AUTOMATIC DETERMINATION OF FOCAL DEPTH PHASES BY INTEGRATING THE CEPSTRAL STACKING METHOD (CSM) CALCULATIONS AND IRIS TOOLS

WASHINGTON STATE DEPARTMENT OF Natural Resources
Peter Goldmark - Commissioner of Public Lands
Division of Geology and Earth Resources
David K. Norman - State Geologist

Recep CAKIR[1], Lingsen MENG[2] and Shelton S. ALEXANDER[3]

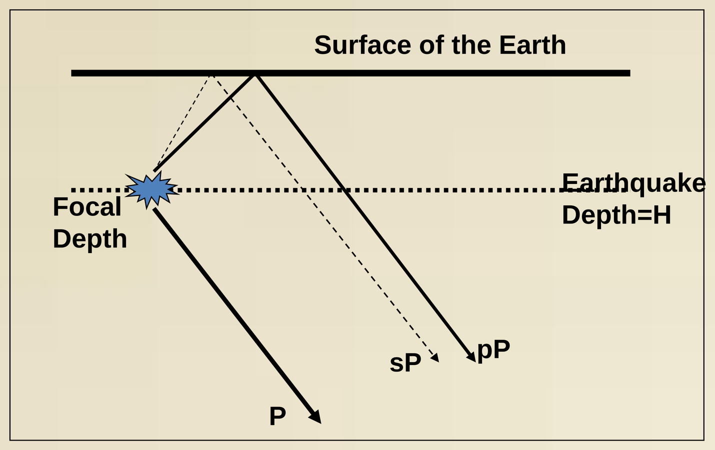
[1]Division of Geology and Earth Resources, Washington State Department of Natural Resources, Olympia, WA 98501, recep.cakir@dnr.wa.gov
[2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, lsmeng@caltech.edu
[3]Department of Geosciences, The Pennsylvania State University, University Park, PA 16802, ssa2@psu.edu

Caltech
PENNSTATE 1855

ABSTRACT

The Cepstral Stacking Method(CSM) initially developed by one of the authors (Alexander) has been shown to determine accurate focal depths for earthquakes and explosions recorded at one or more regional and teleseismic stations. The CSM depths can now be automatically determined using an integrated software environment through the IRIS database and processing system. Seismic Analysis Code (SAC), Standing Order of Data (SOD) along with other commercial scripts are used to make CSM calculations rapid and semi-automatic and/or automatic. Optionally, users can view the stacked cepstral outputs for any given event(s) to verify that appropriate pP and/or sP delay times were picked based on radiation patterns, consistency among stations, elimination of peaks from P to S conversions at the station, or other criteria. If warranted, revised picks can be made and a revised depth determined. In addition, quality checks for the pP and sP depth phases are also possible by using the IRIS tools such as the SOD; a) radiation patterns can be supplied, based on focal mechanisms reported through USGS or CMT, b) depth phases can be calculated using available theoretical travel-time tables, and c) the Tau-p method can be utilized automatically to calculate theoretical pP, sP arrival times using known regional velocity models. A flow chart for this type of automatic detection of the focal depth phases will be shown along with examples of automatic CSM depths determined for selected sets of regional and teleseismic events available in the IRIS database.

CEPSTRAL STACKING METHOD (CSM)



Earthquake focal depth phases; P, pP and sP. Earthquake depth (H) is marked with dotted line.

$$s(t) = f(t) + af(t-t_0) + bf(t-t_1)$$
$$FT|s(t)| = F(\omega)\left|1 + ae^{i\omega t_0} + be^{i\omega t_1}\right|$$

Representation of observed earthquake signal including two delayed signals such as pP and sP

s(t)=Observed earthquake signal
a and ***b***= amplitude and polarity of delayed signals

and

$$P(\omega) = F(\omega)F^*(\omega)\ [1 + ae^{i\omega t_0} + be^{i\omega t_1}]\ [1 + ae^{-i\omega t_0} + be^{-i\omega t_1}]$$

$$= F(\omega)F^*(\omega)\ \{(1+a^2+b^2) + 2a\cos[\omega t_0] + 2b\cos[wt_1] + ab\cos[\omega(t_1-t_0)]\}$$

