
1

**Background & physics >> methods >> example >> issues & path forward**
**Outline & objectives**

- We want to monitor $CO_2$ fluid movement in a reservoir – what do we do?
- What methods do we select?
- What are requirements (using historical experience)?
- Workflow translates requirements to specifications
- Example
- Conclusions:
  - Works really good!
  - Key future focus to see small changes –
    - More accuracy in processing/inversion
    - Add borehole sensors
  - Harvest data via Cloud → better data quality
    Link to injection & 3D model in real time

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## What do we know?

- Dissolved $CO_2$ in reservoirs (brine filled) is more resistive (6-50 times) →
  - Use electric field measurements for the dissolved $CO_2$ & magnetic fields for the brine
  - MUST use grounded dipole to generate vertical & horizontal current flow → unbiased resistivity
- Lateral movement per year: 100 to 200 m
- Visibility of resistive reservoir is influence by OVERBURDEN
- Depth usually > 1500 m



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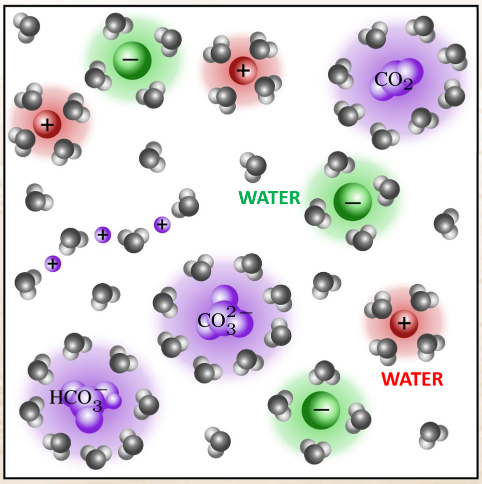
**Background & physics** >> methods >> example >> issues & path forward

## How does $CO_2$ influence the rock resistivity?

- @ > normal brine salinity – fluids are more resistive
- @low salinity → more conductive
- For geophysics: insulator




After Boerner et al., 2015



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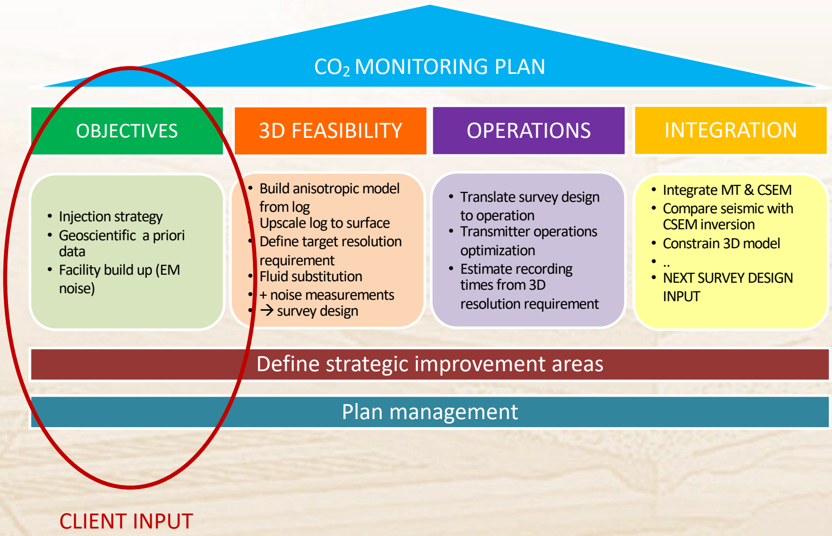
**Background & physics** >> methods >> example >> issues & path forward

**Details of strategic fluid imaging plan**

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**Monitoring strategy : EM component**

- What do we know now?
- Resistive – $CO_2$; Conductive - brine.. Targets both resistive & conductive →CSEM
- Monitoring = repeat = accuracy of measurement < 0.5 %
- DEPTH > 1.5 km avoiding leakage
- CLIENT selects target reservoir → quick evaluation → decide if 3D feasibility required → baseline survey → review strategy before 1st time-lapse

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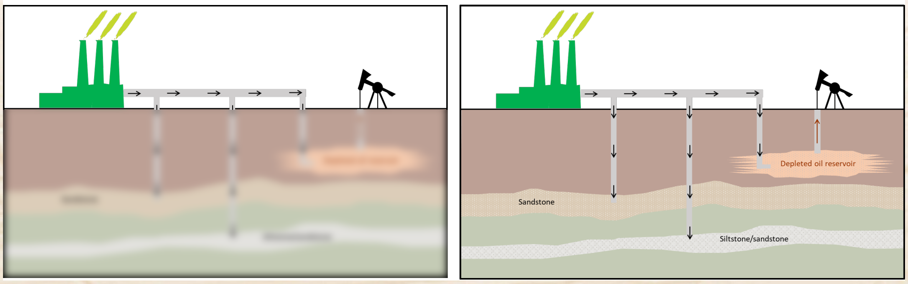
Background & physics >> **Methods** >> example >> issues & path forward

