Users Guide for Consistent Phase Picking at Local to Regional Scales

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Users Guide for Consistent Phase Picking
at Local to Regional Scales

by

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Contents

1 Introduction

Although travel time based earth models and hypocenter solutions strongly depend on the accuracy of used phase data, the description of consistent phase picking receives only little attention in literature. *Simon* (1981), *Kulhánek* (1990), and *Kulhánek* (2002) provide a general overview about seismogram interpretation from local to teleseismic scales. They focus mainly on basic descriptions of phases observable in common seismograms. The assessment of timing uncertainty and phase interpretation, however, is barely discussed. The fundamentals of digital signal processing and their influence on onset properties are described e.g. in *Seidl and Stammler* (1984), *Scherbaum* (2001), and *Scherbaum* (2002). Among the few recent guidelines, the *New Manual of Seismological Observatory Practice* (NMSOP) of *Bormann et al.* (2002) provides an introduction to basic picking principles for local, regional and teleseismic seismograms. Although they already propose to quantify the onset-time reliability, a detailed description for consistent quality assessment is missing, similar to the discussion in *Scherbaum* (2001).

Due to modern digital acquisition systems (timing with GPS or DCF-systems, sampling rates ≥ 80 Hz) and the use of modern analyzing software, onsets of seismic signals can be determined with a precision of up to a few tenth of milliseconds. To benefit from this accuracy in applications like high-resolution tomography, a consistent error assessment in terms of timing uncertainty and phase interpretation is crucial. This user guide provides a detailed description of common problems in routine hand picking and presents a hand picking procedure, which includes a consistent quality assessment for timing uncertainty and phase interpretation. It is focused on crustal and upper mantle phases on local to regional distances, but it principles apply likewise to teleseismic observations.

2 Routine Hand Picking

Especially for local and regional earthquake data, phase picking often becomes inconsistent and ambiguous due to rather complex waveform patterns and the close arrival of different phase types within a short time period of the same coda. In general, the shape of a seismic wavelet is affected by the source time function, the radiation pattern, dispersion, attenuation, scattering, interference with other phases, the signal-to-noise ratio at the recording site, and the characteristic of the recording system. The superposition of these components may lead to highly complex waveforms in case of high-frequency local and regional recordings. Moreover, the picking of later phases such as PmP or S-waves becomes even more difficult, since they interfere with the coda of earlier phases. Since the target accuracy of such arrivals is usually within few hundred milliseconds, errors like phase misinterpretations denote blunders and may significantly bias hypocentre locations and velocity models. Furthermore,

regional studies usually require the compilation of data from several networks. In such a case, merging routine phase data will add even more inconsistency. The possible sources for inconsistent hand picking described in the following sections refer mainly to P-wave picking. However, the basic principles of picking and error assessment of phases is also valid for S-wave picking. In addition, section 2.6 includes problems specific to S-wave picking.

In general, a seismic phase is defined by two visual observations:

1. Change primarily in amplitude:
   The amplitude exceeds the background noise (for a certain amount of time). This can also be denoted as amplitude based signal-to-noise ratio ($ASNR$). We may define a phase, if its amplitude exceeds the background noise at least by a factor of 1.5 ($ASNR \geq 1.5$). Figure 1 represents a typical example for a phase arrival defined by a change of the $ASNR$.

2. Change primarily in frequency:
   A change of the dominant frequency indicates the arrival of a seismic phase. We can refer to this observation as frequency based signal-to-nose ratio ($FSNR$). Unlike the $ASNR$, it is often much more difficult to quantify visually. Moreover, the dominant frequency of noise and signal can sometimes be very similar. But especially for broad time windows, the $FSNR$ can help to determine the approximate position of a phase. Figure 2 represents a typical example for a phase arrival defined by a change of the $FSNR$.

Once a phase is recognised based on $ASNR$ or on $FSNR$ or - most likely - a combination of both, we have to determine the precise wavelet onset ('arrival time'). However, its position is usually not completely independent from the associated overall observation uncertainty. Finally, we have to identify the phase type and to do so, we have to answer questions like: May we assign the ray path to the phase (Pg, Pn, PmP) with certainty or is the station near a triplication point? Are we sure that it is the first arrival or is it possible, that an earlier phase is hidden in the noise? In addition, the visual examination of $ASNR$ and $FSNR$ can be rather subjective and strongly depends on the width of the used time window and also on amplitude scaling. Finally, filtering can affect $ASNR$ and $FSNR$ significantly. In the following sections, we will give examples for these problems and suggest possible solutions in order to minimize inconsistencies during the picking process. Once identified, it should be possible to minimize their contribution by defining certain rules and procedures, which finally add up to a consistent picking workflow and consistent uncertainty assessment for each observation.

2.1 Phase Picking Part I: Phase Timing and its Error Assessment

The basic quantities associated with a picked phase are usually the absolute arrival time and the corresponding observation error. However, it is difficult or even impossible to give a general definition of a seismic onset, which could be used for the actual measurement of first arrival time from a sampled band-limited signal in the presence of noise (*Seidl and Stammler*, 1984). Therefore, the visual determination of absolute arrival times often implies a high degree of subjectivity and inconsistency. Consequently, a physical consistent formulation can only be achieved by a probabilistic point of view. Such an approach directly relates the measured arrival time with the corresponding observation error. Considering the onset of a seismic phase as probabilistic function $P_a(t)$, the arrival time is expressed as the 'most likely' time t_A, with $P_a(t_A) = Max(P_a)$. On the other hand, the 'earliest' possible time for the phase onset is defined as t_E, where the likelihood for onset is approaching zero. Thus $P_a(t_E) \geq 0$. Analogue, the 'latest' possible time for the phase onset t_L, is also defined as $P_a(t_L) \geq 0$.

Figure 1 illustrates the proposed concept for a typical $ASNR$-case in further detail. Although the onset of the phase is rather impulsive and exhibits an almost ideal signal to noise ratio, it is difficult to determine an arrival time consistent with picks of waveforms from same seismic source recorded at other stations. The thick grey band between position '1' and '2' defines the time window that for certain includes the onset of the wavelet. The band outlined by two broken lines denotes the possible threshold of the noise amplitude. In practice, we first determine the position of t_L and t_E. For a consistent determination of t_L and t_E, we have to setup a common procedure. Since the amplitude exceeds the threshold several times at position '2', the end of the grey band is certainly too late to be picked as t_L. Therefore, we define the intercept between signal amplitude and a priori noise threshold (here: 1.5 times the noise amplitude) as t_L. Usually, the consistent determination of t_E is more difficult. In Figure 1 we fit a tangent (dashed line 'a') to the smoothed slope of the onset. If we shift the tangent from t_L towards earlier times, the slope decreases. The earliest possible time t_E corresponds with the first zero slope from t_L towards earlier time. Therefore, the start of the grey band (position '1') is certainly to early and on the other hand, t_A would be too late to be picked as t_E. To ensure t_E includes the zero slope time in present of larger background noise, we could shift it to earlier arrival by approximately half a wavelength of the dominant noise. Subsequently, we pick the arrival of the phase at the most likely position t_A, within the error interval of t_E and t_L (e.g on the seismogram's leading edge). For the special case of an ideal delta-pulse, t_E and t_L would coincide with t_A. Figure 2 illustrates the concept for the $FSNR$-case. Again, the thick grey band between position '1' and '2' defines the time window that for certain includes the onset of the wavelet and the band outlined by two broken lines denotes the possible threshold of the noise

amplitude. The change in frequency is obvious for arrival times greater then position 'b'. Therefore, we define t_L a quarter signal wavelength ($\lambda/4$) after position 'b'. For arrival times earlier than position 'a', the signal frequency (indicated by grey wavelet) is certainly not present. We pick t_E half a signal wavelength ($\lambda/2$) before position 'a'.

Usually, the observation error is related with a discrete weighting or quality class (e.g. 0-5). However, these classes are often defined only through qualitative attributes, like waveform shape (impulsive or emergent). Such classification is not sufficient for a consistent error assessment. Instead, a quantitative weighting scheme has to be defined and the assigned weighting class depends only on the measured time error interval (t_L-t_E). In addition, the measurement of t_L, t_E, and t_A allows us to adjust the weighting class definition even after the picking process.
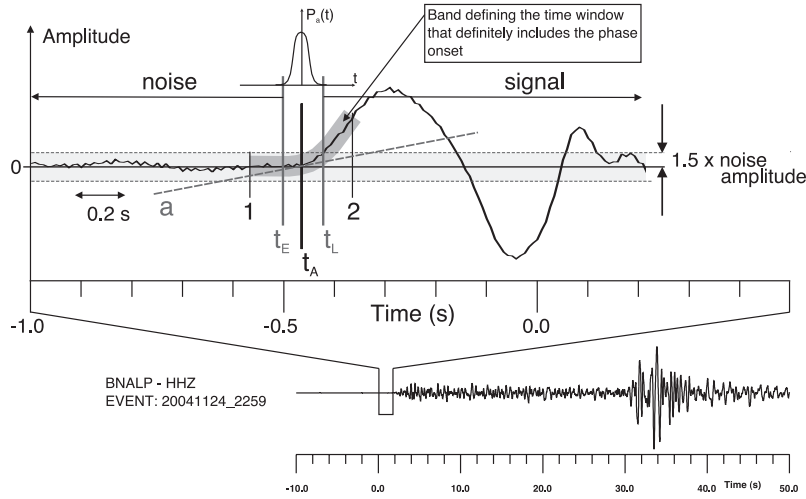

Figure 1: Probabilistic phase picking approach based on change of ASNR: the 'earliest' possible pick corresponds to t_E, the 'latest' possible pick corresponds to t_L. The most likely arrival time t_A is located within this interval. Primarily amplitude is used for determination of t_E and t_L.

