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Application of Neural Networks and Machine Learning in Tiltmeter Analysis in Hydraulic Fracturing Diagnostics*

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Abstract

This article presents a new machine-learning method of processing surface or downhole deformation data during hydraulic fracturing to obtain more reliable fracture diagnostic information such as fracture length and azimuth in real time. The results are then compared to the current method, the inversion of fracture models, by using synthetic and actual data. Several types of neural networks are designed, based on the type of known data and the desired output. These types include feed-forward, time-delay, and pattern recognition neural networks. The number of hidden layers varies between 5 and 20, and number of training samples varies from 10,000 to 50,000 samples. After training, the network was tested against known fractures, and the error of fracture properties was measured. Gaussian noise was added to the input deformation data to simulate real-world conditions.

Four fracture systems are defined in this work: (a) single vertical fracture, (b) dual vertical fractures, (c) vertical + horizontal fractures, and (d) single horizontal fracture. Using a pattern recognition network, 448 of 500 test cases with all possible fracture systems were recognized correctly, which equates to only a 10% error. In the next step, the fracture azimuth was estimated, based on surface tilt data for a single vertical fracture with additional noise on tilt data; the resulting estimate had an error rate of less than 5%. Next, the fracture volume was evaluated from surface tilt-magnitudes with a very low error rate (less than 2%). Fracture half-length and width were also estimated from surface tilt-magnitudes; the error was greater than in the previous steps because the half-length and width are almost interchangeable from the tilt-magnitude point of view. With downhole tiltmeters, the evaluation of fracture height was off by less than 10% for the height and 1% for the TVD of the fracture. Finally, two methods are presented to evaluate the network to obtain the probability of results and the uncertainty of output values for each case. Considering the low error rates and uncertainty in general, neural networks can be used in several aspects of tilt analysis. No applicable method currently exists with which to evaluate fracture properties (azimuth, half-length, height, and proppant volume) from deformation data in real time. This new machine-learning method can be used to quickly perform the deformation data analysis, rather than the current, more manual, inversion fracture models that search for the minimum error.

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Principal Application Engineer

Halliburton

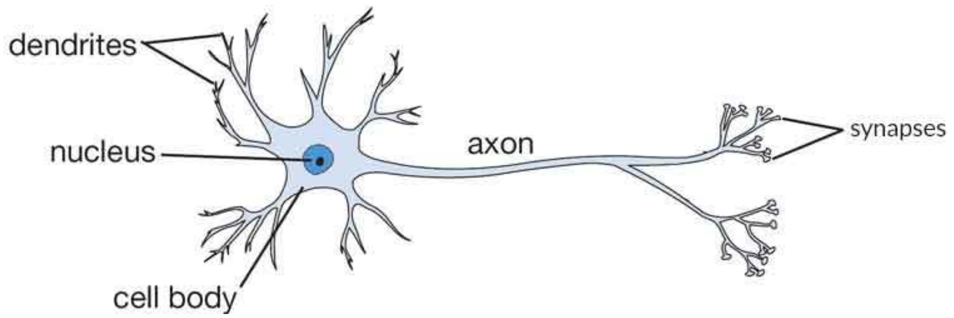
Introduction: Neural Networks

- An artificial neural network (ANN) is an information processing paradigm that is inspired by the biological nervous systems, such as the human brain’s information processing mechanism.
- The key element of this paradigm is the novel structure of the information processing system. It is composed of a large number of highly interconnected processing elements (neurons) working in unison to solve specific problems. NNs, like people, learn by example.
- An NN is configured for a specific application, such as pattern recognition or data classification, through a learning process. Learning in biological systems involves adjustments to the synaptic connections that exist between the neurons. This is true of NNs as well.

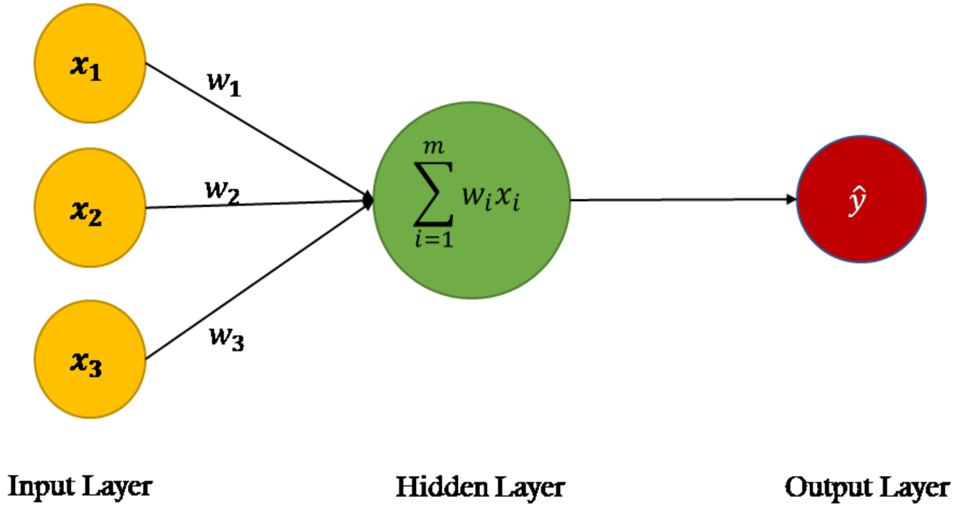
A Simple Neuron

- An artificial neuron is a device with many inputs and one output.
- The neuron has two modes of operation the
  - Training mode
  - Using mode

Biological Neuron



Artificial Neuron



A Simple Neuron (cont.)

- When a neuron receives excitatory input that is sufficiently large compared to its inhibitory input, it sends a spike of electrical activity down its axon. Learning occurs by changing the effectiveness of the synapses so that the influence of one neuron on another changes.