Then

$$C(u) = \{(1+a^2+b^2)\ \delta(t) + 2a\ \delta(t-t_0) + 2b\delta(t-t_1) + ab\ \delta(t+t_0+t_1)\} \bullet \left|F(\omega)F^*(\omega)\right|^{IFT}$$

or

$$C(u) = \left|\{\log[F(\omega)F^*(\omega)]\} + \log[(1+a^2+b^2)] + 2a\ \cos[\omega t_0] + 2b\ \cos[\omega t_1] + ab\ \cos[\omega(t-t_0)]\right|^{IFT}$$

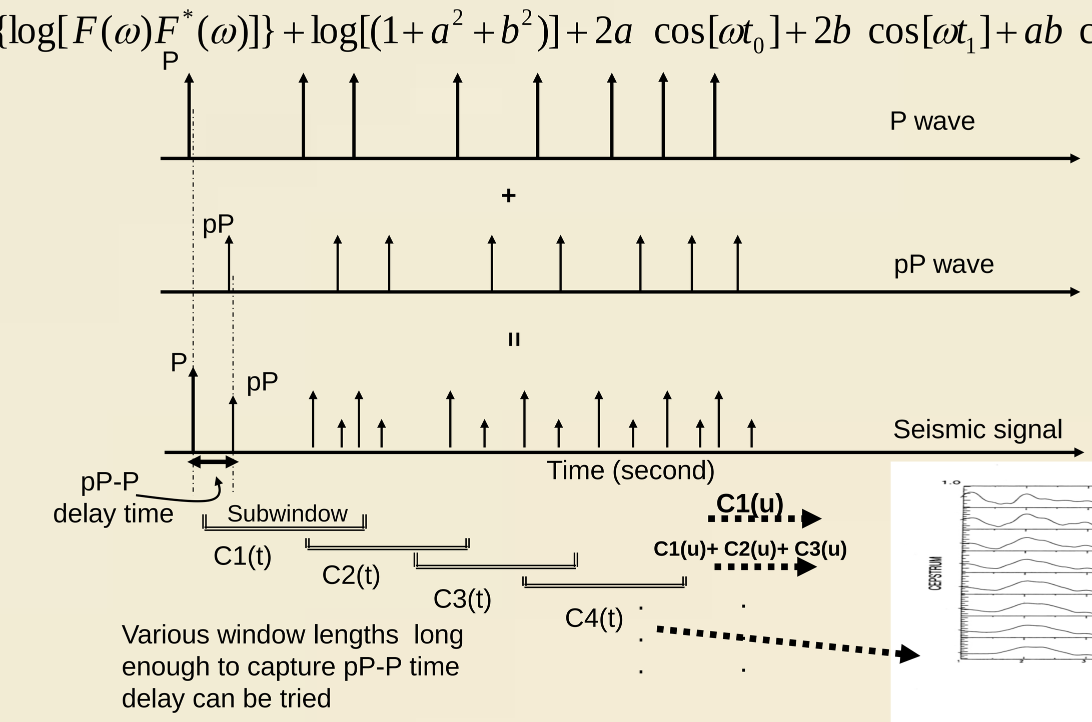
If the logarithm of the power spectrum is transformed instead of the power spectrum (whitens the spectrum used for the cepstrum)

