Automatic P- and S-Phase Picker for High-Resolution Local Source Tomography: Application to the Alpine Region

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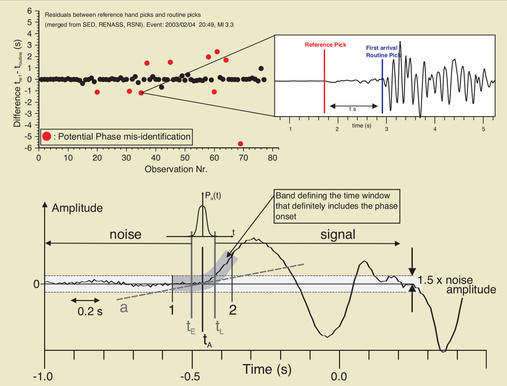
Introduction

Resolution and reliability of tomographic velocity models strongly depend on quality and consistency of available travel-time data. Arrival times routinely picked by network analysts on a day-to-day basis often yield a high level of noise due to mispicks and other inconsistencies, particularly in error assessment.

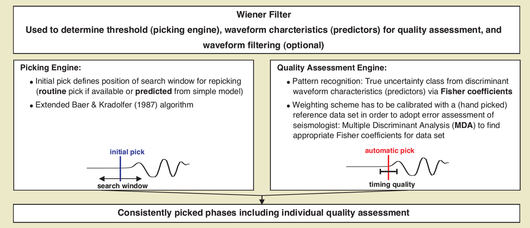
Considerable improvement in the quality of phase data can only be achieved by massive re-picking of seismograms in combination with consistent error assessment of timing and identification of picked phases. Considering the amount of data necessary for regional high-resolution tomography, algorithms combining accurate picking with an automated error assessment represent the best tool to derive large suitable sets of absolute arrival times.



Top: Example of phase misidentification in routine phase data. **Bottom:** Probabilistic phase picking approach, including consistent assessment of uncertainty of phase timing.

Automatic P-Phase Picker: MannekenPix

Basic Concept



Top: Basic principle of the MannekenPix (MPX) algorithm of Aldersons (2004). It combines a single picking engine (Baer-Kradolfer picker) with an automatic quality assessment (via pattern recognition). Automatic picking and quality assessment have to be calibrated with a set of manually picked arrival-times (reference picks/data).

Left: MPX flow-chart. In the first step MPX has to be calibrated and tested with the reference data. On the production mode, the calibrated MPX is applied to the complete waveform data set.

1. Step: Calibration Procedure
=> **Reference Data Set:** consistent manually picked for representative subset of waveform data set
=> Adopt automatic picking and quality assessment to reference data (via MDA)

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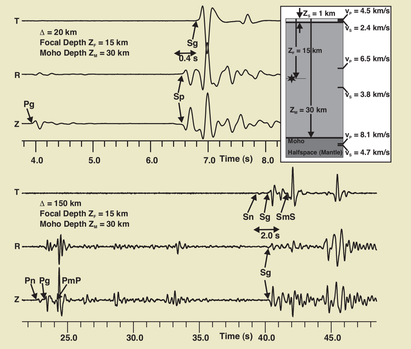
2. Step: Production Procedure
=> Initial picks necessary for all seismograms
=> Apply calibration scheme to complete waveform data set