**Monitoring background: methods**

- DC – large offset (2-5 depth of investigation) → low resolution, depth limited – ERT - MOST COMMONLY TESTED
- MT – better in depth but low coupling to resistors → LIMITED
- CSEM – better coupling, cross- calibration with logs; better signal; resolves resistors & conductors; → METHOD of CHOICE
- OTHERS: Minor extraction of sweet spots in methods → ALL are limited to exactly that

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Background & physics >> **Methods** >> example >> issues & path forward

**Marine CSEM for CO2 monitoring – EMGS feasibility study for Northern Light project**

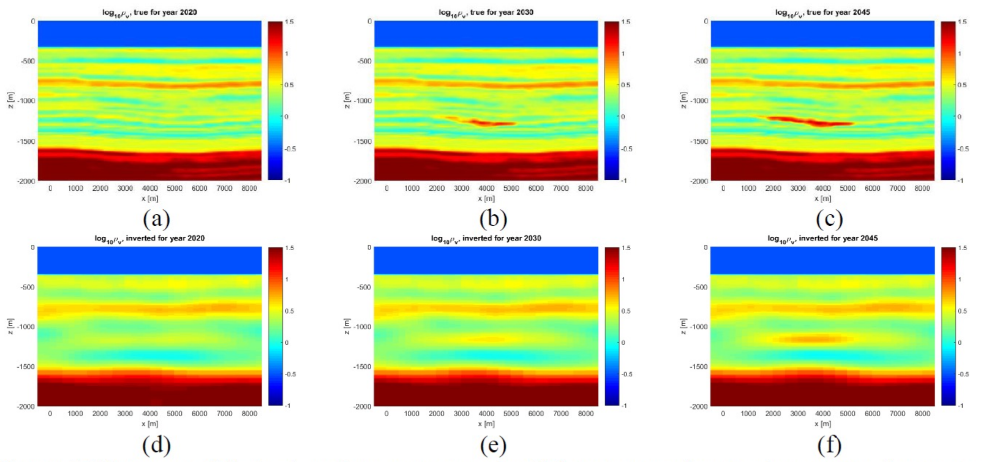


***Figure 2*** *2D true models (a-c) and inversion results (d-f) in terms of vertical resistivity for years of 2020 (baseline), 2030 (10 years injection) and 2045 (25 years injection).*

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## Controlled Source EM (CSEM): careful pilot




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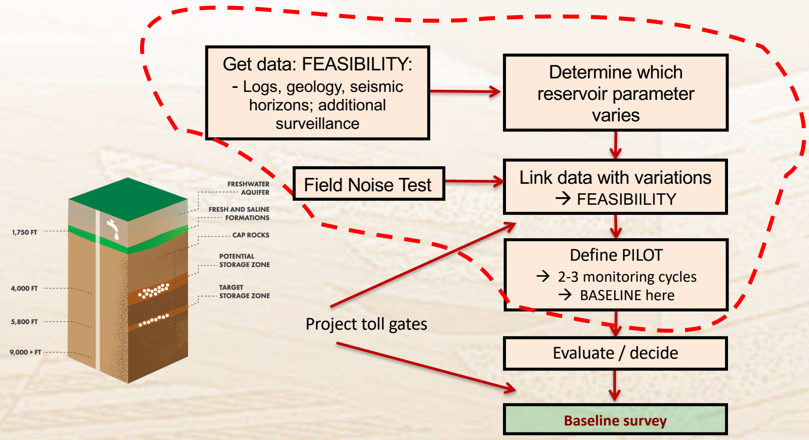
Background & physics >> Methods >> **Example** >> issues & path forward

## CSEM monitoring workflow: From Feasibility to baseline



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## CarbonSAFE III: in North Dakota

**North Dakota CarbonSAFE Phase III – Carbon capture, utilization, and storage (CCUS) project**

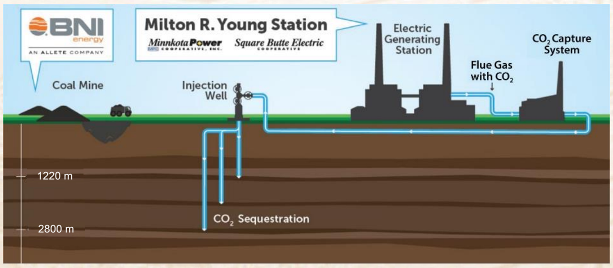
- Part of Project Tundra
- Characterization of a $CO_2$ storage complex near Minnkota's Milton R. Young Station
- Up to 4 million metric tons $CO_2$ per year

**Geophysical Objectives**

- Site characterization
- Baseline data acquisition
- Feasibility study of monitoring methods
- Development of a monitoring plan

**Geophysical Datasets**

- 2D and 3D seismic
- Controlled-source electromagnetic (CSEM) & Magnetotelluric (MT)
- Gravity
- Magnetic




