TEM diffusion rather than SA**
- ***Beamforming is achieved by interfering different field instances together to constructively add signals where desired and destructively cancel signals everywhere else***



- **The proposal**: For TEM use set of reference model subsurface E-field distributions for $\mathbf{N_S}$ source positions and $\mathbf{N_T}$ times (Time as a proxy for Z) as "basis functions" to construct synthetic impulsive E-field distributions in the subsurface
- Call this **Interferography** for the TEM diffusion case as opposed to interferometry for interference of waves, to avoid confusion

Interferographic TEM Method Overview

PROPAGATION OF THE ELECTRIC FIELD GENERATED BY MULTIPLE SOURCES

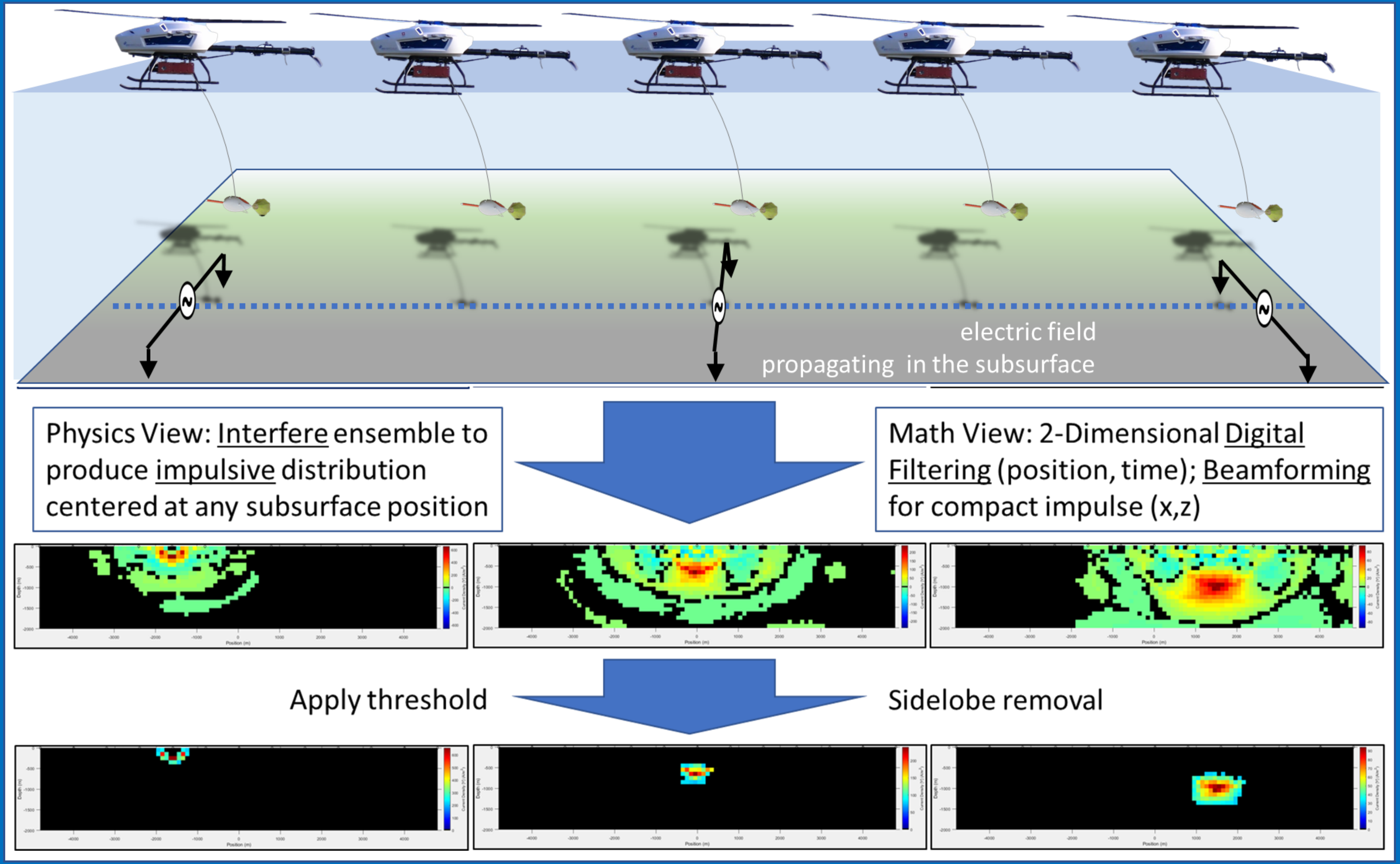


The magnetic field profile is flown in its entirety for each source position.

Typical survey:
~10 source positions,
3-4 decades in time, > 5 times/decade

Use all of the available reference model current sections (x_s,t) as basis functions (inputs to interference weight computations) to form subsurface electric field "impulses" (x,z).

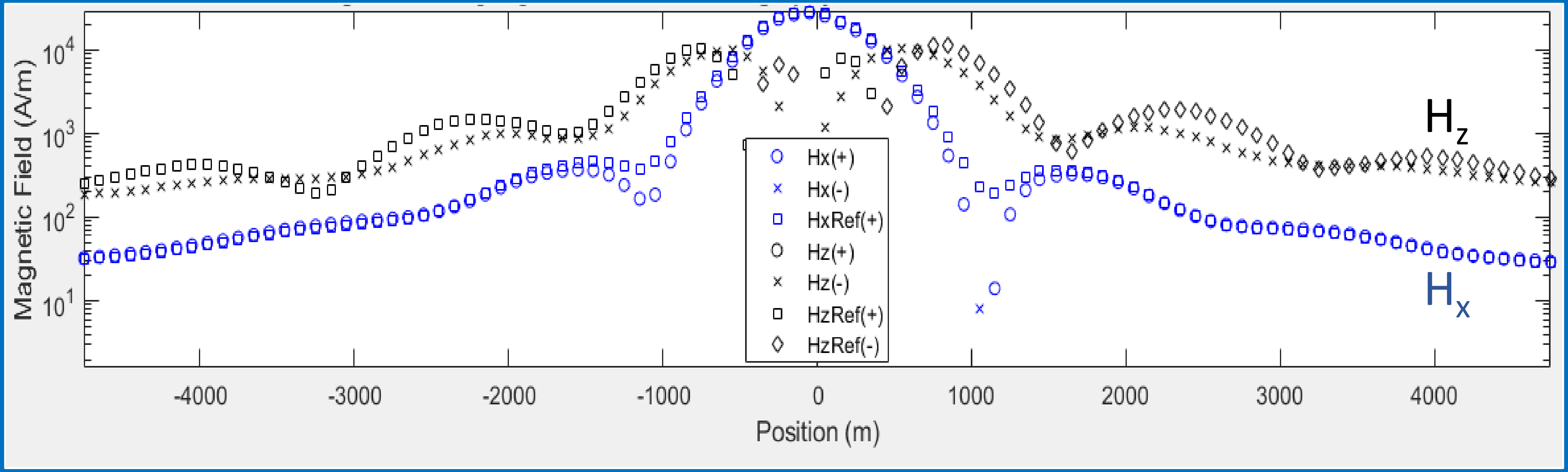
Interferographic TEM Method Overview



Synthetic concentration of electric field at every position in the subsurface promises resolution enhancement

Partial, but significant, unmixing of TEM fields achieved.

Interferographic TEM Method Overview



The weights calculated to produce reference model electric field spatial impulses on a subsurface grid are also applied to acquired and reference model magnetic field profiles. The magnetic field profiles also display a main lobe and additional sidelobes.

Transformed H profiles (reference & data) associated with single transformed electric field distribution in subsurface. [Repeat for all grid element positions.]

ITEM Method

Problem Formulation (2D Case)

$E_y{}^*(x,z;\, x^*,z^*) = w(x_s,t;\, x^*,z^*) \cdot E_y(x,z;\, x_s,t)$

w is set of beamformer weights. Solution for weights to achieve impulsive distributions uses *Lagrange Multipliers* method.*

The solution for the weights has the matrix form:

$\mathbf{w} = \mathbf{C}^{-1}\,\mathbf{E} \,/\, \mathbf{E} \cdot \mathbf{C}^{-1}\,\mathbf{E}$, where **C** is the covariance matrix of all E_y sections (x_s,t)

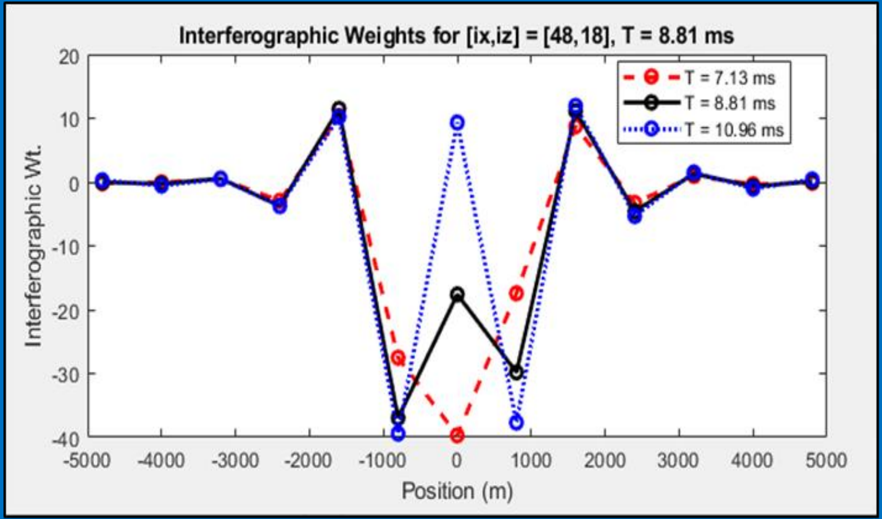
This is called a *Linearly Constrained Minimum Variance* (LCMV) *Beamformer*

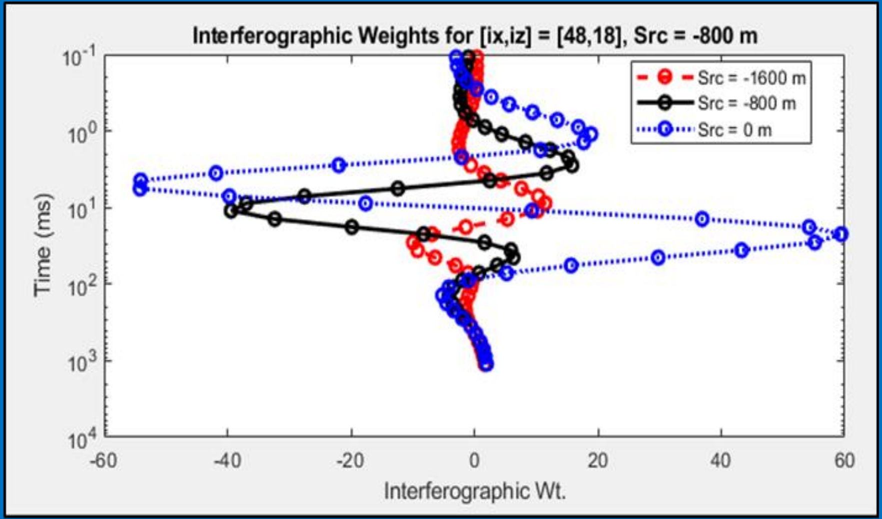
The weights are the recipe for how to interfere all of the original electric field distributions together to form an impulsive distribution centered on each grid element.

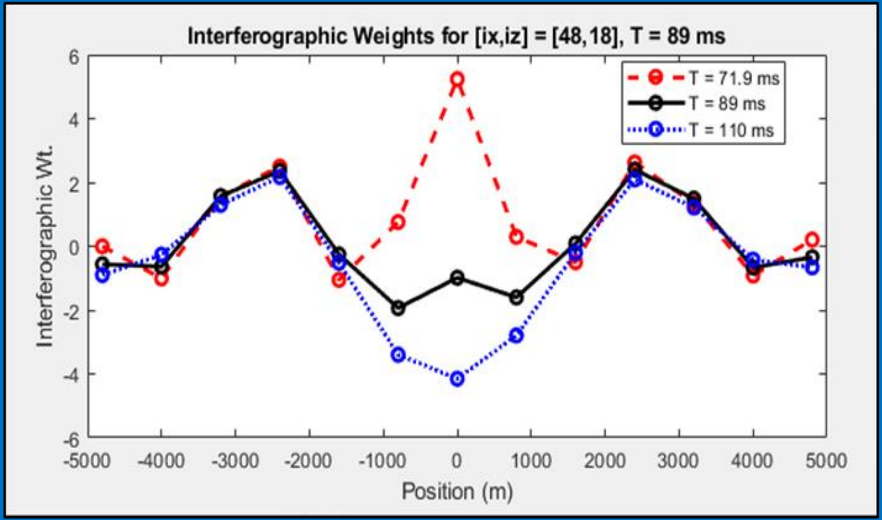
* See Armin Fuchs paper on MEG Beamforming for complete derivation of **w** (functionally identical)

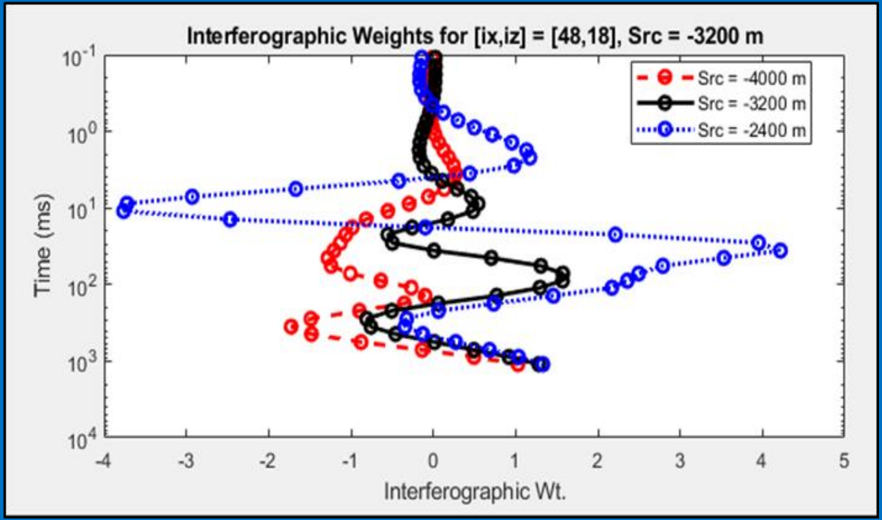
Beamforming Example - Weights

Results for a single element at position x ≈ 0m, z = 650m, using 13 Sources & 41 Times





