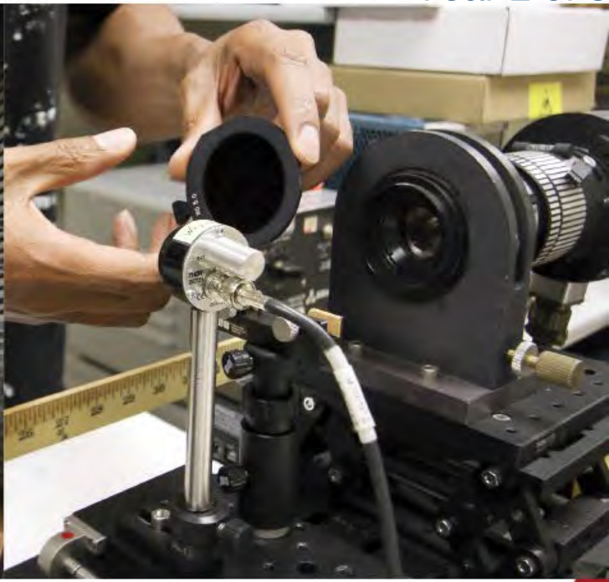
Indirect Measurement of Underground Facility Expansion/Extent through the Multi-Modal Use of Cyber Metadata (Traceroutes) and Physics-Informed Models Applied to Pre-Post Digital Surface Mapping

Project #: NLV-012-21

Year 2 of 3



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Challenge

Estimation of the size and expansion of an underground facility

- ***The estimation of the size and/or expansion of an underground facility is a challenging analysis problem that is of relevance to the non-proliferation community.***
- Direct measurements are infrequently a feasible option and unintended emissions are minimized (geospatial intelligence (GEOINT), human source intelligence (HUMINT)/surveys, electronically-gathered intelligence (ELINT))
- Combining weaker signals and indicators of facility size/expansion from multiple modalities:
  - **Cyber** – High-resolution latency measurements and traceroutes
  - **GEOINT** - Stochastic surface growth/decay from subsidence and/or accumulation of excavated material as indicated via Digital Surface Model(DSM)/Digital Elevation Model (DEM) data

    Current FY Focus
  - **Seismic** – 3D localization records from an array of seismic sensors
- **Measurement combination:** In this work we have a specific goal to combine facility size estimates from the modalities/methods above to create a more-informed estimate with multimodal robustness in a meta-analysis capability.

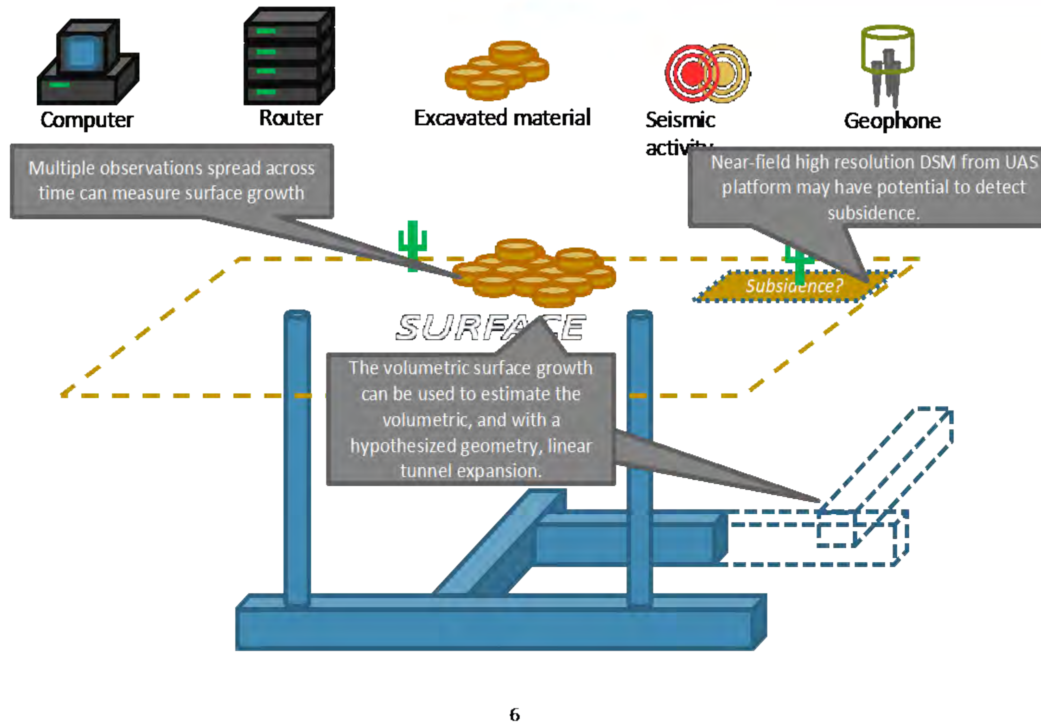
  Current FY Focus
- Deliverables:
  - **Cyber-based scale estimation capability from traceroutes**
  - **DSM/DEM stochastic surface growth/decay capability**
  - **Variable bandwidth Kernel Density Estimation (KDE) for spatial-temporal localization results Geometric Dilution of Precision (GDOP)**
  - **Meta-analysis measurement combination analytic**

Innovation

- Input opportunities for the measurement combination analytic
  - Traceroute/latency-based measurement
  - Seismic localization-based measurement

DSM/DEM-based measurement:

Measurement development began and matured in FY21, focus area of Q1 and Q2 FY22



- Simple workflow:

Tunnel/mine/facility geometry measurement
(Ex traceroutes)

