A Comparison of Acausal and Causal FIR Filtration Effects on Seismic Waveform Data

by

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Introduction

Since the installation of the original BDSN Quanterra data loggers in the early 1990's, acausal FIR filter chains have been used to maintain consistency in the data acquisition systems as the BDSN surface-sited station network expanded and Quanterra data loggers evolved from the original Q680's to newer generations. Owing partly to the cooperative USGS Menlo Park/UCB REDI Project (Gee et al., 1996) with hypocenter locations provided by the USGS Menlo Park and partly to numerous BSL researchers interests involving predominantly the use of lower frequency (1 Hz and lower) seismic waveform data, the effects of acausal FIR filtration were not an impediment to progress. The relatively high crustal seismic wave attenuation in coastal California combined with the strong scattering/attenuation effects of the weathered layer tends to obscure the acausal FIR filter effects when picking phase onset times and first motions from the higher frequency (80+ Hz) seismic waveform data. Now, however, as more emphasis is being placed on robust manual and automated picking of seismic phase onset times and first motions, the acausal FIR filter effects are a significant impediment and we have decided to change the 100 Hz seismic data streams (on which the phase picking is done) from acausal to causal FIR filtration effective July 1, 2003. Switching from acausal to causal 100 sps FIR filtration will result in systematic changes to the resulting seismic waveforms which can impact the utility of seismic pattern recognition and other algorithms to compare events recorded before with those recorded after the acausal to causal 100 sps FIR filtration changeover date. This note describes and shows by example the differences in the acausal and causal FIR filters and their effects on the seismic waveforms.

Acausal and Causal FIR Filter Comparison

The Quanterra data loggers (Quanterra, Inc. of Harvard, MA), used in the Berkeley Digital Seismic Network (BDSN), operate at an initial sampling frequency of 5120 Hz (Q680 models) or 32 kHz (Q4120 models) or 20 kHz (Q730 models). These data loggers employ analog signal enhancement and digital signal processing and decimation to provide basic output sampling frequencies of up to 80 Hz (Q680), 1 kHz (Q4120), or 250 Hz (Q730). A chain of Finite Impulse Response (FIR) divide by 2, 4, 5, or 10 anti-aliasing filters are used to decimate the sampling rate from the initial sampling rate to the desired output sampling rate. The response of these FIR filters may be either linear-phase (constant delay, i.e. acausal) or minimum-phase (causal). Up to the present time BDSN has been using linear-phase (acausal) FIR filters in all Quanterra data loggers except those employed in the Hayward and Parkfield borehole seismic networks. Causal FIR filters have been used in the Hayward and Parkfield Quanterra data loggers since their inception because it was known that the acausal FIR filter effects would render robust manual or automated phase onset time and first motion detection of the wide-bandwidth impossible. The FIR filters used in the BDSN Q680 series data loggers are set in firmware and are thus not readily changeable and they will not be discussed further here.

