FilterPicker6

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FilterPicker6 is an evolution of FilterPicker5. The following updates the algorithmic description of FilterPicker5 in Lomax et al. (2012; http://tinyurl.com/or5cg3q) to document the FilterPicker6 algorithm.

The FilterPicker6 algorithm

FilterPicker6 (FP6) operates on a discretized time-series signal $y(i)$ with sample interval ΔT. This signal may have little or no pre-processing – it may be a broad-band data stream as output from a digitizer without filtering or mean removal. The FP6 algorithm used almost exclusively logical and arithmetic operations (i.e., uses the square-root, but no exponentials, logarithms or transform algorithms) and so is computationally efficient.

The FP6 algorithm makes use of decay constants for accumulating time averaged statistics on the signal independently of the elapsed time since the start of the signal. For a statistic $S=f(y)$, the time averaged value S_{long} is given by,

$$S_{long}(i)=C_{long}\cdot S_{long}(i-1)+(1-C_{long})\cdot S(i) \quad , \tag{1}$$

where $S(i)$ is an instantaneous value of S and C_{long} : $0\leq C_{long}<1$, is a decay constant defined by $C_{long}=1-\Delta T / T_{long}$ where T_{long} is a time-averaging scale.

Simple multi-band processing

The FP6 algorithm processes a set of N_{band} bands with center periods T_n and bandwidth W_b given by the ratio T_n/T_{n-1}. The T_n and N_{band} might be chosen so that $T_{N_{band}-1}=2^{N_{band}-1}\Delta T$ is greater than the largest dominant period of phases to be picked. For example, if ΔT=0.01 sec and phases with a dominant period of up to 1 sec are to be picked, then N_{band} should be at least ceiling[$\log_2(1/0.01)$]+1 = 8, giving $T_n(n=0,7)$ = {0.01, 0.02, 0.04, 0.08, 0.16, 0.32, 0.64, 1.28 sec} for W_b=2.0. N_{band} should not be set higher than necessary since the overall FP6 computation time increases directly with N_{band}.

To perform broadband picking, FP6 first creates a set of band-passed time-series, $y(i)\rightarrow Y_n(i)$, with center periods at T_n, through application of time-domain, recursive 4-pole Butterworth bandpass filters to the raw broadband signal $y(i)$. The filter low- and high-pass corner periods for each band T_n are $T_n/W_b^{1.5}$ and $T_n/W_b^{1.5}$, respectively.

Characteristic function

FP6 constructs a characteristic function (CF), following Baer & Kradolfer (1987), by first defining for each band n an envelope function, E_n,

$$E_n(i)=Y_n^2(i) \quad , \tag{6}$$

and a characteristic function, $F^C{}_n(i)$,

$$F_n^C(i) = \frac{E_n(i) - \langle E_n \rangle (i-1)}{\langle \sigma(E_n) \rangle (i-1)} - 1 \quad , \qquad (7)$$

where $<E_n>(i\text{-}1)$ and $<\sigma(E_n)>(i\text{-}1)$ the time-averages up to sample i-1 of E_n and the standard-deviation of E_n, respectively, are accumulated using the decay constant C_{long} according to eq. (1). The characteristic function F^C_n quantifies the variation of E_n relative to its background level, represented by the mean value $<E_n>$, scaled by $<\sigma(E_n)>$, all within the time scale T_{long} corresponding to the decay constant C_{long}. Note that subtracting 1 from the quotient results in $F^C(i)\approx 0$ for a signal $E_n(i)$ around $<\sigma(E_n)>$ above the background level, and $F^C(i)<0$ for a signal $E_n(i)$ weaker than this level. Negative $F^C(i)$ values provide a penalty to the pick acceptance tests (integrals, see below "Triggering and pick declaration") which helps to suppress triggering after short duration peaks in F^C or a series of weak F^C peaks.

In a final step, a single, summary CF, $F^C(i)$, is formed by setting $F^C(i)=\max\{\alpha_n F^C{}_n(i);\ n=0,N_{band}\text{-}1\}$, where α_n is a "threshold scale factor" which allows adjustment of the relative contribution of each band to $F^C(i)$. The use of the maximum of the CF over all bands to form the summary CF, $F^C(i)$, helps to insure triggering when a phase-onset has a relatively narrow band-width compared to the background noise, especially when the noise level is similar to or greater than the onset level. An alternate use of, for example, the sum of the CF over all bands as a summary CF would effectively fold noise into the summary CF and make triggering less likely for weaker and narrow-band onsets.

