

## SEISBASE – PRINCIPLES OF A PROGRAM AND DATABASE FOR ROUTINE ANALYSIS OF DATA FROM LOCAL SEISMIC NETWORKS, VERSION 4.7

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**ABSTRACT.** An interactive, database-oriented PC program SeisBase for routine processing of data from local seismic networks is presented. The program provides tools for classification of triggered recordings, phase picking, signal processing, localization and determination of the fault plane solutions of local events, for the classification of seismic events according to their origin, and for drawing epicentral maps. Due to the utilization of relational Borland Paradox database for storing the level-one data it is suitable for routine processing of large amounts of triggered recordings from sensitive local networks. Up to 25 three-component stations may be processed simultaneously. A macro language is available to speed up mass data processing. Supported data formats are ESSTF, MARS-88, GSE, ASCII (export from PITSA). The program has been used for routine processing of data from the WEBNET local network and from the mine network in the Kladno colliery, Czech Republic, for three years.

### 1. INTRODUCTION

A number of programs for processing local network seismograms are used worldwide by seismologists. Among them SEIS-89 (Baumbach, personal communication), SNAP (Baer, 1992), Seismic Handler (Stammler, 1993), EVENT (Musil, 1993) and others may be quoted. The well-known PITSA (Scherbaum and Johnson, 1992) is a powerful tool for advanced signal processing of a large amount of data. The efficient ISAM database provides data integrity and safety and also enables first level-one data (phase picks) to be stored. Unfortunately, there is no way of classifying the events by user-defined custom characteristics and some steps of routine processing must be carried out "off-line" by using other programs.

The idea of creating SeisBase originated during a tedious work with interpreting local seismograms using a classical approach: besides a computer and a simple visualization program, the other necessary tool was a pencil and a sheet of paper

for recording notes (types of already processed events, events to be deleted later, name of file where the picks are stored and others). The first troubles appeared when one decided to localize some of the events: one had to select the corresponding phase readings manually and to convert them to the format acceptable by the localization program. Similar difficulties with incompatibility of tools used for routine seismogram analysis motivated us to develop a complex processing program. The new program should integrate all the tools needed for everyday seismologist work and to provide a simple and fast, semi-automatic user interface.

## 2. REQUIRED SOFTWARE CHARACTERISTICS

A typical high-sensitive local seismic network produces up to first hundreds of triggers per day. In processing such amount of data, a quick overview, deletion of useless triggers and well-arranged data organization is required. We made an attempt of classifying seismic data in order to find a suitable data organization (see Table 1).

TABLE 1. Typical Properties of Seismic Data and Proposed Data Organization

| Data level | Data size (kB/event) | Need of updating | Contemporaneous access to: | Concurrency access | Proposed data organization |
|------------|----------------------|------------------|----------------------------|--------------------|----------------------------|
| ONE        | $\leq 1$             | YES              | ALL DATA                   | USEFUL             | RELATIONAL DATABASE        |
| TWO        | 10 ... 100           | NO               | GROUP OF EVENTS            | NOT NECESSARY      | SET OF FILES               |

*Need of updating:* While the level-two data (seismograms) are kept in the original form, the level-one data (phase picks, hypocenter parameters) have to be updated. *Contemporaneous access:* for level-one data a number of events should be accessible within a short time interval (bulletin compilation, drawing of epicentral maps). *Concurrency access:* because level-one data need to be modified, the data integrity must be ensured when multiple two users work with the same data.

The demands of updating and concurrence access to level-one data can be fulfilled by a relational database. With the necessary computer network support this method provides a quick and safe management of a huge seismic database for multiple users. Because all the level-one data should be accessible simultaneously, the database must be located on the permanent disk. On the other hand, the user mostly processes only a small number of seismograms within several minutes, what enables to store the level-two data on a removable storage media (CD-ROM, magneto-optical disk).

The other expected properties are summarized as follows:

- a) Capability of processing the triggered recordings from high-sensitive local seismic networks consisting of both networked and standalone stations. The preferred field data formats are ESSTF, MARS-88.

- b) Quick access to a certain event and all the useful information related to it (type of event, phase picks and their author, hypocenter parameters, comments, quarry blast reports and others).
- c) Versatility. The implemented functions should provide basic interpretation steps, which may be combined to create more complex operations using macro instructions. The user can adapt the program to his/her idea and performs only the operations that cannot be done automatically.

### 3. PROGRAM OVERVIEW

In its current form (version number 4.7), SeisBase provides the majority of the functions required for the seismologist's every-day work. After receiving waveform data the analyst can obtain the final results as localization of events, epicentral maps, fault plane solutions and simple statistical analysis within one SeisBase session. External format conversion programs, additional programs for signal processing, event localization, focal mechanism determination, bulletin compilation and plotting the epicentral maps are not necessary. This simplifies and speeds up the routine work; the operator has all the useful tools available within one program. To enable fast and reliable access to a quantity of level-one data a seismic database is an integral part of SeisBase. Initial versions of SeisBase worked on ASCII database, (Fischer, 1992). It was rather slow and not very reliable. The last SeisBase versions are based on the relational database Borland Paradox, which provides the maximum integrity for the results of seismological interpretation. See Appendix 1 for details of the database structure.

The basic characteristics of SeisBase are as follows:

- maximum number of seismic stations: 25 for signal processing and localization
- maximum number of seismic traces: from 33 to 75 in depending on the graphic resolution selected
- maximum length of seismic trace: 16 000 samples
- supported data formats: ESSTF, MARS-88, GSE, ASCII (export from PITSA)
- ability of processing a seismogram consisting of several triggers (data files)
- hardware platform: IBM-PC 386 and higher, math-coprocessor

### 4. PROGRAM STRUCTURE

SeisBase works with two groups of data: the waveform data and the level-one database. Splitting data into these two groups increases the efficiency of retrieving the level-one data because no waveform data files have to be accessed. This becomes crucial especially in the case of mass data processing when parameters of a number of events are retrieved (drawing the epicenter maps, bulletin compilation). Besides this advantage, there is another reason for using this approach. If the level-one data are stored in a separate database, the waveforms are used only in some interpretation steps (see Fig. 1). Most of other processing can be done using the level-one data stored in a relational database with fast data access.