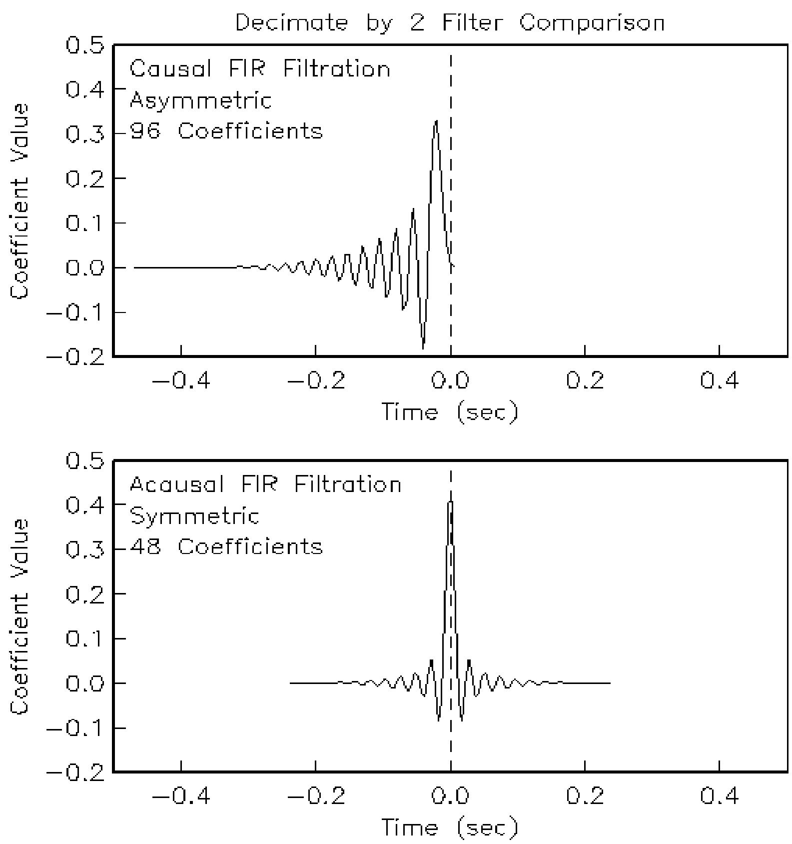

Figure 1. Plot of causal and acausal FIR decimate by two filter coefficients. The vertical dashed line represents the output sample time and the solid lines represent the FIR coefficients at each input sample time.

High-precision event locations rely on robust phase onset time picking and most of the manual and automated phase picking operations in the BSL are done using the 100 Hz BDSN seismic data streams. In order to facilitate robust manual and automated picking of phase onset times and first motions when analyzing this 100 Hz seismic waveform data we have decided to switch from acausal to causal FIR filtration in the BDSN Quanterra data loggers. The predominant acausal FIR filter effects, which distort the seismic waveform, are due to the last acausal FIR filter in the chain. Thus we need only change the decimate by two acausal FIR filter, which decimates the data from 200 Hz to 100 Hz, to a causal FIR filter in order to remove the acausal waveform distortion. This note describes the differences between the divide by two acausal and causal FIR filters and their effects on the resulting seismic signals.

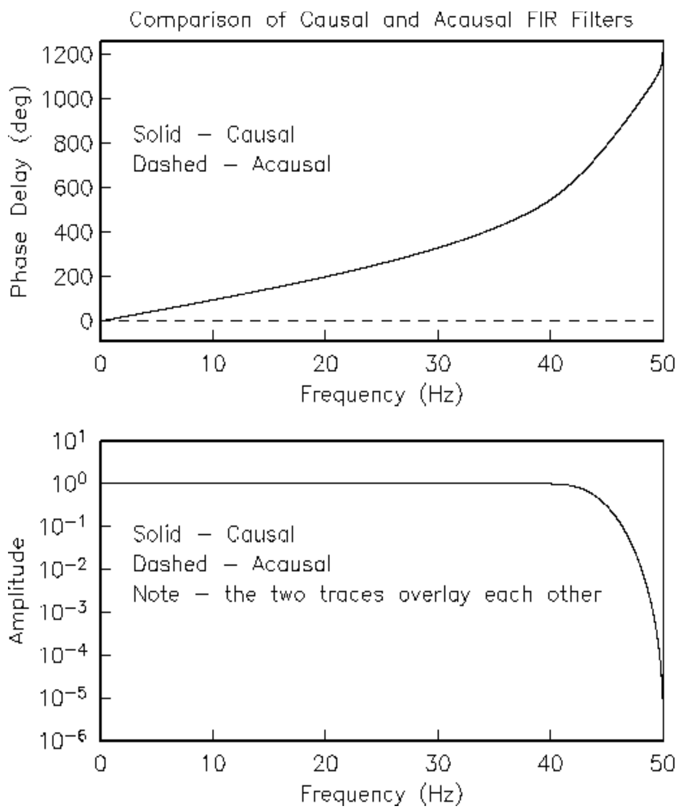

Figure 2. Spectral amplitude and phase response of acausal and causal divide by two FIR filters.

The FIR coefficients for the acausal and causal decimate by two FIR filters are shown in the Figure 1. Note that the causal FIR filter coefficients are asymmetric and non-zero for only negative times and thus the output sample depends only upon the current and previous input samples. Also note that the acausal FIR coefficients are symmetric and non-zero for both positive and negative times and thus the output sample depends upon both future and past input samples. The plots of the coefficients are also equivalent to the impulse responses of the two filters and it is the impulse response of the acausal filter that is the root cause of the difficulties in picking reliable phase onset times and first motions on the current 100 Hz BDSN seismic data channels.