Automatic S-Phase Picker: Combined Approach

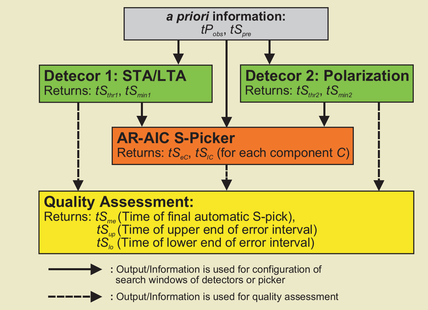
Basic Concept



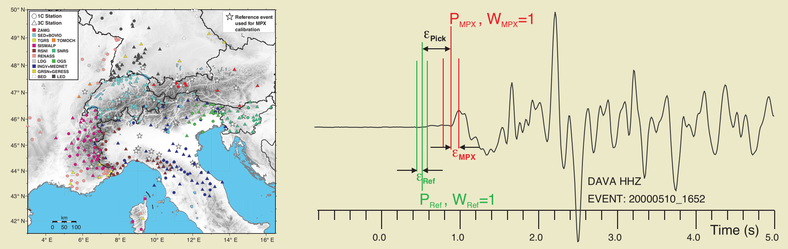
Left: Reflectivity seismograms for an earthquake observed at two different epicentral distances. At very local distances Pg and Sg phases arrive within few seconds. A sedimentary layer close to the surface can generate Sp precursors. At larger distances, Sn is expected to be first arriving S-phase. Compared to later arriving Sg and SmS phases, Sn is usually weak in amplitude and therefore often missed.

Approaches for automatic S-phase picking have to include reliable phase-identification techniques. Due to the character of the later arriving S-wave, single component algorithms like the Baer-Kradolfer picker are not sufficient. Reliable S-picking can only be achived by the use of three-component recordings and the combination of different picking techniques.

Right: Flow-chart of the proposed S-phase picking algorithm. A STA/LTA and a polarization detector are used to identify the first arriving S-phase. Information from the detectors is used to setup search windows of an autoregressive-AIC (AR-AIC) picker. Information from detectors and picker are used to derive final S-pick and its "in-situ" uncertainty in an automatic quality assessment. The picker is calibrated and tested with a set of manually picked S-phases, using a parameter search procedure.

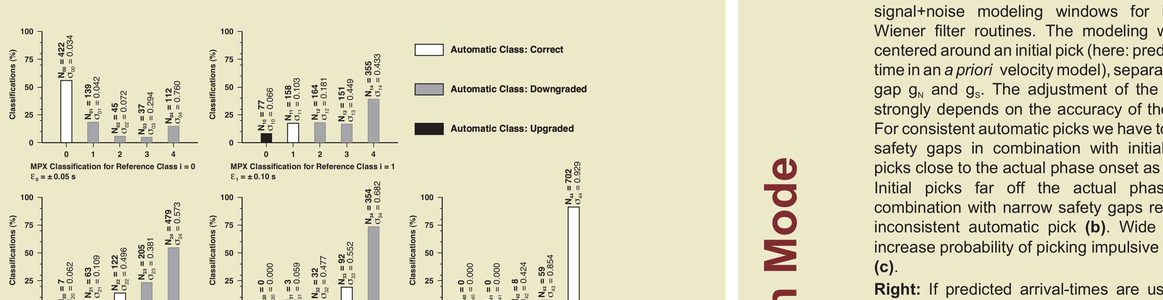


Calibration of Automatic Weighting Procedure



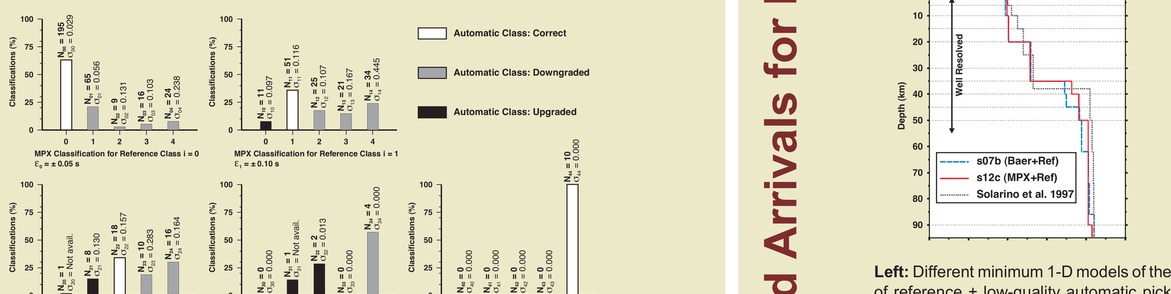
Left: Stations (circles, triangles) in the greater Alpine region used in this study. Colors indicate the corresponding network affiliation. Additional white stars indicate locations of events used for reference picking and subsequent calibration of MPX.

