Very Large Scale Finite Difference Modeling of Seismic Waves

by

Giuseppe A. Sena

Submitted to the Department of
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To my parents,
Giuseppina and Pasquale, and
to my wife Rosy Carolina

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Abstract

In this thesis we develop a method for solving very large scale seismic wave propagation problems using an *out-of-core finite difference* approach. We implement our method on a parallel computer using special memory management techniques based on the concepts of *pipelining*, *asynchronous I/O*, and *dynamic memory allocation.*

We successfully apply our method for solving a *2-D Acoustic Wave* equation in order to show its utility and note that it can be easily extended to solve *3-D Acoustic or Elastic Wave* equation problems. We use second order finite differencing operators to approximate the *2-D Acoustic Wave* equation. The system is implemented using a *distributed-memory/message-passing* approach on an *nCUBE 2* parallel computer at MIT's Earth Resources Laboratory. We use two test cases, a small (256×256 grid) constant velocity model and the Marmousi velocity model (751×2301 grid). We conduct several trials — with varying memory sizes and number of nodes — to fully evaluate the performance of the approach. In analyzing the results we conclude that the performance is directly related to the number of nodes, memory size, and bandwidth of the I/O-subsystem.

We demonstrate that it is feasible and practical to solve very large scale seismic wave propagation problems with current computer technologies by using advanced computational techniques. We compare two versions of the system, one using *asynchronous I/O* and the other using *synchronous I/O*, to show that better results can be obtained with the *asynchronous* version with *pipelining* and *overlapping* of I/O with computations.

Thesis Advisor: M. Nafi Toksöz
Title: Professor of Geophysics

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Contents

Chapter 1

Introduction

The problem of seismic wave propagation can always be reduced to the problem of solving differential equations with specific boundary conditions. In order to solve this differential equation in heterogeneous media, it is often necessary to use numerical techniques, and of several methods for solving differential equations, the method of "finite difference" is the one most widely used (e.g., Forsythe and Wasow, 1960; Forsythe et al., 1977; Burden and Faires, 1985). The method derives its name from the fact that it approximates continuous derivatives on a regularly-spaced "grid" of points used to represent a medium in which waves propagate. The use of a regular grid to represent the medium makes the method favorable for solution on a computer, although one must select the grid spacing and time increments properly to obtain accurate results (e.g., see Harbaugh and Bonham-Carter, 1970). The *finite difference* method is broadly used because of its simplicity, accuracy, and efficiency to solve large scale wave propagation problems.

Figure (1-1) shows a superposition of a 2-D acoustic pressure field generated using a *finite difference* method on a velocity structure from the Marmousi model (EAEG,

1990; Versteeg, 1994) with a grid dimension of 751×2301. As one can see, in the upper left corner a wave is being propagated through the different velocity layers. The Marmousi model is a complex 2-D model based on a profile through the North Quenguela Trough in the Cuanza Basin in Angola. The model is very complex, and contains many reflectors, steep dips, and strong velocity gradients in both directions. A second example (see figure (1-2)) is a three-dimensional acoustic wave propagation through a two-layer graben model (extensional fault-block). The model is represented by a $400 \times 100 \times 100$ grid, and the boundary between the two interfaces is shown via "isosurfacing," a technique for contouring data in three dimensions. In this representation the P-waves, as indicated by clouds of high pressure, have propagated from the source along the channel formed by the graben axis. These waves are both *transmitted* through the bottom velocity layer and *reflected* at the interface back into the upper velocity layer. These are two examples of the large scale seismic wave propagation problems that we are currently able to solve.

When we try to solve *very large scale* problems — i.e., realistic problems involving three-dimensional grids having points numbering in the thousands, it becomes clear that conventional computer technology is not enough to offer cost/effective or even feasible solutions. For example, when solving a *2-D Acoustic Wave Equation* (Claerbout, 1985; Wapenaar and Berkhout, 1989) or any 2-D/3-D wave equation, we are limited by the amount of memory (and possibly virtual memory) and computation speed available to represent the medium and the data set. Therefore, we need to use so-called *high performance computing* technology like supercomputers or parallel computers to solve large scale wave propagation problems.

This thesis presents a method for solving very large scale seismic wave propagation problems in an efficient way using a parallel computer with limited amount of processors and local memory. We apply the proposed method to the simple case of a *2-D Acoustic Wave Equation*, but it can be readily extended to the *3-D Acoustic*

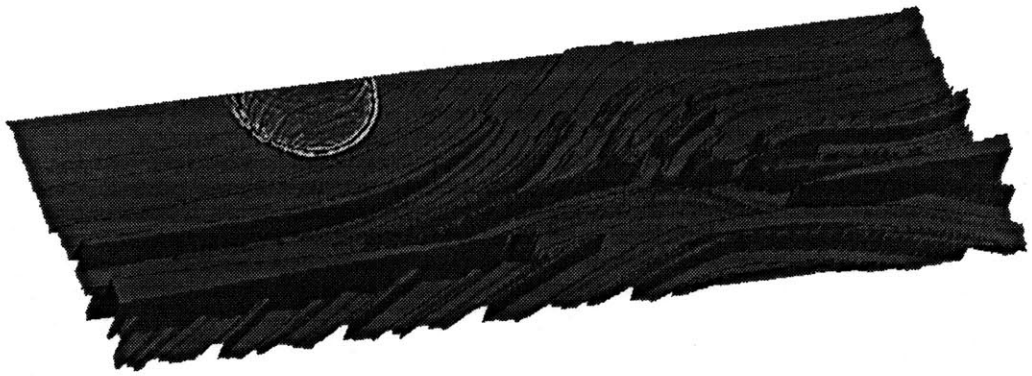


Figure 1-1: A Superposition of a 2-D acoustic pressure field generated using a finite difference method, on a velocity structure from the Marmousi model. Grid dimension is 751 × 2301.

and Elastic Wave Equations.

1.1 Approach

Many methods for modeling seismic waves in homogeneous or heterogeneous acoustic and elastic media have been used, and each one has its advantages and disadvantages. Analytical approaches (Fuchs and Müller, 1971; Chapman and Drummond, 1982; Mikhailenko and Korneev, 1984) can only be applied to simple structures, and in practice none of them give a complete solution to the problem of wave propagation in heterogeneous media. However, it is possible to use numerical methods, like *finite difference*, to find direct numerical solution to the wave equation.

