T3.5-05

New Metrics Developed for a Complex Cepstrum Depth Program

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ABSTRACT

We present research in progress to develop metrics for a semi-automated program to estimate the depth of a very shallow seismic event (depth less than 3 km) in near-real time, by using the Complex Cepstrum algorithm. This method is particularly suitable for shallow event analysis because it provides information on the phase of the signal periodicity, and allows processing within a very narrow time window at the start of the signal onset.

With the initial assumption that the signal includes a first seismic phase and its similar echo, the current metrics evaluate:

1) the Power and Complex Cepstrum correspondence;

2) the correlation between the deconvolved first phase seismogram and its echo;

3) the deconvolved first phase and original signal similarity, and

4) the capability to recover the estimated echo-lag time from the deconvolved seismograms.

OBJECTIVE

Improve automation of shallow event depth estimation. Using analysis metrics, provide a reliable statistic assessment of the measurement confidence and errors.

DATA

- **Synthetic seismograms (142 sps). Up-going, down-going and total theoretical seismograms were computed using a frequency-wavenumber technique for an explosion buried at a depth of 450 m and distance of 390 km (Saikia and Helmberger, 1997). The true *P-pP* time lag was 0.12s. For details on the seismogram generation technique, see Saikia et al., poster at this meeting.**

- **A very shallow earthquake sequence, occurred in Mogul, west of Reno, Nevada USA, with a main shock of Mw 5 at 2.7 km depth, is investigated at PDAR, at the array element PD32 (40 sps).**

METHOD

We believe that the deconvolution process utilizing the Complex Cepstrum iteratively is one of the optimum methods for identifying the associated depth seismic phases.

The Cepstral Algorithms use concepts also addressed in several poster presentations at this conference (Kemerait and Tibuleac, Tibuleac et al., Saikia et al.) and explained in detail by Childers et al. (1977):

- ***Homomorphic deconvolution*** **(the use of the Complex Cepstrum and its phase information for echo detection and wavelet recovery);**
- ***Blind deconvolution*** **(deconvolution without explicit knowledge of the impulse response function used in the convolution);**
- ***Complex Cepstrum*** **(the Inverse Fourier Transform of the logarithm (with unwrapped phase) of the Fourier Transform of the signal);**
- ***Liftering of the Complex Cepstrum*** **("filtering" the echo peaks out of the Complex Cepstrum);**
- ***Power Cepstrum*** **(the Inverse Fourier Transform of the complex logarithm of the Fourier Transform of the signal);**
- ***Minimum – phase signal*****: A signal whose Z-transform has no poles or zeros outside the unit-circle, or no Complex Cepstrum at negative frequencies;**
- ***Maximum –phase signal*****: A signal whose Z-transform has no poles or zeros inside the unit-circle, or no Complex Cepstrum at positive frequencies;**
- ***Mixed-phase sequence*****: A real signal with minimum and maximum phase sequences, with positive and negative values of Complex Cepstrum;**

METRICS

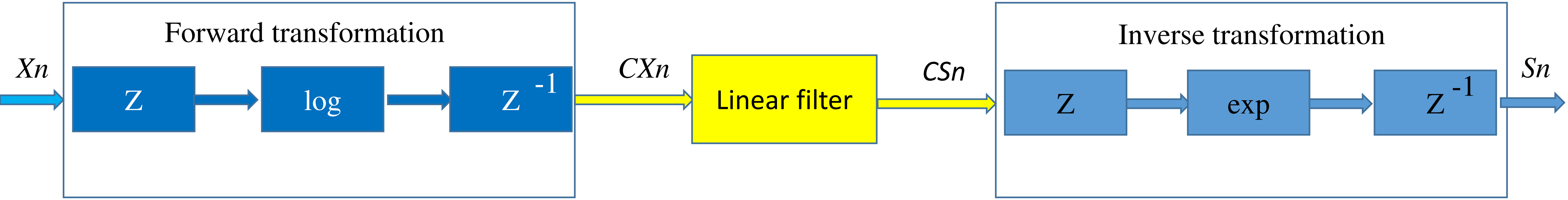
As part of this research, we have developed several metrics to evaluate statistical confidence limits which are described in detail. The metrics discussed here include:

1) **Power and Complex Cepstrum similarity;**
2) **Liftered peak sign;**
3) **Characteristics of correlations between the de-convolved and the original seismogram;**
4) **Deconvolved seismogram and echo similarity;**
5) **Estimated and observed echo lag-time comparison.**

ASSUMPTIONS

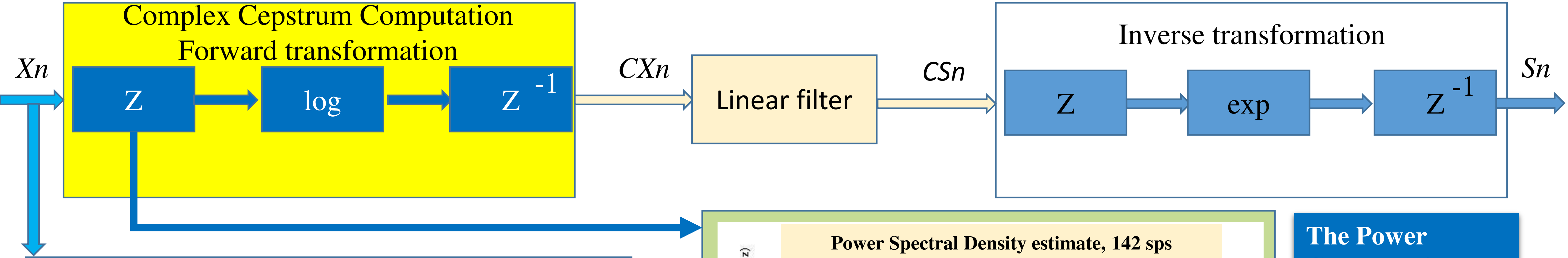
- ❑ **A first arrival is larger than, or equal to the echo;**
- ❑ **The first arrival and echo amplitudes are larger than the seismic noise amplitude;**
- ❑ **A preliminary location is available, and seismic phases are identified;**
- ❑ **A seismic P-velocity model is available at the event location;**
- ❑ **The event location is shallower than 3 km in this presentation.**