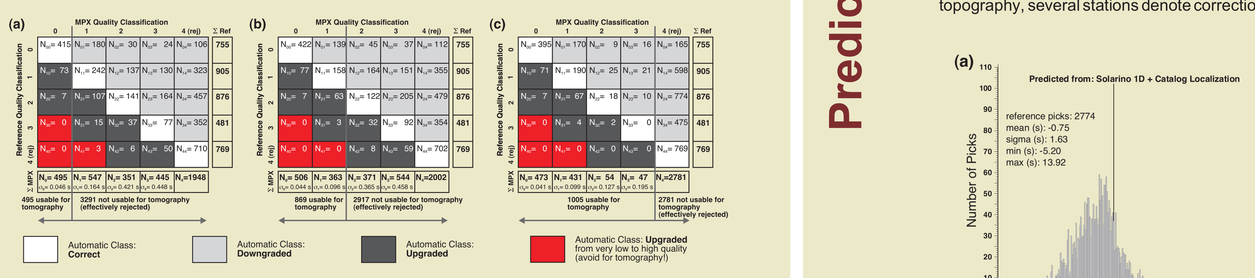
Right: The assessment of automatic picks requires the comparison of picked arrival times and corresponding quality classification with reference picks. In the ideal case, the difference in arrival time between reference and automatic pick (ε_{Pick}) should be included in the uncertainty interval of the automatic classification ($\varepsilon_{Pick} < \varepsilon_{MPX}$). In addition, the automatic quality classification should be similar to the reference data for the majority of picks. Although downgrading of picks by the automatic picker is tolerated, upgrading from lowest to highest quality classes is unacceptable for tomography. To assess the picking performance for a certain calibration scheme, corresponding automatic picks have to be compared to the complete set of reference picks using a bar or matrix representation as shown below.



Above: Performance of MPX for a weighting scheme derived from reference events greater or equal M_L 4.0. The N_i denote the number of picks of reference class i classified by MPX as automatic class j. The σ_i represent the standard deviation for differences between reference picks of class i and corresponding automatic picks of class j. The automatic weighting classifies more than 55% of the class '0' picks correctly. For classes greater or equal 1 MPX downgrades a large number of picks to lower or lowest classes. Within this weighting scheme, only automatic picks of class 0 and 1 can be used for tomography.

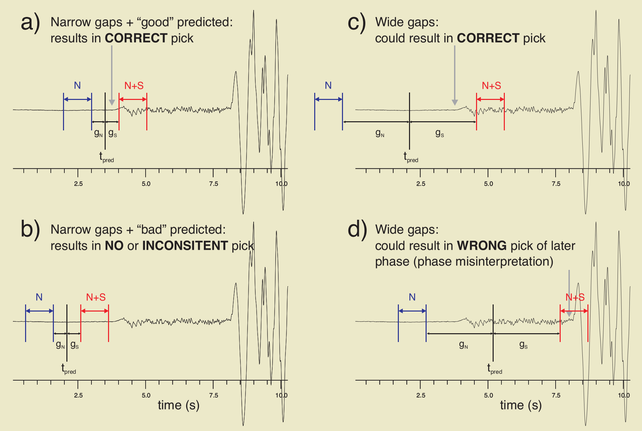
Below: Performance of MPX for epicentral distances < 100 km (predominantly Pg phases). The used weighting scheme is derived from reference picks with Δ < 100 km. Automatic picks of class 0, 1, 2, 3 can be used.