SeisBase is structured into several program levels. Individual levels can be briefly characterized as follows:

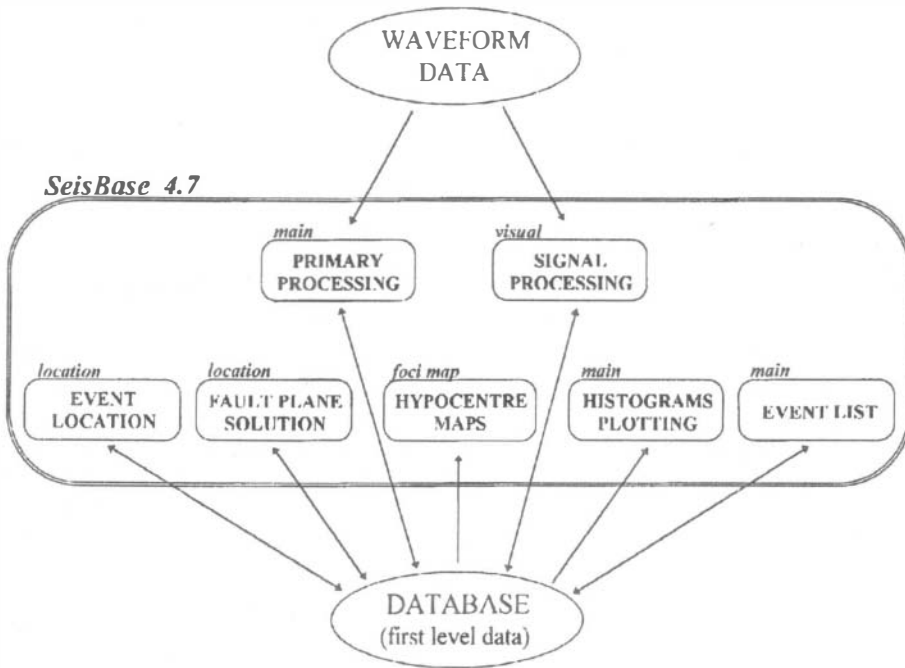


FIG. 1. A block diagram of the data flow between SeisBase and the two data groups; waveform data files and the Borland Paradox database containing the level-one data. Small frames labeled by the program level contain typical routine interpretation tasks solved carried out by SeisBase. Splitting data into two groups, waveform data and database, implies that for the majority of activities performed no access to waveform data is needed.

- *StartUp*: selection of events to be loaded from the database
- *Main*: – database-oriented functions (*Event list*, *Histograms*)  
– viewing the seismograms using QuickView
- *Visual*: phase picking, signal processing
- *Location*: determination of hypocenter coordinates and the fault plane solution
- *Foci map*: drawing hypocenter maps, study of the space-time distribution of hypocenters

At each level the following functions are available:

- *Global menu*: enables a temporary exit to DOS, executing pre-installed external programs, printing the hardcopy of the screen and inspecting the source parameters of the active event
- *Macro mode*: In this mode the keystroke sequences may be stored together with the commands of the macro language in order to either simplify the interactive

control of SeisBase, or perform batch data processing (amplitude picking, localization etc.)

All the program settings are stored in the configuration *login* file; each user may have his/her own, password-protected configuration. When used in a local area network, SeisBase provides sharing of the database tables by multiple users.

## 5. TYPICAL TASKS

Some typical interpretation tasks which may be performed by using SeisBase are described in the following section.

### PRIMARY PROCESSING

In this paper the first step of seismogram interpretation will be referred to understood as primary processing. In this step the operator views the triggers in a chronological order and sorts them into various groups depending on the origin of the triggers and their usefulness for further interpretation. At the same time, some of the useless triggers may be deleted.

After viewing the coinciding seismograms (*QuickView* function), the operator is asked for the type of event. This is a one-character parameter denoting the probable origin of the event (earthquake, quarry blast, teleseismic event, false trigger and so forth). In case of useful triggers, SeisBase adds a unique *event name* to all the triggers occurring within a selected coincidence interval. In this way separate triggers with identical *event name* are associated to create an event. This *event name* also enables to refer the event during further analysis (picking phases, localization and others). In case of false alarm, the coinciding triggers are marked and may be deleted later, their trigger times may be stored as a list of all detected events. To denote some specific properties of the seismic signal at a particular station, a *trigger note* may be specified for each trigger.

### SEISMOGRAM PROCESSING

Multi-station signal visualization, phase picking and analysis of seismograms are provided at the *Visual* program level (Fig. 2). Each station is associated with a screen window of a variable size. The seismic signal of each station may be zoomed either separately or in a synchronized manner. Some of the following tools may be helpful in picking the seismic phases:

- arranging the seismograms from individual stations according to the increasing P- or S-wave arrival time
- various numerical trace operations (addition, subtraction, multiplication, division, comparison, baseline corrections, integration, differentiation, spectral and correlation analysis)
- low-pass, high-pass, band-pass and band-stop filtering using Butterworth cascade filters (Stearns and Hush, 1990)
- particle motion in horizontal and vertical sections; the latter may be interactively rotated
- polarization analysis by using the principal axes of the polarization ellipsoid following the techniques of (Magotra et al., 1987; Roberts et al., 1989)