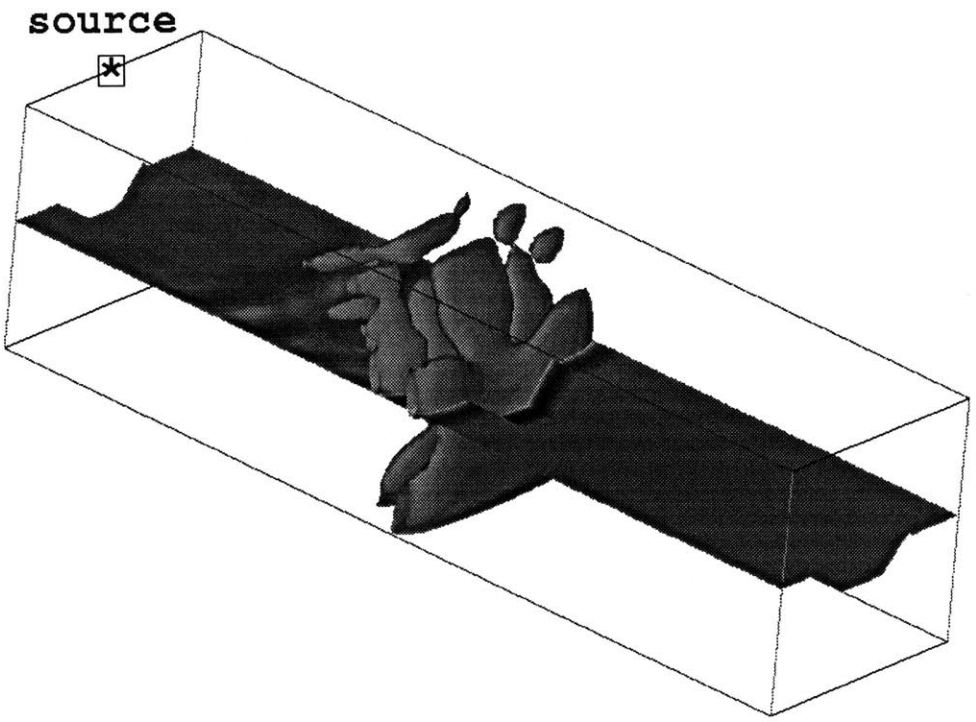


Figure 1-2: A superposition of a 3-D acoustic wavefield on a two-layer graben model. Grid dimension is $400 \times 100 \times 100$.

In this thesis we implement an algorithm for studying large scale seismic wave propagation problems by solving a two-dimensional *Acoustic Wave Equation* (Aki and Richards, 1980; Claerbout, 1985; Wapenaar and Berkhout, 1989). We define the position for an energy source, and given a velocity model we compute how the wave propagates through the medium. We solve the simplified constant density *2-D Acoustic Wave Equation*:

$$\frac{\partial^2 P}{\partial t^2} = v^2 \left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right] P + S(t). \tag{1.1}$$

Using a *finite difference* method to approximate the 2^{nd}–partial derivatives of P,

we approximate equation (1.1):

$$\begin{aligned} P(x,y,t+\Delta t) &\approx \left[2-4v^2\right] P(x,y,t) - P(x,y,t-\Delta t) \\ &+ v^2\left[P(x+\Delta x,y,t)+P(x-\Delta x,y,t)+P(x,y+\Delta y,t)+P(x,y-\Delta y,t)\right] \\ &+ S(t). \end{aligned} \tag{1.2}$$

To solve equation (1.2) we calculate the pressure at time $(t+\Delta t)$ at a point (x,y) — $P(x,y,t+\Delta t)$ — using the last two values in previous iterations at the same point (x,y) — $P(x,y,t)$, and $P(x,y,t-\Delta t)$ —, the pressure values of point (x,y)'s neighbors in the previous iteration — $P(x+\Delta x,y,t)$, $P(x-\Delta x,y,t)$, $P(x,y+\Delta y,t)$, and $P(x,y-\Delta y,t)$ —, and the acoustic wave speed at point (x,y) — v^2.

The *finite difference* approach has become one of the most widely used techniques for modeling wave propagation. Its main disadvantage is its *computational-intensity.* The concept of *elastic finite differencing* was proposed in the classical paper by Kelly et al. (1976), and all finite difference modeling in Cartesian coordinates was done using their approach. Marfurt (1984) presented an evaluation of the accuracy of the *finite difference* solution to the elastic wave equation. Virieux (1986) presented a 2^{nd}-order (in time and space) elastic *finite difference*, introducing the idea of *staggered grids* to allow accurate modeling in media with large values for Poisson's ratio. Actually, the most popular schemes used in seismic applications are the *fourth-order* schemes (Frankel and Clayton, 1984; Frankel and Clayton, 1986; Gibson and Levander, 1988; Levander, 1988), because they provide enough accuracy with a larger grid spacing. The draw back of higher-order schemes is a degraded ability to accurately model complicated media. Comparisons between high and low order *finite difference* schemas are given by Fornberg (1987), Daudt et al. (1989), and Vidale (1990). The *pseudo-spectral* method, which is an extension of traditional 2^{nd}-order temporal methods

(spatial derivatives are computed using Fourier transforms), has also gained acceptance for solving seismic wave propagation problems (Fornberg, 1987; Witte, 1989), but it has the disadvantage that the free-surface and absorbing boundary conditions are generally difficult to implement.

It is important to mention that any 3-D finite difference modeling of real earth problems is computationally intensive and requires large memory. For example, Cheng (1994) presents a three-dimensional finite difference approach for solving a borehole wave propagation problem in anisotropic media, showing the CPU and memory requirements for that kind of application. As another example, Peng (1994) presents a method for calculating the pressure in the fluid-filled borehole by cascading a *3-D elastic finite difference* formulation with the borehole theory. He tried to include the borehole in the finite difference model, but it was not possible with the available parallel computer. He was forced to divide the problem into two parts: propagation from the source to the presumed borehole location using a finite difference method, and coupling into the fluid by applying the borehole coupling equations.

When we use *finite difference* modeling for acoustic or elastic wave equations, it is necessary to include explicit boundary conditions at the edges of the finite grids in order to minimize computational time and memory. It is very common to use absorbing conditions for the sides and bottom of the grid, while either free-surface or absorbing boundary conditions can be applied at the top of the grid. There are several methods to simulate a free-surface (Munasinghe and Farnell, 1973), or absorbing (Clayton and Engquist, 1977; Keys, 1985; Dablain, 1986) boundary conditions for acoustic or elastic wave equations. We will not consider issues surrounding the choice of boundary conditions as their impact on the results of this thesis are negligible.

1.2 Computational Requirement

Finite difference modeling is immensely popular but is also computer-intensive, both in terms of time and memory. Before we begin considering the computational requirements of *finite difference* modeling, let us look at the amount of memory on modern computers as shown by table (1.1). In actual computer architectures an increase in computational power typically implies an increase in main memory as an increased ability to process data is only meaningful when more data can be made available to process.

COMPUTER TYPE	MAIN MEMORY
Typical PC	1-16MB
Workstation	16-128MB
High-end Workstation	128-1024MB
Supercomputer	1-10GB

Table 1.1: Main memory in actual computer architectures.

For memory requirements, let us look at an example. A large, but realistic *2-D Acoustic Wave* propagation problem may need a 10000×10000 grid. If real numbers are represented as 4 *bytes*, we will need about $\approx$ 1144 *Mbytes* of memory. From table (1.1) we deduce that a problem of this size can only be solved on a computer with more than 1 *GB* of main memory. Now suppose that instead of solving a 2-D acoustic wave propagation problem we are solving a *3-D Elastic Wave* propagation problem. This requires nineteen elastic coefficients and displacement/stress information per grid plus additional memory for boundary conditions. A problem comprising a grid of size $1000 \times 1000 \times 1000$ needs a computer with $\approx$ 70 *GBytes* of memory.