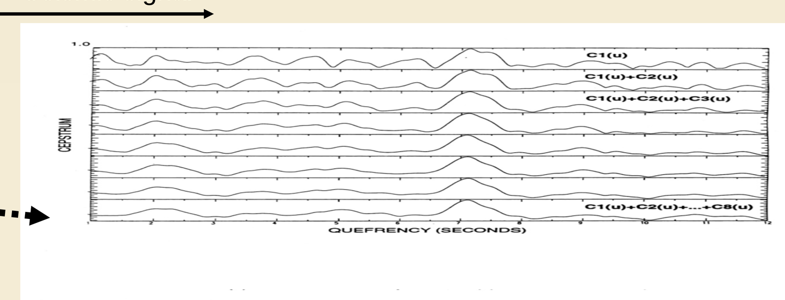
Calculation of Focal Depth from pP and sP delay times

$$(t_{pP} - t_p) = 2h\ .\ \eta_p$$
$$(t_{sP} - t_P) = h\ (\eta_p - \eta_s)$$
$$h = \frac{(t_{pP} - t_P)}{2\eta_P}$$
$$h = \frac{(t_{sP} - t_P)}{\eta_P + \eta_S}$$
$$\eta_p = \left(\frac{1}{\alpha^2} - v^2\right)^{1/2}$$
$$\eta_s = \left(\frac{1}{\beta^2} - v^2\right)^{1/2}$$

$\alpha = P-wave\ velocity$
$\beta = S-wave\ velocity$
$v = Ray\ parameter = \frac{\sin(i)}{\alpha} = \frac{dt}{d\Delta}$,
$i = incidence\ angle\ (take\ off\ angle)$

h = *source depth*
η = *slowness*





CEPSTRAL STACKING METHOD (CSM) DATA PROCESSING WORKFLOW (in SAC)

Select Total Window Length (S – P Maximum)

↓

Select Start Time (P onset)
Select Subwindow Length
Select Percentage Overlap

↓

Calculate Cepstrum of ith Subwindow
Product and/or Sum Stack Subwindow Cepstra (i= 1, N)
Pick (non-zero) Delay Time(s)
of Largest Cepstral Stack Peak(s)

↓

Select Known or Assumed Crustal Velocity Model for Station
Calculate Source Depth from Delay Time of First Large Peak
(pP – P) Calculate Source Depth from Second Large Peak (sP – P)
Assign Final Source Depth from One or Both Depth Estimates

AUTOMATIC PROCESSING

Master script (Matlab)
SOD
Download earthquake catalog and waveform data

INITIALIZE PARAMETERS

- Sub-Window Length (sec)
- Percentage Overlap (%)
- Stacking (product, sum, both)
- Multiple Station Stacking (Y/N)
- Display (all/final sub-stack plots)
- Automatic Depth Estimation (Y/N)

PROCESS Station k (k=1,M)
STACK STATION CEPSTRA
FINAL DEPTH ESTIMATE

AUTOMATIC PROCESSING STEPS

Standing Order for Data (SOD)

Event Search → Output file for event search

Grab Data ↔
- Find network
- Specify network code
- Specify phase (p and s waves begins/ends)
- Set/grab phases based on Earth Models (PREM etc.)
- Early preparation of the data and quality check (e.g., S/N ratios > 2)
-Select Channels (e.g., Z components only)

SAC data stored in a specifed folder ("seismograms")

Depth Phase Calculation: Master Script (Shell or Matlab)
(CSM SAC macro called here)

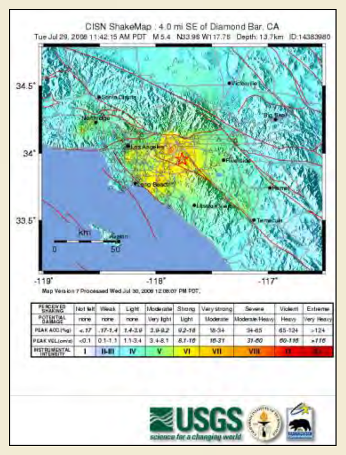
Update event catalog
Check for new event — **No** → Update event catalog
Yes ↓
Activate CSM analysis
↓
Cepstral Peaks for pP and sP → Printout cepstral peaks for visual check