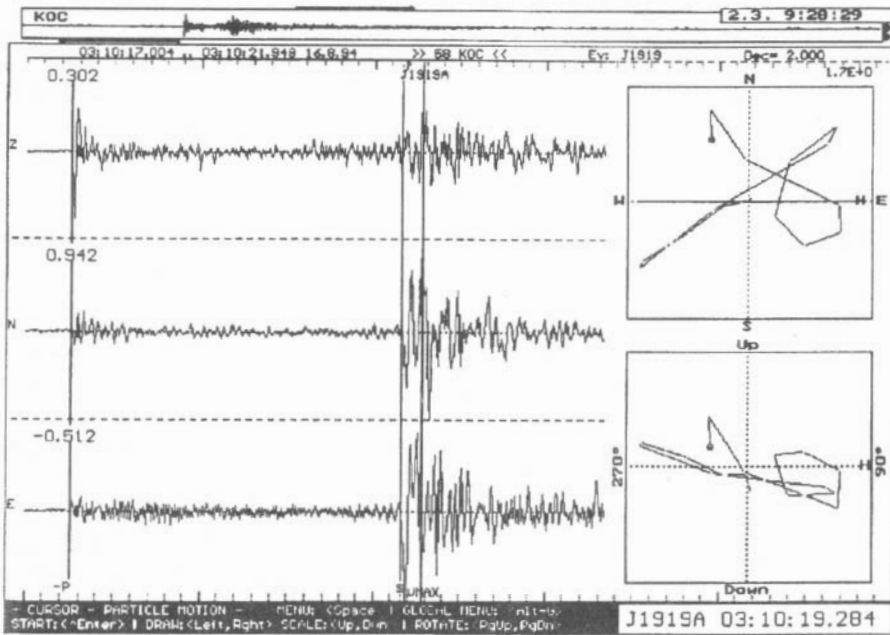


FIG. 2. The screen at the *Visual* level. At the top the vertical component is indicated at its full length using the *Indicator* frame. Time of displayed window (03:10:17.004 .03:10:21.948), station ID and name (58 KOC), event name (J1919) and degree of data decimation are in the in the first line under the *Indicator* frame. On the right a particle motion plot is displayed in the horizontal and vertical sections, the latter may be rotated interactively. The *event* ID and time at the cursor position are shown in the *Watch window*. The amplitudes in  $\mu\text{m/s}$  at the cursor position are indicated on the left.

- signal components rotation
- a family of *Trace-value* functions providing the possibility of searching for typical trace values (extreme and average values). For extreme values the cursor is placed to the position of the extreme
- standard seismogram simulation and signal restitution with the help of program PREPROC (Plešinger et al., 1995)

For details of the corresponding algorithms see Appendix 2. Basic cursor functions provide manual picking of the arrival time and its error, P-wave first motion polarity, phase amplitude, period, azimuth and appending a text note for each phase. Some particular or complex phase picking tasks may be fully automated. This is enabled by the application of the *Trace operations* and *Trace-value* functions within the *Macro instructions* program mode. While the automatic picking

of amplitudes is a simple problem, the automatic picking of P-wave arrival time is more difficult, and the results must be checked manually.

One event may contain up to ten seismic phases. Every seismic record (trigger) may refer up to 26 events. This facility is useful particularly in the case of clustered events when the intervals between adjacent shocks are short and the P- and S-phases of separate events overlap. Provided the hypocenters of such events are close to each other, the command *Cluster events* enables to mark the theoretical positions of separate phase onsets.

SeisBase distinguishes two types of seismic phases, permanent (database) phases and temporary (memory) phases. When the temporary phase is written to the database, also the date and time of the phase creation and the name of operator are stored.

#### DETERMINING THE HYPOCENTER AND FAULT PLANE SOLUTION

Determining focal parameters such as hypocenter coordinates and the fault plane solution is available at the program level *Location*. This level may be called from both the *Main* and *Visual* program levels. All the selections are menu-driven and the results are displayed in the map (Fig. 3).

- *Hypocenter coordinates determination*

Three localization methods are available. (1) Simple *Epicenter* 2D method based on the grid search determines the horizontal coordinates for a user-defined depth. The residuals function is displayed in the form of color scale. (2) The *Hypocenter* 3D method is based on a simplex search and centering of the origin time. While for both the preceding methods the homogeneous halfspace velocity model is used, the last (3) *Fasthypo* method allows a layered velocity model to be used. It is based on an external program FASTHYPO (Herrmann, 1979). For details of the localization procedures see Appendix 3.

All the available stations with at least one picked arrival time can be utilized for localization. When the *Location* level is called from the *Visual* level, temporary phases are used preferably. This allows the influence of the phase picking upon the result of localization to be tested, without changing the default permanent picks. After returning to *Visual*, the theoretical arrival times are indicated in the seismograms. Two types of location results exist: permanent and temporary, they are shown in the map by using a different color. Finally, a *foci note* may be assigned to the permanent location as a verbal classification of the hypocentral position (for example the name of the epicentral area).

For each localization method various predefined velocity models may be used. Since the velocity model and the localization method applied become a part of the localization result, separate hypocenter coordinates may be stored for every event.

The location parameters stored in the database are: hypocenter coordinates and origin time together with their errors, residuals sum, local magnitude of the event, the data (stations, phases) used for the localization, the localization method and velocity model used, the date and time when the localization was carried out, and the name of the operator. Besides the localization results stored in the database,