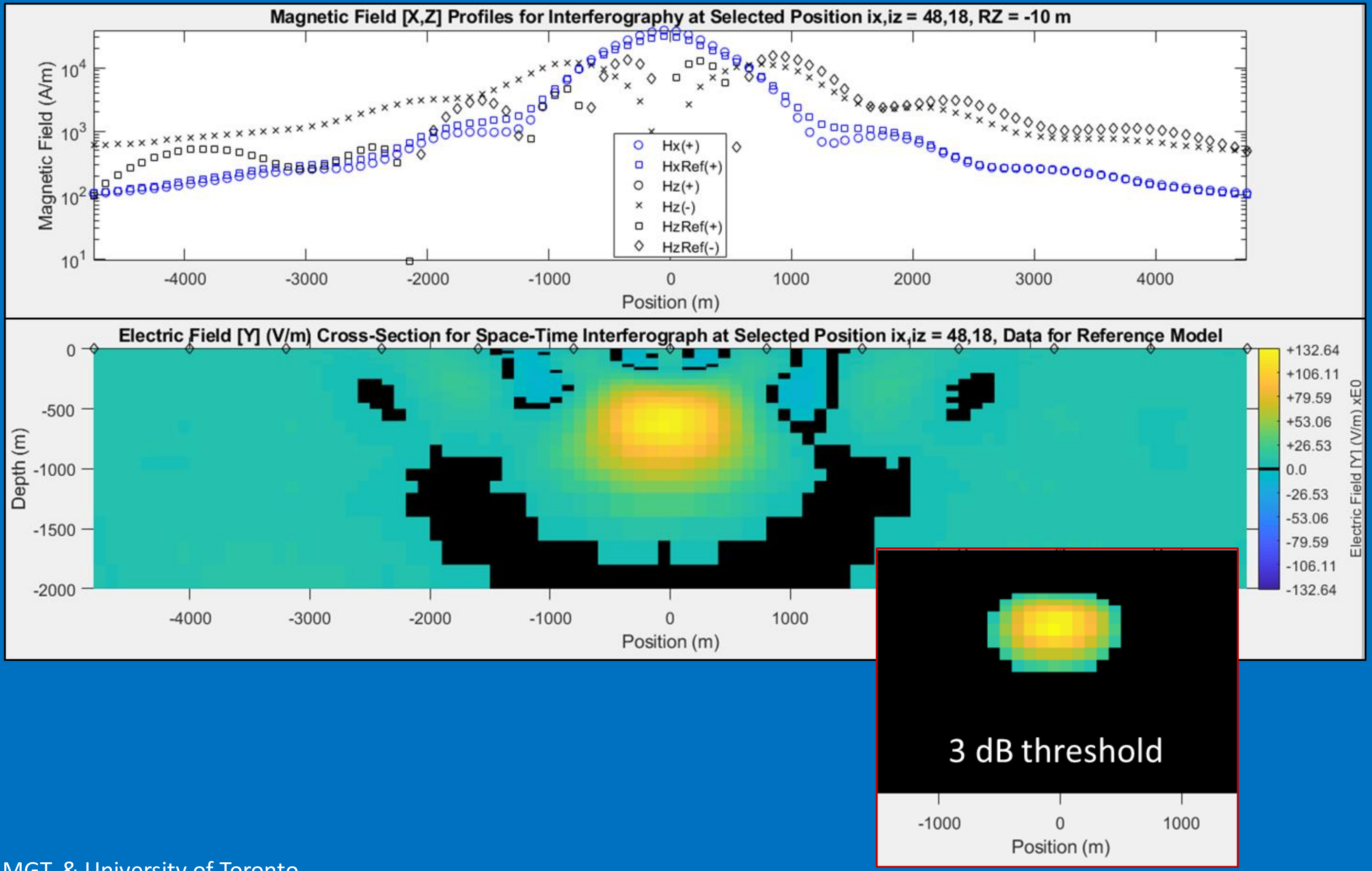




The variation of weights as a function of both source and time form a source-space & time digital filter. The entire set achieves constructive and destructive interference among the input E distributions to create a synthetic impulsive distribution output for each and every grid cell location.

Beamforming Example – EM Fields

Results for a single element at position x ≈ 0m, z = 650m, using 13 Sources & 41 Times

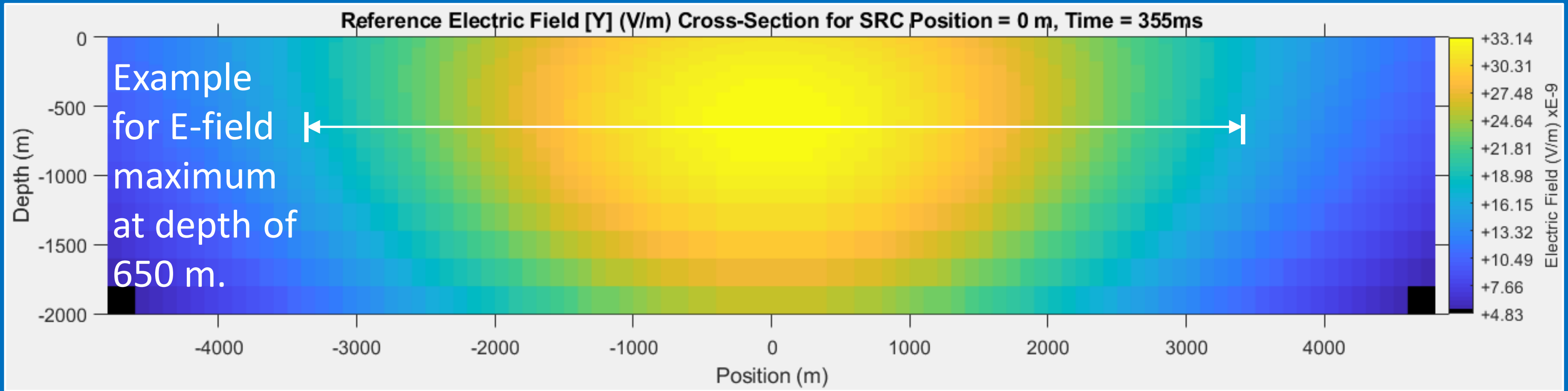


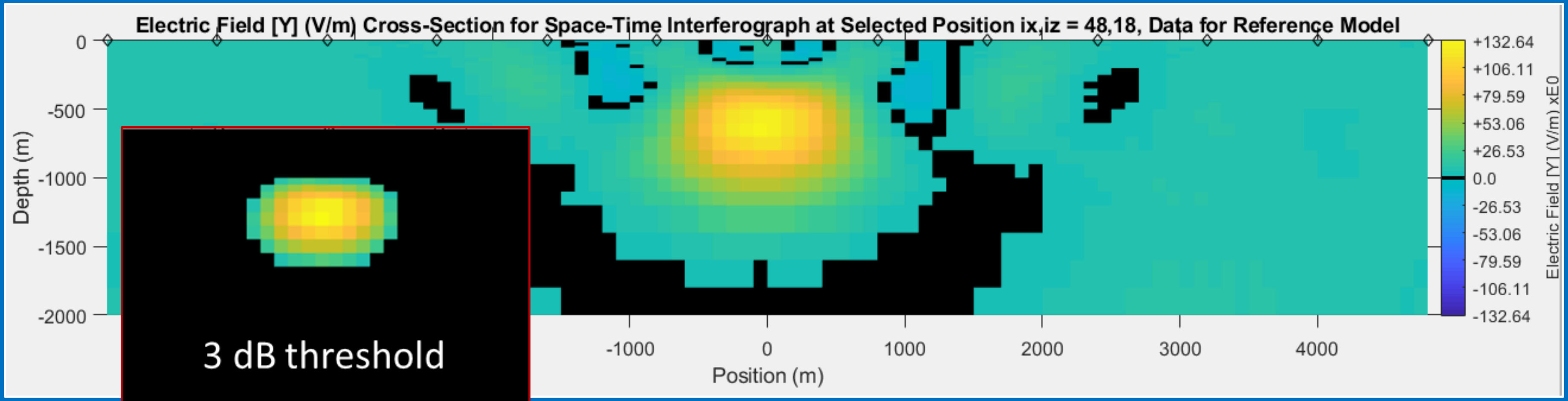
The output subsurface electric field is a compact impulsive distribution surrounded by low amplitude 2D sidelobes. Thresholding is done to remove these sidelobes.

The magnetic field profiles (above) are likewise transformed into impulsive shape.

Comparison of Original & Synthetic Interferographic Distributions

ITEM Method





Establish degree of E-field compaction using ½ amplitude (3 dB) thresholds

Compaction Factors

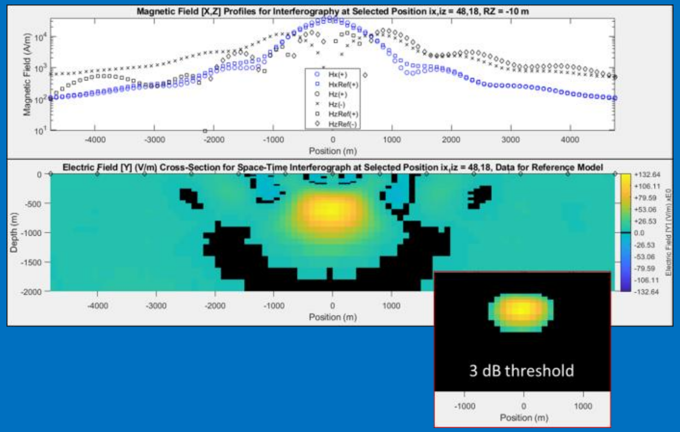
Depth	Factor
87.5m	~2.5
325m	~4
650m	~6
950m	~7

How much resolution improvement can be achieved from this degree of compaction?

Reduction in "spatial bandwidth" also implies processing gain is achieved.

Okay, What do we do from here?

- The Interferographic calculations alone do not give us a geoelectric product, only filtered E_y distributions (reference model) and filtered H_x profiles (reference model and acquired data)



- **Two ways to go from here:**

1) Use beamforming results to directly develop a resistivity image section
2) Internalize the Interferographic processing into 2D/3D optimization SW
    - Likely this is the eventual best path, providing the greatest resolution improvements, but this eventual capability lies in the future

Imaging with TEM Interferographic Products

Observations for 2D Case:

- After Interferographic processing: filtered E_{yf} distributions and H_{xf} profiles
- Each E_{yf} distribution, in 2D case only, represents a bundle of long filaments perpendicular to the vertical plane (y-direction)
- The H_{xf} profiles are nearly symmetric across the element position and optimally coupled to these y-directed filaments; H_{zf} instead is anti-symmetric with a zero crossing over the element position (will not use these)
- As a first order approximation, the ratio of $H_{x,acq}$ to $H_{x,ref}$ varies directly with the conductivity difference of the element (bundle) associated with it; this relationship will gradually fail as the ratio departs more and more from unity
- This is the basis of a fairly straightforward ITEM resistivity imaging algorithm

ITEM Image Formation Process (IFP) [1]

1) For each set of filtered (= interferographic result) acquired and reference H profiles, $H_{xf,acq}$ and $H_{xf,ref}$, for any subsurface filtering location (*ix,iz*), a simple normalized residual is, where the (*kx,kz*) grid denotes the filtering output domain,

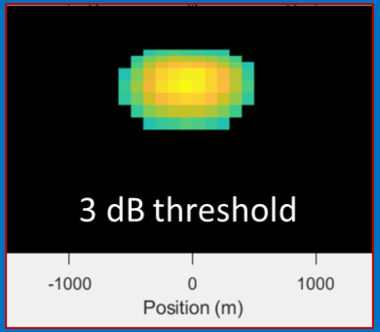
$$H_{resid}(kx) = [\ H_{xf,acq}(kx) - H_{xf,ref}(kx)\ ] \,/\, H_{xf,ref}(kx), \text{ for every } (ix,iz)$$

- H_{resid} values can be + or -.

2) Compute 2 estimates of summed E-field of each element in subsurface using $H_{resid}(kx)$ and the filtered $E_{yf,ref}(kx,kz)$ distribution, for every (*ix,iz*). The filtered E-fields have very limited non-zero range in (*kx,kz*) after thresholding. So any given element in (*kx,kz*) will have non-zero values in a small number of impulsive distributions in close proximity to that cell. Two accumulators are defined as

$$A_E(kx,kz) = \textstyle\sum_{ix} \sum_{iz} E_{yf,ref}(kx,kz), \text{ and}$$

$$A_R(kx,kz) = \textstyle\sum_{ix} \sum_{iz} [E_{yf,ref}(kx,kz) \cdot H_{resid}(kx)]$$



ITEM Image Formation Process (IFP) [2]

3) Ratio the two accumulators

$$\Delta j(kx,kz) = A_R(kx,kz) \,/\, A_E(kx,kz)$$

- *Δj* (y-directed for 2D case) is estimated change in current in each subsurface cell relative to the reference case
- *Δj* can be **+**, indicating higher conductivity σ (lower resistivity ρ), or **-**, indicating lower σ (higher ρ).