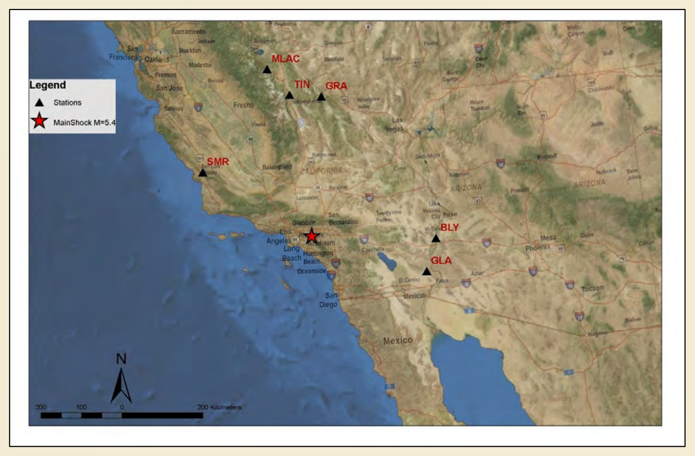
```
#!/bin/bash
cd /home/lsmeng/matlab/cepstrum/# enter the data directory
dir *.sac  > dirlist#obtain initial event list
Nold=`ls -1 *.sac  | wc -l | awk '{print $1}'`# intial number of events
while [ 1 ] ; do # keep monitoring the directory; sleep 1# pause every second
ls -1 *.sac > dirlist# new event list
N=`ls -1 *.sac  | wc -l | awk '{print $1}'`
# new number of events: echo $N; echo $Nold
if [ $N > $Nold ]; then# newevent comes in; echo $N
newevent=`gawk -v E=$N '(NR==E){print $0}' dirlist`#filename of the new event
echo $newevent
# excecute CSM script on newevent here
############
begin sac; m cepstrum; cepstrum peaks for each station; stacking over stations
end sac
Nold=N;#update Nold
fi; done
```

Other Supportive Information
(Miller, 2010)

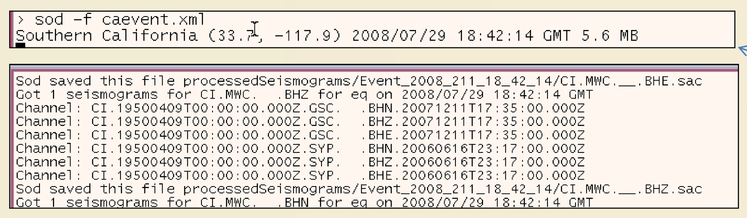
Duct Tape Tools
SAC, SOD, TauP, GMT,…

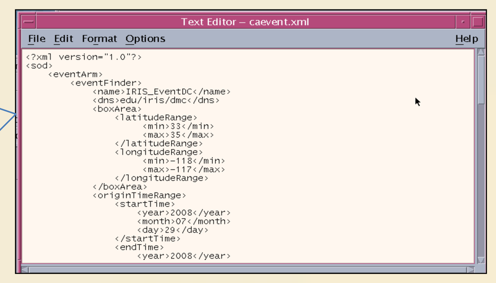
EXAMPLE: 2008 M5.4 Chino Hill Event, California, USA