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(Ex traceroutes)

Bayesian inference to recover tunnel geometry parameters:
Approximate Bayesian Computation Sequential Monte Carlo (ABC SMC)

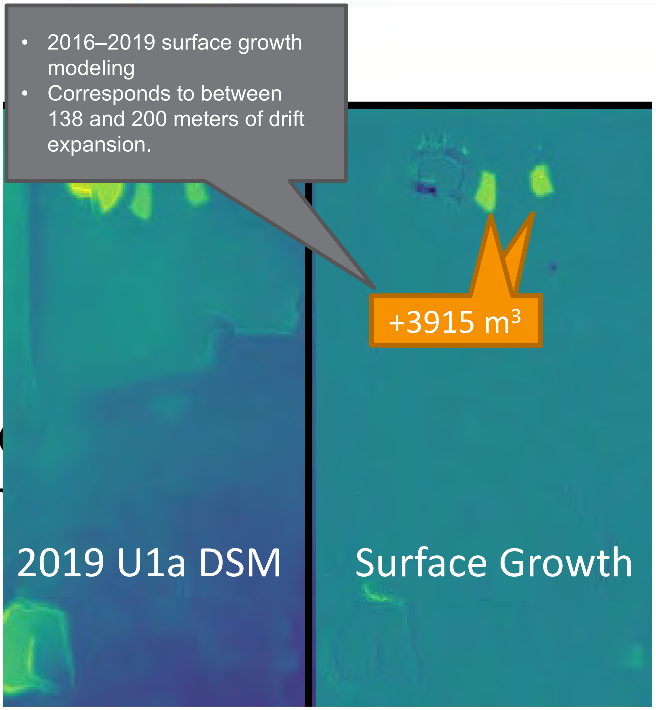
Multi-measurement informed tunnel/mine/facility estimate

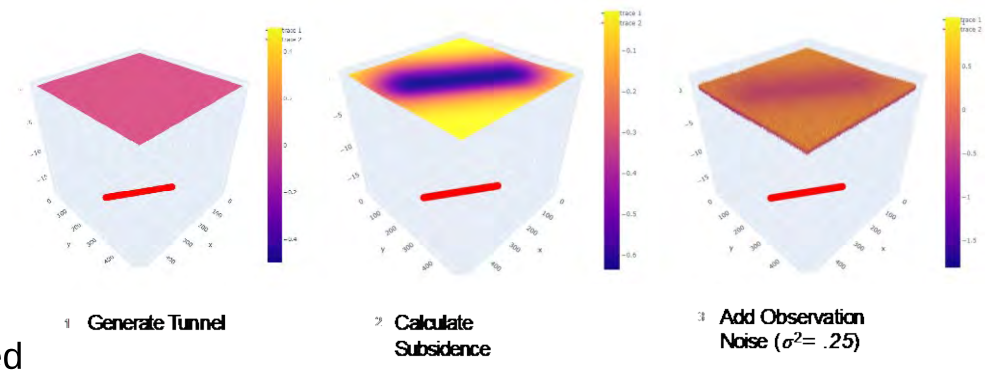
"Measurement Combination Analytic"

Technical Approach (Current Year)

Subsidence-based inference and measurement combination analytic

- *Year 1:* *Assessed stochastic surface growth (excavated material deposits on surface) for tunnel/mine expansion*
- **Year 2:** Bayesian inference to recover tunnel ge based on observed data and alternate measurer priors (traceroute, seismic localization).
- Parametric subsidence model
  - Parametric subsidence models are available for ***some*** geophysical environments and mining methods
    - Ex: Alluvium clay: Loganathan, N., H. G. Poulos. 1998. "Analytical Prediction for Tunneling-Induced Ground Movements in Clays." *J Geotech Geoenviron Eng*. **124**(9): 846-856.
  - Non-parametric subsidence model
  - Subsidence model = forward simulation based on geophysics
  - Inference where the model is a simulation





Results: Parametric Subsidence Model

- "Analytical Prediction for Tunneling-Induced ground Movements in Clays" by Loganathan and Poulos (1998).

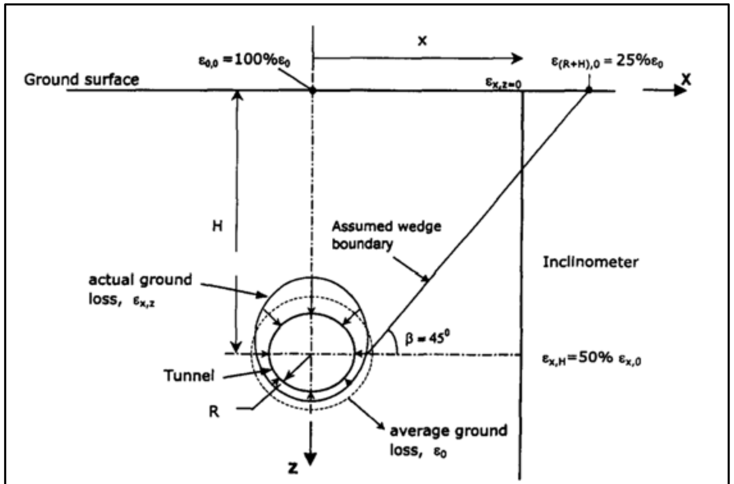


FIG. 4. Ground Deformation Patterns and Ground Loss Boundary Conditions

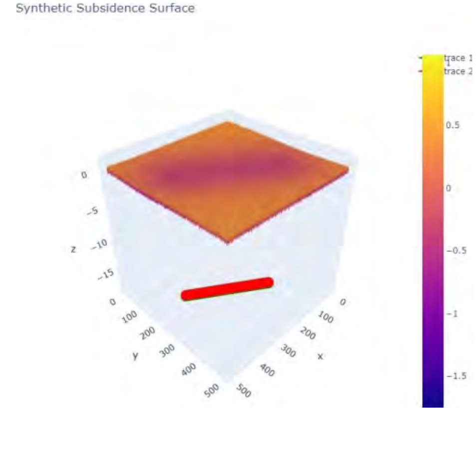
Assuming δ = 0 for the undrained condition, and substituting (6) in (11), the modified formula for the prediction of the horizontal ground movements around a tunnel may be given as