While it is possible to solve most 2-D wave equation problems on existing supercomputers, it is clear that for three-dimensional elastic wave propagation problems, particularly those involving anisotropic media, we need alternative approaches to deal

with realistic applications.

A good review of finite difference modeling to seismic wave propagation is given by the *SEG/EAEG 3-D Modeling Project* (Aminzadeh *et al.*, 1994). This project is divided into three working groups, two of which are constructing realistic representations of earth structures in petroleum producing regions with the third group focused on the numerical modeling of seismic waves through these structures. The subsurface structures under consideration include a salt dome model and an overthrust environment model. Among the aims of the project is to determine how best to apply finite difference methods to model wave propagation through these three-dimensional models, to design an algorithm or suite of algorithms for simulating the propagation and finally to use the finite difference modeling technique to generate a synthetic surface seismic survey. Once generated, the synthetic survey will be used to test seismic imaging techniques in a controlled environment, i.e., where the "true" earth structure is known. The project combines the efforts of petroleum companies and computer manufacturers working together with U.S. national laboratories. The U.S. national laboratories have made an enormous effort to implement parallel versions of 3-D acoustic wave propagation code to solve very large scale 3-D wave propagation problems with the computer resources available. Based upon the original earth model specifications, they have estimated that the total computer time available in the U.S. national laboratories' supercomputers is exceeded by the total time needed to generate synthetic data from the overthrust and salt models. Because of this they have been forced to reduce the size of the Salt model in order to be able to solve the problem with the available resources. Clearly, some new approaches are needed if we intend to model large scale problems in an efficient and effective way.

In this thesis, we look at the implementation of finite difference wave propagation on a parallel computer with a limited amount of per-processor-memory, using techniques such as parallel data decomposition, message passing, multiprocessing,

multiprogramming, asynchronous I/O, and overlapping of computations with I/O and communication. It is the combination of these advanced techniques that makes it now feasible to solve large scale wave propagation problems in an efficient way. We develop a system that can be run on one or more processors without any user intervention. When a real problem does not fit in conventional memory, the system automatically decomposes the problem into small subproblems that can be solved individually.

Even though our system is implemented on an *nCUBE 2* parallel computer (a hypercubic machine), the code can be easily ported to other MIMD (*Multiple Instructions over Multiple Data*) machines like Thinking Machines' CM-5, just by modifying the functions that manage the I/O and the communication. This is possible because the system was developed using ANSI standard C code and standard message passing functions.

1.3 Objectives

Having described the problem, the objectives of this thesis are:

1. *To develop a general technique to model very large scale seismic wave propagation problems using the finite difference methods.*

2. *To propose a general framework to solve analogous geophysics problems that share similar data structures and solution methodology with the problem of seismic wave propagation.*

3. *To implement this technique using a parallel computer in order to show its utility.*

Objectives 1 and 2 enable us to define a general technique that could be applied not only to the problem of seismic wave propagation, but also to other geophysics problems that use similar data structures and numerical algorithms (e.g., digital image processing). Objective 3 is the ultimate goal. We show that our technique is applicable for solving large scale seismic wave propagation problems that were previously impossible to solve.

Given these objectives, this thesis makes the following important and original contributions:

1. *Definition of a paradigm for solving wave propagation problems out of core memory.* A double 1-D decomposition technique is applied to divide the original problem between several processors, and every subproblem into smaller blocks that can fit in main memory.

2. *Combine advanced computer techniques to increase the performance.* We use several techniques together — asynchronous I/O, overlapping of computations with communications and I/O, multiprocessing, and pipelining — in order to increase the performance of the system.

3. *Fast and efficient implementation of these methods on a parallel computer.* We developed a parallel algorithm on a *distributed memory* machine using *message-passing* as a communication and synchronization mechanism, for solving large wave propagation problems using a finite difference method.

Other important contributions include:

1. Comparison between the use of *asynchronous* versus *synchronous* I/O based on memory size, number of processors used, type of disks, and block size.

2. Show the necessity of very high I/O-bandwidth for supercomputer applications as a function of the number of processors.

3. Show the relation between inter-processor communication and number of processors in a *"distributed-memory/message-passing"* model, in order to understand the importance of balancing computation with communications.

Our approach to solve the problem is to divide the data set between the group of processors following a "divide-and-conquer" strategy, so that every processor cooperates with the others by solving its own subproblem and then combining the results. The system automatically detects the amount of main memory available in every node in order to determine if the problem can be solved in main memory or if it will be necessary to solve the problem *"out-of-core"*. If the problem does not fit in main memory, using a special algorithm the system attempts to define the size of the largest data block that can be kept in main memory in order to obtain the maximum efficiency. Therefore, every node performs another 1-D data decomposition to solve its own subproblem. These blocks are processed by every node using special techniques like pipelining at the block level, overlapping of computations with communication via message passing, along with I/O using asynchronous operations.

1.4 Thesis Outline

Chapter 2 of this thesis begins with the wave equation and the use of a finite difference method to solve the *2-D Acoustic Wave Equation.* We explain the system developed using a *Top-Down* methodology. We also discuss the design and implementation of the system, as well as memory requirements for different wave equation problems. In addition, we present a detailed explanation of different system components, like the memory and I/O management techniques used, and data decomposition algorithm.

Chapter 3 gives a description of the two test cases used to measure the performance, presents the results obtained from several runs using different parameters, and we also analyze and interpret these results in order to draw several conclusions about the system.

Chapter 4 presents the final conclusions and gives recommendations for future research.

Appendix A contains the auto-documented C source code of the system. This material is provided to facilitate the reproduction of these results and bootstrap further applications of this work. Appendix B presents the hardware and software platform used during the design, development, and test phases of the project for the *2D-Acoustic Wave Propagation* system. Appendix C describes the I/O data files needed to execute the program.

Chapter 2

Approach

In this chapter we describe the solution of the wave equation using a finite difference method (Forsythe and Wasow, 1960). We will also discuss different computer-related topics that must be considered in order to obtain an efficient solution, and provide a general description of the software developed using a *Top-Down* approach. At the end, we will talk about memory and CPU requirements, and we will also give a detailed description of the data decomposition algorithm, and memory and I/O management techniques used.

2.1 Acoustic Wave Equation

In this thesis we implement an algorithm to solve a two-dimensional *Acoustic Wave Equation* (Mareš, 1984; Claerbout, 1985). After it is successfully applied to this simple case, we can extend the approach to three-dimensional problems as well as those problems that involve more complicated forms of the wave equation, including wave propagation in elastic and anisotropic media.

Let us first define the following parameters:

- ρ= mass per unit volume of the fluid.
- u= velocity of fluid motion in the x-direction.
- w= velocity of fluid motion in the y-direction.
- P= pressure in the fluid.