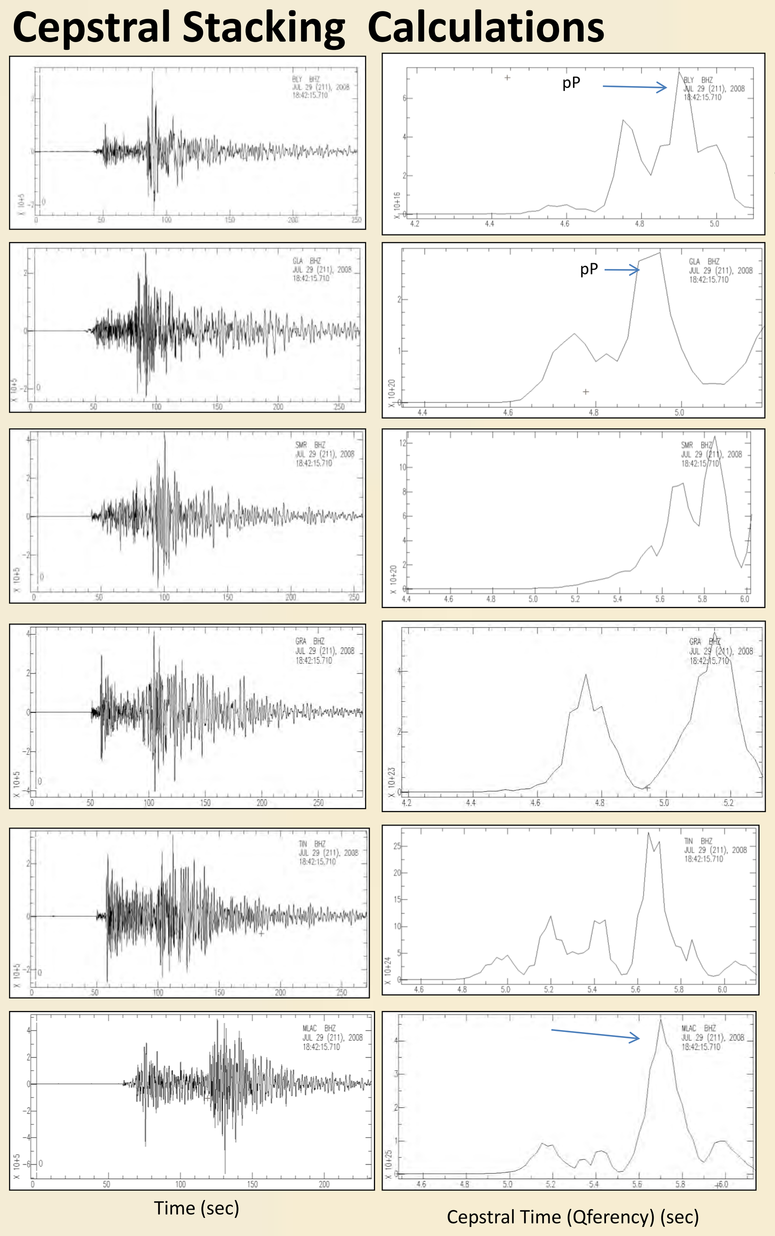
Searching Event and Grabing Data





Checking for New Data in Local Folder and Initiating Cepstral Stacking Calculations

Cepstral Stacking Calculations



BLY.BHZ - Distance= 250km
Peak at 4.9 sec , Depth~ 14.7 km for Vp=6 km/sec
Peak also observed @ 5.5 and 5.7 (strong)
CSM parameters: Window Length = 10 sec,
Overlap % = 60 (for subwindows)

GLA.BHZ - Distance= 290km
Peak at 4.95 sec , Depth~ 14.9 km for Vp=6 km/sec
Peak at 5.75sec (strong)
CSM parameters: Window Length = 10 sec,
Overlap % = 60 (for subwindows)

SMR.BHZ - Distance= 305km
Peak at 5.9 sec , Depth~ 17.7 km for Vp=6 km/sec
CSM parameters: Window Length = 10 sec,
Overlap % = 60 (for subwindows)

GRA.BHZ - Distance= 340km
Peak at 4.7 , 5.2, 5.85 (strong), 6 sec ,
Depth~ 14.1 or 15.6 km for Vp=6 km/sec
CSM parameters: Window Length = 10 sec,
Overlap % = 60 (for subwindows)

TIN.BHZ - Distance= 347km
Peak at 5.2 or 5.7 sec ,
Depth~ 15.6 or 17.1 km for Vp=6 km/sec
CSM parameters: Window Length = 10 sec,
Overlap % = 60 (for subwindows)

MLAC.BHZ - Distance= 419km
Peak at 5.2 or 5.7 sec ,
Depth~ 15.6 or 17.1 km for Vp=6 km/sec
CSM parameters: Window Length = 10 sec,
Overlap % = 60 (for subwindows)