$$U_x = -R^2 x \left[\frac{1}{x^2+(H-z)^2} + \frac{3-4\nu}{x^2+(H+z)^2} - \frac{4z(z+H)}{(x^2+(H+z)^2)^2}\right] \cdot \frac{4gR+g^2}{4R^2}\exp\left\{-\left[\frac{1.38x^2}{(H+R)^2}+\frac{0.69z^2}{H^2}\right]\right\} \qquad (12)$$

R-radius, *H*-depth, *z*-original surface, δ-distance from tunnel, *v*–Poisson's ratio, *g*-gap parameter

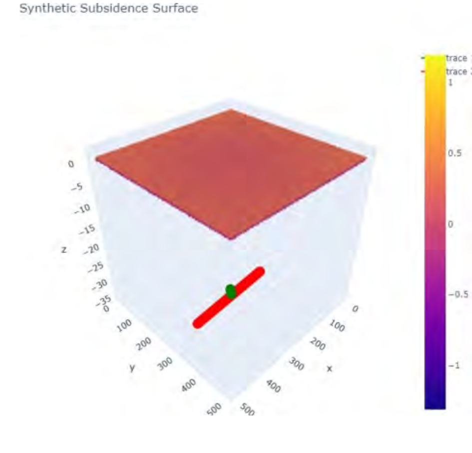
- **Sampling/Inference**
  1. Start with flat surface (z=0)
  2. Randomly generate tunnel (depth, radius, angle, length)
  3. Calculate subsidence
  4. Make noisy observation
  5. Use L-BFGS for prediction

Synthetic Subsidence Surface



Real: H = 188.44, R = 9.47, θ = 2.58, L = 300.72
Pred: H = 186.22, R = 12.31, θ = 2.58, L = 300.33

Synthetic Subsidence Surface



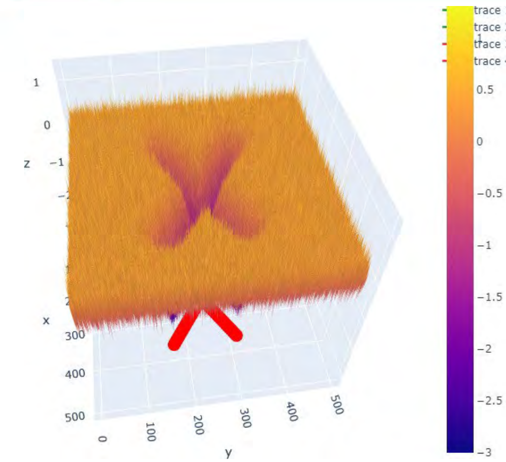
Real: H = 339.85, R = 3.14, θ = 0.94, L = 22.94
Pred: H = 353.08, R = 2.99, θ = 0.09, L = 313.81

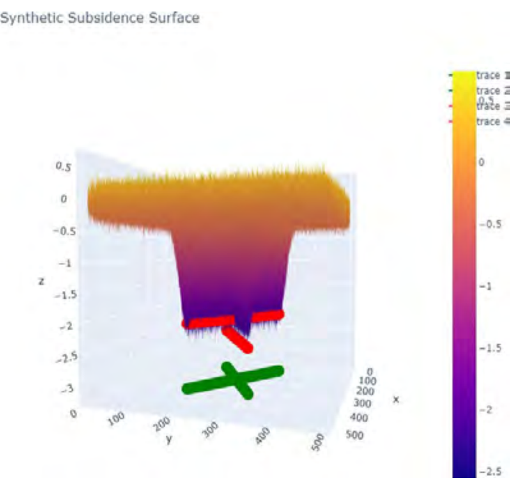
SITE-DIRECTED RESEARCH & DEVELOPMENT

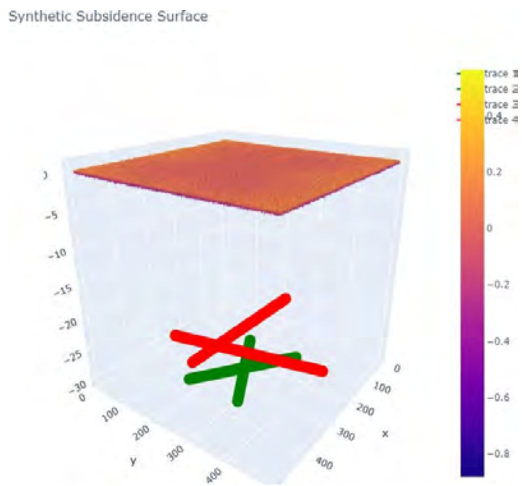
Results:
Parametric Subsidence Model

Early attempts at extending to multiple tunnel segments

- Take a surface with multiple tunnel segments below it, predict as if just one segment exists.
- Subtract the effect of this tunnel from the surface observations and repeat.
- Add back in the first predication and subtract the second prediction and keep repeating.