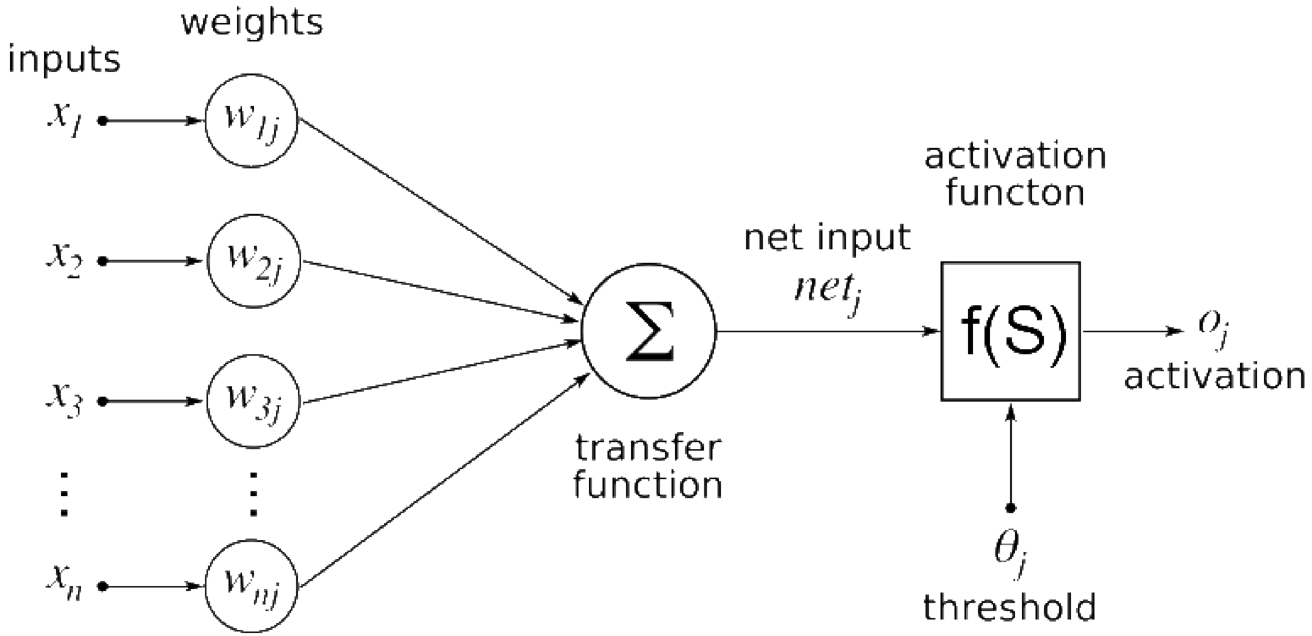


Diagram of an Neural Network

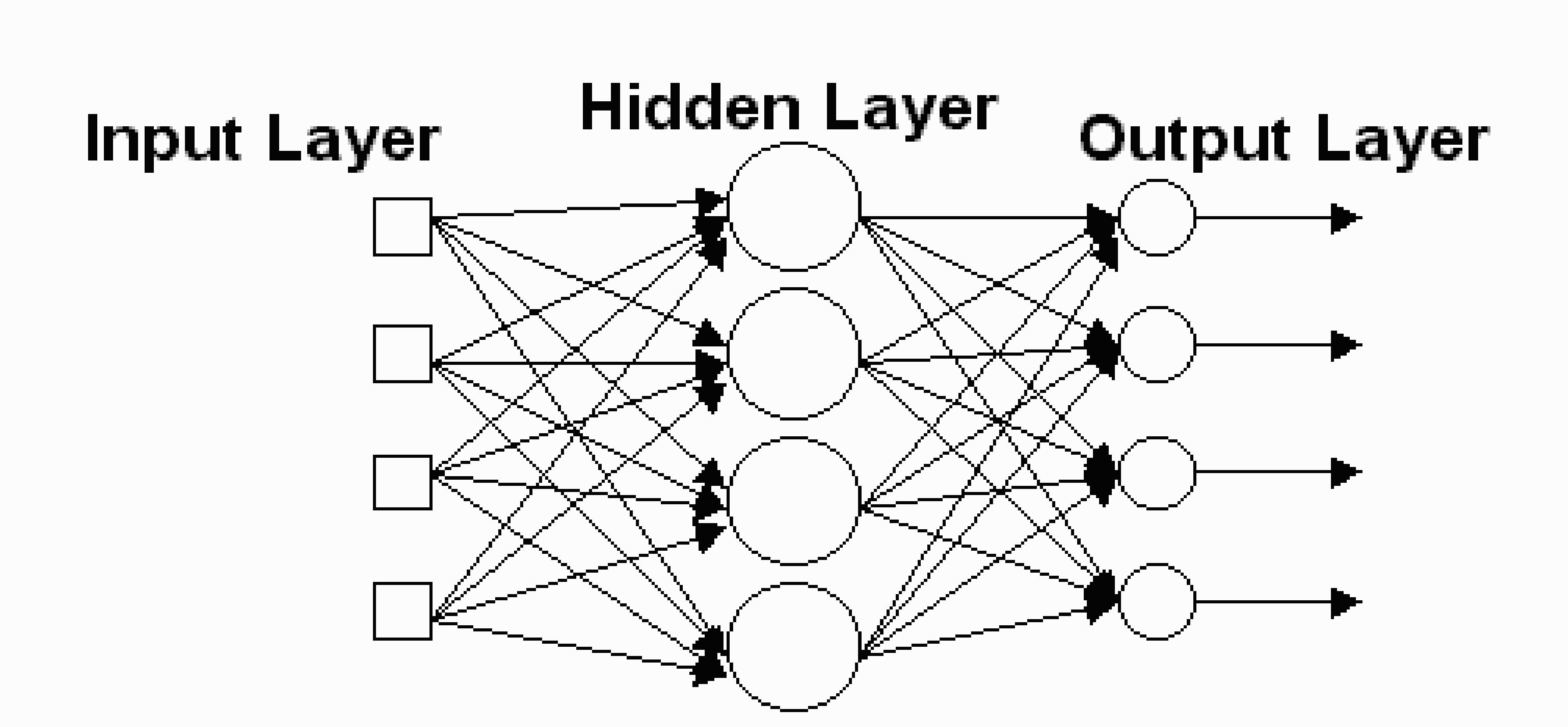
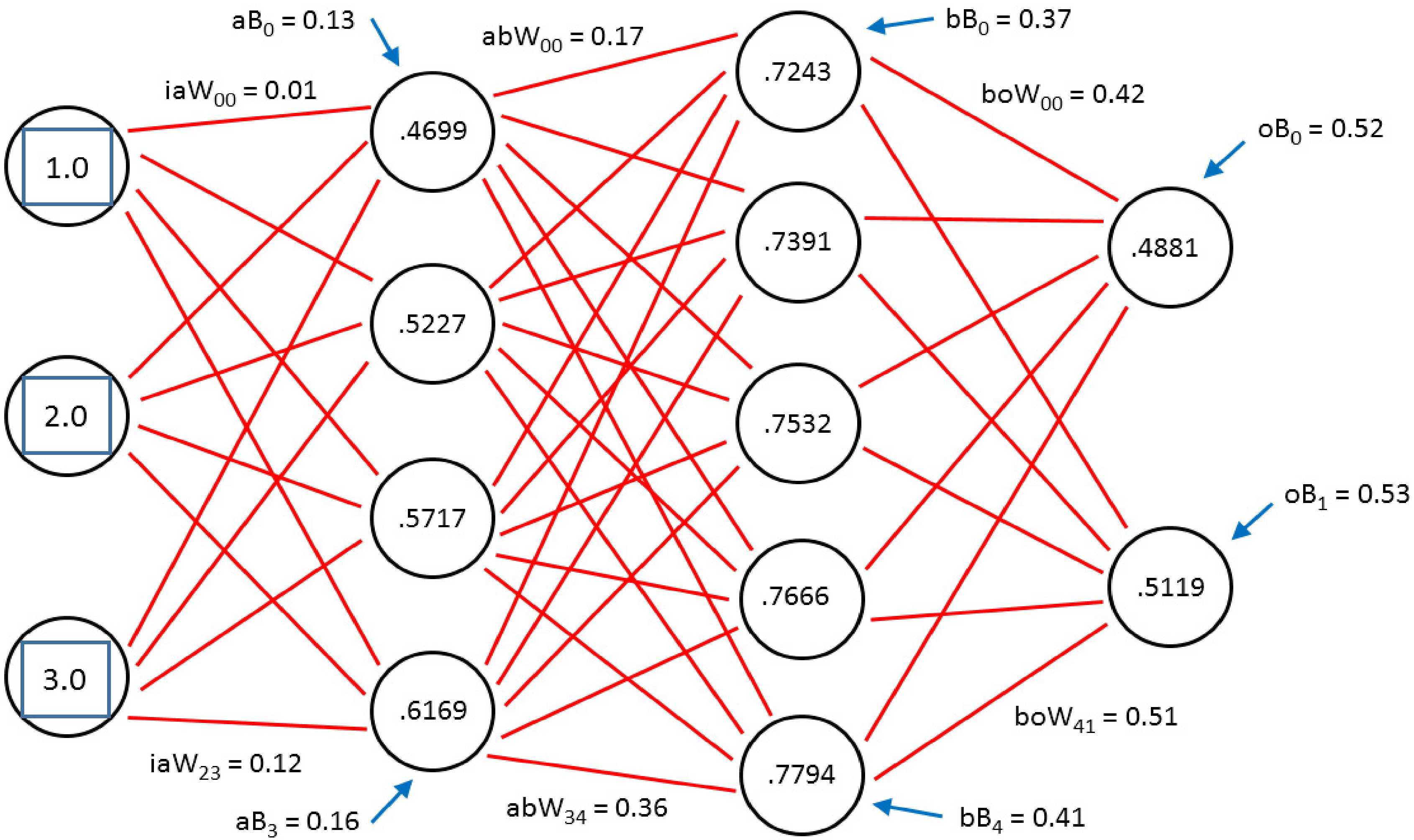


Diagram of an Neural Network



Feed-Forward Networks

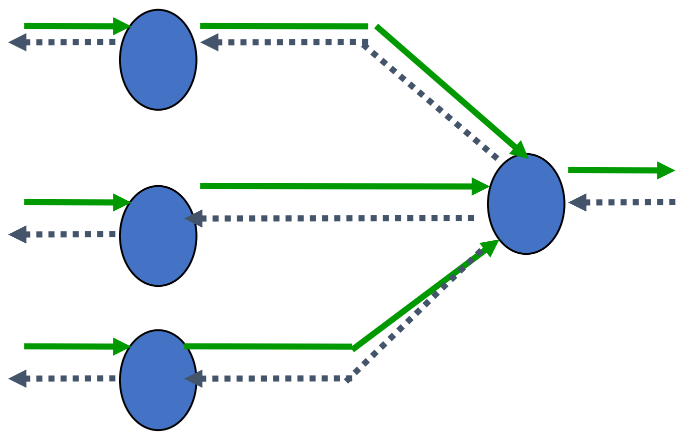
- Feed-forward NNs allow signals to travel one way only, from input to output. There is no feedback (loops) (i.e., the output of any layer does not affect that same layer).
- Feed-forward NNs tend to be straight forward networks that associate inputs with outputs.

Supervised Learning

- Supervised learning, which incorporates an external teacher, so that each output unit is told what its desired response to input signals ought to be.
- The goal is to determine a set of weights which minimize the error. One well-known method, common to many learning paradigms, is the least mean square (LMS) convergence.

Back Propagation

Back-propagation training algorithm:

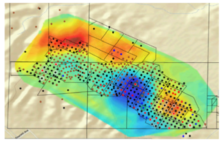


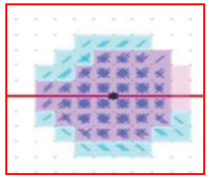
Network activation
Forward Step

Error propagation
Backward Step

Backprop adjusts the weights of the NN in order to minimize the network total mean squared error.

Microdeformation – Evolution (*1992 – current*)





1992 — Tiltmeter Fracture Mapping

1994

1996 — Offset Well Tiltmeter

1998 — Tiltmeter Reservoir Monitoring

GPS Data Integration

2000 — Web-based Client RM Services

2002 — Treatment Well Tiltmeter

2004 — InSAR Reservoir Monitoring

2006 — InSAR / GPS Integration

GIS Integration

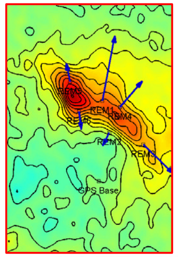
2008 — Intelligent Field Workflows

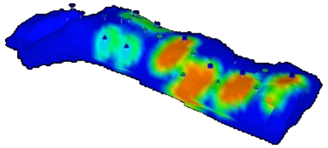
2010 — Reservoir Simulator Integration

2012 — Stimulated Reservoir Characterization (SRC)

Subsea Tiltmeter Development

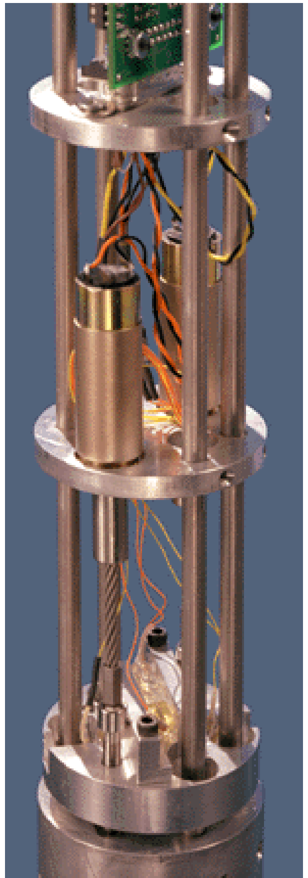
2014 — Hybrid Frac Diagnostics (FracHeight)

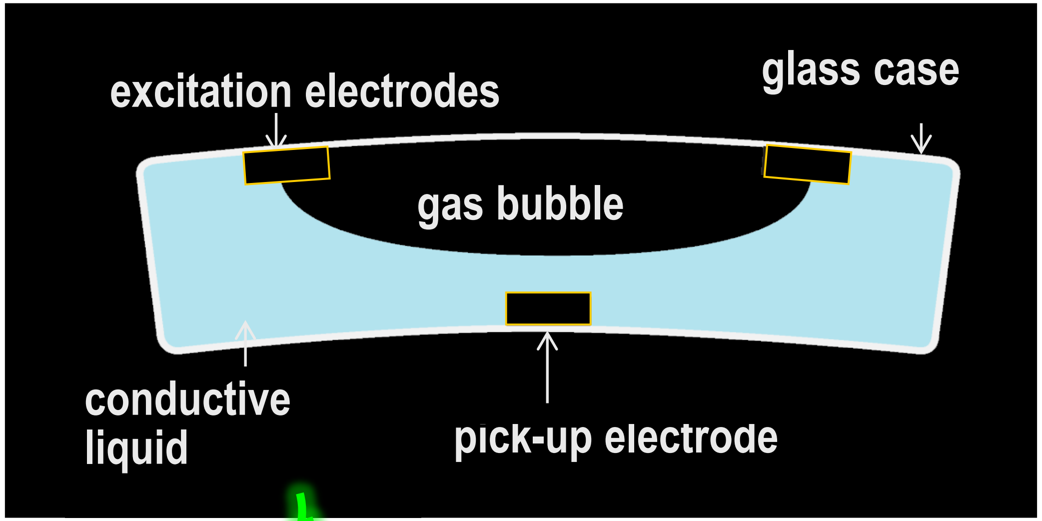




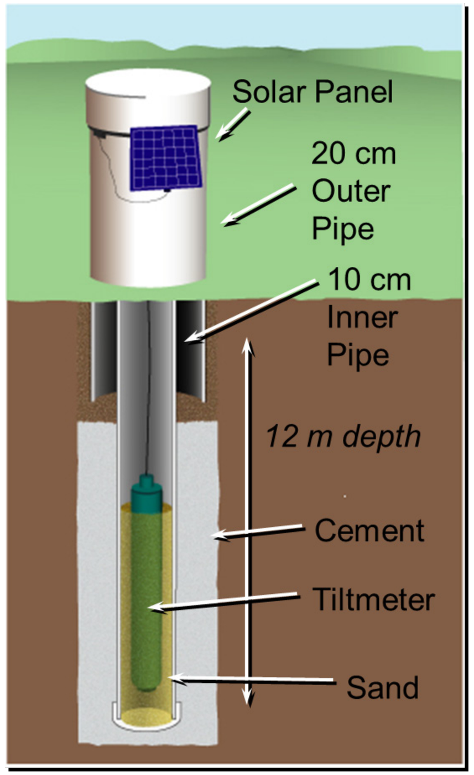
Principal of a Tiltmeter

A tiltmeter is like an extremely sensitive carpenter's level
When the sensor tilts the resistance between the electrodes changes





It can measure tilt down to approx 1 *nanoradian.*
1 billionth of a radian
or approximately
one thousandth of a millimeter per km