After Barajas-Olalde et al., 2021



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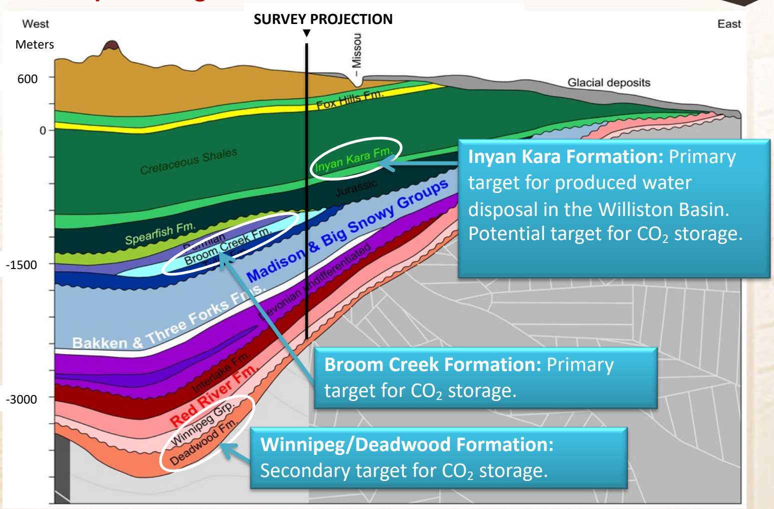
## CarbonSAFE III: Anisotropic model from composite logsGEOLOGY

- **Inyan Kara Fm**
  - Sequence of sandstones, silty sandstone & shale
    - Thickness in study area: ~ 55 m
    - Average porosity: 20 %
    - Average permeability: 200 mD
- **Broom Creek Fm**
  - Eolian and nearshore marine sandstone-carbonate cycles: sandstone, dolomite sandstone, dolostone, & anhydrite
    - Thickness in study area: ~ 86 m
    - Average porosity sandstone: 23 %
    - Average permeability sandstone: 222 mD
- **Deadwood Fm**
  - Marine siltstones, sandstones & shales on top of Precambrian basement
  - Porosity: Sandstone (11 %), Carbonate (3.7 %); Shale (1.0-23.0 %), Siltstone (0.1-18.0 %)
  - Permeability: Sandstone (70 mD), Carbonate (7.0 mD), Shale (14 mD), Siltstone (0.88 mD)

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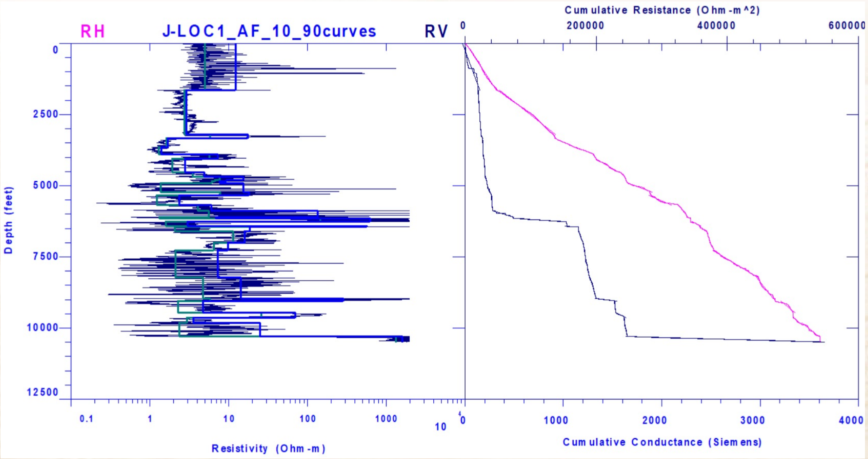
Background & physics >> Methods >> **Example** >> issues & path forward

**Build anisotropic model from composite logs**




- 31 layers
- Use
  - Rv for CSEM – E field
  - Rh for CSEM – H field
  - Rh for MT

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Background & physics >> Methods >> **Example** >> issues & path forward

**Build anisotropic model: Fluid substitution**

- Analyze logs to provide real substituted resistivity value
- If not available: Use literature, scale literature RES by brine salinity, use Archie (or shale correction)
- Determine substituted resistivity and scale model using anisotropy from logs
- Verify scaling with forward models (1D) as above
- When modeling, check for shoulder bed influence and rescale, compare scaling (1D & 3D) versus logs
- WATCH: artifacts in 3D models at high contrast boundaries – compare to log
- Result: table of benchmark models



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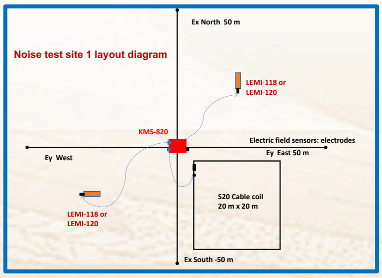
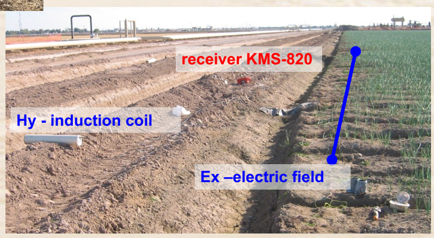
Transition >> Changes >> **Example** >> Conclusion