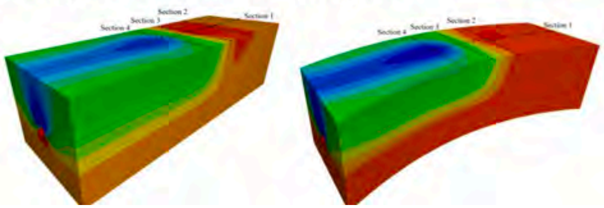




- Piecewise Linear Tunnel Subsidence: Couldn't find in literature
- Tunnel Intersection Subsidence
  - "Three-Dimensional Numerical Analyses of Perpendicular Tunnel Intersections" (Chortis & Kavvadas)
  - No mention of subsidence, everything is Numerical.
- Twin Tunnel Subsidence:

$$U_z = U_{max}\left[\exp\left\{-\frac{x_A^2}{2i^2}\right\} + \exp\left\{-\frac{x_A^2 - d}{2i^2}\right\}\right]$$

- "Ground loss model for analyzing shield tunneling-induced surface settlement along curve sections" Deng et al.



▶ Challenges led to the consideration of a non-parametric subsidence model that could natively represent multiple/complex mine geometries.

Results: Non-Parametric

Parameter	Symbol
Mass node position, velocity, acceleration	$R = [R_x, R_y, R_z], V, A$
Spring lattice topology (adjacency matrix)	A_{LSM} (sparse)
Non-linear spring lattice parameters	$L_0, L(t), K_0, K_0'$ $\kappa = \frac{K_0}{L_0} \cdot \left(\frac{L_0}{L}\right)^{K_0'}$

- Sparse Linear Algebra
  LSM force computations

$$D_x = diag(R_x)$$

$$\Delta X = D_x \cdot A_{LSM} - A_{LSM} \cdot D_x$$

$$\Delta L^2 = \Delta X^2 + \Delta Y^2 + \Delta Z^2$$

$$\vec{F} = \left[\frac{\Delta L}{L} \cdot \Delta X \cdot \kappa \quad \frac{\Delta L}{L} \cdot \Delta Y \cdot \kappa \quad \frac{\Delta L}{L} \cdot \Delta Z \cdot \kappa\right]$$

New workflow
- Create a physics based model for Subsidence
  1. Voxel Simulation
  2. Finite Element methods
  3. Spring Mass Lattice
- Model Based Statistical Inference: Approximate Bayesian Computation

- Contemporary/proprietary methods exist that do not allow for machine iteration and large quantities of trials (for simulating subsidence).
- The ABC approach can be demonstrated even with low complexity simulations: Spring lattice simulations
  - A lattice of non-Hookean springs with spring coefficients determined by elastic modulus estimates for the medium
  - Fast computation:
    - **Excise a tunnel or tunnels**
    - **Integrate the dynamical system of springs**
    - **Subsidence estimated from lattice surface**
- Lattice Spring Model (LSM)-based forward simulations have many other applications (e.g. shock physics) that can be used to develop the inference capability in a lower dimensional application.
  - **Particles colliding with a target object (1D)**
    - **Inference recovers ballistic particle velocities (1D)**
  - **Subsidence from excavated tunnel (3D)**
    - **Inference recovers tunnel radius, length, position, orientation.**

ABC SMC Algorithm

1. Initialize Thresholds $\varepsilon_1 > \varepsilon_2 > \cdots > \varepsilon_T$
2. Set $t = 1$
   - For $i = 1, \cdots, N$
     - Until $\rho(x, x_{obs}) < \varepsilon_1$
       - Sample $\theta_i^{(1)} \sim p(\theta)$
       - Simulate $x \sim p\left(x \middle| \theta_i^{(t)}\right)$
       - Set $w_i = 1/N$
3. For $t = 2, \cdots, T$
   - Until $\rho(x, x_{obs}) < \varepsilon_t$
     - Pick θ_i^* from $\theta_j^{(t-1)}$ with probabilities $w_j^{(t-1)}$
     - Sample $\theta_i^{(t)} \sim K_t\left(\theta_i^{(t)} \middle| \theta_i^*\right)$
     - Simulate $x \sim p\left(x \middle| \theta_i^{(t)}\right)$
     - Set new weights

$$w_i = \frac{p(\theta_i^{(t)})}{\sum_j w_j^{(t-1)} K_t\left(\theta_i^{(t)} \middle| \theta_i^{(t-1)}\right)}$$

   - Normalize weights

Sequence of more accurate acceptance thresholds

Accept "Close" Simulation
Shock Problem:
- Average diff in Velocity
Subsidence Problem:
- Average diff in Elevation

Sample Parameters
Shock Problem:
- Velocity profile of particles
Subsidence Problem:
- Radius, Length, Depth