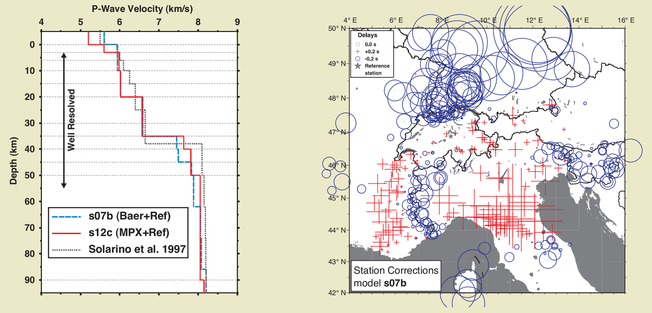
Performance of MPX for three different calibration schemes using a matrix representation. **(a)** Similar to Di Stefano et al. (2006), all reference picks are used for the MDA. For our data set, only automatic picks of class 0 satisfy the requirements for use in tomography. **(b)** Only waveforms of events greater or equal M_L 4.0 are used for the MDA. Automatic picks of class 0 and 1 can be used for tomography. **(c)** Distance-dependant calibration as used in this work. Automatic picks of class 0-2 and, in this case, also class 3 (downgraded picks of class 0-2) can be used for tomography.

Predicted Arrivals for Production Mode



Top: MPX uses a static setup for noise and signal+noise modeling windows for its adaptive Wiener filter routines. The modeling windows are centered around an initial pick (here: predicted arrival-time in an *a priori* velocity model), separated by safety gap (g_1 and g_2). The adjustment of the safety gaps strongly depends on the accuracy of the initial pick: For consistent automatic picks we have to use narrow safety gaps in combination with initial (predicted) picks close to the actual phase onset as shown in **a)**. Initial picks far off the actual phase onset in combination with narrow safety gaps result in no or inconsistent automatic pick (**b)**. Wide safety gaps increase probability of picking impulsive later phases (**c)**.

Right: If predicted arrival-times are used as initial picks, appropriate velocity models (preferable minimum 1-D model) and hypocenters have to be used for forward calculations. Both, velocity model and appropriate hypocenters can be obtained by iterative application of automatic picking, 1-D travel-time inversion, and hypocenter relocation as shown in the rightward flow-chart.



Left: Different minimum 1-D models of the Alpine region. Model s07b was derived from inversion of reference + low-quality automatic picks and is used to calculate predicted arrival-times for MPX. Model s12c was derived from inversion of high-quality automatic (MPX) + reference picks.
Right: Station corrections corresponding to model s07b. Due to site-effects and Moho topography, several stations denote corrections up to several seconds.

A priori information:
Velocity model (e.g. literature)
Initial hypocenters (from catalogue/bulletin)

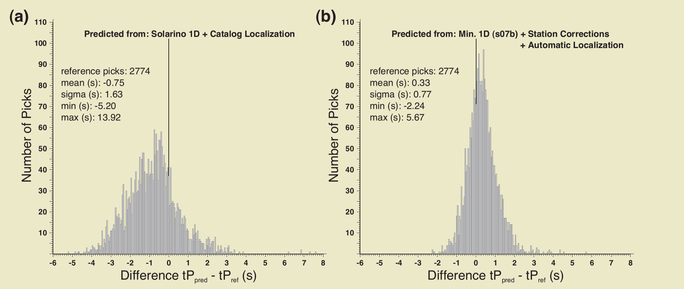
1. Use reference picks (or available routine picks) to update a priori model by minimum 1-D inversion: M1D01 (1D velocity+statcor?)

2. Original Baer-Kradolfer picker (without any quality assessment) applied to associated waveforms. Relocate all events in M1D01 using low quality automatic picks. Remove obvious outliers (residual cut-off), relocate filtered data, extract high-quality events (RMS, Nobs, gap).

3. Merge reference picks with selected low quality auto-picks. Down-weight auto-picks with respect to reference picks. Invert combined data set for new minimum 1-D model using M1D01 and catalogue locations as initial values.
New model: M1D02 (1D velocity+statcor)

4. Relocate all events in M1D02 using low quality automatic picks from 2.. Remove obvious outliers (residual cut-off), relocate filtered data, extract well-locatable events (Nobs, gap).