2.2 Phase Picking Part II: Phase Identification and its Error Assessment

Although phase misinterpretation can result in significantly large errors, phase identification is typically not supplied with any observation error or uncertainty attribute at all (unlike arrival time of a phase). As demonstrated by synthetic travel time curves in Figure 3, the first arrival of the local or regional P-wave coda is usually Pg (direct wave as illustrated in inset of Fig. 3) or Pn (Moho-refracted wave). Whether Pg or Pn is the fastest wave depends on epicentral distance Δ, crustal thickness z_M, and focal depth z_F. Discrimination between Pg and Pn can become rather difficult in the distance range of phase tripli-
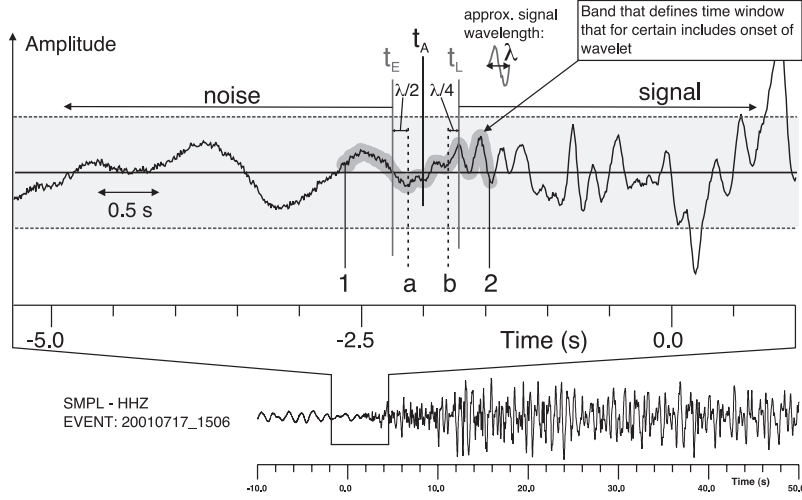
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Figure 2: Probabilistic phase picking approach based on change of $FSNR$: the 'earliest' possible pick corresponds to t_E, the 'latest' possible pick corresponds to t_L. The most likely arrival time t_A is located within this interval. Primarily frequency is used for determination of t_E and t_L.

cation (see Fig. 3). The Moho-reflected PmP phase always arrives after Pg and Pn, although its amplitude can become the dominant phase in the coda. The synthetic reflectivity seismograms (*Fuchs and Müller*, 1971) in Figure 3 (vertical components) denote the expected amplitude ratios between Pg, Pn, and PmP for this simplified crustal model. Especially for large epicentral distances, Pn is sometimes masked in the noise and Pg or PmP can likely be interpreted as the first arrival. As an example, Figure 4 presents a velocity reduced record section of a local earthquake near Walenstadt, Switzerland with a focal depth of 13 km. Based on waveform characteristics alone, phase interpretation appears rather difficult for some stations in the distance range of phase triplication (e.g. SPAK and SIERE). In addition, amplitude ratio between Pg and Pn denotes strong variations between some stations (e.g. EMV and HEI) probably due to 3D Moho topography. In this case, Pn is likely to be missed and Pg will be picked as first arrival phase.

Since most applications like hypocenter localisation and travel time tomography are (still) based on first arrivals only, we have to setup an error assessment for phase identification to avoid such inconsistency. The relevance of phase interpretation becomes even more evident for S-wave picking. For use in routine first-arrival studies and subsequent special studies, we define an error assessment for phase identification as shown in Table 1.

As illustrated in Figure 4, the determination of the phase type from the pure waveform characteristics can become quite ambiguous, especially in the range of the crossover distance between Pg and Pn. As a rule of thumb, we define the following waveform characteristics:

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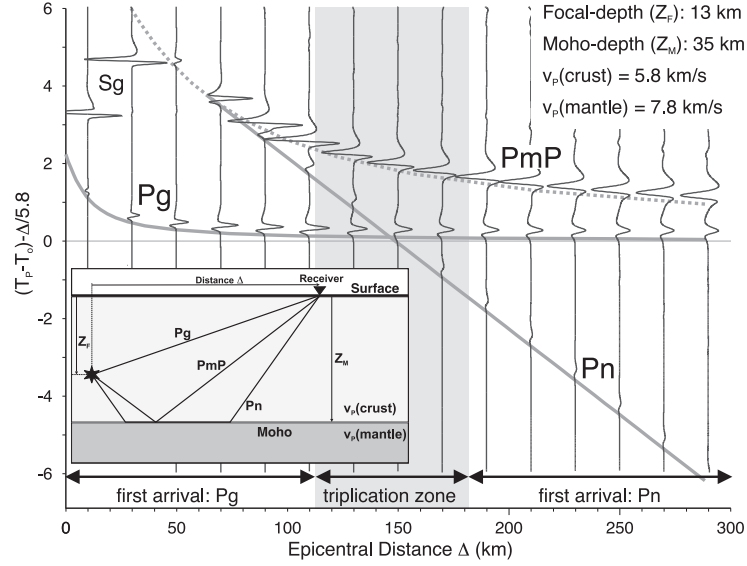
Figure 3: Reflectivity seismograms (vertical components) and synthetic travel time curves (solid and dashed lines) for main phases observed in local and regional earthquakes (one layer over half space). Focal depth is set to 13 km and time axis is reduced by 5.8 km/s. Phase identification is expected to be difficult in the distance range of phase triplication. The position and width of this zone mainly depends on focal depth and Moho topography.

Phase label	Phase is ...	Phase used for routine 1st arrival studies
Pg	Direct (crustal)	Yes (if first arrival)
Pn	Moho-refracted	Yes (if first arrival)
PmP	Moho-reflected	No
P1	Unknown type, but certainly first arrival	Yes
P2	Unknown type, second arrival	No
P3	Unknown type, third arrival	No
P	Unknown type, uncertain if first arrival	No

Table 1: Error assessment used for phase identification. Definition analogue for S-wave.

- **Pg**: Impulsive high-frequency onset (dispersion tends to sharpen the wavelet front), first arrival close to epicentre.

- **Pn**: Usually small amplitude impulse or emergent onset, lower frequency content (absorption leads to smoothed wavelet front), first arrival for larger epicentral distance, usually followed by strong Pg and PmP phase (delay up to several seconds).

- **PmP**: Usually strong amplitude due to high reflectivity of Moho, wavelet with high-frequency reverberations. Never first arrival.

2.3 Phase Picking Part III: First Motion Polarity and its Error Assessment

Information about first motion polarity is mainly needed for focal mechanism determination. Usually the polarity is denoted as 'Up' or 'Down'. Figure 1 represents an example for certain polarity identification. On the other hand, it is impossible to determine any polarity for the example of Figure 2. However, besides these two obvious cases, it is sometimes necessary to use an intermediate quality class for the first motion polarity. Time 'a' and 'b' in Figure 5 represent two possible positions for arrival time picks. In this case, the polarity is depending on the location of the pick. If the pick is assigned to position 'a', the polarity would be 'Up'. If position 'b' is used, the polarity has to be 'Down'. In both cases, we are not sure about the actual polarity, therefore we have to introduce an intermediate quality classes '+' or '-'. The error assessment used here is summarized in Table 2.

Polarity label	Polarity is ...	Weight
U/D	Up/Down	Polarity is identified with certainty
+/-	Up/Down	Polarity is identified but uncertaint
N	None	Polarity cannot be identified

Table 2: Error assessment used for first motion polarity.

2.4 Size of Time Window and Amplitude Scaling

The influence of time window size and amplitude scaling on picking accuracy and phase identification as described e.g. by *Douglas et al.* (1997) is demonstrated in Figure 6a-d. In the uppermost example, the used time window is 5 s (Fig. 6a). The picked onset is labelled as P_a. For a narrower time window of 1.5 s, P_a seems a bit too late (Fig. 6b). Thus, we would pick the phase at position P_b in this window. The result is even more different, if time window size remains the same, but the amplitude is multiplied by a factor of 5 (Fig.
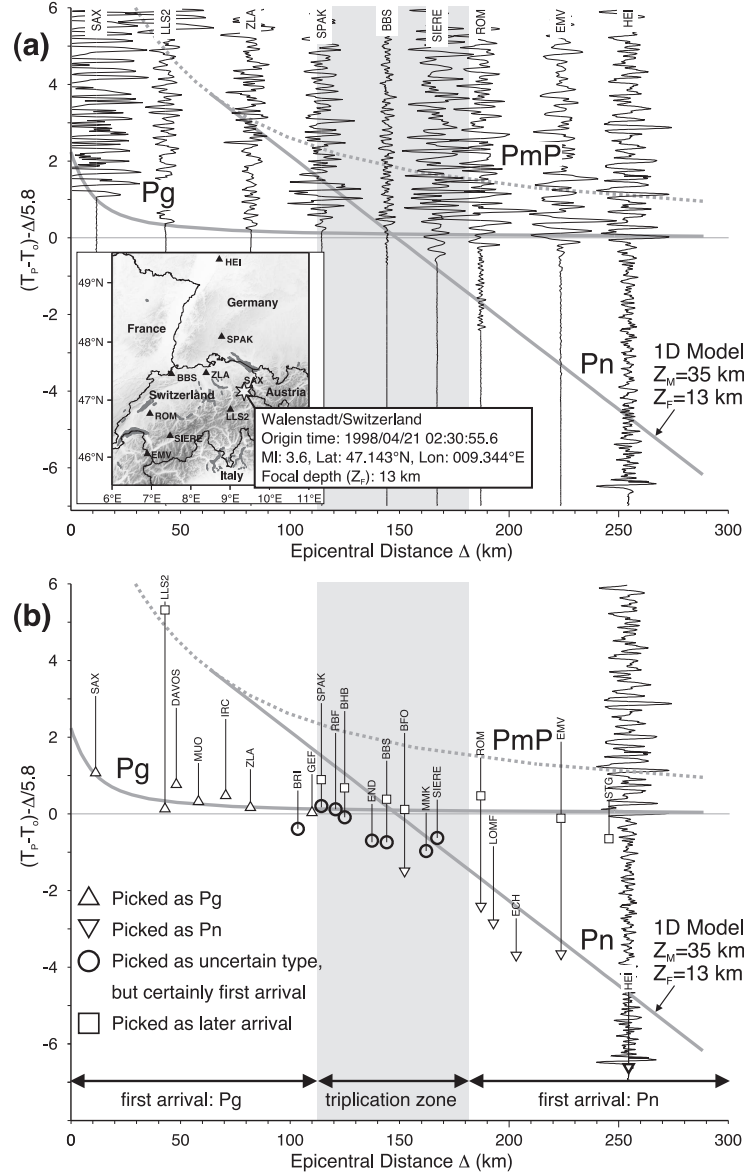
Figure 4: a) Velocity reduced record section of a local earthquake near Walenstadt, Switzerland. Amplitudes are normalised to maximum amplitude of each trace. Synthetic travel time curves for Pg, Pn, and PmP are indicated by solid and dashed lines analogue to Figure 3. Discrimination of phase type from waveform characteristics only might be difficult for stations in triplication range (e.g. SPAK and SIERE). Denote differences in amplitude ratio between Pg and Pn for station EMV and HEI. Deviations between expected and observed Pn arrival are related to 3D Moho topography. b) Velocity reduced phase picks, crosschecked against synthetic travel time curves derived from simplified crustal model.
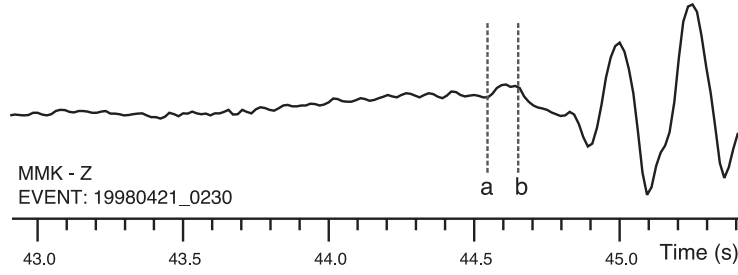
Figure 5: First motion polarity and its error assessment: In this example the first motion polarity is not independent from the pick position. If the pick is assigned to position 'a', the polarity would be 'Up'. If position 'b' is used, the polarity has to be 'Down'. In both cases, we are not sure about the actual polarity, therefore we have to use the intermediate quality classes '+' or '-'.