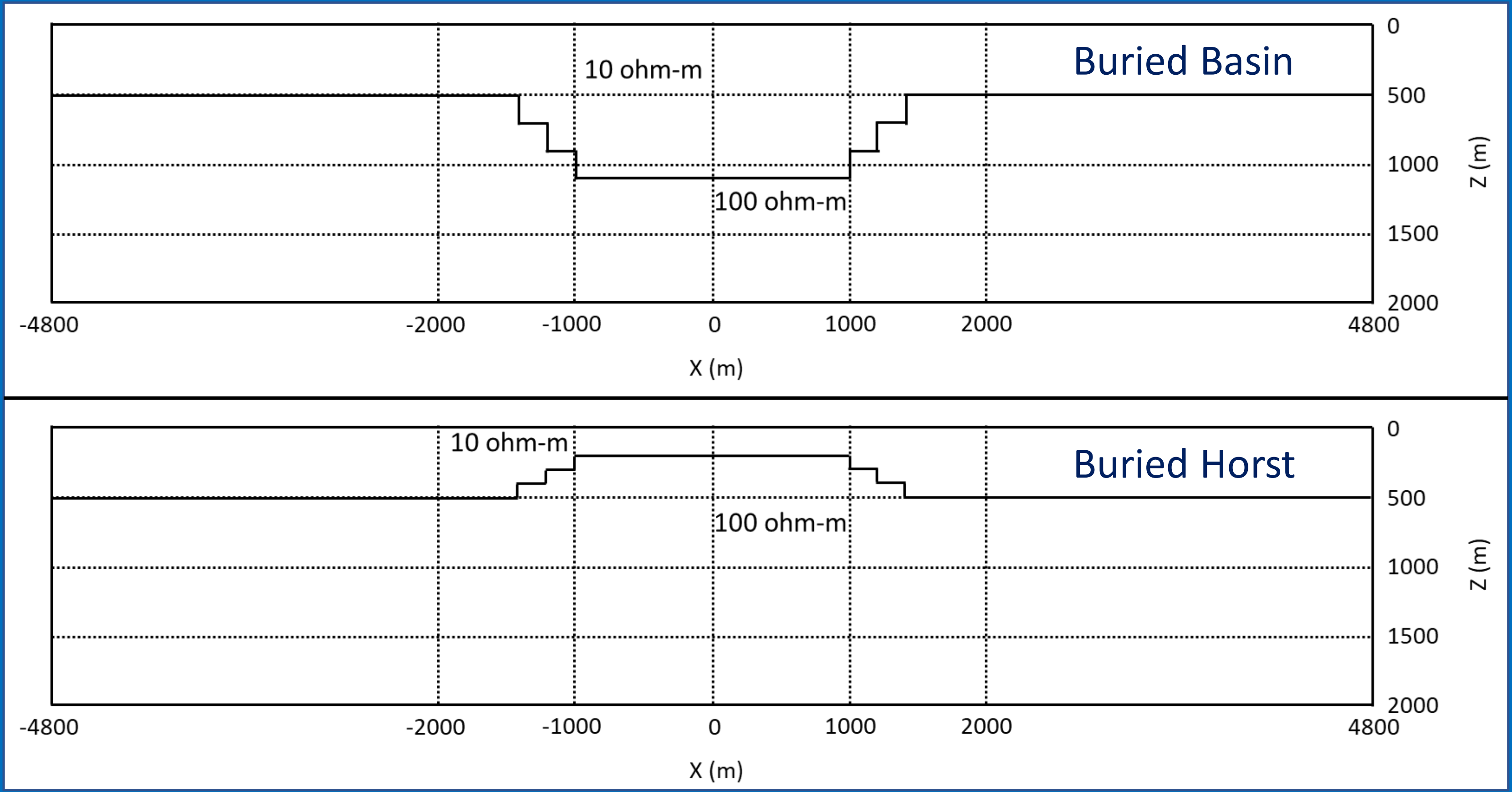
4) A resistivity estimate for a cell (*kx,kz*) is given by

$$\rho_{est}(kx,kz) = \rho_{ref}(kx,kz) \,/\, (1 + \Delta j(kx,kz)), \quad \Delta j > -0.8628,$$

$$\rho_{est}(kx,kz) = \rho_{ref}(kx,kz) \,/\, 10^{\Delta j(kx,kz)}, \quad \Delta j \leq -0.8628$$

- Mostly linear but for *Δj* values increasingly negative the mapping is nonlinear

Numerical Models for Testing



Simulated Survey Parameters:

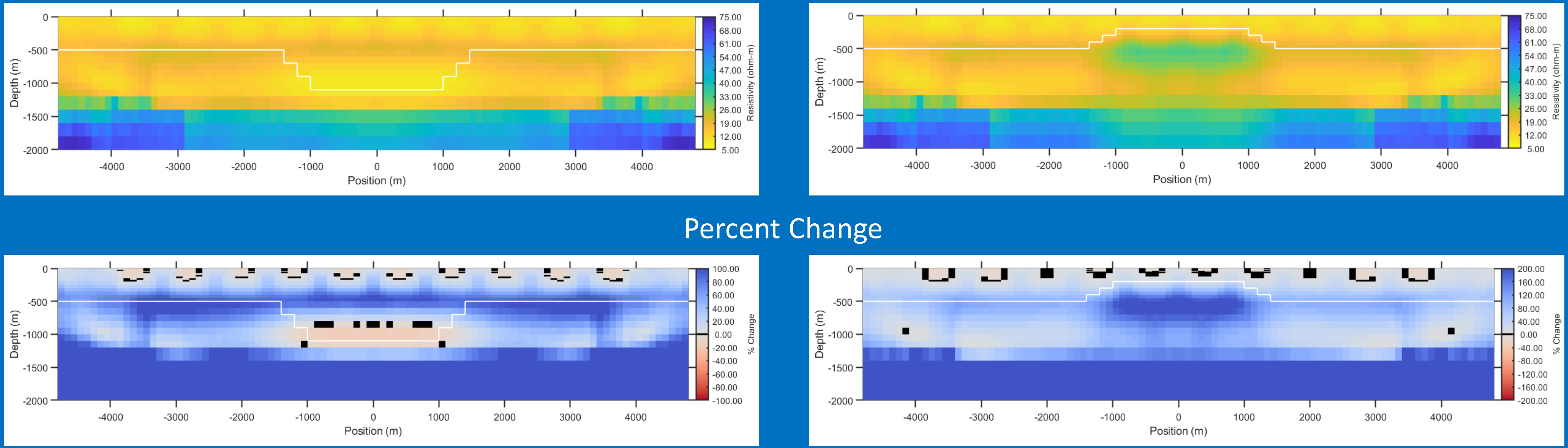
Semi-airborne survey
9600 m flight line
Drone altitude = 10 m
13 source positions
Source separations = 800 m
Gr. Wire (y) length = 1000 m
Profile/Grid Δx = 100 m
Grid z-spacing: variable
(12.5 m -> 200 m)
Time range = ~0.1 ms - ~1 s

Imaging for Buried Basin & Horst Models
10 ohm-m HS Reference Model *(3 dB Threshold)*

Synthetic Tests

Basin Model | Resistivity Image | *Horst Model*

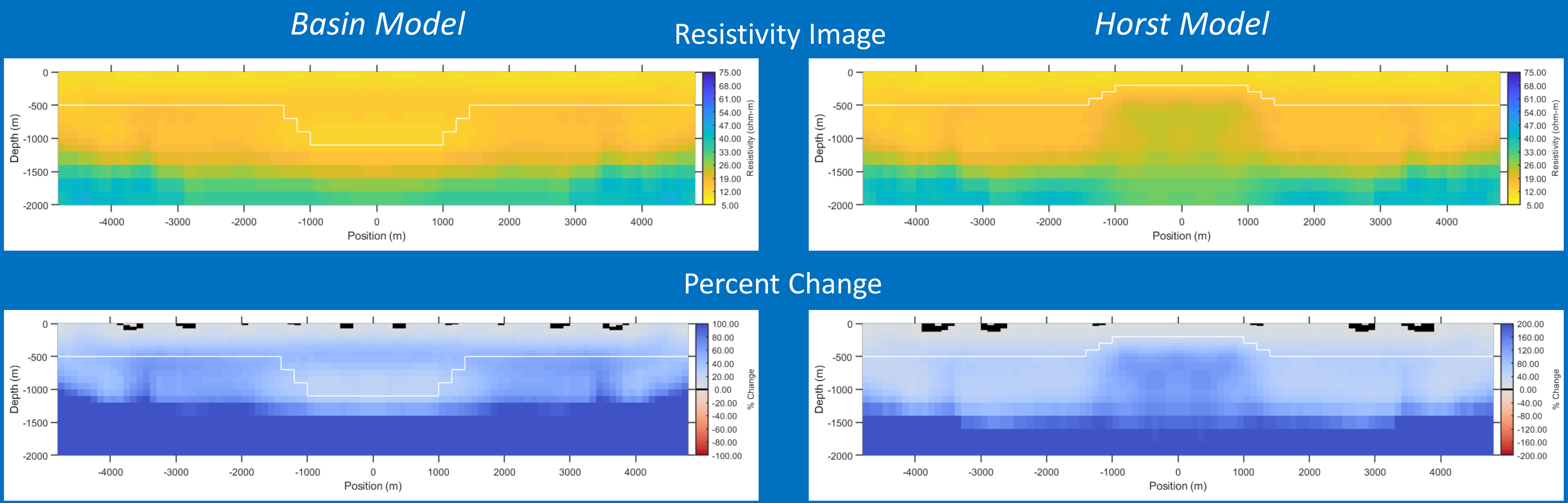
Percent Change



Lateral position of image structure:	Good for both
Vertical position of image layers and structure:	Too deep
Shape:	Good for horst, less so for basin
Section and structure anomaly resistivities:	In right direction, subdued (gradations, artifacts)
Artifacts / Noise:	Near surface (src separation), moderate depths, edge effects

Imaging for Buried Basin & Horst Models
10 ohm-m HS Reference Model (10 dB Threshold)

Synthetic Tests



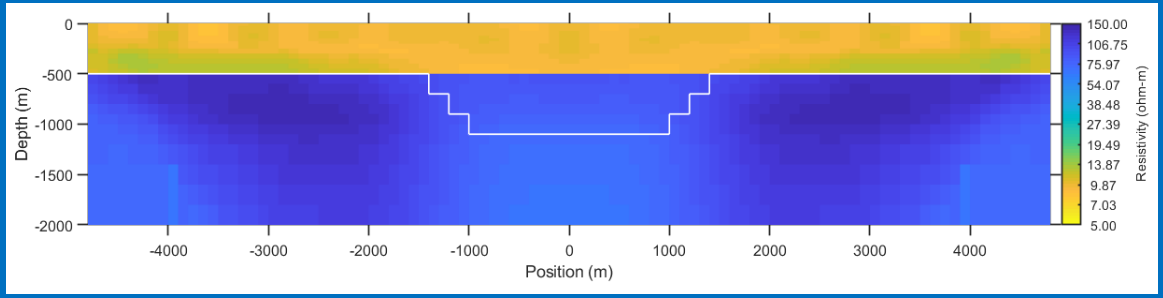
Lateral position of image structure:	Good for both (same as 3 dB case)
Vertical position of image layers and structure:	Too deep but layers are somewhat better than 3 dB case
Shape:	Fair for horst, less so for basin (same as 3 dB case)
Section and structure anomaly resistivities:	In right direction, much subdued (more than 3 dB case)
Artifacts / Noise:	All are better compared to 3 dB case

Imaging for Buried Basin & Horst Models

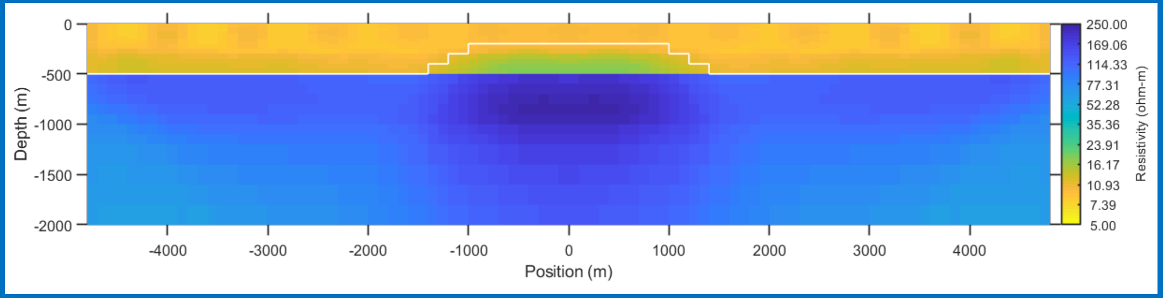
2 Layer Reference Model *(3 dB Threshold)*

Resistivity Image

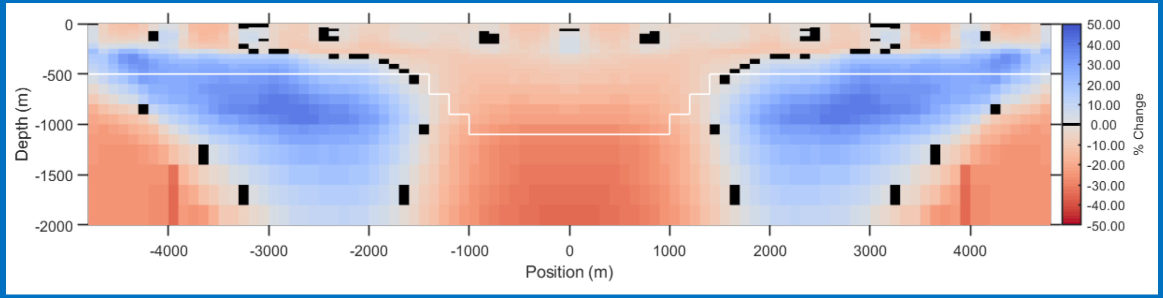
Basin Model

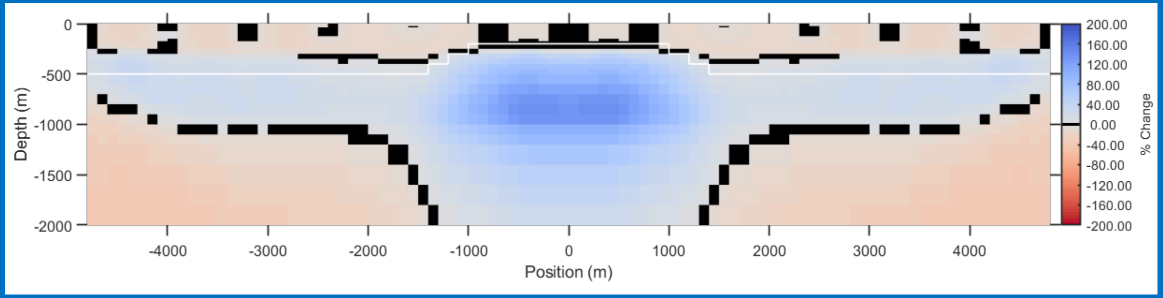


Horst Model



Percent Change





Lateral position of image structure:	Good for both
Vertical position of image structure:	Pretty good for horst, poor for basin
Shape:	Fair for horst, not so for basin
Section and structure anomaly resistivities:	In right direction, subdued (gradations, artifacts)
Artifacts / Noise:	Near surface (src separation), greater depths, few edge effects