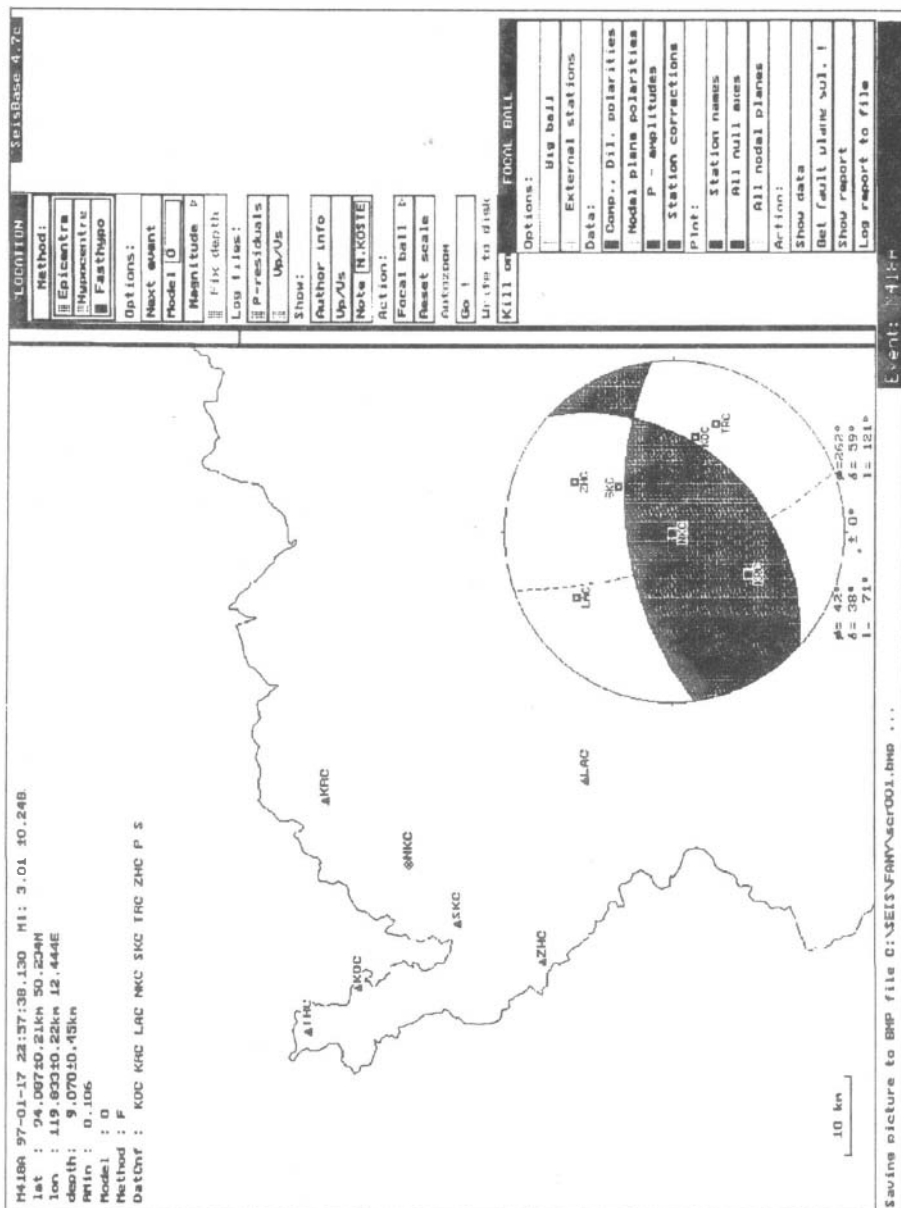


FIG.3. The Location screen providing the determination of the hypocenter coordinates and fault plane solution. Three localization methods are available: internal: *Epicenter*, *Hypocenter* and external: *Fasthypo* (Herrmann, 1979).



time residuals at particular individual stations and the average  $v_p/v_s$  ratio derived from phase picks can be logged in separate ASCII files.

- *Local magnitude determination*

The local magnitude is determined in the course of the localization procedure as a mean value of the station magnitudes. For this purpose SeisBase provides a general formula with adjustable coefficients. The effects of geometrical spreading, attenuation and station corrections are taken into account. All stations with picks of maximum phase of S-wave are used, the input quantity being either the ground velocity or displacement. For details determination see Appendix 3.

- *Fault plane solution determination*

The fault plane solution can be determined using the command *Focal ball* at the *Location* program level. For this purpose the method of grid search and Fourier decomposition after (Maeda, 1992) is applied. The method is based on the analysis of both P-wave polarities and amplitudes and uses the lower hemisphere equal-area projection. The user can display all the station readings available, choose the data to be used (polarities, amplitudes, station corrections) and perform the command *Get fault plane solution*. All the possible fault plane solutions are displayed together with the value of the strike, dip, rake and uncertainty of the optimum solution. An additional report containing amplitude residuals and compatibility of polarities at particular stations may be displayed or logged to a disk file. The optimum solution is stored in the database together with other hypocenter parameters.

## EVENT SELECTION

For the majority of tasks encountered in processing a huge number of seismic data, quick access to a certain event is crucial. The seismic database which is an integral part of SeisBase simplifies the selection of events to be processed. In principle, two ways of event selection exist. First, the events to be loaded from the database may be selected at the StartUp level. The available constraints applied for event selection are: station name, event name, trigger type, trigger and foci notes, magnitude and time intervals, number of coinciding stations, and others.

Second, when the *Main* program level is running, two methods for searching events are available. While the *Search command* moves the cursor directly to the trigger with the inquired attribute (*trigger type* and *time*, *station name*, *event name*), the *Mark* command allows marking of triggers by using further attributes such as *trigger* and *foci note*, *local magnitude* and *accessibility of waveforms*. Marked triggers can either be processed separately by *Tools* (drawing the *Foci map* (see Fig. 4), creating *Event list* or plotting *Histograms*) or they can be also deleted or copied to another disk. To get further information about the highlighted triggers, some event parameters (notes, magnitude etc.) may also be observed in the *Watch window*.

## DRAWING THE LOCATION MAP

Drawing hypocenters on a geographical map of the area is available in the *Foci map* program level. Besides common event selection methods described in the last

