Simulation and Analysis for Rapid and Non-Invasive Soil Carbon Measurement Using Mobile Inelastic Neutron Scattering (MINS) Technology

THE UNIVERSITY OF TEXAS AT ARLINGTON

Jose A. Cortes[1], Andrzej Korzeniowski[1], Galina Yakubova[2], Aleksandr Kavetskiy[2], and Allen Tobert[2]

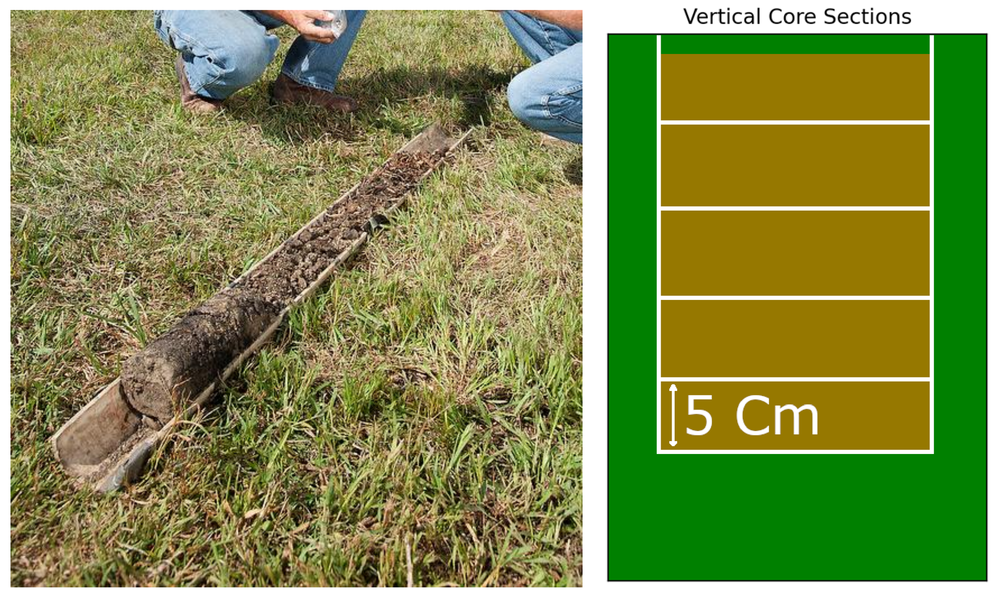
The University of Texas at Arlington, Arlington, Texas.[1] United Sates Department of Agriculture Agricultural Research Service Auburn Lab, Auburn, Alabama.[2]

Mathposium, November 15, 2024, SEIR Bldg, University of Texas at Arlington

Mobile - INS System

Introduction and Background

Soil nutrient measurements aid farming and emission management. **Core harvesting** is the common method to determine soil carbon content. Soil cores are taken to a lab for **Dry Combustion,** this gives precise measurements.



Figures A – Core Harvest for Dry Combustion

Alternatively, the **Mobile Inelastic Neutron Scattering System (MINS)** Detects levels of carbon in a scanned region on site, avoiding the cost and time of lab analysis.

Figures B – Mobile INS

Lab Analysis:
↑ Precision ↑ Cost ↓ Speed
MINS System:
-- Precision ↓ Cost ↑ Speed

Figure C - ContraMP320 Neutron Generator (DT)

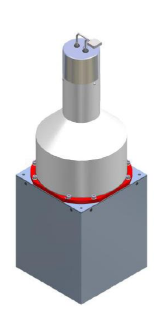
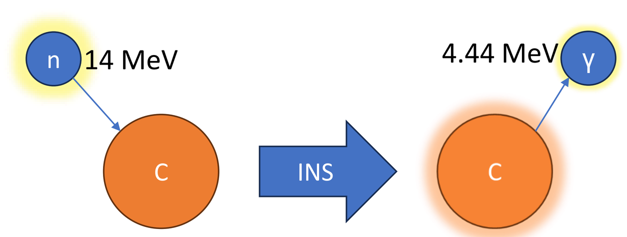


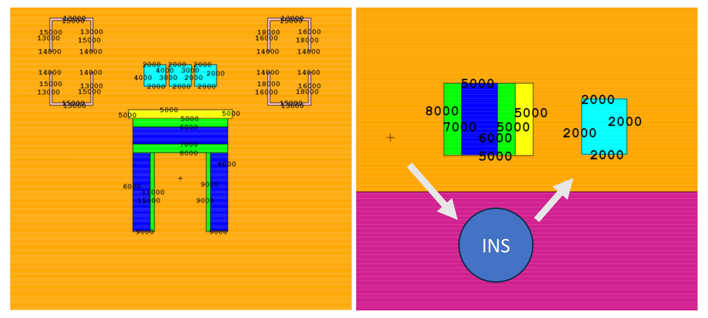
Figure D - NaI Gamma-Detector

Inelastic Neutron Scattering (INS) can occur when a neutron hits elements such as carbon. After collision, energy from the excited atom scatters out at characteristic energy signals.