Imaging for Buried Basin & Horst Models

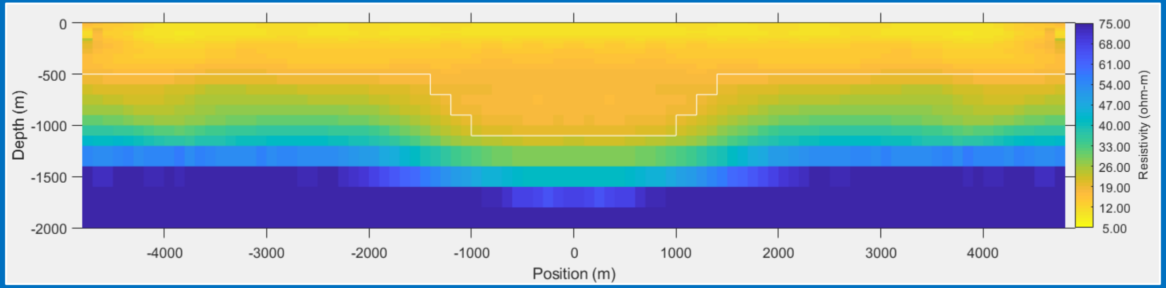
Gradual Resistivity(z) Reference Model *(3 dB Thr)*

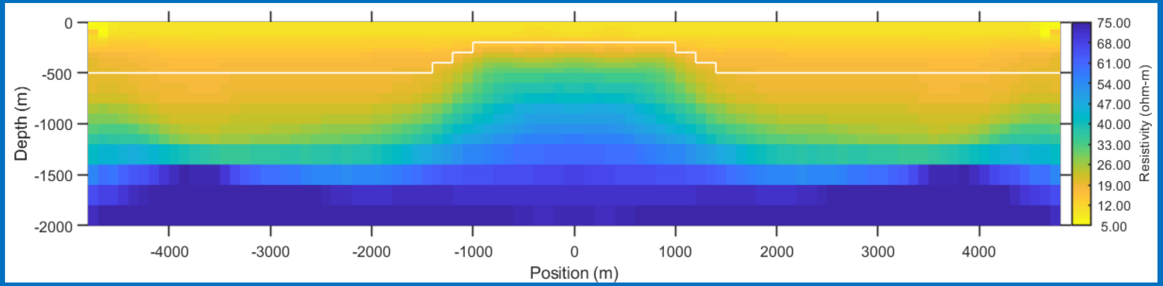
Synthetic Tests

Basin Model

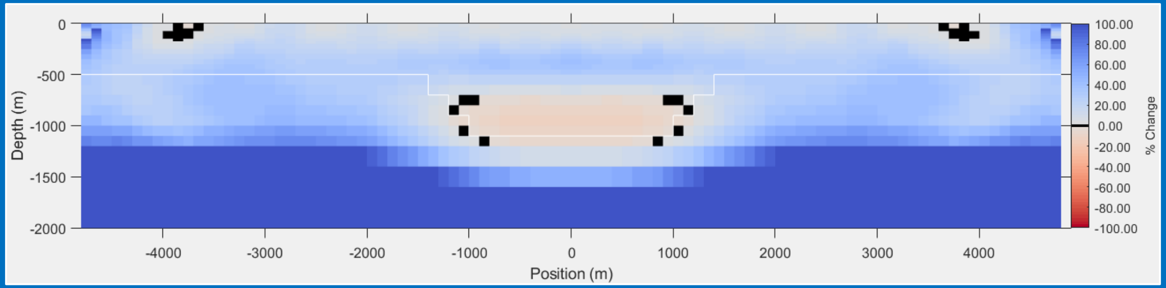
Resistivity Image

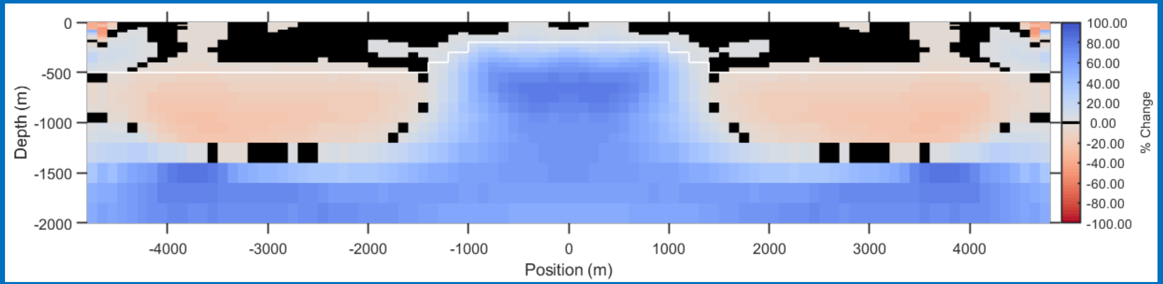
Horst Model





Percent Change





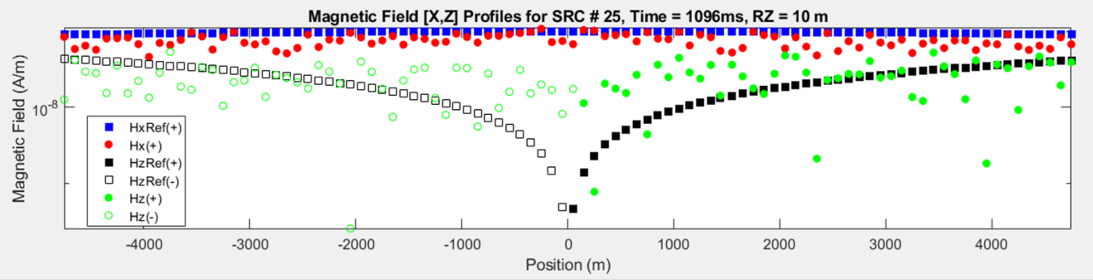
Lateral position of image structure:	Good for both
Vertical position of image layers and structure:	Slightly too deep
Shape:	Fair
Section and structure anomaly resistivities:	In right direction, better (gradations, artifacts)
Artifacts / Noise:	Near surface (src separation), moderate depths, few edge effects

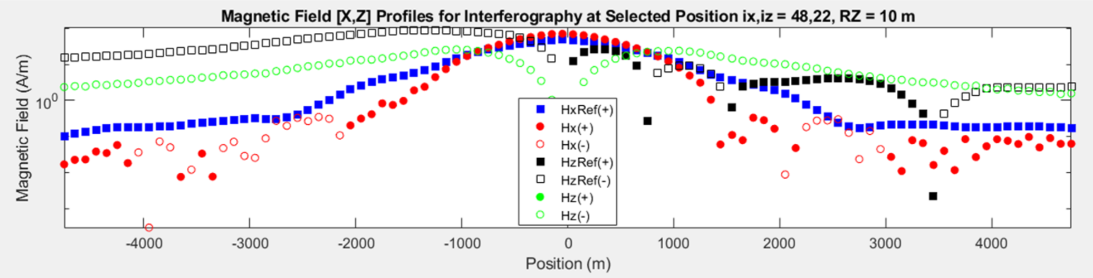
All in all, the best image results

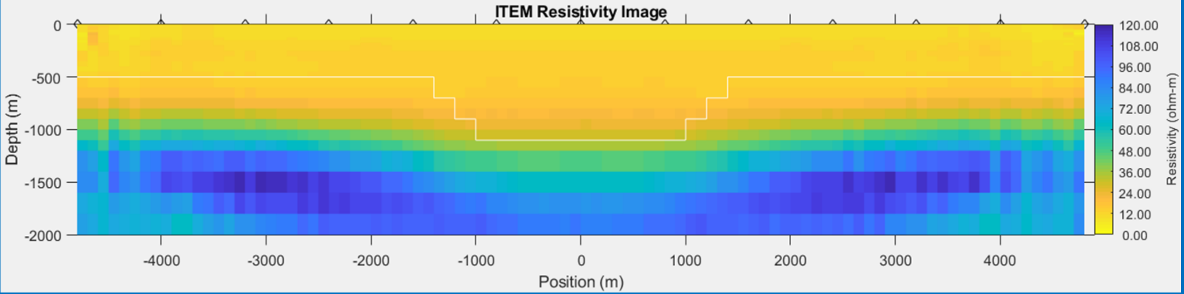
Good starting point for inversions

Testing with Synthetic Noise Added

Noise Floor 50 dB below Max H

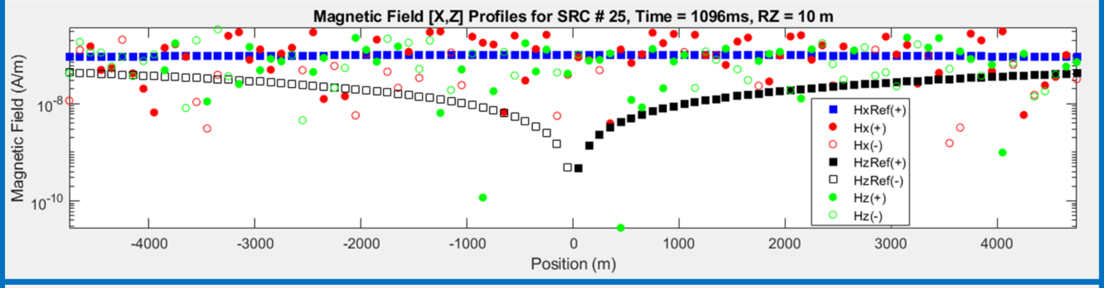


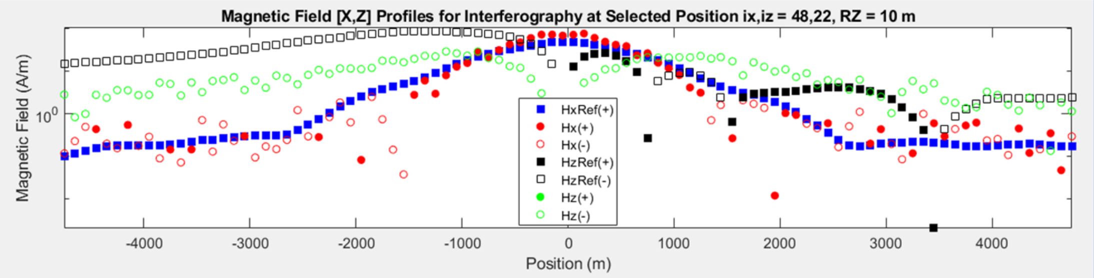


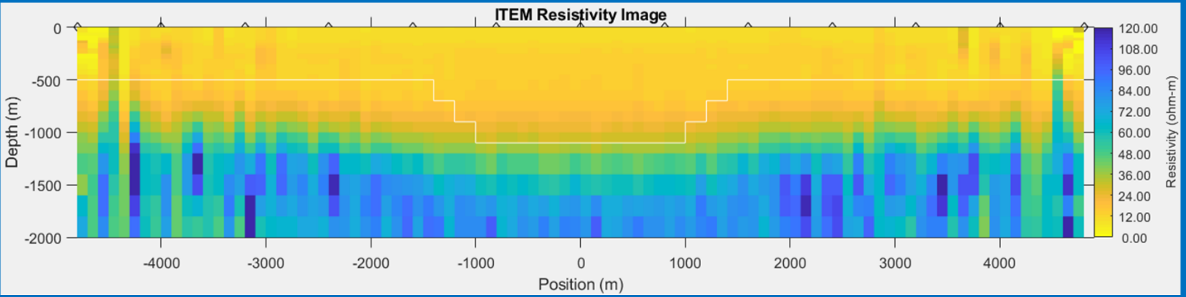


D = 1050m

Noise Floor 40 dB below Max H







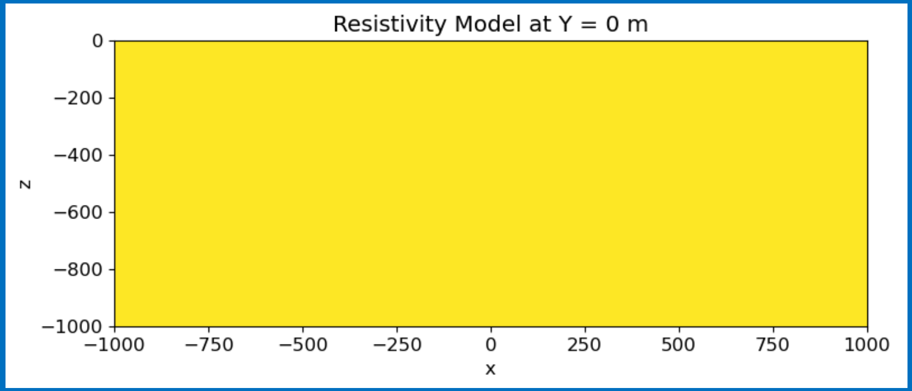
First Exercise to Compare and Integrate ITEM Processing into 3D EM Inversion

- Unsuccessful in search for acceptable 2D/3D inversion code for processing grounded wire results
- Therefore, tested ITEM for loop sources and compared with inversion results using SIMPEG, from University of British Columbia
- Again modeled structural cases of buried basin and buried horst, but on smaller scale than for grounded wire testing
- We used 17 source loop positions of size 40x40 m along a 2000 m profile
- The baseline geoelectric model is 2 layers - 10 ohm-m over 100 ohm-m with a layer depth of 160 m
- In particular, we are testing the idea of utilizing ITEM results as ***initial models*** for costly 3D inversion, in addition to non-assisted inversions
- Thanks! to Kyubo Noh for his excellent help and work on this exercise