Cepstral Analysis Steps and Metric application

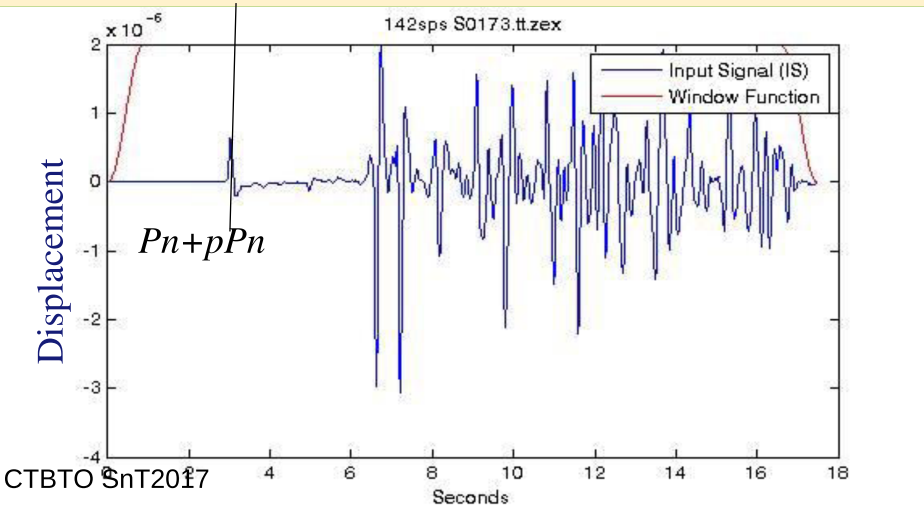


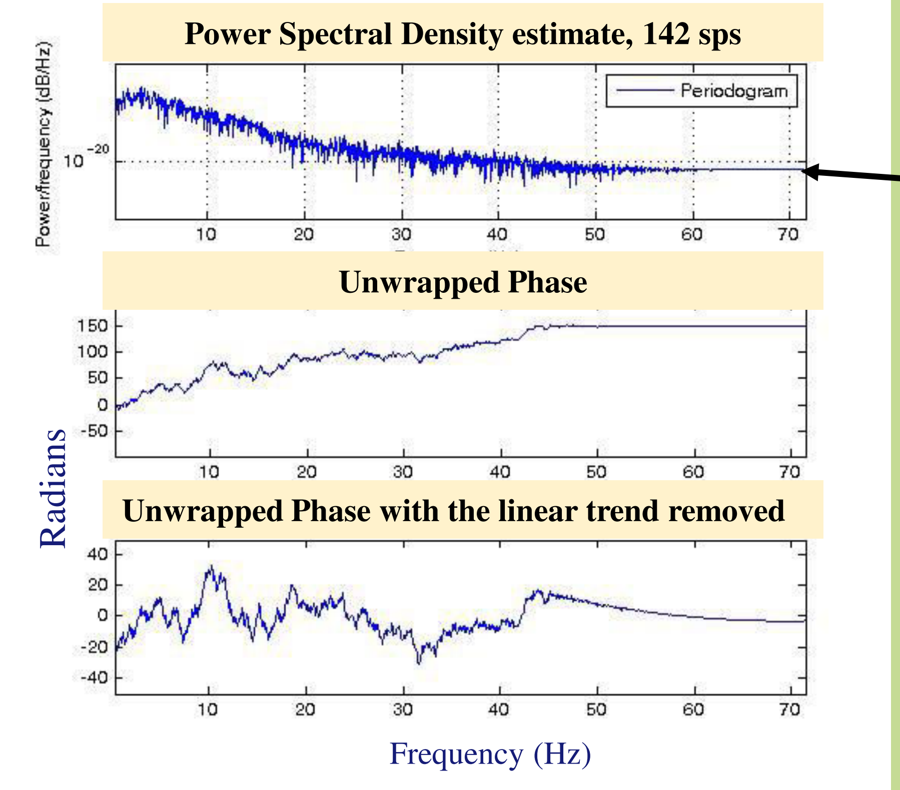
- Select the input signal *Xn* (iteratively adjust window lengths for the input signal);
- Estimate Complex Cepstrum *CXn* and reiterate through possible peaks for the deconvolution process (iterating on the input into the linear filter box) ;
- Prune cepstrum (linear filter box above) and estimate *CSn;*
- Inverse transform and estimate the wavelet *Sn* and echo, which is *Xn-Sn*.
- Apply a series of metrics and iterate for optimal deconvolution

Cepstral Analysis Steps and Metric Application



Synthetic waveform, with a Tukey window, of a synthetic explosion at 450m depth and 390km virtual distance, with no noise, and no attenuation (see Saikia et al. at this meeting for details), 142 sps.

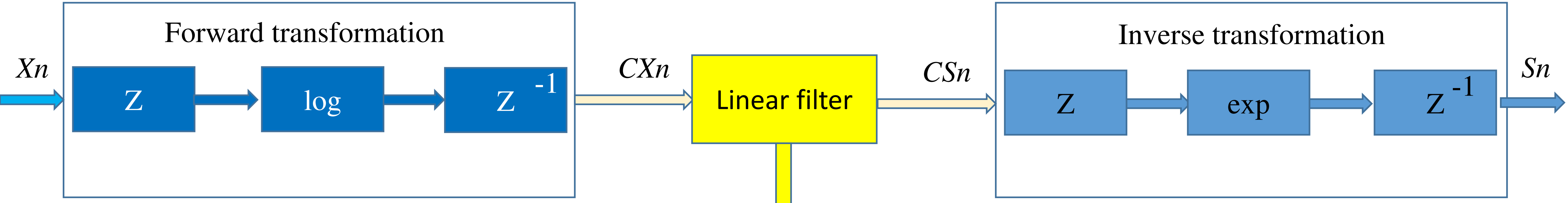


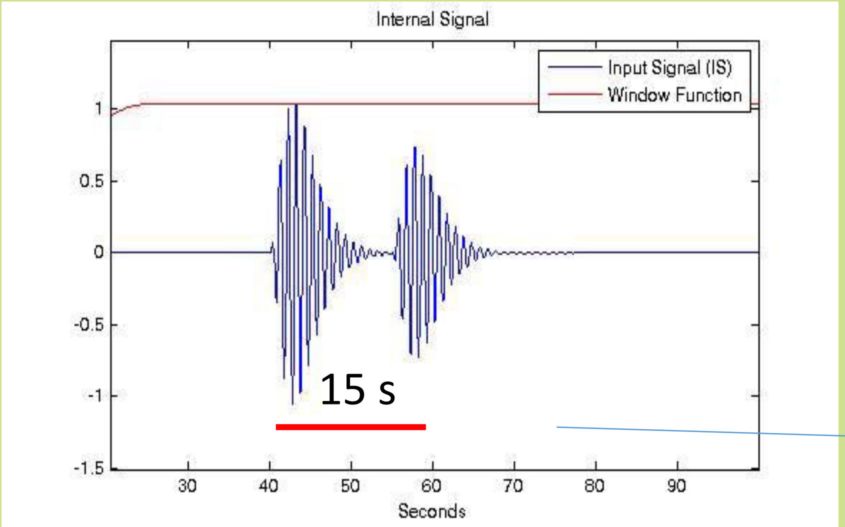


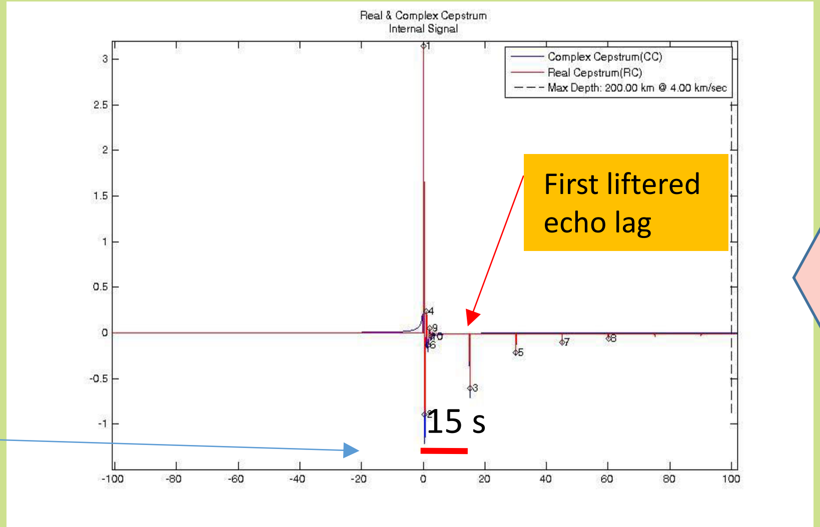
The Power Cepstrum is the power spectrum of the logarithm of the Power spectrum.
A Butterworth, 6 pole, zero phase filter was applied from 0.1 – 18 Hz.

Also see comments in Kemerait and Tibuleac, poster at this meeting.