Very strong peak at ~ 5.7sec for stations (distance 250-419 km)
Event Cepstral Depth ~ 17.1 km

Requires cepstral stacking over stations

CONCLUSIONS

- Recent IRIS tools allow automatic determination of the depth phases (pP-P and sP-P delay times)
- Various side scripts (such as DUDE, Miller 2010) can be developed around the SOD for the quality checks (radiation patterns, tau-p for theoretical pP and sP arrivals, signal quality or S/N greater 1 signals, p-wave arrival time set and SAC macro for CSM calculations and more)
- Stacking of cepstrums over stations will further enhance the resolution of depth phases .
- The Cepstral Stacking Method (CSM) provides accurate focal depths from one or more regional stations (+/- 1 km or better typically).
- Use of CSM depth calculations for one or more regional recordings include more accurate hypocenters of events, fault rupture geometry from multiple aftershocks, and discrimination between shallow explosions and crustal earthquakes.
- Regional crustal events (usually 3 < M < 6) show a close agreement between the CSM and standard hypocentral depths, indicating the existence of a fairly good crustal model for the region.

REFERENCES

Alexander, S. S., 1996, A New Method for Determining Source Depth From a Single Regional Station, Seis. Res. Ltrs., Vol. 67, No. 1, p. 63
Alexander, S. S., 1996, Use of the Cepstral Stacking Method (CSM) for Improved Source Depth Determinations from Combined Single-Station and Array or Network Observations at Regional Distances, Proc. of the 18th Annual Seismic Research Symposium on Monitoring a Comprehensive Test Ban Treaty, 4-6 Sept. 1996, PL-TR-96-2153, Env. Res. Papers, No. 1195, 647-656.
Alexander, S. S. and C-C. Yang, 1997, Accurate Depth Determinations and Other Diagnostic Event Characteristics in Near-Real Time from Regional Signals, Proc. of 19th Annual Seismic Research Symposium on Monitoring a Comprehensive Test Ban Treaty, 23-25 Sept. 1997, 181-190.
Alexander, S. S. and C-C. Yang, 1997, Use of Cepstral Stacking Method (CSM) for Improved Source Depth Determinations from Combined Single-Station and Array or Network Observations at Regional Distances, Seis. Res. Ltrs., Vol 68, No. 2, p. 309.
Cakir, R., L. Meng, M. Foundotos and C-W Chen, 2010, Automatic determination of depth phases and earthquake focal depth using Cepstral Stacking Method (CSM) and Standing Order of Data (SOD), EarthScope USArray Data Processing and Analysis 2010 Workshop, [http://www.iris.edu/hq/es_course/content/2010.html]
Miller, M. 2010, DUDE: Discovery Using Duct-tape Excessively. EarthScope USArray Data Processing and Analysis 2010 Workshop, [http://www.iris.edu/hq/es_course/content/2010.html]
Owens, T.J., H. P. Crotwell, C. Groves, and P. Oliver-Paul, 2004, SOD: Standing Order for Data. Seismological Research Letters, 75:515–520, 2004
Pacific Northwest Seismic Network (PNSN), PNSN Notable Earthquakes, http://www.pnsn.org.
Goldstein, P., A. Snoke, (2005), "SAC Availability for the IRIS Community", Incorporated Institutions for Seismology Data Management Center Electronic Newsletter.
Yang C-C, 1996, Investigation of Cepstral Stacking Methods for the Time Delay Extraction, M.Sc Thesis, Electrical Engineering, The Pennsylvania State University, PA, USA.

The facilities of the IRIS Data Management System, and specifically the IRIS Data Management Center, were used for access to waveform, metadata or products required in this study. The IRIS DMS is funded through the National Science Foundation and specifically the GEO Directorate through the Instrumentation and Facilities Program of the National Science Foundation under Cooperative Agreement EAR-0552316. Some activities of are supported by the National Science Foundation EarthScope Program under Cooperative Agreement EAR-0733069.

IRIS
earthscope www.earthscope.org