Using conservation of momentum:

$$mass \times acceleration = force = -pressure\ gradient \tag{2.1}$$

Or,

$$\rho\frac{\partial u}{\partial t} = -\frac{\partial P}{\partial x} \tag{2.2}$$

$$\rho\frac{\partial w}{\partial t} = -\frac{\partial P}{\partial y} \tag{2.3}$$

Let us define $\mathcal{K}$ as the *incompressibility* of the fluid. The amount of pressure drop is proportional to $\mathcal{K}$:

$$pressure\ drop = (incompressibility) \times (divergence\ of\ velocity) \tag{2.4}$$

In the two-dimensional case this relation yields:

$$-\frac{\partial P}{\partial t} = \mathcal{K}\left[\frac{\partial u}{\partial x} + \frac{\partial w}{\partial y}\right] \tag{2.5}$$

In order to obtain the two-dimensional wave equation from equations (2.2), (2.3), and (2.5), we divide equations (2.2) and (2.3) by ρ and take its x-derivative and y-derivative respectively:

$$\frac{\partial}{\partial x}\frac{\partial}{\partial t}u = -\frac{\partial}{\partial x}\frac{1}{\rho}\frac{\partial P}{\partial x} \tag{2.6}$$

$$\frac{\partial}{\partial y}\frac{\partial}{\partial t}w = -\frac{\partial}{\partial y}\frac{1}{\rho}\frac{\partial P}{\partial y} \tag{2.7}$$

Following this step we take the time-derivative of equation (2.5) and assuming that $\mathcal{K}$ does not change in time (the material in question does not change during the experiment), we have:

$$\frac{\partial^2 P}{\partial t^2} = -\mathcal{K}\left[\frac{\partial}{\partial t}\frac{\partial}{\partial x}u + \frac{\partial}{\partial t}\frac{\partial}{\partial y}w\right] + S(t) \tag{2.8}$$

Where, $S(t)$ is the source term. Now, if we insert equations (2.6) and (2.7) in equation (2.8) we obtain the two–dimensional *Acoustic Wave Equation*:

$$\frac{\partial^2 P}{\partial t^2} = \mathcal{K}\left[\frac{\partial}{\partial x}\frac{1}{\rho}\frac{\partial}{\partial x} + \frac{\partial}{\partial y}\frac{1}{\rho}\frac{\partial}{\partial y}\right]P + S(t) \tag{2.9}$$

Assuming that ρ is constant with respect to x and y, it is very usual to see the *Acoustic Wave Equation* in a simplified form. Using this approximation we obtain the reduced and most common form of equation (2.9),

$$\frac{\partial^2 P}{\partial t^2} = \frac{\mathcal{K}}{\rho}\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right]P + S(t) \tag{2.10}$$

Substituting the relation,

$$v^2 = \frac{\mathcal{K}}{\rho} \tag{2.11}$$

into equation (2.10) we obtain the following representation for the *Acoustic Wave Equation*:

$$\frac{\partial^2 P}{\partial t^2} = v^2 \left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right] P + S(t) \tag{2.12}$$

Now we approximate the *Acoustic Wave Equation* — equation (2.12) — using a finite difference method. The definition of the 1^{st} derivative of a function $f(x)$ respect to x is:

$$f'(x) = \frac{df}{dx} = \lim_{h \to 0} \frac{f(x+h) - f(x)}{h} \tag{2.13}$$

Using the definition given by equation (2.13) we can approximate the 1^{st}– and 2^{nd}–partial derivative of P respect to t:

$$\frac{\partial P}{\partial t} \approx \frac{P(t+\Delta t) - P(t)}{\Delta t} \tag{2.14}$$

$$\frac{\partial^2 P}{\partial t^2} \approx \frac{P'(t+\Delta t) - P'(t)}{\Delta t} \tag{2.15}$$

If we approximate $P'(t+\Delta t)$ and $P'(t)$ in equation (2.15), using the approximation obtained in equation (2.14), and after reducing the expression we have the following approximation of the 2^{nd}–partial derivative of P respect to t as a function of P:

$$\frac{\partial^2 P}{\partial t^2} \approx \frac{P(t+2\Delta t) - 2P(t+\Delta t) + P(t)}{\Delta t^2} \tag{2.16}$$

Equation (2.16) is an approximation using the values of P at $(t+2\Delta t)$, $(t+\Delta t)$, and (t). This is a three–point approximation centered at point $(t+\Delta t)$ (Burden and Faires, 1985), but if we use the same approximation centered at point (t), we obtain the following formula from equation (2.16):

$$\frac{\partial^2 P}{\partial t^2} \approx [P(t+\Delta t) - 2P(t) + P(t-\Delta t)] \tag{2.17}$$

We can also use equation (2.17) to approximate the 2^{nd}–partial derivatives of P respect to x and y, and express P the three equations as a function of x, y, and t to obtain the following expressions:

$$\frac{\partial^2 P}{\partial t^2} \approx [P(x,y,t+\Delta t) - 2P(x,y,t) + P(x,y,t-\Delta t)] \tag{2.18}$$

$$\frac{\partial^2 P}{\partial x^2} \approx [P(x+\Delta x,y,t) - 2P(x,y,t) + P(x-\Delta x,y,t)] \tag{2.19}$$

$$\frac{\partial^2 P}{\partial y^2} \approx [P(x,y+\Delta y,t) - 2P(x,y,t) + P(x,y-\Delta y,t)] \tag{2.20}$$

If we now use approximations given by equations (2.18), (2.19), and (2.20) in the *Acoustic Wave Equation* — equation (2.12) —, and simplify it to obtain:

$$\begin{aligned} P(x,y,t+\Delta t) \approx & \left[2-4v^2\right] P(x,y,t) - P(x,y,t-\Delta t) \\ & + v^2 [P(x+\Delta x,y,t) + P(x-\Delta x,y,t) + P(x,y+\Delta y,t) + P(x,y-\Delta y,t)] \\ & + S(t) \end{aligned} \tag{2.21}$$

We use equation (2.21) in our algorithm to approximate the *2D–Acoustic Wave Equation.* As can be seen, we approximate the pressure at time $(t+\Delta t)$ in a particular

point (x, y) – $P(x, y, t + \Delta t)$ – using the last two values in previous iterations at the same point (x, y) – $P(x, y, t)$, and $P(x, y, t - \Delta t)$, the pressure values of point (x, y)'s neighbors in the previous iteration – $P(x + \Delta x, y, t)$, $P(x - \Delta x, y, t)$, $P(x, y + \Delta y, t)$, and $P(x, y - \Delta y, t)$, and the speed at point (x, y) – v^2. This finite difference equation is referred to has being 2^{nd}–order in space and time. Higher-order finite difference approximations exist (Abramowitz and Stegun, 1972, Ch. 25) and may be used to derive higher-order finite difference wave equations.

Given equation (2.21) it is important to understand how CPU time and memory usage vary as a function of problem size, the seismic (acoustic) velocity of the medium, and frequency of the source wavelet. These physical parameters influence the choice of finite difference parameters: the grid spacings Δx and Δy, and the time step Δt. The problem size is defined by the region of earth – an area or volume – in which we will numerically propagate waves. With regard to the velocity, two issues are important: what is the range of velocities in the region of interest, and what is the scale of the smallest heterogeneity in the region. Lastly, the wavelet used as the source function in the modeling represents that produced by a real field instrument. This wavelet typically has a characteristic or center frequency along with a finite frequency bandwidth. For specific velocity distribution and a maximum frequency of interest spatial finite difference operators can produce sufficient accuracy when we have a small grid spacing relative with the wavelength of interest. Controlling the choice of a spatial sampling interval is the notion of *numerical dispersion* (Trefethen, 1982). With second order finite difference spatial operators, we typically choose Δx less than or equal to approximately 1/6 of the smallest wavelength on the grid (i.e., $\Delta x \leq\approx \frac{1}{6}\frac{Vp(min)}{f(max)}$, where $Vp(min)$ is the minimum velocity in the grid, and $f(max)$ is the maximum frequency). Moreover, for numerical stability reasons the time discretization should be taken as: $\Delta t \leq \frac{\Delta x}{\sqrt{2}Vp(max)}$, where $Vp(max)$ is the maximum velocity in the grid.