Run Simulation

Use smaller tolerance for better samples

Use "Best" samples from previous round

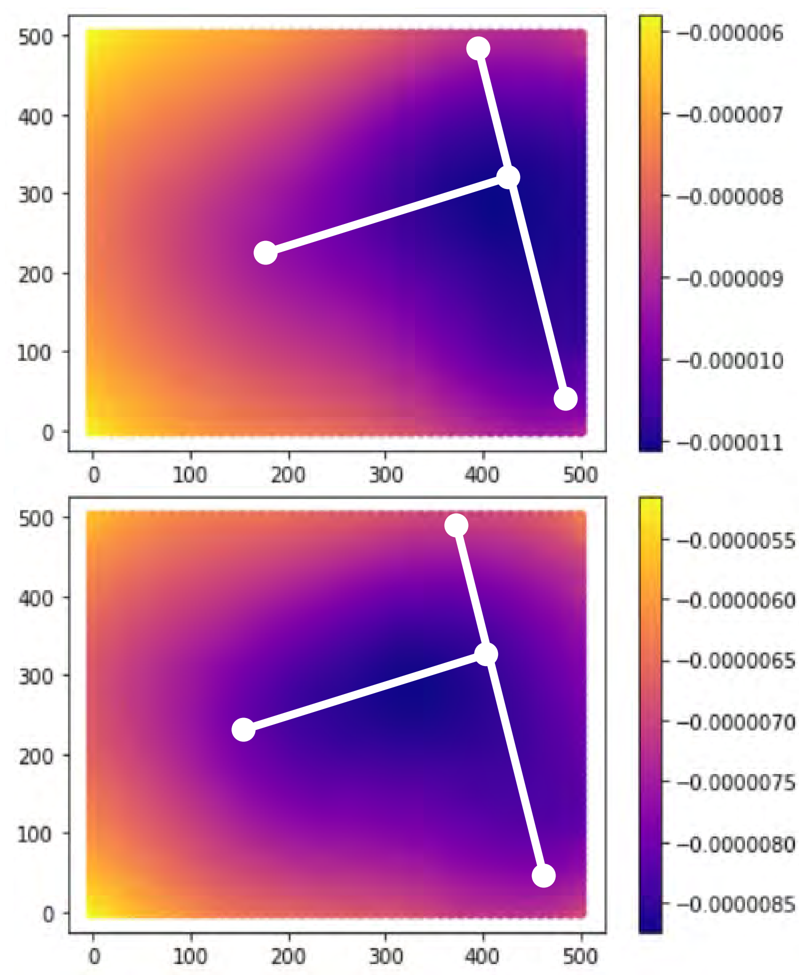
Sample parameters near the previous best

Rank quality of new samples

Results:
LSM-Based Forward Simulation

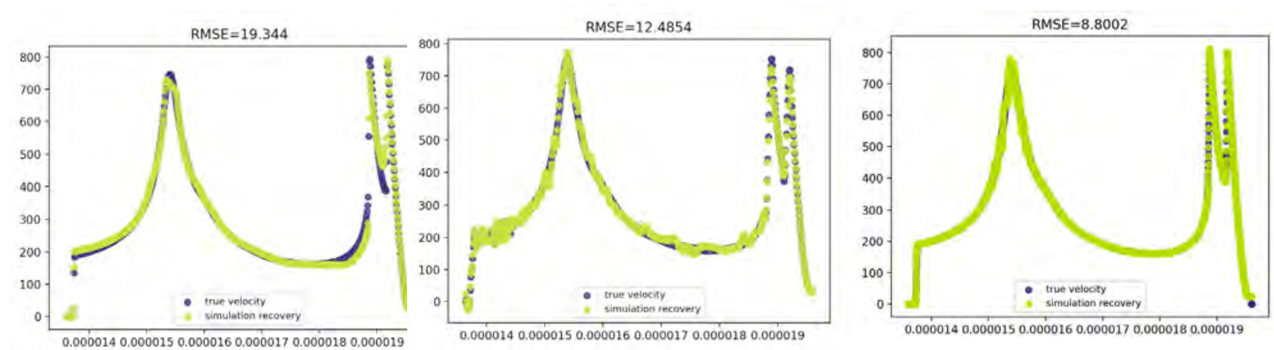
Subsidence with multiple tunnels

- LSM with 50×50×50 mass nodes and over 2,000,000 springs connecting them
- Subsidence forward model details:
  - Tunnel 1:
    - Depth: -200 units
    - Radius: 7.996 units
    - Start point: (486.08, 9.25) “bottom right blob in picture”
    - End point: (397.34, 499.15) “top right blob in picture”
  - Tunnel 2:
    - Depth: -200 units
    - Radius: 7.816 units
    - Start point: (130.64, 216.99) “bottom left blob in picture”
    - End point: (365.37, 331.44) “top left blob in picture”
- This example has some properties of what the surface subsidence should look like; however, the subsidence should be more discrete so this tells us that we need to tune parameters of the LSM to match the soil and to simulate for a longer window of time.
- 10-15 minute computation time, 10k integration time steps, 0.8 seconds per integration time step.



Summary of Results, Path Forward

- Simulation based statistical inference provides a flexible framework for parameter estimation that is compatible with multiple-measurement applications.
- A fast low-fidelity surrogate simulator is crucial to allow for high iteration count and large quantities of simulations.
- Project developed a python-based forward simulation capability that can be used for a wide variety of materials and geophysical environments (namely: Alluvium, LiF, Sn, Ta, Al).
- 1D test problems have shown successful recovery of large parameter quantities (inference on particle velocities as opposed to particle displacements).
  - 1000 particle velocities recovered from a 1D lattice with 20k mass nodes.
  - 1D lattice => shock physics applications
  - Began a shock physics collaboration with Lawrence Livermore National Laboratory (LLNL) using LSM based inference.
- **Underway**: 3D subsidence inference using ABC SMC. What we have found:
  - Validation of 3D latices is challenging, 1D is easy (great place to start exercising inference capabilities).
  - **Lesson**: Find a 1D test problem to rapidly develop the methods.