Use selected events from 4. for repicking with MPX. Use hypocenters from 4. and model M1D02 (1D velocity+statcor) to calculate predicted arrival times for each seismogram.

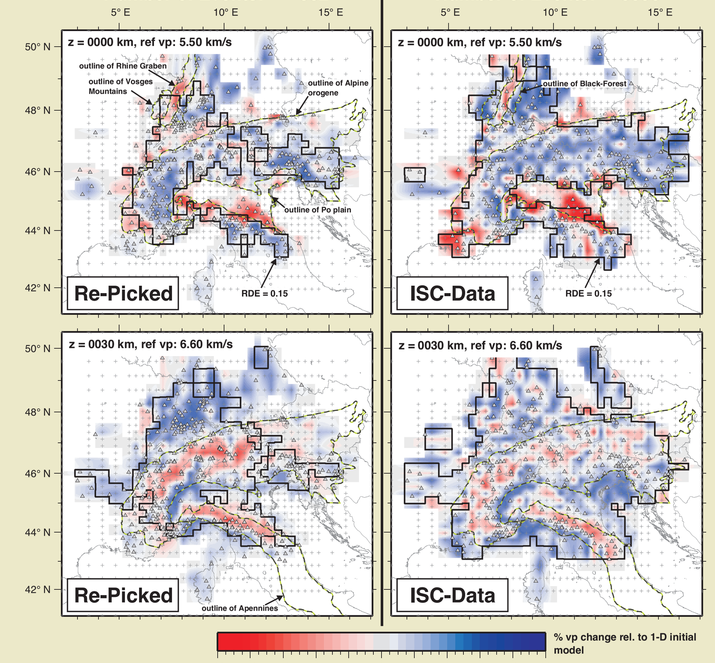


Improvement in accuracy of predicted arrival-times using appropriate minimum 1-D model + relocated hypocenters. **(a)** difference between predicted and reference picks using a standard model + catalogue locations. **(b)** using minimum 1-D model + relocated hypocenters.

Local Source P-wave Tomography with Highly Consistent Data Set

Re-Picked Data Set
Number of Phases: 13,309
Number of Events: 552

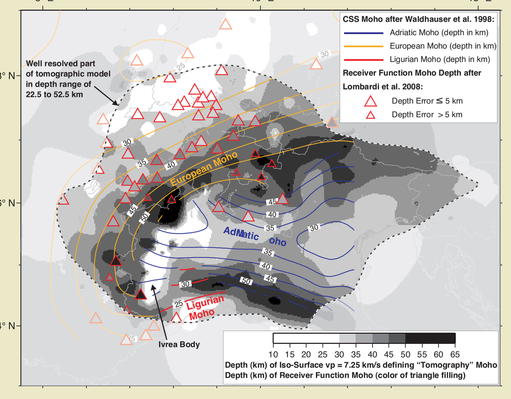
ISC Data Set
Number of Phases: 94,968
Number of Events: 3393



Top: Comparison of tomographic images based on high-quality re-picked phase data (left column) and standard routine phase picks extracted from the ISC data base (right column) at 0 and 30 km depth. The v_p velocity structure of the Alpine region is shown as percentage change relative to the 1-D initial model s12c (same for re-picked and ISC).

Note how the tomographic image of 30 km depth obtained from re-picked phase data is much more reliable in the well-resolved region - showing much fewer single cell anomalies of checkerboard type - while for shallow depth, the performance of the two data sets is virtually the same with the larger ISC data set resolving a significantly larger region.