We should note that for an application of specified size, using a small grid spac-

ing (Δx and Δy) increases the computing time and the memory usage, but also increases the accuracy – limited by the precision of the computer used. When modeling wave propagation in complex and highly varying media, we often must discretize the medium at a very high spatial sampling rate to adequately represent the heterogeneity. In this case, low order finite difference schemes tend to be more efficient than high order schemes. Conversely, less complicated earth models imply coarser spatial sampling. For this case, high order finite difference schemes provide greater efficiency. Numerical dispersion can also be reduced by directly reducing the time step Δt, but this again leads to longer compute times. In cases when high order spatial operators are adequate, it is necessary to use very small time steps for temporal operators to reduce dispersion errors.

2.2 Implications for other Wave Equation Problems

When we model *Seismic Wave Propagation* problems it is clear that the CPU time and memory requirements increase as the complexity of the problem increases. Table (2.1) shows memory requirements for typical wave equation problems.

As can be seen, when we increase the complexity and size of the problem the space complexity also increases. Therefore, we have to understand that the main limitation with today's seismic wave propagation modeling is precisely the amount of main memory available in current computers. For example, the *SEG/EAEG 3-D Modeling Project* in its 2^{nd} update (Aminzadeh *et al.*, 1994) presents several projects that are currently under study. One of them is a 3-D Salt Model of size $90000ft$ in offsets x and y and $24000ft$ in depth z. In order to perform a 3-D finite difference simulation using the current resources available at the US National Labs it was necessary to

Wave Equation Problem	Space Complexity	Relative Complexity
$2-D$ Acoustic	$\propto 3(nx \times ny)$	1.0
$2-D$ Elastic Isotropic	$\propto 8(nx \times ny)$	$2.\hat{6}$
$3-D$ Acoustic	$\propto 3(nx \times ny \times nz)$	nz
$3-D$ Elastic Isotropic	$\propto 12(nx \times ny \times nz)$	$4nz$
$3-D$ Elastic Transverse Isotropy	$\propto 15(nx \times ny \times nz)$	$5nz$
$3-D$ Elastic Orthorhombic Anisotropy	$\propto 19(nx \times ny \times nz)$	$6.\hat{3}nz$
$3-D$ Elastic Anisotropic	$\propto 31(nx \times ny \times nz)$	$10.\hat{3}nz$

Table 2.1: Space complexity for different wave equation problems.

reduce the model by half in the three spatial directions. Therefore, the total size was reduced by a factor of 8, and the number of shots by a factor of 4. In another example, (Cheng, 1994) presents a 3-D finite difference method to solve a 3-D Elastic Wave equation in orthorhombic anisotropic medium, in which case to solve a real problem of size $1000 \times 1000 \times 1000$ a computer with ≈ 70 $GBytes$ of RAM memory will be needed, making the memory requirements the limitation point. Therefore, his code in its current form can only be used to solve problems of size $400 \times 100 \times 80$ in an MIMD computer with 128 nodes.

2.3 System Resources Management

In this section we will explain how computer system resources are used in order to achieve high levels of efficiency. The four main resources we manage in our system are: CPU, Memory, Communication, and I/O.

2.3.1 CPU

The most straight forward way to speedup an application is by using more than one processor to solve the problem. Even though our system can be executed in a computer with just one CPU, better results can be obtained by running it on a parallel computer with hundreds or thousands of processors. The idea of using several processors to solve a problem is directly attached to the need for a good data decomposition algorithm.

Figure (2-1) shows an example of a data decomposition approach and the corresponding load distribution between several processors — i.e. 8 processors. For our *2-D Acoustic Wave Propagation* problem we adopted a simple 1-D decomposition algorithm in which the input matrix is only decomposed in the y-direction (rows) in such a way that every processor will have almost the same amount of work to do. This decomposition strategy results in a difference of almost one row between any pair of nodes. This is very important in order to balance the work load between the nodes, so that we can use the processors in a most efficient way. Notice that if we use an unbalanced decomposition algorithm there will be idle processors while others will have to much work to do. A well-balanced decomposition approach will reduce significantly the total execution and communication time for the application.

Another advantage of the *parallel* approach versus a *serial* one is the fact that ideally we can increase the speedup by increasing the number of processors in the system. Of course, this is not always possible in practice due to the overhead imposed by the communication and synchronization on a parallel computer architecture. Therefore, we can increase the speedup by increasing the number of processors up to a point at which the overhead due to communication and synchronization is greater than the gain in speed. For this reason it is critically important to find the optimum number of processors on which to run our application, based on the problem size.

Another important aspect in the area of CPU management is the ability for multiprogramming in every node. This will let us execute several processes in every processor in order to overlap, in time, independent tasks.