Initial Models for Buried Basin & Horst Inversions

Unassisted inversion initial model

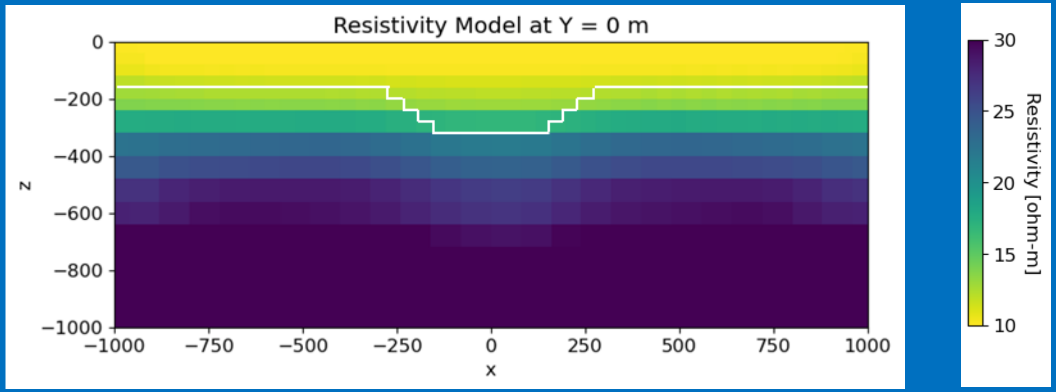
Half-space model



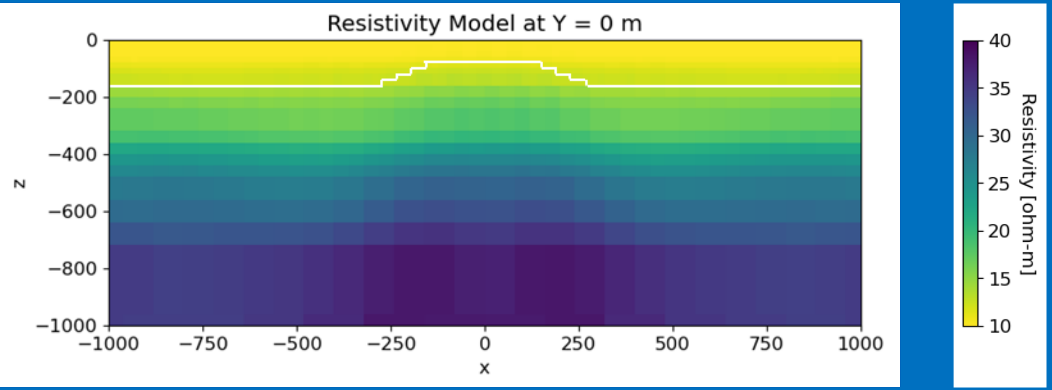
vs.

ITEM results (from gradual layered reference models) as initial models for inversion

ITEM result – Basin Model



ITEM result – Horst Model

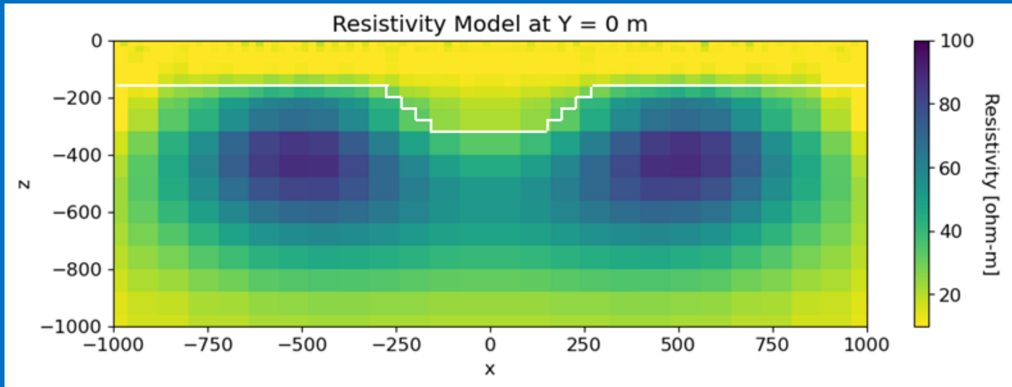


Inversion methodology: Least-squares optimization
Algorithm: SimPEG (Heagy et al., 2017)
Data weighting: Data magnitude + whitening noise (mitigating sign-reversal effect)

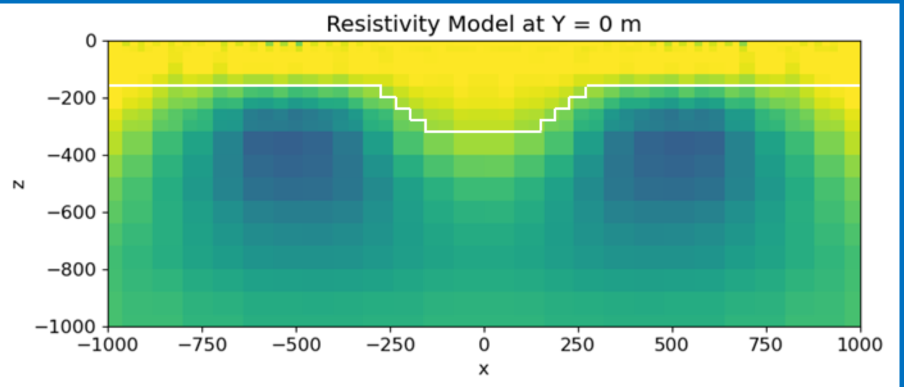
Inversions for Buried Basin & Horst Models

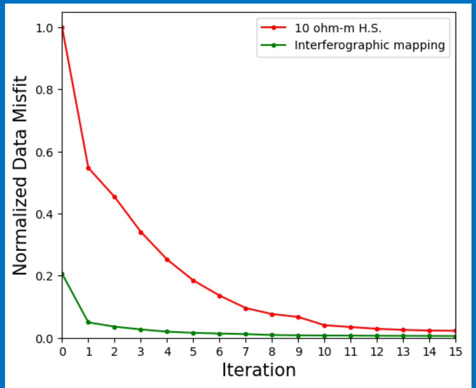
Basin Model

After half-space initial



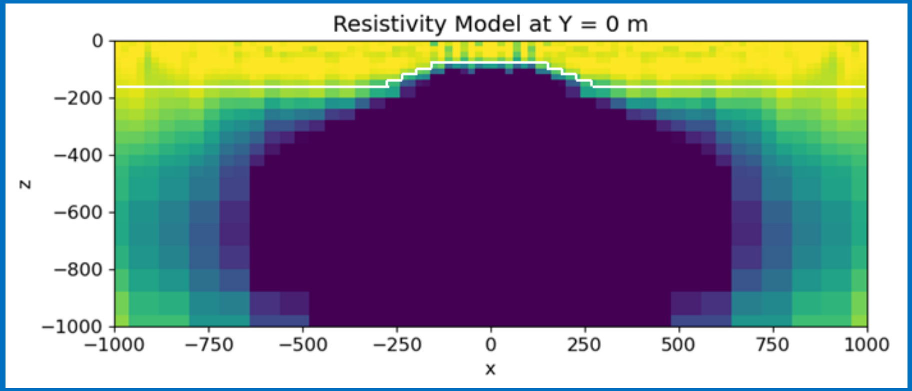
After ITEM result – Basin Model



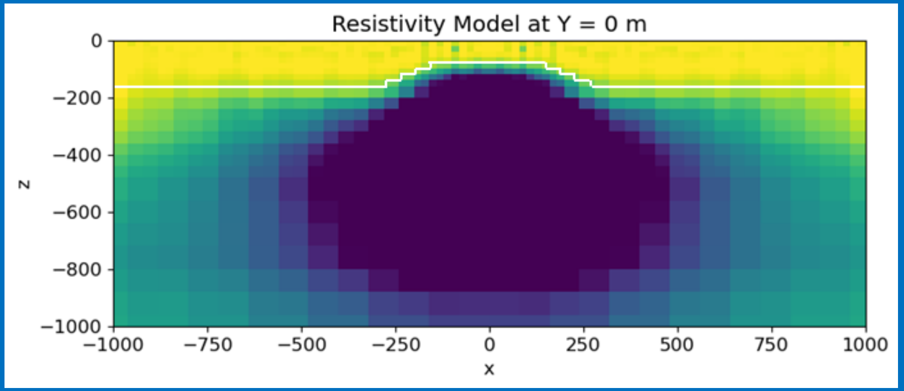


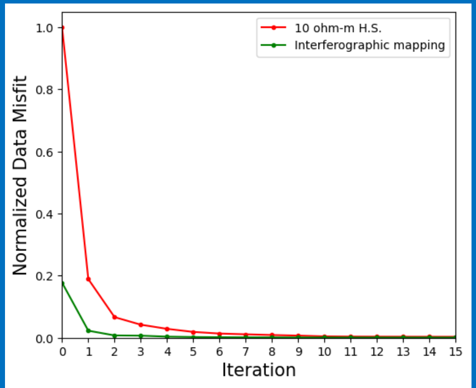
Horst Model

After half-space initial



After ITEM result – Horst Model





ITEM result as starting model: better starting point in data domain (~ 20% level of initial data misfit) leads to

1) faster convergence to saddle points in data domain,

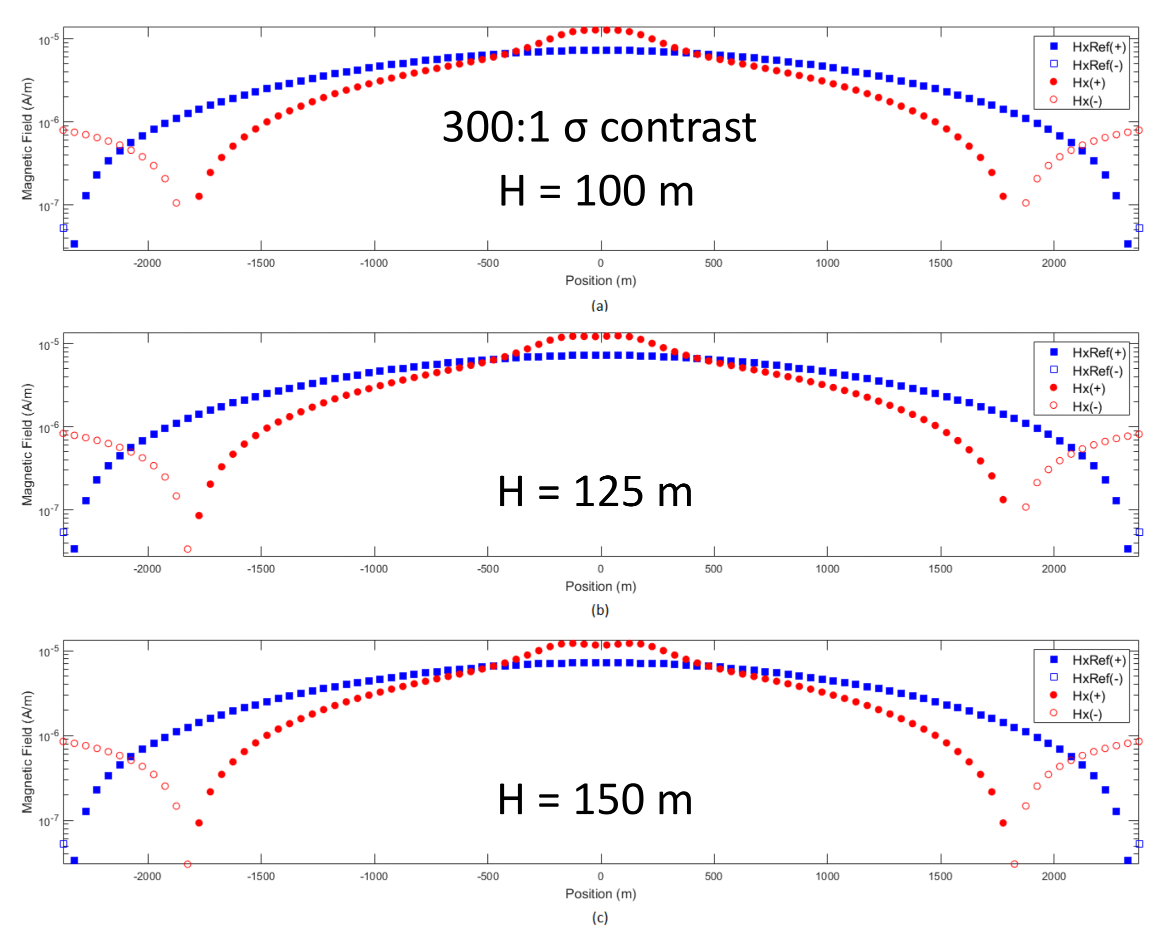
2) generally less inversion artifacts in both near surface and deep structures in model domain.