Perfect Case: Explanation of Cepstrum Peaks for a Model Seismogram with P and pP



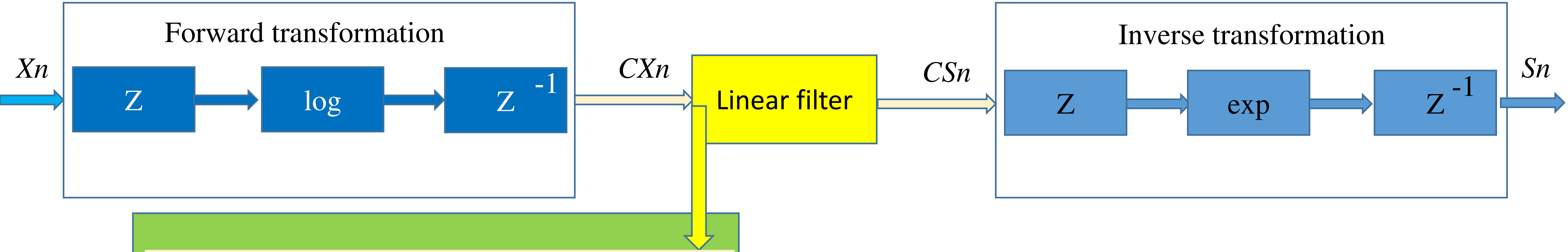


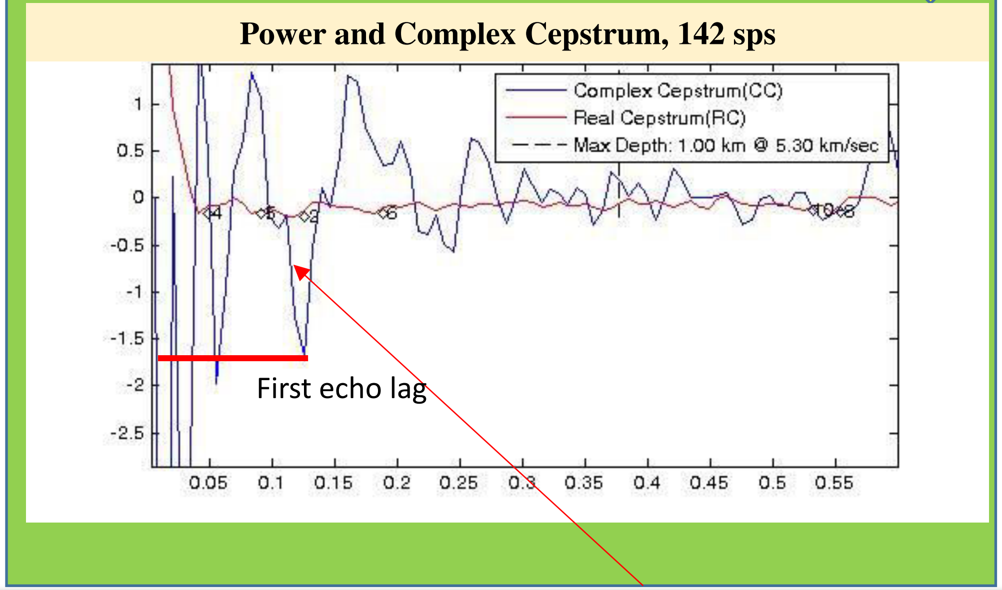


A perfect example of Power and Complex Cepstrum,

Complex Cepstrum of a Berlage function with an echo similar to the initial wavelet, opposite polarity and 70% reduced amplitude, delayed 15s. All the peaks are negative (if the echo has opposite polarity), and the Power and Complex Cepstrums are coincident and of negative sign.

Step 1: Stable cepstral feature indicators

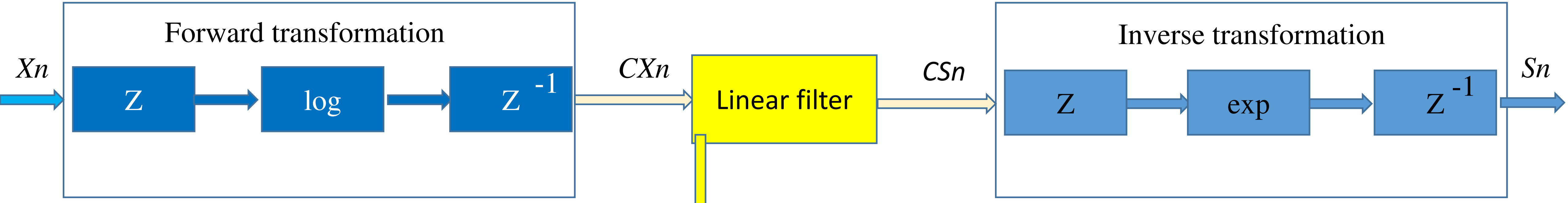




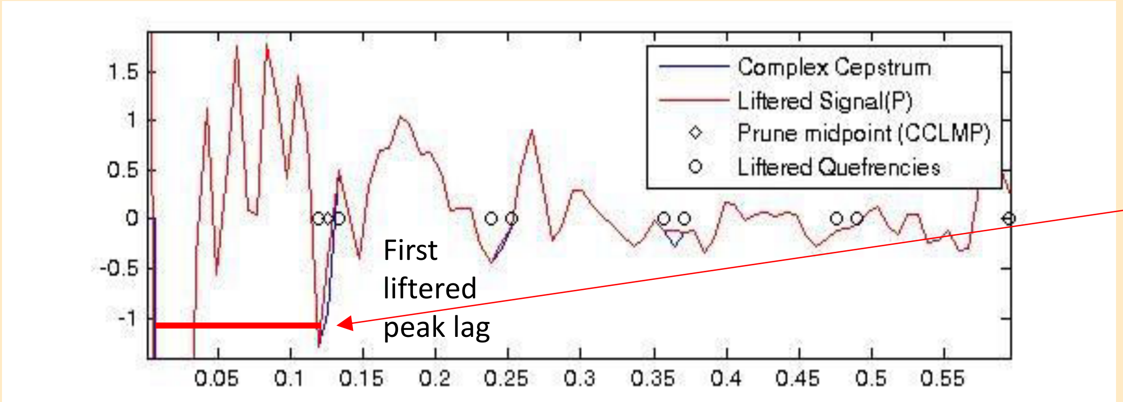
Working on a new metric: Identification of the first liftered peak position as the time lag at which the Power and Complex Cepstrum are consistently coincident and of the same sign, independent of window size, filtering and unwrapping algorithms.

Indicator: The Power and Complex Cepstrum should be equal for a minimum phase signal hypothesis, and would have peaks at the same lags after ideal phase unwrapping. The location of the highest Complex Cepstrum (*CXn*) (negative in this case) peak due to the echo should also correspond to the largest *CXn* amplitude.

Step 2: Liftering. The signs of the liftered cepstral peaks should correspond to the echo hypothesis



LIFTERING



Liftering is performed manually or automatically.

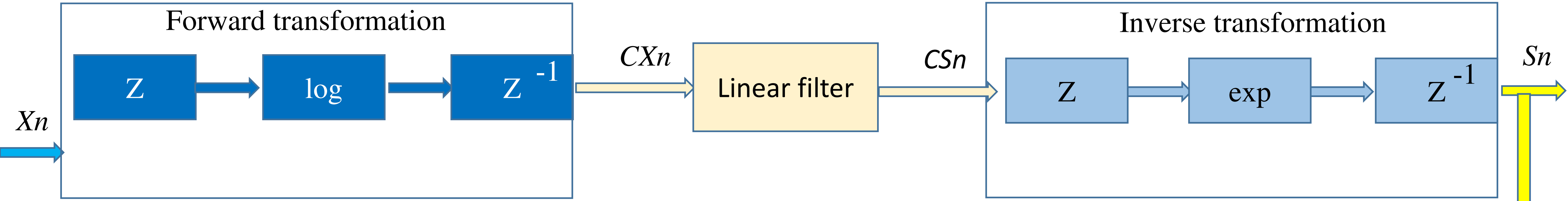
Metric 2: The liftered *CXn* peak sign is negative when an inverse polarity echo has lower amplitude than the *Sn*.

Working on a new metric: depending on

1) **the type of echo (same, or opposite polarity) and**
2) **the echo (*Xn-Sn*) amplitude vs the *Sn* amplitude.**

The metric will quantify the polarity and energy in the first three *CXn* liftered peaks and will allow only the cases when the observations correspond to the hypothesis.