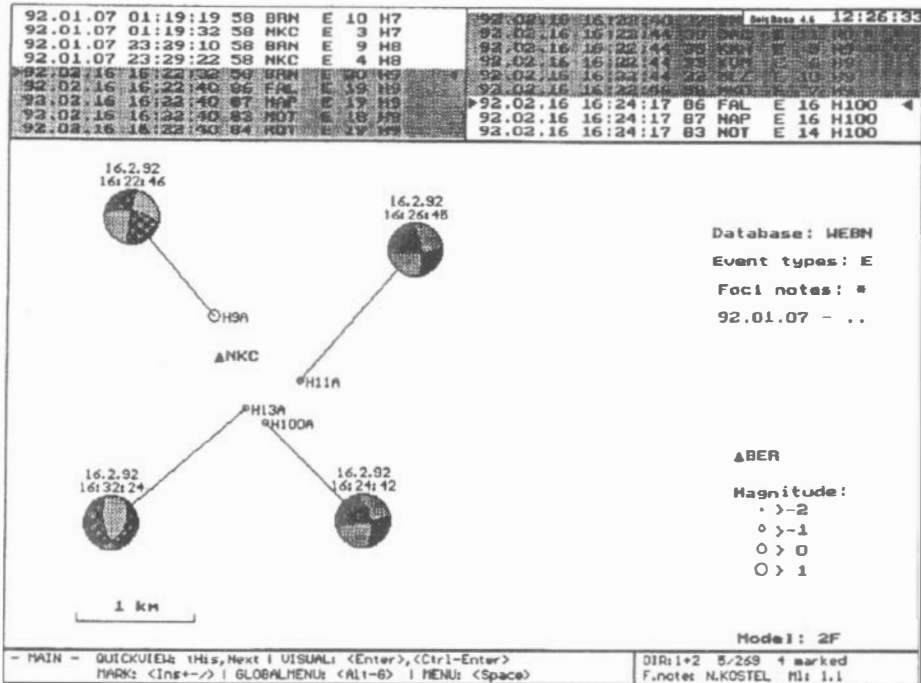


FIG. 4. One or two application windows appear on the *Main* screen. In this figure a list of triggers with highlighted coinciding triggers at different stations is displayed at the top. The lower window contains a map of epicenters obtained within the *Foci map* program level. For each epicenter its local magnitude and a lower hemisphere projection of the fault plane solution are displayed. The bottom of the screen at each program level shows a short help information (on the left) and a *Watch window* (on the right). Status information and selected event characteristics can be observed there.

paragraph, the events to be plotted can be selected by specifying an additional mask (*velocity model* and *localization method* applied, minimum magnitude and *foci note*). In the set of available symbols denoting a hypocenter a fault plane solution is included, too. Three drawing modes are available: horizontal plane, three perpendicular sections and 3-D view. For all the modes the view may be zoomed, shifted and rotated. For the purpose of studying the space-time distribution of individual hypocenters, the user may "walk" through the map by highlighting the actual focus and observing its hypocenter parameters in the *Watch window*. Simultaneously *foci note* may be edited to express the focal position in a verbal form.

## COMPILING A BULLETIN

Bulletin compilation and creation of a list of event parameters for further processing by other programs are available using the *Event list* command at the *Main* program level. Individual trigger attributes (*trigger time*, *trigger type*, *trigger note*, *station name etc.*) and event parameters (phase picks, hypocenter parameters) may be selected for listing either to an ASCII file or on the screen.

## MACRO INSTRUCTIONS

For routine data processing the automation of the whole task, or frequently repeated keystroke sequences are provided. At each program level 40 function keys may hold *Macro instructions* – a keystroke sequence combined with commands of a simple macro language. The macro language enables program elements like loops, branches and subroutines to be created. Functions for mass data processing such as picking amplitudes, events localization, magnitudes determination, stacking of seismograms and others may be written using this language. If the data are processed interactively (primary processing, phase picking), some of the keystroke sequences may be stored as a small macro program, and the user only carries out the more sophisticated work.

## 6. CONCLUSION

The PC program SeisBase has been briefly presented given in this paper. Due to its integration with an efficient seismic database and a semi-automatic user interface it is capable of serving as a powerful tool for routine data processing of large amounts of data coming from sensitive local networks. A variety of tasks starting with primary seismogram processing up to obtaining the fault plane solutions may be carried out using SeisBase. The program has been used for routine processing of data at the WEBNET local network (Horálek et al., 1996) and the mine network in the Kladno colliery (Czech Republic) since 1993.

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## APPENDIX 1: SEISMIC DATABASE STRUCTURE

The seismic database holds all the level-one data. It consists of a number of .DB tables and .PX index files in the Borland Paradox format. The access to the database is provided by built-in function calls to the Paradox Engine library. This means no further runtime support (runtime database modules) is required. The database is divided into single-year tables families; SeisBase opens all tables

required. In total six types of tables are used for each year. The tables are labeled using the following convention:

- pos. 1-5: name of seismic network, common for all the tables of one database
- pos. 6-7: year minus 1900
- pos. 8: specifier – a letter denoting the type of table

The following tables create the seismic database:

- *trigger table, specifier E* – holds the information about triggers and their coincidence (definition of seismic events)
- *phase picks table, specifier B* – holds the phase picks (time, amplitude, prevailing period and azimuth)
- *location table, specifier L* – holds the hypocenter parameters (coordinates, magnitude, fault plane solution, link to velocity model)
- *comments table, specifier C* – holds the comments for all preceding tables
- *location data table, specifier D* – holds the configuration of seismic station used for the locations
- *login table, specifier L* – holds all the SeisBase logins; any time SeisBase is started a new row is added

A scheme of the database structure and the links between the tables are shown in Fig. 5.

## APPENDIX 2: ALGORITHMS FOR SEISMOGRAM PROCESSING

### *Seismogram Plotting*

Two methods of plotting the seismograms are used within SeisBase. The *Quick-View* function uses decimation in the course of data reading and scales the time axis of the seismogram proportionally to the horizontal size of the screen window. The decimation rate is determined automatically, so that the seismogram may be displayed at full length, with no memory limitations.

In *Visual*, where no distortion of signal is allowed, the decimation rate for seismogram reading is user-controlled and the signal is displayed in the way that the number of samples is an integer multiple of the screen pixels, or vice versa. In this way the time of the cursor may be determined uniquely and no interpolation is needed. For signal plotting three decimation modes are provided. Besides plotting all the samples or the average value of the samples corresponding to one screen pixel, also the sample with the largest distance from the sample last displayed may be plotted. Compared with plotting of the average value, this decimation mode preserves the frequency information better.

### *Trace Operations*

The *Trace* operations menu provides various numerical operations with signal traces. The operations are applied to the seismogram section displayed on the screen and the original signal is retained in the memory so that it may be restored later. Some of the algorithms used will be described in the following.