## CarbonSAFE III: Noise test – multiple sensors, verify noise sources



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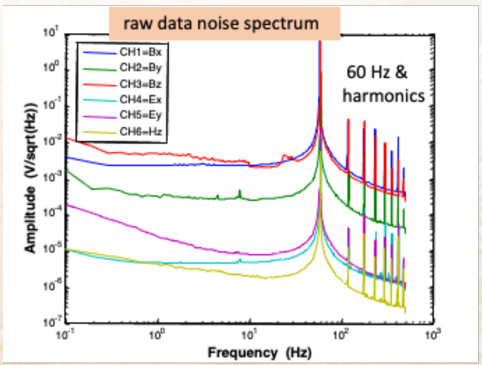
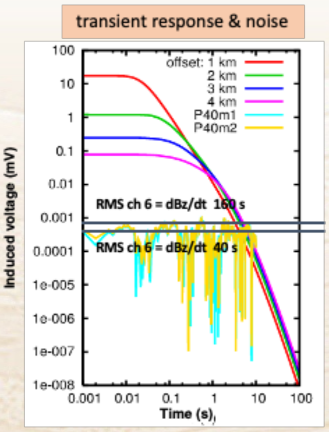
Background & physics >> Methods >> **Example** >> issues & path forward

## CarbonSAFE III: Noise spectra & 3 models



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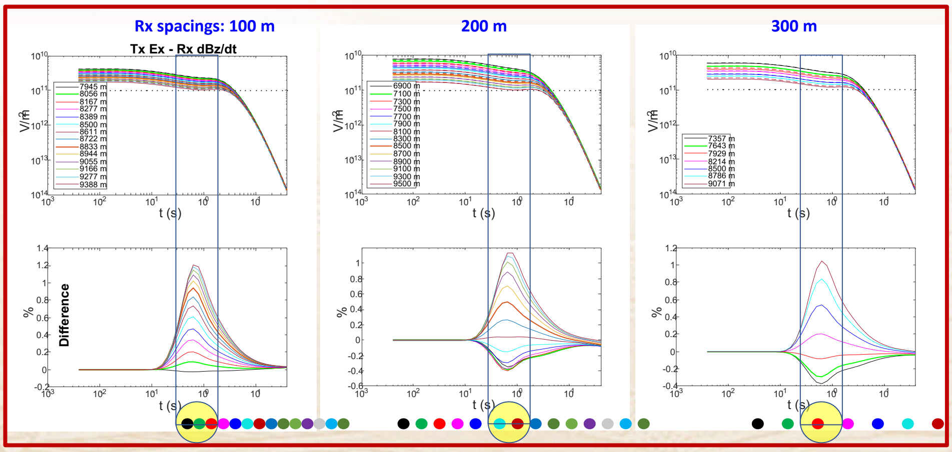
Background & physics >> Methods >> **Example** >> issues & path forward

## CarbonSAFE III: 3D models dBz/dt – station spacing

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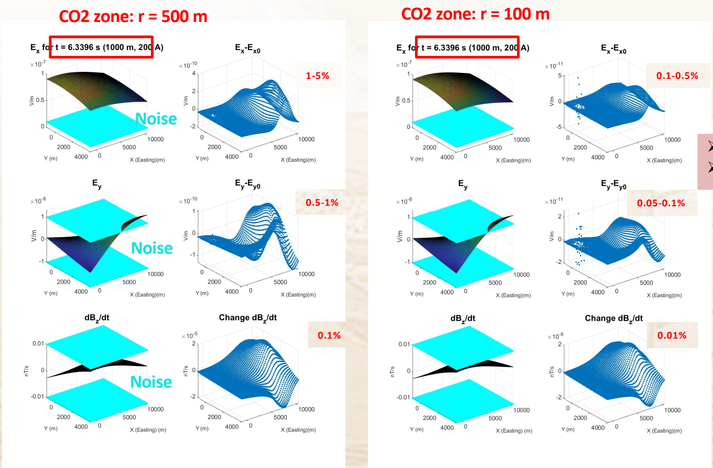
Background & physics >> Methods >> **Example** >> issues & path forward

## CarbonSAFE III: 3D models X-directed Tx, Broom Creek, 12th bed, 3D case (60%)




- 6.3 s after turn-off
- Absolute change

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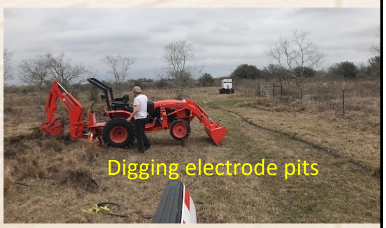
Background & physics >> Methods >> **Example** >> issues & path forward

## Field operations – field test Hockley salt dome

1. Build systems
2. Calibrate in lab (chamber)
3. Field test (components)
4. System integration field test in Houston (Hockley salt dome)