Impact

- New collaboration started with LLNL Design Physics on LSM-based statistical inference for momentum diagnostics.
- Paper in preparation: 1D LSM-based statistical inference to recover particle parameters of shocked lithium fluoride.
- Seismic localization analytic enhancements for Advanced Data Analytics for Proliferation Detection (ADAPD) Defense Nuclear Nonproliferation Research and Development (DNN R&D) joint venture (FY20)

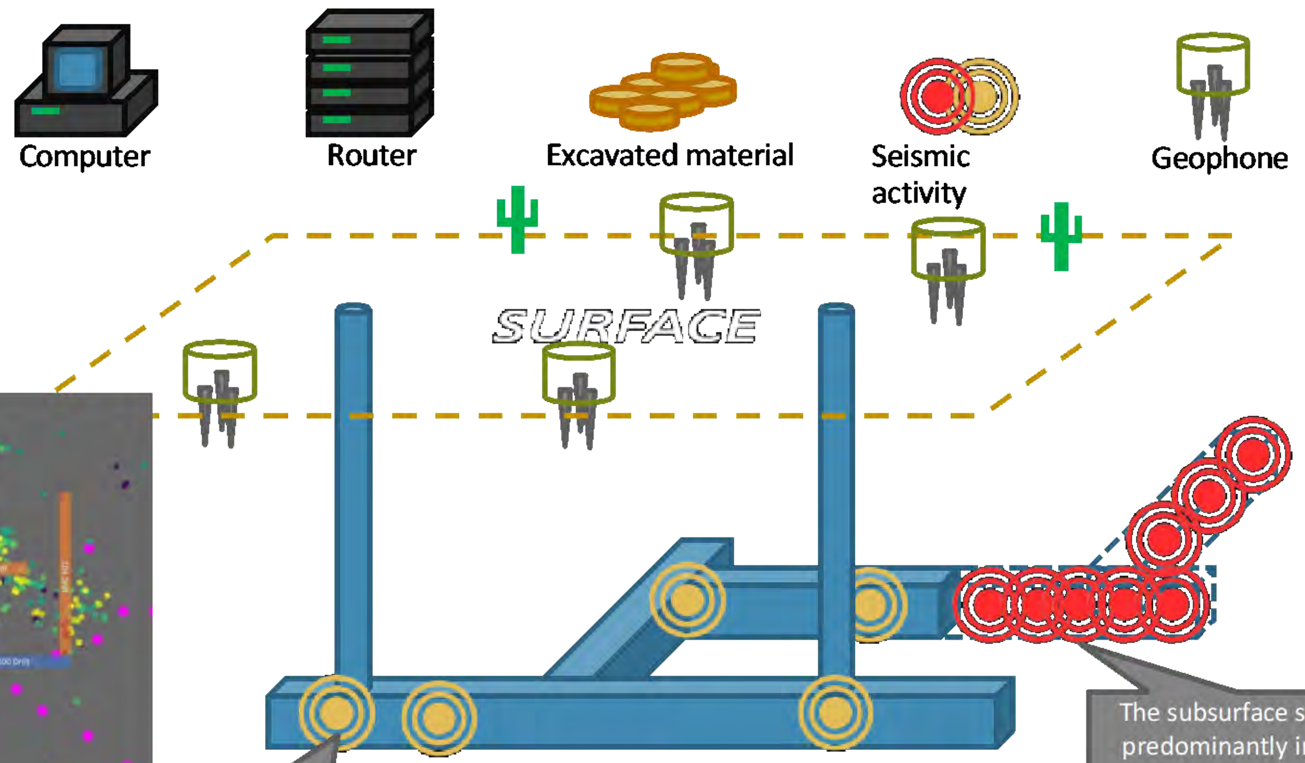
Backup slides

- FY21 work: seismic localization based measurement
- FY21 work: traceroute/latency based measurement

Seismic Localization-Based Tunnel Geometry Estimation

Seismic-based measurement:

Measurement development began and matured in FY21, ground truth, validation experiments, and new application areas in FY22

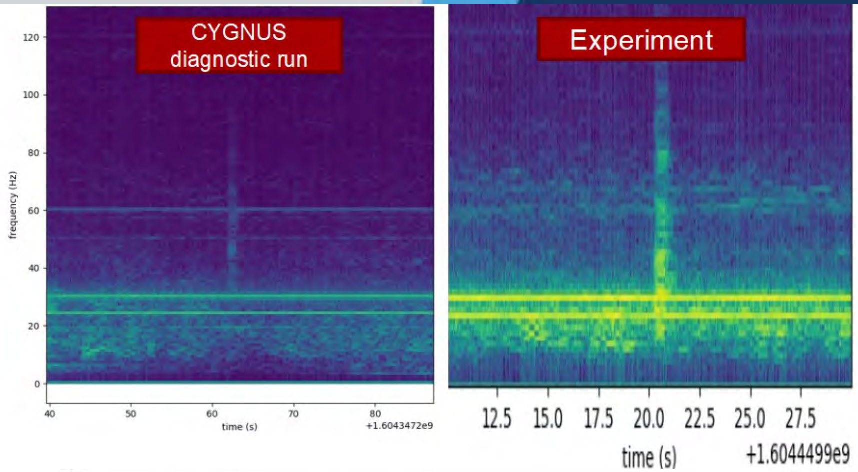


A localization analytic developed by the NNSS ADAPD researchers in 2019/2020 searches the multivariate time series generated by the geophone array for source locations.

ADAPD was predominantly interested in surface acoustic-propagation localization results for pattern-of-life analysis. The subterranean localization capabilities are a bonus this SDRD was happy to utilize.