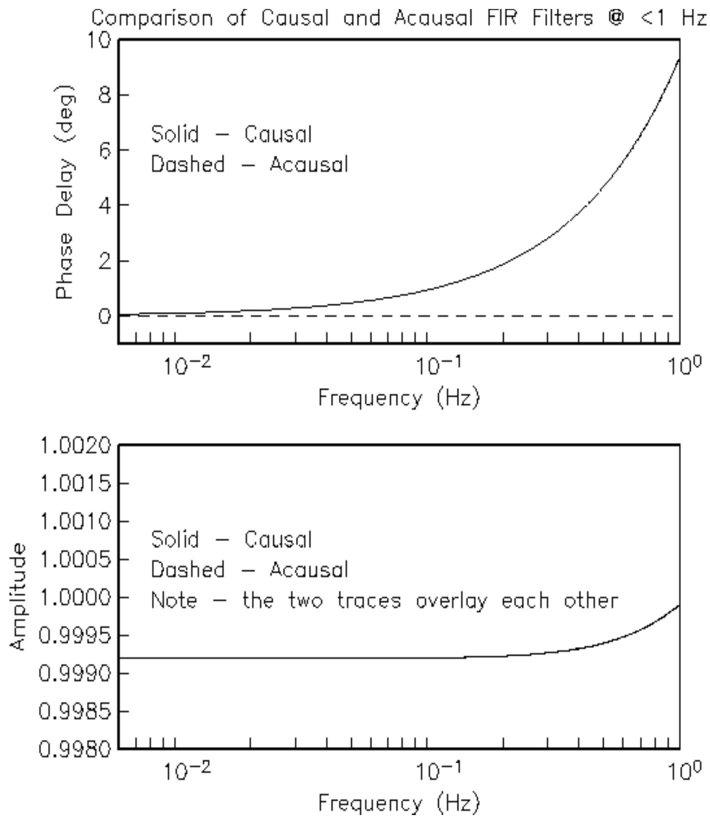

Figure 3. Expanded view of Figure 2 showing the response at frequencies below 1 Hz.

Seismic signals which have sharp onsets generate acausal signals which can precede the actual onset time by up to half the length of the acausal divide by two FIR filter (0.235 seconds). Under these conditions, the resulting onset times determined by either manual picking or automated phase picking algorithms will be biased early and there is roughly a 50 percent probability that the first motion will be incorrect. The amount of bias in the onset time and the probability of the first motion being correct are highly dependent upon the spectral characteristics of the seismic signal. If the seismic signal contains significant energy near the 100 Hz FIR cutoff frequency of 40 Hz (0.8 of the 50 Hz Nyquist frequency), the effects will be quite pronounced and obvious upon close inspection of the resulting seismic waveform. On the other hand, if the seismic signal contains little energy above a quarter of the FIR cutoff frequency, say, the effects are insidious in that they will not be so pronounced and not so easily identifiable upon visual inspection of the seismic waveform. The causal FIR filtration does not exhibit any of these problems. Hence the incentive is to switch from acausal to causal FIR filtration for the 100 Hz channels used in manual picking and by automated phase picking algorithms.

One way of showing the differences is to compare the spectral amplitude and phase response of the two FIR filters as shown in the Figures 2 and 3. The amplitude responses of the causal and acausal divide by two FIR filters are identical because the causal filter was derived from the acausal filter by manipulating the spectral phase characteristics while leaving the spectral amplitude characteristics unchanged (Scherbaum, 1996). The acausal FIR filter has zero phase and group delays at all frequencies while the causal FIR filter has phase and group delays which vary with frequency as shown in Figure 4. The group and phase delays asymptotically approach -25.8 ms at 0 Hz. The small and nearly constant low frequency (<1 Hz) group and phase delays of the causal divide by two FIR filter imply that the effect of inserting a causal FIR filter in the FIR filter and decimation chain, used to derive the lower frequency seismic waveforms will not have an adverse effect on the resulting waveforms.