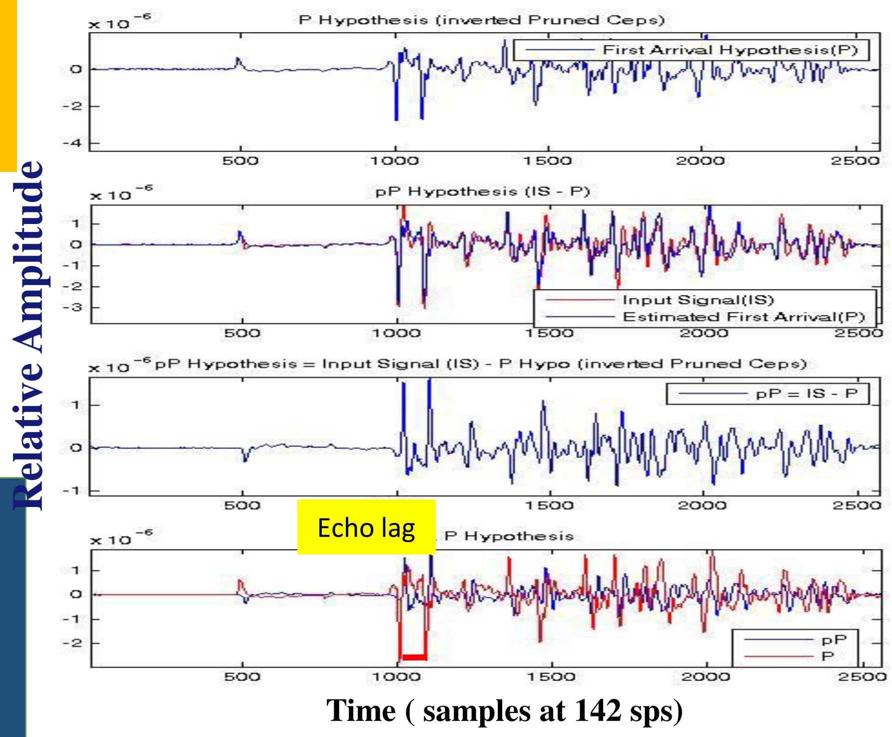
Step 3: Deconvolve the wavelet *Sn* and the echo (*Xn-Sn*)



REPORT

Cceps_prune.m filtered 0.1 - 18 Hz
Pruning: Manual
Time-range (s) :(0.119,0.133)
Sample-range (samples):(17,19)
Estimated depth: 0.295 – 0.357 km using twice the time from source to the source at 5.38 km/s
Estimated depth: 0.450 m when using the ray parameter and the velocity model
Estimated echo time delay: 0.12 s
True time delay: 0.12 s
Correlation #1:(Xn*Sn): 0.87
Correlation #3:((Xn-Sn)*Sn): -0.92
Correlation #2:((Xn-Sn)*Sn): -0.93
Correlation Ratio (#1/#2): -0.93 Power Ratio: power(Xn-Sn)/power(Sn) : 0.60
Cross-Correlation Lag (Expected – Estimated) = 1 sample

Example of deconvolved waveforms for a liftered first peak (right) and analysis report (left)

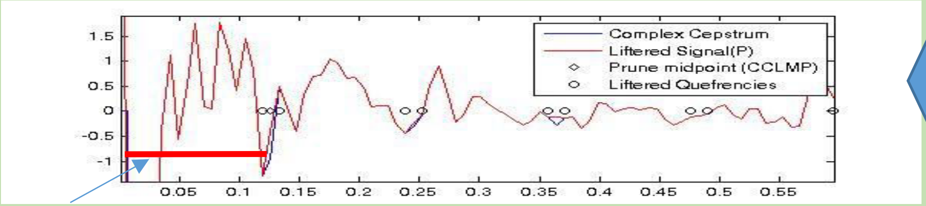


Sn: First arrival deconvolved after Complex Cepstrum Lifter;
Xn: Original signal;
Xn-Sn: First echo hypothesis.

Step 3: Deconvolution results when liftering the first Complex Cepstrum echo (Right – Good) and the second Complex Cepstrum echo (Not used)

Good - used

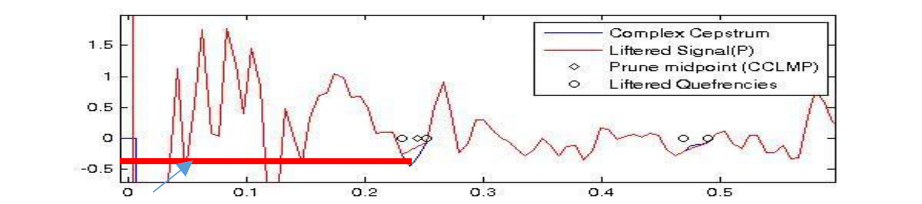
Not used, but not bad!



First liftered peak lag

Time (s)

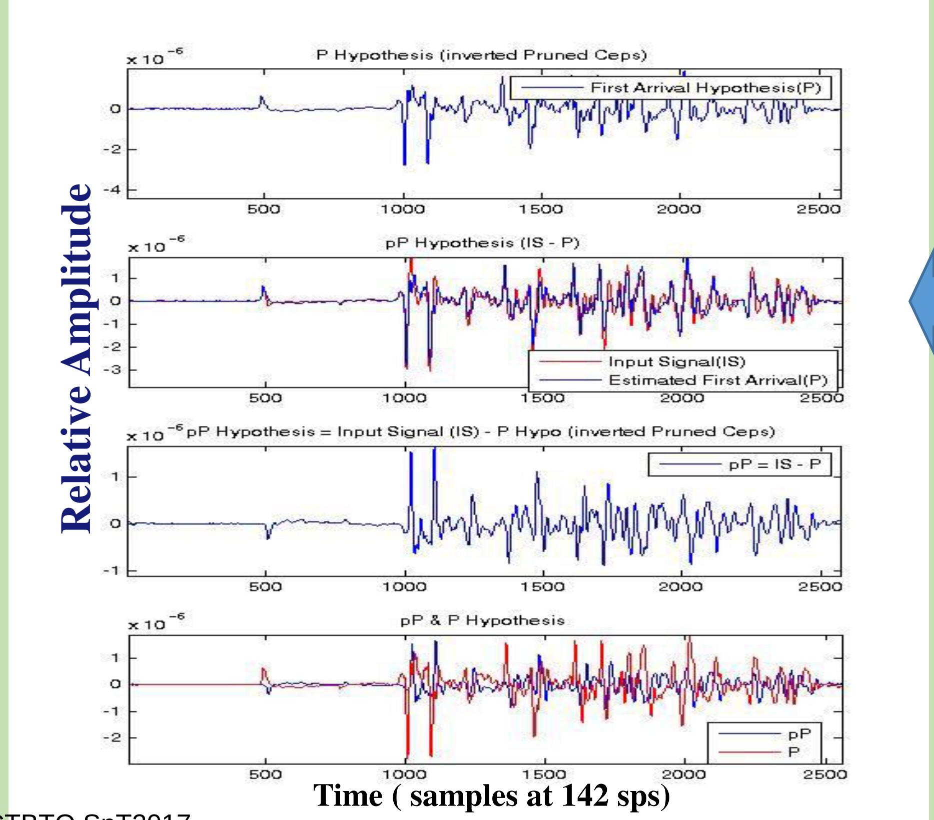
Note that the first three liftered peaks are negative, for the "Good" case.



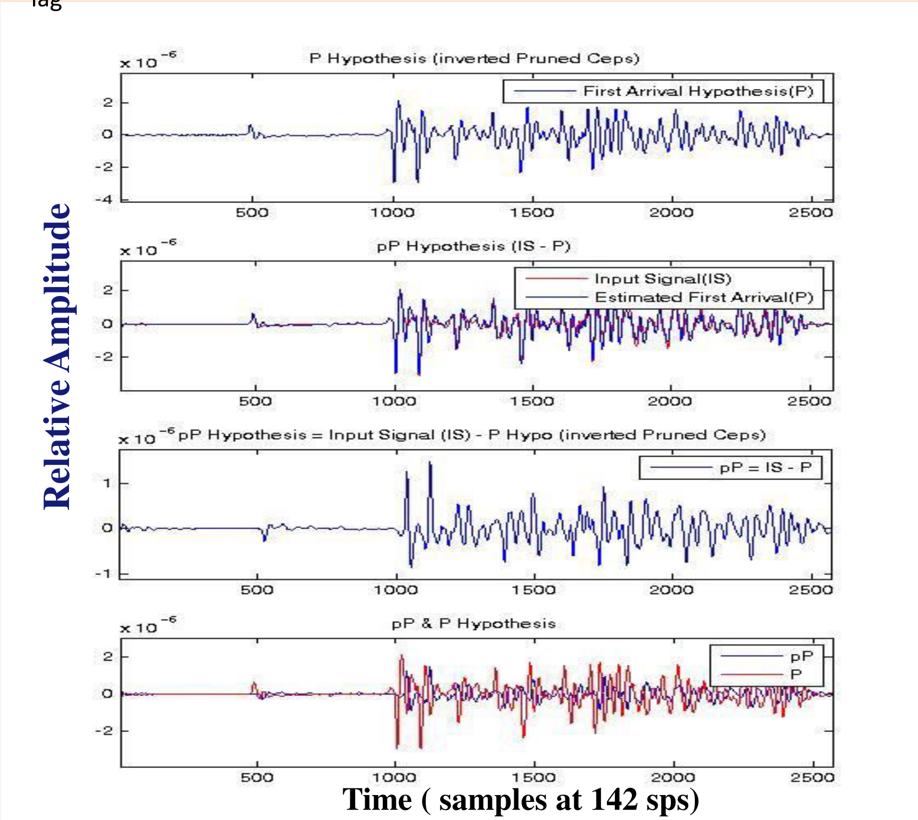
SECOND liftered peak lag

Time (s)

P : First arrival hypothesis deconvolved after liftering based on Complex Cepstrum Lifter;IS: Original signal; pP : (IS - P) First echo hypothesis.