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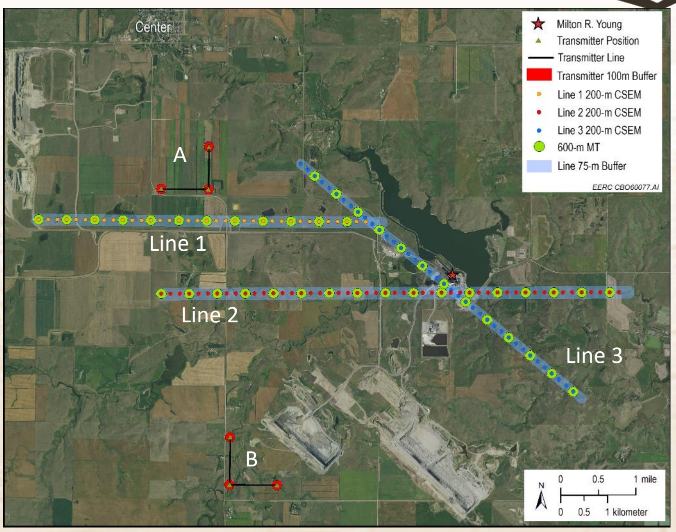
Background & physics >> Methods >> **Example** >> issues & path forward

## CarbonSAFE III: acquisition layout

- **MT**
  - To measure the model's baseline background resistivity
  - 42 Stations, 600 m spacing
  - Remote station near Grand Forks, North Dakota
- **CSEM**
  - 124 Stations, 200 m spacing
  - Two transmitter sites (A & B), 400 A
  - Time domain
- 24 hours operation
- No equipment breakdowns
- Real-time data upload for QA
- Production: Pickups: 24, deployment:16, fully recorded sites:17 / day

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## Acquisition options

- Standard: Night – MT. &. Day CSEM
- 24 hours operation for CSEM
  - More routine
  - Generator stays warm
  - Electrode pit remain stable
  - High production rate
  - Q/A via Cloud enabled receivers
- **CON 24/7:** Processing more complex as data must be demerged by transmission cycle and then remerged with transmitter current




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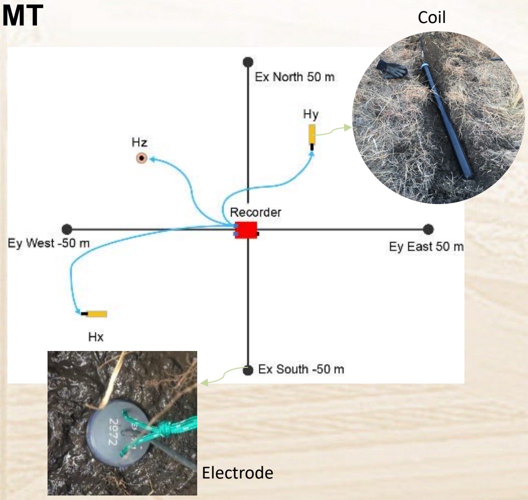
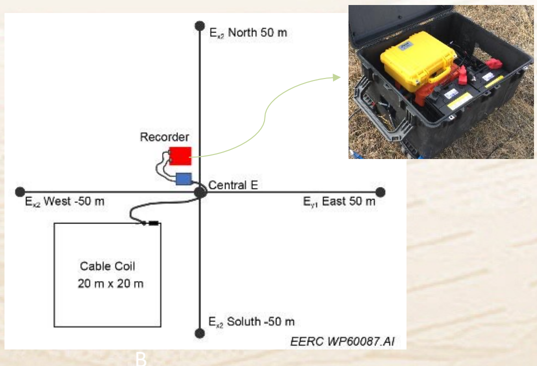
## Field layouts

