



Experiments in Active and Passive Detection of Small Border Tunnels

Neill P. Symons, Robert E. Abbott, Gregory J. Elbring,
Hung D. Nguyen, William T. O'Rourke, K. Terry Stalker

Sandia National Laboratories

Phone: (505) 844-5782

Email: npsymon@sandia.gov

Tunnel Detection and Characterization History

2006 Otay Mesa Tunnel

Past Program Experience



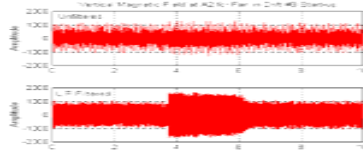
Autonomous Monitoring Systems



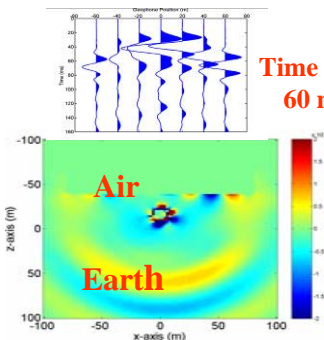
DARPA Sensor Dart



Signals and Analysis



Time slice
60 ms



3D Modeling

**Shallow
Tunnel
Activity**



**Application to Large
Tunnel HDBT's**

- ≈\$10M in LDRD Funding
- DARPA PASEM Program
- DTRA & IC Support

S&T Foundations

- DOE Basic Energy Sciences
- DOE Fieldable Sensor Systems
 - DOE Fossil Energy
- DOE Weapons Support in Geomechanics
 - Geologic Test Support
- Non-Proliferation Global Monitoring



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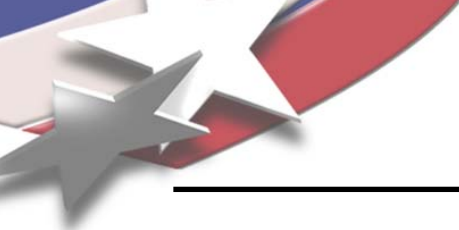
Sandia Border Tunnel Goals

Develop fieldable system that provides actionable information

- **Apply technology and expertise to the detection and characterization of Border Tunnel activities**
- **Integrate into existing monitoring systems**
- **Work with end-users to refine system**

Support Law and Immigration enforcement community

- **Rapid response capability**
- **Subject Matter Expert expertise applied to the problem**
- **Suite of Technologies**
 - **Localization**
 - **Signature development**
 - **Signal Processing**
 - **Algorithms for Automated Detection and Characterization**
 - **User Interface**
- **Fly Away Kit to provide integrated capability**
- **Next generation system development for long term solution**



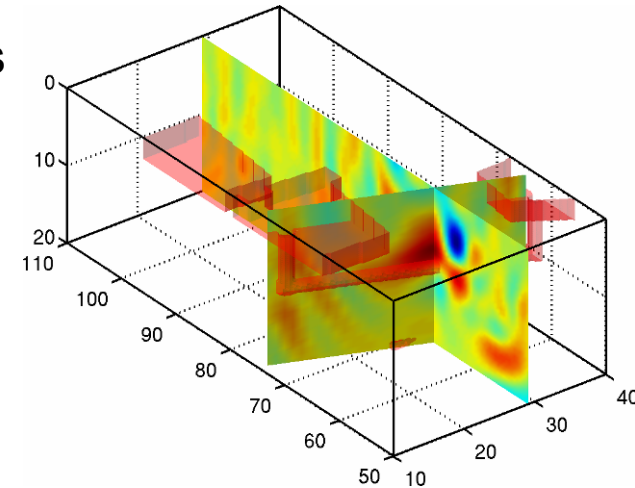
Sandia's Approach

Multi-Program NNSA Laboratory View

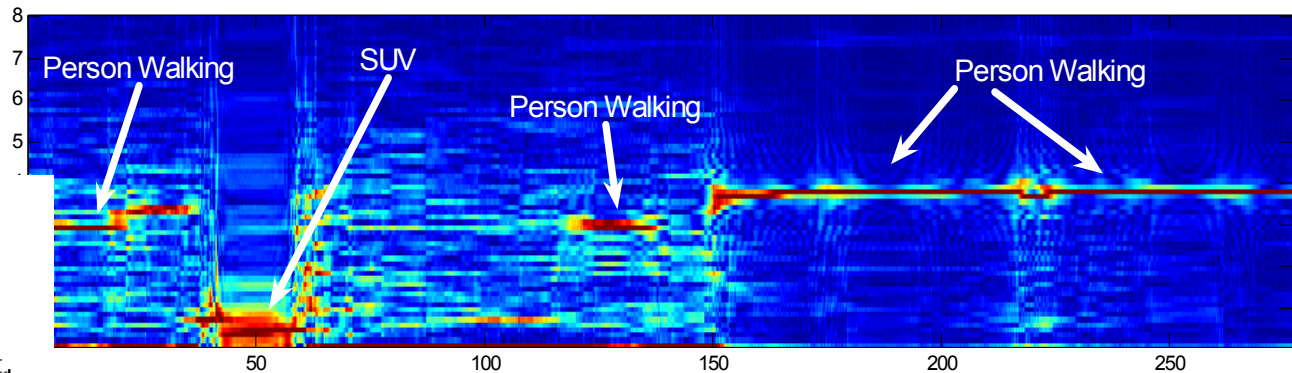
- **Multidisciplinary Team**
 - **Geoscience, Signal Processing, Real-Time Processing, Systems Integration, Test**
 - **Draw from Multiple Areas of the Laboratory**
- **Combine Modeling, Analysis and Test**
- **Requirements driven Spiral Development**
- **Systems View**
 - **Basic Understanding - Phenomenology**
 - **Sensors, Signals, Processing, Analysis**

Sandia Capabilities

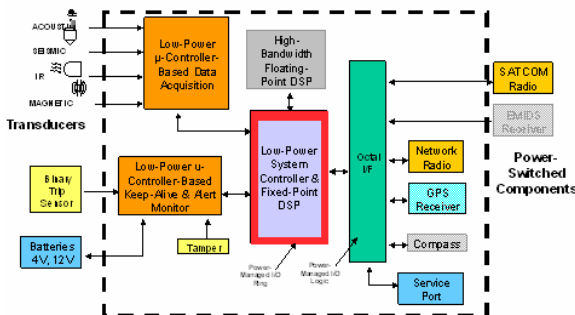
- Systems modeling and simulation for complex systems
- Passive geophysical monitoring of large underground complexes
- Development and testing of unattended ground sensor systems
- Realistic 3D modeling of geophysical sources and propagation for understanding phenomenology
- Advanced algorithm development for source detection, characterization and location



3D Geophysical Models



Advanced Classification Algorithm

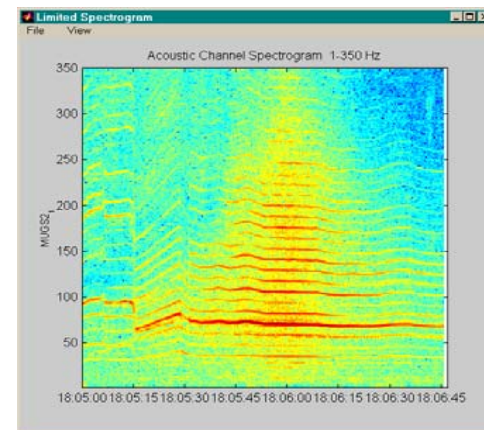


Flexible System Architecture

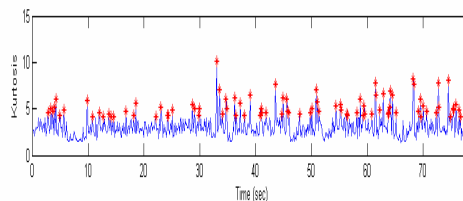
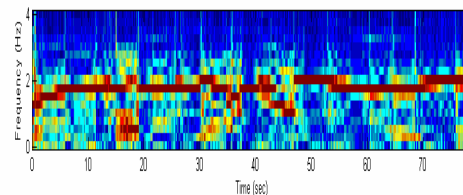
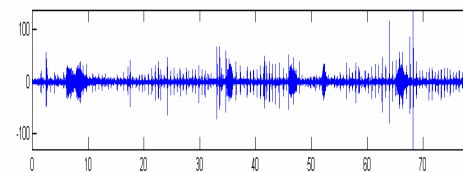
Signal Detection Algorithms

- Adaptive Energy Detector
 - Machinery start – up
 - Large impulses (objects dropped)
- Harmonic Line association
 - Vehicles
 - Infrastructure equipment (generators, fans)
- Statistical and Persistence Measurement
 - Footsteps
 - Impulsive (Possibly Digging) Noises
- Localization
 - FK Analysis
 - RTM
 - Time of Flight
- Analyst / Operator Tools
 - Layered Data Fusion

•Need to Apply and Optimize for Tunnel Activities
•Embed in Fly Away Kit



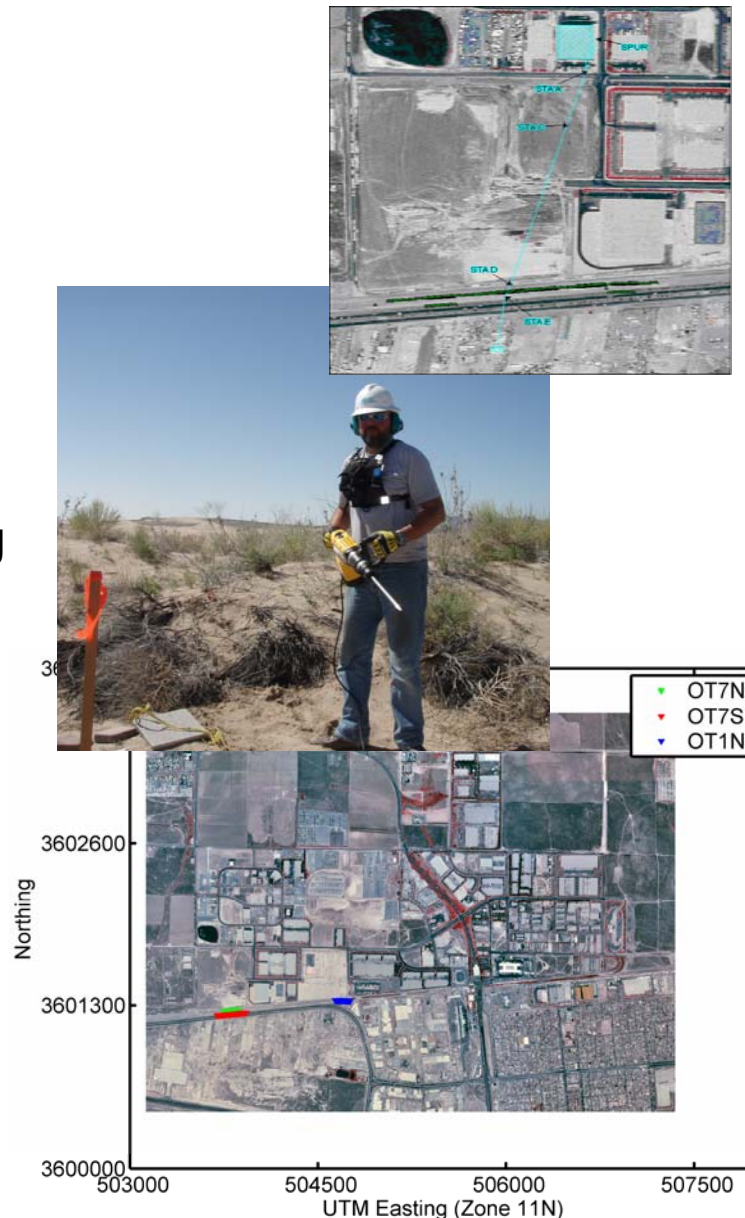
Large Vehicle



Footsteps

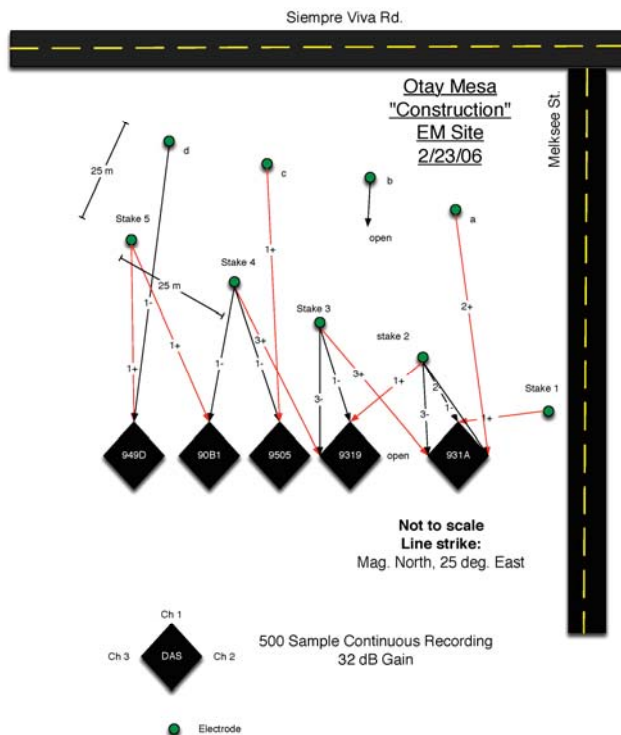
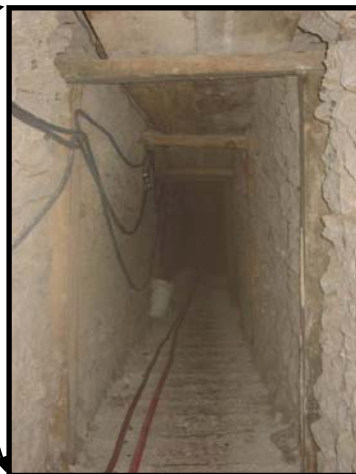
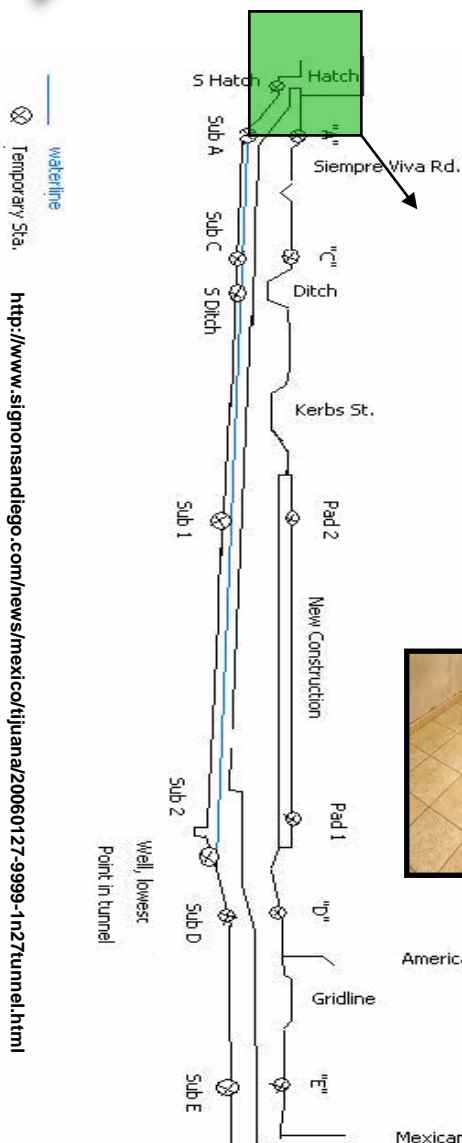
Three Major Experimental Deployments

- Otay Mesa 2006
 - Seismic and EM data
 - Roosevelt Easement
 - Formerly vacant lot
 - Tunnel Exit (passive seismic only)
- Analog Site 2007
 - Seismic data only
 - Much bigger data-set
 - Complete control of site and **safe** working environment
 - Active line over tunnel
 - Passive data collection for construction signatures
- Otay Mesa 2007
 - Active and passive seismic data
 - Active lines over OTM#1 (1993 tunnel) and OTM#7 (2006 “V&F” tunnel)
 - Passive data collected into arrays for ~10 days

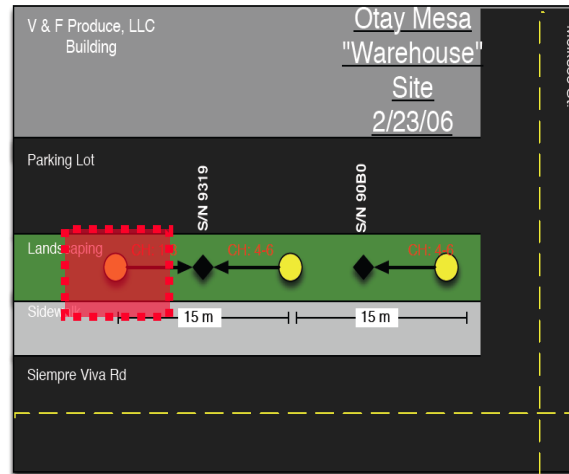
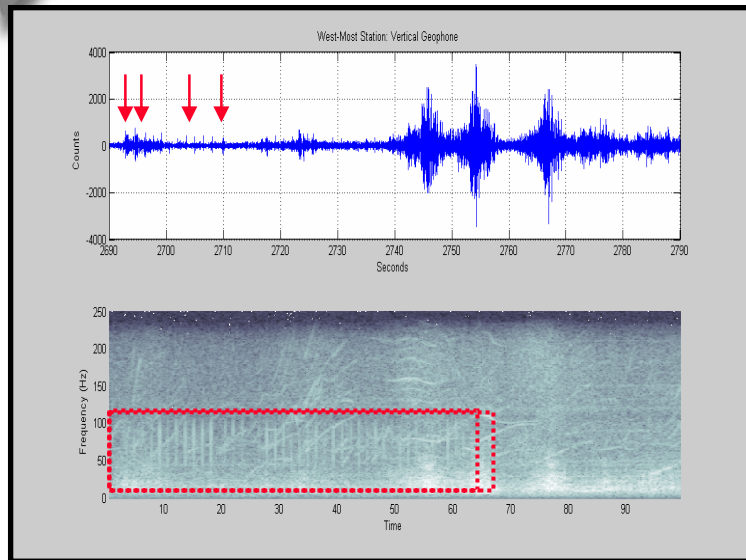


Otay Mesa Data Collection 2006

- Collection of Passive Seismic & EM Data
- Participated in Government Review of success of a variety of detection techniques (J. McKenna, ERDC 2007)

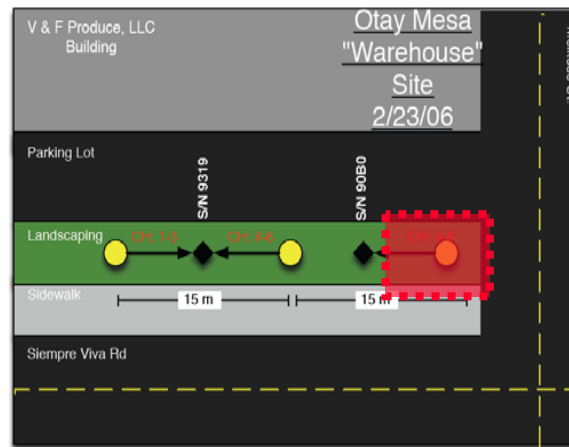
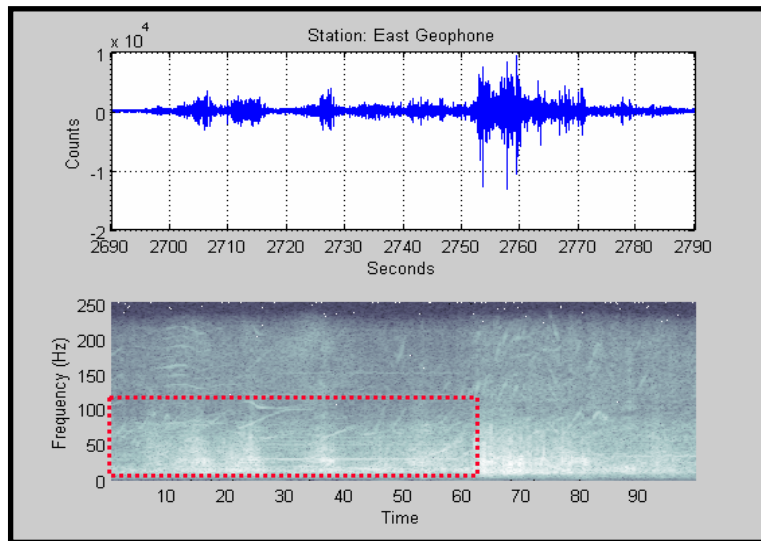


Pick Construction Signatures Feb 2006 Roof Blows at 1Hz



West Geophone

- Distinct Signature
- Detectable over background
- Appears to be Highest SNR of the 3 components
- 50-100Hz



East Geophone

- Extremely Weak Signature
- Not readily Detectable over background
- Will require advanced signal processing

Analog Tunnel Site Data Collection – April 07

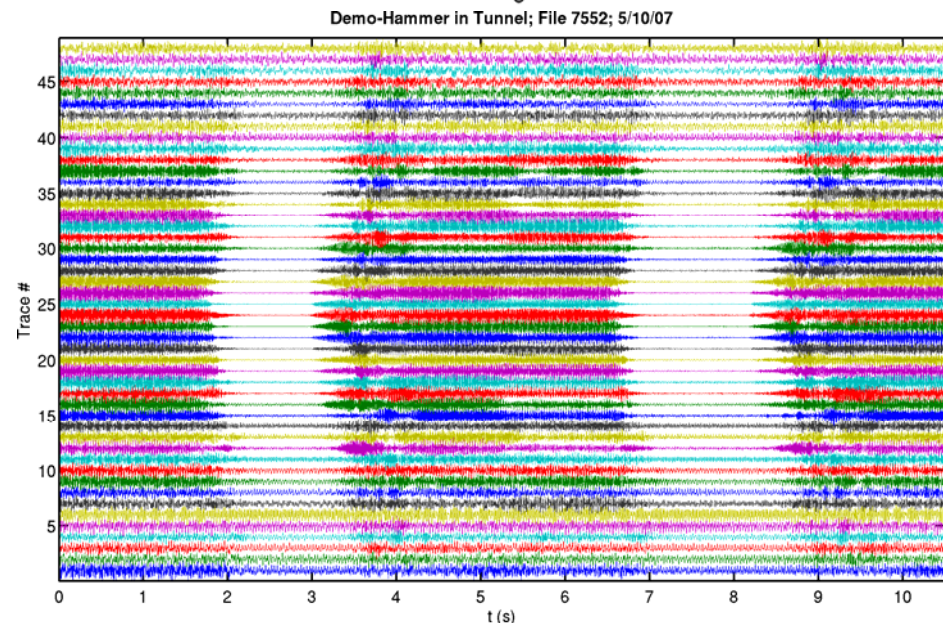
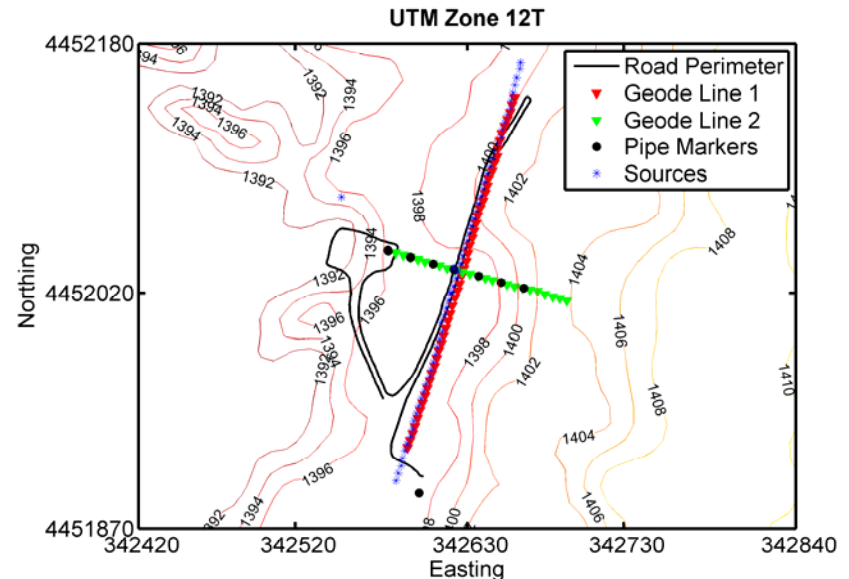
(Controlled, Safe, Quiet, Accessible Site)

- Laboratory Directed Research and Development (DOE Funds)
- Develop signatures and methods for detection of tunnel construction activities
 - Jackhammer
 - Hand hammer
- Active seismic methods for tunnel detection
 - 2D seismic tomography
 - Reverse-time migration
 - Surface-wave analysis
- Pick a quiet site with a tunnel that we can get inside
 - Test high power digging sources
 - Tradeoff
 - Casing makes this a safe site for work
 - Casing means that this not “completely realistic”
 - Also a packed sand background
 - We did cut though the case for direct ground access



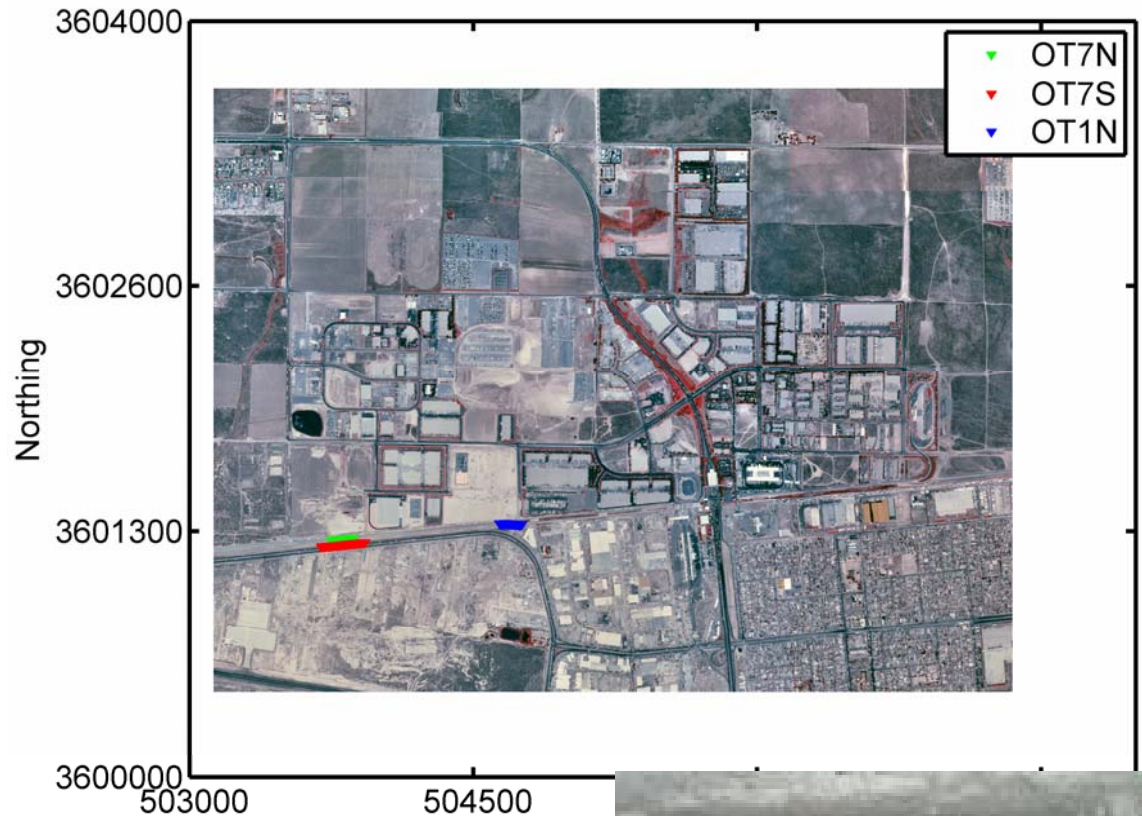
Demolition Hammer Data

- A small jackhammer
 - Good tool to use for building a small tunnel
 - One person can use it horizontally against a face
 - 15 amps, power can be supplied through a standard (low gauge) extension cord
 - Widely available consumer item
 - Matches the “look” of the tool marks from known tunnels
- We will never be able to use this type of equipment in real tunnel
 - Significant vibration
 - Collapse hazard
 - We are governed by OSHA, MSHA, etc.
- Analysis of signatures indicates statistical similarity to footsteps and hand hammer
 - Existing algorithms should detect with minor parameter tuning



Otay Mesa June 2007

- Two primary sites for data collection
 - Otay Mesa #7
 - Lines on North and South side of easement
 - Otay Mesa #1/2
 - One line swings from south to north
 - Follows all weather access road
- Arrays installed at both sites
 - OT #7
 - Surface arrays during active source data collection
 - OT #1/2
 - Surface and downhole array during active source collection and left in for passive monitoring

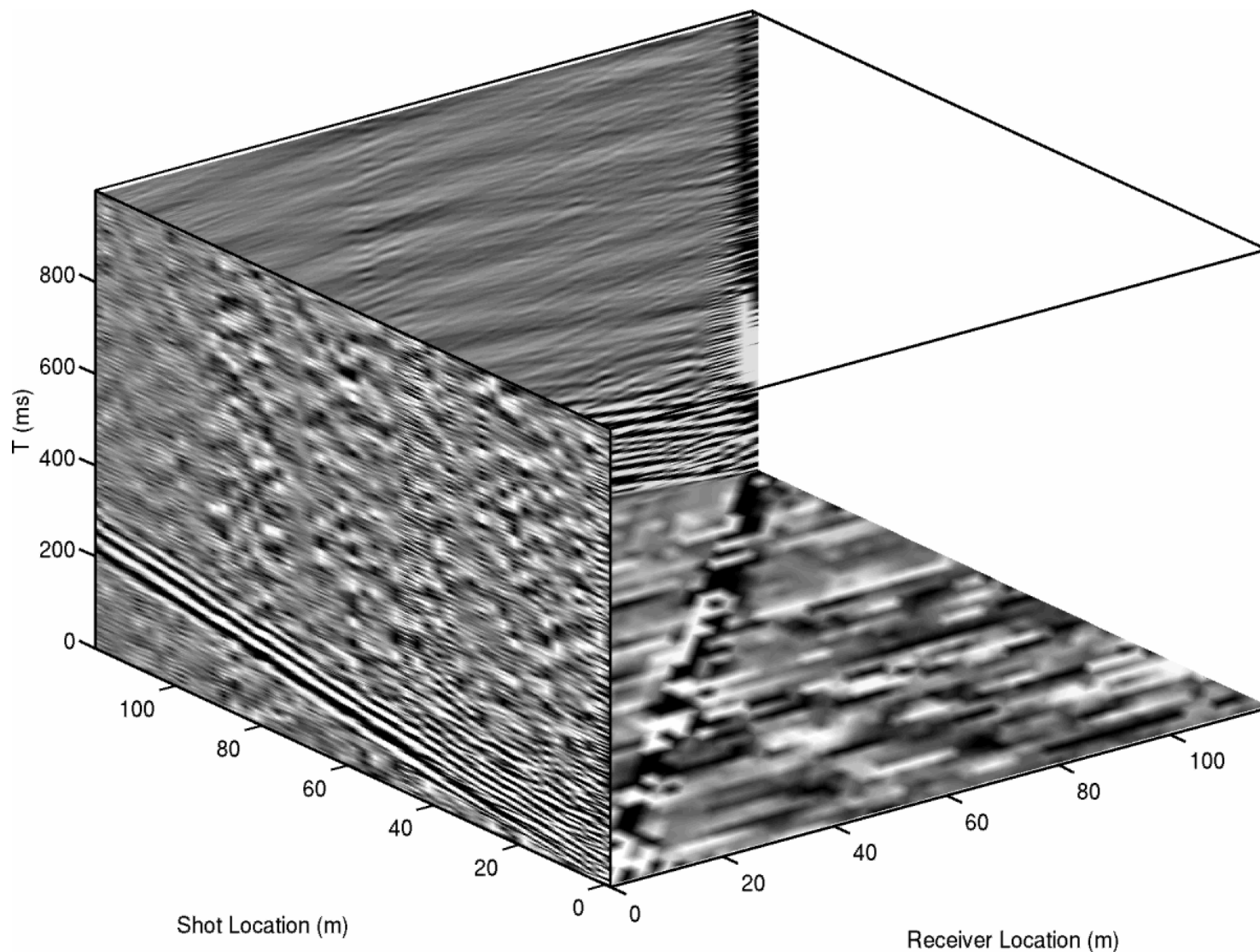


- Active source line Thursday, June 28
 - 2.5m receiver and source spacing
 - 1 shot off each end (49 shots total)

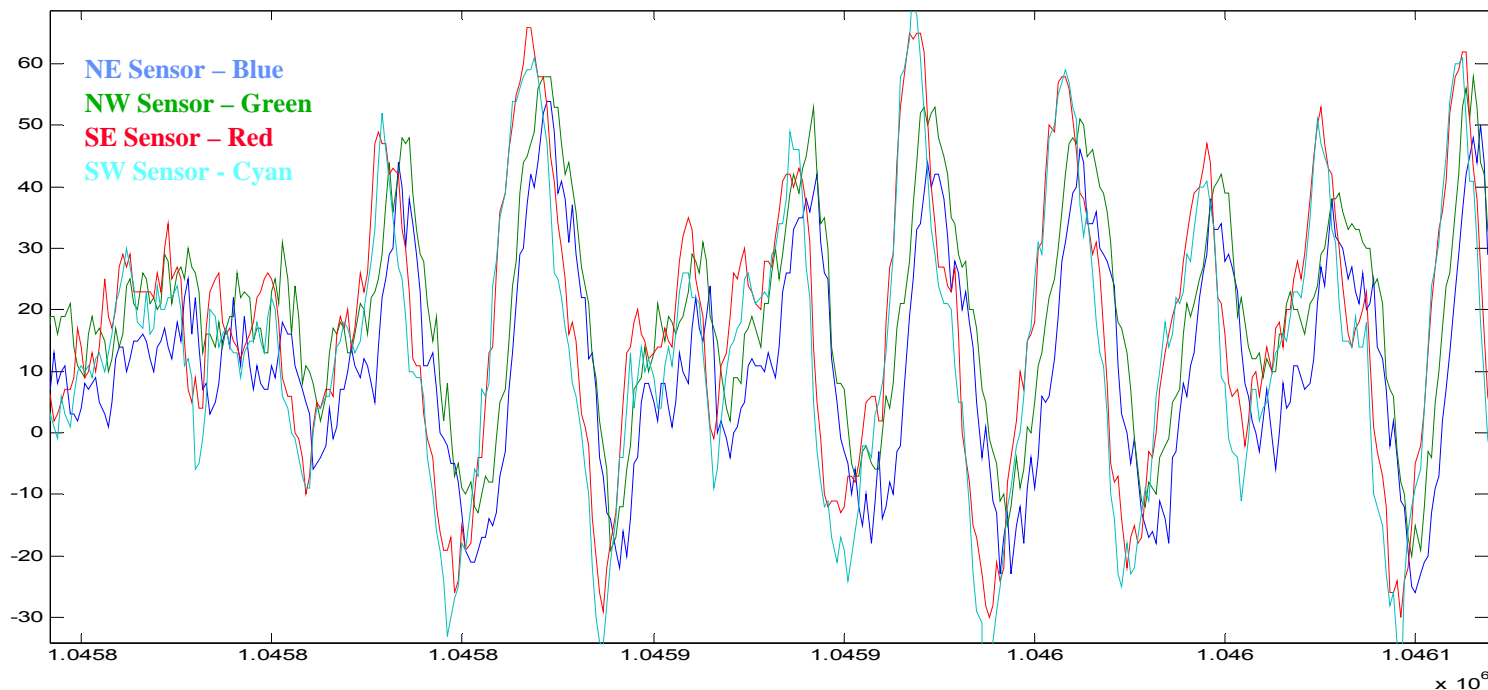


Active Data

- Analysis is only just starting
 - Lots of noise
 - Appear to be coherent reflectors at late times
 - Will use to develop model for advanced processing techniques
 - Reverse-time migration

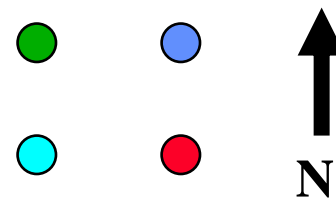


Analysis of Tunnel Array Data



- **Just scratching the surface**

- **Developing a seismic site model with the active data**
- **Initial results indicate arrays can be used to determine direction to sources**





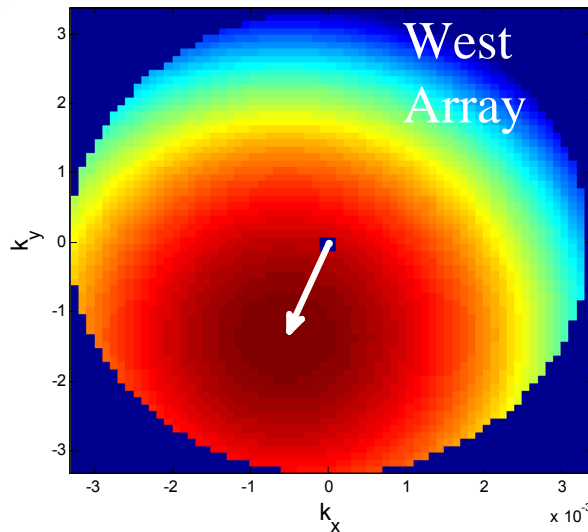
Developments

- FK analysis of array data from Otay Mesa 2007 collection
 - Clear identification of vehicles from the US and Mexican side
 - Allows for the rejection of spurious signals
- Systems Study methodology
 - Initial results for Otay Mesa
- Development of Fly-away Kit
 - This will be our deployment platform
 - Incorporate signal detection/processing algorithms as they are developed
- Analysis of acoustic data from Otay Mesa
 - Develop a methodology for easy analysis of acoustic **and** seismic data
 - We have over a week of seismic data from the 2007 collection

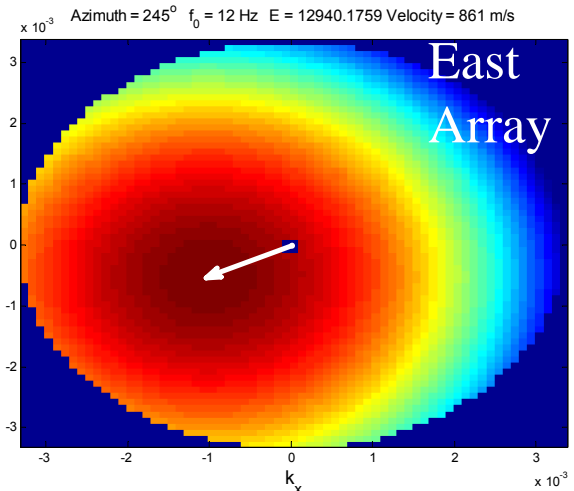
FK Analysis with Arrays

Vehicle on Mexico Side

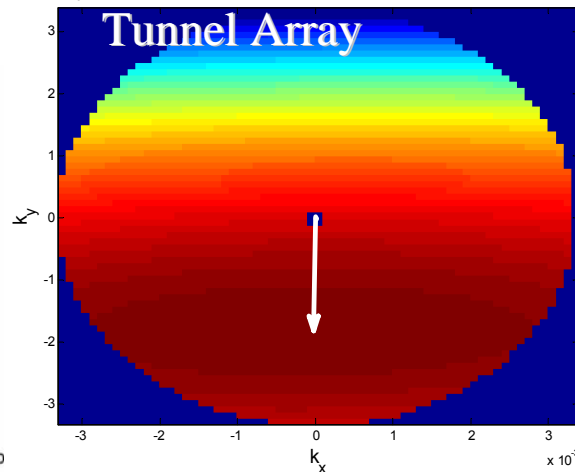
Azimuth = 200° $f_0 = 12$ Hz $E = 16799.8732$ Velocity = 684 m/s
 $\times 10^3$



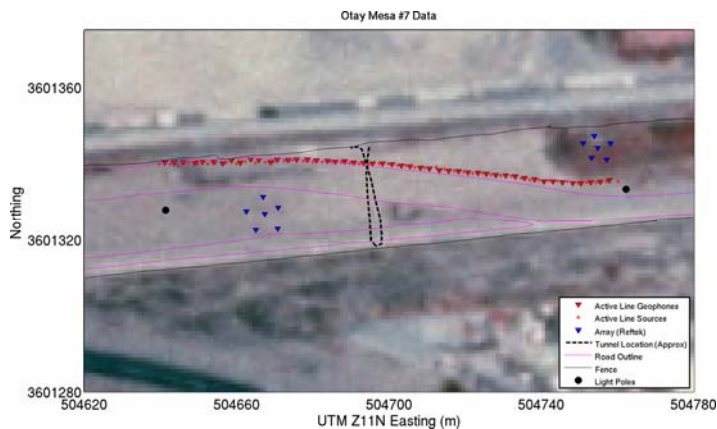
Arrival Vectors point in the direction of peak energy. Length of arrow is proportional to wave slowness (inverse velocity).



Azimuth = 180° $f_0 = 12$ Hz $E = 11704.9344$ Velocity = 500 m/s
 $\times 10^3$



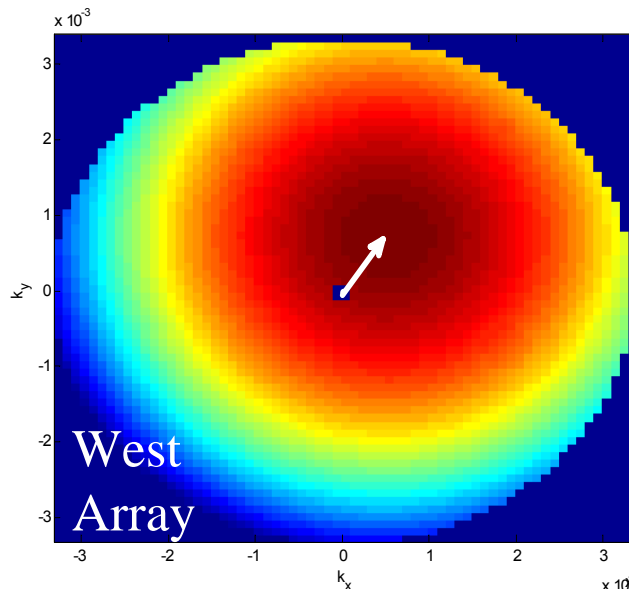
Tunnel may be acting as a waveguide. Therefore, energy appears to come from inside the tunnel.



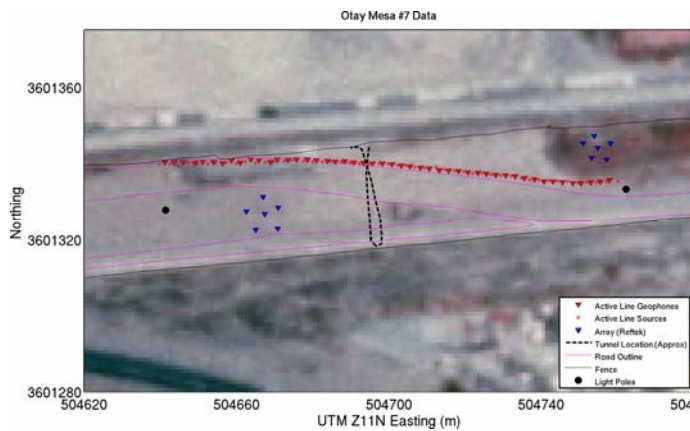
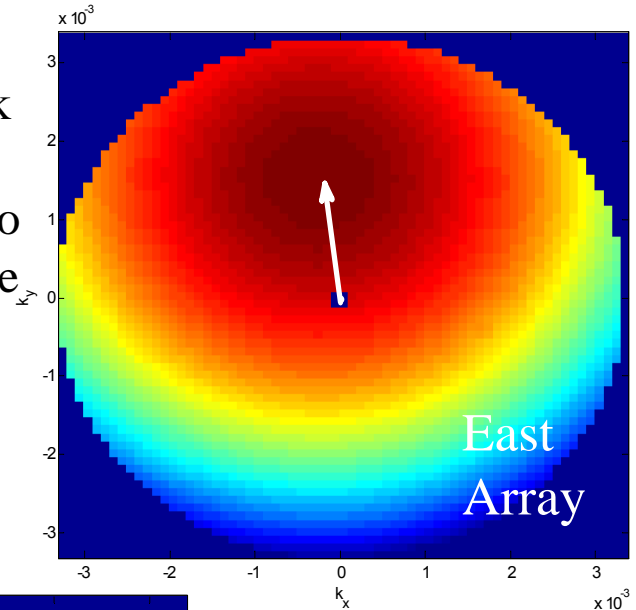
All three arrays point to activity on the Mexico side.

FK Analysis

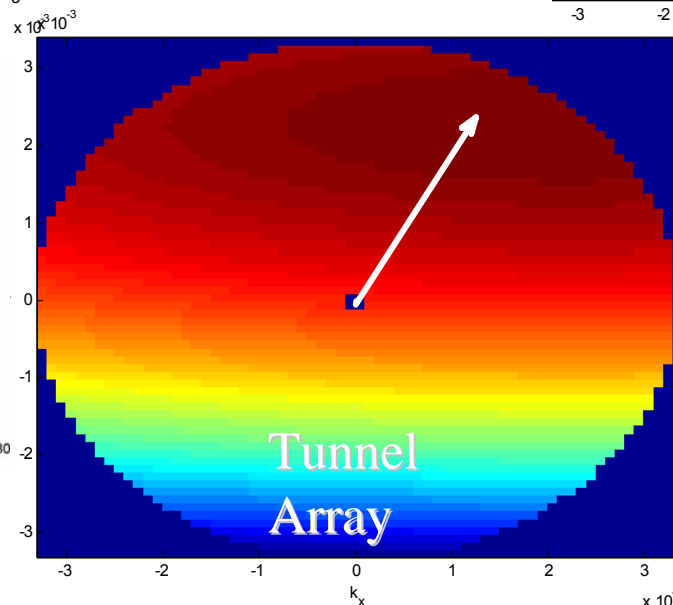
Vehicle on US Side



Arrival Vectors point in the direction of peak energy. Length of arrow is proportional to wave slowness (inverse velocity).



All three arrays point to activity on the US side.



Vehicle appears to be east of tunnel between surface arrays



Array Analysis Summary

- **Array Analysis shows great promise**
- **Localize vehicle traffic – eliminate as clutter source**
- **Beginning to look at other localizing other sources**
- **Beginning to discriminate above vs below ground**
- **Path Forward –**
 - **Developing a seismic site model with the active data**
 - **Automatic event detection on array data**
 - **Use arrival direction for “interesting event” discrimination**

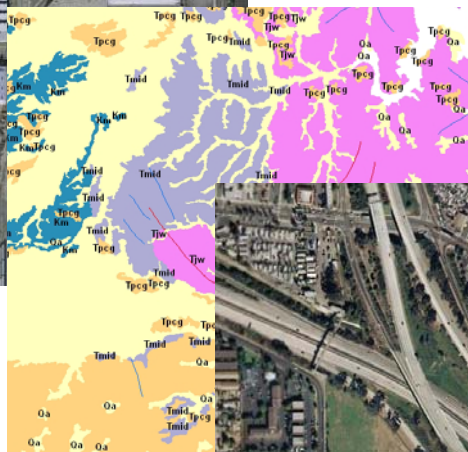
Systems Study Summary

Interactive Analysis and Data Visualization

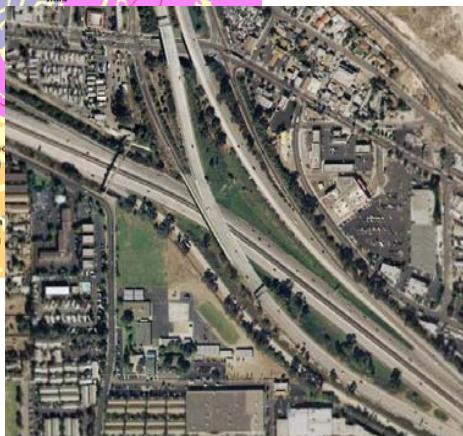
Border GIS Spatial Data



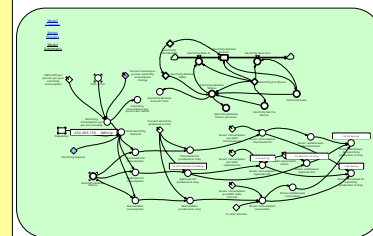
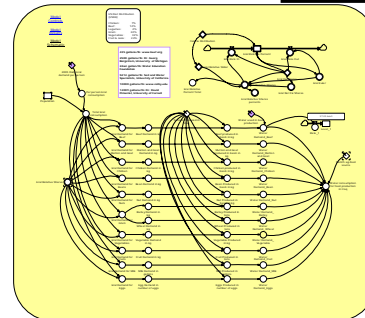
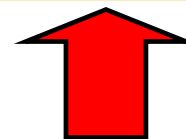
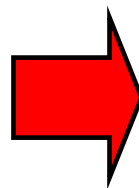
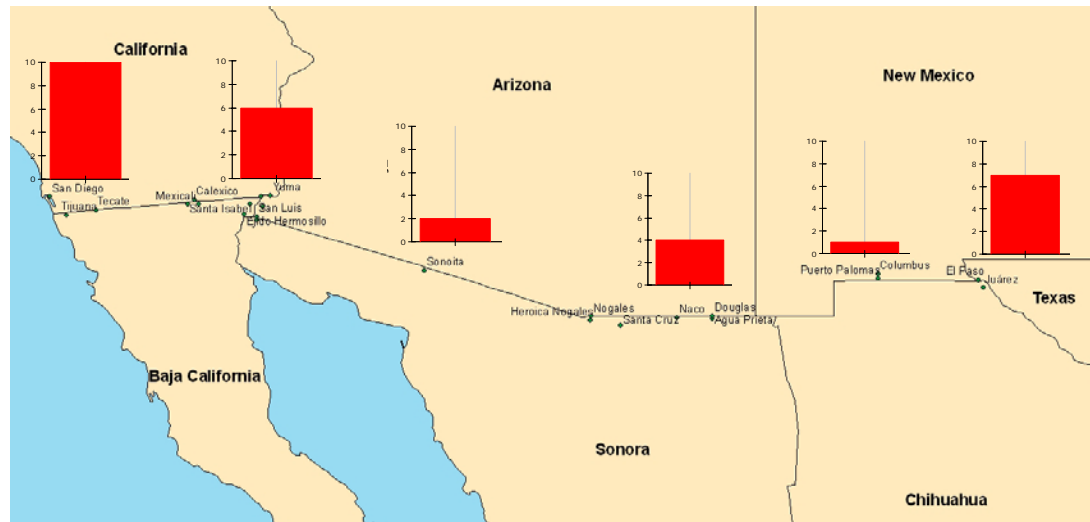
Land Use and
Building Density



Subsurface Geology



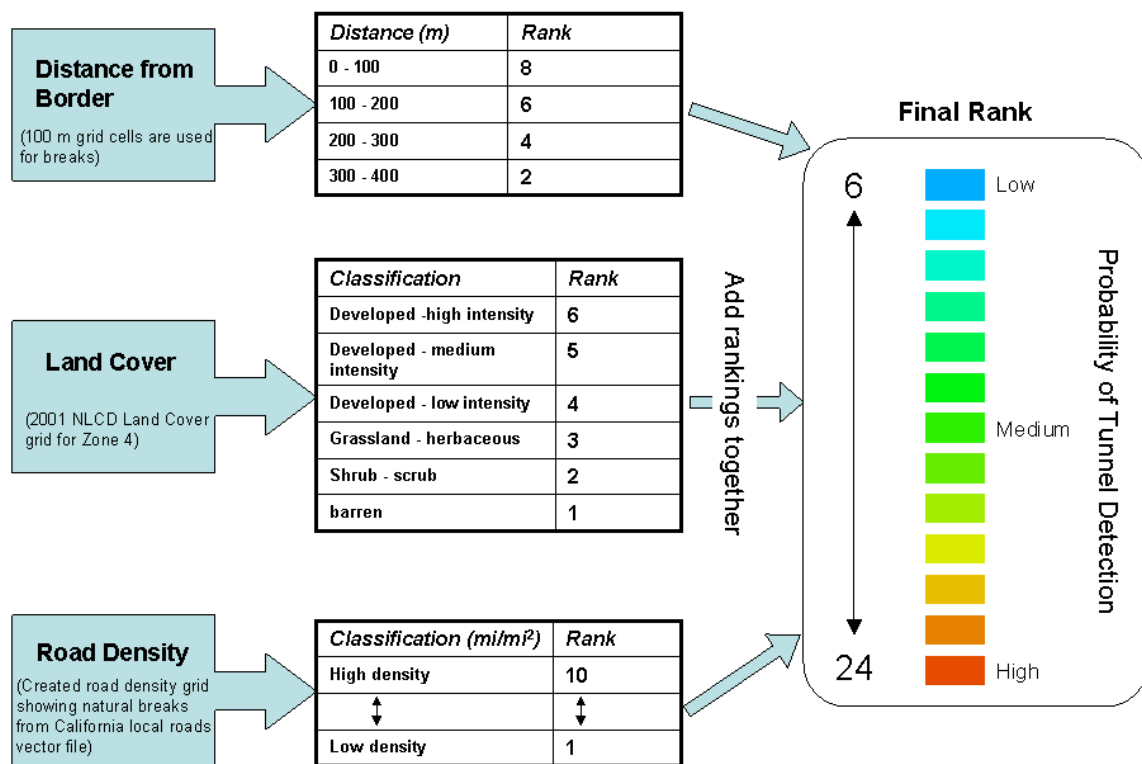
Transportation Corridor Density



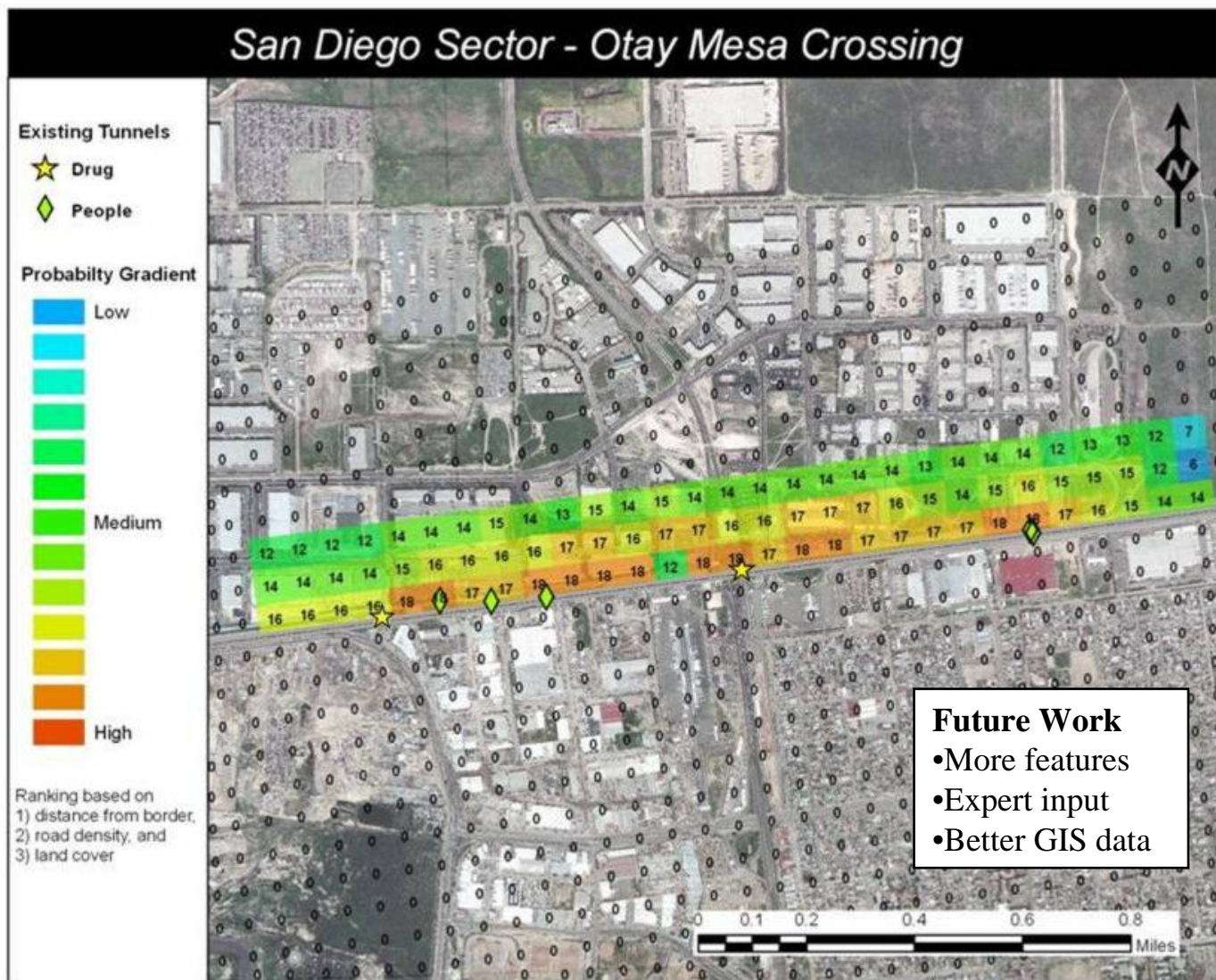
Data Synthesis with System Dynamics Model

Systems Study

- Reduces Area Coverage requirement
 - Impossible (and unnecessary) to cover ~2000 miles of border
- Facilitates Resource Application
- Currently using
 - Distance from Border
 - Land Cover
 - Road Density
- Future features
 - Water Table
 - Geology
 - Topology
 - Zoning
- Empirically based weighting



Initial Results

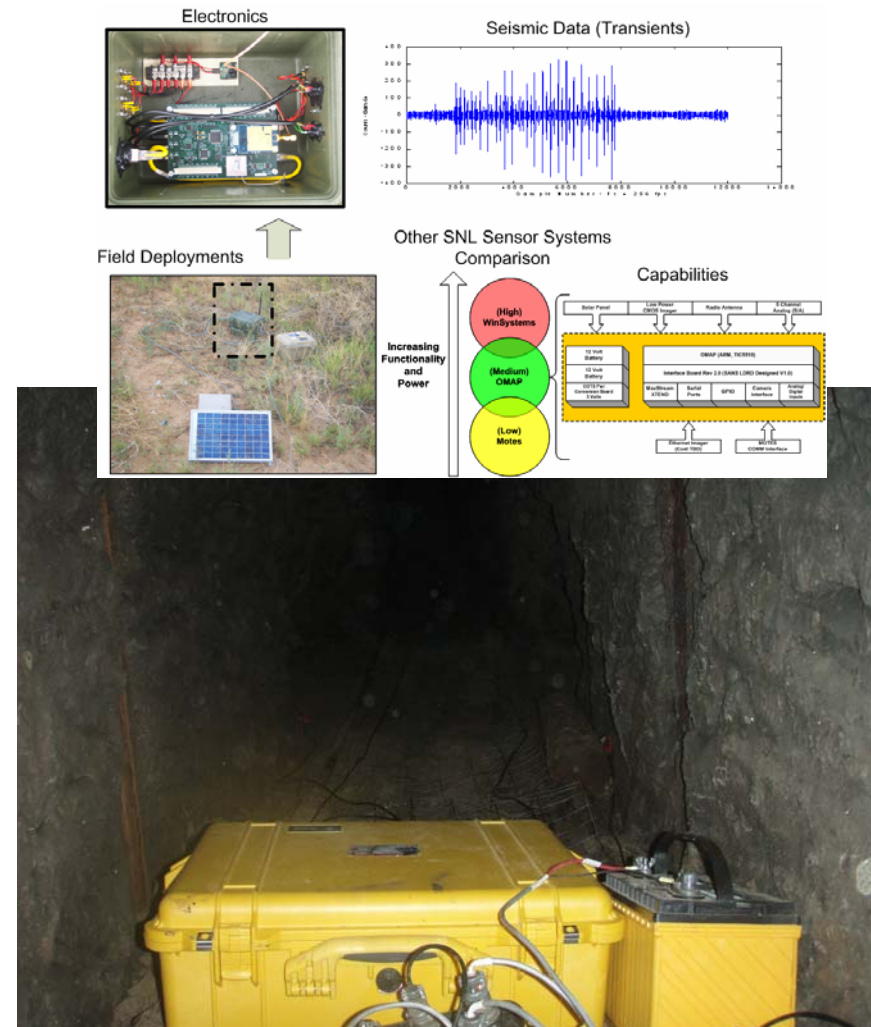


Existing tunnels brought in to see how predicted matches with observed.

Fly-away Kit Capability

A Platform for Spiral Capability Insertion

- Physical Sensor System
 - Seismic / Acoustic / EM Sensors
 - Data Capture & Storage
- Exploitation and Analysis Tools
- Subject Matter Expert (SME) Support
- Spiral Development
 - Provide Initial Capability
 - Support Operations with SME
 - Learn Customer Requirements
 - Refine Physical Sensor System
- Long Term Technical / Operational Partnership
 - System Study of Border Tunnel Requirements
 - Train Border Patrol / Military Operators
 - Transfer Cutting Edge Technology to Industry



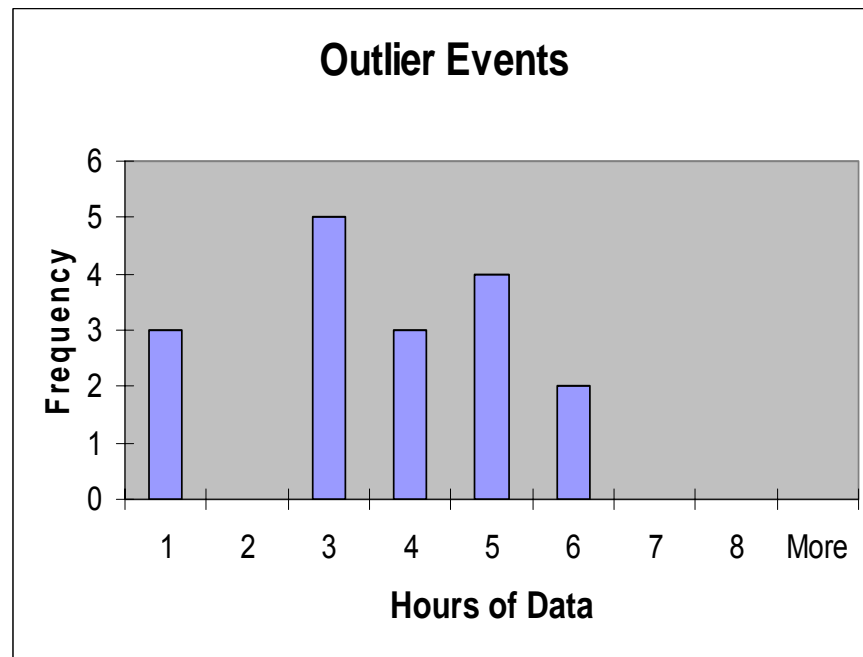
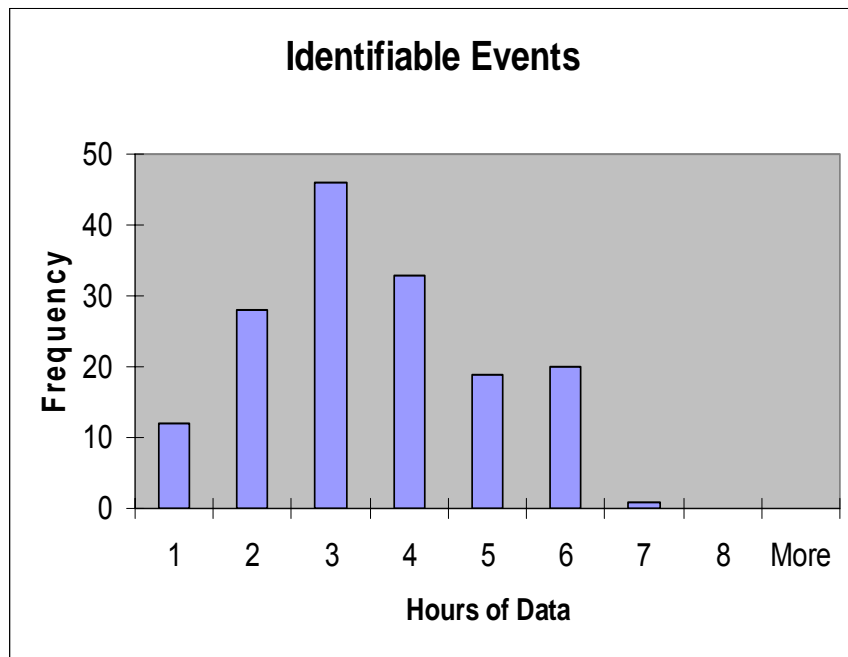