Figures E – Inelastic Neutron Scattering

Monte Carlo Neutron Particle Sim, MCNP6.2 is used to generate detector readings called spectrums. The spectrums are generated on pure carbon – silicone mixes of 0 to 30% carbon



Figures F – MINS in MCNP6.2

Leading Analysis Method

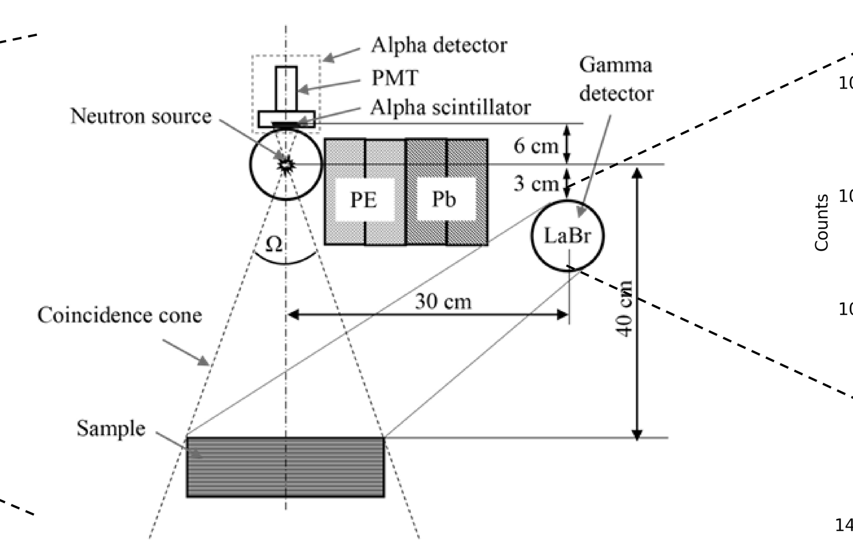


Figure G –MINS Architecture

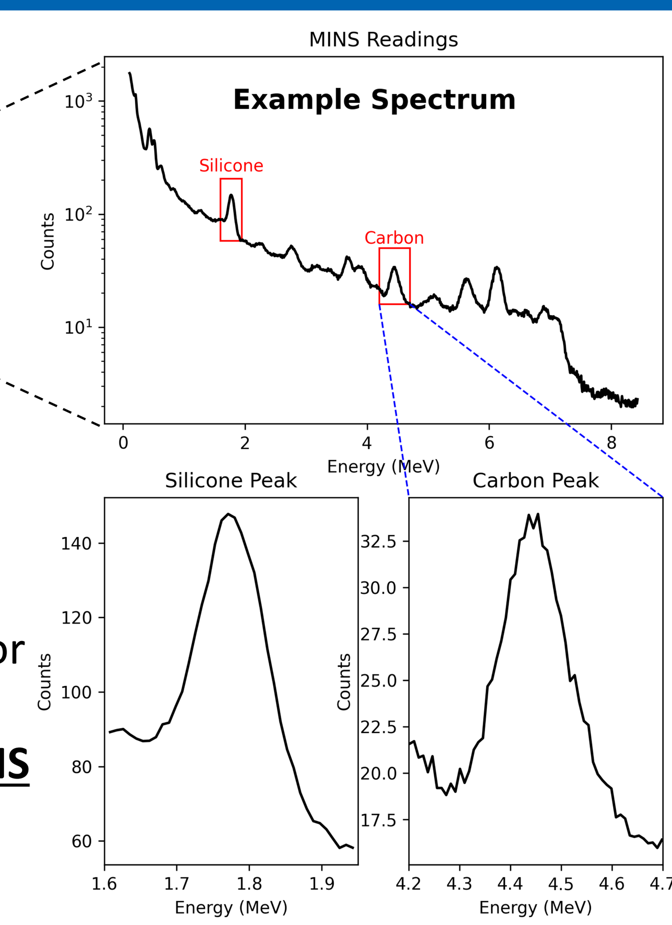


Figure H – Simulated MINS Readings

The **MINS system** utilizes a neutron generator to emit fast neutrons ($10^9 n/\text{sample}$), which interact with carbon nuclei in the soil. The **INS** events produce gamma radiation signatures that are captured by energy detectors. Analysis is done on the **Recorded Spectrums**

Method 1: Peak Fitting (PF)

The sum of a **peak function** and **baseline function** are fit onto the true spectrum.