Since the time-average values $<E_n>(i\text{-}1)$ and $<\sigma(E_n)>(i\text{-}1)$ vary continuously in response to changes in the background signal levels, $F^C(i)$ is automatically adaptive relative to recent signal levels. In addition, the use of band-passed signals makes $F^C(i)$ insensitive to the absolute signal amplitude (after a stabilization time much larger than each band center period T_n), thus the picker can be applied directly to broadband signals which have offsets, micro-seismic noise or other noise at periods longer than $T_{N_{band}}$, i.e. longer than the dominant period of any phases of interest.

Triggering and pick declaration

The summary CF $F^C(i)$ is monitored at each time step to check for triggers and pick acceptance. A trigger is declared when $F^C(i) \geq S_1$, where S_1 is a predefined trigger threshold, the corresponding trigger time, t_{trig}, is stored, and the band with largest $F^c{}_n(i)$ is defined as the primary trigger band, k. Given a trigger and predefined time widths, T_{up} and T_{upMin}, $T_{upMin}< T_{up}$, a pick is accepted if two tests are satisfied: Firstly, within a window from t_{trig} to $t_{trig}+T_{up}$, the integral of $F^C(i)$, $\sum_{up}F^C(i)\Delta T$, must exceed the value $S_2 \cdot T_{up}$, where S_2 is a predefined threshold; this test measures if the average of the CF within window T_{up} is greater than S_2. Secondly, within a window from t_{trig} to $t_{trig}+T_{upMin}$, the integral of $F^C(i)$, $\sum_{upMin}F^C(i)\Delta T$, must exceed the value $S_1 \cdot T_{upMin}$; this test measures if the average of the CF within window T_{upMin} is greater than S_1, and helps to suppress picking on signals with duration $< T_{upMin}$. Additionally, to help prevent picking of short duration signals and spikes (a single data point with anomalously large amplitude), the contribution to $\sum_{up}F^C(i)\Delta T$ from any data points is limited to $5 \cdot S_1$. Since $F^C(i)$ is the maximum over all bands, the integrals of the form $\sum_u F^C(i)\Delta T$ and the declaration of picks take into account broadband energy. To avoid excessive picking during larger events, following each declared pick, a new pick cannot be declared before $F^C(i)$ drops below $F^C(i)=0$, e.g. signal $E_n(i)$ drops below the background level.

Pick time, uncertainty, polarity and strength

Each time the CF, $F^C{}_n(i)$, for each band n rises past the time-average $<F^C{}_n>$ (accumulated using the decay constant C_{long} according to eq. (1), with $<F^C{}_n>$ constrained to $-0.5 \leq <F^c{}_n> \leq S_1/2$), the corresponding sample time is stored as a potential pick uncertainty start time, t_n^{unc}, for the corresponding band. The pick time, t_{unc}, is set to t_k^{unc} for the primary trigger band, k. Thus t_{unc} is set near the last point with CF within the pre-phase signal or noise CF for band k, and earlier than t_{trig}, at which there is certainty of phase energy ($F^C(i) \geq S_1$). If the time difference t_{trig} - t_{unc} is greater than twice the trigger band period, i.e. $2T_k$, then t_{unc} is delayed enough to satisfy this condition. If the time difference t_{trig} - t_{unc} is less than 1/4th of the trigger band period, i.e. $T_k/4$, then t_{trig} is delayed and t_{unc} advanced enough to satisfy this condition. Finally, t_{unc} and t_{trig} are corrected (advanced) by a phase shift corresponding to the bandpass filter used for the shortest period band that triggered. The pick time, t_{pick}, is halfway between t_{unc} and t_{trig}, and a pick uncertainty, σ_{pick}, is set equal to ½ the interval from t_{unc} to t_{trig}, giving a pick time with uncertainty specified by $t_{pick} \pm \sigma_{pick}$. The maximum value $F^C(i)$ in the window from t_{trig} to $t_{trig}+T_{upMin}$ is taken as an indicator of pick strength.

The polarity of the pick is determined by comparing the sums of the values and the sums of the absolute values of the first differences of the filtered signal values, $Y_k(i)$, between t_k^{pick} and t_{trig}. If the value sum is greater than 66% of the absolute value sum, then the polarity is set as the sign of the value sum, otherwise the polarity is set as unknown.

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