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# Experiments in Active and Passive Detection of Small Border Tunnels

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# Tunnel Detection and Characterization History

2006 Otay Mesa Tunnel

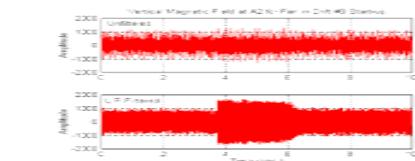
## Past Program Experience



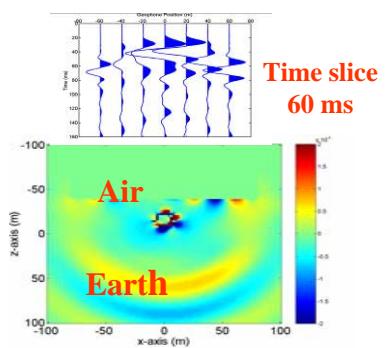
Autonomous Monitoring Systems



DARPA Sensor Dart



Signals and Analysis



3D Modeling

*Shallow  
Tunnel  
Activity*

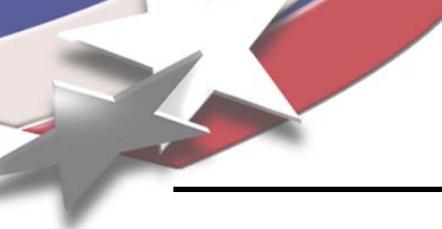
*Application to Large  
Tunnel HDBT's*

**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



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



# Sandia Border Tunnel Goals

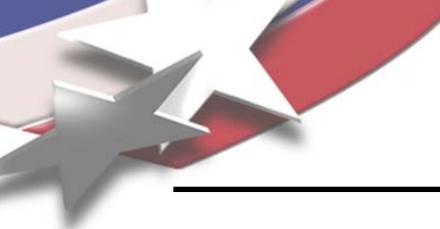
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## Develop fieldable system that provides actionable information

- 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

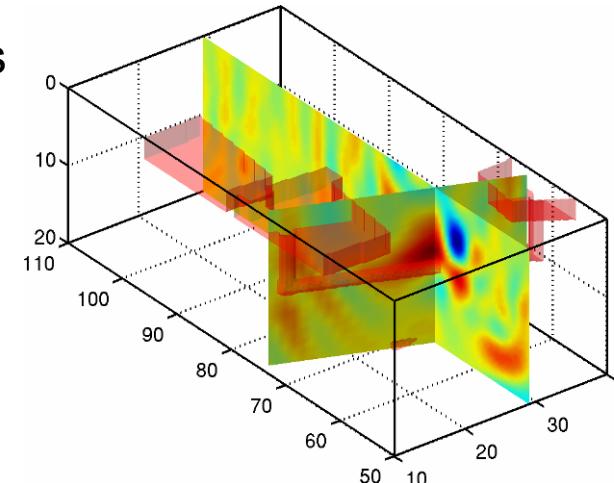
## Multi-Program NNSA Laboratory View

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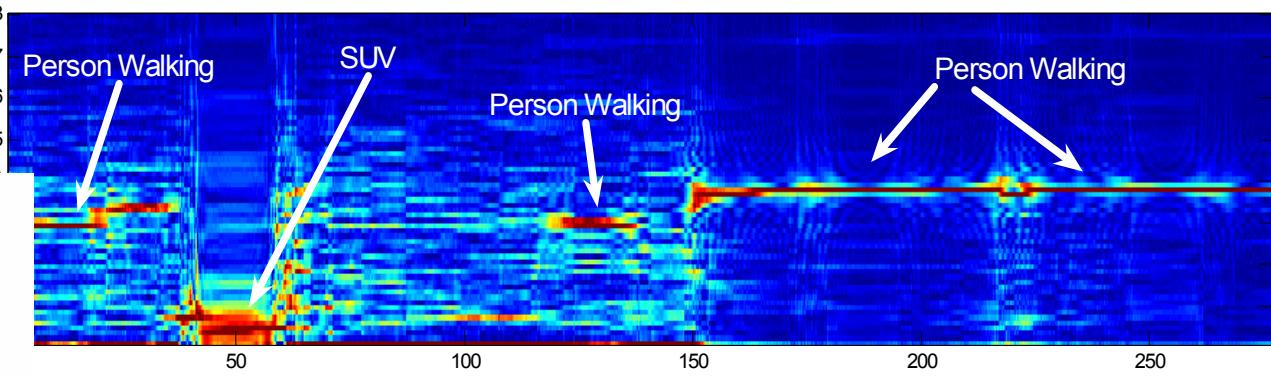
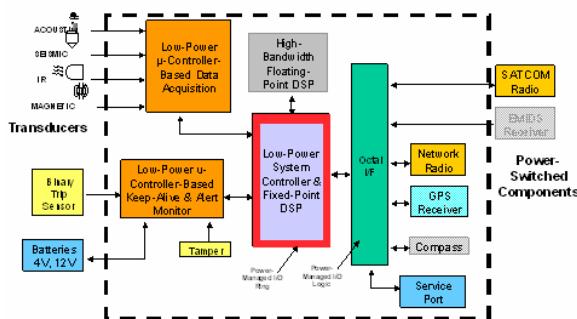
- **Multidisciplinary Team**
  - **Geoscience, Signal Processing, Real-Time Processing, Systems Integration, Test**
  - **Draw from Multiple Areas of the Laboratory**
- **Combine Modeling, Analysis and Test**
- **Requirements driven Spiral Development**
- **Systems View**
  - **Basic Understanding -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

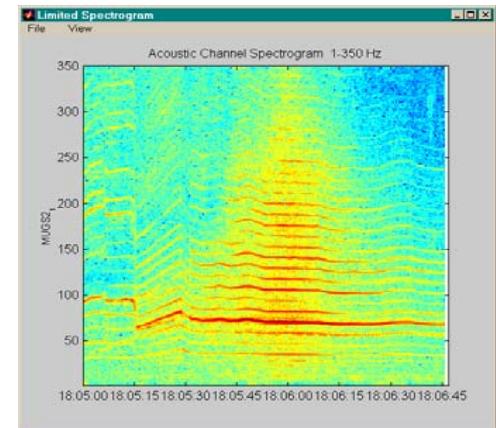


Advanced Classification Algorithm

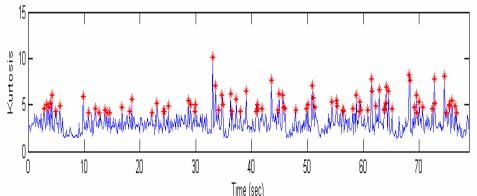
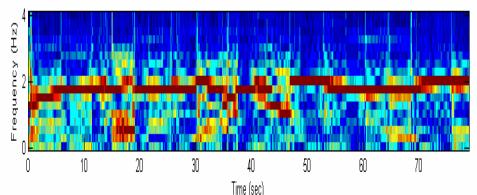
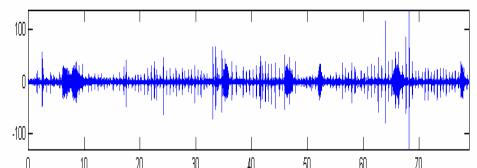
Flexible System Architecture

# 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



**Large Vehicle**

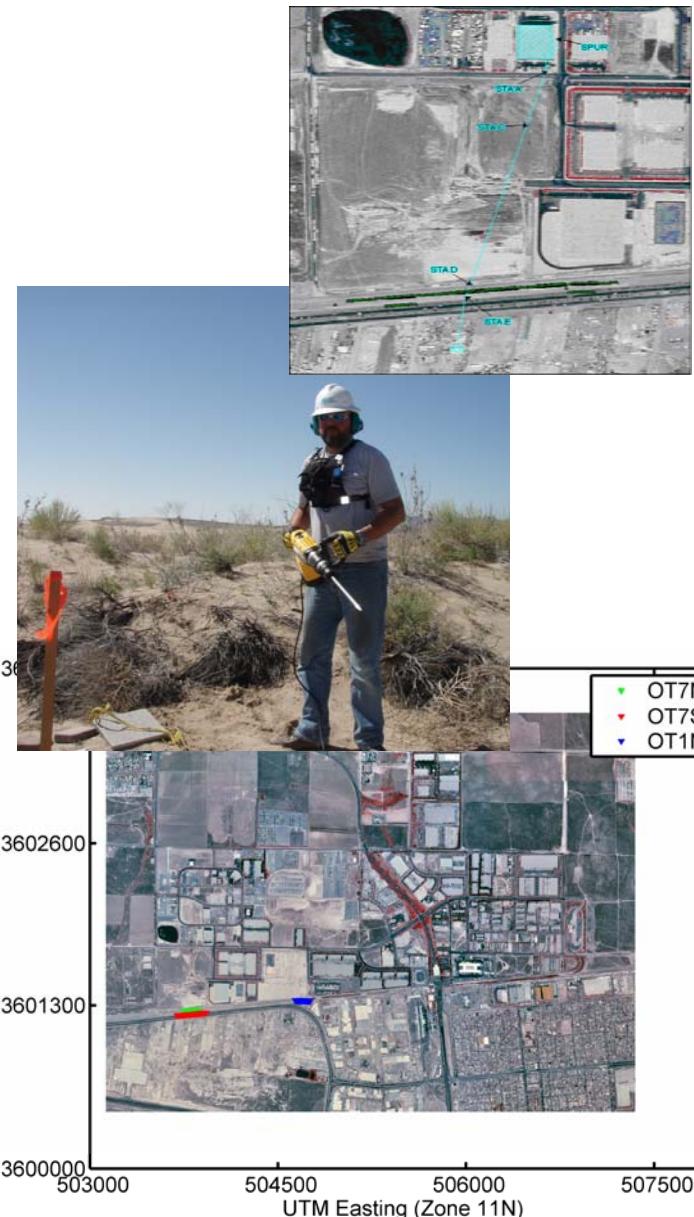


**Footsteps**

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

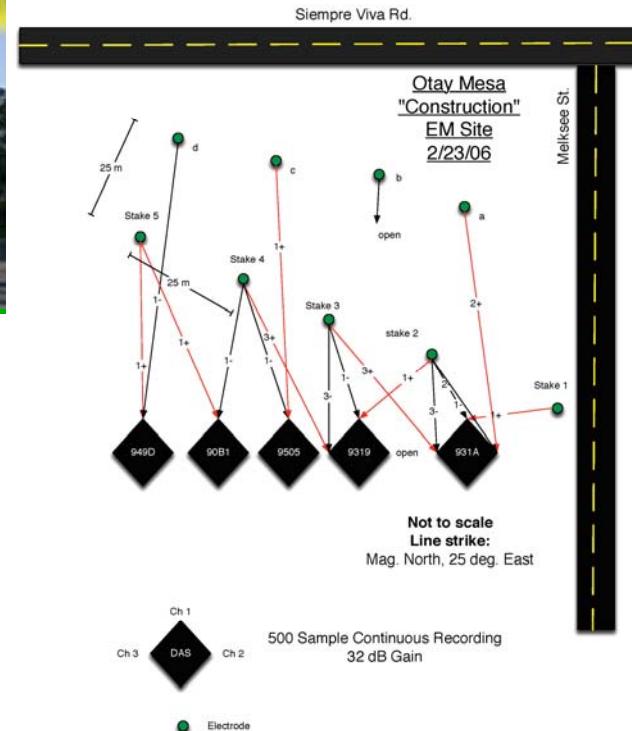
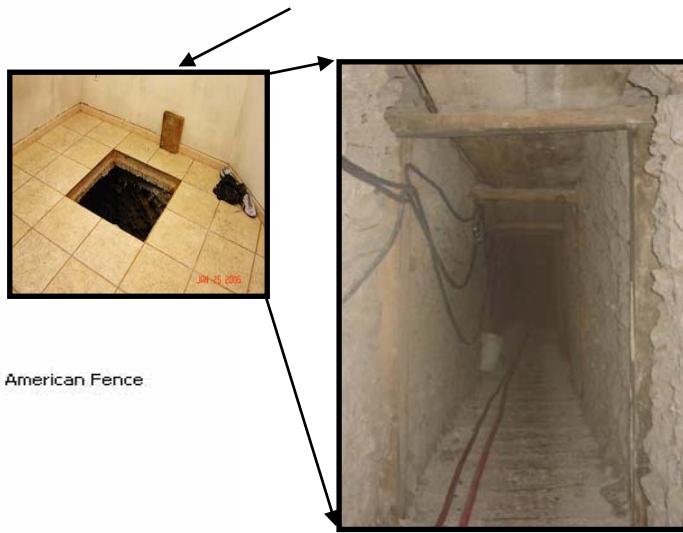
# Three Major Experimental Deployments

- 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



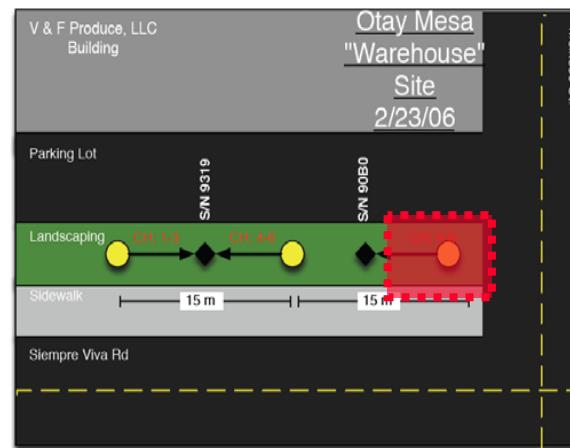
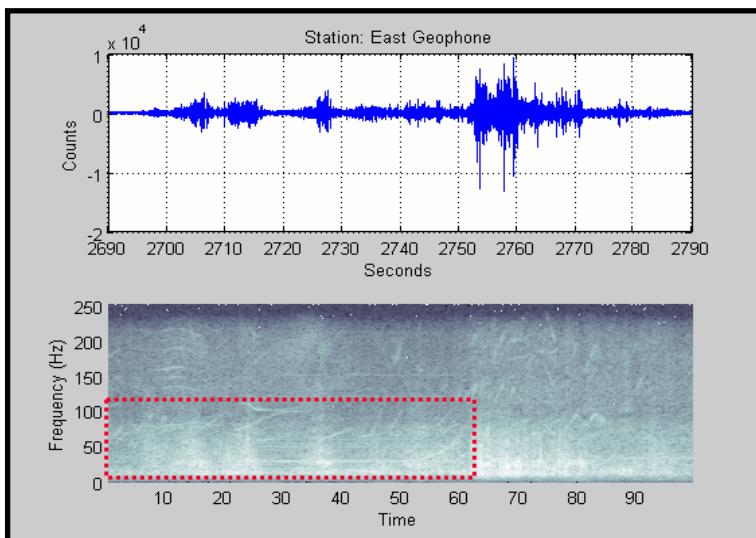
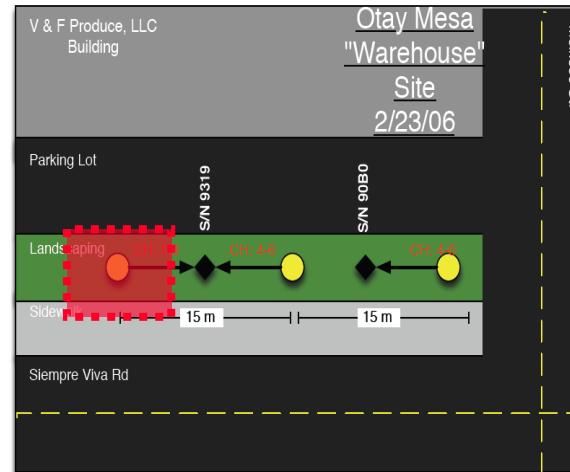
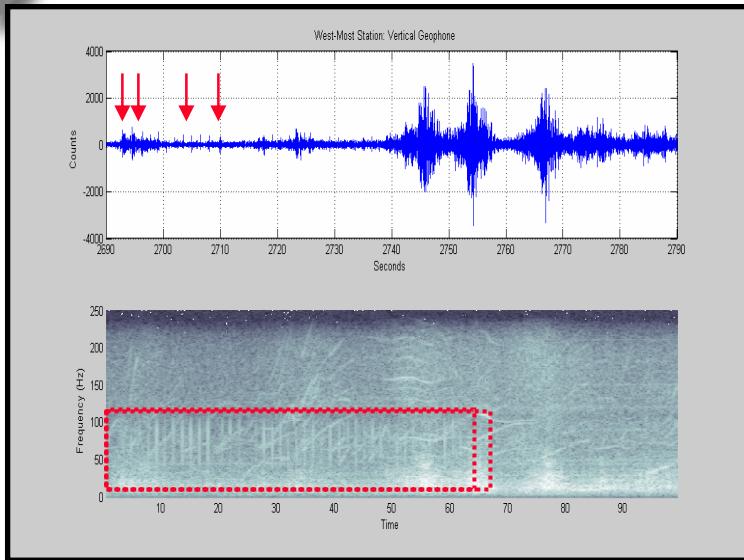
# Otay Mesa Data Collection 2006

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



**K. Keisling (JTFN)**

# Pick Construction Signatures Feb 2006 Roof Blows at 1Hz



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

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



# Analog Tunnel Site Data Collection – April 07

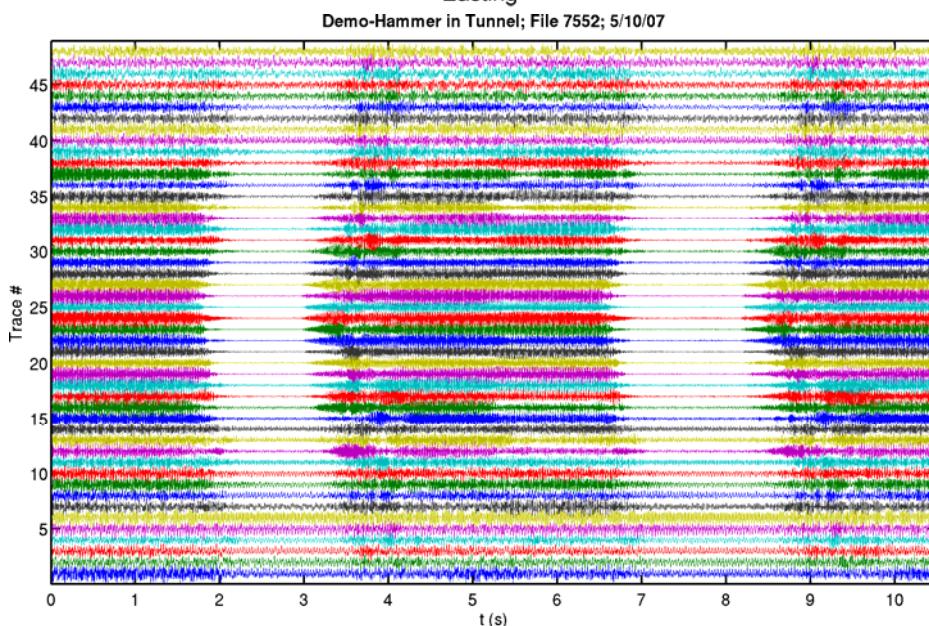
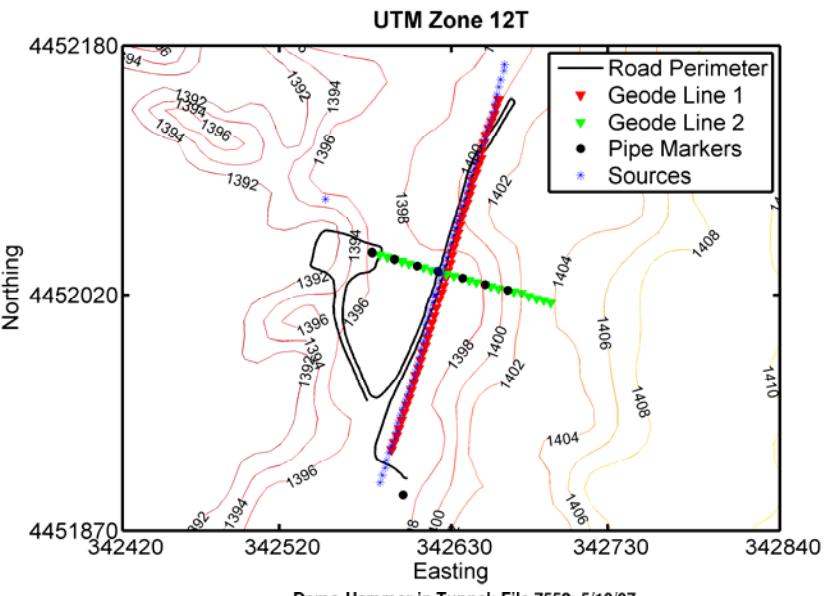
## (Controlled, Safe, Quiet, Accessible Site)

- 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



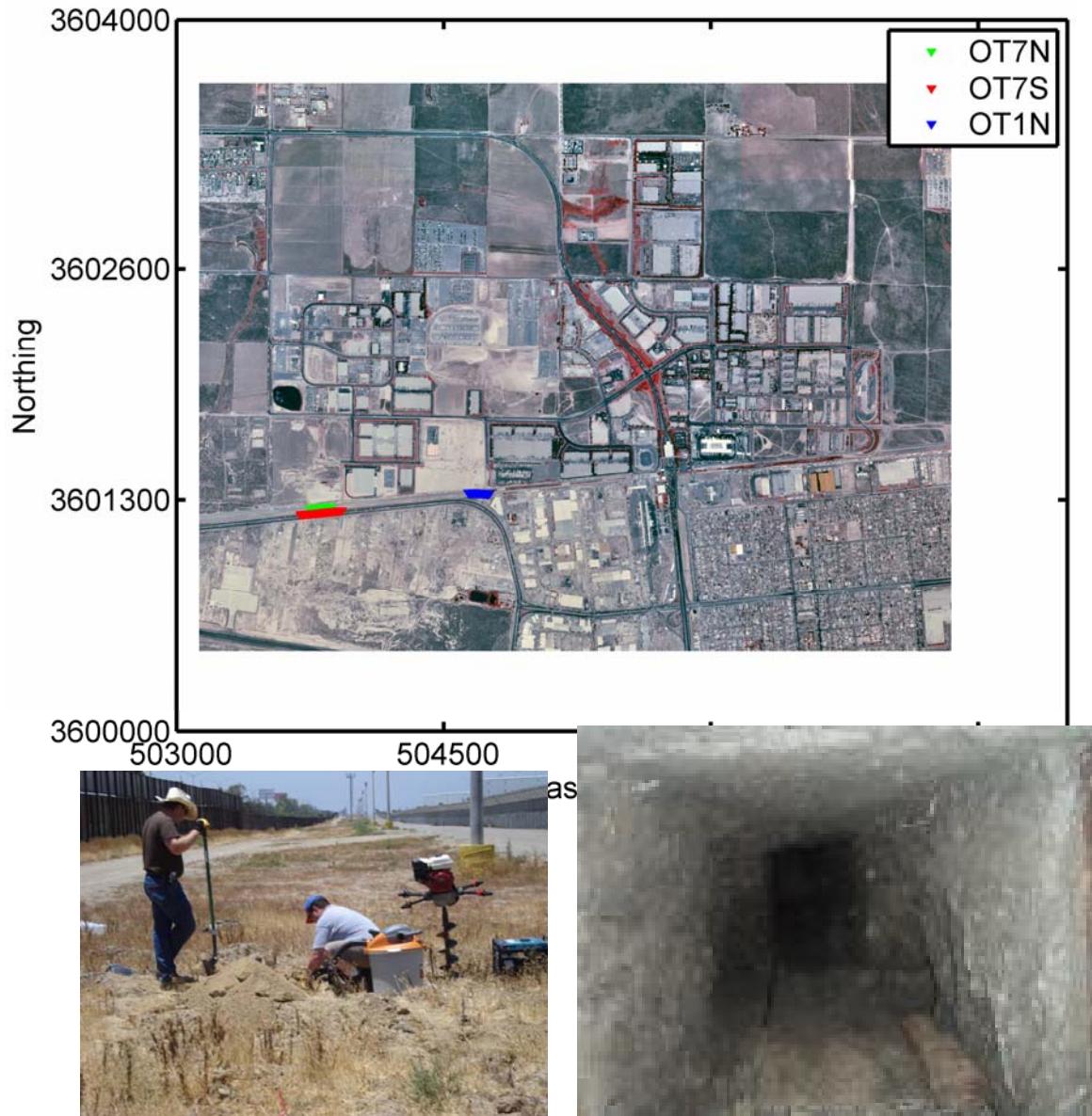
# Demolition Hammer Data

- 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

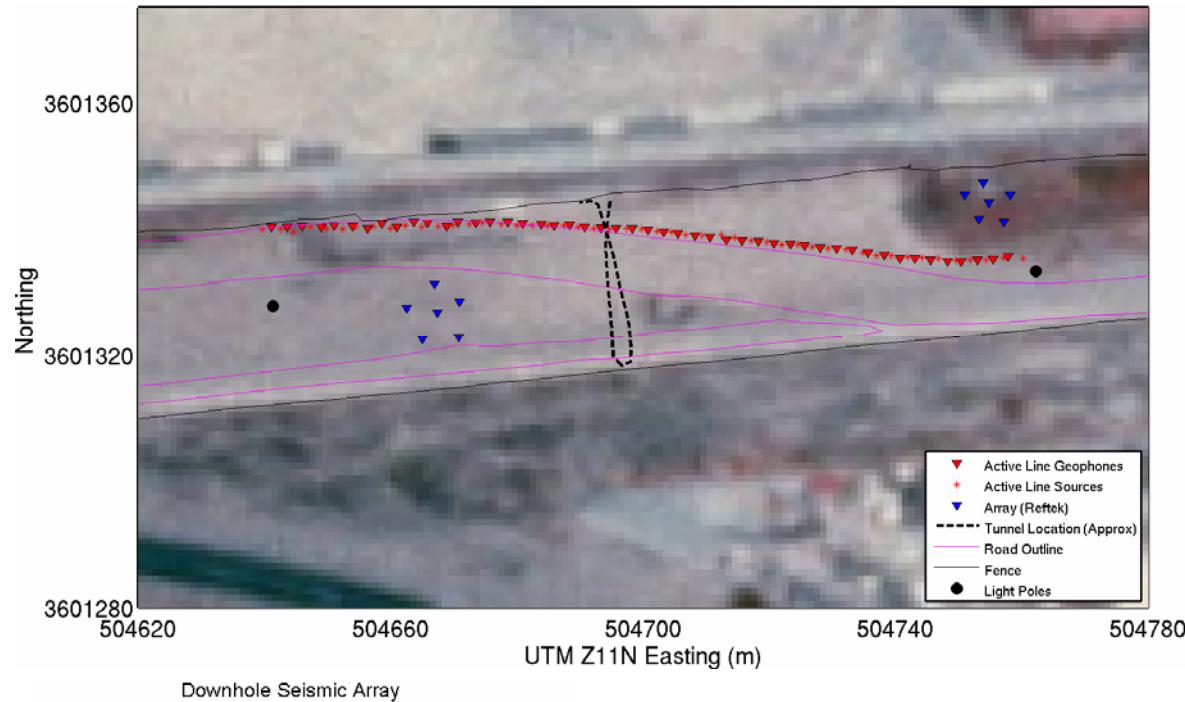
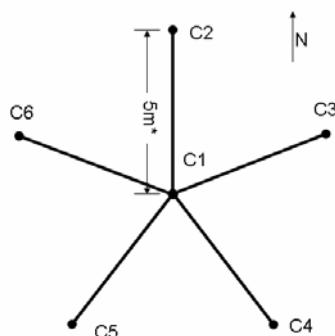
- Two primary sites for data collection
  - Otay Mesa #7
    - Lines on North and South side of easement
  - Otay Mesa #1/2
    - One line swings from south to north
    - Follows all weather access road
- Arrays installed at both sites
  - OT #7
    - Surface arrays during active source data collection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



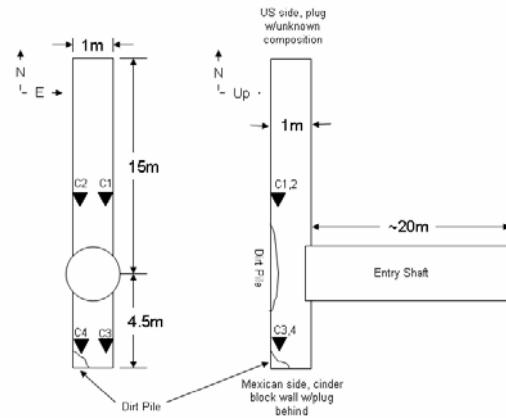
# Otay Mesa #1/2 Collection

- Collaborated with NORTHCOM and Huitt-Zollars to collect at Otay Mesa prior to tunnel fill activities
- Operational Interface with San Diego Border Tunnel Task Force for collection
- Arrays placed Wednesday June 27
  - Recorded until 7/5 downhole, 7/7 surface
- Active source line Thursday, June 28
  - 2.5m receiver and source spacing
  - 1 shot off each end (49 shots total)

Surface Seismic Arrays

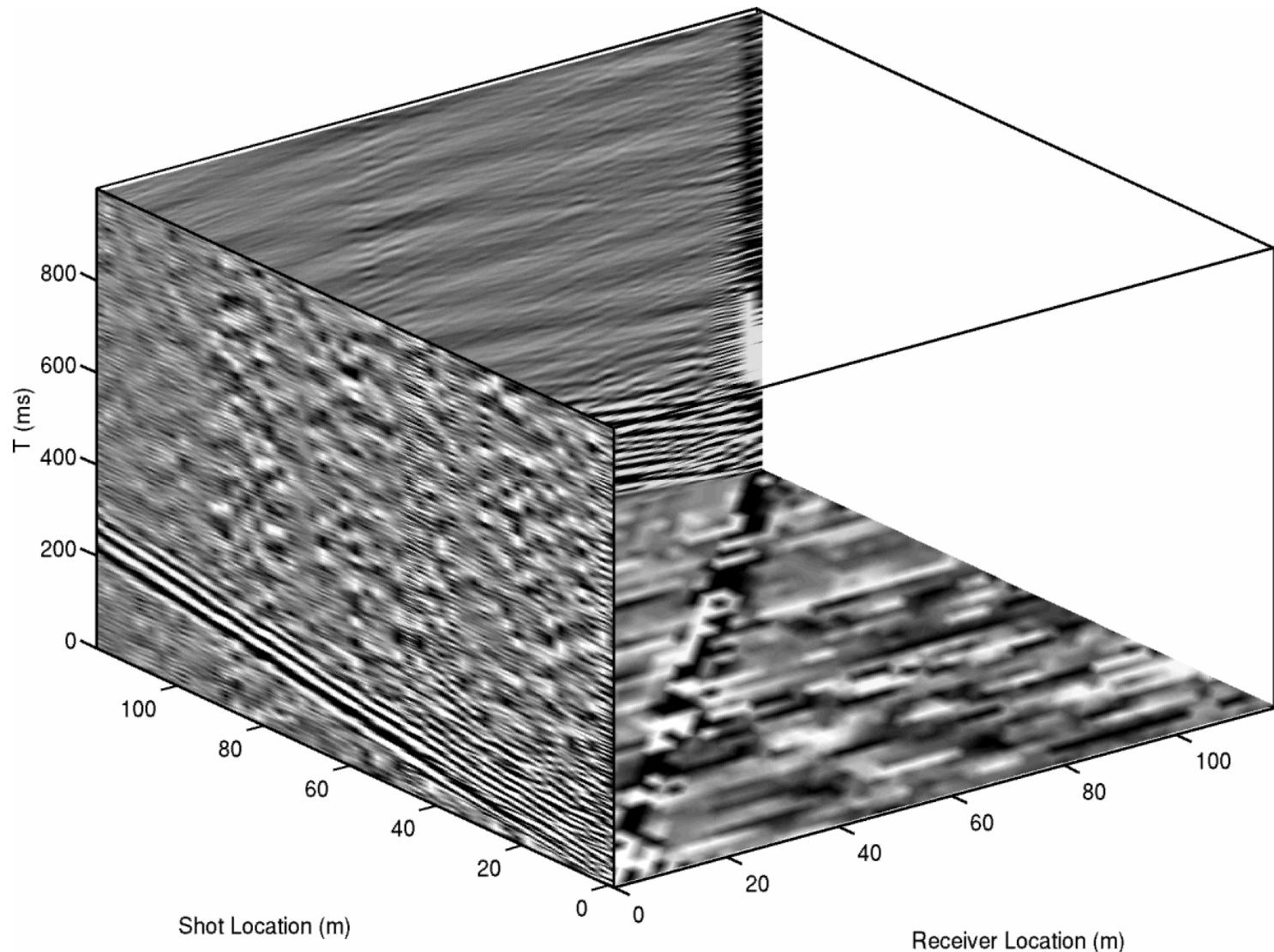


Downhole Seismic Array

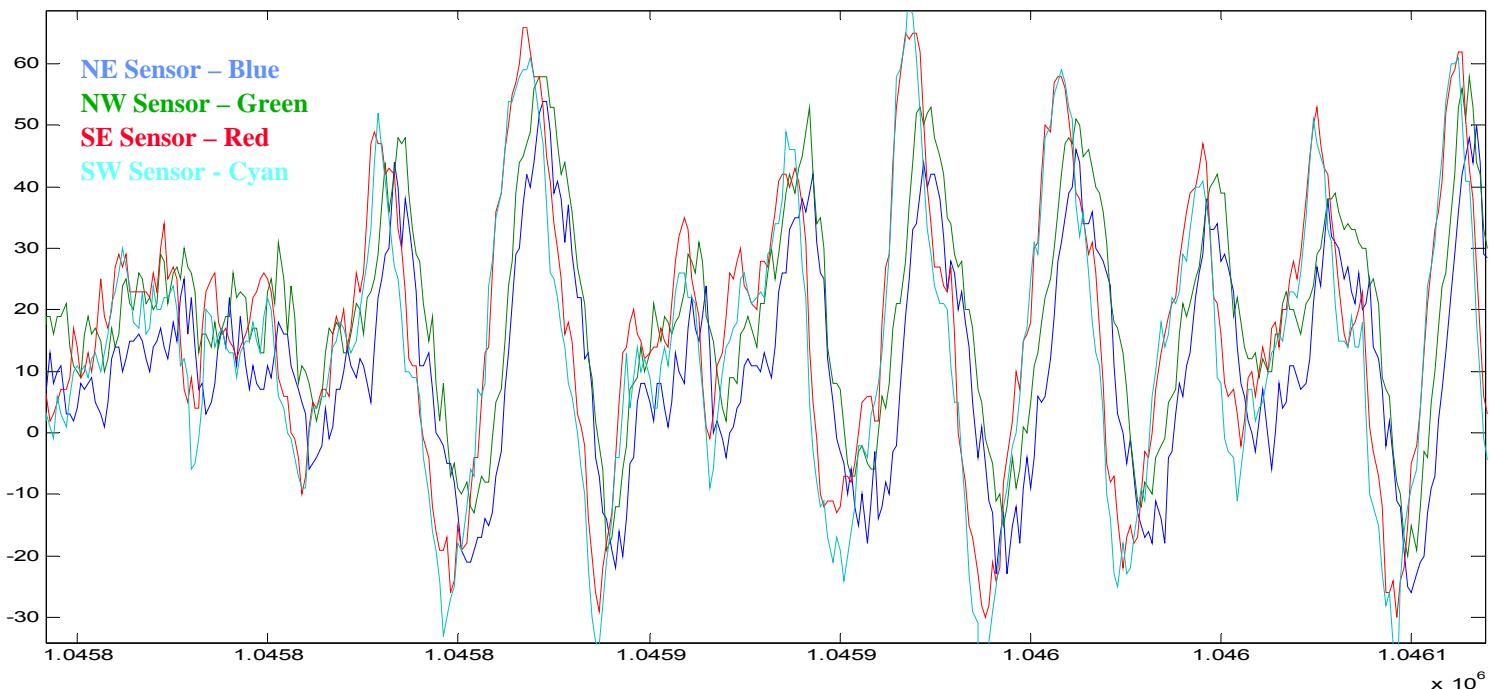


# Active Data

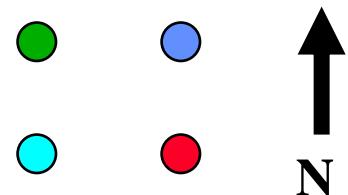
- Analysis is only just starting
  - Lots of noise
  - Appear to be coherent reflectors at late times
  - Will use to develop model for advanced processing techniques
    - Reverse-time migration

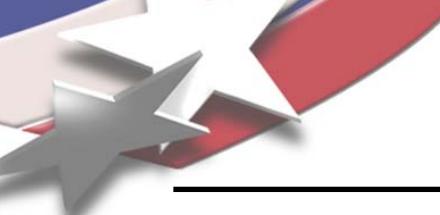


# Analysis of Tunnel Array Data



- 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

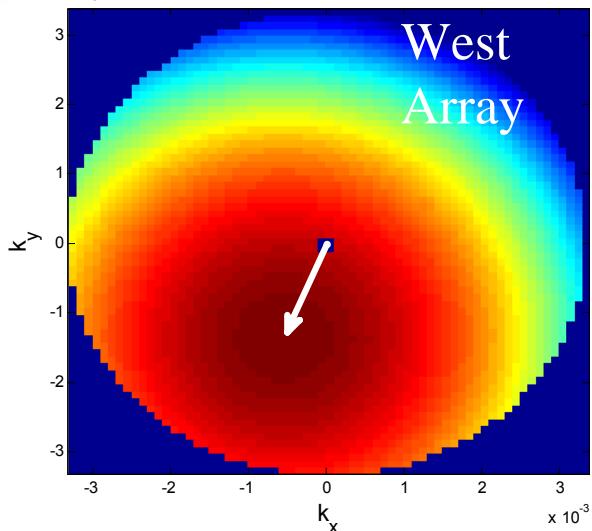
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- FK analysis of array data from Otay Mesa 2007 collection
  - Clear identification of vehicles from the US and Mexican side
  - Allows for the rejection of spurious signals
- Systems Study methodology
  - Initial results for Otay Mesa
- Development 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

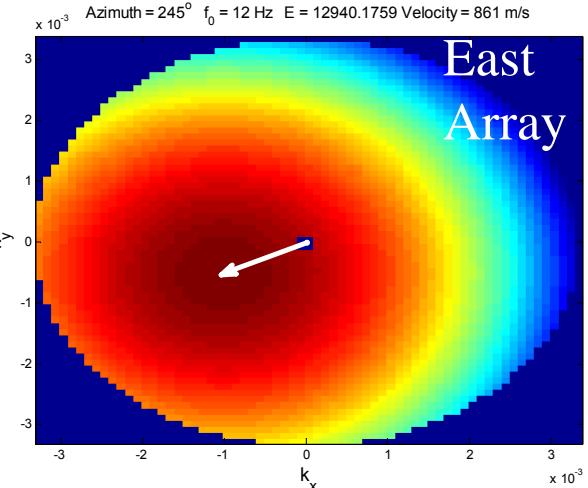
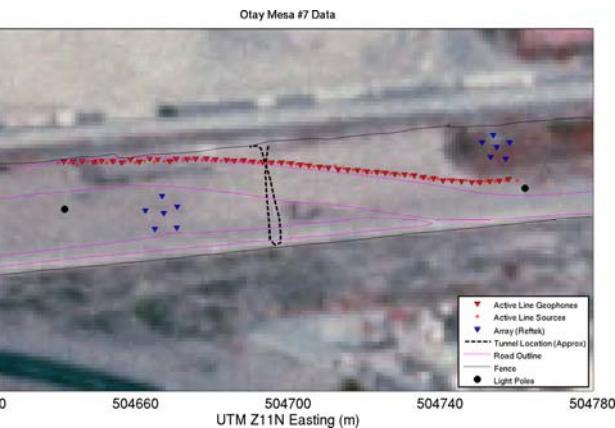
# FK Analysis with Arrays

## Vehicle on Mexico Side

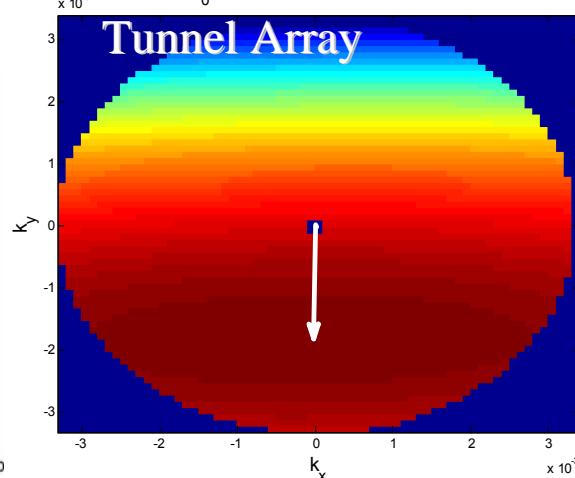
Azimuth = 200°  $f_0 = 12$  Hz  $E = 16799.8732$  Velocity = 684 m/s



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



Azimuth = 245°  $f_0 = 12$  Hz  $E = 12940.1759$  Velocity = 861 m/s

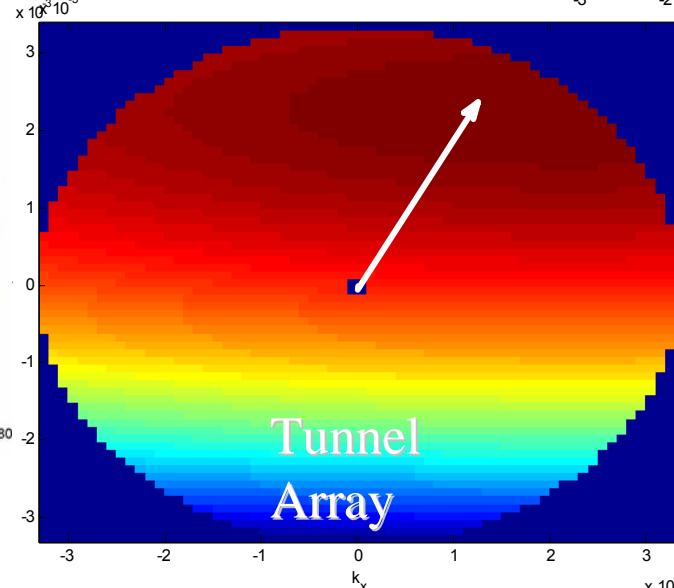
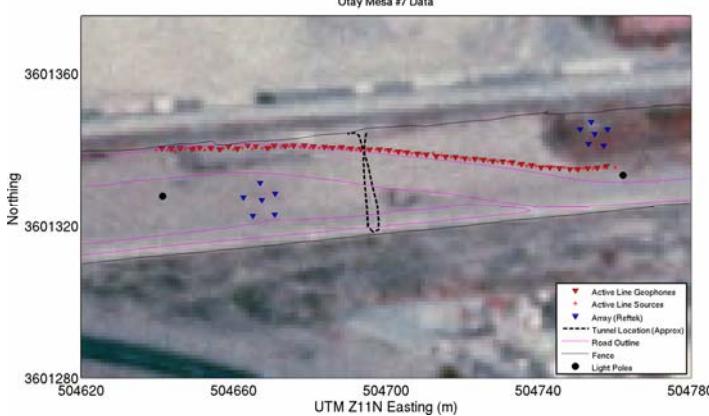
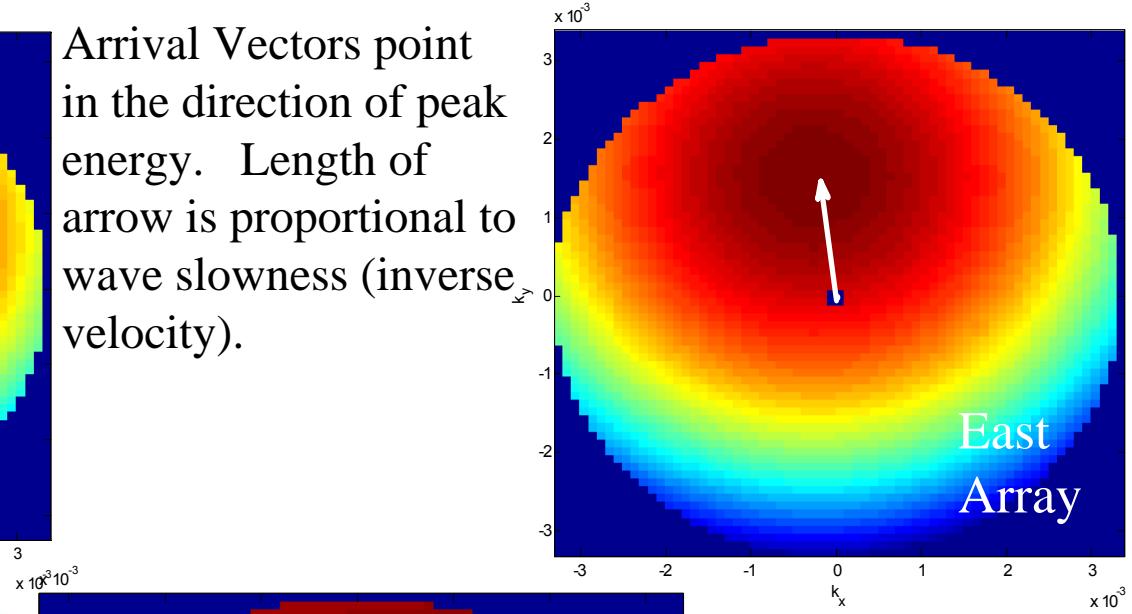
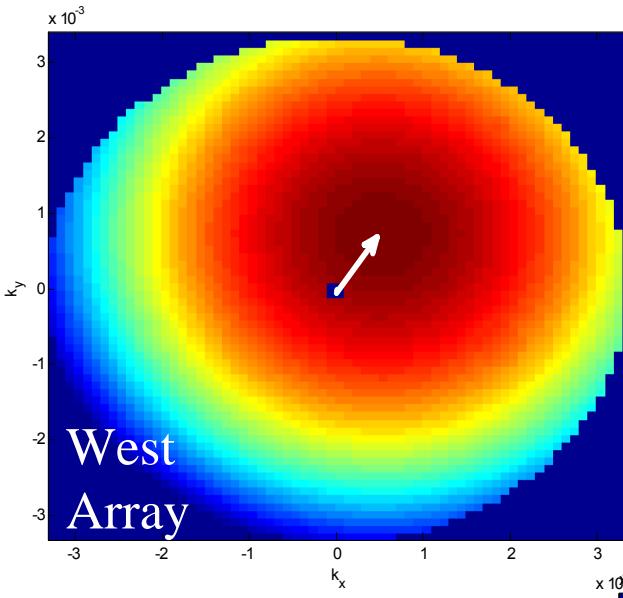


Tunnel may be acting as a waveguide. Therefore, energy appears to come from inside the tunnel.

All three arrays point to activity on the Mexico side.

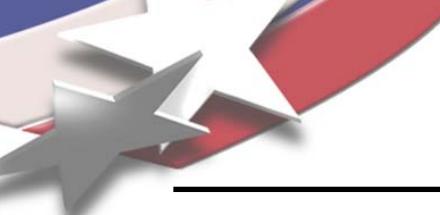
# FK Analysis

## Vehicle on US Side



Vehicle appears to be east of tunnel between surface arrays

All three arrays point to activity on the US side.



# Array Analysis Summary

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- **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

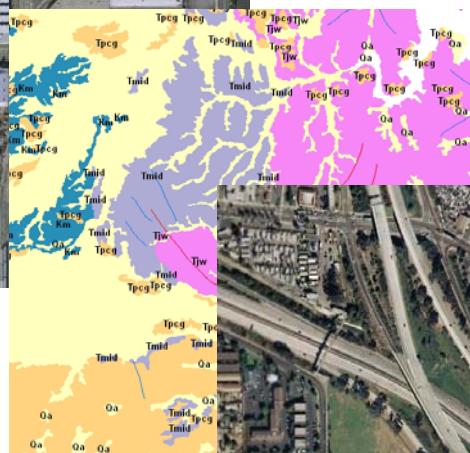
# Systems Study Summary

## Interactive Analysis and Data Visualization

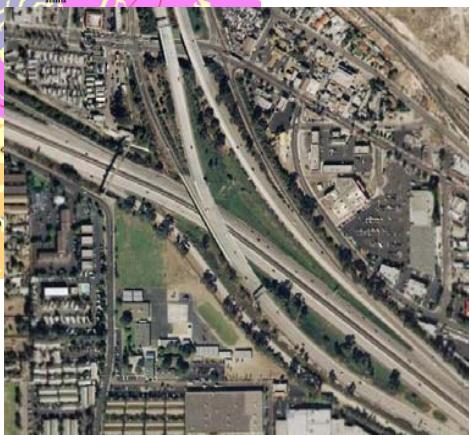
### Border GIS Spatial Data



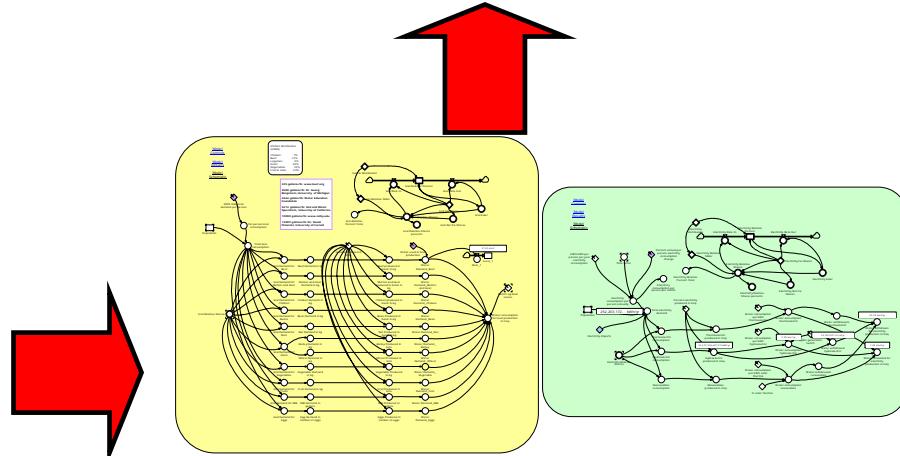
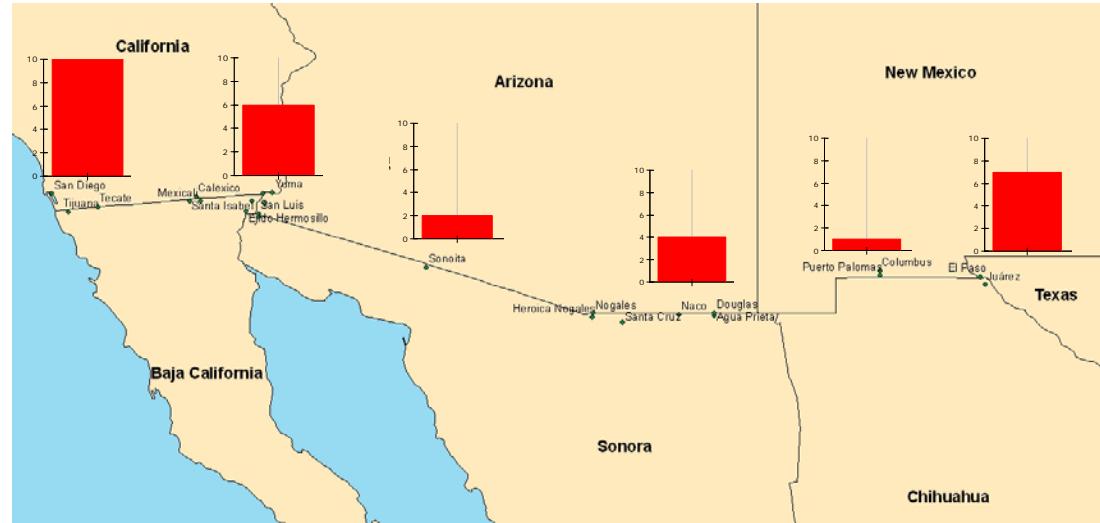
Land Use and Building Density



Subsurface Geology



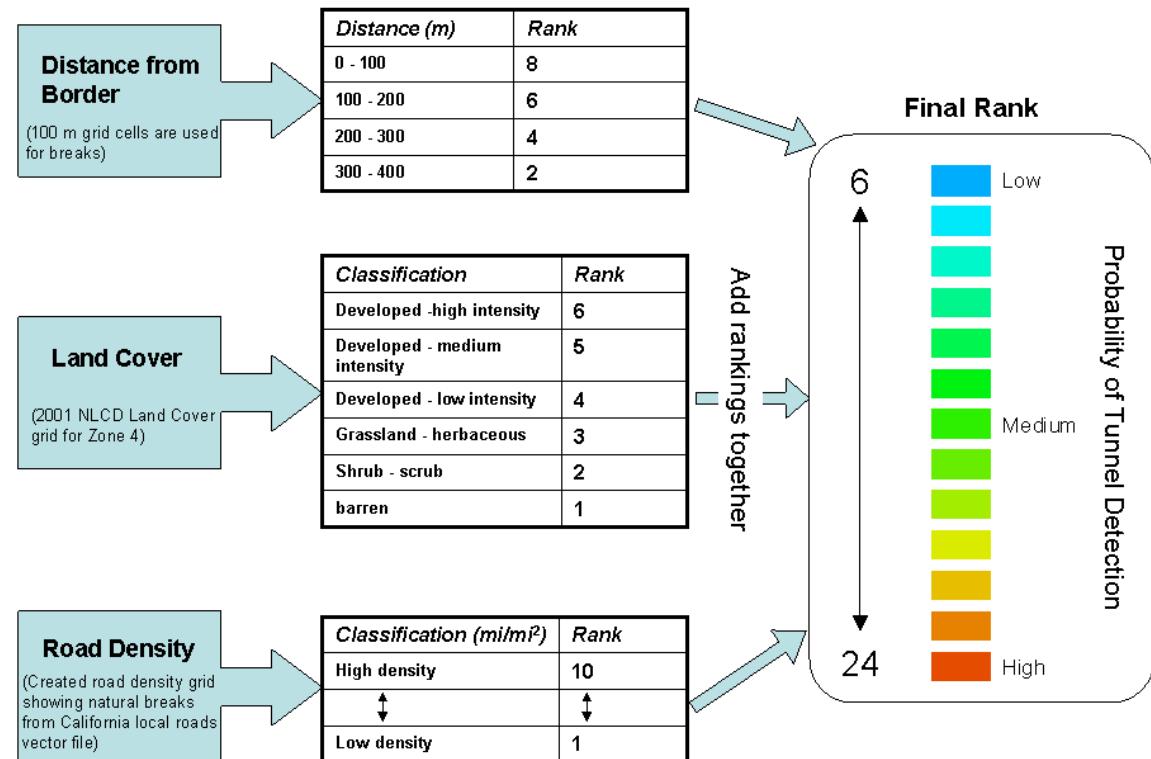
Transportation Corridor Density



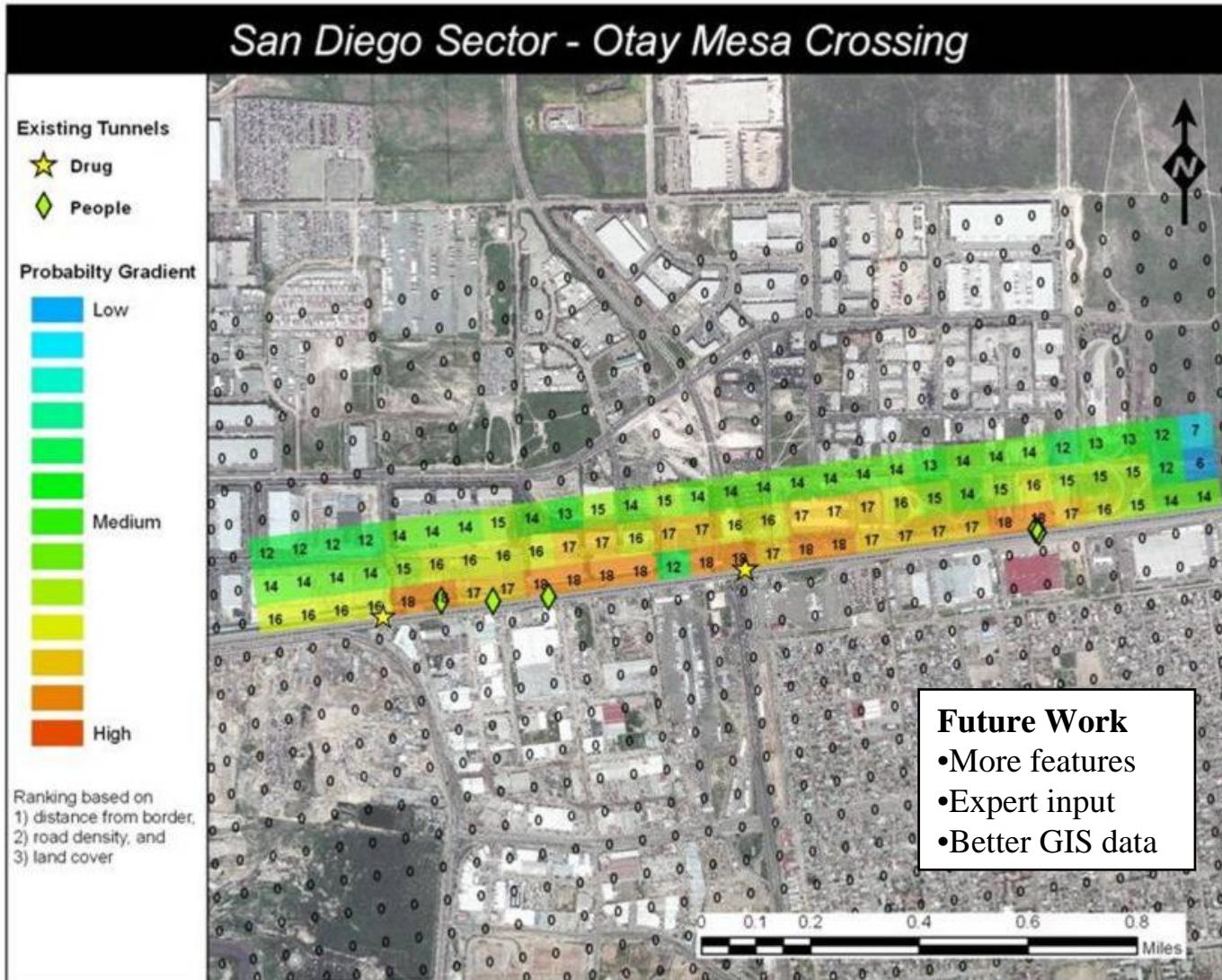
Data Synthesis with System Dynamics Model

# 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

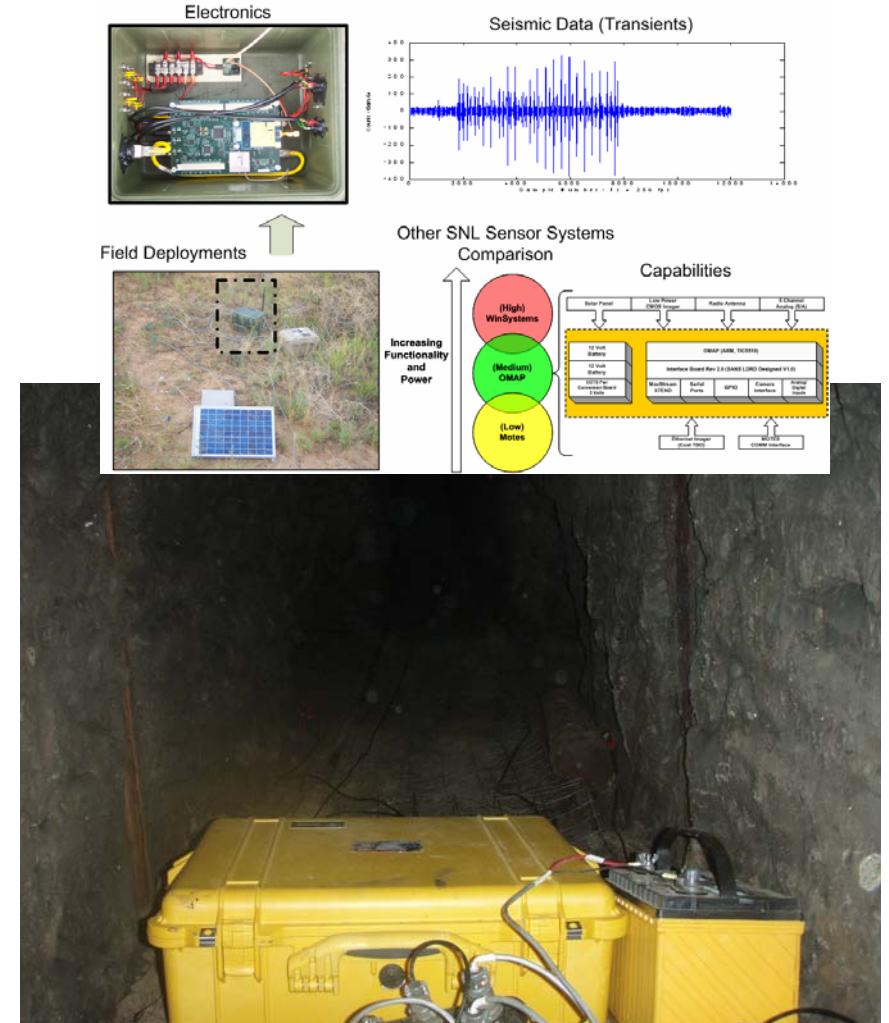


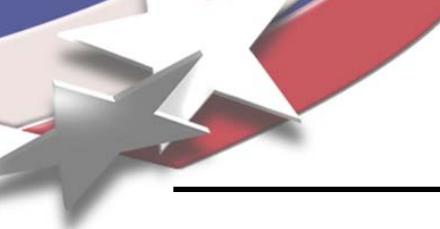
Existing tunnels brought in to see how predicted matches with observed.