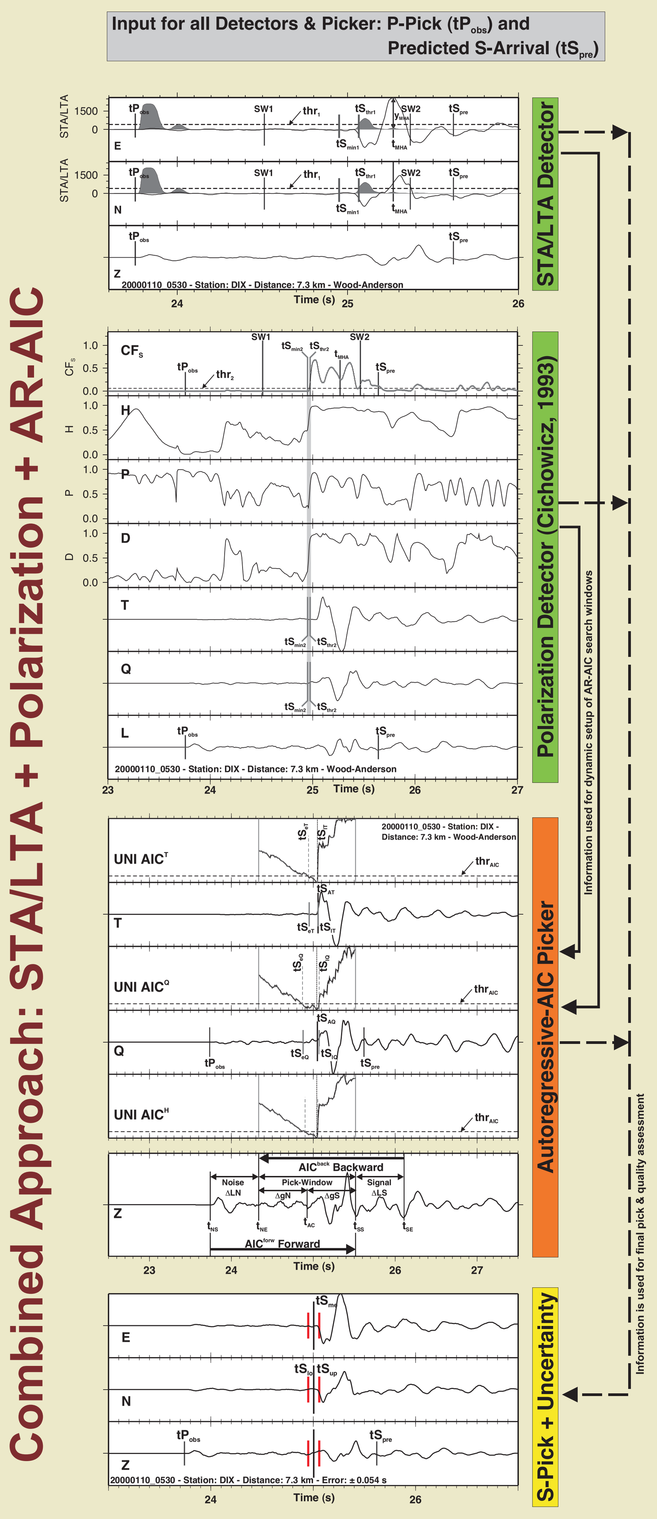
Bottom: "Tomographic" Moho as derived from iso-surface of v_p = 7.25 km/s in the 3-D model based on re-picked data. The very good agreement with Moho models from Controlled Source Seismology (CSS) and receiver function studies demonstrates the consistency of the re-picked data set.

