

# 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  $\Delta T$ . 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,

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

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  $\Delta T = 0.01$  sec and phases with a dominant period of up to 1 sec are to be picked, then  $N_{band}$  should be at least  $\text{ceiling}[\log_2(1/0.01)] + 1 = 8$ , giving  $T_n(n=0,7) = \{0.01, 0.02, 0.04, 0.08, 0.16, 0.32, 0.64, 1.28 \text{ sec}\}$  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,  $E_n$ ,

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

and a characteristic function,  $F_n^C(i)$ ,

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

where  $\langle E_n \rangle(i-1)$  and  $\langle \sigma(E_n) \rangle(i-1)$  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  $F_n^C$  quantifies the variation of  $E_n$  relative to its background level, represented by the mean value  $\langle E_n \rangle$ , scaled by  $\langle \sigma(E_n) \rangle$ , 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  $E_n(i)$  near the background level, and  $F^C(i) < 0$  for a signal  $E_n(i)$  weaker than background.

In a final step, a single, summary CF,  $F^C(i)$ , is formed by setting  $F^C(i) = \max\{F_n^C(i); n=0, N_{band}-1\}$ . 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  $\langle E_n \rangle(i-1)$  and  $\langle \sigma(E_n) \rangle(i-1)$  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  $F_n^C(i)$  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,  $F_n^C(i)$ , for each band  $n$  rises past the time-average  $\langle F_n^C \rangle$  (accumulated using the decay constant  $C_{long}$  according to eq. (1), with  $\langle F_n^C \rangle$  constrained to  $-0.5 \leq \langle F_n^C \rangle \leq S_1/2$ ), 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  $1/4^{\text{th}}$  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,  $\sigma_{pick}$ , is set equal to  $\frac{1}{2}$  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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