Solar Panel
20 cm
Outer
Pipe
10 cm
Inner
Pipe
12 m depth
Cement
Tiltmeter
Sand

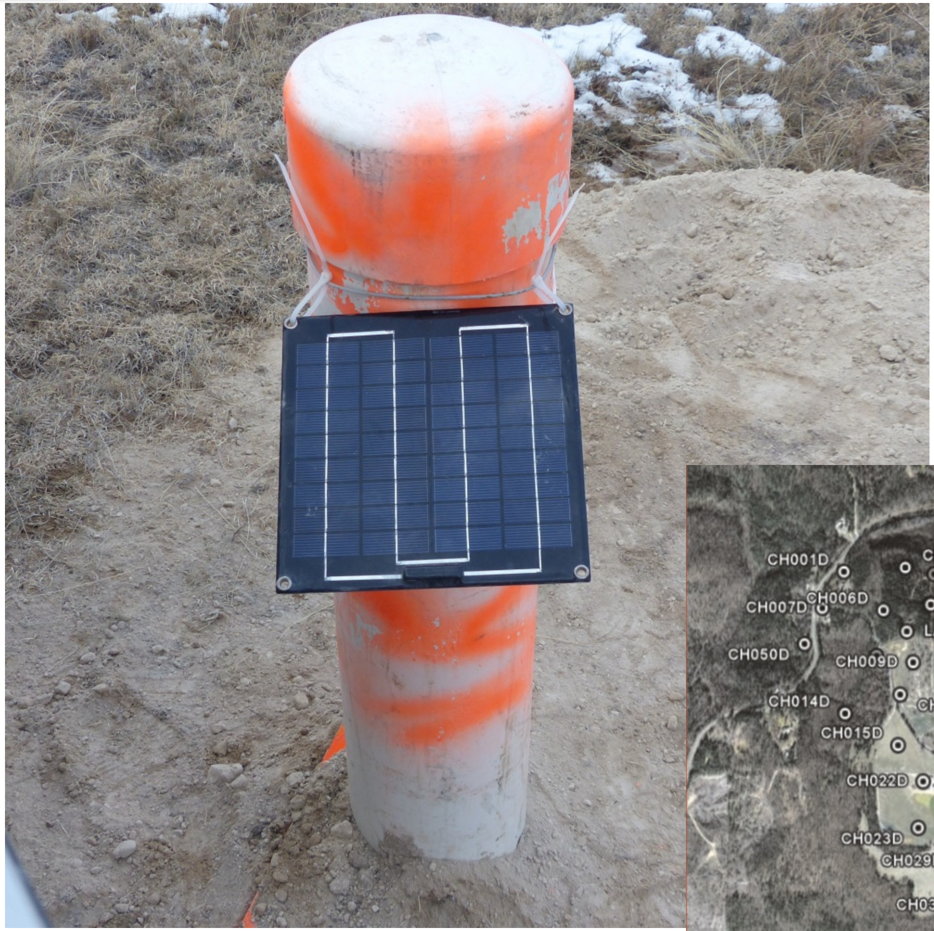



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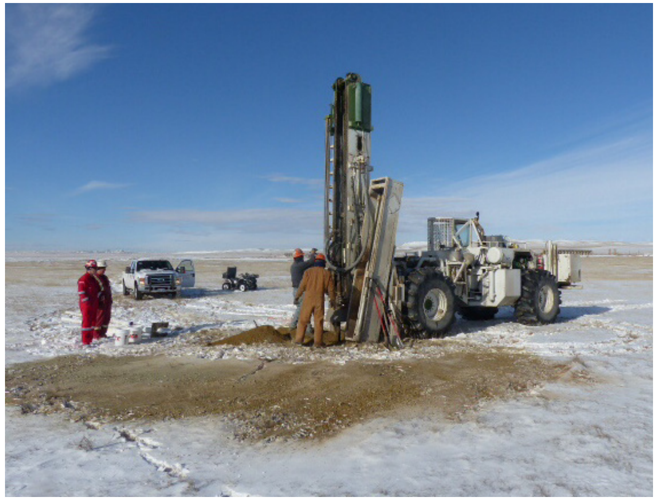
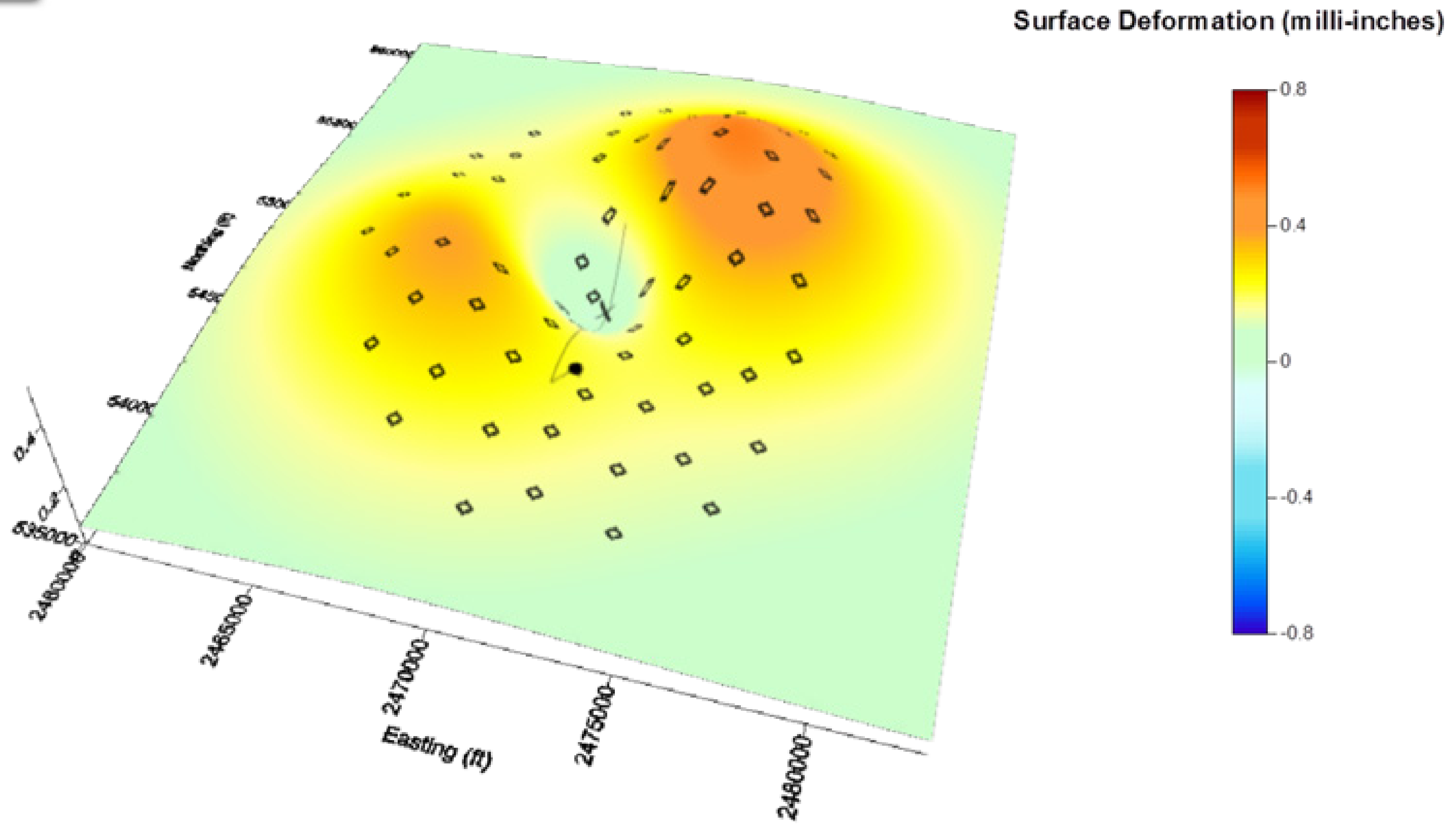
Image State of Arkansas



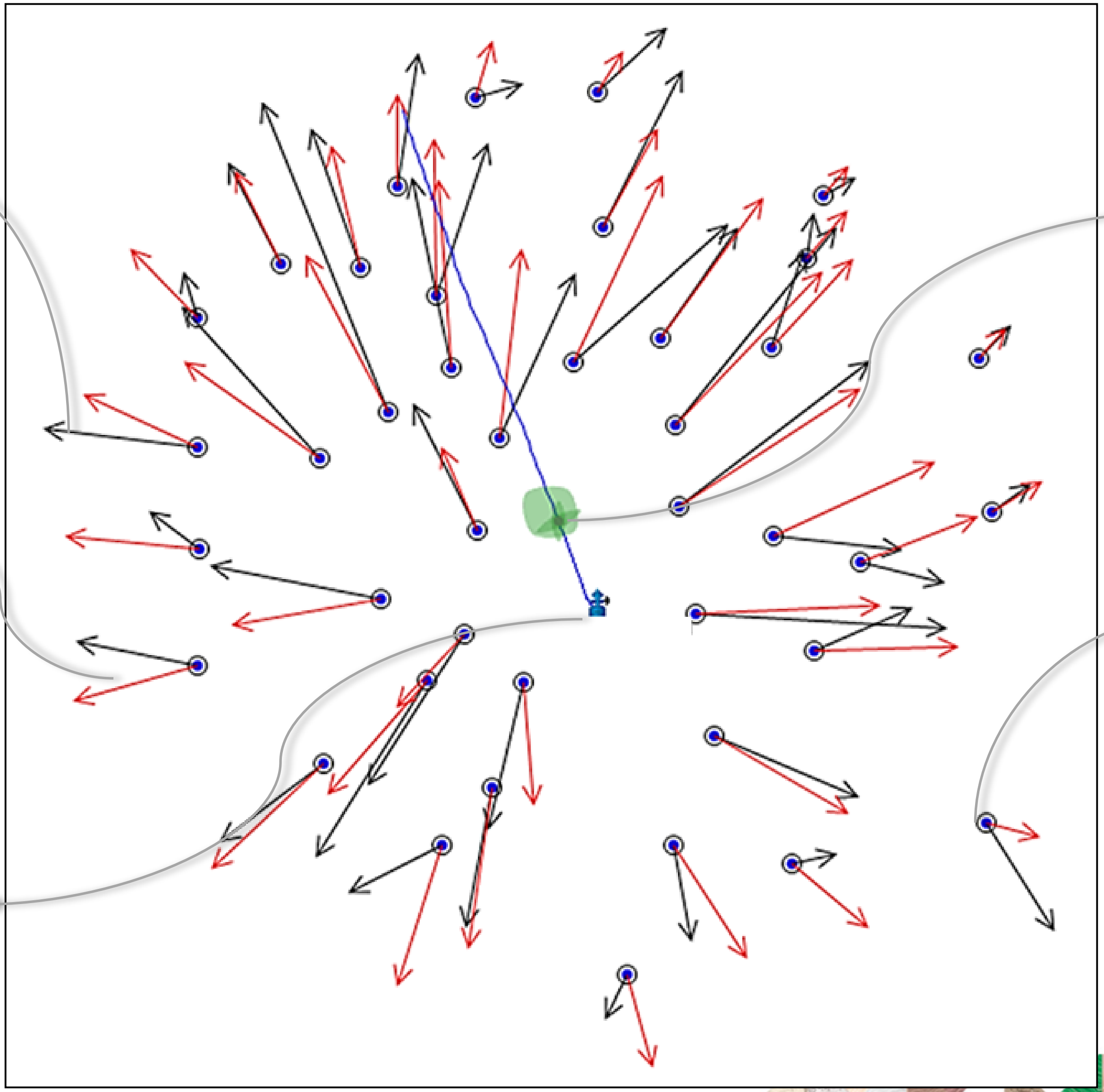

Surface Deformation (milli-inches)
0.8
0.4
0
-0.4
-0.8
Easting (ft)
2460000
2465000
2470000
2475000
2480000
535000
5400
0.2
0.4