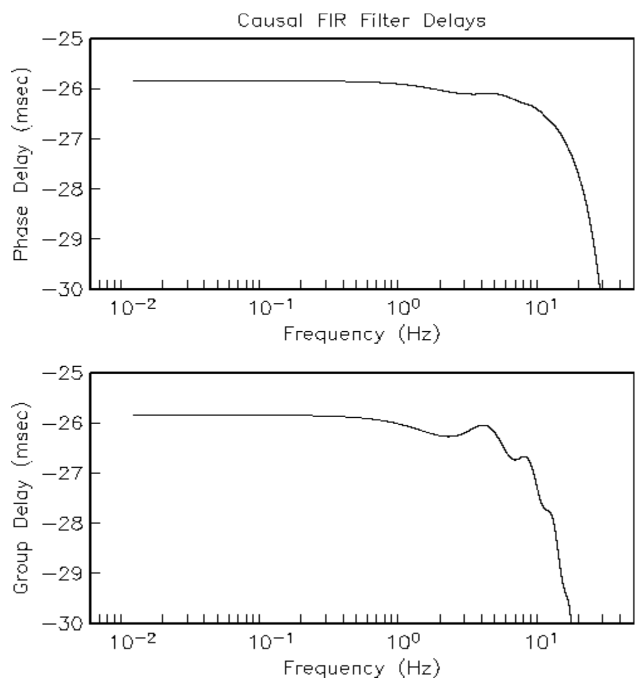

Figure 4. Causal divide by two FIR filter phase and group delays.

Waveform Examples

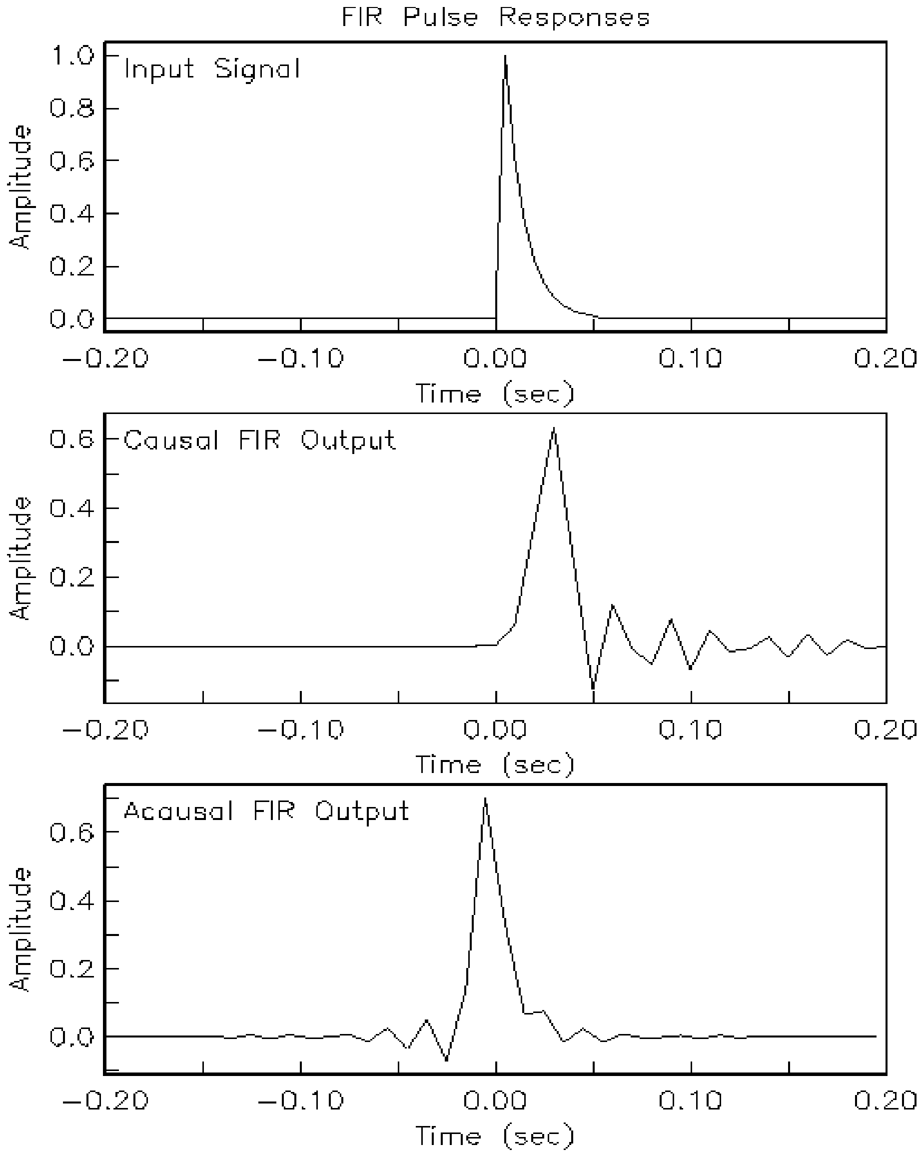

Figure 5. Comparison of acausal and causal FIR filter response to a common impulsive input signal (top trace).