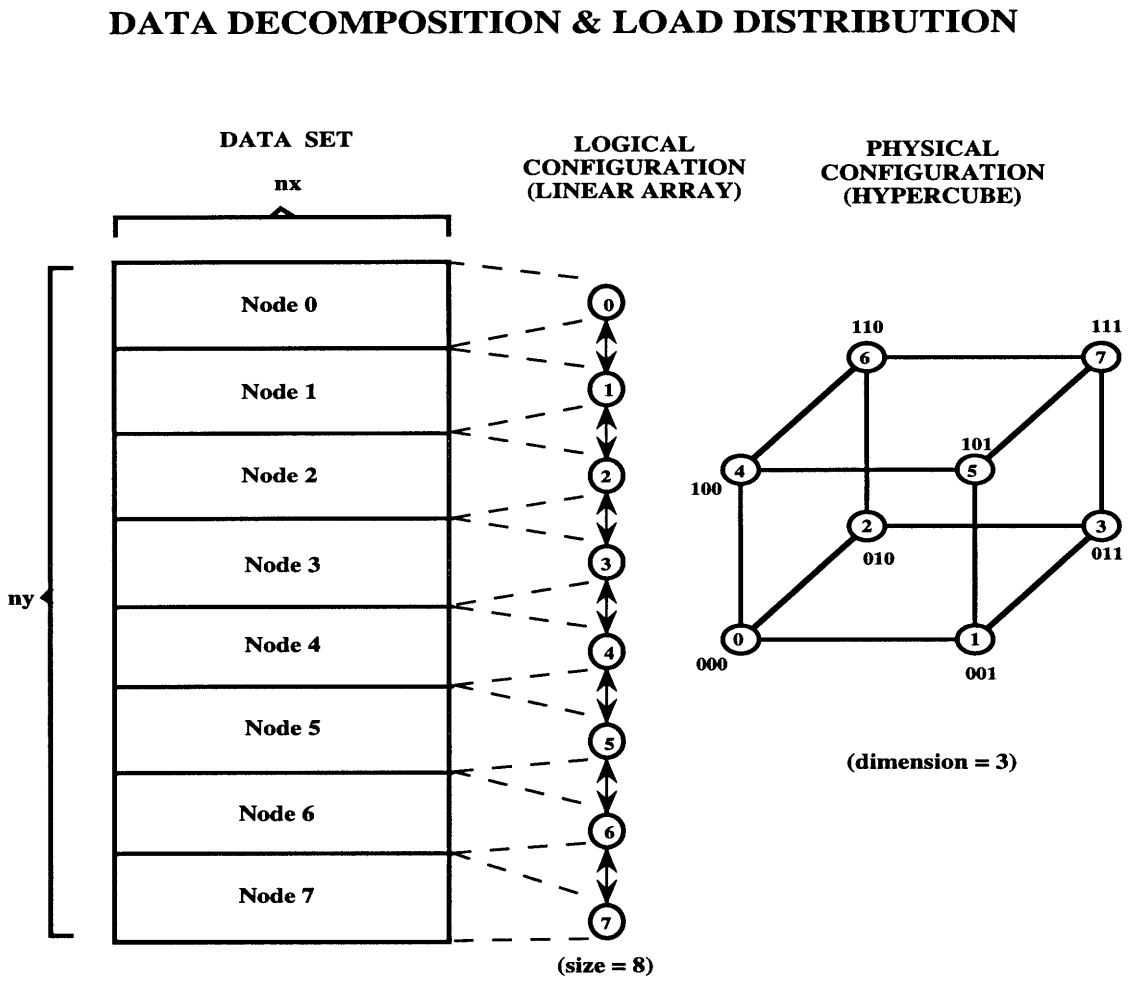


Figure 2-1: Data Decomposition algorithm and How the work load is distributed among the processors

2.3.2 Memory

Main memory is another very important computer resource we need to manage efficiently in order to increase the performance of our application.

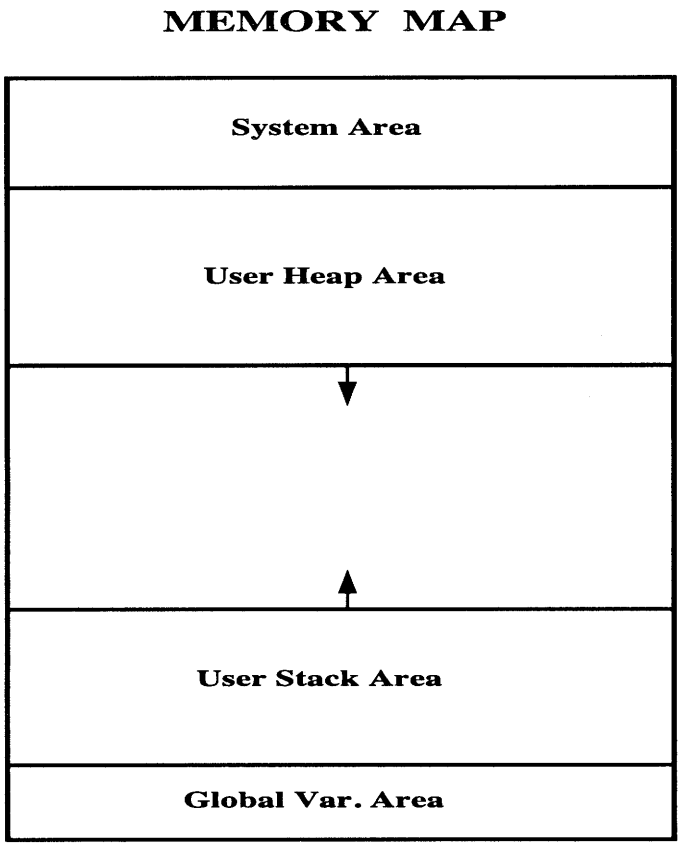


Figure 2-2: Basic Memory Map for a conventional processor

Figure (2-2) shows a typical memory configuration on a conventional computer. In the *system area* is where the Operating System (OS) keeps its data structures. Basically, the user area is divided in three main blocks:

- *Global Variables Area*: to keep global variables and constants defined in the

user program's outer block.

- *User Stack Area*: to keep function parameters and local variables during function calls.
- *User Heap Area*: to keep dynamic data structures allocated at run time.

Depending on the OS and computer the *heap* and *stack* area may or may not grow at run time. In addition, there are other computer architectures which may define additional memory areas.

2.3.3 Communication

In any parallel application we always have to find a trade-off between communication and computation. When using a *distributed-memory* architecture it is very important to keep a balance between the time spent doing computations and the time spent sending and receiving messages. It is *not true* that when we increase the number of processors the speedup increases proportionally.

Another advantageous capability of most distributed memory computers is asynchronous message-passing — the ability to overlap inter-processor communication with computation owing to the availability of special purpose hardware for communication, which enables a node to be sending and receiving a message while the CPU is doing computations. This feature let us send/receive data to other nodes while every node is working in its own data set, therefore minimizing the time spent waiting for messages.

2.3.4 Input/Output

Data input/output (I/O) capabilities also can affect the performance of a parallel application. One of the biggest problems is that I/O devices are very slow respect to CPU and/or main memory. Therefore, every time one requests an I/O operation the application is slowed down to wait for the I/O device — using synchronous operations — to perform the operation. The generation of asynchronous I/O requests in order to overlap I/O operations with computations, as proposed here, alleviates this problem. Using asynchronous I/O we request data blocks in advance — i.e. blocks that are going to be needed in the future — and we continue with the processing of previous data blocks without waiting for the I/O operation to be completed. Thus, there are I/O operations in progress while the program is performing computations. When the requested data block is needed the program waits until the block is in main memory. The advantage of using this approach instead of using synchronous I/O, is the fact that, we are doing useful work while the I/O operation is in progress. This overlapping, in time, also minimizes the waiting time due to I/O operations.

2.4 General Description of the System

The system developed accepts two input files, propagates the seismic wave in time, and produces a snapshot of the pressure field file every specified number of time steps. One of the input files is a velocity file, while the other has all general parameters describing the problem needed for the run. In addition to the pressure field file produced, the system generates another file with detailed timing information showing how much time was spent doing computation, I/O, communication, and initializations. In the following chapters we are going to describe exactly the information in every input/output file.

From now on when we talk about *small* problems, we are referring to problems in which the 2-D velocity matrix and all related data structures needed to solve the wave equation have dimensions such that the total memory available in the conventional or parallel computer is *enough* to fit the problem into main memory and solve it without using any special memory management technique. Even though we are not interested in such problems, the system lets us solve them without any additional overhead and they serve as a baseline for comparison. Consequently, when we talk about *large* problems, we refer to problems in which the 2-D velocity matrix and all related data structures needed to solve the wave equation have dimensions such that the total memory available in the conventional or parallel computer is *not enough* to fit the problem in main memory, and therefore it will be necessary to apply different advanced computer techniques to solve the problem in an efficient and useful way.

