Bats do it... dolphins do it...

• Seismologists do it... glaciologists do it... Hydrologists do it...
• Basic idea: Make a sound and listen for an echo.
• How long did it take for the echo? (velocity)
  – Tells us about composition/ layer thickness
• Echos from layers within the earth/ ice
  – Tells us about rock properties/ presence of fluids

After Sridhar Anandakrishnan, Penn State
If you don’t have many local sources… passive-source seismology has limited-resolution for subsurface imaging

One example of Vs velocity models from N. Tibet
Fundamental mode Rayleigh waves (2 plane wave tomography)

Ceylan et al., 2012
If you don’t have many local sources... active-source seismology allows much higher resolution subsurface imaging

Karplus et al., 2011
Overview: Acquisition & Processing
Physics: Rock physics, velocities, amplitudes, reflection / refraction raypaths
Mathematics: Time & frequency domains, Fourier transforms, amplitude & phase spectra, digital filtering, convolution, correlation
Sources & Receivers: dynamite, vibroseis, airguns; geophones & hydrophones
Arrays: surface sampling, surface ghosts, frequency effects CMP (common-midpoint) method, Stacking charts, Survey design
Velocity: measuring interval, rms, stacking, NMO & apparent velocities
Statics: refraction statics, automatic statics
Migration and DMO: migration equation; effects on stack data; wavefront, Kirchhoff, f-k, & finite-difference methods; time vs. depth migration
VSP (vertical seismic profiling), 3D seismics, S-waves, AVO (amplitude-vs-offset)
## Historical development of active-source

<table>
<thead>
<tr>
<th>Year</th>
<th>Acquisition</th>
<th>Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1849</td>
<td>First controlled-source seismic experiment (Robert Mallet exploded a barrel of gunpowder near Dublin)</td>
<td></td>
</tr>
<tr>
<td>1919</td>
<td>First reflection experiment (quarry near DC, 4/12/1919, Clarence Karcher)</td>
<td></td>
</tr>
<tr>
<td>1925</td>
<td>First oil discovered by refraction (Orchard Dome, SW of Houston using fan-shooting to spot fast velocities through shallow salt domes)</td>
<td></td>
</tr>
<tr>
<td>1928</td>
<td>First oil discovered by reflection (Maud field, Oklahoma)</td>
<td></td>
</tr>
<tr>
<td>1930s</td>
<td><strong>Automatic gain control (AGC)</strong></td>
<td></td>
</tr>
<tr>
<td>1940s</td>
<td>First marine profiles</td>
<td></td>
</tr>
<tr>
<td>1950s</td>
<td>Analog magnetic recording</td>
<td>Common midpoint method (CMP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trace stacking</td>
</tr>
<tr>
<td>1960s</td>
<td>Digital recording</td>
<td>Deconvolution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vibroseis source (on land)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Airgun source (at sea)</td>
</tr>
</tbody>
</table>
Reflection (near-vertical; offset $\leq$ penetration) vs.
Refraction (wide-angle; penetration $\leq$ offset)
Single shot geometry:
all traces share a common source;
the ensemble of recordings (traces) is a “common-source gather” or “shot gather”

CMP geometry:
all traces share a common surface source-receiver mid-point;
for 1D geology, all traces share a common depth point (CDP)
Trace stacking enhances signal, and reduces noise.

Summing 3 traces provides a “stacking fold” of 3.
Sources: hammer on aluminum plate
Sources: Betsy seis gun
Sources: accelerated weight drop
Sources: vibroseis
Sources: explosions
IRIS active seismic source facility at UTEP

- Contact: Galen Kaip (gkaip@utep.edu) or Steve Harder at UTEP (harder@utep.edu)
- Resources, training opportunities, support for experiments
- UTEP ENAM project team (minus Steve Harder):
IRIS PASSCAL active-source equipment

- ~1200 “Texan” recorders w/ geophones – 1 component (includes ~320 UTEP Texans) – no longer supported
- L28 and L22 short period geophones
- 14+ Geodes – 24 channels (1-3 component)
- 3 Stratavisors – 60 channels
- 63 Fairfield 3C 5-Hz nodes
- 1 PEG-40 weight drop
Seismic wavefield: interpreting shot gathers

Compressional and Shear

Body Waves
- direct
- refracted
- reflected
- diffracted

Surface Waves
- Rayleigh
- Love

Air-Coupled Waves

Adapted from Lee Liberty
Research example: 500-m shallow seismic line, NM
Research example: 500-m shallow seismic line, NM

Betsy seis gun
Active-source survey geometry

• 500 m long line

• Shots: Betsy seis gun: 5-10 m spacing

• Reftek Texans & 4.5 Hz geophones: 5 m spacing (100 1-C stations)

• Fairfield nodes: 10 m spacing (47 3-C stations)
Goals of shallow seismic survey