In order to demonstrate the differences in the waveforms which can result from acausal and causal divide by two FIR filtration, we show the results of passing a single fast-rise-time pulse through an acausal and through a causal filter in Figure 5. The pulse convolved with the acausal FIR filter generates significant acausal signal artifacts prior to the onset of the input signal which render it impossible to unambiguously determine the onset time and first motion. On the other hand, the same pulse when convolved with the causal FIR filter does not generate any such artifacts and determination of the onset time and first motion are both robust and unambiguous. Thus there is an incentive to use causal filters when the goal is to obtain robust onset time and first motions via either manual observation or automated picking algorithms.

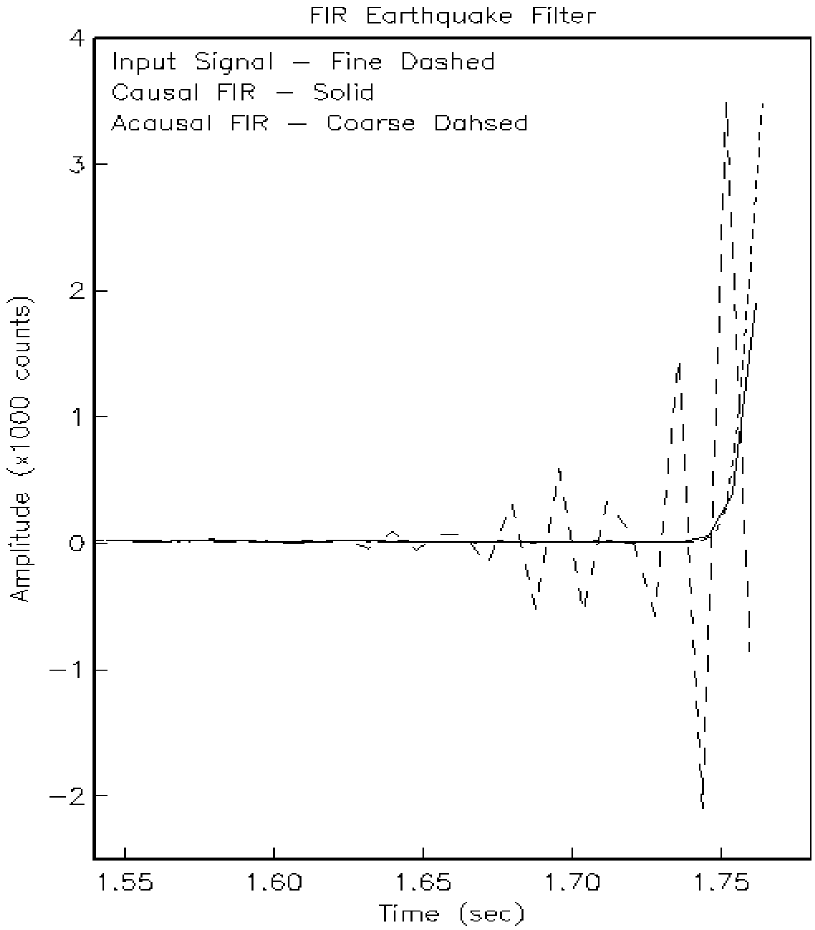

Figure 6. Example of the differences when the acausal and causal FIR filters shown in Figure 1 are applied to a seismic signal. Shown is the P-wave onset from a local earthquake located 4.1 km from the seismic station and at a depth of 6.8 km. The fine dashed line is the input signal, the solid line is the causal FIR filtered output and the coarse dashed line is the acausal FIR filtered output. For reference, the P-wave SNR is 60+ dB above the background noise RMS level of 0.010 on the plot scale.