In order to attack these typically *CPU-bound* problems with such extremely large memory requirements it is necessary to use advanced technologies and techniques in order to obtain significant results. The technologies and techniques used to develop our system are:

- *Parallel Processing:* use of several processors working cooperatively to solve a problem,
- *Multiprogramming:* ability to execute several tasks simultaneously in the same processor, sharing system resources,
- *Dynamic Memory:* allocation/deallocation of RAM memory *on the fly*, i.e., while the program is running,
- *Message Passing:* communication and synchronization technique used to share data between processors in a distributed memory system,
- *Data Decomposition:* technique used to decompose a data set between a group

of processors using specific criteria, such that, the resulting subproblems are smaller than the original one and the data communication requirements between the processors is minimized,

- *MIMD Architectures:* (MIMD stands for Multiple Instruction on Multiple Data) a computer architecture hierarchy which defines machines with multiple processor units, where each one can be executing different instructions at a given time over different data elements. These machines are based primarily upon the ideas of *Parallel Processing* and *Multiprocessing*,

- *Asynchronous I/O:* generation of asynchronous I/O requests without having to wait for data to be read or written in order to continue the execution,

- *Pipelining Processing:* a technique for decompose a task into subtasks, so that they can be sequenced, in time, like in a production line,

- *Task Overlapping:* a technique used to generate simultaneously multiple independent tasks, such that, they can overlap in time owing to the fact that they use different system resources. This technique is based upon the concepts of *multiprogramming* and *synchronization.*

It is the combination of these techniques and concepts which let us develop an efficient and valuable system. In the following sections we are going to explain how all these concepts were used to develop the system.

The only input needed from the user is the *root file name* which will provide the necessary information to the system in order to read the velocity and parameters input files. First, the system detects the basic information about the machine, such as the number of processors and processor IDs, etc., and reads all global parameters needed for the model. After doing that, the 2D input matrix is decomposed between the processors in chunks of about the same number of rows — we use a simple *1D*

data decomposition technique, and we perform the initializations needed. Then we determine if we are dealing with a *small* or a *large* problem based on the number of processors used, the memory available, and the problem size. This will make us solve the problem in core memory, the conventional way, or out of core memory, using advanced computer techniques. If the problem does not fit in main memory, every processor further decomposes its own subproblems into smaller blocks such that every one can be solved in local memory. After allocating and opening all necessary files the system enters the outer loop in which it performs the number of iterations or time-steps specified by the user in order to propagate the seismic wave a desired distance. With every iteration each processor computes one block at a time using a combination of several computer techniques like *pipelining*, *asynchronous I/O*, and *overlapping* of computations with communication and I/O. Therefore, in every time step a processor can be reading and writing several data blocks, sending and receiving edges to and from adjacent nodes, and solving the wave equation for the current block, simultaneously. All this is possible because every processor possesses independent hardware units for performing computations, I/O, and communication; which are able to operate in parallel with the other units. It is this overlapping and pipelining of operations which give us the high performance expected.

The user must notice that in a computer system without such features, these operations must be sequentialized in time. Therefore, every time we send an edge to our neighbor processor we also have to wait until it is received, and when we request to read or write a block we must also wait until the I/O operation has finished. Moreover, while we are computing, it will be impossible to request an I/O operation, or to send or receive messages. As a result, the time spent in every of these operations will have to be added to obtain the total running time, because there is going to be impossible to overlap independent operations.

2.5 Algorithm Design

In this section we are going to explain a high level *top-down design* of our *2-D Acoustic Wave Propagation* system, without getting into programming details. In addition, we are going to give a general description of the most important procedures in *pseudo-language*. The programming details will be covered in the following section.

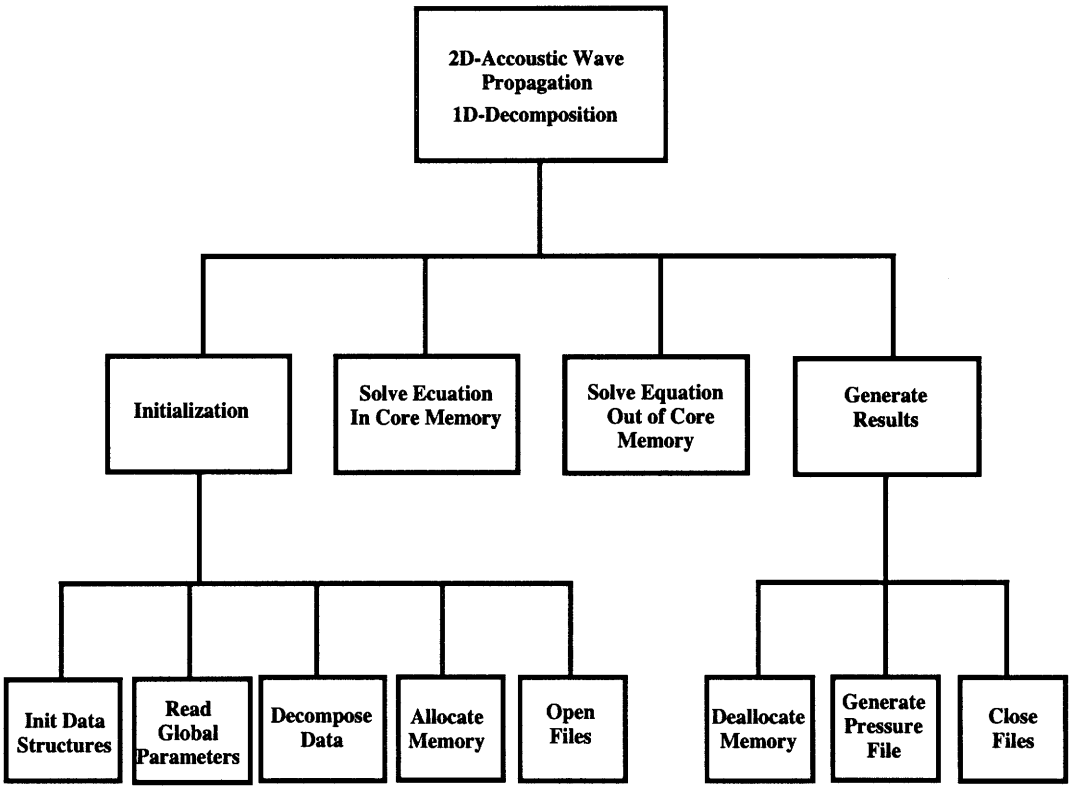


Figure 2-3: Top-Down Decomposition

Figure (2-3) shows the *top-down* decomposition of our *2-D Acoustic Wave Propagation* system with the more important modules. At the first level the problem can be decomposed in four modules: *INITIALIZATION*, *SOLVE-EQUATION-IN-CORE-MEMORY*, *SOLVE-EQUATION-OUT-OF-CORE-MEMORY*, and *GENERATE-RESULTS*. The first module to be executed is the *INITIALIZATION* module. After that, if the problem fits or not in main memory, the *SOLVE-EQUATION-IN-CORE-MEMORY* module or the *SOLVE-EQUATION-OUT-OF-CORE-MEMORY* will be executed. The last module to be executed is the *GENERATE-RESULTS* module. In the following paragraphs we will show the general design of each one of these main modules.