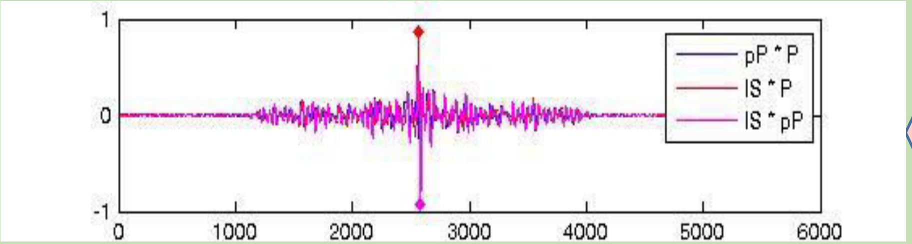


Note higher amplitude echo for "Good"



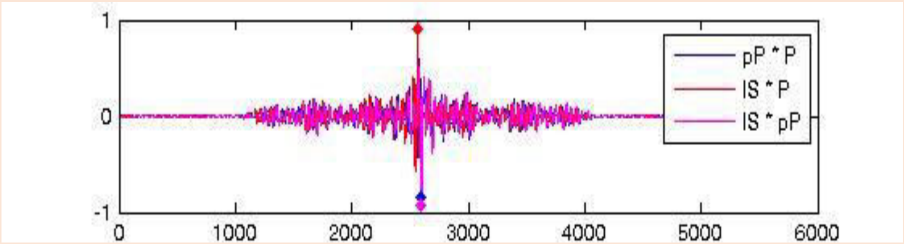
Step 3: Deconvolution results when liftering the first Complex Cepstrum echo (Right – Good) and the second Complex Cepstrum echo (Not used)

Good - used



Time (samples at 142 sps)

Not used, but not bad!

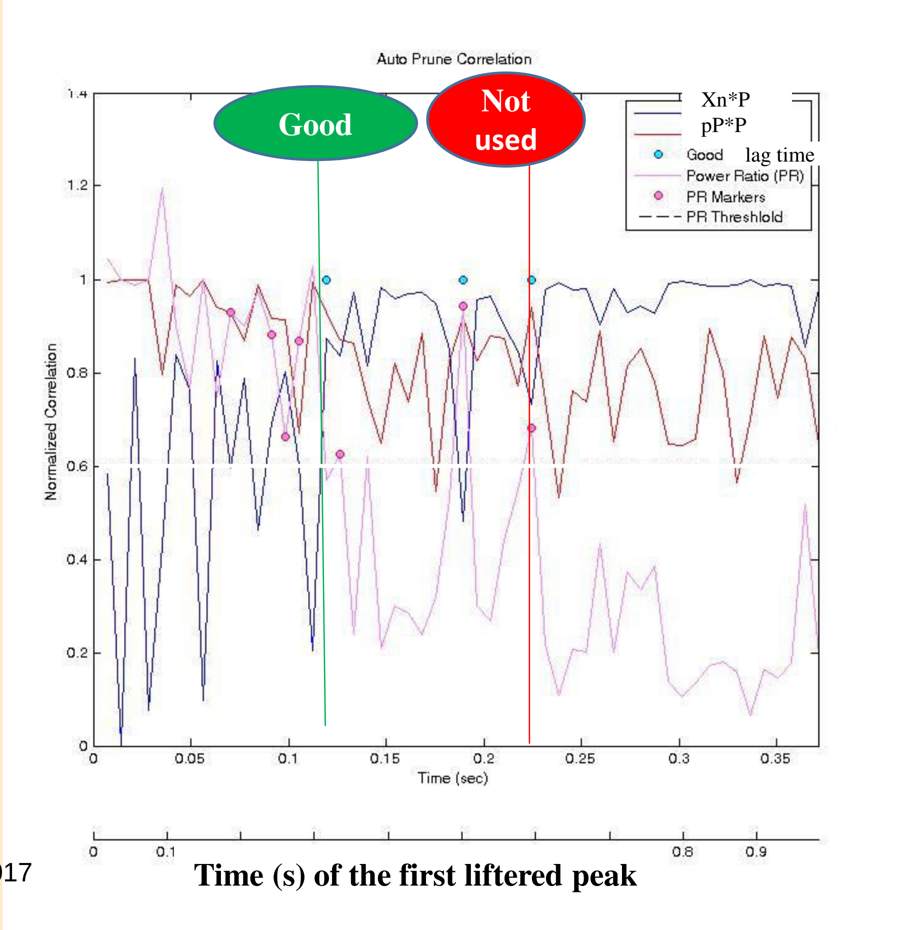


Time (samples at 142 sps)

The liftered first echo time lag and the deconvolved echo and waveform lag correspond within 1 sample point in both cases. Narrow crosscorrelation peaks show high deconvolved echo similarity.

Step 3. In progress: Deconvolved signal metrics estimated using automatic liftering are used to find the best first liftered cepstra echo time lag

Preliminary tests of individual metric values estimated when the Complex Cepstrum is automatically pruned (liftered), in a moving, three-sample point window, with no overlap, are shown below. The metric values correspond to the center of the window.



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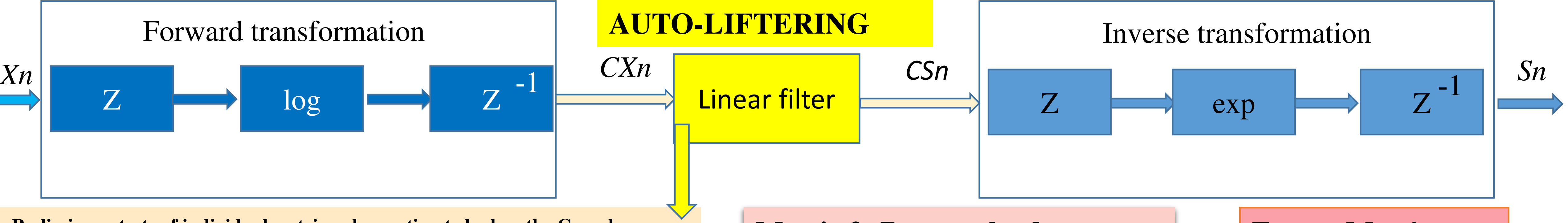
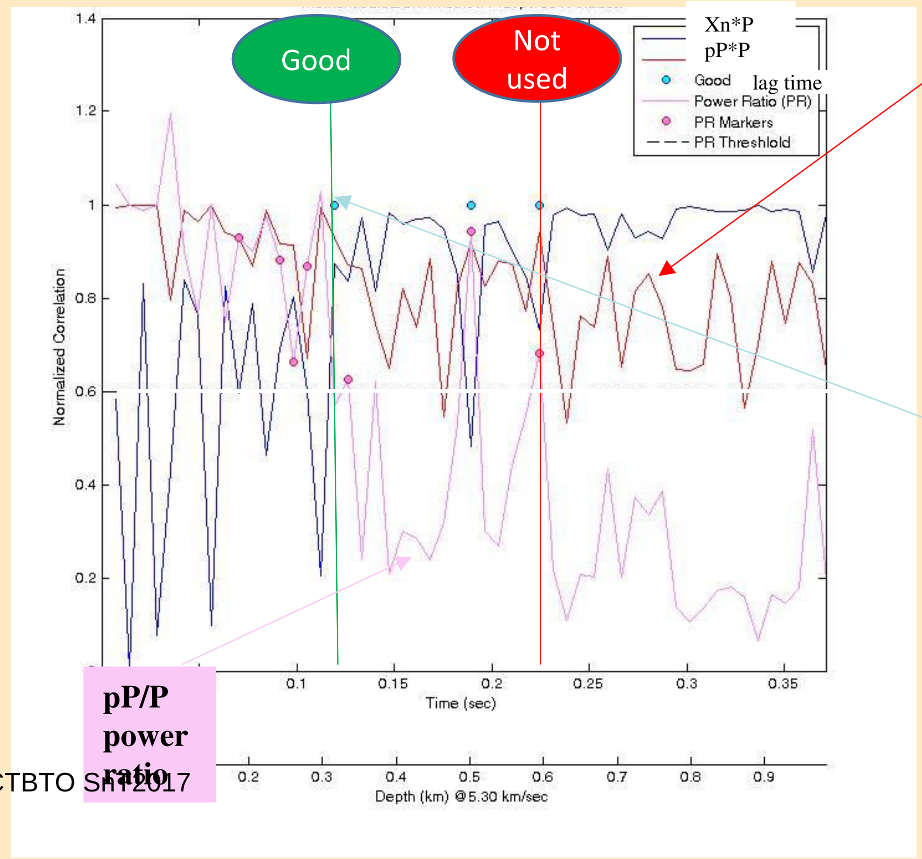
Metric 1: Characteristics of correlations between the de-convolved and the original seismogram:

Metric 1.1: Maximum Xn*Sn (blue) and Xn*(Xn-Sn) crosscorrelation values (red) are empirically best when higher than 0.7. At lower values the signal and first arrival are not similar, and at highest values (1.0) no echo is deconvolved.

Metric 1.2: Crosscorrelation power ratio of the Sn and (Xn-Sn) deconvolved waveforms values (magenta) are empirically best between 0.3 and 0.6.



Preliminary tests of individual metric values estimated when the Complex Cepstrum is automatically pruned (liftered), in a moving, three-sample point window, with no overlap, are shown below. The metric values correspond to the center of the window. "Yes" and "No" show two possible pruned first echo time lags discussed here. Note that the echo is named "pP" here and pP and P have opposite polarity.



Metric 2: Deconvolved seismogram and echo silmilarity. Absolute, maximum (Xn-Sn)*Sn crosscorrelation values (red) are empirically best between 0.3 and 0.95. At lower values, the deconvolved first arrival and the first arrival are not similar or are similar, however, the (Xn-Sn) amplitude is much smaller than the Sn amplitude.

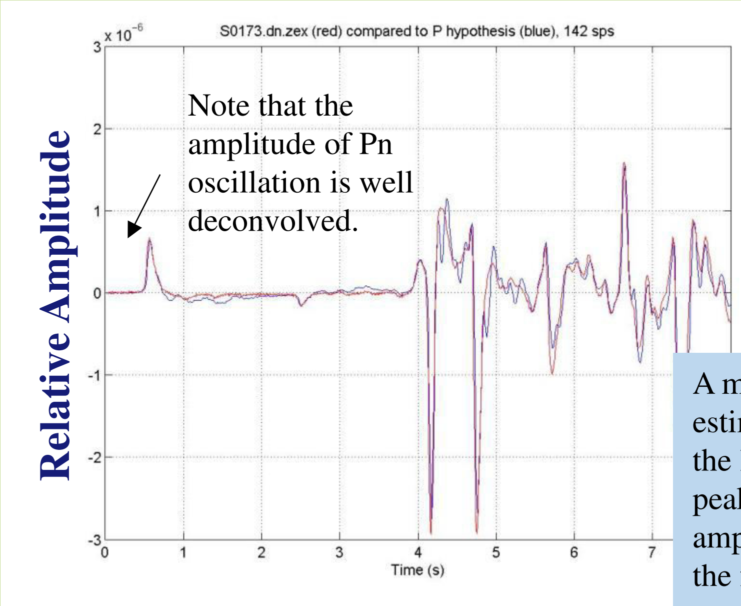
Future Metric: a weighted product of the metrics 1,2 and 3 values will be used for best echo position identification and statistical significance assessment.

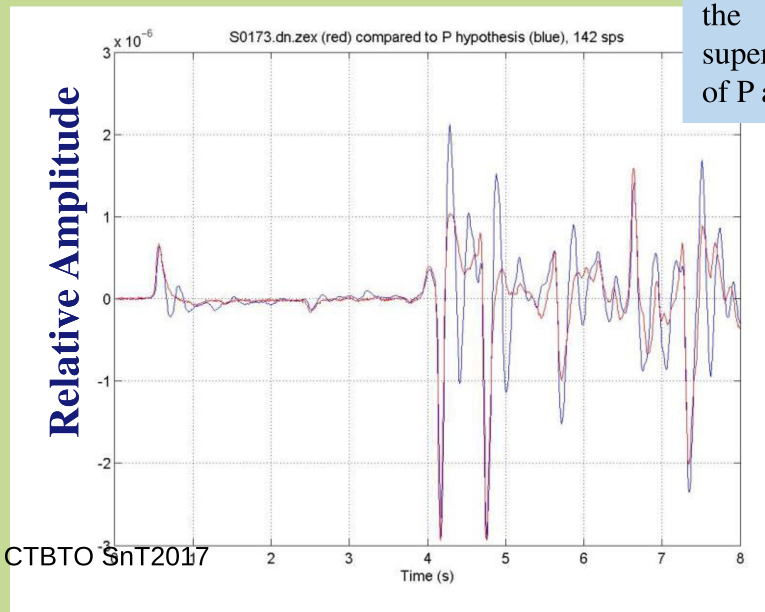
Metric 3: Estimated and observed echo lag-time comparison.
Blue dots show positions of the liftered first peak for which the estimated echo lag after deconvolution is within 3 samples of liftered echo lag. Note multiple "good" time lags around 0.15s. The true echo is at 0.11s.

YES

No

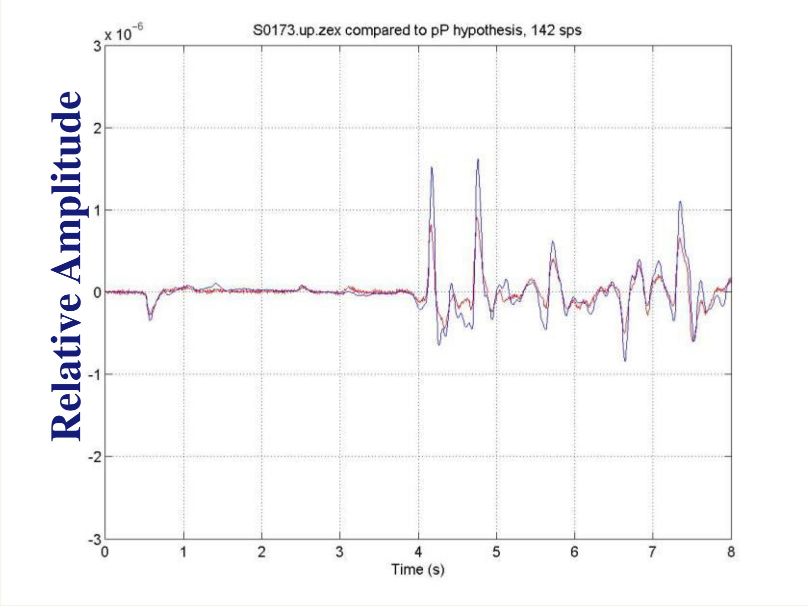
Note good retrieval of P and pP wavelet for optimal liftering.