### MT




### CSEM

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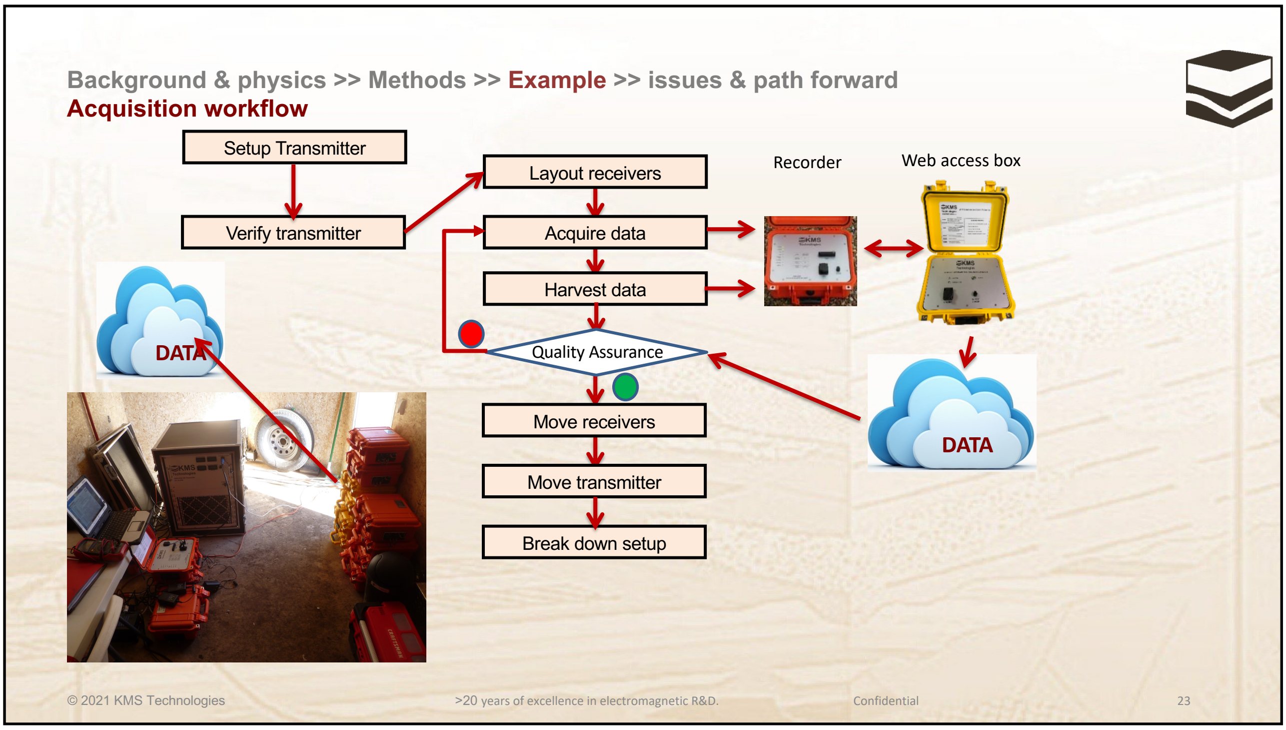
Background & physics >> Methods >> Example >> issues & path forward
Acquisition workflow
Setup Transmitter
Verify transmitter
Layout receivers
Acquire data
Harvest data
Quality Assurance
Move receivers
Move transmitter
Break down setup
Recorder
Web access box
DATA
DATA
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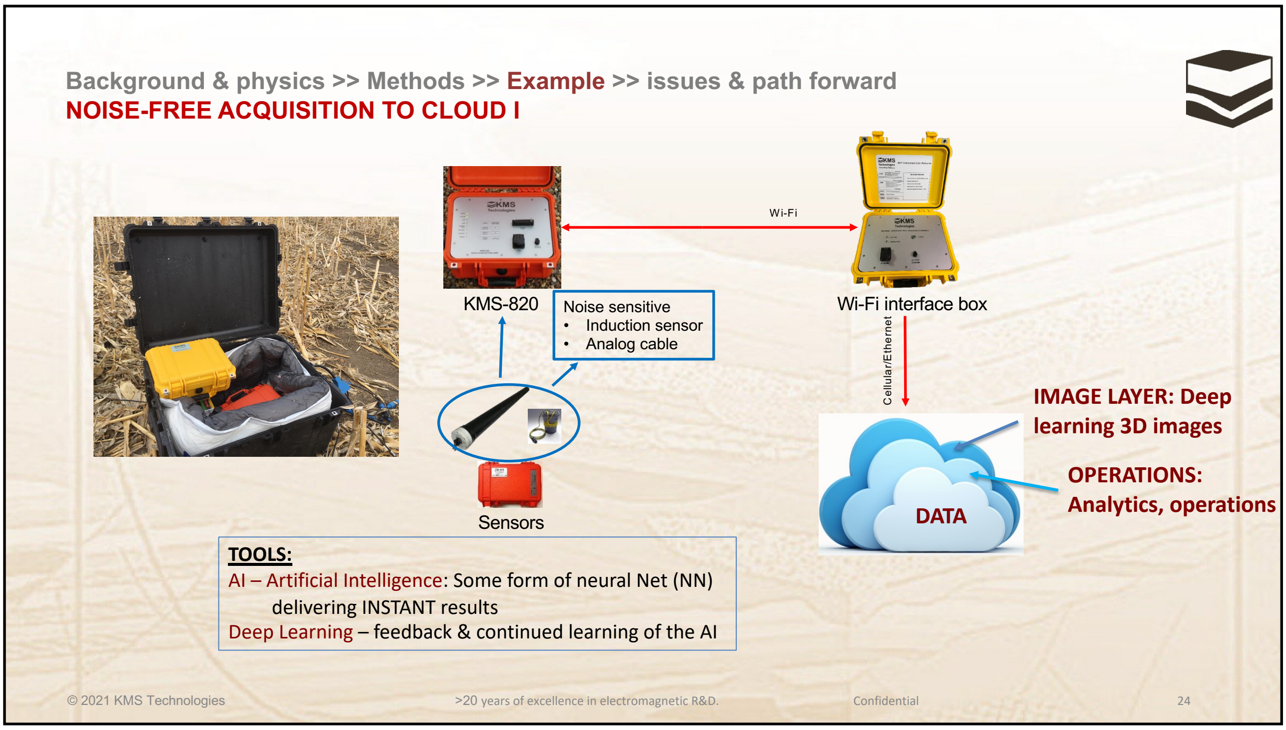
Background & physics >> Methods >> Example >> issues & path forward
NOISE-FREE ACQUISITION TO CLOUD I
Wi-Fi
KMS-820
Noise sensitive
• Induction sensor
• Analog cable
Wi-Fi interface box
Cellular/Ethernet
Sensors
IMAGE LAYER: Deep learning 3D images
OPERATIONS: Analytics, operations
DATA
TOOLS:
AI – Artificial Intelligence: Some form of neural Net (NN) delivering INSTANT results
Deep Learning – feedback & continued learning of the AI
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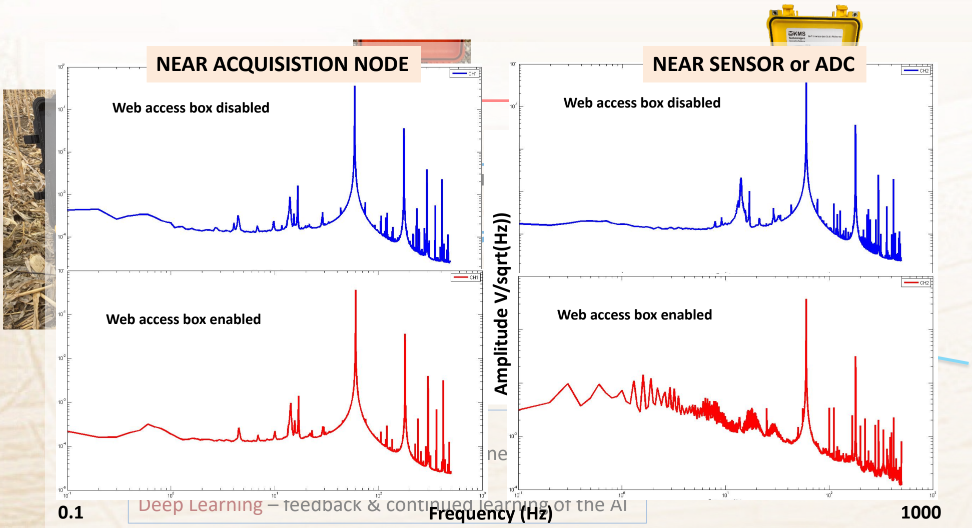
## NOISE-FREE ACQUISITION TO CLOUD II