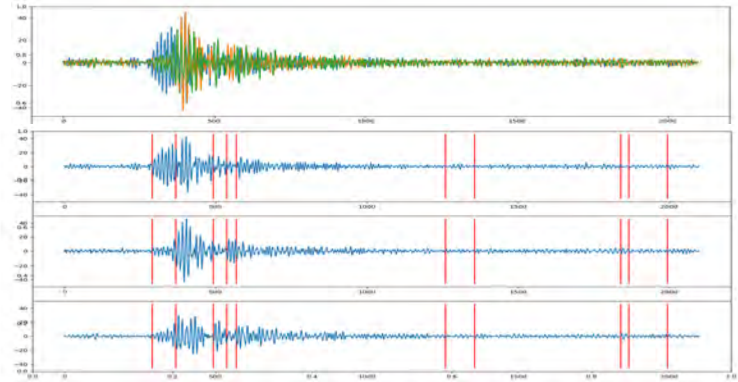
The subsurface signals are predominantly impulsive, and required development of a refined propagation velocity model and edge-finding analytic in cooperation with ADAPD.

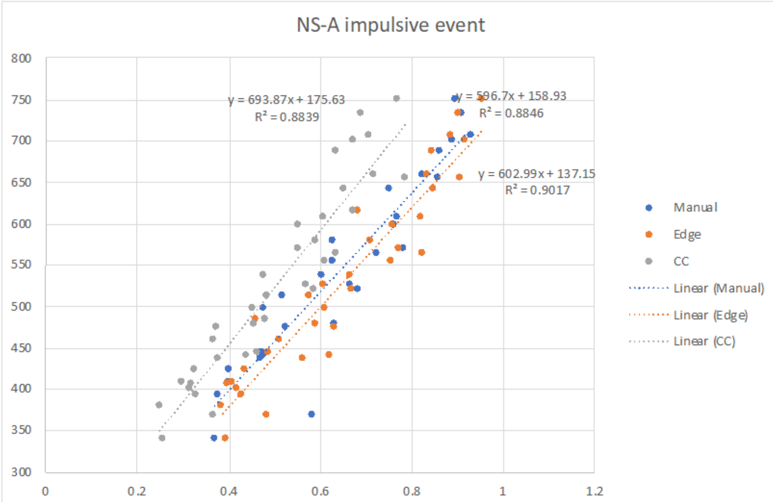
Technical Approach and Results (Past Years)

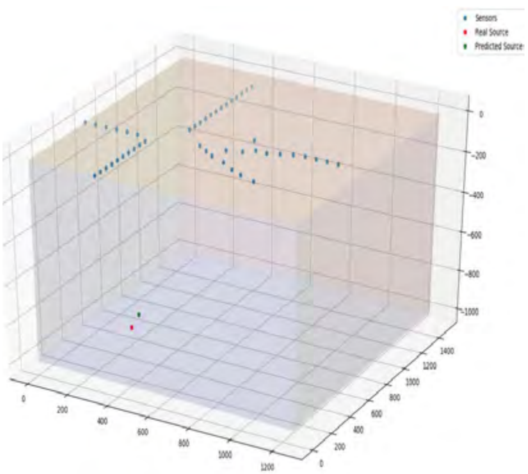


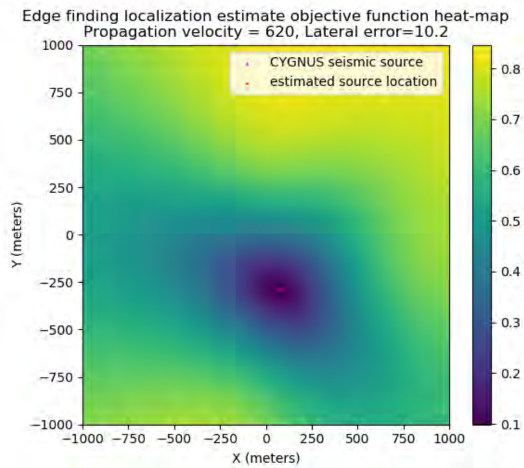
Seismic localization data

- Fall 2020 and Spring 2021: Investigations revealed ground truth matched impulsive events in seismic data (upper left)
- U1a seismic propagation velocity model development (lower left, lower right)
  - Joint UA + NNSS + Sandia collaboration FY21
- NNSS Summer Intern Program + UA-developed edge-finding automatic time-picking algorithm (mid and lower right).
  - Multivariate Bayesian offline change point detection algorithm
- UA: GP-bootstrapping signal simulator localization analytic testing (lower-right)