6c) and 10 (Fig. 6d) respectively. An earlier phase is visible, which could be picked as P_c (Fig. 6d). But not only the absolute timing of the picked phase depends on window size and amplitude scaling, also the assigned uncertainty interval. The error interval might be smaller for the narrower time window and the magnified case.

2.5 Aliasing and Waveform Filtering

From signal theory we know, that the correct digital representation of a continuous waveform depends on the sampling frequency. To avoid aliasing, a signal with frequency f has to be sampled with a sampling frequency $\Delta f > 2f$. Thus, the Nyquist frequency is defined as $f_N = 1/(2\Delta t) = \Delta f/2$. Any frequencies higher than f_N are aliased into lower ones. Therefore, we have to ensure that picking accuracy and also phase identification will not be affected by sampling rates, which are rather small. As an example we consider a waveform sampled at $\Delta f = 20$ Hz or $\Delta t = 0.05$ s, which corresponds to a Nyquist frequency of $f_N = 10$ Hz. Concerning the observation error of a phase pick, the uncertainty intervals can not be smaller than the sampling interval. Therefore, the minimum picking uncertainty is defined as $\pm\Delta t$. To avoid possible inconsistency due to significant different sampling rates, we suggest to use only data with $\Delta f \geq 40$ Hz for local earthquake studies.

Aliasing occurs when the data are sampled, and once this occurs, the data cannot be 'unaliased'. Therefore, seismic data are usually filtered with an analogue anti-aliasing filter to remove frequencies above the Nyquist frequency before sampling. Furthermore, modern acquisition systems make use of oversampling and decimation techniques (*Scherbaum*, 2001). Such systems imply digital anti-alias filters, which often denote symmetrical or acausal impulse responses to avoid time shifting of the phases (zero-phase). As a consequence, the onset of very impulsive signals (also signal with frequency close to Nyquist frequency) may be obscured by 'acausal' precursory oscillations and their true onset becomes hard, if not impossible, to determine. As an example for such precursors,
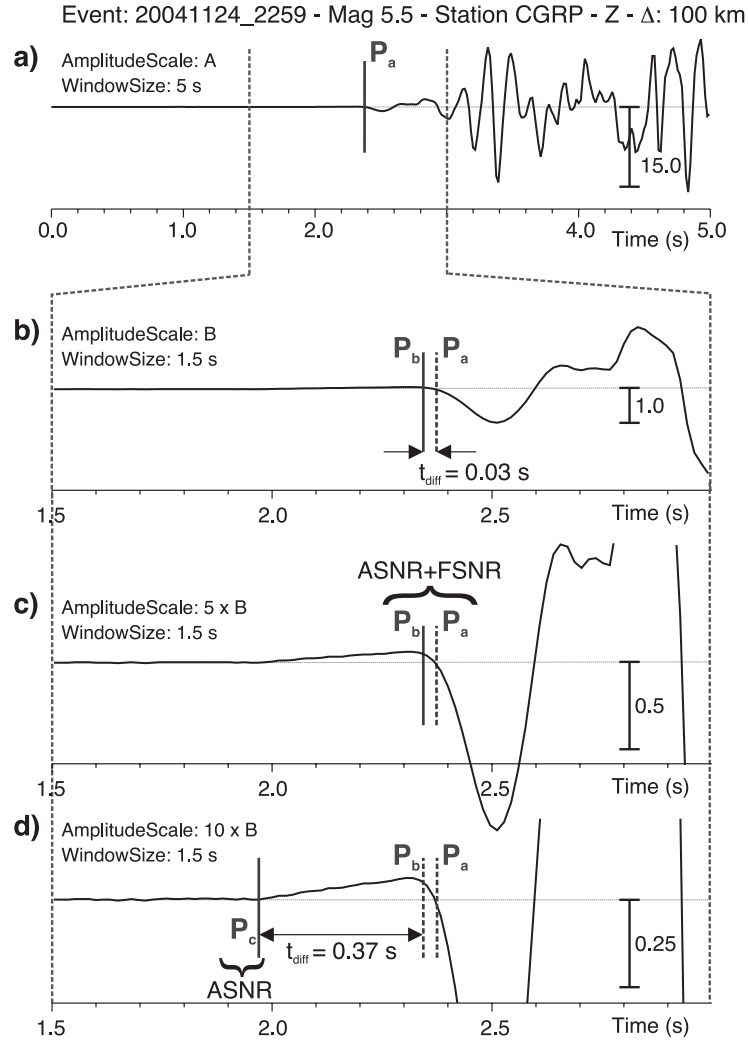
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Figure 6: Different phase picking, caused by variable use of time window size (a, b) and amplitude scaling (c, d).

Figure 7 shows the P-wave recording of a local earthquake near Davos, Switzerland (2006/10/24 13:08, Ml=2.6) at the nearby station DAVOX. In principle, this effect can be minimized by an inverse filtering process, described e.g. in *Scherbaum* (2001). However, this nontrivial procedure requires knowledge of the original anti-alias filter coefficients. Especially for large and inhomogeneous data sets, compiling the correct information can be rather difficult or even impossible. An alternative way to deal with this problem is to apply a consistent error assessment to it, as it is described above. The significance strongly depends on the amplitude scaling as discussed in 2.4 and low-pass filtering or integration of the signal may also help to reduce the amplitudes of such precursors. Since these precursors are present only for very impulsive and high-frequent wavelets, they are expected to be limited to recordings close to the epicentre and/or low sampling rates.
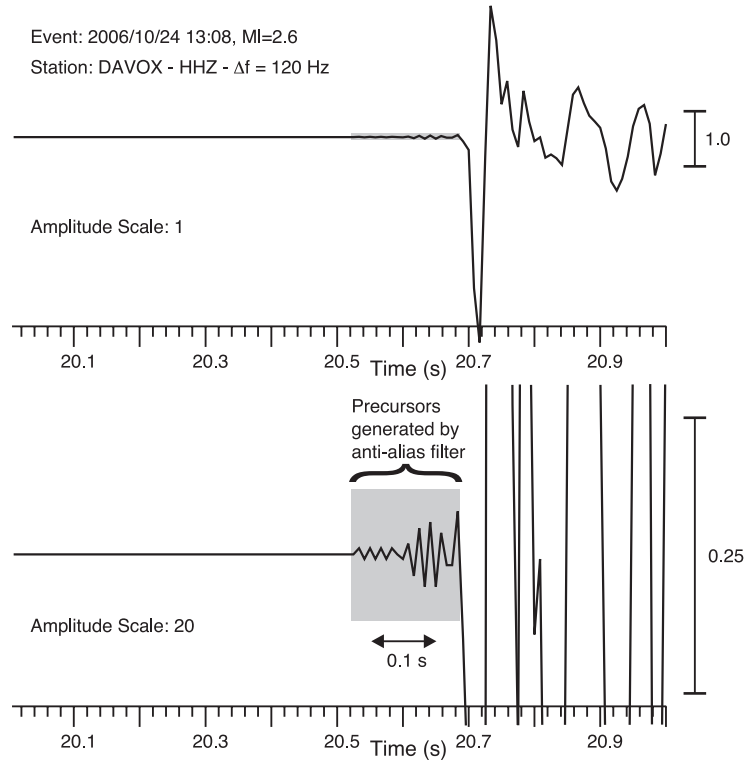
Figure 7: Precursors caused by acausal anti-alias filtering observed at broadband registration of local earthquake near Davos, Switzerland (2006/10/24 13:08, M_l=2.6). Sampling frequency is 120 Hz. The precursors become obvious for enlarged amplitude scale (lower trace).

