RESEARCH PROGRAMME
OF SEISMIC WAVES IN COMPLEX 3-D STRUCTURES

The research is focused primarily on the fundamental issues of high–frequency seismic wave propagation in complex 3-D isotropic and anisotropic structures, which go beyond the traditional approaches. The ray method and its recent extensions, as well as its combination with other methods are mainly applied and investigated. The emphasis is put on new, stable, more efficient and flexible algorithms for both forward numerical modelling and inversion of seismic wave fields in 3-D inhomogeneous, isotropic and anisotropic structures. Considerable attention is also devoted to applications involving S waves, converted waves, S–wave splitting and coupling in anisotropic media, particle ground motions, etc. Much more detailed information can be obtained at "http://seis.karlov.mff.cuni.cz/consort/main.htm".

The research programme was begun on October 1, 1993. The programme will go into its eighth year on October 1, 2000.

RESEARCH PROGRAMME FOR THE EIGHTH YEAR

October 1, 2000 — September 30, 2001

1. *Program packages*

Package MODEL:

Model: General 3-D layered and block isotropic or anisotropic structures, containing isolated bodies, pinchouts, etc. Inside the layers and blocks, the elastic parameters may vary in all three dimensions. Dissipation and non–planar topography can be considered. Possibility of model smoothing, data fitting by inversion, conversion of model parametrization, structural interface triangulation and VRML visualization.

Planned innovations: Interface from and to GOCAD.

Package CRT:

Model: Using package MODEL.

Type of waves: Arbitrary type of elementary seismic body wave corresponding to the zero–order ray theory (P,S, converted).

Computations: Arbitrary position and shape of the source, initial–value ray tracing by numerical integration of ray equations, two–point ray tracing by the shooting method, travel–time computation, dynamic ray tracing, paraxial–ray propagator matrix, geometrical spreading, vectorial amplitudes, polarization vectors. The package may be applied to the evaluation of the elastodynamic ray–theory Green function, and to the computation of synthetic seismograms, including the coupling ray theory for weak anisotropy and the response of fine layers at receiver sites (program package RMATRIX by C.J. Thomson, linked to the CRT package).

Aquisition schemes: Surface seismics (land and marine), VSP, cross–hole, OBS, OBC.

Planned innovations: Anisotropic common–ray approximation of the coupling ray theory for S waves. The package will be extended to solve various inversion problems, travel–time tomography in particular.

Package ANRAY:

Model: 3-D laterally varying structures containing isotropic and anisotropic non–vanish-

ing layers. Specification of elastic parameters inside individual layers either by linear interpolation between isosurfaces of elastic parameters, or by B–spline interpolation within a 3-D rectangular grid of elastic parameters.
Types of waves: Arbitrary type of elementary seismic body wave (P, S, qP, qS1, qS2, any converted wave, coupled qS waves).
Computations: Numerical integration of ray tracing and dynamic ray tracing equations, calculation of ray vectorial amplitudes, ray–theory Green function including the Green function in the quasi–isotropic approximation for S waves, ray synthetic seismograms, particle ground motions.
Aquisition schemes: Surface seismics (land), VSP, cross–hole.
Planned innovations: (a) Further development of the quasi–isotropic (QI) approximation: further evaluation of its validity by comparing the QI results with results of more precise methods; incorporation of reflection and transmission within the QI computations. (b) Checks of stability of the anisotropic stiffness tensor with respect to interpolation. (c) Calculation of pressure in the surface liquid layer; calculation of the conversion coefficients at the anisotropic solid/liquid interface. (d) Ray tracing tests with RHS specified by the polarization vectors. (e) Modifications of outputs so that the graphical software developed for the MODEL and CRT packages can be used.

Package NET:
Model: Using package MODEL or using gridded velocities.
Types of waves: First arrivals, constrained first arrivals.
Computations: Arbitrary position and shape of the source. First–arrival travel times in the whole model are computed. The algorithm of computation is independent of the model's complexity.
Aquisition schemes: Surface seismics (land and marine), VSP, cross–hole, OBS, OBC.

Package FD:
Model: Using package MODEL.
Type of waves: Complete elastic wave field.
Computations: Presently 2-D, without fluids.
Aquisition schemes: Surface seismics (land).
Planned innovations: 3-D, hybrid methods.

Package FORMS:
Computations: Data input and output used by other packages, management and plotting of synthetic seismograms, 2-D and 3-D graphics including 3-D virtual reality, manipulation and calculation with gridded data (data cubes), programs for matrix and vector operations necessary for inversion, other general–purpose seismic software.

2. *Sample data for the program packages*

Examples of the input data describing or approximating models delivered by the consortium members or other typical models will be prepared. Examples of the input data to perform calculations in such models will also be prepared.

3. *Two–point ray tracing in complex isotropic 3-D structures*

The two–point ray tracing code will further be tested and applied to various models. Attention will also be devoted to the calculation of two–point rays diffracted from edges and corner points, and to the possibility of calculating the corresponding amplitudes and contributions to synthetic seismograms (edge waves).

4. *Synthetic seismograms in 3-D isotropic complex structures*

Methods to calculate synthetic seismograms in complex structures will be studied, mutually compared and combined.

5. *Seismic wave propagation in weakly anisotropic inhomogeneous media*

Study of the inaccuracy of the coupling ray theory due to the differences between the reference and exact rays. Estimation of frequencies at which the quasi–isotropic common–ray or anisotropic common–ray approximation of the coupling ray theory should be replaced by the anisotropic ray theory, or by the coupling ray theory along the anisotropic ray theory rays.

Development of an efficient P–wave ray tracing for weakly anisotropic inhomogeneous media.

6. *Applicability of the high-frequency asymptotics in the vicinity of S–wave singularities*

Anisotropic S–wave ray tracing in a vicinity of singularities in inhomogeneous anisotropic media. Investigation of accuracy of various high–frequency approximations (zeroth–order anisotropic ray approximation, quasi–isotropic approximation, higher–order anisotropic ray approximations, Gaussian beams, etc.) for S waves, propagating in strongly or weakly anisotropic homogeneous or inhomogeneous media in the vicinity of singularities, by comparison with other more precise methods (exact solutions, finite differences, etc.).

7. *R/T coefficients for inhomogeneous waves in dissipative elastic media*

Computation of R/T coefficients at structural interfaces and thin transition layers between two isotropic dissipative media will be tested further. The main attention will be devoted to frequency–independent reference R/T coefficients.

8. *Computation of ray–theory travel times, amplitudes and other quantities at the nodes of 3-D grids*

Algorithms of fast calculation of ray–theory travel times in dense rectangular grids will be investigated further. The accuracy and efficiency of the interpolation of ray–theory travel times within ray cells in 3-D models will be studied further, and the relevant numerical algorithms will be improved, or new ones will be proposed. If possible, attention will also be devoted to the interpolation between different shot and receiver positions.

9. *Accuracy of seismic modelling*

The research will be concentrated mainly on the accuracy of travel–time calculations, on the accuracy of finite–difference modelling of seismic wave fields, and on the accuracy of other modelling methods designed or studied within the framework of the project. The main attention will be devoted to the estimation of the feasibility and costs of ray tracing, and to the high–frequency validity of velocity models.

10. *Lyapunov exponents and model smoothing*

Construction and smoothing of velocity macro models will further be studied, with emphasis on the application of Sobolev scalar products and Lyapunov exponents. Attention will be paid to a possible extension of the estimation of Lyapunov exponents to smooth 3-D models and to 2-D models with structural interfaces.

11. *Seismic tomography*

Development of theory, algorithms and programs applicable in seismic travel–time tomography and inversion of the coherency panels, with emphasis on the estimation of their accuracy.

Further development of algorithms for seismic travel–time tomography in anisotropic media, synthetic tests of possibility to discriminate anisotropy from inhomogeneity. Extension to other types of data acquisition, extension to shear wave data, study of effects of noise. The theoretical investigation will also be aimed at the determination of the resolution of the elastic parameters with respect to the measurement geometry.

12. *Decomposition of a wave field into Gabor wavelets*

Discretized integral decomposition of a spatial wave field at a fixed time or a time–dependent wavefield along a smooth surface into Gabor wavelets in 2-D or 3-D. The Gabor wavelets may be frequency–dependent and their shape may be smoothly varying in space and time, which requires much more general decomposition than the integral Gabor transform. The decomposition into Gabor wavelets may be useful for the decomposition of a general wave field into Gaussian beams or packets.

13. *Migrations*

Resolution and accuracy of migrations will be studied. Attention will be paid to the physical meaning of the migrated sections and to their sensitivity to the velocity model, including its anisotropy.

Algorithm of the Gaussian–packet prestack depth migration will be developed. Gaussian packets should be very efficient and offer explicit correspondence between the time and depth sections. Attention will be paid to the optimization of the shape of Gaussian packets.

14. *Gaussian–packet "finite elements"*

In the beginning of each time interval of a given duration, the wave field may be decomposed into Gaussian packets propagating throughout the corresponding time interval and yielding the wave field in the beginning of the next time interval.

15. *Finite–difference solutions of the elastodynamic equations*

The main attention will be paid to the development of a new 3-D elastic code and to the hybrid DW–FD and Ray–FD methods.

16. *Concluding remarks*

In addition to this programme, we will certainly be responsive to specific technical suggestions and recommendations of the consortium members within the general framework of the project. The research in most directions listed above will continue into the future years of the project.