Gauss Peak Function: (Caused by **INS**)

$$f(x) = a\exp\left(-\frac{(x-b)^2}{2c^2}\right)$$

Baseline Function:

linear:

$$f(x) = ax + b$$

exponential falloff:

$$N(t) = N_0 e^{-\lambda t}$$

(Caused by **other**)

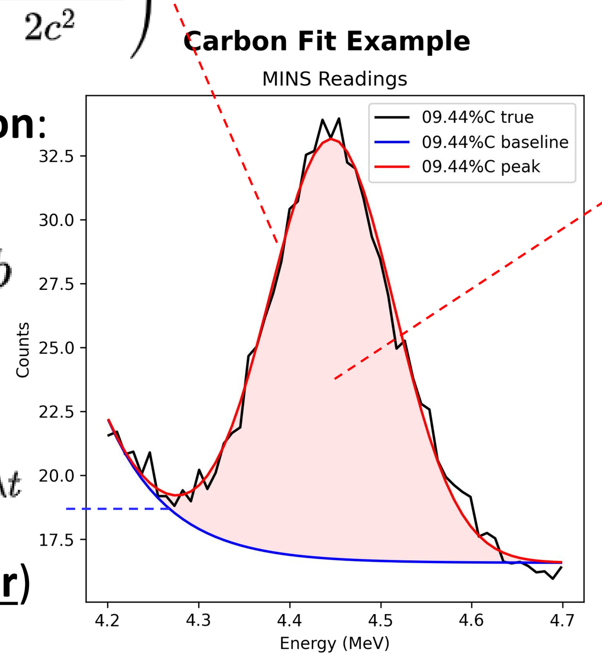
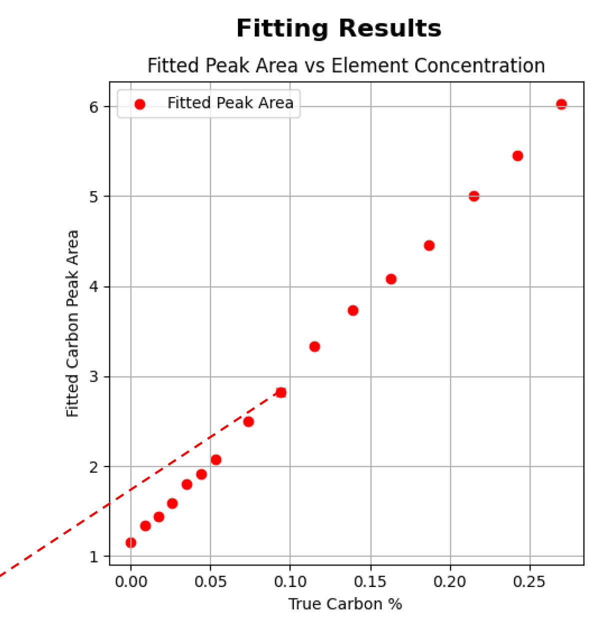


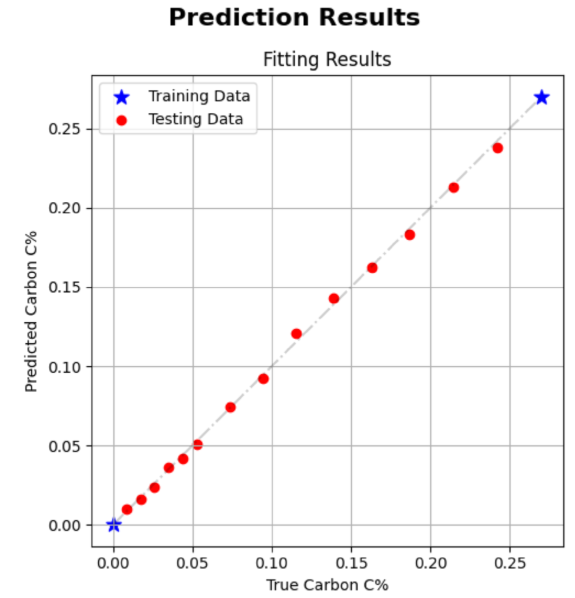
Figure I – Peak Fitting

Fitting is done with the least-squares method

The **peak areas** are correlated to the carbon content of the soil. The outermost values are used as the training data for linear regression in a final prediction:



Figures J – C% vs Peak Areas



Figures K – True C% vs Predicted C%

Mean Squared Error: 7.56223e-06

Other Analysis Methods

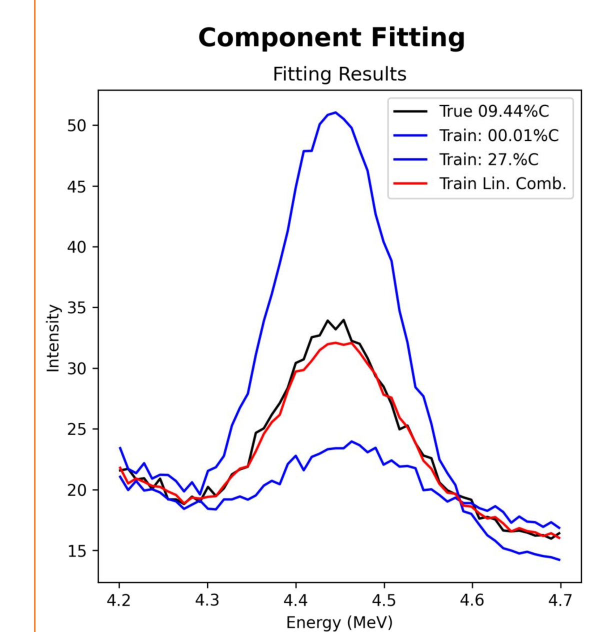


Figure L – Simulated MINS Readings

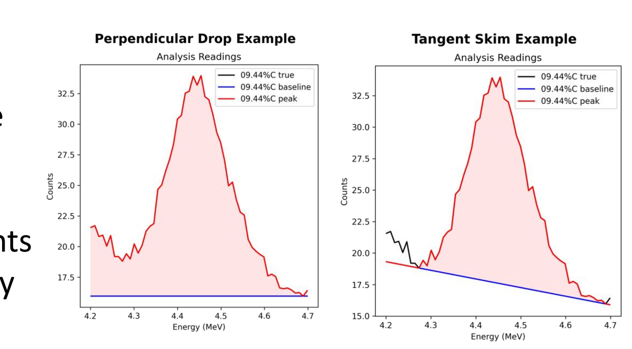
Method 2: Component Fitting (CF)

The tested spectrums are treated as a linear-combination of training spectrums. The coefficients of the fit are multiplied by the elemental concentrations

$$spec_{true} = \Sigma(w_i * spec_i)$$

$$c\%_{true} = \Sigma(w_i * c\%_i)$$

Classical Methods:



Figures M – Classic Methods

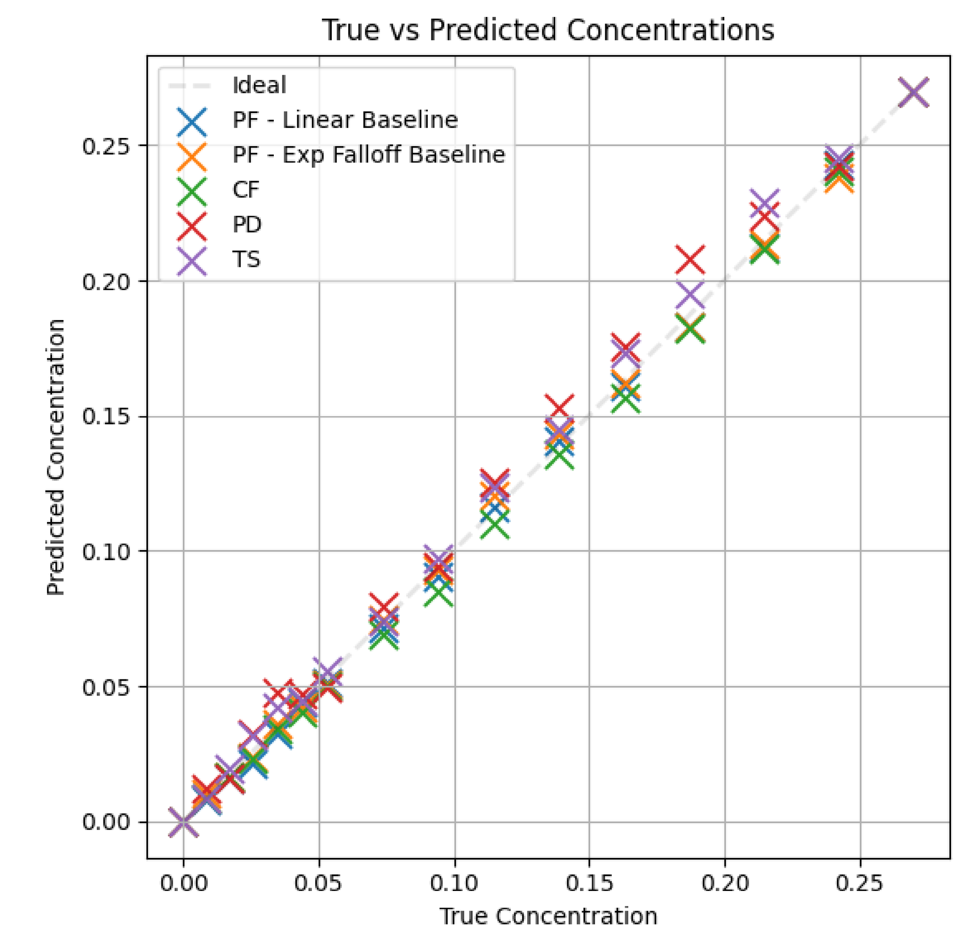
Perpendicular Drop (PD)
The minimum of the element window is taken as the baseline