Filters are usually applied to enhance the signal to noise ratio in the presence of noise. However, filtering can significantly change the shape of a wavelet and may also lead to a phase shift of the signal. Therefore, care has to be taken by applying filters during the picking process. Figure 8 demonstrates the effect of a 2nd order Butterworth high-pass filter (1 Hz) on a short period

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recording. The filter causes a minor change in waveform, but no phase shift is observed. However, the effect on the wavelet can become significant for signals of different frequency content as demonstrated in Figure 9. Position 'a' and 'b' represent two possible arrival picks for each waveform. In the worst case, time difference between those two positions could exceed 0.2 s, a value much larger than the uncertainty of each individual pick. Furthermore, the filter process affects the first motion polarity in this example.
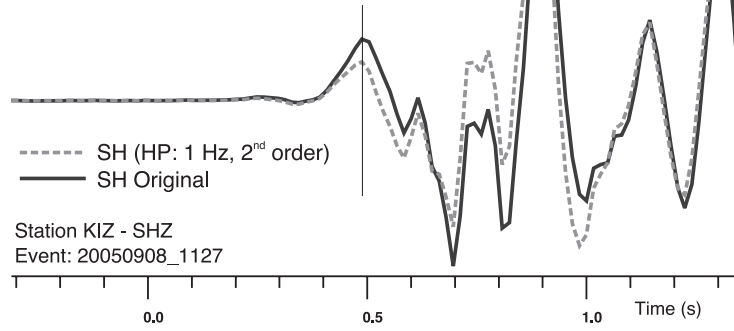
Figure 8: Effect of 2nd order Butterworth high-pass filter (1 Hz) on short period waveform. The filter leads to minor change in waveform, but no phase shift is observed.

2.6 Additional Comments for S-Wave Picking

Most of the previous findings regarding consistent assessment and picking of P-arrivals can also be applied to S-waves. However, picking of S-waves is usually more difficult, since their onset is superposed by the P-wave coda. Furthermore, we have to consider S-wave splitting due to possible seismic anisotropy and the presence of Sp-converted precursors.

Polarization of Wavefield

Figure 10 illustrates the particle motions of P and S-wave in horizontal (a) and vertical (b) planes. The particle motion of the P-wave is parallel or longitudinal to the direction of wave propagation $\vec{k}$. The displacement field of the S-wave is transverse to $\vec{k}$ and can be subdivided into a vertical component (SV) and a horizontal component (SH). The vector $\vec{k}$ can be described in the cartesian ZNE-system of the seismometer (vertical, north-south, east-west) by two angles: the backazimuth (BAZ) and the angle of incidence (i). Both angles can be determined from polarization analysis of a three component recording in a window around the P-wavelet. If station and epicenter coordinates are known, BAZ can also be derived from the orientation of the great-circle including station and epicenter. If focal depth and epicentral distance are known, we can also determine the theoretical angle of incidence in a specified velocity model. Both angles can be used to rotate the ZNE coordinate system into a local ray-system. Within the ray system P, SH, SV components can
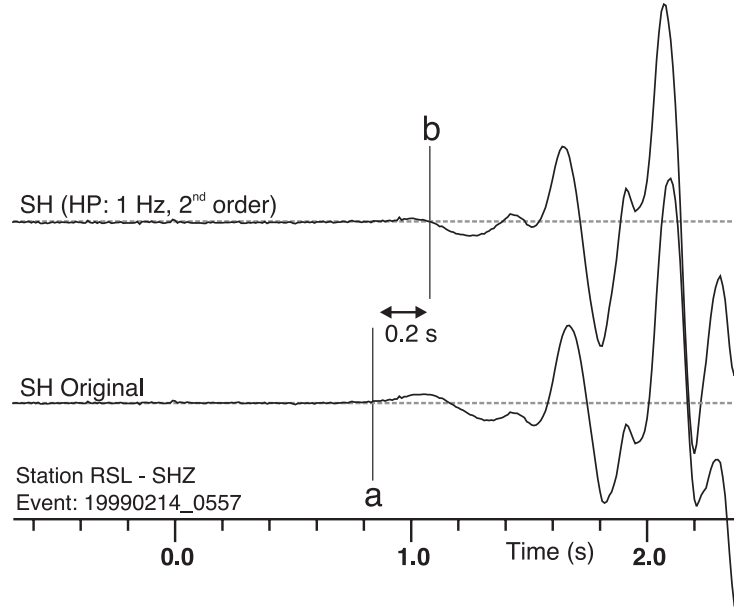
Figure 9: Effect of 2nd order Butterworth high-pass filter (1 Hz) on short period waveform. In this example, the filter leads to a significant change in waveform. The earliest low-frequency onset is only hardly observable on the high-pass filtered trace. Position 'a' and 'b' represent two possible arrival picks for each trace. The time difference between those two positions could exceed 0.2 s.
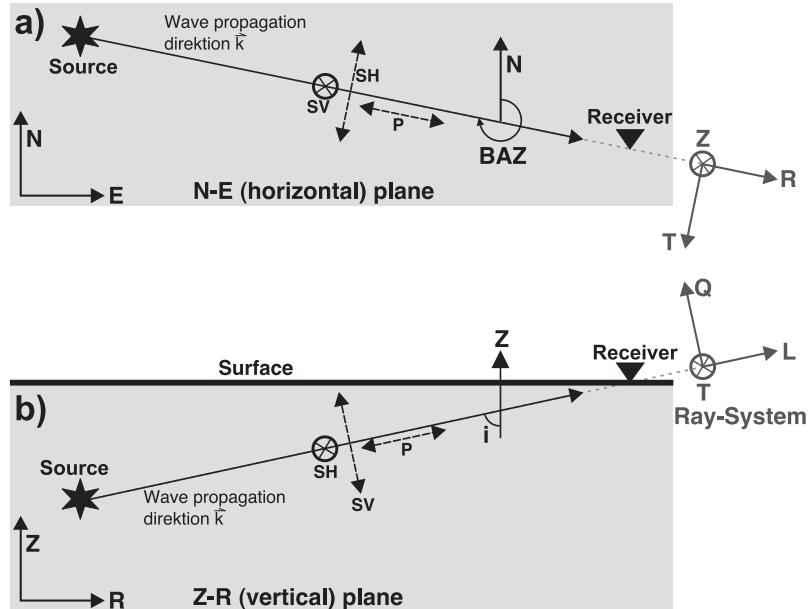
Figure 10: Particle motion for P and S-wave along wave propagation direction. a) Horizontal plane. b) Vertical plane.

be partly separated from each other. The horizontal rotation of ZNE by the backazimuth BAZ results in the ZRT-system as demonstrated in Figure 10a. The T-component denotes the transverse component, R coincidences with the radial component. In the ideal case of a flat layered isotropic medium, the T-component contains only pure SH energy. P- and SV-energy are still mixed on Z and R, depending on the incidence angle i. An additional rotation of ZRT by the incidence angle i results in a decoupled ray-system LQT. The complete P-energy is recorded on the L-component (longitudinal) and the Q-componet contains the SV energy. The T-componet remains the same like in ZRT. Since P and SV waves are coupled, SV energy can partly be converted into P waves by transmission of an interface. If such interface is close to the surface and denotes a strong velocity contrast (e.g. basement-sediment interface), Sp precursors are generated which are very close to the initial S-wave. These Sp precursors can be misinterpreted as the onset of the S-wave. The use of a ray-system can be used to identify such precursors. They are usually not present on the T-component, since there is no coupling between SH and P. However, the ratio between radiated SH and SV energy strongly depends on the focal mechanism and the observation azimuth. To avoid the misinterpretation of Sp precursors we recommend the use of a ray system (ZRT or LQT) and to pick the S-wave preferable on the T-component. Furthermore, the use of a ray-system can be helpful for a better discrimination of S-energy from P-coda and the identification of S-wave splitting.

3   Consistent Hand Picking Procedure

The findings discussed in the previous sections will be combined to a standard procedure for consistent reference P- (and S-)phase picking in the following sections. Especially the consistent choice of time window length and amplitude scaling will be discussed in detail, since it represents one of the major sources for inconsistent picking.

3.1   Consistent Waveform Filtering

As demonstrated in section 2.5, filtering may lead to inconsistent picking. Therefore, we suggest the following procedure for reference picking:

- Be sure, filter does not lead to phase shift of signal. Use e.g. minimum phase filters or 2nd order Butterworth filter.

- Broadband (BB) channels (HH, BH):
  Always apply high-pass filter (corner frequency 1 Hz). It will remove the long period noise often present in BB recordings, and in addition, it will simulate the BB signal approximately towards the characteristic of a short-period sensor. Such simulation minimizes the inconsistency due to different sensor types.

- Short-period (SP) channels (EH, SH):
  Apply 1 Hz high-pass filter only if necessary, e.g. in presence of low-frequency noise. Compare original waveform with filtered one before final picking. Also check, if the filter changes first motion polarity.

- Apply possible low-pass or band-pass filters only if necessary e.g. in presence of high-frequency noise. Compare original waveform with filtered one before final picking.