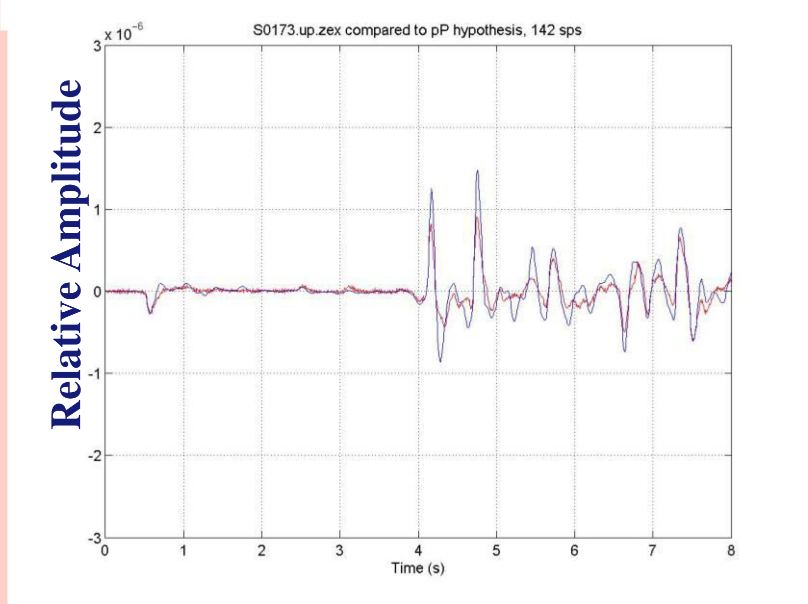




A magnitude estimate using the largest peak-to-peak amplitude in the first seconds would be affected by the superposition of P and pP.

The differences, however, are subtle when liftering removes the secondary echoes, and not the main echo. Also note that this is a special case, when the sample rate is very high, with no noise or attenuation added.



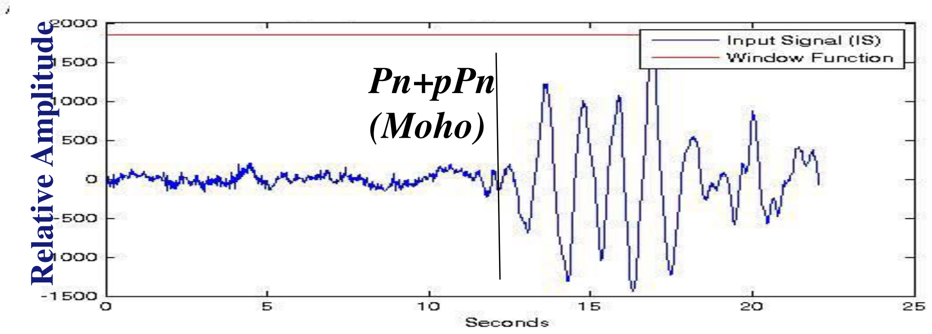


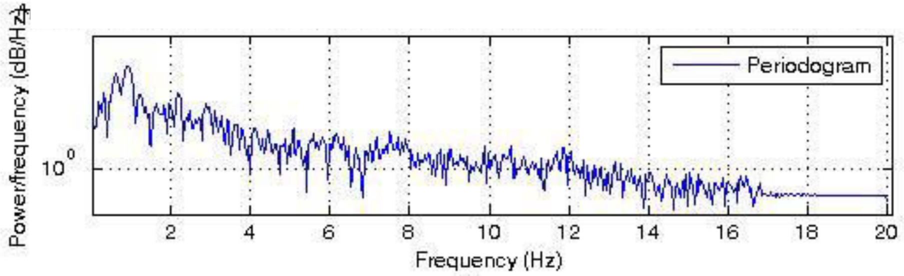
Time-range (s) :(0.234,0.245)
Sample-range (samples):(33,36)
Sample-Midpoint (sample):34.5
Estimated echo time delay: 0.24s
True time delay: 1.1 s
Correlation #1:(IS*P): 0.90
Correlation #2:(pP*P): -0.84
Correlation #3:(pP*IS): -0.93
Correlation Ratio (#1/#2): -1.0
Power Ratio: power(pP_hypo)/power(xcor_P_hypo): 0.44

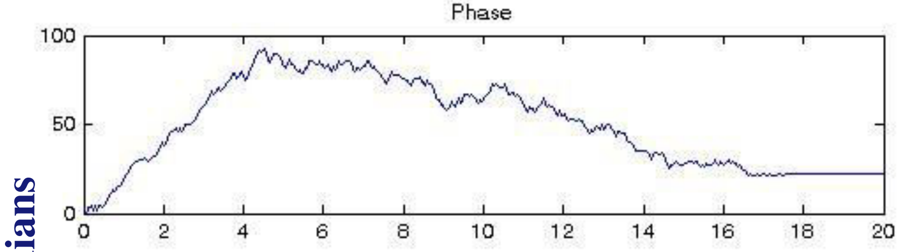
--- VALIDATION SECTION --

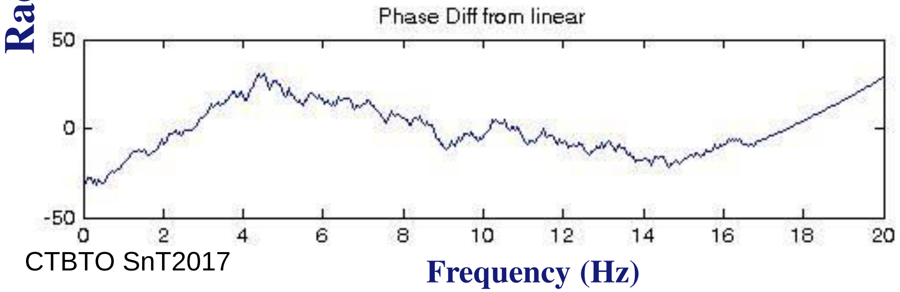
Cross-Correlation Lag (Expected – Estimated) = 0 samples

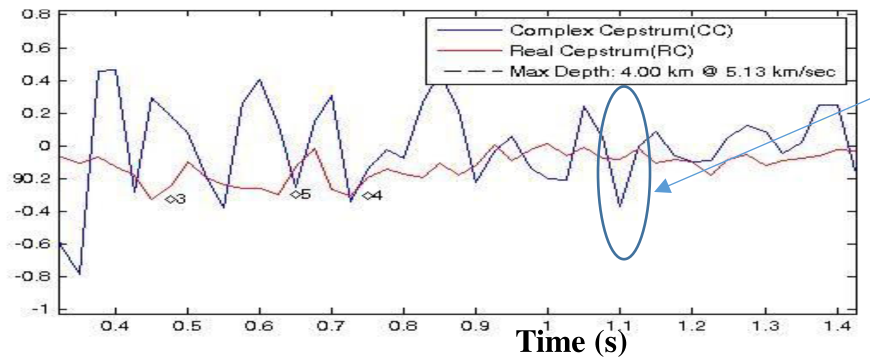
Cepstral Analysis Steps and Metric application for a very shallow earthquake in Mogul, west of Reno