Field Data: Map View

Black: Measured Tilt on Surface

Red: Theoretical Tilt on Surface

Oil Wellhead



Theoretical Induced Fracture at Depth

Installed Tiltmeter

Application of Neural Networks in Microdeformation Analysis

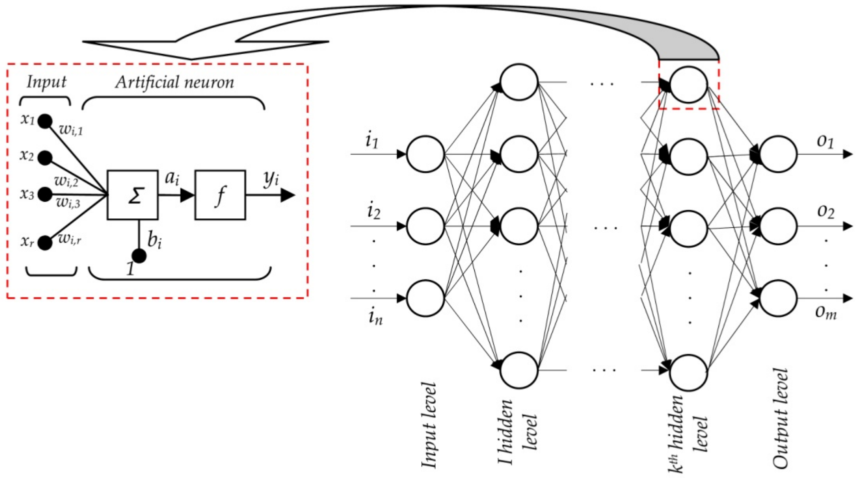
Machine Learning Implementations

- Different types pf networks were used for these purposes:
  - Tilt prediction during frac'ing
  - Surface tilt $\Rightarrow$ fracture network system
  - Surface tilt $\Rightarrow$ fracture azimuth
  - Surface tilt $\Rightarrow$ fracture volume
  - Surface tilt $\Rightarrow$ fracture HL and width
  - Downhole tilt $\Rightarrow$ fracture height and TVD

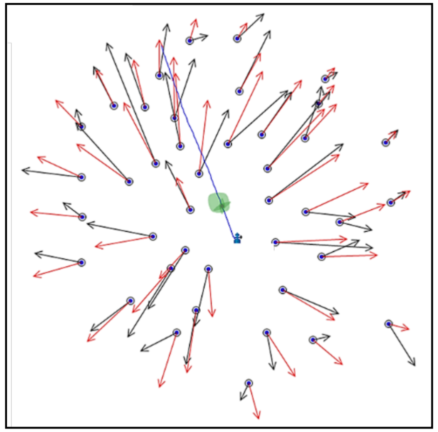
Applying Tilt Data into a Neural Network

Inputs:
Tilt of each channel of all sites
+
Some known data

T1x
T1y
T2x
T2y
.
.
.
Tnx
Tny

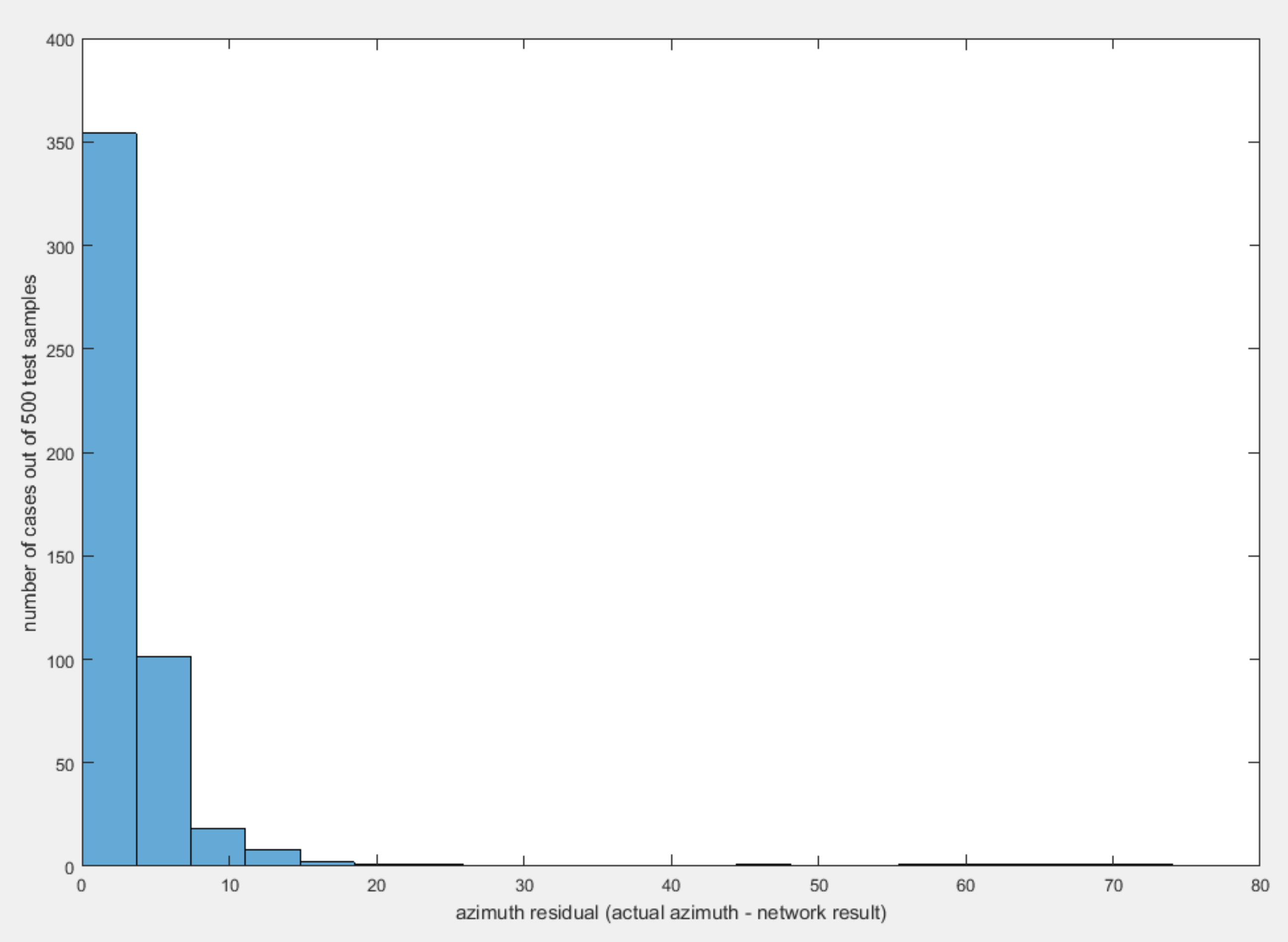


Output(s):
Could be fracture azimuth, volume, height etc.



A Glance to Results

- Estimation of frac azimuth based on surface tilt data for a single vertical fracture with noise on tilt data sigma=0.05



A Glance to Results

- FracHeight example
- Error percentage of height and TVD of the fracture

Designing the Network

- Type of network was feed forward, time delay, or pattern recognition.

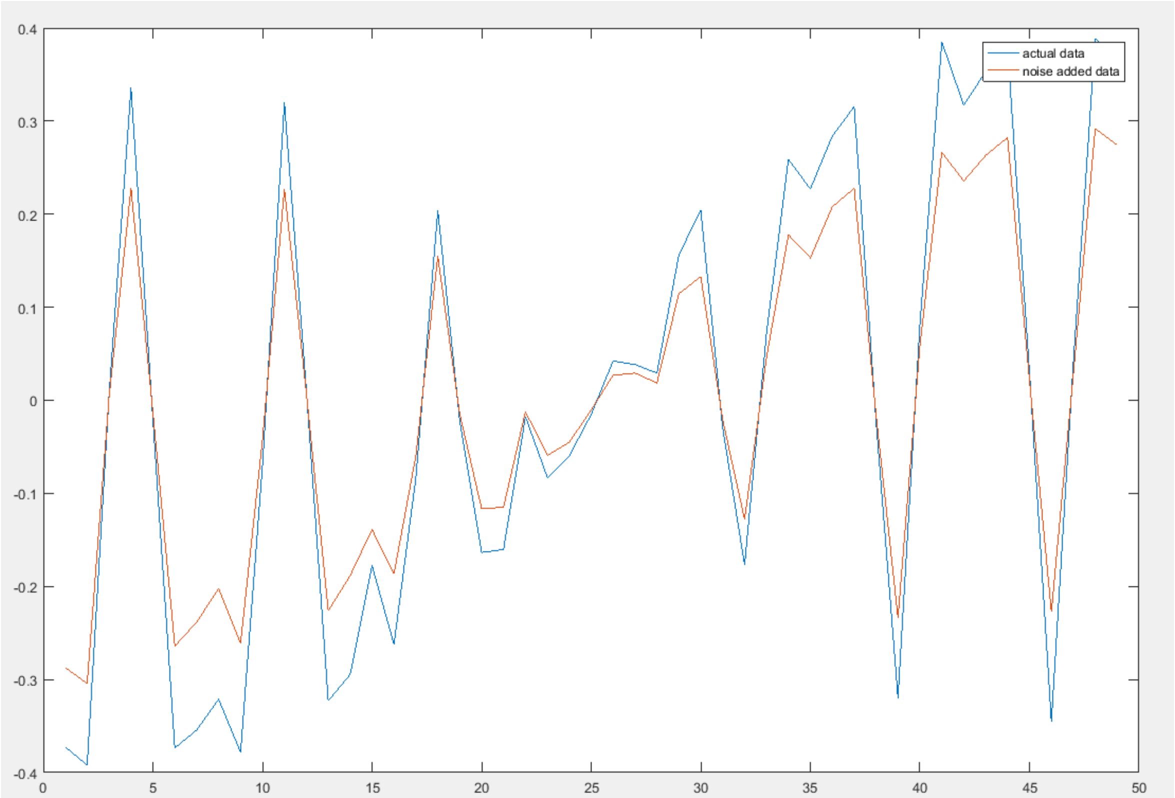
- Number of hidden layers varies between 5 to 20 for more complex scenarios.

- Number of training samples was 10,000 to 50,000 samples. In some cases more samples wouldn't improve the performance.

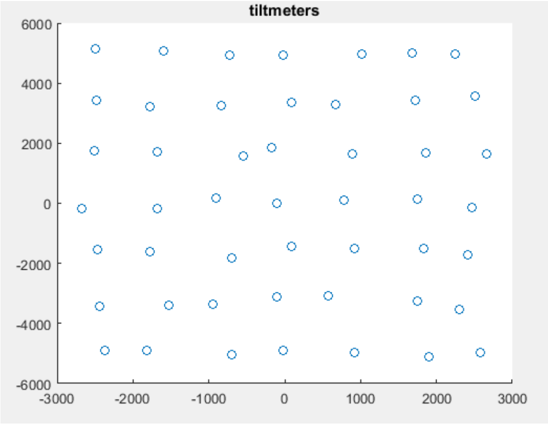
- Training function was Levenberg-Marquardt backpropagation in most cases.