Analysis of In-Tunnel Sound

- **Acoustic Data Recorded June 2007 at Otay Mesa 1993 Tunnel**
 - **Commercial voice recorder placed inside tunnel by law enforcement and contractor personnel**
 - **38.5 hours of audio data recorded between June 4, 2007 to June 6, 2007 (stored in 2 large files)**
- **Analyzed data and grouped signals into 4 identifiable classes**
 - **Vehicles, voices, transients, and outlier signals.**
 - **156 in known classes, 80 in outlier classes**
 - **Known class – identified by type / source**
 - **Outlier class-all the signals that we are unable to readily identify**
 - **Further analysis will move some outliers into known classes**

Outlier Signals:

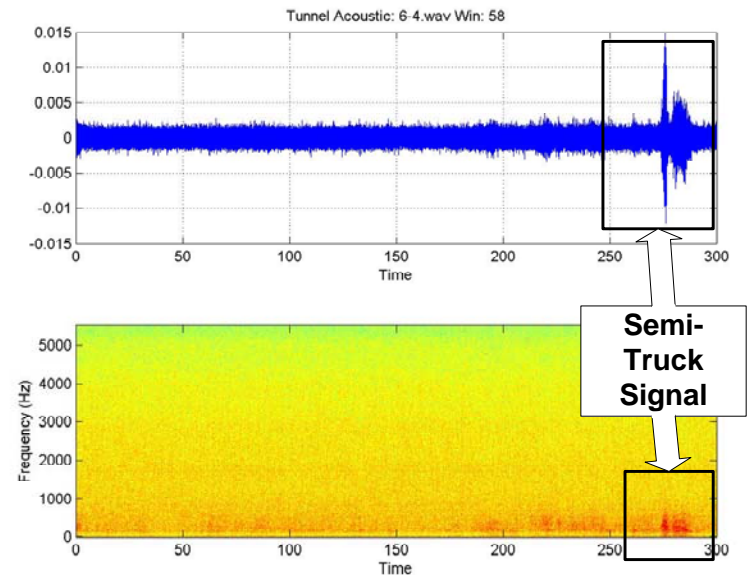
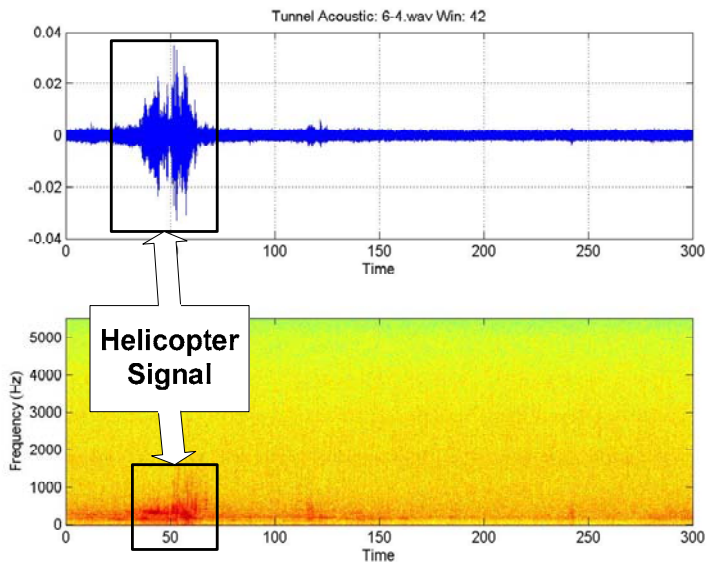
Identifiable Events vs. Outlier Events



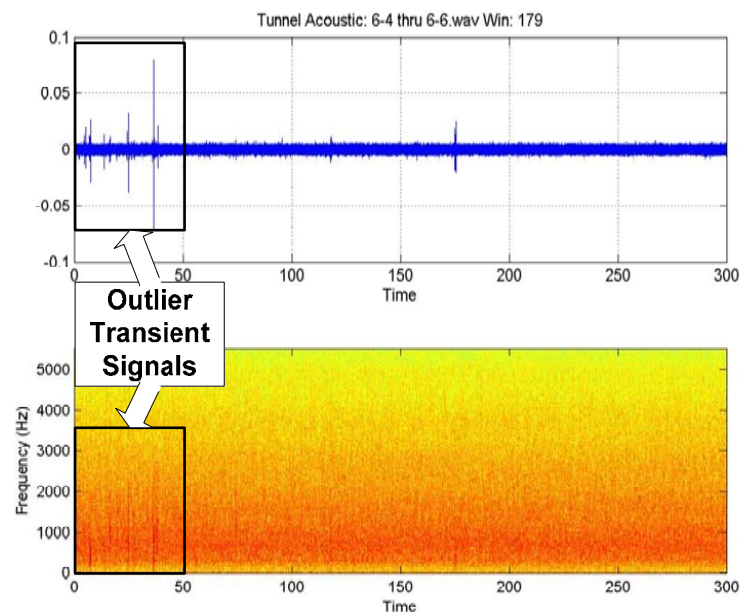
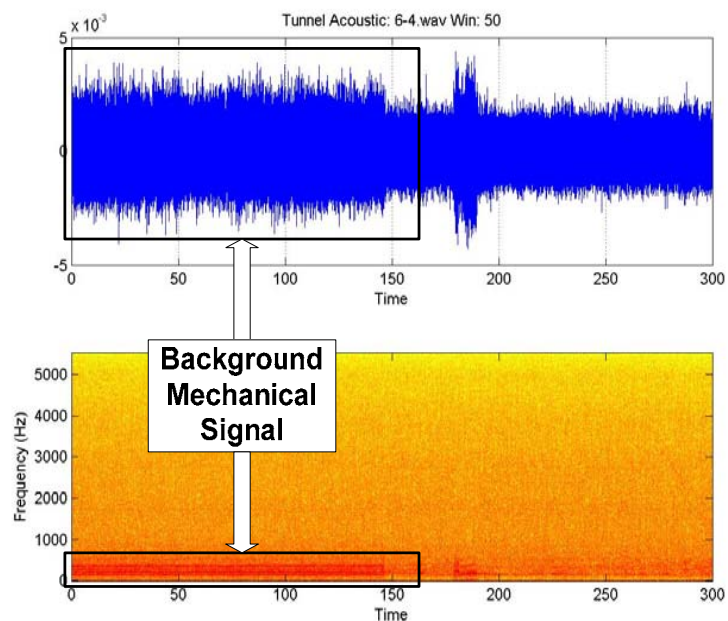
- The left figure shows the number of identifiable events by time in the first data file.
- The right figure shows the number of outlier events by time in the first data file.

Identifiable Signals

- Over 90% of the signals are identifiable. These signals consist of trucks, cars, helicopters, and airplanes.
- The figures below show two examples of identifiable signals: a helicopter and a semi-truck.



Outlier Signals



- The left figure shows a background mechanical signal that lasted 2m 29s
- The right figure shows 6 transient signals that all sound like footsteps in the tunnel.



Summary and Conclusions

- **Advanced geophysical sensing and signal processing techniques developed over the past several years for DOE and DoD customers are applicable to border tunnels**
- **Sandia has developed and fielded sophisticated autonomous sensors systems for Situation Awareness and site security**
- **Sandia has worked with NORTHCOM and the San Diego Tunnel Task Force providing an ad hoc quick response fielding at the Border**
- **We look forward to continued work with the Border Security Community to develop and field robust technologies**
 - **A more robust ‘fly away kit’ capability**
 - **Advanced in-place sensor system for persistent tunnel SA**
- **Refinement of techniques and integration into existing monitoring systems will require resources and a close partnership of the technical and operator communities**