Long Range Science Plan for Seismology

Seismically Monitoring the Earth

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Acknowledgements and Outline

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Outline:
• Monitoring: What, Why, How
• 4 Areas of science underpinning monitoring
• 3 Grand Challenges
What is seismic monitoring?

- Applied Seismology
- Using observables to make inferences about Earth events
- Listening to the Earth

Listening to the Earth
ParkeHarrison, Robert and Shana, b.1968/64
21.6 x 16.5 cm
Photogravure
Seismically listening to the Earth: What can we hear?

**Background Noise - interactions with the oceans and atmosphere**
Seismically listening to the Earth: What can we hear?

Events - for example:

**Earthquakes** and **Explosions** at 100km distance
(calculated for NTS conditions)
Why are we listening/monitoring?

- Natural Hazard Response and Mitigation
  - Earthquakes
  - Tsunamis
  - Volcanoes
  - Other (e.g. rockfalls, landslides, bollides, glacier movement, etc.)

- Natural Resource Management (hydrocarbons, minerals, geothermal)
  - Exploration/Assessment
  - Extraction hazard and regulatory monitoring

- Nuclear Explosion Monitoring
  - Treaty Verification

- Forensic Applications
  - Accidents (e.g. factory/gas line/munitions explosions)
  - Terrorism

- Military/Security Applications
  - Bomb damage assessment
  - Border/Facility monitoring (e.g. tunneling)

- Waste/Storage Management
  - Carbon Sequestration (e.g. 4D)
  - Nuclear (e.g. Yucca Mountain)
How do we monitor?

Real-time operational monitoring systems

Schematic Seismic Processing Pipeline

Signals

- Detection
- Association
- Location
- Event Characterization
- Analyst review

Algorithms and Calibrations

Integration

Scientific Research and Development Results

Notify Authority

This is where Seismological advances can dramatically improve monitoring:

- Lowering thresholds and increasing throughput
- Improving accuracy and precision
- Identifying new kinds of sources
How do we improve our monitoring capabilities?

Earth Monitoring Science

Source Physics
- Sources: earthquake, explosion, mine blast, collapse, volcano, accident, bolide, etc.
- Source-Medium Interactions & Signal Generation

Signal Propagation
- Solid Earth
- Oceans
- Atmosphere
- Space

Sensors
- Data collection: seismic, infrasound, hydroacoustic, radionuclide, optical, EM, InSAR, radiation, etc.

Signal Analysis
- Signal Processing: Measurements: times, amplitudes, spectra, full waveform, pulse shape, radionuclide, pressures, etc.
- Results and Context: Where, What, Why and Confidence in results
In Source Physics we must understand how target and background sources generate signals.
Example: moment tensor full waveform modeling at intermediate periods can separate source types

Moment tensor full waveform 1-D modeling identifies the seismic signal associated with the August 2007 Crandall Mountain coal mine accident as due to a cavity collapse.

Point-source eigenvalues on a Hudson et al. (1989) source plot

Dreger, Ford and Walter in 11 July 2008 Science
In Signal Propagation we must understand and predict the media’s effect over a wide frequency range.

Development of accurate 3D models

Development of 3D computational capability

Brocher et al, 2006

Rodgers et al, 2008
Example: 3D wavefield calculations will help explain and predict complex observations.

Example of large 6-8 Hz Pn/Sn variation in the Middle East

Two mb~4.5 events about 550 km away

February 2005 Kerman earthquake simulations by A. Rodgers et al. on BlueGene/L
Example: 3D wavefield calculations are becoming more feasible

Computing requirements for regional-scale (500 km) seismic simulation

- Current BlueGene/L Capability
- Thunder
- Surface waves
- Earthquake Strong-Motion
- Body-wave Source Discriminants
For Sensors we want to improve sensitivity, and lower power requirements and device costs

Current Sensors

Future Sensors

Imperial College Prototype MEMS seismometer
(AFRL BAA FA8718-06-C-0011)
Dense sensor deployments allow non-aliased wavefeld sampling and new kinds of processing.

Ammon and Lay 2007

Similar to Ishii et al 2005
In Signal Analysis we want to exploit all available signal within the context of empirical and model data.
Cross-correlation and matched-field examples

Matched Field is “adaptive optics” for seismology
- Data processed coherently in space, but not in frequency
  – Distinguishes closely-spaced sources heretofore inseparable
  – Works where waveform correlation methods fail

18,886 events (BLUE) at 363 stations (GREEN).

17% (RED) correlate (CC> 0.5) with at least one other event at station WMQ

Schaff and Waldhauser, 2007

Harris et al., 2008
Grand Challenge 1: More Data

Seismology is a data-driven science: We need to increase the available data by orders of magnitude

Middle East Example:
- Currently existing and openly available
Grand Challenge 1: More Data

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- National Networks not all openly available
Grand Challenge 1: More Data

Seismology is a data-driven science: We need to increase the available data by orders of magnitude

Middle East Example:
- Currently existing and openly available
- National Networks not all openly available
- Future Possibilities:
  - Eurasia Array
  - Africa Array
  - …
Grand Challenge 2: Better data exploitation

With nearly all the world’s continuous seismology data online, what new kinds of processing/analysis should we be doing?

Goals: Use all time-bandwidth available and compare to all empirical and model data
Grand Challenge 3: Putting it all together

How do we meld many disparate/conflicting results into a single global reference model for the Earth?

In principle this is just multi-set inversion but how to do it practice?
Grand Challenge 3: Putting it all together

How do we meld many disparate/conflicting results into a single global reference model for the Earth?

One suggestion - Take a page from the Climate Modelers: DOE Office of Science sponsored PCMDI: “Program for Climate Model Diagnosis and Intercomparison”

How about a TERRA Program: “Testing Earth Realizations and Reconciling Anomalies?”
Summary

- Monitoring is ultimately advanced by its ability to predict the observables (noise and events)
  - Source Physics
  - Signal Propagation
  - Sensors
  - Signal Analysis

- The long-range goal is end-to-end prediction capability across the full spectrum of observable seismic amplitudes and frequencies

- Some Grand Challenges:
  - How do we expand worldwide data?
    - National Networks
    - New deployments
  - How do most effectively process the seismic data we observe?
    - empirical+model based full time-bandwidth processing
  - How do we create a 3-D Earth Reference Model for Monitoring?
    - Something like a TERRA Program to evaluate and reconcile models