To further demonstrate the differences between acausal and causal FIR filtration, we applied the causal and acausal FIR filters shown in Figure 1 to the Z-component borehole accelerometer recording of a local ML 4.12 earthquake which occurred 6 km NNW of Berkeley along the Hayward fault zone in December 1998. The input signal was recorded at 500 Hz and the Q4120 data logger uses causal FIR filtration. The causal FIR filter shown in Figure 1 was applied to the raw acceleration data to obtain a causal 250 Hz signal. The 250 Hz signal was then separately passed through the acausal FIR filter and the causal FIR filter to obtain the 125 Hz filtered waveforms that are plotted in Figure 6. The acausal FIR filtered signal contains significant oscillating signal which begins more than 0.1 sec prior to the P-wave onset. This oscillatory signal is an artifact of the acausal FIR filtration and it is the reason that neither phase onset times or first motions can be robustly determined from acausal FIR filtered seismic data. The causal FIR filtered signal, on the other hand, is well behaved and the phase onset time and first motion are unambiguous.

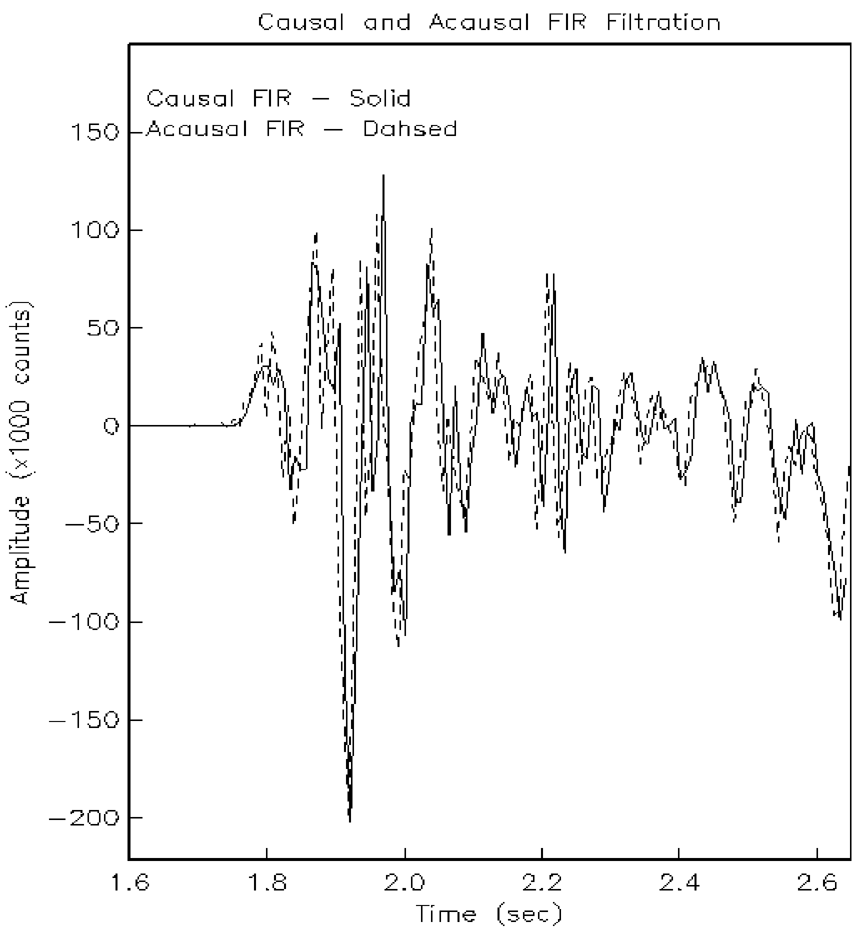

Figure 7. The entire P-wave signal, the beginning of which was shown in Figure 6.

The P-wave signal from the M 4.12 earthquake described above is shown in Figure 7 where the differences between the causal and acausal FIR filtered signals are readily apparent. This difference will effect the use of cross correlation or phase coherency methods to identify highly similar earthquakes. Figure 8 shows the results of a spectral phase coherency analysis between the acausal and causal waveforms shown in Figure 7. The solid line in Figure 8 was determined by shifting the time of the causal waveform to find the time shift which maximized the phase coherency in the 5-25 Hz frequency band. The resulting shape of the phase coherency trace is a result of the best fit of a linear time shift to the non-linear phase delay shown in Figure 2. As long as the phase coherency calculated at frequencies below half of the 50 Hz FIR cutoff frequency, say, the method can be used without modification to identify highly similar events. Accounting for the causal FIR filter phase delay is required to maximize the sensitivity of the phase coherency method (as shown by the dashed line in Figure 8) to detect small differences at the higher frequencies (approaching the FIR cutoff frequency).