Training Process

- Inputs for training is based on Okada model with exposed Gaussian noise to be close to reality:



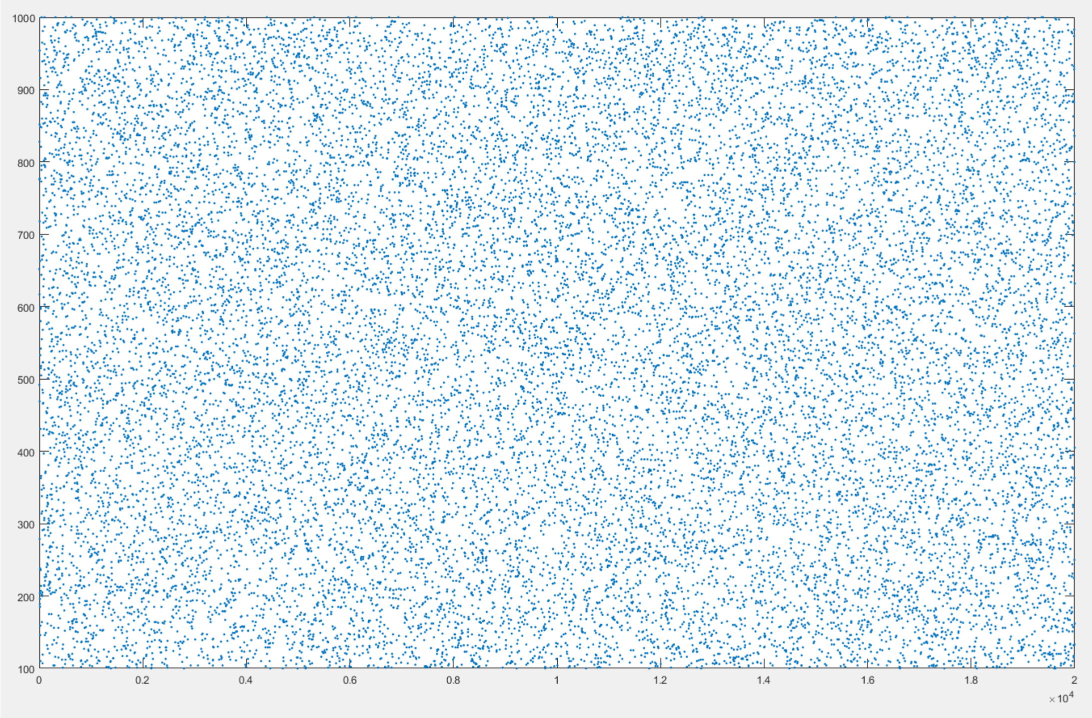
Example of X channel tilt with and without noise (sigma= 0.05) for tiltmeters



Tiltmeters Distribution

Training Process

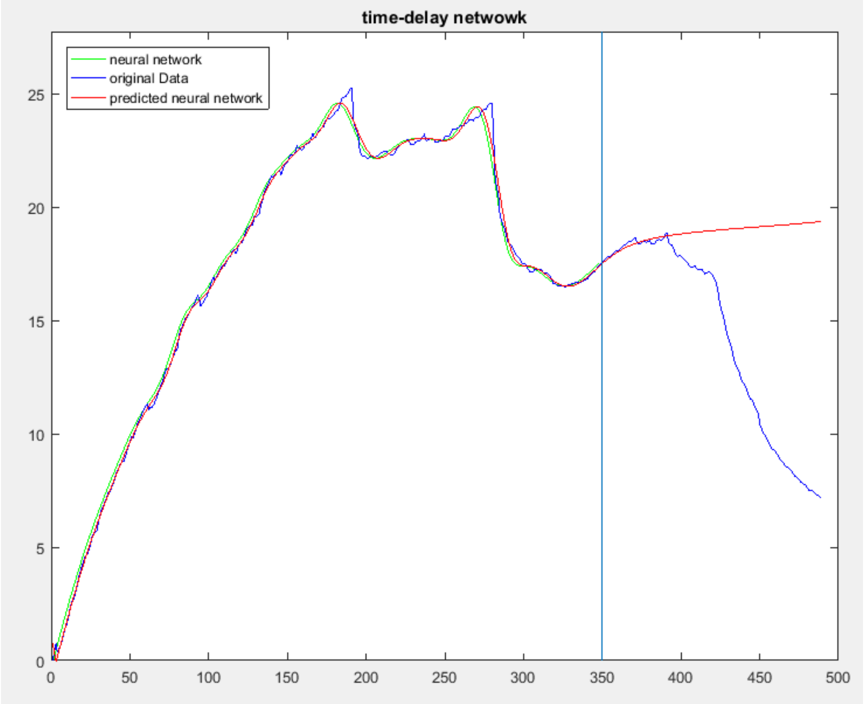
- Output for training varies based on the situation, for examples the height of fracture for downhole tilt data would be the target.
- Example of random distribution of height scenarios for 20,000 cases, height is between 100 to 1,000 ft:



Random distribution of test cases – Height vs Case#

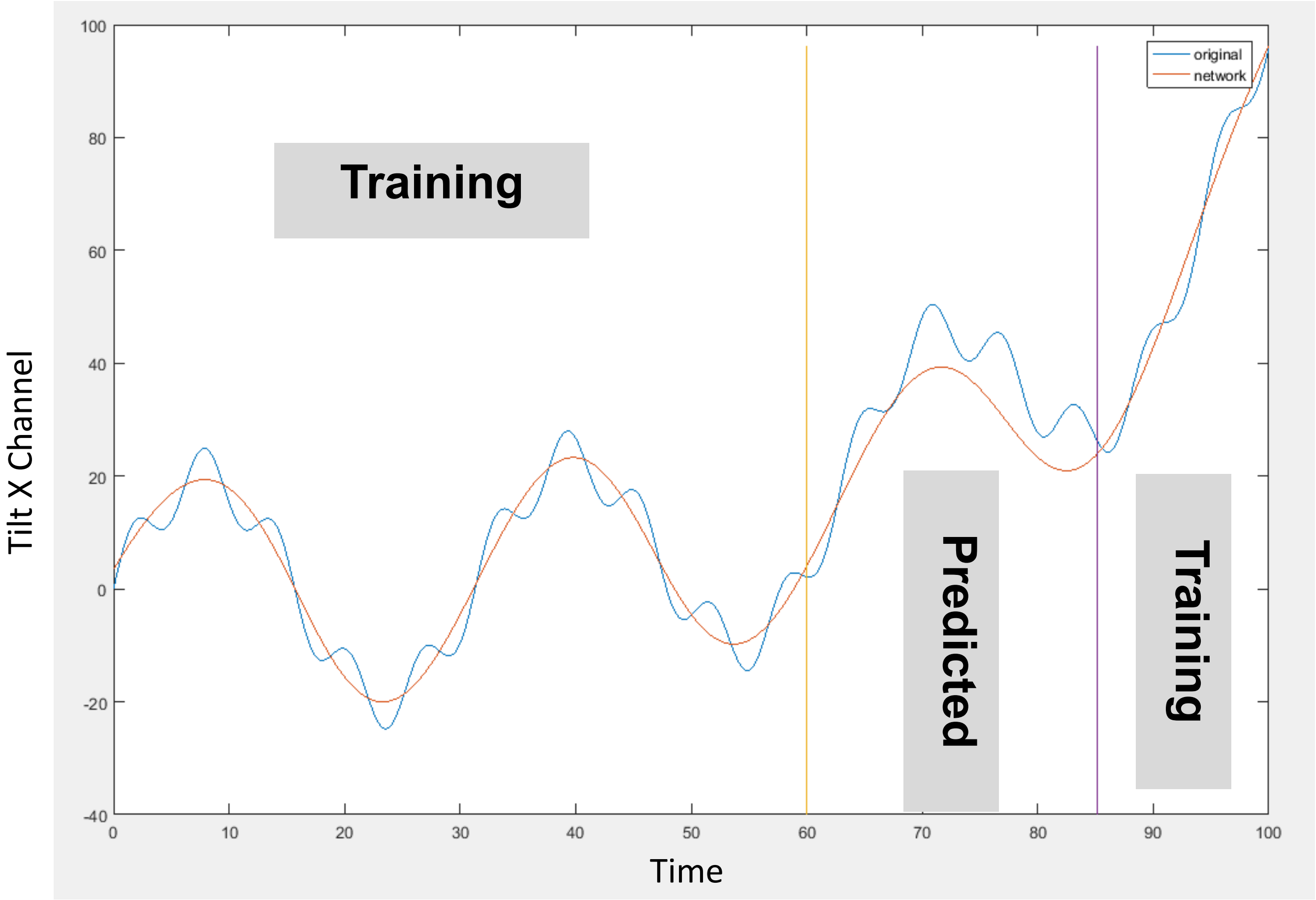
Example of Tilt Prediction

- It's a **Time Delayed** network.
- Y channel of an actual surface tilt; network predicted from point# 350 forward (red):
- Can be used for background noise estimation during the frac.
- Not ALWAYS matched the actual tilt due to random nature of data.



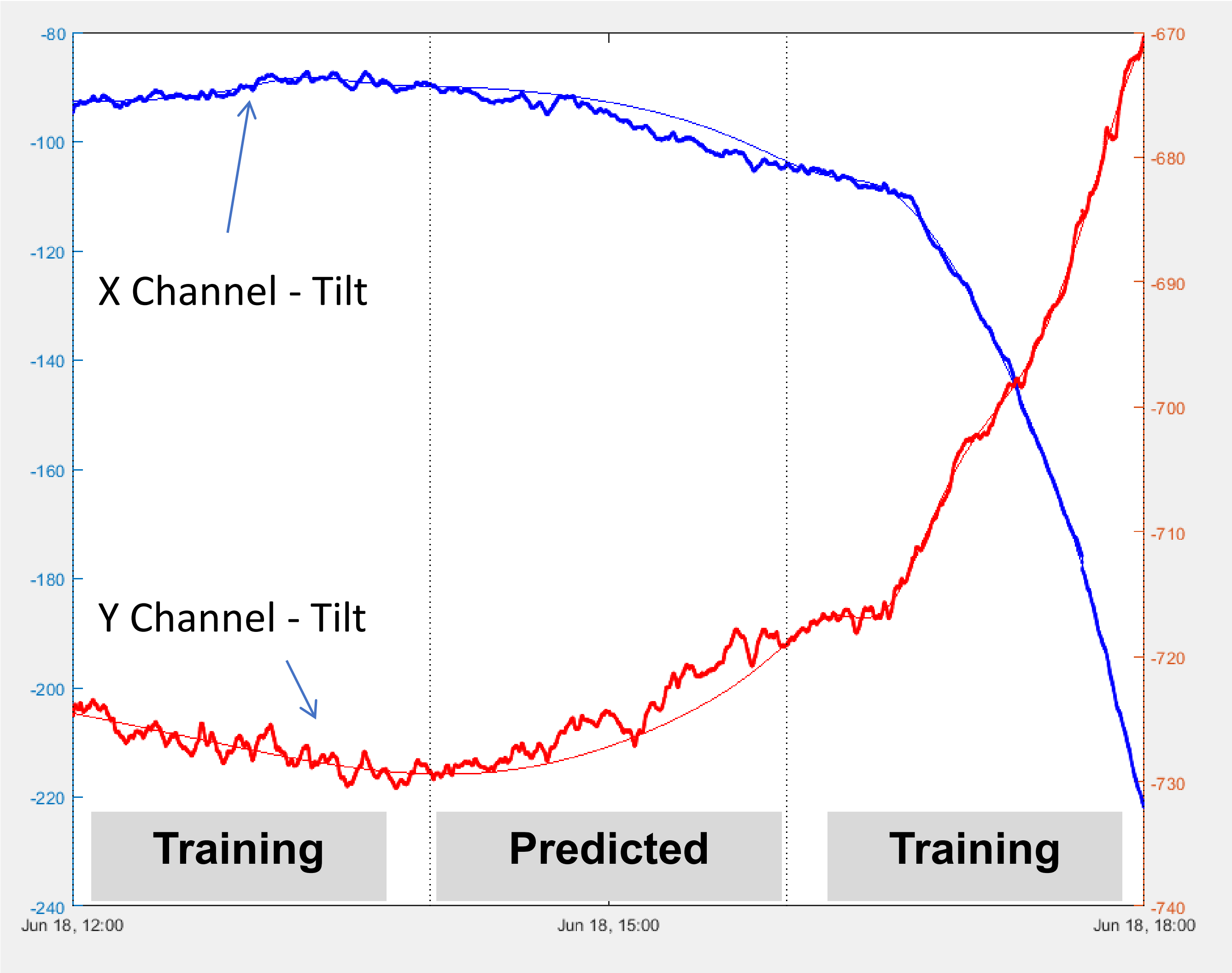
Example of Tilt Prediction

- Can be set for gap prediction with a FitNet network:



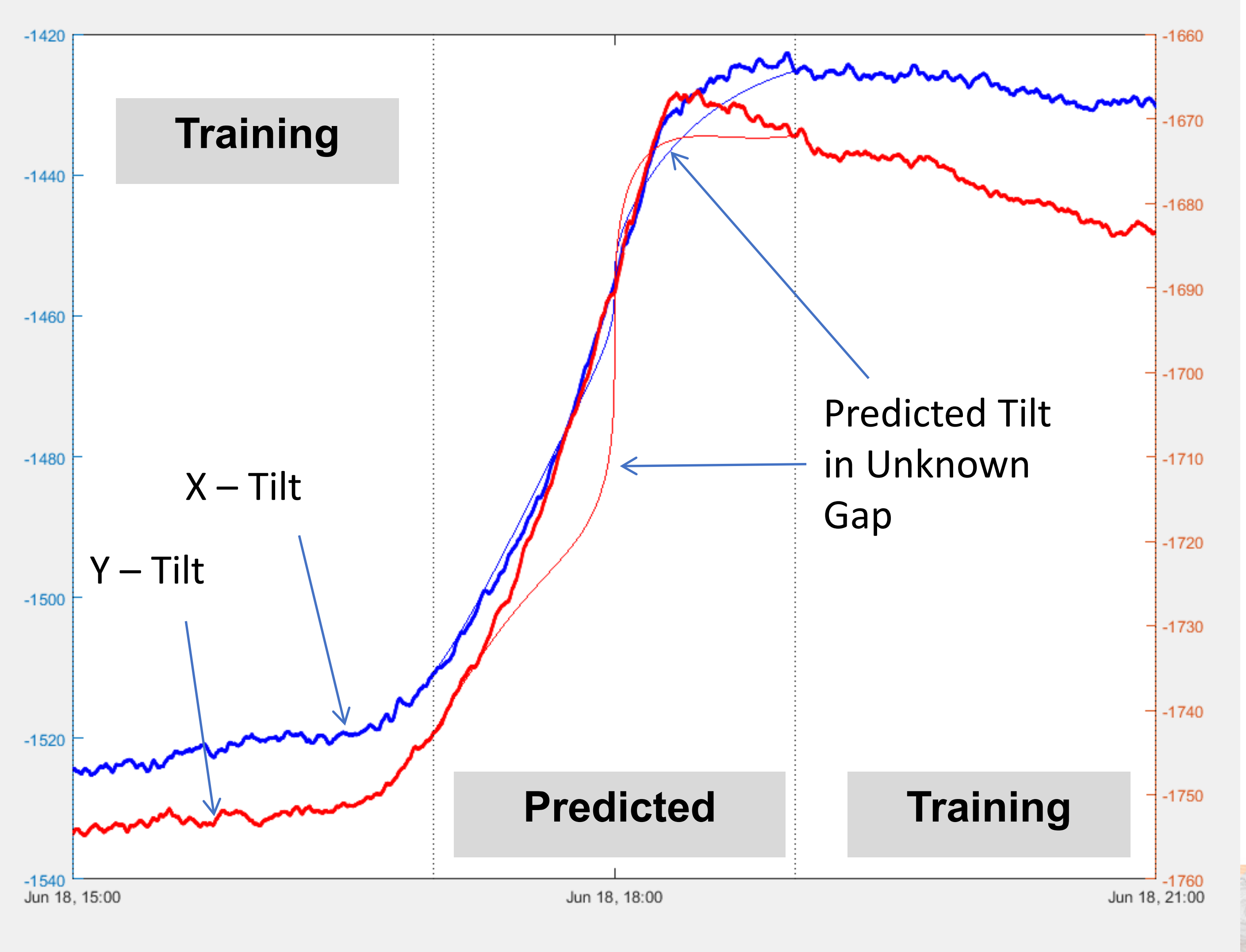
Example of Tilt Prediction

- With real data:



Example of Tilt Prediction

- More complex example:



Fracture Mapping Workflow

Field Raw Tilt Data → Detecting the Fracture System → Estimating Azimuth → Estimating Frac Volume → Estimating Half-length and Height → Fracture Dimensions and Orientation ✓

I. Detecting the **Fracture System**

II. In the next step, the fracture **azimuth** was estimated

III. Next, the fracture **volume** was evaluated

IV. Finally, fracture **half-length** and **width** together were estimated.

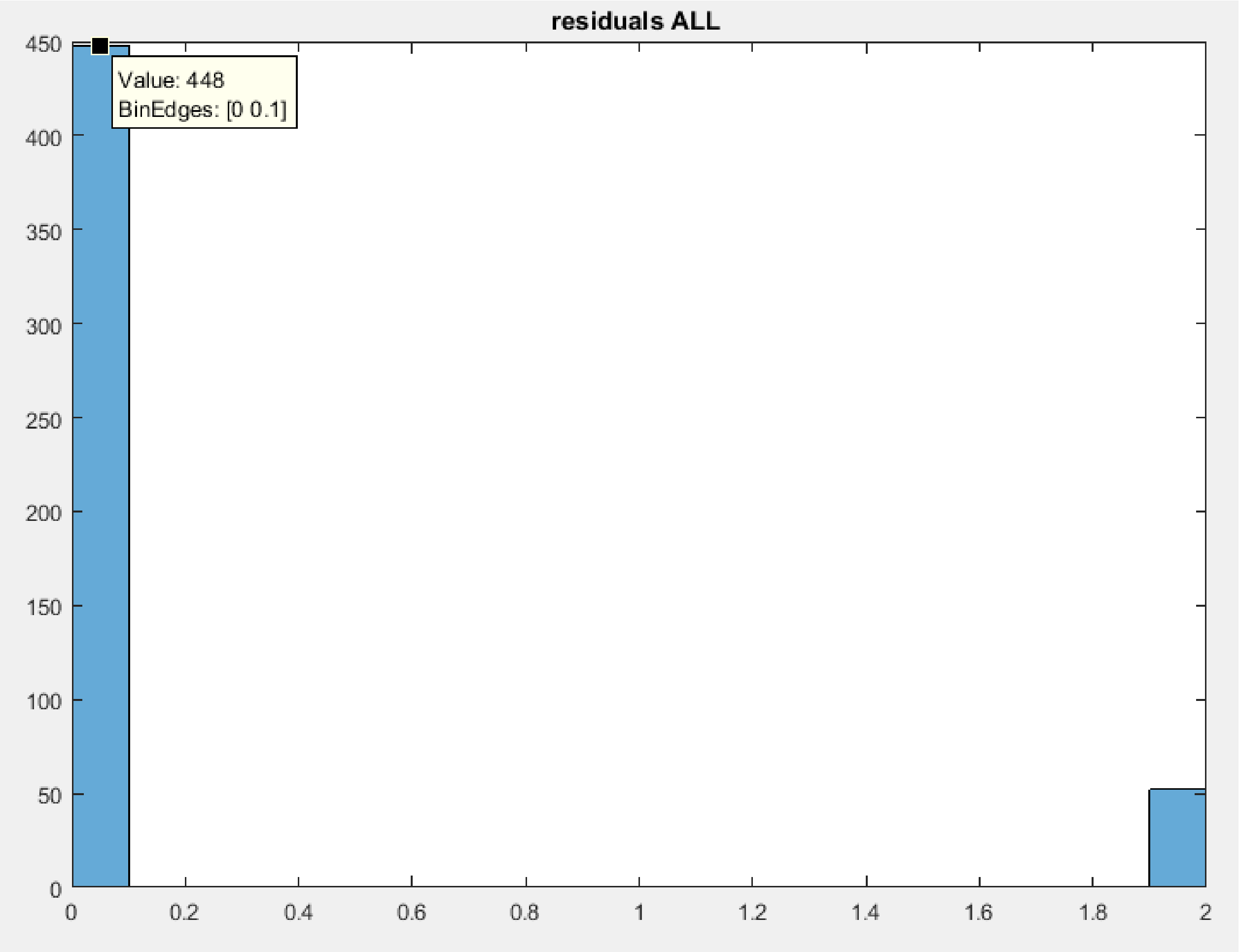
Fracture Network System Detection

- It’s a **Pattern Recognition** network.
- Four types of fracture system are defined:

    1. Single vertical fracture
    2. Dual vertical fracture
    3. Vertical + horizontal fracture
    4. Horizontal fracture

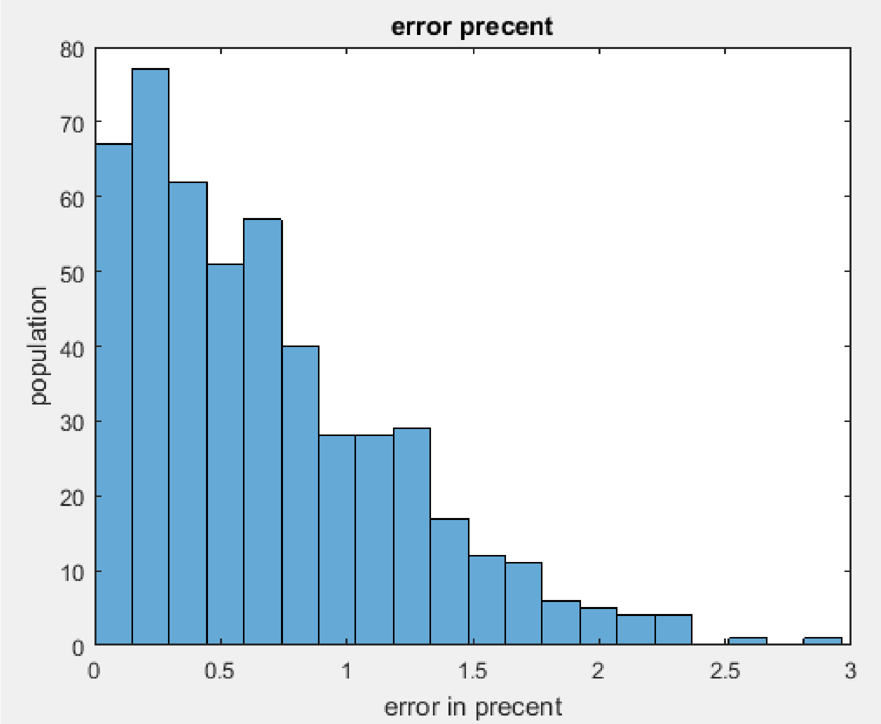
Example of fracture system detection (Cont.)

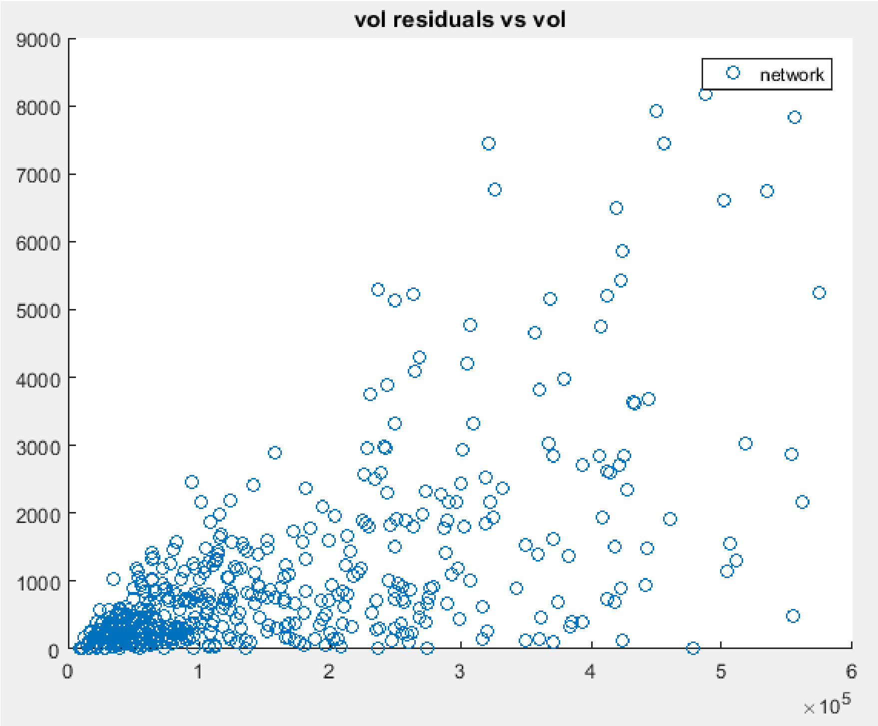
- Out of 500 test samples with all possible frac systems, 448 cases were guessed right, which means 10% error.