- Determine subsurface lithologies for top ~100 m based on velocity
- Determine depth of water table
- Determine depth extents and geometry of andesite
- Look at contact relationships between andesite and surrounding lithologies/ sediments
- Build on existing subsurface models of this region from gravity, electromagnetics, ground penetrating radar
- Test the Fairfield 5-Hz nodes compared to the Reftek Texans with a 4.5 Hz geophone
First arrival Vp~1.8-2.0 km/s.
P-waves, S-waves, “ground roll” (surface waves)
Velocity modeling, CMP stacking, reflection analysis, attenuation, etc.
Seismic data processing software

- Seismic Unix
- Landmark ProMAX
- Paradigm Focus
- Dolphin Geophysical OpenCPS (free for academic institutions)
Refraction velocity modeling

- Colin Zelt: RAYINVR, ZP, …
  http://terra.rice.edu/department/faculty/zelt/rayinvr.html

- John Hole: FAST 2D, FAST 3D, …
  http://www.geophys.geos.vt.edu/hole/software.html

- Cerveny SEIS81, …
  talk to Europeans (or me...)

- MATLAB options exist, but I don’t know how robust they are

- SAC and earthquake tomography tools (e.g., Cliff Thurber at UW Madison)

- Full waveform inversion (e.g., Joanna Morgan, Mike Warner at Imperial in UK, John Hole at Virginia Tech, Stanford Exploration Project, UTIG - Austin, others...)

Reflection seismic interpretation

• IHS Kingdom

• Opendtect – Open Source seismic interpretation
http://www.opendtect.org/

• SeisWorks – Landmark/Haliburton

• Petrel – Schlumberger

• MATLAB options exist, but I don’t know how robust they are
Processing the data: Seismic Unix – home page

http://www.cwp.mines.edu/cwpcodes/

CWP/SU: Seismic Unix

28 years of Seismic Unix!

The Seismic Unix Project is partially supported by the CWP Consortium Project. In the past, the Seismic Unix Project received partial support from the Gas Research Institute (GRI) and the Society of Exploration Geophysicists Foundation.

CWP/SU: Seismic Unix release 44 full source code, documentation and release notes

<table>
<thead>
<tr>
<th>Installation instructions</th>
<th>Read these installation instructions first!</th>
</tr>
</thead>
<tbody>
<tr>
<td>Legal statement</td>
<td>Legal Statement and Licensing (a Free BSD style license)</td>
</tr>
<tr>
<td>SU 44R10 Full Source Code (current release)</td>
<td>CWP/SU: Seismic Un*x Release 44R10 as a gzipped tar archive. Released on 24 April 2017</td>
</tr>
</tbody>
</table>
Online tutorial resource:
Tips for setting up Seismic Unix

• Login to your account on karst:
  • ssh -Y hpstrnXX@karst.uits.iu.edu
• Set environment variables in your bash shell.
  • For example:

    export CWPROOT=/N/u/hpstrn60/Karst/SeisUnix
    export PATH=$PATH:$CWPROOT/bin

/N/u/hpstrn60/Karst/docs/PresentationFiles/Karplus.ActiveSource+Wavefields.v2.pdf
Seismic Unix help

• suhelp – list all available SU programs
• suname <program> – list SU programs with short description
• sudoc <program> – program documentation
• sufind <keyword> – search sudoc for keyword
• sukeyword –o – list header variables
Pipe (|), redirect out (>), redirect in (<)

• $ suplane | suxwigb (pipe)

• $ suplane > test.su (redirect out)

• $ suxwigb < test.su (redirect in)

• $ suplane | suxwigb & (ampersand)
  (& frees up the terminal and runs the process in the background)
Basic examples with Seismic Unix

> suplane | suxwigb (Create 32 traces with 3 planes)
> suplane | suspecfx | suxwigb
> suplane > test.su
> suspecfx < test.su > test2.su
> suxwigb < test2.su label1='freq (Hz)' label2='trace number'
title='Amplitude Spectrum' &
IRIS Wavefields active-source component

3 shot locations, all in OK, at some distance from the receivers.

4 shots per location with 3 different sizes.
IRIS Wavefields active-source-style processing

For example:
- Use local earthquakes for refraction-style velocity modeling
- Use local earthquakes for reflection-style processing/migration/stacking
Seismic Unix: looking at a Wavefields record section

Earthquake parameters:
2016-07-02 13:53:12 (UTC)
36.537°N 97.571°W
9.1 km
Seismic Unix: looking at a Wavefields record section

> segyread - read SEG-Y standard files
> segywrite - write SEG-Y standard files
> sukeyword –o - prints a complete list of header values
> surange - provides the range of header values for a dataset

Copy data file eq.segy to your workspace:
```
cp /N/u/hpstrn60/Karst/karplus/eq.segy .
```

Now we want to read that file into SU. Create a text file called read_data.bash, and type the following into that file:
```
segyread tape=eq.segy conv=1 endian=0 | segyclean > eq.su
```
Seismic Unix: exploring the data

That file includes all 3 components of data in one SEG-Y file. We want to create individual files for the 3 different components.