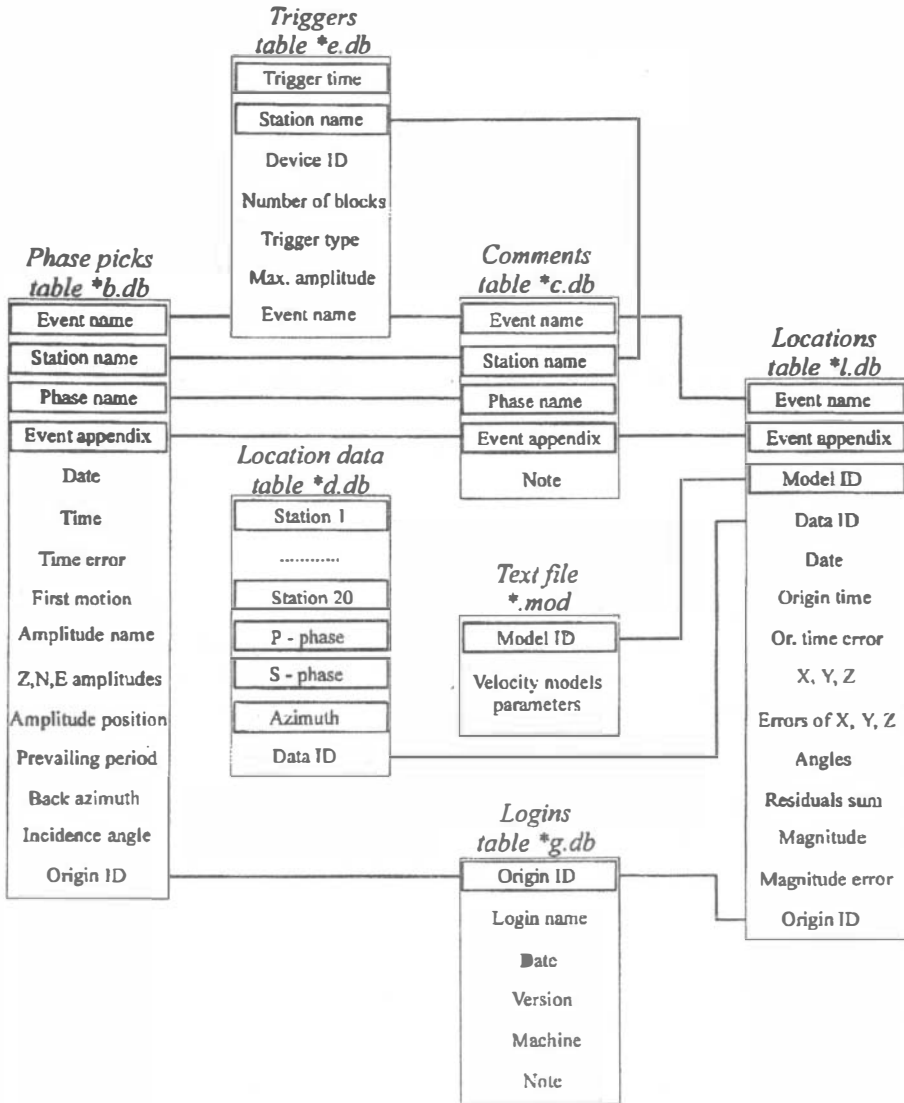


FIG. 5. The seismic database consists of six Paradox tables; the primary keys and their links to other tables are highlighted. Most of the table fields are self-explanatory, others are explained below. *Event name* has the form Character+Number, for example J1026; *Event appendix* is one character distinguishing multiple events within one trigger; *Angles* express either the main axes of the location ellipsoid, or the three axes of the fault plane solution; the *Location data* table holds the combination of seismic stations and phases used for the localization.

*Averaging* is available as a special command and is also used within the *Polarization* commands. A running window with exponential weight

$$y_n = (1 - c)y_{n-1} + cx_n, \quad (1)$$

where  $x$  and  $y$  are the original and averaged traces, respectively, is applied for averaging. Length  $T$  of the window, which is user-defined, is related to coefficient  $c$  and sampling frequency  $f_s$  as

$$c = 1 - \exp(-2\pi T/f_s). \quad (2)$$

Averaging may be useful for the simulation of various detection algorithms utilizing the STA/LTA ratio.

*Polarization* analysis provides the computation of components of the signal covariance matrix

$$C = \begin{pmatrix} \sigma_{zz} & \sigma_{zn} & \sigma_{ze} \\ \sigma_{nz} & \sigma_{nn} & \sigma_{ne} \\ \sigma_{ez} & \sigma_{en} & \sigma_{ee} \end{pmatrix} \quad (3)$$

and its diagonalization in order to obtain the principal axes of the polarization ellipsoid. Here  $\sigma_{zn}$  denotes the mean value of the cross-variance of the vertical and north components in a running window (1). Diagonalization can be performed by using and its diagonalization in order to obtain the principal axes of the polarization ellipsoid. For this purpose three different methods. The method proposed by (Magotra et al., 1987) uses only the horizontal components to find the maximum eigenvalue of the covariance matrix in the horizontal direction. The covariance matrix is rotated about the  $z$  axis until the radial and transverse components become uncorrelated. The backazimuth is obtained as

$$\varphi_0 = \frac{1}{2} \arctan \left( \frac{2\sigma_{ne}}{\sigma_{nn} - \sigma_{ee}} \right). \quad (4)$$

The incidence angle is evaluated in a similar way in SeisBase using covariances in the  $rz$  plane;  $r$  is the radial component in the  $\varphi_0$  direction.