Example of Fracture Volume Estimation

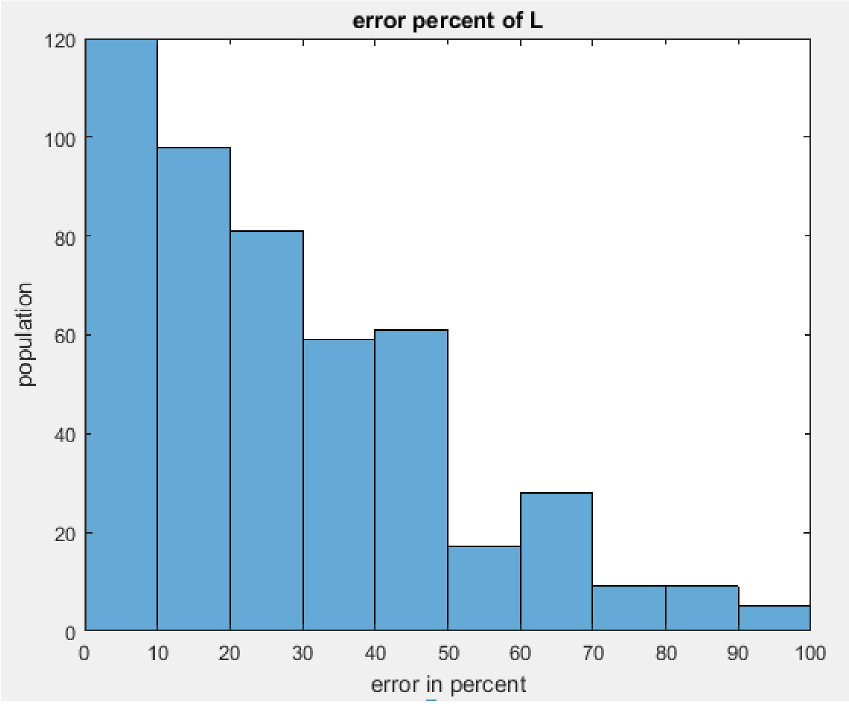
- Fracture volume is estimated from surface tilt magnitudes:
- Very low error:

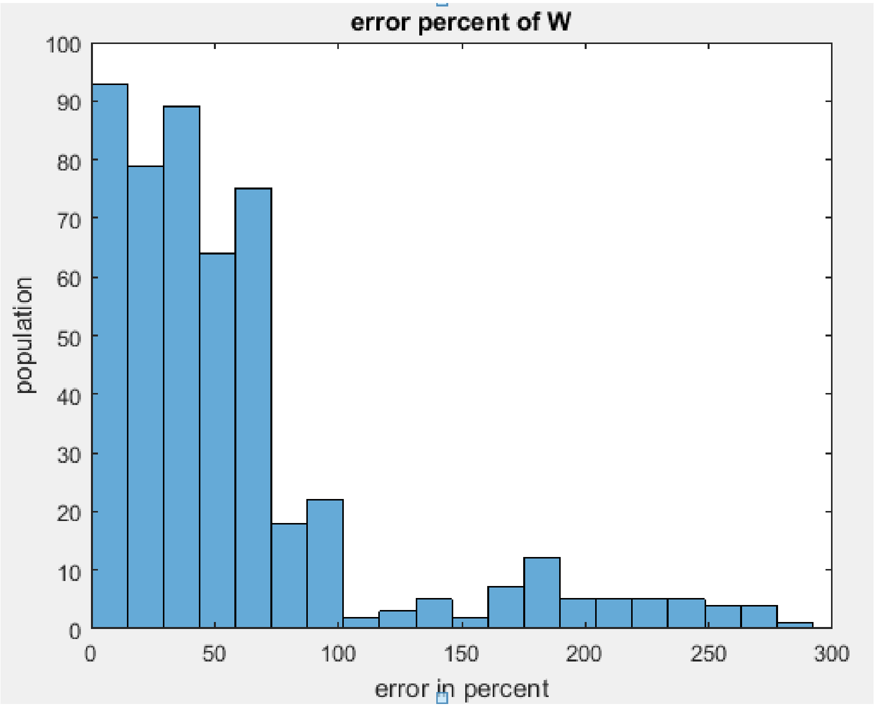




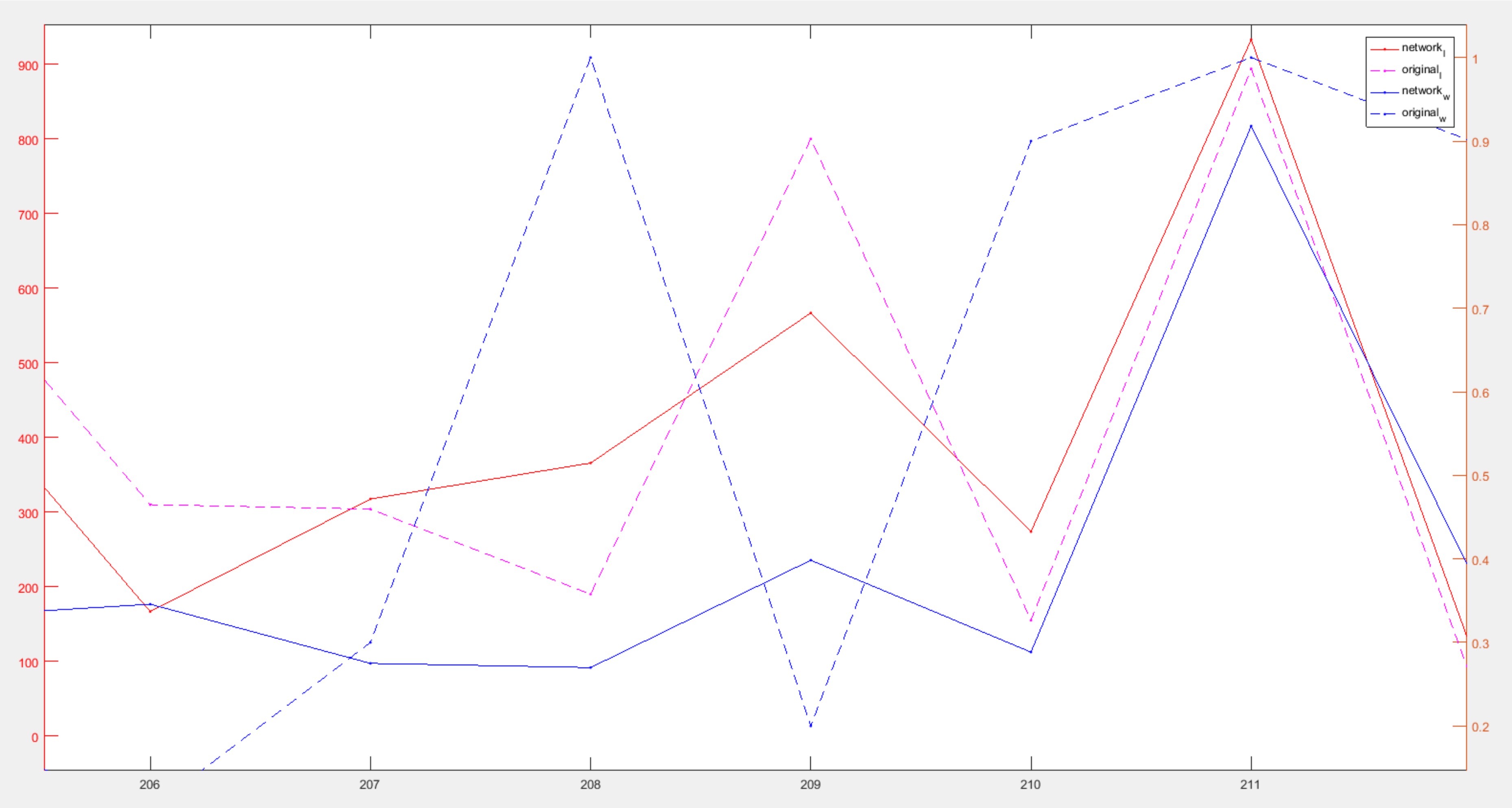
Example of Fracture HL and Width Estimation

- Fracture Half-length and width is estimated from surface tilt magnitudes:
- High error since HL and width are almost interchangeable from tilt-magnitude point of view (inj depth=5,000 ft):