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Background & physics >> Methods >> **Example** >> issues & path forward

## How do we quality control the data?

- We know the average 3D anisotropic model in the area.
- Variations are gentle (except SE).
- Check via inversion- SIMILARITY to log
- Verify sensitivity via Eigenvalues (from inversion)
- NEXT: Time-lapse measurements



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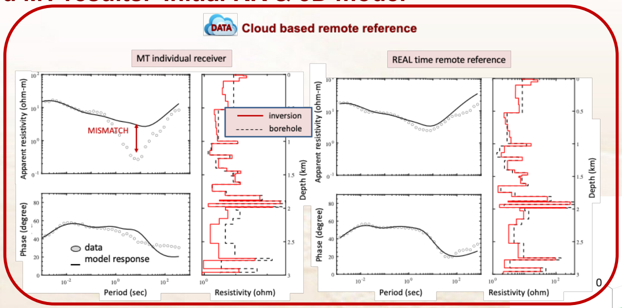
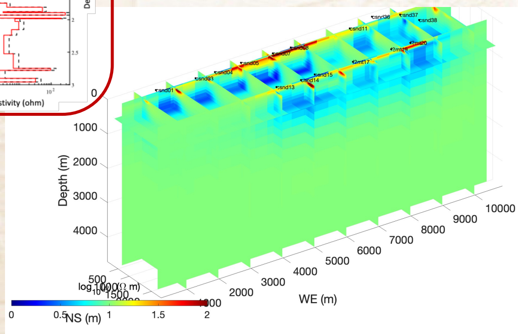
Background & physics >> Methods >> **Example** >> issues & path forward

## CLOUD based MT results. Initial RR & 3D model



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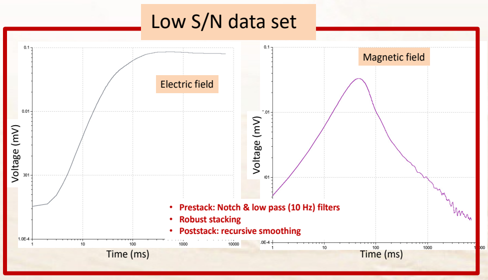
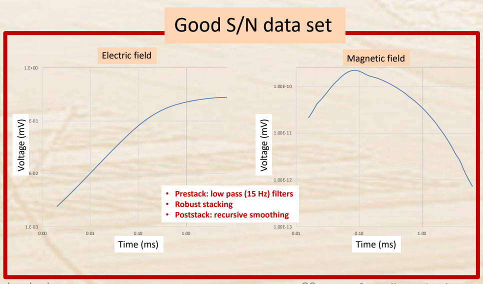
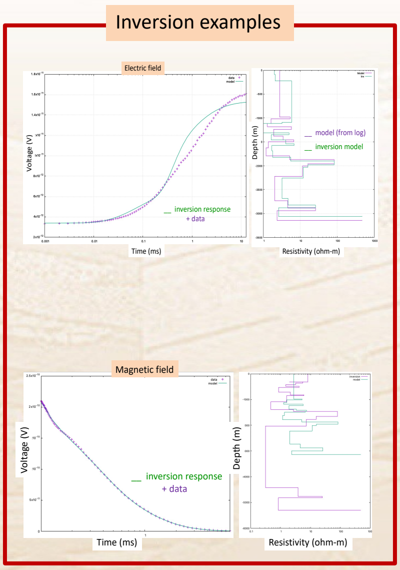
## Importance of CLEAN data



