3D Finite Difference modeling in Nucleus+

Introduction

Nucleus+ Finite difference modeling capabilities feature 1D, 2D and 3D visco-elastic modeling in isotropic and anisotropic media. The modeling options range from acoustic constant density models to visco-elastic with variable density. Isotropic and Vertical Transverse Isotropy (VTI) are supported. VTI anisotropy is handled with a minimal performance penalty compared to isotropic modeling.

The finite difference suite also contains a model import functionality allowing the import of gridded models from either SEG-Y or NORSAR-3D property cubes. A complete model editing suite is available in the package. It allows the user to quickly perform spatial resampling, add local diffractors, and add anisotropy to an existing model. Like all forward modeling algorithms in Nucleus+, source and receiver directivity can be accounted for. The source directivity is estimated using the Marine Source Modeling module of the package. Hydrophone (pressure) and multicomponent geophone recordings (particle velocity component or acceleration component) can be output at that stage. Different seismic acquisition schemes are handled such as streamer surveys (narrow-azimuth and wide-azimuth), OBC layouts, and grid survey design and navigation data (imported from P1/90 or SPS).

The finite difference module of Nucleus+ is integrated with the entire seismic forward modeling suite. Elements such as survey, vessel, and source specifications can be reused in the other modules of the software, such as the ray tracing or the 1D recursive reflectivity modeling. A special effort has been made to make the algorithm user friendly, introducing a flexible parameterization and an easy job submission on massive clusters.

Summary

3D finite difference modeling can produce realistic, full scale simulations of actual 3D seismic surveys. The method accounts for the whole wavefield (reflection, refraction and diffraction events, in addition to converted modes) and the data can be created with or without interbed or surface-related multiples. The resulting traces can be used, for example, for survey design, feasibility projects or to test processing algorithms (typical examples are demultiple and imaging).

PGS has extended the capabilities and scope of the Nucleus modeling package to a new platform known as Nucleus+. The finite difference modeling capabilities of Nucleus have been upgraded to a fully functional and parallel 3D finite difference code. The code is parallelized over shots and the computation of each shot can make use of multiple threads. The code is available from simple acoustic to visco-elastic propagation. VTI anisotropy can be accounted for as well.

Nucleus+ is licensed with full support and maintenance arrangements. Several relevant TechLinks are available on the PGS website.
Algorithm

The main advantages of a visco-elastic finite difference scheme are that the geometry of the model can be generally inhomogeneous and that all wave types are included. These may be P-waves, S-waves, conical waves and surface waves. All coupling (reflection and transmission) of these wave modes are also included.

The finite difference code is implemented to handle several modeling problems at an optimum speed of calculation. The algorithm used is an optimized high-ordered staggered-grid scheme, formulated in a stress-acceleration domain. The scheme is very flexible and can be operated as a classical low-order scheme with dense sampling or as a high-order scheme with longer operators and coarser sampling. The high-order schemes are the most efficient and can operate close to the Nyquist sampling limit. Numerical dispersion is low and well controlled when proper derivative operators are chosen. The code has been parallelized at two levels:

1. Different shots can be sent to different compute nodes
2. Each shot can run multi-threaded within a compute node. Threading has been optimized for the CC-numa architecture such as the Intel Nehalem or AMD Opteron processors

The stability and dispersion limits are automatically computed by the algorithm. The most critical criteria for estimating those parameters are the minimum and maximum velocities in the model and the maximum frequency of the source impulse. Depending on the operator length, the velocity range in the model and the source pulse, the algorithm automatically finds the optimum parameterization in order to avoid dispersion and ensure the stability of the computations.

The absorbing boundary layer uses the Perfectly Matching Layer (PML) technique. This absorbing boundary condition is stable even when the ratio of the P-wave velocity to S-wave velocity is much greater than 2. This technology provides up to an extra 40 dB attenuation (Figure 1) and a decrease in the computational time as the thickness of the absorbing layers is reduced.

Surface related multiples are generated by the free surface at the top of the velocity model. An accurate free surface boundary condition is obtained at the nodes on the edges of the model by a modification of density and Lamé parameters on these nodes and by boundary conditions on the time variant fields. The free surface boundary can be replaced by an absorbing boundary layer in order to exclude the surface related multiples from the modeled data.

In order to keep the computational time and the memory requirement as limited as possible, the wavefield is not propagated in the whole velocity model. Instead, for each shot point, a local velocity field is extracted based on the extension of the survey.
Benchmark

The finite difference modeling tool was benchmarked with the SEG Advanced Modeling SEAM model\(^1\). The SEAM model (Phase 1) describes a realistic deep water salt structure in the Gulf of Mexico (GOM) covering 60 blocks down to 15 km depth. In this model the SEAM consortium has generated industry-standard 3D acoustic variable-density finite difference synthetic data. The model is 35 km East-West, 40 km North-South and 15 km deep on a 20x20x20 m grid. The Earth model is derived from the rock properties to ensure physical consistency across the elasticity parameters. The velocity ranges from 1490 m/s in the water to 4800 m/s in the Cretaceous unit. The density ranges from 1.003 g/cm\(^3\) to 2.904 g/cm\(^3\). The input signal is an Ormsby high cut filter converted to minimum phase. The dominant frequency is 14 Hz (see Figure 2).

The survey layout consists in shots and receivers positioned on a regular grid at 15 m depth. Shots were regularly positioned every 150 m in X and Y. A regular grid of 661x661 receivers was attached to each shot with receiver spacing of 30 m in each direction. The modeling used was acoustic with variable density and did not account for source or receiver directivity (Figure 3). The free surface multiples were included. Frequencies up to 30 Hz were modeled in this example, typical of GOM seismic imaging. The resemblance between the PGS and SEAM modeled shot gathers is excellent as shown in Figure 4.

\(^1\)http://www.seg.org/resources/research/seam

![Figure 2: Input wavelet used for the FD modeling](image1)

![Figure 3: P-velocity field and snapshot of the wavefield overlaid](image2)
Conclusions

Finite difference seismic wavefield modeling is considered to be the most accurate form of forward modeling as the method is capable of computing all the wave types and modes, and accounts for both surface and interbed multiples. In addition, there are no limitations regarding the complexity of the Earth model as long as it can be correctly described as a regularly sampled property grid and fits into the computer memory available.

Nucleus+ offers an extensive suite of features for finite difference modeling in 1D, 2D and 3D, from purely acoustic to visco-elastic. The suite is integrated with the entire Nucleus+ package, allowing the seamless exchange of various data and model elements (e.g. models, source/receiver arrays, seismic data, etc). Nucleus+ is licensed for external customers with full support and maintenance arrangements.