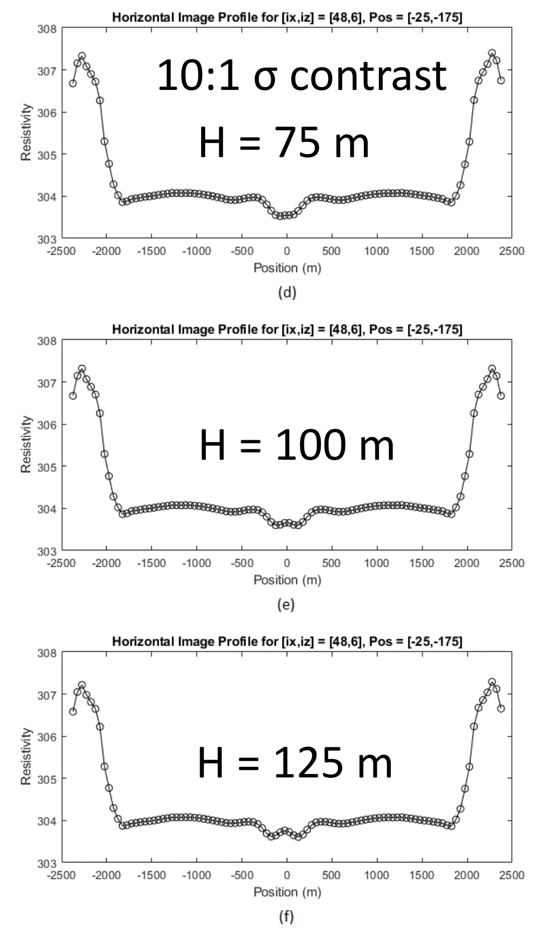
On Resolution

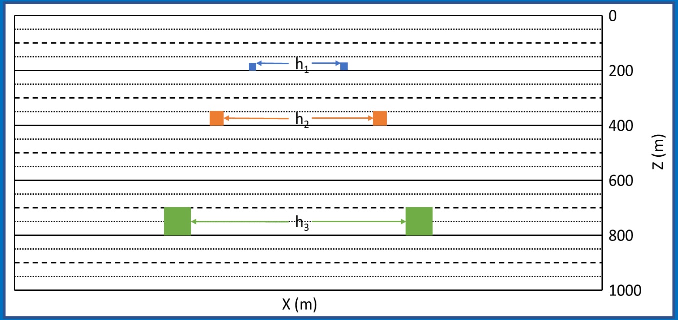
- Since ITEM looks to be an improvement in structural resolution, how do we address that in a specific, technical way?
- No existing baseline method(s) to describe/measure "resolution"
- One thing we can do:
  - In signal processing world, a common exercise is to define the minimum separation between 2 signals where they can be discerned as 2 signals as opposed to one spread out signal
  - Let's do this for lateral spatial separation of two anomalous targets

1) Run test models for 2 small conductors at different separations, repeat for 3 depths
2) For one source in original $H_x(t)$ profiles (the time where maximum anomaly is seen), determine minimum separation where the 2 conductors clearly discernible
3) For ITEM processing, use the image resistivity section, extract a single $\rho(x)$ profile at the depth of the modeled targets, determine minimum separation where the 2 conductors clearly discernible

Lateral Resolution of Two Conductors –
Comparison of Original Data and ITEM ρ Section Depth Slice







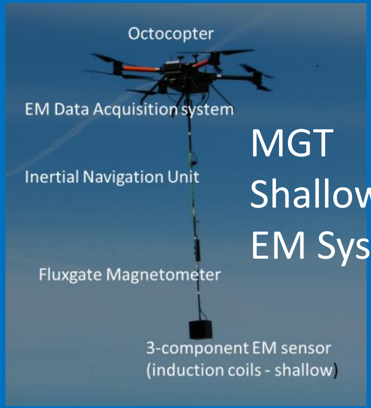
Depth to Top of Targets	TEM Profile Minimum Separation	ITEM Image Minimum Separation
175 m	150 m	100 m
350 m	250 m	150 m
700 m	425 m	250 m

On Resolution - Comments

- The 2 target exercise is an example of a quantifiable resolution test, others needed
- Specifically, metrics defining spatial resolution as well as resistivity contrast resolution, as well as overall image recovery of test structures, are much needed
- A Working Group, within the academic EM geophysics community, is proposed to establish Resolution Benchmark Models with associated technical metrics, for both ideal and noise contaminated cases
- The Resolution Benchmarks should be applicable for both imaging algorithms and inversions (1D/2D/3D)

- Occam approaches, imposing smoothness constraints that address non-uniqueness and numerical issues, are not ideal for descriptions of real geology, which is mostly only locally smooth or not smooth at all
- ITEM internalization into optimization software is going to come into direct conflict with such Occam smoothness constraints – this will need to be solved to achieve the full gains in resolution possible with ITEM processing

Discussion



MGT
Shallow
EM System

- **Field tests are the immediate next step**
- Can do ITEM with either grounded wire or loop sources
- Establish the problem areas for application of ITEM (IMO: deep, structural)
  - Those problems that are not well solved with existing capabilities (geophysics/drilling)
  - Those problems (e.g., monitoring) that could always benefit from improved resolution
  - If computing resources for inversions are a bottleneck, ITEM imaging is a worthwhile alternative
- Commercial success depends on well optimized system & field practices, drones

Discussion

- Attract others into working with Interferographic TEM
- ITEM achieves partial, though significant, unmixing of TEM fields
- Likely a range of theoretical and practical improvements to the present methodology are possible
- Full integration into 2D/3D EM optimization SW (eventual best solution, IMO) still to be done
- Full 3D interferographic formulation still to be done

With the Interferographic TEM framework, we can systematically probe the limits of achievable resolution as well as engineer the electromagnetic field structure to suit our needs.

Conclusions

- Subsurface targets are better illuminated and resolved with distributed multiple source, multiple receiver systems
- EM spatial resolution improvements can be achieved by the Interferographic TEM technique that synthetically compacts and sharpens the shape of EM field structure into impulsive distributions
- Basis of ITEM array processing is a never before used, in EM geophysics, space-time digital filtering technique using a LCMV Beamformer algorithm. Partial, though significant, TEM field unmixing is achieved.
- ***ITEM resistivity image result depends on the reference model used***
- Data processing for useful image products is very time efficient for quick turnaround look at field results
- A quickly obtained subsurface image provides an intelligent starting point for more elaborate 2D/3D modeling and inversion

Conclusions – Big Picture

Current State-of-the-Art

Classic TEM Data

Diffuse EM Field Structure

TEM Information Highly Mixed

Data Analysis

Additional State-of-the-Art?

Multi-Source, High Density TEM Data

Interferographic Processing:
Beamforming (and similar techniques)

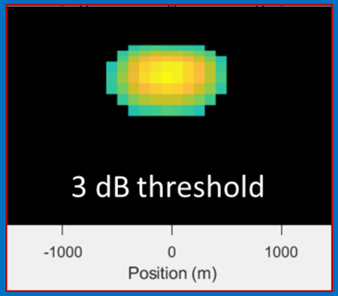
Providing Localized EM Field Structure

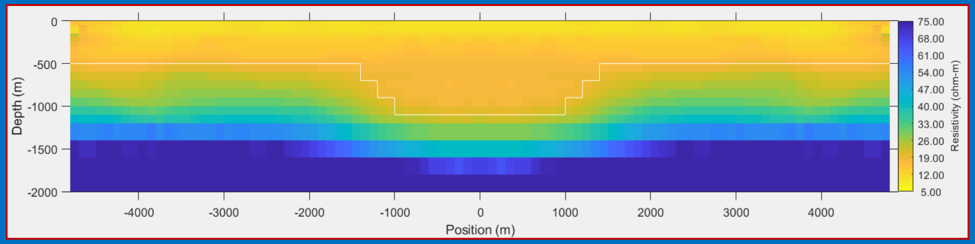
TEM Information Unmixing

Data Analysis

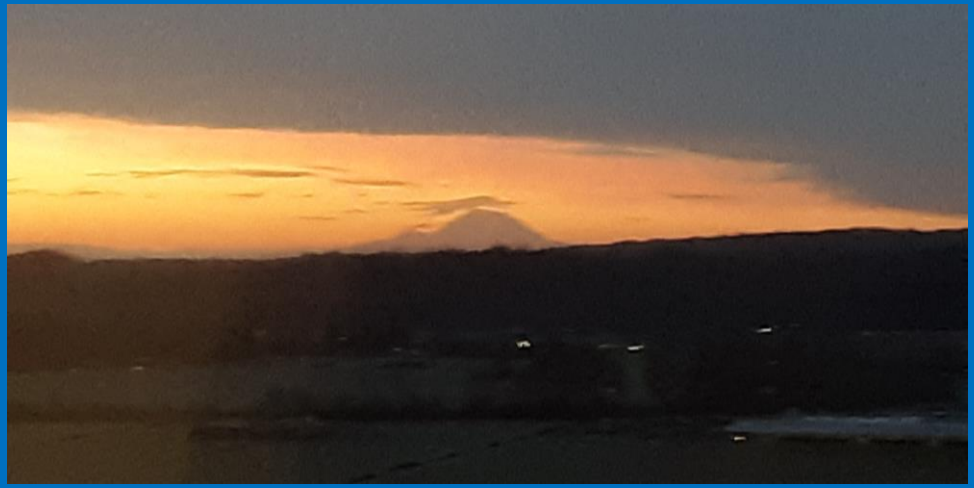
THANK YOU!

A Request:





Please email me your assessment of this method and presentation; it's valuable for improving both.



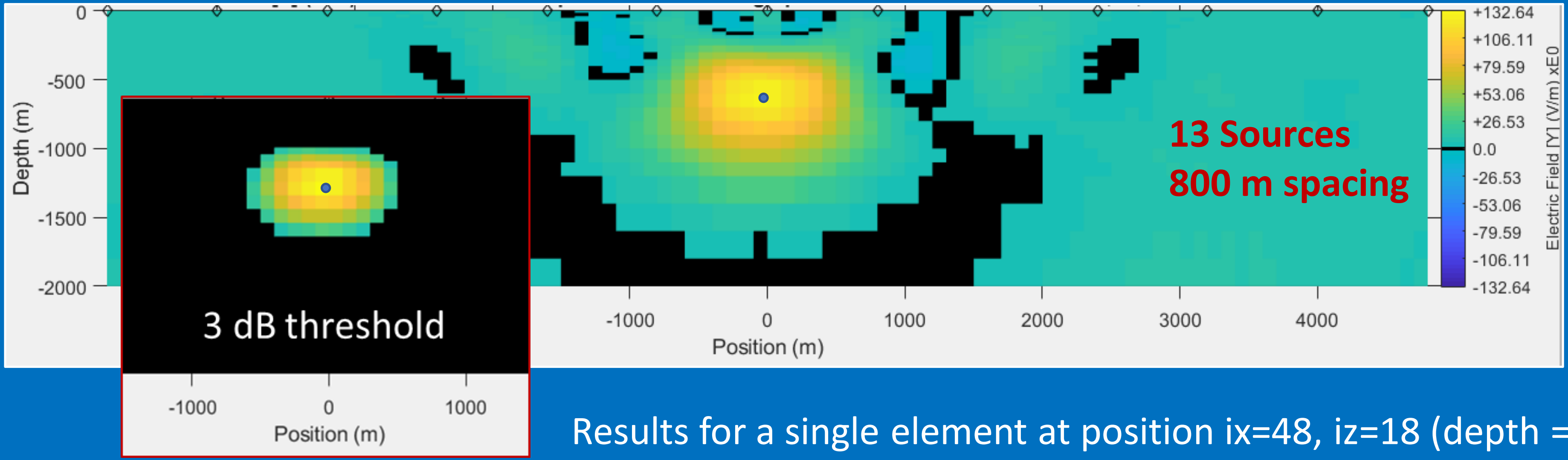
{Positive, Neutral, Negative}, Why

bjames.egisllc@gmail.com

Thank you very much for your kind attention and your feedback!

Extra Slides

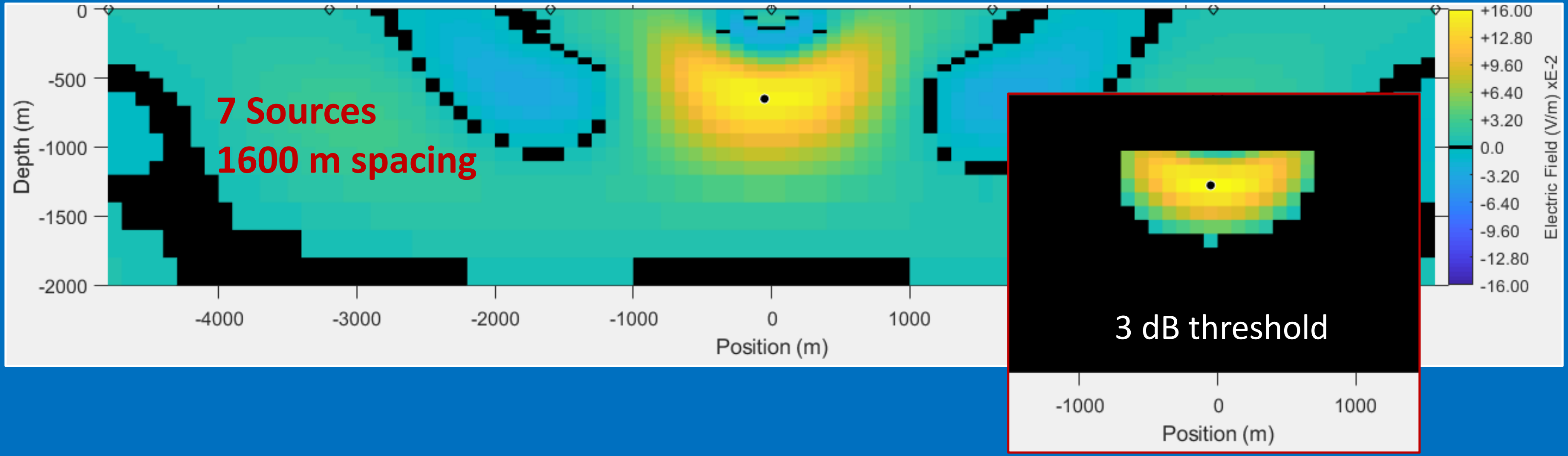
Interferographic Comparisons (Vary NS)