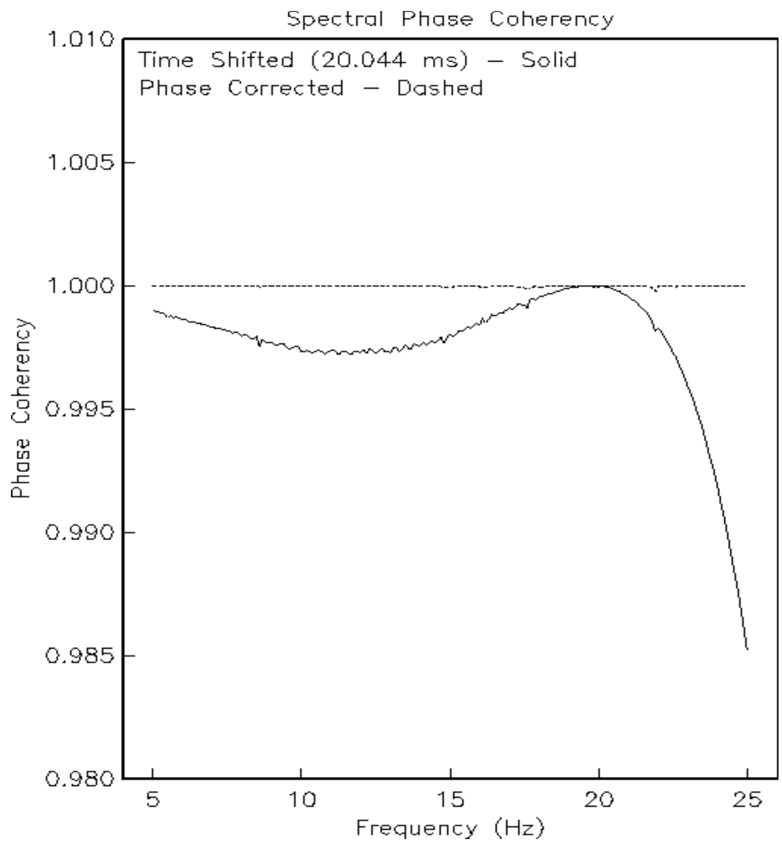

Figure 8. Spectral phase coherency as a function of frequency between the acausal and causal time series shown in Figure 7. The solid line is the results of determining the time shift (20.044 ms) which maximizes the spectral phase coherency in the 5-25 Hz frequency band and the dashed line is the results of the determining the spectral phase coherency after correcting for the frequency dependent phase distortion of the casual filter.

Conclusions

Switching from acausal to causal filtration in the 200 Hz to 100 Hz decimate by two FIR filters in the FIR filter chains in the Quanterra data loggers will vastly improve the robustness of manual and automated phase onset time and first motion determination. The switch will add a small delay the waveforms sampled at 1 Hz and lower frequencies with group and phase delays which asymptotically approach 25.8 ms at zero frequency as shown in Figure 4. The switch to causal FIR filtration will be most pronounced at the higher frequencies approaching the 40 Hz FIR cutoff frequency. At the higher frequencies, the phase delay of the causal FIR filters will effect the use of cross correlation and phase coherency methods used to identify highly similar events recorded before and after the July 1, 2003 switch from acausal to causal FIR filtration of the 100 Hz data streams. However, as shown in Figure 8, the phase delay of the causal FIR filter, as shown in Figure 2, is easily computed and compensated for when using cross correlation or phase coherency methods. Thus switching from acausal to causal FIR filtration in the BDSN Q4120 and later generation Quanterra data logger derived 100 Hz data streams has significant advantages for manual and automated phase picking and it has no significant disadvantages.

References

Gee, L. S., D. S. Neuhauser, D. S. Dreger, M. E. Pasyanos, B. Romanowicz, and R. A. Uhrhammer, The Rapid Earthquake Data Integration System, Bull. Seis. Soc. Am, 86, 936-945,1996.

Scherbaum, Frank. *Of Poles and Zeros: Fundamentals in Digital Seismology*, Volume 15 of Modern Approaches in Geophysics, *G. Nolet, Managing Editor,* Kluwer Academic Press, Dordrecht, xi + 257 pp., 1996.