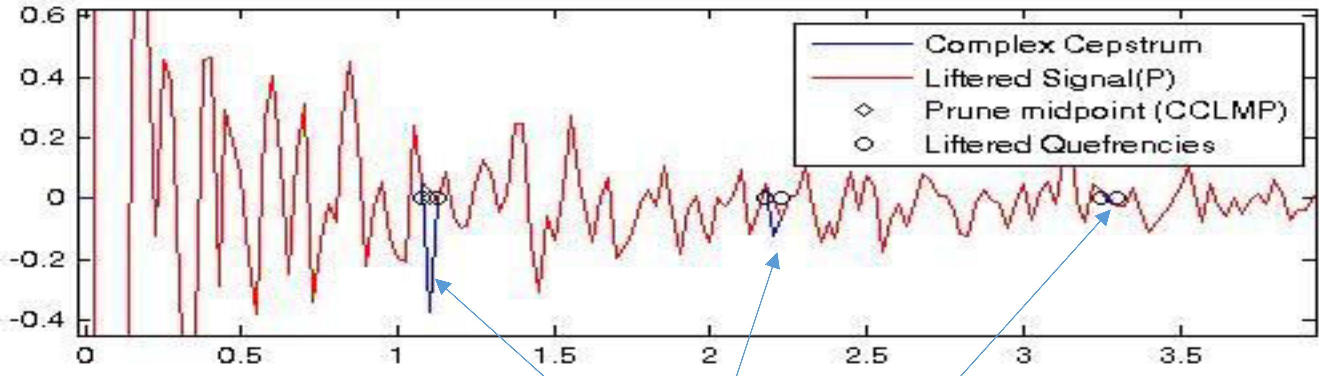








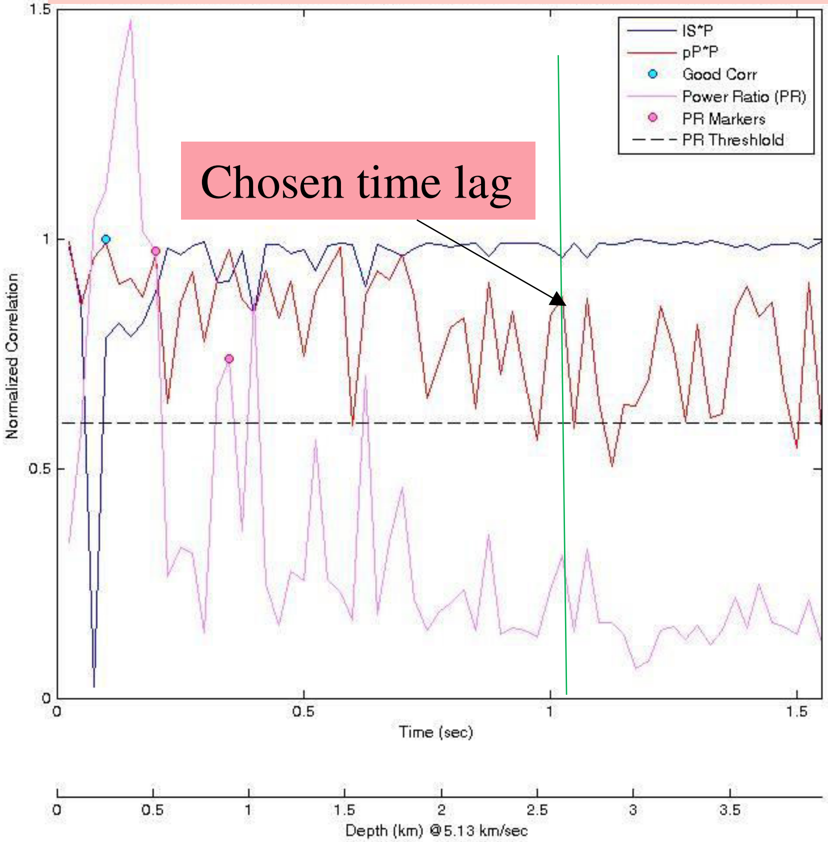
Liftered first echo

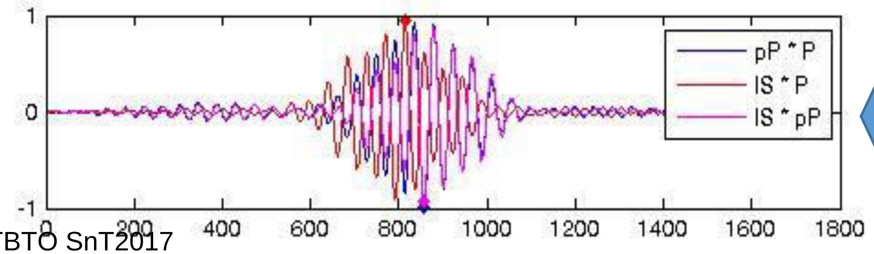


The first three liftered peak signs are consistent to the pP assumption.

Cepstral Analysis Steps and Metric application for a very shallow (depth 2.7 km, GT 1) earthquake in Mogul, west of Reno, Nevada

Auto-Prune Metrics

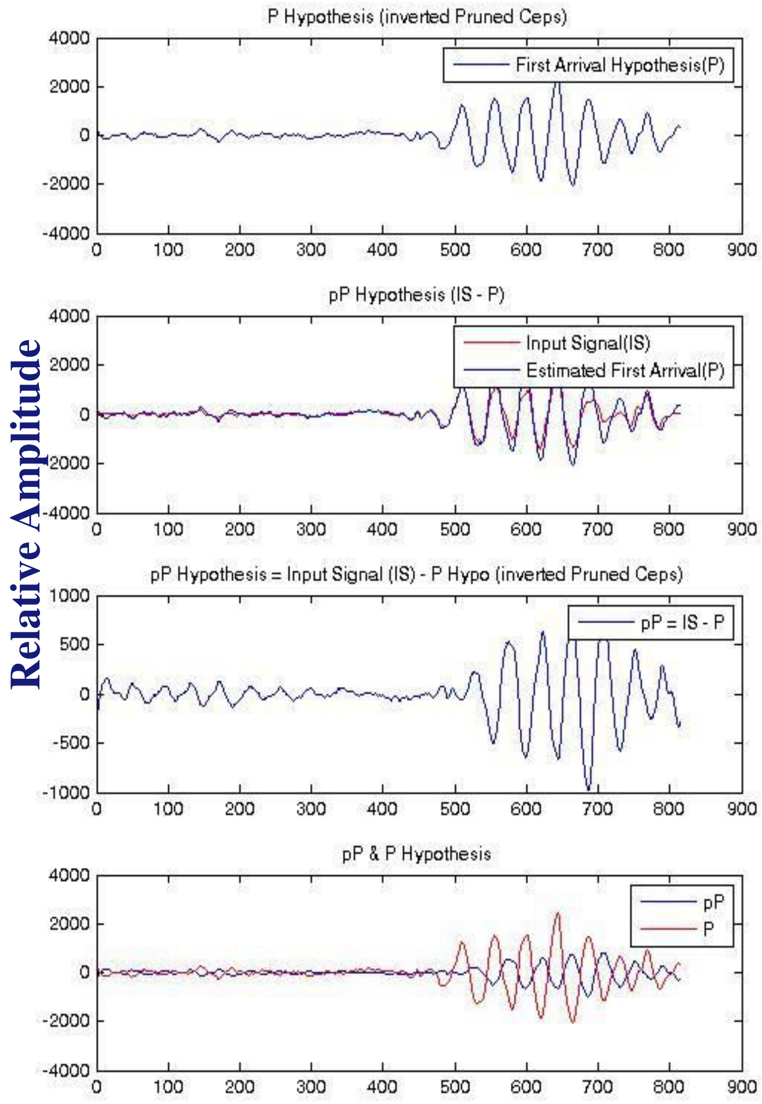




Time (samples at 40 sps)

Estimated Depth : 2.77 - 2.84 km
GT1 depth main shock: 2.7 km
Sample Range: 43.00 - 45.00
Time Range: 1.08-1.11
Velocity at epicenter : 5.13 km/sec
Sample-rate resolution: 0.0687 km
Correlation IS*P : 0.95
Correlation pP*P : -0.97
Correlation pP*IS: -0.93
Power Ratio pP_hypo/ power(xcor_P_hypo)= 0.40

Note crosscorrelation "ringing" due to the narrow band signal recorded at regional distance.



Time (samples at 40 sps)

SUMMARY

Depth estimates are currently evaluated using a set of metrics, which are investigated for application to near-real time algorithms.

Signal window length, signal seismic phase content, signal-to-noise ratios, the waveform sample rate and frequency content, the phase unwrapping algorithms and the liftering choices significantly affect the complex cepstrum shape and thus the current depth estimates.

Consideration of multiple choices in the selection of these parameters is necessary, as the depth estimate should remain constant across a set of reasonable values.

Further investigations

will require optimization of the deconvolution to obtain the best metrics and most stable Complex and Power Cepstrums, through:

1. **Systematical variation of a set of input parameter values, such as window length, filter, and phase unwrapping algorithm constants;**
2. **Investigations towards an optimal phase unwrapping algorithm;**
3. **Optimal inclusion of seismic phases in the analysis window, as a function of epicentral distance and type of event;**
4. **Iterations to adjust the liftering of the first Complex Cepstrum peak, and of the next peaks with minimum distortion of the "cepstral noise";**
5. **Use of combinations of the existing metrics, and new metrics to estimate depth, and confidence limits for the depth values;**
6. **Integration with synthetic waveform modeling (see Saikia et al., poster at this conference).**