The method of (Roberts et al., 1989) rotates the covariance matrix about the  $z$  axis, so that the vertical and transverse signals may become uncorrelated. In this case the rotation azimuth is determined through

$$\varphi_0 = \arctan \left( \frac{-\sigma_{ez}}{-\sigma_{nz}} \right). \quad (5)$$

The incidence angle using this technique is

$$\theta = \arctan \left( \frac{\sqrt{\sigma_{nz}^2 - \sigma_{ez}^2}}{\sigma_{zz}} \right). \quad (6)$$

Finally the method plots the “predicted” coherence expressing the degree of linear polarization of the signal (Roberts et al., 1989). A test of both these techniques is given by (Walck et al., 1991).

While in the two preceding methods matrix  $C$  is rotated about the  $z$  axis only, in the the third method uses all three signal components are used to find the three eigenvalues  $\lambda_1, \lambda_2, \lambda_3$  of  $C$ . The characteristic equation of  $C$  is solved using the goniometric method. The azimuth and incidence angle of the P-wave arrival is given by the direction of the eigenvector  $u(z, n, e)$  corresponding to the largest eigenvalue. Following (Jurkewics, 1988), the azimuth and the incidence angle are

$$\varphi_0 = \arctan \left( \frac{u_{31}}{u_{21}} \right), \quad \theta = \arccos |u_{11}|. \quad (7)$$

The degree of linear polarization is indicated by the rectilinearity parameter

$$R = \frac{(\lambda_1 - \lambda_2)^2 + (\lambda_1 - \lambda_3)^2 + (\lambda_2 - \lambda_3)^2}{2(\lambda_1 + \lambda_2 + \lambda_3)^2} \quad (8)$$

which is unity when the signal is linearly polarized, and decreases to 0 when it is unpolarized (Samson and Olson, 1980).

Frequency *Filtration* uses recursive Butterworth two-pole cascade filters (Stearns and Hush, 1990). Up to five filter sections may be used which corresponds to the rolloff from 12 to 60 db/octave. To obtain a zero phase filter, reverse filtering is provided, too.

*Spectra* calculation and *Cross-Correlation* are performed using FFT routines provided in the Turbo Numerical Methods Toolbox.

#### Trace Values

A set of *Jump-to-value functions* provides automatic search of typical trace values. Besides the self-explanatory values such as extremes and mean values, two quite unusual quantities should be mentioned here. First, the *Half integral* function finds the position  $h$  in trace  $x$  of length  $n$ , at which the following relation holds

$$\sum_{i=1}^h x_i = \sum_{i=1}^n x_i. \quad (9)$$

Second, the *Balance* function gives the ratio

$$\sum_{i=n}^{n+d} x_i / \sum_{i=n-d}^n x_i \quad (10)$$

where  $n$  is the cursor position and  $d$  is the selected window length. This quantity is helpful especially as a detector for the purpose of automatic phase picking.

## APPENDIX 3: METHODS OF HYPOCENTER PARAMETERS DETERMINATION

*Localization Algorithms*

Both the internal localization methods, *Epicenter* and *Hypocenter* utilize P and/or S arrival-time readings; the *Epicenter* method also allows the use of azimuth readings to improve results of the localization when only a few stations are available. The residuals sum has the form

$$S_0 = \sum \left( \frac{\bar{t}_0 + T_i(x_0, y_0, z_0) - t_i}{\sigma t_i} \right)^2 + q \sum \left( \frac{\varphi'_i(x_0, y_0) - \varphi_i}{\sigma \varphi_i} \right)^2 \quad (11)$$

for the *Epicenter* method, and

$$S_0 = \sum \left( \frac{\bar{t}_0 + T_i(x_0, y_0, z_0) - t_i}{\sigma t_i} \right)^2 \quad (12)$$

for the *Hypocenter* method, where  $t_i$  are arrival times with uncertainties  $\sigma t_i$ ,  $T_i(x_0, y_0, z_0)$  is the travel time from hypocenter  $(x_0, y_0, z_0)$  to the  $i$ -th station,  $\varphi'_i(x_0, y_0)$  is the theoretical azimuth from the epicenter  $(x_0, y_0)$  to the  $i$ -th station and  $\varphi_i$  is the observed azimuth with uncertainty  $\sigma \varphi_i$ . The centered origin time  $\bar{t}_0$  is a mean value:

$$\bar{t}_0 = \frac{1}{n} \sum_{i=1}^n (t_i - T_i(x_0, y_0, z_0)). \quad (13)$$

The uncertainty  $\sigma t_i$  of arrival times is the *Time error* value, which may be picked together with the arrival times. If no  $\sigma t_i$  is specified, an uncertainty of 10 ms for P and 20 msec for S-phase is taken by default. Direct usage of time error for expressing the reliability of time picks is probably more physically meaningful than assigning a weight, which is common in some location programs. The weight of azimuth residuals in equation (11) is artificially increased by an adjustable factor  $q$  since the range of possible directions between the epicenter and a seismic station is much smaller than the range of possible travel times. For both the methods, a homogeneous halfspace velocity model is used to calculate the travel times, different altitudes of seismic stations being taken into account. In the *Epicenter* method the uncertainty of the epicenter coordinates is estimated as the size of an error ellipsoid defined by the area with residuals that are smaller than the standard deviation of the residuals minimum, or

$$S_0 < \frac{n}{n-2} S_{0 \min} \quad (14)$$

For the *Hypocenter* method the error of location is derived from data covariance matrix  $C_t$  and the matrix of derivatives  $D$  as (Matsu'ura and Hasegawa, 1987)

$$C_x = \left( D^T (C_t)^{-1} D \right)^{-1}. \quad (15)$$

The residuals minimum stored in the database is the normalized square root of the residuals sum, e.g.

$$R_{\min} = \frac{\sqrt{S_0}}{n}. \quad (16)$$



The *Epicenter* method calculates the residuals sums for a user-specified depth in a grid of  $30 \times 30$  nodes and displays the level of the residuals sums function using a logarithmic color scale (see Fig. 3). To improve the location accuracy, the map may be zoomed either manually or automatically. The rate by which the station configuration affects the shape of the residuals function can be observed by switching the stations on and off. Since the residuals function has the same form for both methods, the *Epicenter* method may be also used to display the shape of the error ellipsoid at the depth obtained by the *Hypocenter* method.