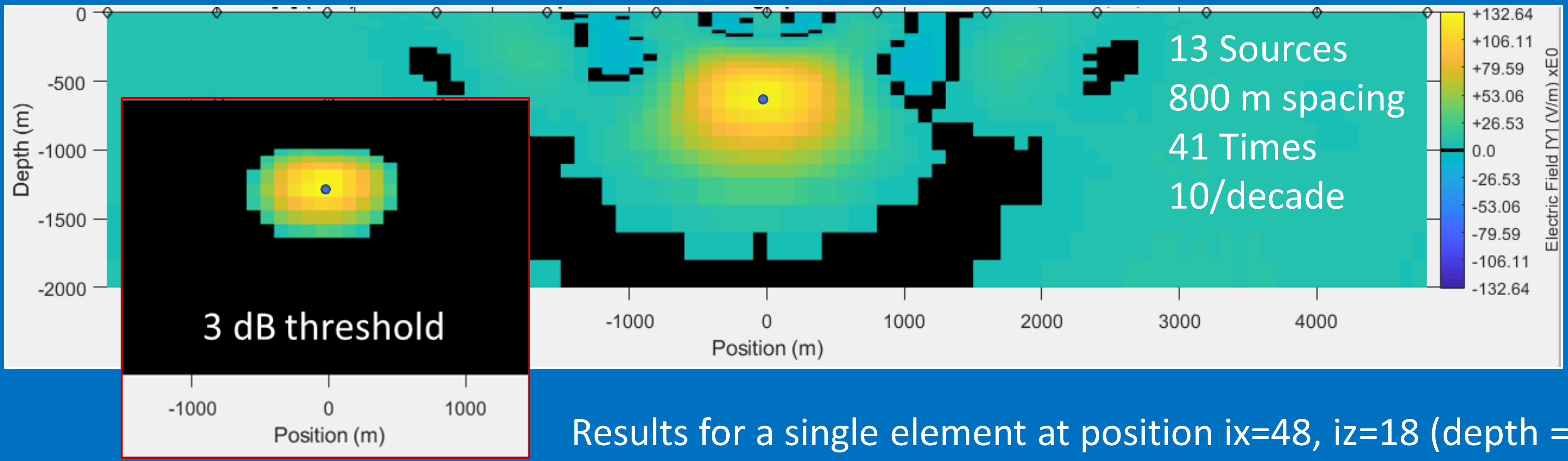
Results for a single element at position ix=48, iz=18 (depth = 650m)

Recommended
Sources ~ 9-10

Survey line extent > 3x target extent



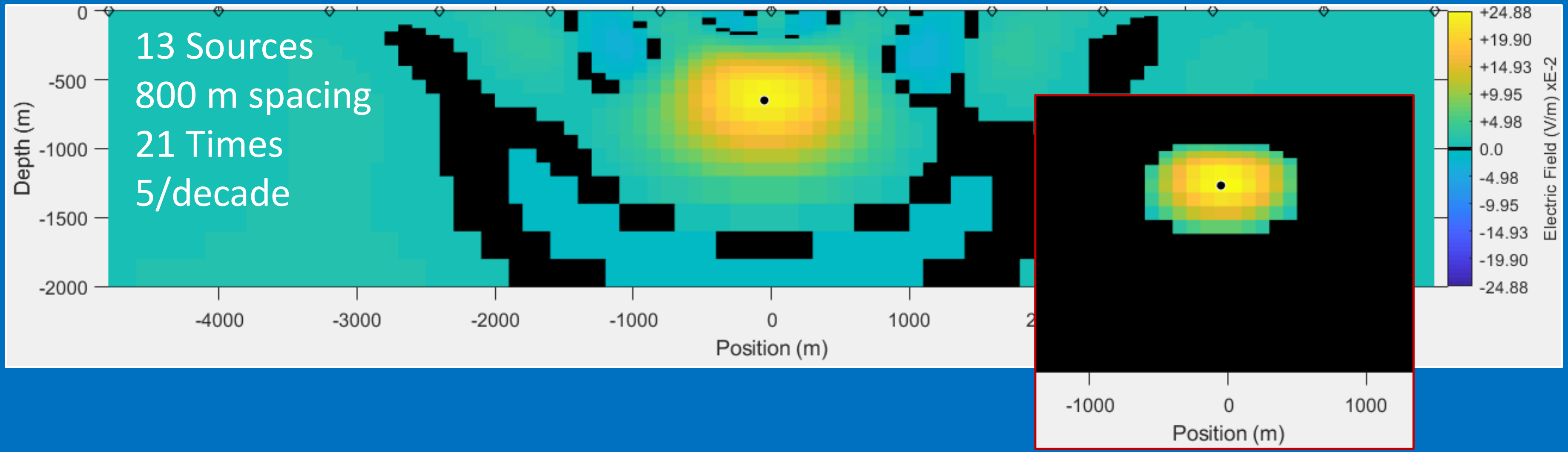
Interferographic Comparisons (Vary NT)



Results for a single element at position ix=48, iz=18 (depth = 650m)

5+ times/decade is sufficient.

3 decades in time is usually sufficient (as long as the range is correct). But 4 decades could be needed for increased depth of investigation.

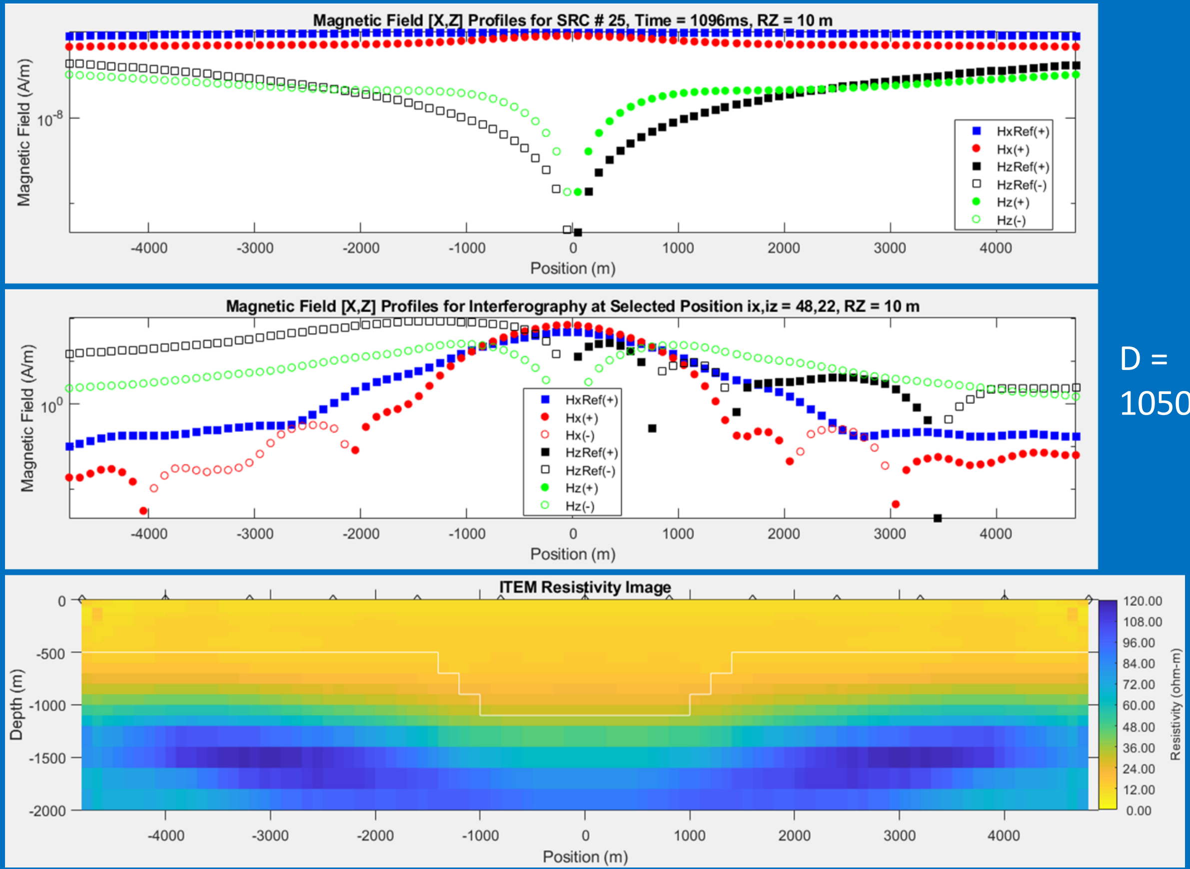


Defining a Gradual Model

- The previous results suggest insufficiencies for both halfspace models as well as, surprisingly, a 2 layer model that matches the background case for the two structural model test cases
- The implication is to use a gradual model ρ(z) reflecting the existence of the two layers
- Use an idea similar to that used by Christensen in his TEM imaging work
- Determine the best fit halfspace ρ(t) for the $H_x(t)$ profiles (for each source)
- Convert the ρ(t) function into ρ(z) by assigning each ρ(t) value to the element depth containing the maximum value of each $E_y(t)$ section
- For the set of NS ρ(z) results, can define easily define the mean, median, minimum and maximum
- Experiment shows median sometimes better than mean (smoothness) – min or max may also be useful – for use as reference model
- This is a simple operation, constructed of a set of halfspaces.
- Use these versions of $E_y(t,x,z)$, $H_x(t)$, and ρ(z) as the reference model