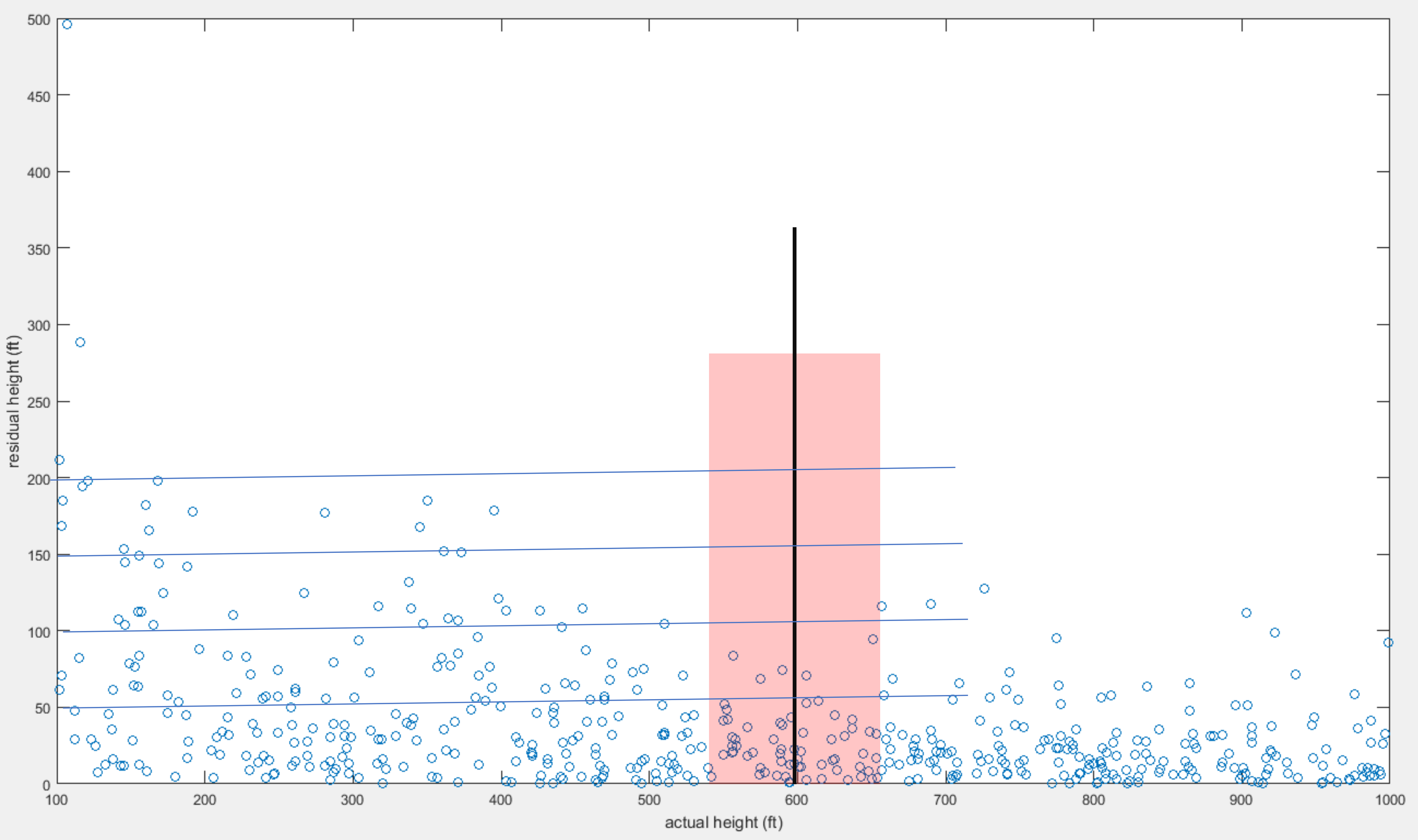


Example of Fracture HL and Width Estimation



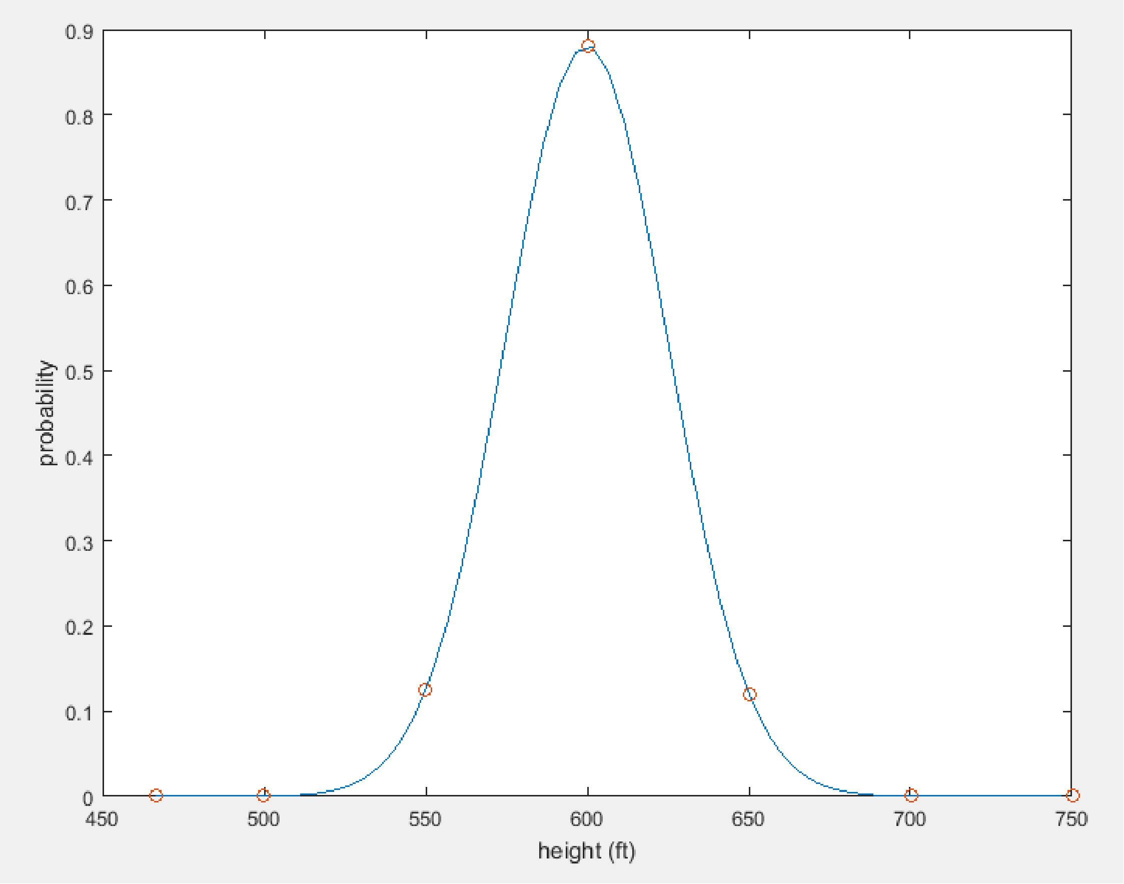
Network Evaluation (Method 1)

- Example of frac height probability:



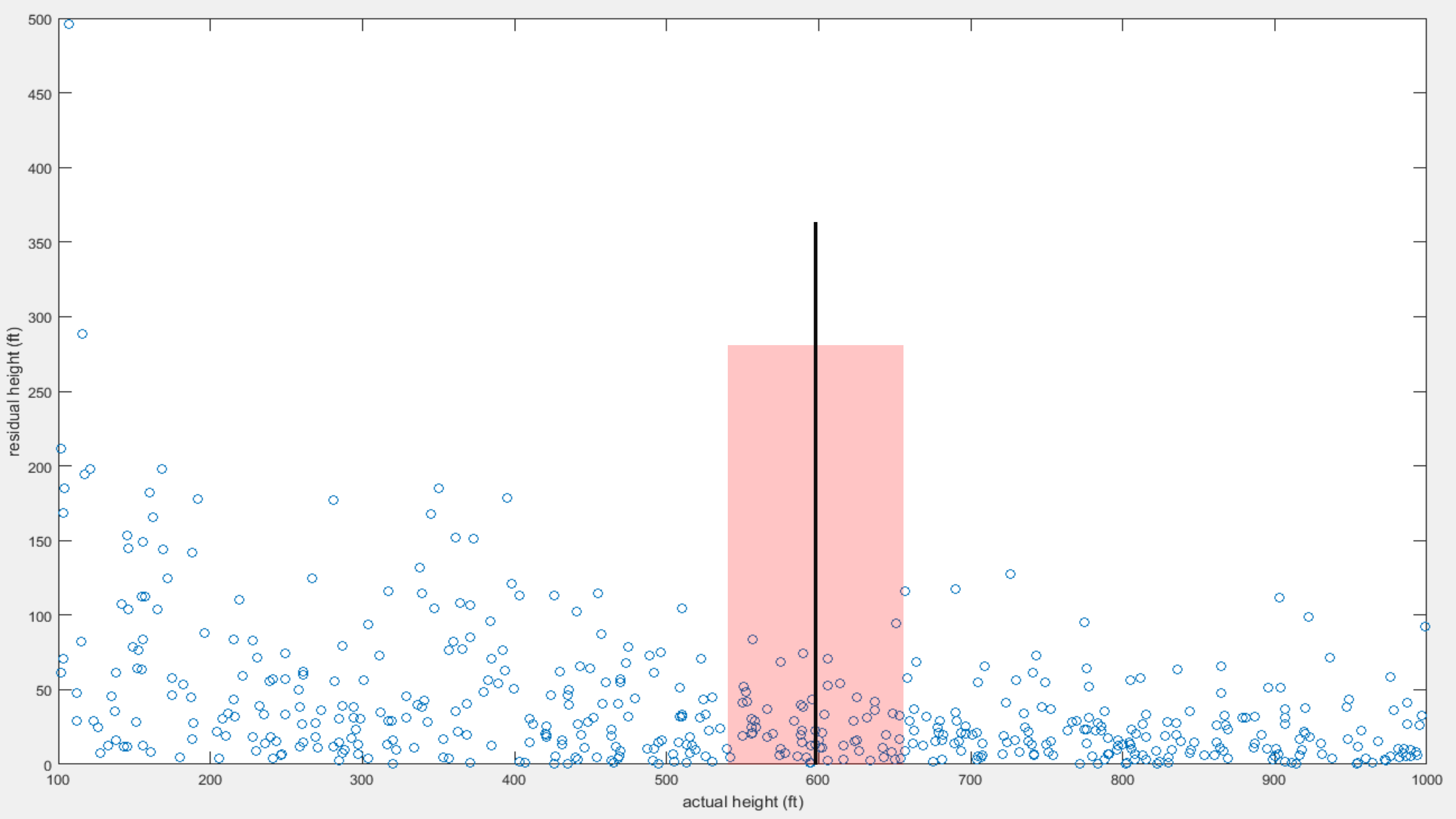
Network Evaluation (Method 1) (Cont.)

- Example of fracture height probability function for 600 ft height output:



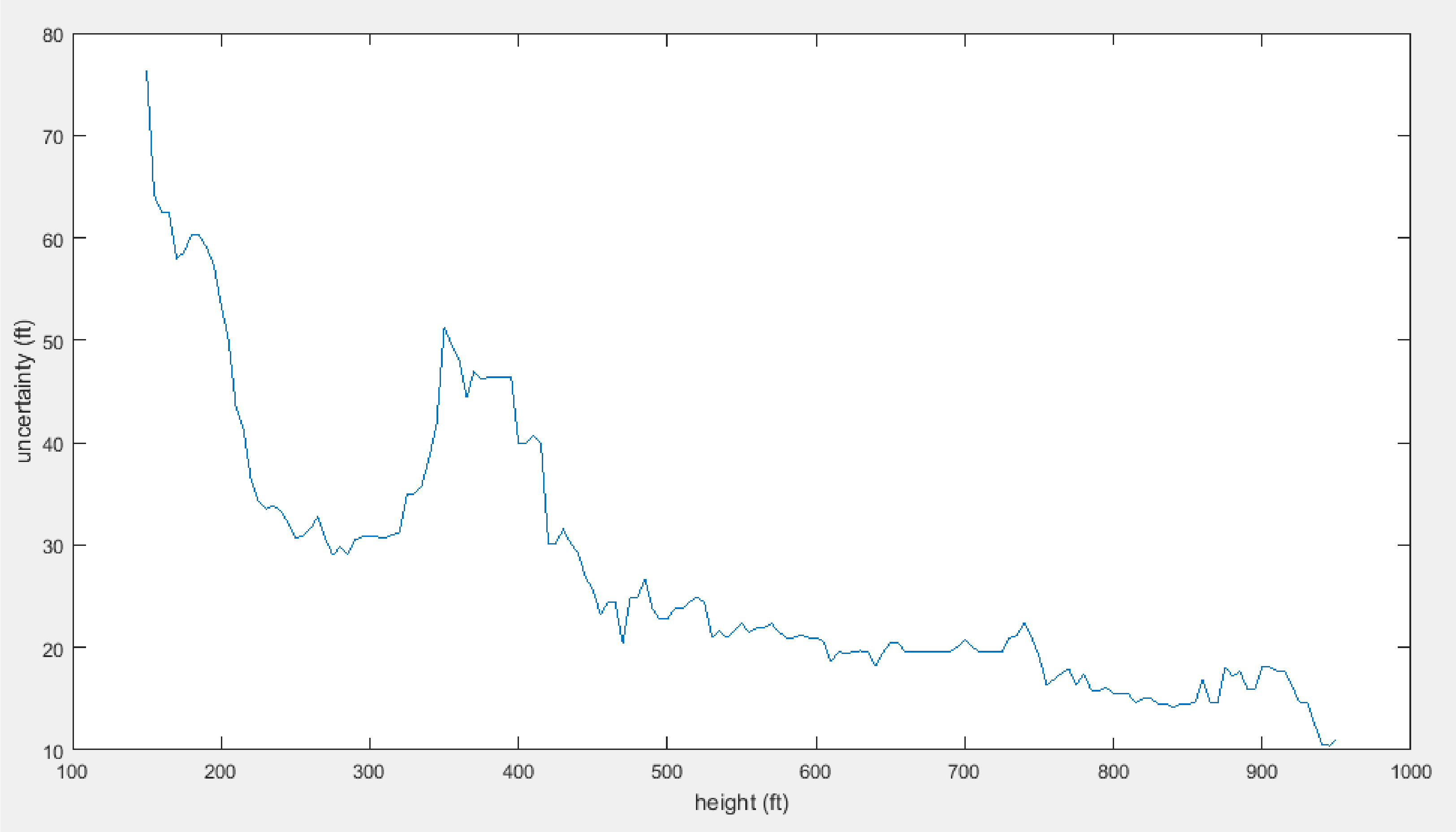
Network Evaluation (Method 2)

- Example of fracture height uncertainty:



Network Evaluation (Method 2, cont.)

- Based on median of data in the range (±50ft of the target):



Conclusions

- Based on synthetic data, Neural Networks can be used in several aspects of tilt analysis.
- Pros and cons:
    - The error could be very low for some properties of the fracture such as fracture network complexity detection, fracture orientation, and displaced sand volume.
    - Neural Networks like conventional methods, won’t give desirable results for the width and the length of the fracture.
    - Unlike current methods, this method can be used in real-time jobs to process the data instantly, no human processing needed.

Conclusions (Cont.)

- Two methods for evaluating a machine for surface tilt data processing were proposed:
  - Based on the probability of the reported output
  - Uncertainty of the result in measured unit

- What's next:
  - Working with actual data and compare results with current method

- Questions??