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Background & physics >> Methods >> Example >> issues & path forward

## CLOUD / AI / DL lead to next improvements - OVERVIEW

### Reservoir monitoring workflow, approximate times & technical tasks

| 2-3 months | 2-3 months | 3-6 months | 3-6 months | 2-3 months | 3-6 months | 2-3 months |
|---|---|---|---|---|---|---|
| **3D Feasibility** | **Baseline survey** | **Processing evaluation** | **Predictive optimization** | **Repeat Time-lapse survey** | **Time lapse processing** | **Fluid image** |
| • Log analysis<br>• Upscale model<br>• Derive 3D anisotropic model<br>• Reservoir fluid variations<br>• Derive 3D modeling task<br>• **Perform 3D modeling** *<br>• **Analyze target variations** * | • Receiver deployment<br>• Transmitter setup<br>• **Quality Assurance** * | • Data merge<br>• Processing<br>• Evaluation | • **3D modeling** *<br>• Noise merge<br>• Gen. synthetic data<br>• Processing<br>• Evaluate | • Receiver deployment<br>• Transmitter setup<br>• **Quality Assurance** * | • Data merge<br>• Processing<br>• Focus anomaly | • **3D modeling** *<br>• Model adjustment<br>• Direct image<br>• Integration |

* denotes time consuming tasks




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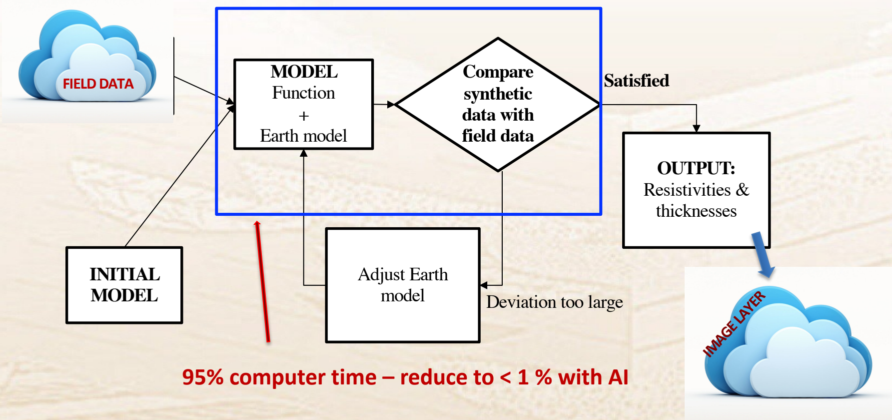
Background & physics >> Methods >> Example >> issues & path forward

## CLOUD / AI / DL: 3D inversion – optimized interpretation







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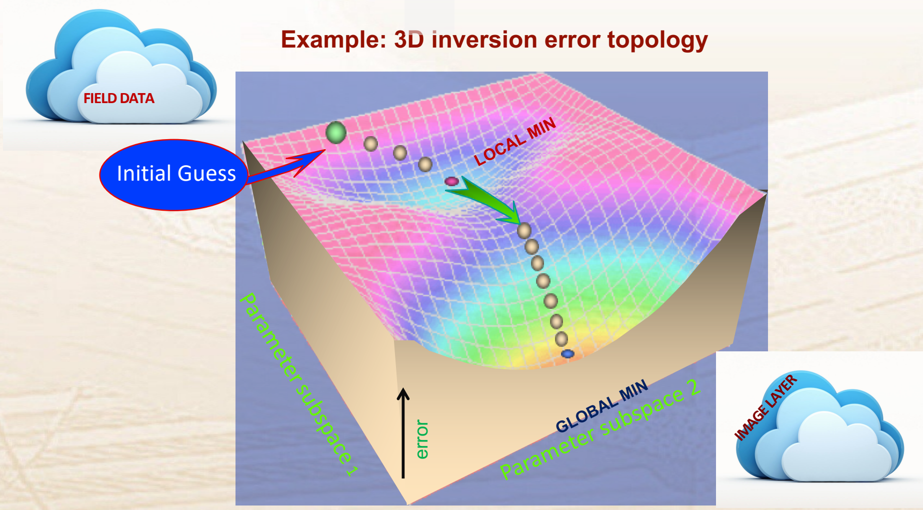
**CLOUD / AI / DL: Avoid the pitfalls**

**Example: 3D inversion error topology**



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Background & physics >> Methods >> Example >> **issues & path forward**

**Conclusion: Using EM for CCUUS**

- EM is a key methods for fluid monitoring
- CCUS has strong resistivity contrast
- For EM it requires: HIGH power CSEM
- To date, only limited results with ERT (borehole), MT; No real case history yet available
- CSEM: Technology is here – commercial
- Future Cloud based and AI enabled for real time monitoring



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## Thank You!


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