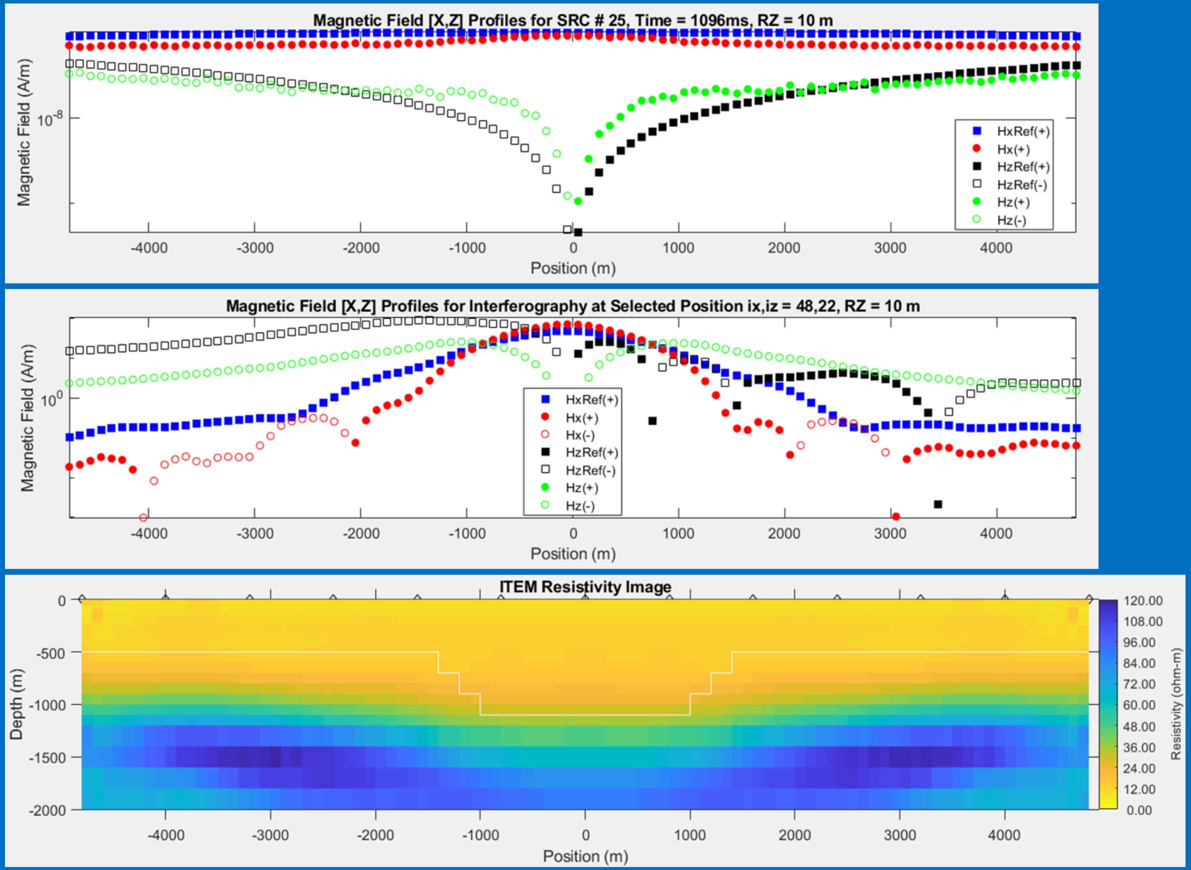
Testing with Synthetic Noise Added

No Noise



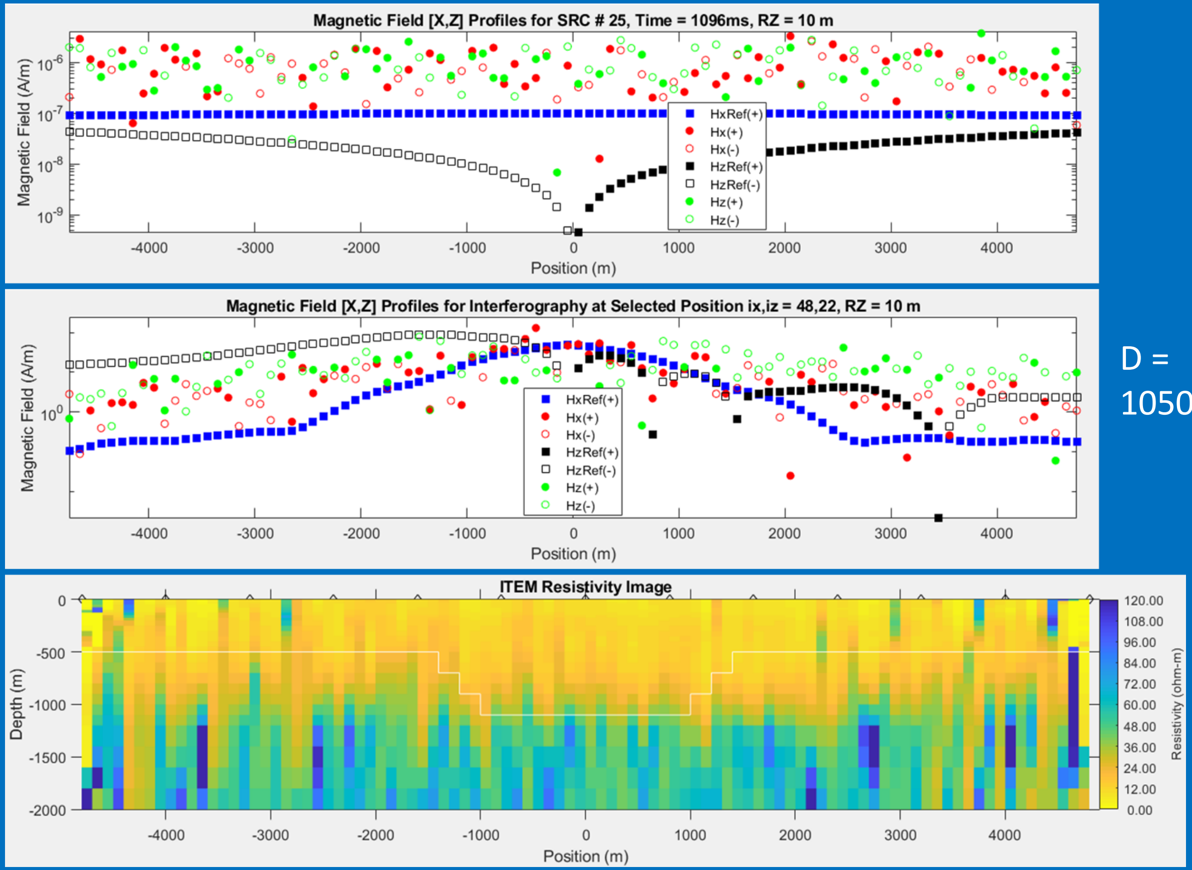
D = 1050m

Noise Floor 60 dB below Max H



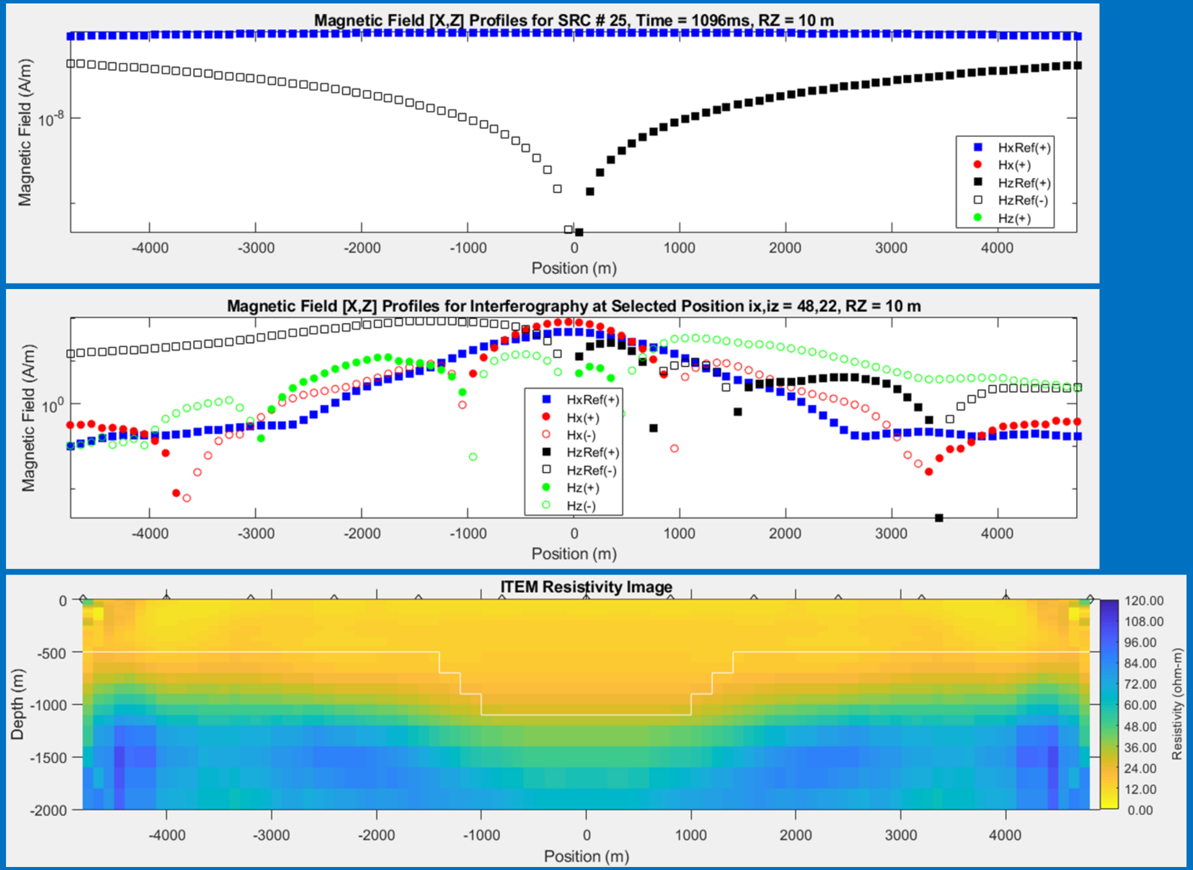
Testing with Synthetic Noise Added

Noise Floor 30 dB below Max H

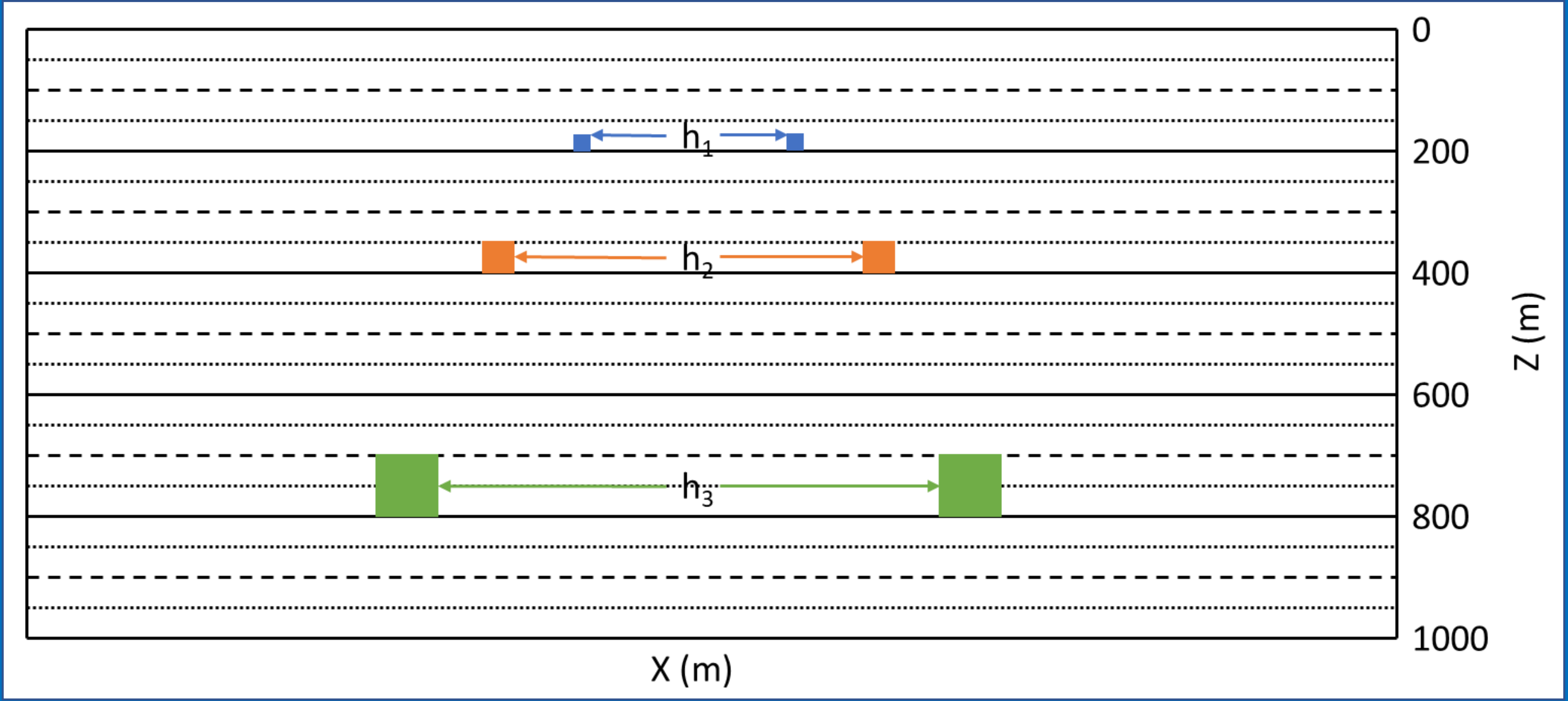


D = 1050m

Data Truncated 40 dB below Max H



A Test for Lateral Resolution of Two Conductors

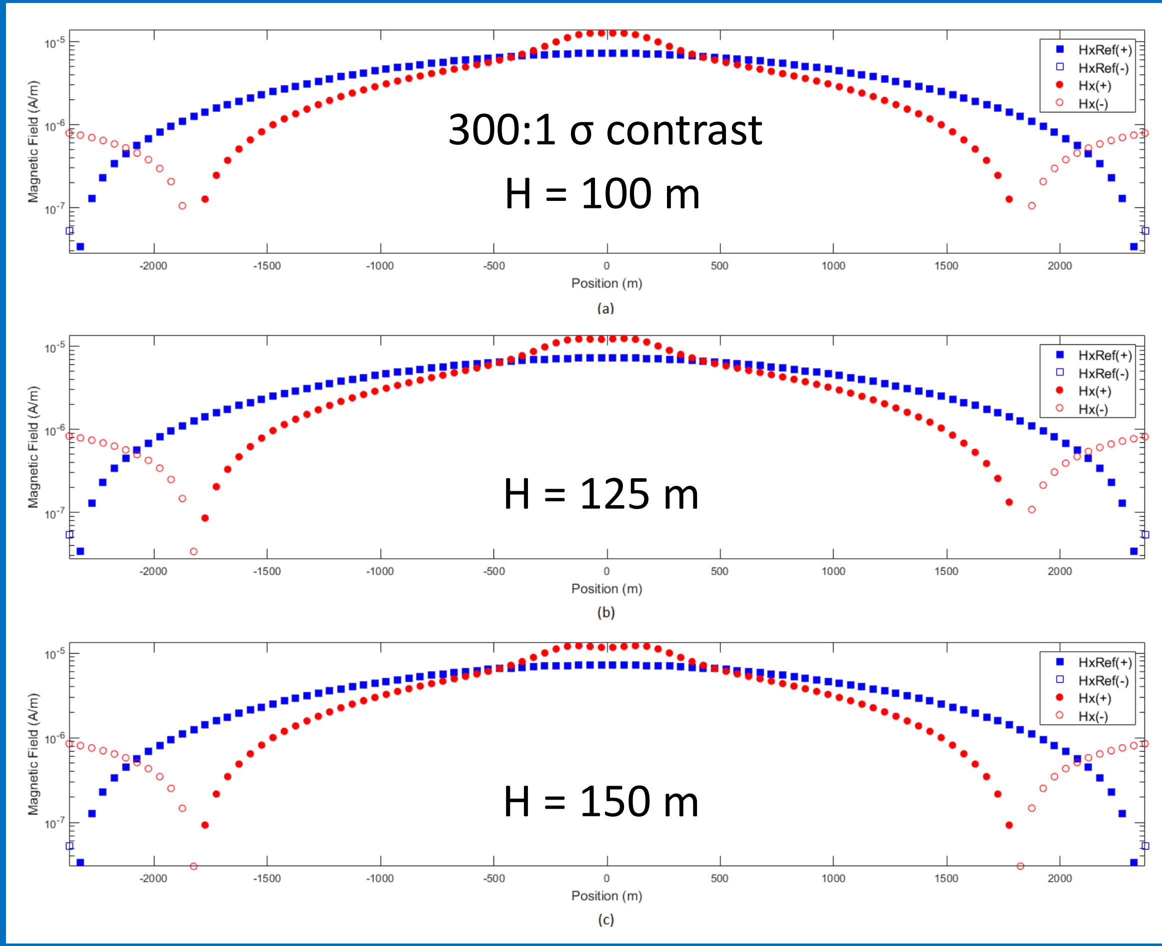


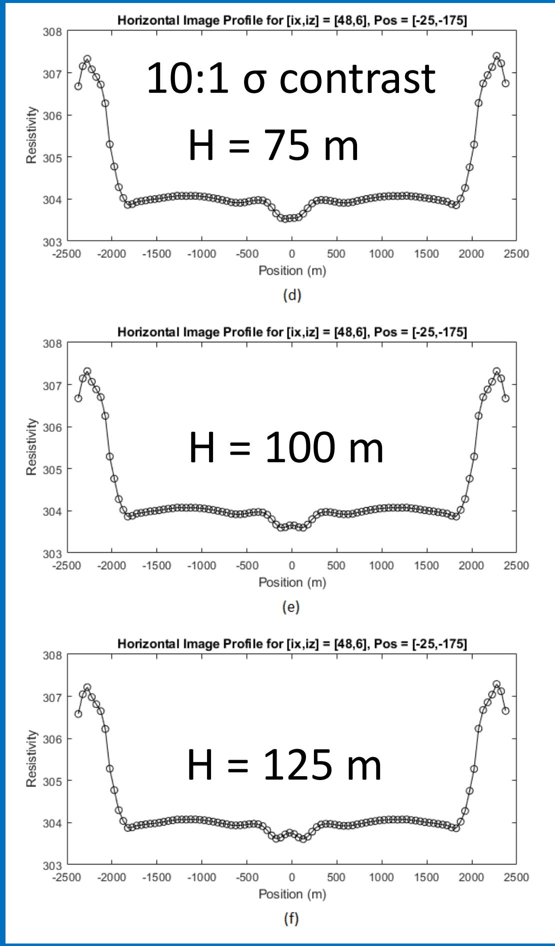
Three model cases for resolution evaluation between standard TEM data and ITEM processing results using elongated conductors. Conductor length in each case is 1000 m. The distance, h, between the pair of bodies is varied (increment = 25 m) to determine the minimum distance where two signals can be observed in the data.

Lateral Resolution of Two Conductors –

Comparison of Original Data and ITEM ρ Section Depth Slice

Resolution





The general conclusion is that the current version of ITEM processing & imaging improves lateral resolution (reduces the minimum visible separation) by ~ 40% compared to unprocessed TEM H_x data. The resolution improvement may increase with depth.

Vertical resolution is not assessed at this time, and is not expected to be as good as lateral resolution.

Depth to Top of Targets	TEM Profile Minimum Separation	ITEM Image Minimum Separation
175 m	150 m	100 m
350 m	250 m	150 m
700 m	425 m	250 m