3.2   Consistent Window Size and Amplitude Scaling

The example in Figure 6 indicates, that there is a strong need for a uniform concept in order to minimize subjectivity in phase picking due to irregular choice of time window size and amplitude scaling. On the other hand, it turns out to be very delicate to define universal rules, especially, if the method should be feasible for picking of large data sets. A consistent choice of time window and amplitude scaling should satisfy two conditions: A fixed time window length and amplitude normalisation with respect to a reference scale. As already mentioned, universal rules for these conditions are difficult to define. Concerning the time window length, the choice depends on the dominant frequency of the signal, but also on the $ASNR$. In the presence of strong noise or in case of a weak and emergent signal, it is often better to use a broader time window to determine the change in frequency and track back the transition from signal

to noise. Likewise, it is not possible to define a universally usable reference phase for amplitude scaling. In addition, many picking tools normalise the amplitude to the maximum amplitude within the selected time window and therefore amplitude scaling depends also from the size and the position of the time window. A possible approach to minimize the inconsistency related to time window choice and amplitude scaling consists of a mixture of iterative selection of window sizes and sliding them stepwise from the noise part towards the signal dominated part. For a further description, we apply this approach to the example shown in Figure 6. A priori, we define four possible time windows used for picking:

High-resolution window (HRW): 2 s $ASNR \geq 3$
Mid-resolution window (MRW): 5 s $2 \leq ASNR < 3$
Low-resolution window (LRW): 10 s $ASNR < 2$
Very-low-resolution window (VRW): 15 s

In the first step we choose a broad overview window, which includes the whole P-, or even parts of S-coda (Fig. 11a). 'P-PRED' denotes the theoretical arrival time predicted in the min. 1D model for an a priori hypocentre (e.g. from catalogue). The predicted arrival time can be useful, however, it is not necessary. We pick the approximate position P_{aprox} of the earliest arrival visible in this window. Based on P_{aprox}, the maximum noise and signal+noise amplitude is estimated. To avoid parts of the signal in the pure noise window, we setup a safety gap of ± 0.5 s around P_{aprox}. We use a length of 3 s for the noise window and 0.5 s for the signal+noise window. We define the noise threshold as ± 1.5 times the absolute noise amplitude within the noise window. In addition, we calculate $ASNR$ from the absolute noise and signal+noise amplitudes.

Depending on the resulting $ASNR$, we choose the appropriate window size. In Figure 11b $ASNR$ is several times larger than 3, therefore we use HRW-size for picking. Between Figure 11b and 11e, the time window is shifted stepwise towards earlier times. The maximum amplitude within each time window is used for amplitude scaling. As long as the upper and lower noise threshold (dashed horizontal lines) are close to each other, the time window can be shifted further to earlier times (here, same effect like enlarging the amplitude scale). Finally, in Figure 11e, the amplitude scaling allows an almost perfect discrimination between noise and the rising signal. In this example, the suggested procedure prevents the missing of the small precursors, but also relates their amplitude to the much stronger amplitude of the following phase.

If we could not clearly distinguish between noise and signal with the actual window size, or if we are not sure whether it is definitely the first arrival (e.g. in the present of strong noise), we repeat the sliding procedure with a larger time window (MRW or LRW). Subsequent, we apply the consistent error assessment as described in section 2.1 to determine t_L, t_E, and t_A. For this purpose, displaying the exact upper and lower noise threshold is very useful for the consistent determination of t_L.
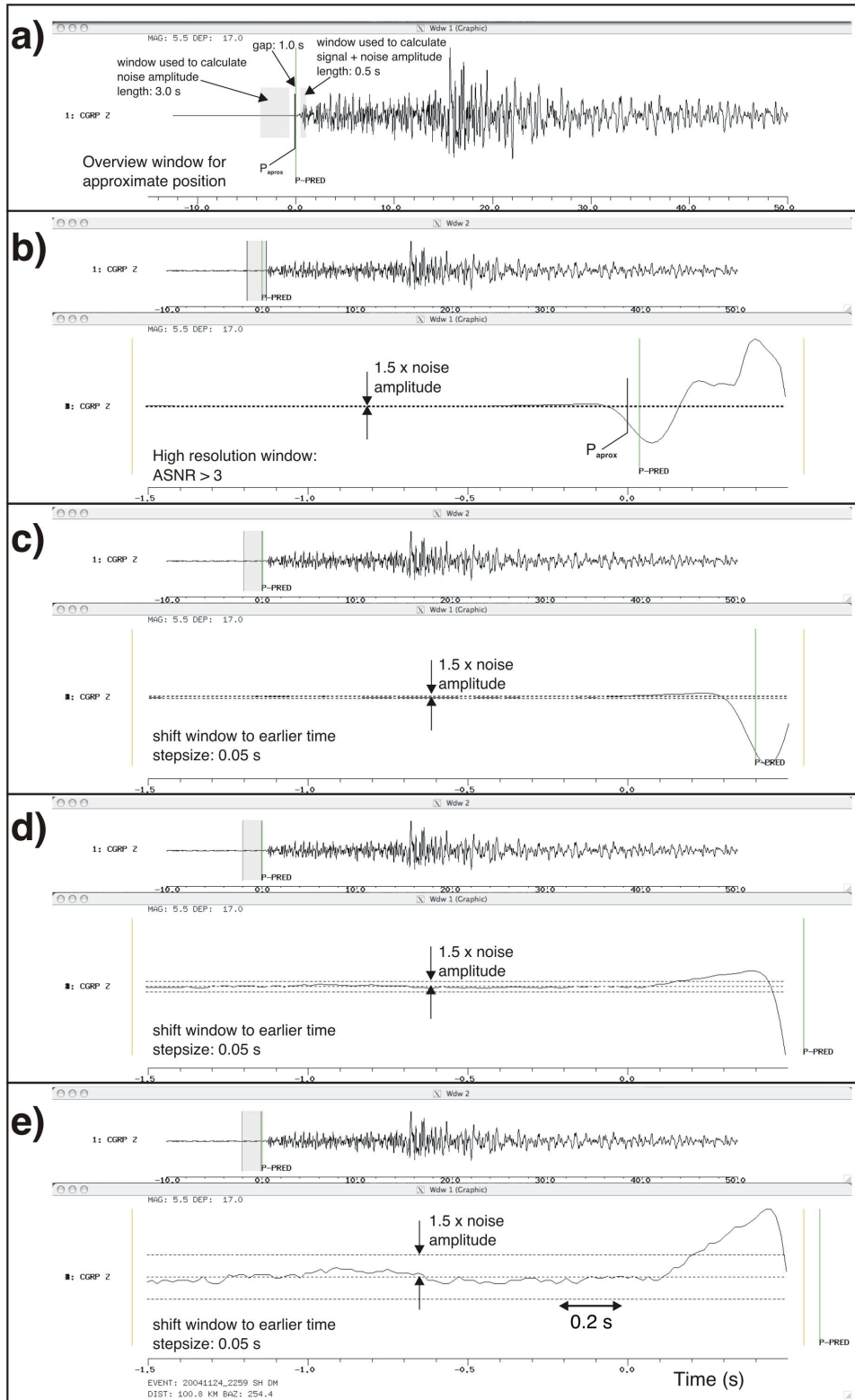
Figure 11: Sliding time window procedure used for consistent phase picking.

3.3 Consistent Phase Identification

Provided that a hypocentre is found, the actual phase identification can be crosschecked against a simplified crustal model afterwards (analogue to Figure 4b). Another helpful tool to minimize inconsistency due to phase misinterpretation is the use of synthetic or predicted arrival times, especially during repicking of data. Assumed a reasonable local or regional velocity model is available and a preliminary hypocenter is present (e.g. from bulletin data), we can calculate synthetic first arrival times for each event-station pair, prior to the picking process. The use of synthetic arrivals provides three major advantages. First, they could guide the picker to the right phase (reliability depending on model quality) and therefore minimize phase misinterpretation. Second, they can be used to arrange the seismograms according to their expected arrival time. Thus, we start the picking at the closest station and do not waste too much time with likely low quality arrivals. In addition, it allows us to track the change in waveform from station to (neighbouring) station. Third, it represents a rough test for correct synchronization of the timing system. In case of obvious timing error of a station, we would observe a large discrepancy between synthetic arrival and actual waveform.

4 Reference Hand Picking Using the Seismic-Handler Package

In order to integrate the steps described in the previous sections into a consistent and guided picking procedure we developed different macros, which can be used in the command line version of the Seismic-Handler (SH) package of *Stammler* (1993). The main focus of this procedure is the compilation of a set of highly consistent picks, which could be used to calibrate automatic phase picking algorithms and to assess their performance. The so-called reference picks have to be provided with attributes for timing, phase identification, and first motion polarity together with an error assessment for each attribute as described in the previous sections. Since these picks will be used as reference for the automatic picking algorithms, we will use all available *a priori* information (such as preliminary hypocenter, station coordinates, corresponding predicted arrival times, etc.) to correctly identify and pick those phases.

In this section we describe briefly the installation of SH package and the installation and usage of SH macros for consistent hand picking. The picking macros described here require the correct installation of the command-line version of the SH-package. Furthermore, it requires some specific setup of the SH environment, including path definitions e.g. for custom SH command-macros (SHC-files) and the definition of custom header values of the binary SH file format (Q-format). At the moment, the file format supported by the picking macros is purely GSE2 and each GSE2 file is expect to contain multiple channels (stations, components) for one event. It is expected that a preliminary

location exists for the event and the coordinates for all stations included in the GSE2 files are known (see section 4.4 for details on formats).

In the next sections the symbol '`$`' indicate commands executed in the bash or korn shell, '`%`' indicate commands executed in the csh or tcsh, and '`sh>`' indicate commands executed in the SH environment. The shell-variable '`$HOME`' points to the home directory of a user. For example, the home directory of a user 'diehl' on a Linux system would be something like `/home/diehl/`.

Setup-files, SHC-macros and external tools are provided in the tar-archive `SH_PickRef.tar`, which can be downloaded from:

`http://www.ldeo.columbia.edu/~tdiehl/software.htm`

Unpack the tar-archive via:

`$ tar xvf SH_PickRef.tar`

The following subdirectories and files should now be present in directory `SH_PickRef/`:

- **README**: README-file explaining the content of files and subdirectories.

- **doc**: Directory, which contains some documentation on the package (e.g. this document).

- **bin**: Directory, which contains all external routines (csh-scripts and Fortran codes).