Tangent Skim (TS)
The baseline is the Tangent of the minimums of both peak valleys

Results

The MINS System is very effective at measuring carbon in simulated environments. **Peak fitting with a linear baseline** being the most effective method under simulated conditions.

Future Work includes testing to see how the error for the methods changes depending on the number of particles that are emitted from the neutron source, as well as under more complex soil conditions.



Figures N – Prediction

Spectrum Analysis Method	MSE
Peak Fitting – Linear Baseline	6.00647e-06
Peak Fitting – Exponential Baseline	7.56223e-06
Component Fitting	1.89773e-05
Perpendicular Drop	0.00741817
Tangent Skim	0.00504626

[1] J. Copley, 'Introduction to Neutron Scattering', presented at the Summer School on the Fundamentals of Neutron Scattering, NIST Center for Neutron Research, Jul. 17, 2013. [Online]. Available: https://www.ncnr.nist.gov/summerschool/ss13/pdf/SS2013_Lecture_Copley.pdf
[2] C. J. Werner, et al. MCNP User's Manual Code Version 6.2. Los Alamos National Laboratory Tech. Rep. LA-UR-17-29981. Los Alamos, NM, USA. October 2017.
[3] Kavetskiy, A.G., Yakubova, G.N., Prior, S.A., Torbert III, H.A. 2024. Monte-Carlo simulations for soil content determinations on Atlas. SCINet Newsletter, https://scinet.usda.gov/news/newsletter
[4] C. R. Bates, S. R. Bolding, C. J. Josey, J. A. Kulesza, C. J. Solomon Jr., and A. J. Zukaitis, "The MCNPTools Package: Installation and Use", Los Alamos National Laboratory Tech. Report. LA-UR-22-28935, Los Alamos, NM, USA, August 2022, doi:10.2172/1884737.
[5] Pauli Virtanen, et al. (2020) SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. Nature Methods, 17(3), 261-272.
[6] "d2399-1" by USDAgov is licensed under CC BY 2.0.
[7] Gehl, R.J., Rice, C.W. Emerging technologies for in situ measurement of soil carbon. Climatic Change 80, 43–54 (2007). https://doi.org/10.1007/s10584-006-9150-2
[8] [1] L. Wielopolski, A. Chatterjee, S. Mitra, and R. Lal, 'In situ determination of Soil carbon pool by inelastic neutron scattering: Comparison with dry combustion', Geoderma, vol. 160, no. 3, pp. 394–399, 2011, doi: https://doi.org/10.1016/j.geoderma.2010.10.009.
[9] Matejovic, Igor. "Determination of carbon and nitrogen in samples of various soils by the dry combustion." *Communications in Soil Science and Plant Analysis* 28.17-18 (1997): 1499-1511.
[10] O'Haver, T. (2025, February). A pragmatic introduction to signal processing: with applications in scientific measurement. University of Maryland. https://terpconnect.umd.edu/~toh/spectrum/TOC.html

Mississippi State Univ. Atlas Cluster - Computation
USDA Agricultural Research Service - Funding
UTA Math Department - Funding

Pickard Hall, Room 413
411 S. Nedderman Dr.,
Arlington, TX 76019

linkedin.com/in/cortesjoseandres/
jose.cortes@uta.edu

www.github.com/JoseACortes/MINS