The *Hypocenter* method uses a simplex algorithm to search for the minimum of the residuals function (12). The first trial is taken in the middle of the map frame selected and searching is terminated as soon as the change of all three coordinates is smaller than 1 m within the last 10 steps. During the search the trial epicenter is displayed in the map so that the user may observe the progress of the localization.

Apart from the internal localization methods, the external method *Fasthypo* requires P-wave arrival time readings for all the stations. The weights of the individual phase particular picks, which are required by the FASTHYPO program (Herrmann, 1979), are derived from the arrival time errors. The results of location (coordinates with errors, theoretical arrival times, residuals sum) are imported to SeisBase and handled the same way as the results of other localization methods (*Epicenter*, *Hypocenter*).

#### *Magnitude Determination*

The local magnitude in SeisBase is determined as the mean value of magnitudes obtained at separate stations of the network. Besides the mean magnitude also its variation is calculated and stored in the database. In order to allow the users to calibrate the magnitude determination with respect to the conditions of a particular local seismic network, a general formula

$$M_1 = \log A - p \log T - (1 - p) \log 2\pi + s \log \Delta + \alpha \Delta + c + C \quad (17)$$

is provided. Here  $A$  denotes the maximum amplitude of S-wave determined from of ground motion velocity or displacement,  $T$  is the prevailing period,  $p = 0$  if  $A$  is the velocity and  $p = 1$  if  $A$  is the displacement,  $s$  is the exponent of geometrical spreading,  $\alpha$  is the exponent of absorption and  $\Delta$  denotes the hypocentral distance in km. Additive constant  $c$  differs for every station and the relation between the  $c$ 's for particular stations expresses the correction for local site responses. An additional constant  $C$ , which is common for all the stations, serves to calibrate the formula for the magnitudes obtained from other seismic stations operating in the area. Using this general formula, a variety of particular formulae may be obtained, starting with the original Richter magnitude. Since the coefficients are a part of the user configuration of SeisBase, once the formula is calibrated, it becomes invariant until it is modified by the user.

#### *Determining the Fault Plane Solution*

The method of fault plane solution determination is based on the paper (Maeda, 1992). Since the method was slightly modified when implemented in SeisBase, its principles will be described in the following section.

All the possible positions of the null axis are examined using a grid search with a step of  $10^\circ$ . During the grid search the compatibility of observed and theoretical polarities is examined. Besides positive and negative polarities, SeisBase also allows null polarities to be used. Such polarities may be picked at the stations lying in the vicinity of the nodal line thus showing an emergent P-wave onset. The null polarity is taken as conformable if the corresponding station projection lies within a predefined angle interval around a nodal plane. For each null axis an azimuth of the nodal plane is determined using the Fourier method (Maeda, 1992). The result of this procedure is a set of possible and equivalent fault plane solutions.

In the next step an optimum solution is sought. Two methods may be used for this purpose. If no first motion amplitudes are available, the only way is to use some averaging technique. After (Maeda, 1992) weight  $w_1 = \sum A_i k_i$  is calculated, where  $A_i$  is the amplitude of P-wave radiation pattern. Factor  $k_i$  is the observed polarity in the case of nonzero polarities, for null polarities it takes the following values:  $k_i = 1$  if the projection of the null polarity lies within a predefined angle interval, otherwise  $k_i = -1$ . To minimize the influence of incompatible polarities upon the optimum solution, weight  $w_2 = \sum A_i$  is updated for incompatible polarities only.

If more than two P-wave amplitude readings are available, SeisBase can fit the observed amplitudes to the P-wave radiation pattern of the double-couple source so that a more reliable averaged focal mechanism may be obtained. Denoting  $a_{ci}$  the logarithm of P-wave amplitude observed at the  $i$ -th station and corrected for the hypocentral distance and site amplification, the following simple relation holds

$$a_{ci} = K + a_{0i}, \quad (18)$$

where  $a_{0i}$  is the logarithm of the theoretical P-wave amplitude and  $K$  is proportional to the magnitude of the earthquake and, therefore, should be invariant with respect to the stations. The correction for attenuation and site response may be done by using similar values of attenuation and station corrections as are available for the magnitude determination. Since only P-wave amplitudes are used, no correction for free-surface effects is applied. Taking the average proportionality constant  $K$ ,

$$K = \frac{1}{n} \sum_{i=1}^n (a_{ci} - a_{0i}), \quad (19)$$

the centered residuals sum of amplitudes is

$$S_0 \sim (a_{ci} - a_{0i} - K)^2. \quad (20)$$

Depending on the data available and on the user configuration of the *Focal Ball* procedure, the optimum solution selected by SeisBase must fulfill the following criteria:

- Polarities only:

- (1) the number of compatible polarities must be the maximum possible, and

- (2) if all observed polarities are compatible, the optimum solution is the solution with the maximum weight  $w_1$ , otherwise, if some observed polarities are incompatible, the optimum solution is the solution with the minimum weight  $w_2$

- Amplitudes only:

The optimum solution is the solution with the minimum residuals sum of amplitudes  $S_0$

- Polarities & Amplitudes:

The optimum solution is the solution with the minimum residuals sum of amplitudes  $S_0$ , whereas  $S_0$  is evaluated only for the solutions with compatible polarities.

The uncertainty of the optimum solution is estimated as a mean angle between the optimum solution and individual "candidate" solutions. While for polarities the candidate solutions are all the possible solutions, for amplitudes the set of candidate solutions is limited to those whose  $S_0$  lies within the range of the standard deviation, e.g.

$$S_0 < \frac{n}{n-2} S_{0 \min} . \quad (21)$$

The way of obtaining the station projections on the focal sphere depends on the localization method. In the *Hypocenter* method straight rays are used, and for underground stations the radial component of the amplitude is calculated which also enables focal mechanisms in mine networks to be determined. The azimuths and take-off angles provided by the FASTHYPO program are used for the hypocenters localized using the *Fasthypo* method.

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