- **lib**: Directory, which contains an example of a MPX station file 'sed_stations.GSE_SED.alias' (needed to calculate synthetic arrival times, see Table 4 for format description). The MPX station file has to be specified in the csh-script `bin/GSE2calcSynt.csh`. In addition, 'lib' contains an example of an SH station-flie 'STATINF.DAT', which has to be located in the global SH 'input-directory' (described below). See Table 3 for format description.

- **sh**: Directory, which contains all SH command macros necessary for reference picking, startup-files, custom filters and additional custom input+globals files.
  The command-macros are stored in: `sh/command`
  The SH startup file is: `sh/private/SH_USER_STARTUP.SHC`
  The custom filters are stored in: `sh/filts`

- **TauP**: Directory, which contains the *TauP* package (*http://www.seis.sc.edu/software/TauP/index.html*), which is used for calculating synthetic arrival times for first arriving P+S phases.

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- **Testcase_Alps**: Directory, which contains a test case from the Alpine region.

- **Testcase_Greece**: Directory, which contains a test case example from Greece.

- **cshrc**: File, which contains template-entries for a .cshrc file necessary for reference picking.

- **bashrc**: File, which contains template-entries for a .bashrc file.

4.1   Installation & Setup of the SH Package and Picking Macros

The basic steps to install the SH package on UNIX based systems are described in the documentation of the package (*http://www.seismic-handler.org*). Installation of SH requires:

- UNIX system (e.g. Linux, OSX)

- C-compiler (e.g. gcc)

- X11(including libraries)

- f2c (converts Fortran source code to C)

The picking macros require some settings in the SH-startup file loaded immediately after SH is executed. Copy the 'command' and 'globals' directory from `SH_PickRef/sh/` to your local SH directory `$HOME/sh` (for newer SH-versions this might be something like `$HOME/shfiles`):

```
$ cp -r SH_PickRef/sh/command $HOME/sh/
$ cp -r SH_PickRef/sh/globals $HOME/sh/
```

Now copy the filter-files provided in `SH_PickRef/sh/filts` to your global SH filter-directory. Assuming the SH-package on your system is installed in `/usr/local/sh`, copy (Remark: depending on your SH-installation path, this command might require root-permission):

```
$ cp SH_PickRef/sh/filts/*.FLF /usr/local/sh/filter/
```
or something like:
```
$ sudo cp SH_PickRef/sh/filts/*.FLF /usr/local/sh/filter/
```

Now copy the provided SH startup file to your local private directory (backup potential existing startup files first):

```
$ cp SH_PickRef/sh/private/SH_USER_STARTUP.SHC $HOME/sh/private/
```

and adjust corresponding paths in SH-Startup file (items A), B), see comments in startup file). Please note that syntax of paths definitions can defer for different SH versions (again, see comments in provided startup file). Open the startup file with an editor and adjust paths for your system:

```
$ vi $HOME/sh/private/SH_USER_STARTUP.SHC
```

All necessary SH-command files (macros) for picking are now in the local SH-directory `$HOME/sh/command`. The command, which executes the reference picking in the SH environment is `$HOME/sh/command/PICK_REF.SHC` (its use is described in further detail in section 4.3).

To use the SH-utilities you have to add the corresponding path to your C-shell PATH-variable. Assuming the SH-package on your system is installed in /usr/local/sh, add something like the following line to your csh-startup file (`$HOME/.cshrc`):

```
setenv PATH ${PATH}:/usr/local/sh/util
```

Finally, we have to add information about all stations included in the reference data set to the SH-station file. The SH-station file is expected to be in the global SH 'input-directory'. Again, assuming the SH-package on your system is installed in `/usr/local/sh`, the SH-station file is:

```
/usr/local/sh/inputs/STATINF.DAT
```

You have to add your information on stations (including station code, latitude, longitude) to this file or create a new file containing just your stations (recommended e.g. to avoid ambiguous station codes). Be aware that editing or replacing the SH-station file might require root-permission. For a format description of the SH-station file see Table 3.

If you want to use customized frequency bands of the waveform filters instead of the default ones (see 4.3 for default filters) you have to perform the following steps (in this example we discuss a customized band-pass (BP) filter):

- Create a new SH-filter file: Start SH in the csh-environment (`$ csh`, `% SH`) and call SH-command makef (`|sh> makef`). Then follow the menu of the makef-command to create a new BP filter. Alternatively, you can create a 3rd order FFT bandpass (2-15 Hz) with the SH-utility 'butfreq' (the same routine is called by the makef command). If the SH utilities are installed in /usr/local/sh/util, use:

```
/usr/local/sh/util/butfreq bp f 2 15 -o=3 -f=BP_2_15_HZ_O3
```

Either way, you should now find a new SH-filter file in the current directory called e.g. 'BP_2_15_HZ_O3.FLF'.

- Now move this filter file to your global SH-filter directory, in this example:

```
% mv BP_2_15_HZ_O3.FLF /usr/local/sh/filter/
```

(depending on SH-installation path, this command might require root permission).

- In future, the filter definition should be provided in a separate parameter-file, but for the moment the following steps solve the problem:

- Change to your local sh/command directory, something like:

```
% cd $HOME/sh/command/
```

- To change the BandPass (BP) filter definition for P-picking open 'PICK_PHASE_P_ECB.SHC' with an editor. Find the following line: '!Manual selection: BP Filter', should be around line 94. Replace the following BP definition

```
fili f BP_1_30_HZ_O2
```

by the new definition:

```
fili f BP_2_15_HZ_O3
```

(should be around line 96).

- To change the BandPass (BP) filter definition for S-picking open 'PICK_PHASE_S_ECB.SHC' with an editor. Find the following line: '!Manual selection: BP Filter', should be around line 117. Replace the following BP definition

```
fili f BP_1_30_HZ_O2
```

by the new definition:

```
fili f BP_2_15_HZ_O3
```

(should be around line 119).

- Similarly, you can customize the setting for low-pass (LP) and high-pass (HP) filters.

4.2 Installation & Description of External Routines

Installation and use of the external routines requires:

- Fortran77-compiler (e.g. g77, gfortran)

- Java environment (test with `$ java -version`)

4.2.1 Installation and Setup of External Routines (csh, f77)

If not existing, create a local 'bin-directory' and add it to your C-shell PATH-variable. For example:

```
$ mkdir $HOME/bin
```

and add something like the following line to your csh-startup file (`$HOME/.cshrc`):

```
setenv PATH ${PATH}:${HOME}/bin
```

Now copy all C-shell scripts from `SH_PickRef/bin` to your local 'bin-directory':

```
$ cp SH_PickRef/bin/*.csh $HOME/bin
```

The C-shell script 'bin/GSE2calcSynt.csh' requires some setup. It basically controls the calculation of the synthetic arrival times for each event/station pair. The same script is needed to prepare the data for automatic picking with the MPX software (*Aldersons*, 2004). Therefore, it requires information on the stations (coordinates) in the MPX station-format, which is described in more detail in Table 4. Open the script 'bin/GSE2calcSynt.csh' with any editor (vi) and adjust path and name of the MPX station file (defined around line 27). There are further options possible, e.g. which method will be used for calculating the synthetic arrival times (around line 35). You have the choice between routines provided by TauP and NonLinLoc (*Lomax et al.*, 2000). The NonLinLoc option requires a complex setup, therefore we restrict the descriptions to the TauP option. For the TauP option, you just have to adjust the MPX station file as described above.

The C-shell script 'bin/sh2snap.csh' converts the pick file created by the SH-macros (*.MANUPICK.SH, format described in Table 6) to the SED/MPX pick file format (*.MANUPICK, format described in Table 7). At this stage, the quality class is assigned to each pick (based on earliest, latest, and most likely pick and pick-window length). Therefore, the weighting scheme has to be defined in 'bin/sh2snap.csh' (around line 25). Open the script 'bin/sh2snap.csh' with any editor (vi) and adjust the weighting scheme in item A).
The line '#Number of error classes:' indicates the beginning of the weighting

scheme definition. You have to specify the number of weighting classes N followed by upper error intervals ε_i, which define each class i. The error of a pick has to be $\leq \varepsilon_i$ to be accepted for class i. The error interval of the lowermost class (rejected) corresponds to the maximum error interval. Picks with errors larger this value will be rejected (indicated by class $i = N - 1$). The highest quality class corresponds to $i = 0$, the lowest class corresponds to $i = N - 1$ (rejected picks with weight zero).

The line '#Time windows:' indicates the beginning of the window-weighting definition. The window-length used for picking a certain phase might influence the precision of the pick as described earlier. For each of the possible windows-lengths (H, M, L, V) you can provide a defined set of valid quality classes. E.g. for the high-resolution window (H), you might allow all classes (0-4) to be picked. For a low-resolution window (L) only class 1-4 might be picked. If a class 0 was picked in an low-resolution window, the quality will be automatically downgraded to the first valid class specified for this window. If you want to disable this window-weighting just allow all classes for all window-lengths.

Once the SH-picking macro is finished for an event, it will automatically execute the script 'bin/sh2snap.csh' and convert the SH pick-file. If you decide that the used weighting scheme was not appropriate, you can always adjust it in 'bin/sh2snap.csh' and repeat the conversion manually (see section 4.4).