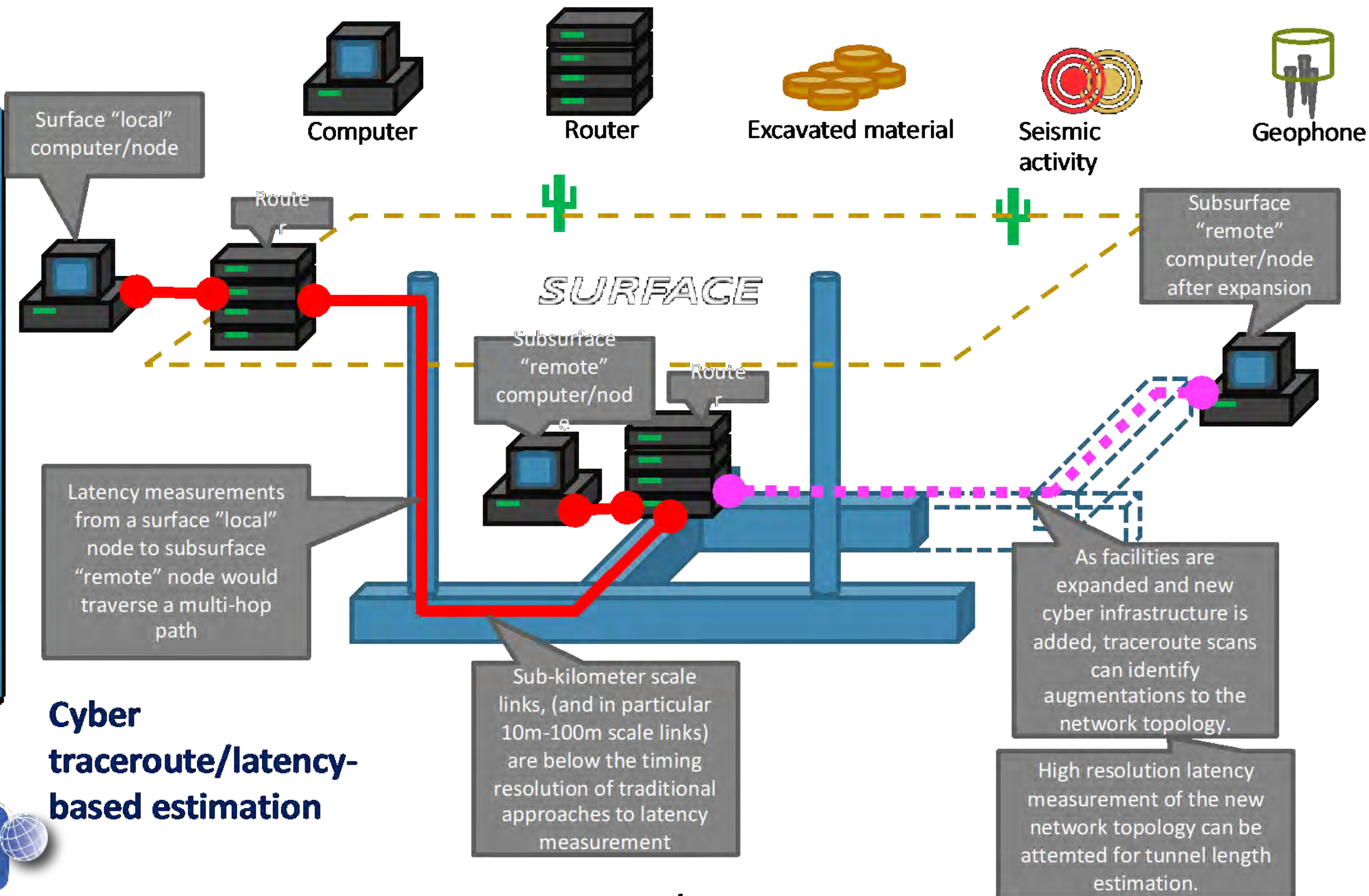


Innovation

Traceroute/Network Latency Tunnel Length Estimation

Cyber-based measurement:

Measurement development began in FY21, continues through to the present…



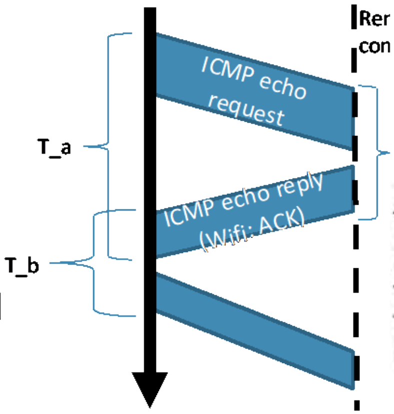
Cyber traceroute/latency-based estimation

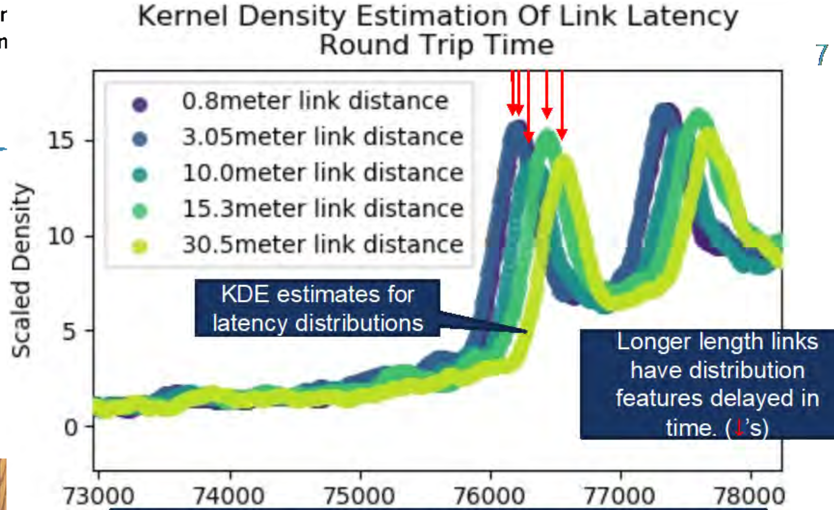
SDRD SITE-DIRECTED RESEARCH & DEVELOPMENT

Technical Approach and Results (Past Years)

Traceroute/Latency

- Analytic improvements and further experimentation on the cyber latency testbed have resulted in a 42.4 ns accuracy latency measurement capability (24x improvement over clock resolution) that has been applied and validated under controlled conditions.
- This corresponds to a distance measurement accuracy in Cat5e/Cat6/optical fiber of $\approx 4.2\ m$
- Innovations/progress points:
  - Packet-level timing (abandon OS timing)
  - Variable bandwidth KDE within the noise-assisted subsample signal detection analytic.
  - Estimation of the unobservable “remote delay” through the use of a designed experiment utilizing a second probing computer.





When we compute the time shifts corresponding to the KDE features that are correlated to link length we can compute high accuracy link lengths: