RESEARCH PROGRAMME
ON 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 the forward numerical modelling of seismic wave fields in 3-D inhomogeneous, isotropic and anisotropic structures. Considerable attention is also devoted to applications involving shear waves, converted waves, shear wave splitting in anisotropic media, particle ground motions, etc.

The research programme started on October 1, 1993. The fourth year of the programme will start on October 1, 1996.

RESEARCH PROGRAMME FOR THE FOURTH YEAR

October 1, 1996 — September 30, 1997

1. *Revisions of packages MODEL, CRT and NET*

All future revisions of program packages MODEL, CRT, and NET, delivered to the sponsors in the first year of the project, will be delivered to the sponsors in the next years of the project.

Packages MODEL and CRT:
Model: General 3-D layered and block isotropic structure, containing isolated bodies, pinchouts, etc. Inside the layers and blocks, the velocity and density varies laterally in all the three dimensions. Dissipation may be considered.
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, two-point ray tracing by the shooting method, initial-value ray tracing by numerical integration of ray equations, 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 the synthetic seismograms.
Applications: Reflection methods, refraction methods, VSP, hole-to-hole.

Package NET:
Model: General 3-D layered and block isotropic model. The medium parameters are specified at grid points of a 3-D rectangular mesh. The same model as in the complete seismic ray tracing may also be used.

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 computations include also travel time of all non-ray waves (such as the first arriving diffracted waves in shadow zones, head waves, etc.). The algorithm of computation is independent on a model complexity.
Applications: Tomography for an arbitrary source-receiver configuration, wavefront reconstruction, etc.

2. *Ray tracing and synthetic wavefields in 3-D inhomogeneous anisotropic structures*

All future revisions of program package ANRAY, delivered to the sponsors in the second year of the project, will be delivered to the sponsors in the next years of the project.

Package ANRAY:
Model: 3-D laterally varying structure containing isotropic and anisotropic nonvanishing layers. Specification of elastic parameters inside individual layers either by linear interpolation between isosurfaces of elastic parameters or by a B-spline interpolation within a 3-D rectangular grid.
Types of waves: Arbitrary type of elementary seismic body wave (P, S, qP, qS1, qS2, any converted wave).
Computations: Arbitrary position of the point source, numerical integration of ray tracing and dynamic ray tracing equations, calculation of ray vectorial amplitudes, ray Green function, ray synthetic seismograms, particle ground motions.
Applications: Reflection methods, refraction methods, VSP and/or crosshole configuration.
Main innovations: a) testing of the B-spline approximation of the distribution of elastic parameters inside layers, development of "interfaces" for specification of simpler types of models; b) computation of the complete propagator matrix along rays; c) modification of input data systems; d) further debugging, removing inconsistencies in the extensive description of the package.

3. *Sample data for the program packages*

The examples of input data for the MODEL package, describing or approximating models delivered by the sponsors or other typical models, will be prepared. Upon request, also the sample data for programs CRT or NET to perform calculations in such models will be prepared. The examples of input data for the ANRAY package, for models delivered by the sponsors or other typical models, will be prepared too.

4. *Two-point ray tracing in complex isotropic structures*

The two-point ray tracing code will 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.

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

The advantage of the two-point ray tracer will be taken for the computation of ray synthetic seismograms.

6. *Ray tracing for common-offset and common-midpoint configurations*

Study of possibilities of efficient calculation of rays for common-offset and common-midpoint configurations.

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

Study of possibilities to calculate qP wave Green functions in general weakly anisotropic media using the first-order perturbation theory. Study of qS waves signatures in arbitrary weakly anisotropic media.

8. *Replenishing incomplete sets of anisotropic elastic parameters*

Study of replenishing incomplete sets of anisotropic elastic parameters with default values. If all 21 real parts and 21 imaginary parts of the complex-valued components of the stiffness matrix are not known, the missing parameters may be supplied in such a way that the resulting anisotropic medium is in some sense the closest one to the isotropic medium.

9. *Synthetic seismograms for sources and receivers situated at the Earth's surface, at structural interfaces, and close to them*

Development of the code for the calculation of synthetic seismograms using the radiation patterns of sources situated close to structural interfaces in 3-D models. The radiation patterns derived and studied in previous years of the project will be generalized for this purpose. Attention will be devoted to sources situated at the sea bottom.

10. *Fast computation of ray-theory travel times*

Algorithms of fast calculation of ray-theory travel times in dense rectangular grids will further be investigated. Accuracy and efficiency of the interpolation of ray-theory travel times between rays in 3-D models will be studied and the relevant numerical algorithms will be proposed. If possible, attention will also be devoted to the interpolation between different shot and receiver positions.

11. *Second-order methods in grid travel-time tracing*

Accuracy and efficiency of grid travel-time tracing methods to evaluate first-arrival travel times will further be studied.

12. *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 wavefields, and on the accuracy of other modelling methods designed or studied in the framework of the project.

13. *Seismic tomography*

Development of theory and algorithms applicable in seismic travel-time tomography with emphasis on the estimation of its accuracy.

14. *Finite-difference solutions of elastodynamic equations*

The research will concentrate on the hybrid Ray-FD code. The method will employ the already existing codes for the Ray and FD methods, respectively, as well as the coupling technique validated in the hybrid DW-FD method (hereinafter DW=Discrete Wavenumber). Testing will start with 2-D models for which the Ray, DW, or FD synthetic seismograms can be computed separately, without any hybrid combination. The intention of the tests is to understand the applicability limits of the method.

Comparisons of the Ray and DW synthetic seismograms will be carried out for absorbing media with the intention to validate the absorption tretament in the Ray method.

Investigation of the accuracy of the elastic FD method and DW-FD method for models with non-planar topography will be finished. An attempt will be made to evaluate a suite of the benchmark models by several methods in an international cooperation (E. Priolo - Trieste, S. Gaffet - France), and to display the results on a ftp server.

First attempts will be made to write a hybrid (DW-FD, or Ray-FD) code in which a 3-D elastic FD method will be locally applied.

Possible simplifications of the 3-D elastic FD simulation in media displaying a predominant 2-D structural features will be studied.

15. *Concluding remarks*

In addition to this programme, we will certainly be responsive to specific technical suggestions and recommendations of sponsors within the general framework of the project. The research in most directions listed above will continue to the fifth year of the project.