In the next step compile all Fortran codes in `SH_PickRef/bin` and copy the executables to your local 'bin-directory', e.g. by:

```
$ g77 -o $HOME/bin/GSE2prep4synt SH_PickRef/bin/GSE2prep4synt.f
$ g77 -o $HOME/bin/mergePicks SH_PickRef/bin/mergePicks.f
$ g77 -o $HOME/bin/sh2snap SH_PickRef/bin/sh2snap.f
```

4.2.2   Installation of the TauP-Tool

To use the TauP-tools in the C-shell environment, copy the directory `SH_PickRef/TauP` somewhere to your computer (here e.g. to the existing directory `$HOME/programs`):

```
$ cp -r SH_PickRef/TauP $HOME/programs/
```

Finally, you have to include the 'TauP/bin-directory' to your C-shell PATH-variable in `$HOME/.cshrc`, by adding a line like the following:

```
setenv PATH ${PATH}:${HOME}/programs/TauP/bin
```

In the last step you have to include the java class-file 'TauP/taup.jar' to your C-shell CLASSPATH-variable. This can be simple achived by adding the following line in `$HOME/.cshrc`:

```
setenv CLASSPATH ${HOME}/programs/TauP/taup.jar
```

To test if the installation of the TauP-Tool was successful, change to the C-Shell environment and start one of the TauP-routines:

```
$ csh
% taup_time
```

You should now be able to calculate travel times for different distances and focal depths. Quit 'taup_time' by choosing option 'q' in the command line. For further details on the TauP-Tool see:
http://www.seis.sc.edu/software/TauP/index.html

4.3   Using the SH Picking Macros

In this section we will explain the usage of the SH picking macro `$HOME/sh/command/PICK_REF.SHC` and its subroutines with the example provided in directory `SH_PickRef/Testcase_Alps/20070402_0910/`. The picking procedure is roughly divided in 3 stages as illustrated in Figure 12. All three stages are executed and controlled from one single SH-macro (`PICK_REF`). Besides information on stations, the picking macro requires a waveform file in

---

Input per event:
- Waveform data in GSE2 format (so far): <EventID>.GSE2
- Hypocenter summary info in SED/MPX ASCII-format: <EventID>.MANULOC
- Station coordinates (SH and MPX format)

Stage 1: done by external routines (csh, fortran, etc.)
- Based on preliminary hypocenter + stations coordinates calculate epicentral distance for each seismogram and prepare for synthetic travel-time calculation
- Calculate predicted arrival times for P+S first arrivals:
  - using taup-package (standard earth model)
  - using NonLinLoc routines (min. 1D model or 3D model), not described at the moment.
- Sort stations according to predicted arrival time and establish pick file for picking process.

Stage 2: Pick loop over stations
- Pick first and later arriving P phases (on Z-component)
- Pick first and later arriving S phases (if ZNE are available)

Stage 3: Reformatting Pick file to SED/MPX format
- Convert SH-pick file and translate error interval in quality classes (0-X)

Figure 12: Overview over the SH-reference picking procedure. All stages are executed and controlled with SH-macro PICK_REF.

GSE2 format and a preliminary location (for details on formats see section 4.4) similar to the examples provided in our test-case. The following tables describe an example for a picking session, Figure 13 summarizes the flow chart of the picking-loop.

Description/Question (**Q:**)	Comand/Answer
Change to test-case directory, which contains GSE2-file and location-file	`$ cd SH_PickRef/Testcase_Alps/20070402_0910/`
Change to C-shell environment (SH works only in csh)	`$ csh`
Start SH command line version (in directory with GSE2 file and location-file)	`% SH`
Start the SH reference picking-macro	`|sh> PICK_REF`

General Parameters for Picking:	
Q: Event-ID of event to pick? expect waveform file as `<Event-ID>.GSE2` hypocenter summary as `<Event-ID>.MANULOC`	`20070402_0910`
Q: Overwrite existing picks? Y = new phase-file N = append to existing phase-file (default)	`Y`
Q: Pickmode? PS = pick P+S (default) PS3C= special for S-picking on 3 component (not in use at present)	`PS`
Q: Input format? GSE2 or Q-file (SH binary format) Use GSE2 for first call of this event	`GSE2`

The Pick Loop:

Q: Filter -AUTO (Default): Depending on channel ID HH/BH → HP EH/SH → DM -HP: High-Pass (default: 1 Hz, 2nd order) -BP: Band-pass (default: 1 - 30 Hz, 2nd order) -LP: Low-Pass (default: 30 Hz, 2nd order) -DM: Remove mean (demean) -NO: No filter -DS: Despike + Demean -WA: Wood-Anderson (only in S-loop) -IN: Integration of trace (only in S-loop) See comments in section 4.1 on how to customize filter settings	`AUTO`
Q: Pick P-wave? -Y: Yes (default) -N: No (skip seismogram) -R: Repeat P-pick loop for this station -Q: Quit picking (save all picks and close session)	`Y`
Q: Pick approximate position of first arrival to setup window for S/N ratio determination	Pick in window
Q: Chose pick-window length? -AUTO (default): Length depending on S/N S/N ≥ 3.0 → length = H 2.0 ≤ S/N < 3.0 → length = M S/N < 2.0 → length = L -H: High-resolution (2 s) -M: Medium-resolution (5 s) -L: Low-resolution (10 s) -V: Very low resolution (15 s)	`AUTO`
Q: Shift window left/right or pick LATEST possible arrival	Click left or right of golden vertical line to shift window or click on seismogram to pick latest possible arrival.
Q: Pick EARLIEST possible arrival	Click on seismogram to pick earliest possible arrival (click right of latest-possible to revise latest possible).
Q: Pick MOST-LIKELY arrival	Click on seismogram to pick most likely arrival (most likely has to be located between earliest & latest, otherwise latest and earliest will be revised).
Q: Accept pick or revise it?	Click right of latest to accept pick, click left of earliest to revise it.
Q: Assign phase type (phase identification) considering epicentral distance, focal depth and Moho topography. See Table 1 for description of possible labels	`Pg`
Q: Assign polarity of first motion considering position of most likely pick. See Table 2 for description of possible labels	`D`
Q: Screen-shot of pick-window? Y: Screen-shot saved to /sh/shscratch/SH_HC???.ps N: No screen-shot (default)	`N`

Q: Use pick?   Y
-Y (default): Flag pick as used for 1st arrival time
studies.
-N: Do not use pick as used for 1st arrival time
studies (rejected class)
-R: Repeat P-pick loop for station (revise)
-L: Pick is later phase such as PmP (pick is not con-
sidered for 1st arrival time studies)

Q: Further Later phases to pick?   N
Y=Pick further later phases such as PmP if present
N=Pick S (if station is three-component station ZNE)
or next station

Remark 01: After accepting/rejecting a pick, the corresponding information is immediately written
to the SH-phase file (in our example `20070402_0910.MANUPICK.SH`). If you choose the append option,
you have to pick only stations, which are not yet included in the existing MANUPICK.SH file.

Remark 02: If you want to revise a pick of a certain station after having accepted it, simply quit the
pick-loop and open the corresponding SH-phase file (in our example `20070402_0910.MANUPICK.SH`)
with an editor (vi) and delete all pick-lines (P+S+later phases) associated with this station. Then,
start `|sh> PICK_REF` again for the same event-ID and choose the 'append to existing phase file' option.
The first station to pick in the new session should be the deleted station. This procedure can also
be used if the picking macro has crashed for some reason. In the worst case you loose the 'last' pick.
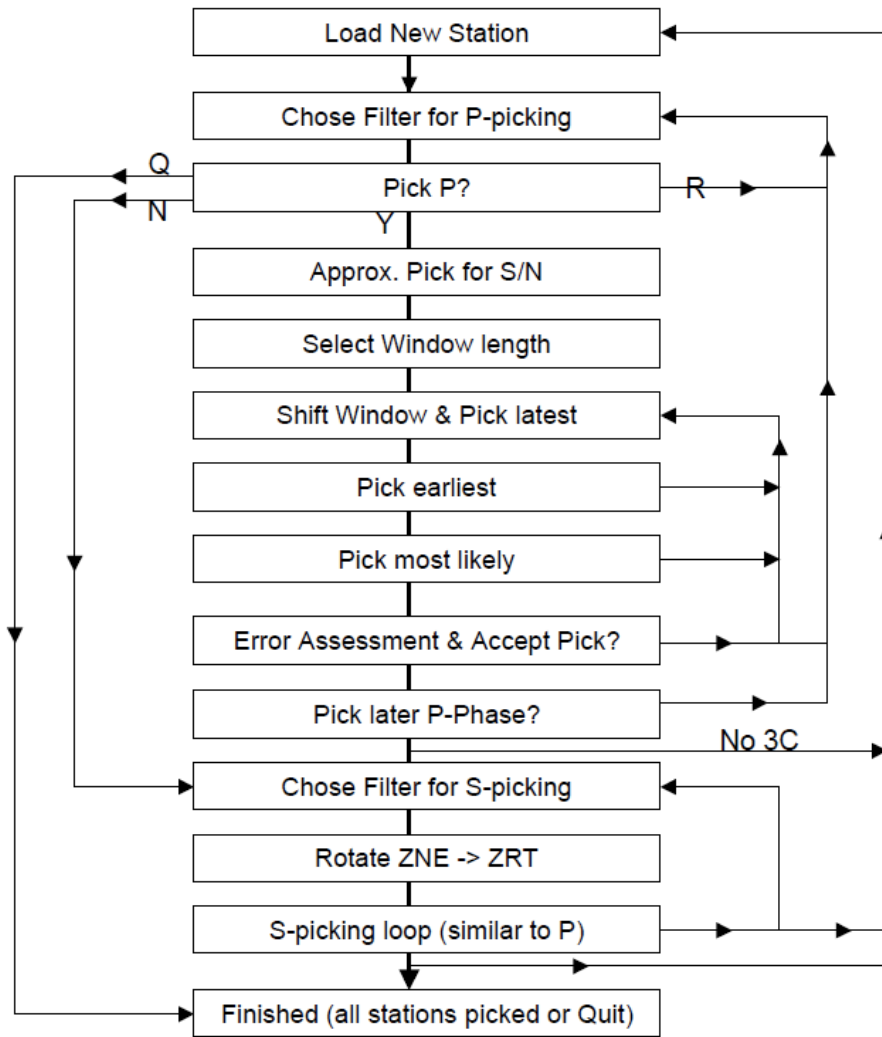
Figure 13: Flowchart of the SH pick-loop.

4.4   Format of Input/Output Files

INPUT: As discussed earlier, the picking procedure requires some input files. Information on stations have to be provided in two files:

- SH-station file, format described in Table 3.