# 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

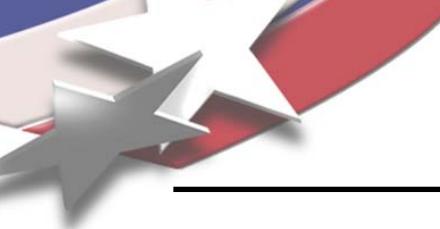




# Analysis of In-Tunnel Sound

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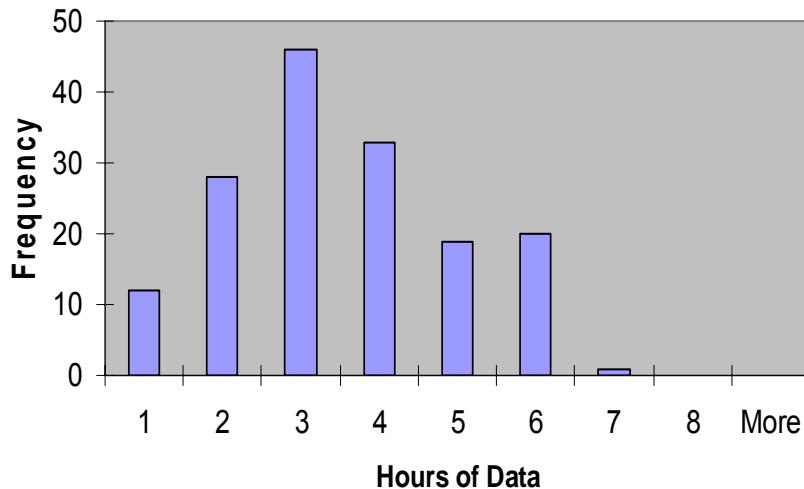
- Acoustic Data Recorded June 2007 at Otay Mesa 1993 Tunnel
  - Commercial voice recorder placed inside tunnel by law enforcement and contractor personnel
  - 38.5 hours of audio data recorded between June 4, 2007 to June 6, 2007 (stored in 2 large files)
- Analyzed data and grouped signals into 4 identifiable 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



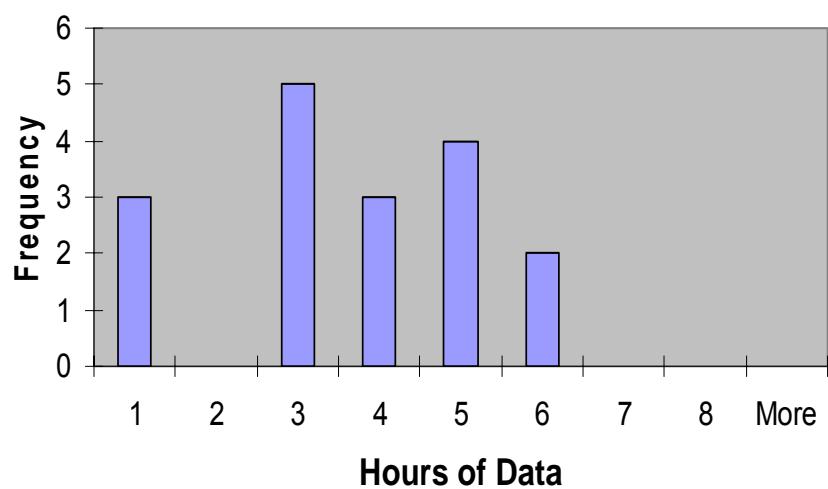
# Outlier Signals: Identifiable Events vs. Outlier Events

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Identifiable Events



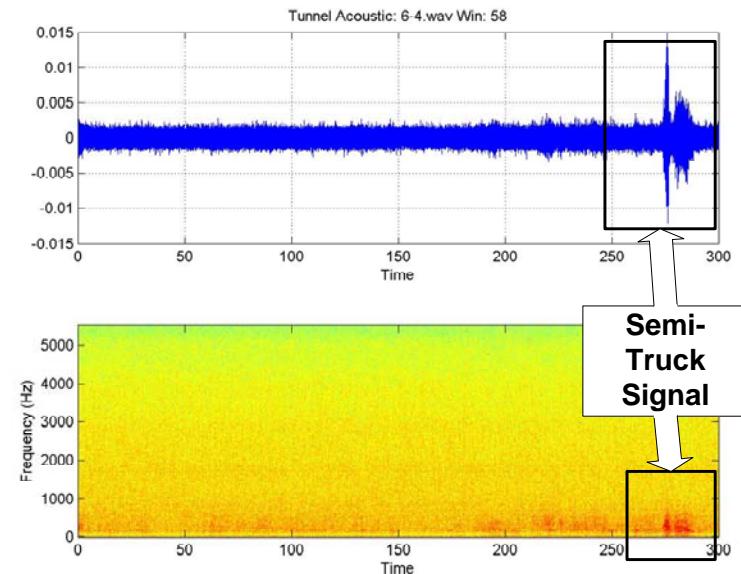
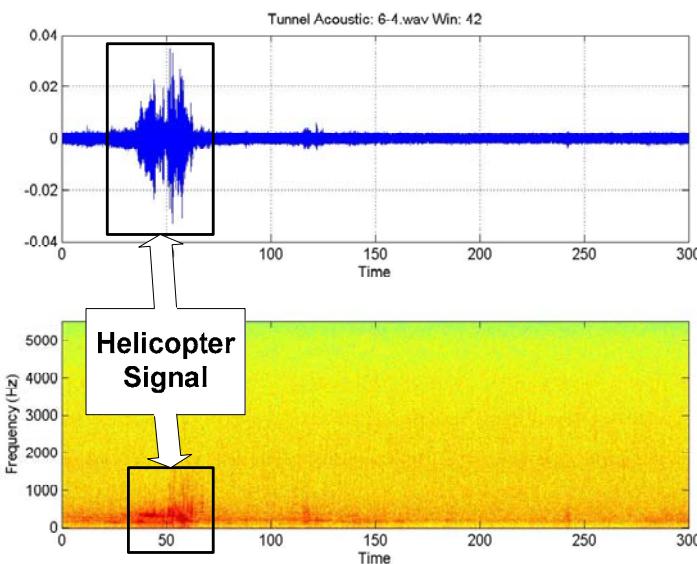
Outlier Events



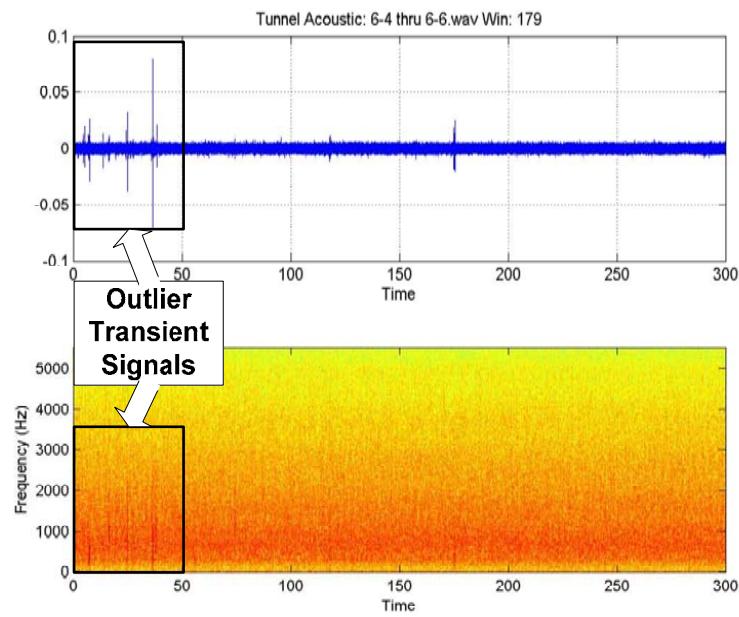
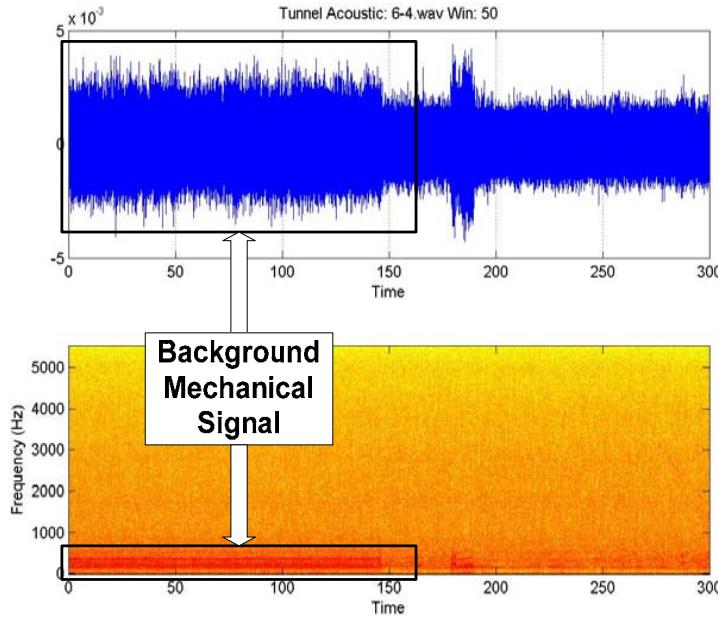
- The left figure shows the number of identifiable events by time in the first data file.
- The right figure shows the number of outlier events by time in the first data file.

# Identifiable Signals

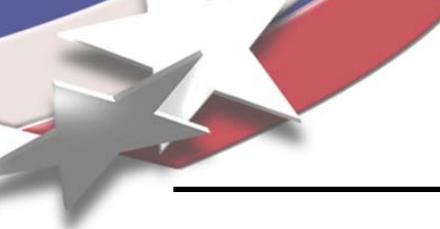
- Over 90% of the signals are identifiable. These signals consist of trucks, cars, helicopters, and airplanes.
- The figures below show two examples of identifiable signals: a helicopter and a semi-truck.



# 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

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- 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