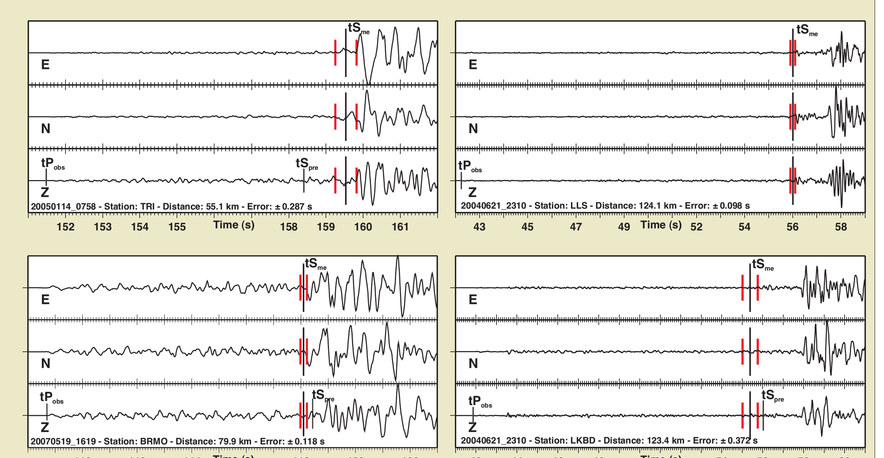


Conclusion from P-Wave Study:

Although the loss-rate of the automatic approach is much higher (compared to manual picking), the data provided by the automatic picker is of very high quality. As demonstrated in this study, the lack of consistency is not compensated by the quantity of the available arrival-time data. Consistent automatic re-picking of arrival times significantly improves the resolution and the reliability of tomographic images.

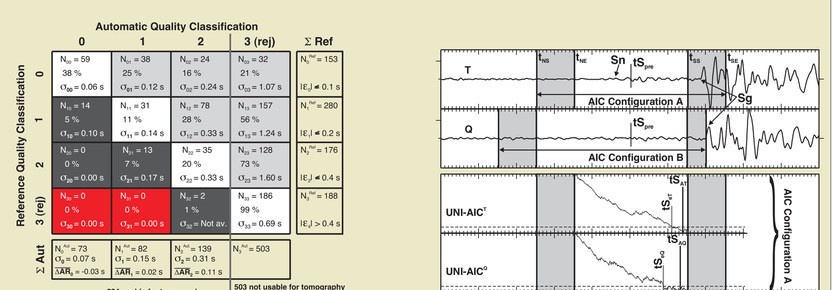
Combined Approach: STA/LTA + Polarization + AR-AIC





Further examples of automatic S-phase picks and corresponding uncertainty estimates at different epicentral distances. **Left column:** First arriving S-wave is Sg phase. **Right column:** First arriving S-wave is Sn phase.

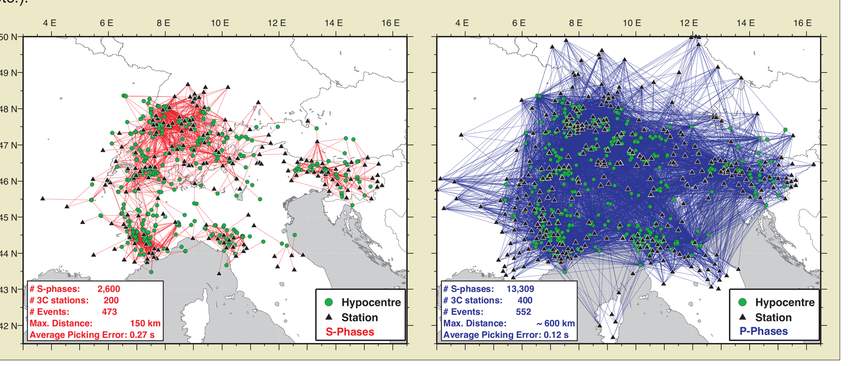
Case Study: Application to the Alpine Region



Top: Performance of automatic S-wave picker compared to manually picked S-phases (reference picks) for 4 quality classes. The number of picks of reference class i classified by the automatic picker as class j is represented by N_{ij}. Accuracy of automatic picks is comparable to manual picking. Compared to manual picking, automatic quality assessment is more conservative.

Right: Phase identification beyond the cross-over distance: Correct identification of Sn requires appropriate search window configuration of AR-AIC picker. Future approaches have to improve reliability of detectors at regional scales.

Bottom: Ray-coverage of final data sets derived from automated re-picking approaches in the greater Alpine region. Left: Automatic S-picks. Right: Automatic P-picks. The sparse coverage of S-phases is mainly caused by the lack of regional observations, smaller number of three-component stations, and problems in data quality (clipped amplitudes, etc.).



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