- MPX-station file (specified and used in 'bin/GSE2calcSynt.csh'), format described in Table 4.

The SH-macros require:

- Waveform file in GSE2 format (all stations and channels in one single file, 'WID2 '-line indicates start of new trace, 'CHK2 '-line indicates end of trace). See GSE2 manual for further details. File name convention for GSE2-files: `<EVENT_ID>.GSE2`, where `<EVENT_ID>` is expected to be of the following form:
  `YYYYMMDD_HHmm`, where YYYY: Year of approx. origin time, MM: Month of approx. origin time, DD: Day of approx. origin time, HH: Hour of approx. origin time, mm: Minute of approx. origin time. Approximate origin time is not used and can also be replaced by any running number of format `XXXXXXXX_XXXX` (e.g. 00000000_0001).

- Location file in the summary-card format of the Swiss Seismological Service (SED), which is also used for MPX.
  File name convention: `<EVENT_ID>.MANULOC`, where `<EVENT_ID>` is expected to be identical with the corresponding Waveform ID (see comments above). See Table 5 for format of location summary line.

OUTPUT: The SH picking-macro basically produces an ASCII file containing all informations associated with each reference pick for each station:

`<EVENT_ID>.MANUPICK.SH`

The format is described in detail in Table 6. This phase file is converted into the SED/MPX ASCII phase-file format via

`$ sh2snap.csh <EVENT_ID>.MANUPICK.SH <EVENT_ID>.MANUPICK`

As described previously, the error intervals of each pick will be associated with an discrete quality class (according to the weighting scheme specified in `sh2snap.csh`) in this step. The resulting SED/MPX file is

`<EVENT_ID>.MANUPICK`

A detailed description of the SED/MPX *.MANUPICK file can be found in Table 7.

```
BFO lat:48.33010 lon:8.32960 name:GRSN
```

Column	Format	Description	In Example
1	free	Original station code as provided in waveform file	BFO
2	free	Latitude: indicated by preceding identifier 'lat:' followed by latitude (you can also insert blank between identifier and latitude-value).	lat:48.33010
3	free	Longitude: indicated by preceding identifier 'lon:' followed by longitude (you can also insert blank between identifier and longitude-value).	lon:8.32960
4	free	Network Name: indicated by preceding identifier 'name:' followed by network (and any comment), again, you can insert blanks.	name:GRSN

Table 3: **INPUT.** Example (uppermost line) and format description of the SH station-file line (STATINF.DAT). See SeismicHandler documentation for further description.

```
ALTMA__=_ALTM__-48.9952-111.5199_-0.430____BED-------_-12.370_-10.000
```

Position	Format	Description	In Example
01-05	a5	Original station code as provided in waveform file (upto 5 characters)	ALTMA
06-07	2x	2 x Blank	
08-08	a1	'='	=
09-09	1x	1 x Blank	
10-13	a4	Velest station alias code (4 character)	ALTM
14-15	2x	2 x Blank	
16-23	f8.4	Latitude	-48.9952
24-32	f9.4	Longitude	-111.5199
33-33	1x	1 x Blank	
34-39	f6.3	Elevation in km	-0.430
40-44	5x	Optional: 5 x Blank	
45-53	a9	Optional: Network Name	BED——
54-54	1x	Optional: 1 x Blank	
55-61	f7.3	Optional: Station-Correction P	-12.370
62-62	1x	Optional: 1 x Blank	
63-69	7.3	Optional: Station-Correction S	-10.000

Table 4: **INPUT.** Example (uppermost line) and format description of the MPX station-file line. In the example, blanks are represented by '_'. Format describers correspond to Fortran convention.

```
20070402091033445778N008303E02527Ml00000000000000000000SEDE000000000000_____SED_CLF
```

Position	Format	Description	In Example
01-12	i4.4,4(i2.2)	Origin time: YYYYMMDDHHmm	200704020910
13-14	i2.2	Origin time: INT(SS)	33
15-15	i1.1	Origin time: INT((SS-Int(SS))*10)	4
16-17	i2.2	Latitude: INT(lat)	44
18-20	i3.3	Latitude: INT((lat-Int(lat))*1000)	778
21-21	a1	Latitude: Hemisphere (N or S)	N
22-24	i3.3	Longitude: INT(lon)	008
25-27	i3.3	Longitude: INT((lon-Int(lon))*1000)	303
28-28	a1	Longitude: Hemisphere (E or W)	E
29-31	i3.3	Focal Depth: INT(depth)	025
32-33	i2.2	Magnitude: INT(magnitude*10)	27
34-35	a2	Magnitude Type: Ml (local magnitude)	Ml
36-54	i19.19	SED specific fields, unused here: fill with zeros	0000000000000000000
55-57	a3	SED location line identifier, always 'SED'	SED
58-58	a1	SED Location method, here 'E'	E
59-81	i12.12	SED specific fields, unused here: fill with zeros	000000000000
≥ 82	a	Optional comment: source of location (catalog)	SED_CLF

Table 5: INPUT. Example (uppermost line) and format description of the SED/MPX location summary line (*.MANULOC). In the example, blanks are represented by '_'. Format describers correspond to Fortran convention. Origin time description: YYYY = Year, MM = Month, DD = Day, HH = Hour, mm = Minute, SS = Second. 'INT(X)' = Integer part of value X.

```
PG U Y N 21-JUN-2004_23:09:00.000 6.719000e+01 -1.400000e-02 1.600000e-02 \\
      H H Z 20040621_2310 H 8.333000e-03 BALST
```

Column	Format	Description	In Example
1	free	Phase type (e.g. PG, PN, PM, P1, P?, P2), PG: Pg, PN: Pn, PM: PmP, P?: uncertain if first arrival, etc.	PG
2	free	First-motion polarity (U/D/+/-/N)	U
3	free	Use Pick? (Y/N/L/Q) Y: Yes, N: No, L: is Later phase, Q: Quit pick loop (line will be ignored)	Y
4	free	Further later phases to pick? (Y,N)	N
5	SH-date	Reference date	21-JUN-2004_23:09:00.000
6	free	position of most likely pick (seconds with respect to reference date)	6.719000e+01
7	free	position of earliest possible (seconds with respect to most likely position)	-1.400000e-02
8	free	position of latest possible (seconds with respect to most likely position)	1.600000e-02
9	free	1st character of channel identifier of seismogram: Band (e.g. H, B, E, S)	H
10	free	2nd character of channel identifier of seismogram: Gain (e.g. H, L)	H
11	free	3nd character of channel identifier of seismogram: Component (e.g. Z, N, E)	Z
12	free	Event ID	20040621_2310
13	free	Window-length used (H, M, L, V)	H
14	free	Sampling interval (seconds)	8.333000e-03
15	free	Station code	BALST

Table 6: OUTPUT. Example (uppermost line) and format description of the SH pick-file line (*.MANUPICK.SH).

```
Hdr Line 1      _1_1____0.00___0.00__1.710_1_____INST
Hdr Line 2      __0.000____0.000__0.00_0000_00_00_00_00__0.00_0___TRIAL
Hdr Line 3      sh-pick_____AUTOR
Hdr Line 4      2004/06/21_23:09_____Loca
Pick Lines      BALST___Pg_____IU__67.190_1_0.00_____0_XXX_____0_Pick_HHZ__0.000__-0.014__0.016_0
Indicates       _____SKIP
end of pick
lines
```

Format of Hdr Line 4:

Position	Format	Description	In Example
01-04	i4.4	Reference date: Year	2004
05-05	a1	slash	/
06-07	i2.2	Reference date: Month	06
08-08	a1	slash	/
09-10	i2.2	Reference date: Day	21
11-11	1x	1 x blank	
12-13	i2.2	Reference date: Hour	23
14-14	a1	colon	:
15-16	i2.2	Reference date: Minute	09
55-58	a	Event type (Loca: local earthquake)	Loca

Format of Pick Line:

Position	Format	Description	In Example
01-07	a7	Station code	BALST
08-08	1x	1 x blank	
09-15	a7	Phase type	Pg
16-16	1x	1 x blank	
17-17	a1	Waveform characteristic (I=Impulsive, E=Emergent), here derived from quality class.	I
18-18	a1	First-motion polarity	U
19-19	1x	1 x blank	
20-26	f7.3	position of most likely pick (seconds with respect to reference date)	67.190
27-27	1x	1 x blank	
28-28	i1.1	Use Pick? 1: Yes, 0: No (uncertain or later phase)	1
29-29	1x	1 x blank	
30-33	f4.2	SED specific fields, unused here	0.00
34-34	1x	1 x blank	
35-42	i8	SED specific fields, unused here	0
43-43	1x	1 x blank	
44-52	a9	SED specific fields, unused here	XXX
53-53	1x	1 x blank	
54-54	i1.1	SED specific fields, unused here	0
55-55	1x	1 x blank	
56-59	a4	Pick identifier, always 'Pick'	Pick
60-60	1x	1 x blank	
61-63	a3	Channel ID	HHZ
64-64	1x	1 x blank	
65-71	f7.3	SED specific fields, unused here	0.000
72-72	1x	1 x blank	
73-79	f7.3	position of earliest possible (seconds with respect to most likely position)	-0.014
80-80	1x	1 x blank	
81-87	f7.3	position of latest possible (seconds with respect to most likely position)	0.016
88-88	1x	1 x blank	
89-89	i1.1	Quality class (0 to $N-1$) based on error interval	0

End of Pick Line Indicator:

Position	Format	Description	In Example
55-58	a4	Indicates end of pick lines, always 'SKIP'	SKIP

Table 7: OUTPUT. Example (uppermost line) and format description of the SED/MPX phase file (*.MANUPICK). In the example, blanks are represented by '_'. Format describers correspond to Fortran convention. Header lines 1 to 3 are dummy lines used by SED. *.MANUPICK files are converted from *.MANUPICK.SH files via `sh2snap.csh`.

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