susort < eq.su fldr offset > eq_sort.su
susplit < eq_sort.su key=fldr stem=eq_middle=fldr suffix=.su numlength=1 verbose=1 close=1

This creates eq_fldr1.su, eq_fldr2.su, eq_fldr3.su.

surange < eq_fldr1.su
sugethw < eq_fldr1.su key=sx | more
sukeyword sx

>sugethw - gets the header values from each trace
>sushw - sets a new header value for each trace
>suwind - window trace data by keyword

http://www.seismicunix.com/w/Seismic_Unix_data_format
Seismic Unix – trace display

suximage - X windows image plot
suwigb - X windows bit-mapped wiggle plot
supsimage - postscript image plot
supswigb - postscript bit-mapped wiggle plot
supswigp - postscript polygon-filled wiggle plot
spsplot - plot postscript velocity models
ximage - uniformly sampled X image plot
Write another script file to read in the *.su file and display it in the x windows.

suxwigb < eq_fladr1.su
suxwigm/suximage

X Functionality:
Button 1  Zoom with rubberband box
Button 2  Show mouse \((x_1, x_2)\) coordinates while pressed
q or Q key Quit
s key      Save current mouse \((x_1, x_2)\) location to file
p or P key Plot current window with pswigm (only from disk files)
a or page up keys enhance clipping by 10%
c or page down keys reduce clipping by 10%
up,down,left,right keys move zoom window by half width/height
i or +(keypad) zoom in by factor 2
o or -(keypad) zoom out by factor 2
l           lock the zoom while moving the cursor
u           unlock the zoom
1,2,...9 Zoom/Move factor of the window size
Write another script file to read in the *.su file and create a postscript display of it.

```
sufilter f=2,4,16,32 < eq_fldr1.su | suwind tmin=0 tmax=8 | suxwigb
```

Try changing the window and filter parameters and see what happens.
E-W record section: earthquake vertical
E-W record section: earthquake E-W horizontal

Trace for station on E-W line
E-W record section: earthquake N-S horizontal

Trace for station on E-W line
E-W record section: earthquake vertical

Trace for station on E-W line
E-W record section: explosion vertical

Trace for station on E-W line
E-W record section: explosion E-W horizontal

Trace for station on E-W line
E-W record section: explosion N-S horizontal
Additional processing for single channel data

- sufilter → bandpass filter – 1-d operation
- sumix → trace mixing
- sushw → set header word
- sustack → stack on header word
- suop → arithmetic operations
- suop2 → arithmetic operations between 2 datasets
- sugain → trace gain (AGC, amplitude recovery)
- sukill → kill traces
Picking first arriving refractions

> sufbpickw < *.su window=.01 | suximage perc=99

Use sumax to get the values

> sufbpickw < *.su window=.01 | sumax mode=max verbose=1
SU velocity models

• makevel - make a velocity function
• triseis - generate Gaussian beam synthetic seismograms
• sufdmod2 (sufdmod1) – finite difference modelling
• suea2df - (an) elastic anisotropic 2D finite difference forward modeling, 4th order in space
sushw - Set one or more header word using trace number, mod and integer divide to compute the header word values or input the header word values from a file

key=cdp,... header key word(s) to set

a=0,... value(s) on first trace
b=0,... increment(s) within group
c=0,... group increment(s)
d=0,... trace number shift(s)
j=ULONG_MAX,ULONG_MAX,... number of elements in group

The value of each header word key is computed using the formula:

• \( i = \text{itr} + d \)
• \( \text{val(key)} = a + b \times (i \mod j) + c \times \left(\text{int}(i / j)\right) \)
• where \( \text{itr} \) is the trace number (first trace has \( \text{itr}=0 \), NOT 1)
suchw- Change Header Word using one or two header word fields

key1=cdp,...  output key(s)
key2=cdp,...  input key(s)
key3=cdp,...  input key(s)
a=0,...  overall shift(s)
b=1,...  scale(s) on first input key(s)
c=0,...  scale on second input key(s)
d=1,...  overall scale(s)
e=1,...  exponent on first input key(s)
f=1,...  exponent on second input key(s)

The value of header word key1 is computed from the values of key2 and key3 by:

\[
\text{val(key1)} = \frac{(a + b \times \text{val(key2)}^e + c \times \text{val(key3)}^f)}{d}
\]
Processing resource

Also, Sheriff & Geldart, 1995
Exploration Seismology
Finding a dataset

• If you are doing passive data processing, maybe there is an active-source dataset nearby?
• What kind of analysis will you do?
  – Reflection?
  – Refraction?
  – Other processing?
• What hypotheses do you want to test?
Finding a dataset – nodes

- Sweetwater, Texas data

- Oklahoma IRIS wavefields experiment
Finding a dataset

• Search IRIS for assembled SEGY datasets: http://ds.iris.edu/SeismiQuery/assembled.phtml

• Search UTIG or LDEO Academic seismic portals: http://www.ig.utexas.edu/sdc/
  http://www.marine-geo.org/portals/seismic/