2.5.1 *INITIALIZATION* Module

In this module we perform the initialization of all data structures necessary for the rest of the system. We also read global parameters of the problem, decompose the data set, etc. The modules executed by the *INITIALIZATION* Module are:

- *Init-Data-Structures* Module: initialization of data structures used throughout the program such as I/O, communication, and manipulation structures.
- *Read-Global-Parameters* Module: read from disk all parameters defining the problem: dimension, iterations, wavelet type, etc.
- *Decompose-Data* Module: decomposes the data set between available processors based on the number of processors and the grid dimension.
- *Allocate-Memory* Module: dynamically allocates all necessary memory to read, write, and process a block, as well as the necessary memory for message passing and block manipulation.

- *Open–Files* Module: opens the necessary files to perform the computations and generate the results.

2.5.2 *SOLVE–EQUATION–IN–CORE–MEMORY* Module

In this module we solve the equation *in core* memory when the problem fits in main memory. The *pseudo-code* description of this module is:

```
MODULE_IN_CORE_MEMORY()
{
FOR (every time step) DO
  UPDATE value in source position;
  IF (I am not NODE 0) THEN
     SEND upper edge TO up neighbor;
  IF (I am not the last NODE) THEN
     SEND lower edge TO down neighbor;
  COMPUTE-IN-CORE-MODEL();
  IF (I am not NODE 0) THEN
     RECEIVE upper edge FROM up neighbor;
     COMPUTE upper edge;
  END-IF;
  IF (I am not the last NODE) THEN
     RECEIVE lower edge FROM down neighbor;
     COMPUTE lower edge;
  END-IF;
END-DO;
};
```

Figure 2-4: Algorithm for Solving the Acoustic Wave Equation In-Core Memory

2.5.3 *SOLVE–EQUATION–OUT–OF–CORE–MEMORY* Module

In this module we solve the equation *out of core* memory when the problem does not fit in main memory. The *pseudo-code* description of this module is:

```
MODULE_OUT_OF_CORE_MEMORY()
{
FOR (every time step) DO
  UPDATE value in source position;
  ASYNCHRONOUSLY READ BLOCK (0);
  IF (I am not NODE 0) THEN
     SEND upper edge TO up neighbor;
  ASYNCHRONOUSLY READ BLOCK (1);
  WAIT for block (0);
  COMPUTE BLOCK (0);
  FOR (every block B>0) DO
    ASYNCHRONOUSLY READ  BLOCK (B+1);
    ASYNCHRONOUSLY WRITE BLOCK (B-1);
    WAIT for block (B);
    COMPUTE BLOCK (B);
  END-DO;
  ASYNCHRONOUSLY WRITE BLOCK (next to last);
  COMPUTE BLOCK (last);
  ASYNCHRONOUSLY WRITE BLOCK (last);
  WAIT for blocks (next to last) and (last);
  IF (I am not the last NODE) THEN
     SEND lower edge TO down neighbor;
     RECEIVE lower edge FROM down neighbor;
     COMPUTE lower edge;
     ASYNCHRONOUSLY WRITE lower edge;
  END-IF;
  IF (I am not NODE 0) THEN
     RECEIVE upper edge FROM up neighbor;
     COMPUTE upper edge;
     ASYNCHRONOUSLY WRITE upper edge;
  END-IF;
  WAIT for upper and lower edges to be written;
END-DO;
};
```

Figure 2-5: Algorithm for Solving the Acoustic Wave Equation Out-of-Core Memory

2.5.4 *GENERATE–RESULTS* Module

Its purpose is to gather the results generated by the program, deallocate memory, and close files. The modules executed by the *GENERATE RESULTS* Module are:

- *Deallocate–Memory* Module: deallocates the memory used by the dynamic data structures in the program.
- *Generate–Pressure–File* Module: generates a resulting pressure file depending on the "snapshot" specification.

- *Close–Files* Module: close the files used during the computations, and all output files.

2.6 Implementation Details

In this section we are going to explain in detail several implementation decisions we made during this project. We will talk about the data decomposition algorithm used, and memory management and I/O management techniques used.

2.6.1 Data Decomposition Algorithm

We use a *1D-data decomposition* algorithm in order to divide the work between the processors. Therefore, because we manage matrices of $(ny \times nx)$, we distribute the ny rows between the available processors at execution time. Of course, There is a good reason to do that. We are using a *one-point finite difference* method in order to solve the wave equation, therefore in order to compute the pressure at any point at time (t) we use the actual value at time (t), the value of the *speed* at that point, and the pressure values at time $(t-1)$ of the four point's neighbors — *north*, *south*, *west*, and *east* neighbors (see figure (2-6)).

Due to the fact that we are using a *one-point finite difference* method every processor must send its pressure field lower and upper edges at time $(t-1)$ to its neighbors, so that, every processor can compute the edges of the pressure field at time (t). Figure (2-7) shows this decomposition. Every internal node send its upper and lower edge to its *north* and *south* neighbor, except *node 0* and the *last node*. For this kind of data communication it is more efficient to use a *1D-data decomposition* approach, because the edges (matrix rows) are kept in memory in consecutive bytes, and the process of

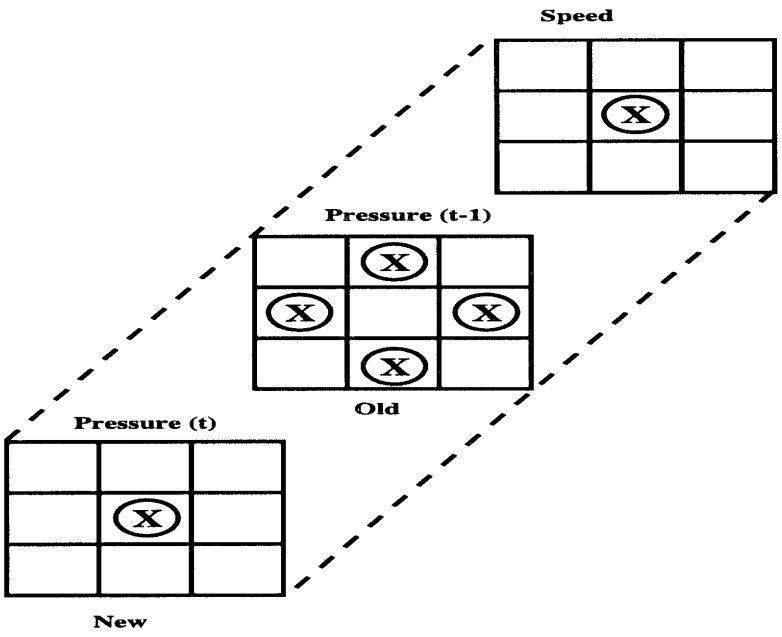


Figure 2-6: Finite Difference Computation

sending them does not involve any kind of data movement before the transmission. On the other hand, if we would have used a *2D-data decomposition* algorithm for this problem every time we send a column we would have first moved the column elements to a contiguous memory area in order to send it, yielding a very inefficient communication pattern. This happens because elements in the same column of a matrix are not saved in consecutive memory locations, when the computer system you are using keeps matrices by row in main memory.

The *1D-decomposition* algorithm used tries to be fair and assigns about the same number of rows to every processor in order to balance the work load. Indeed, the only two options are:

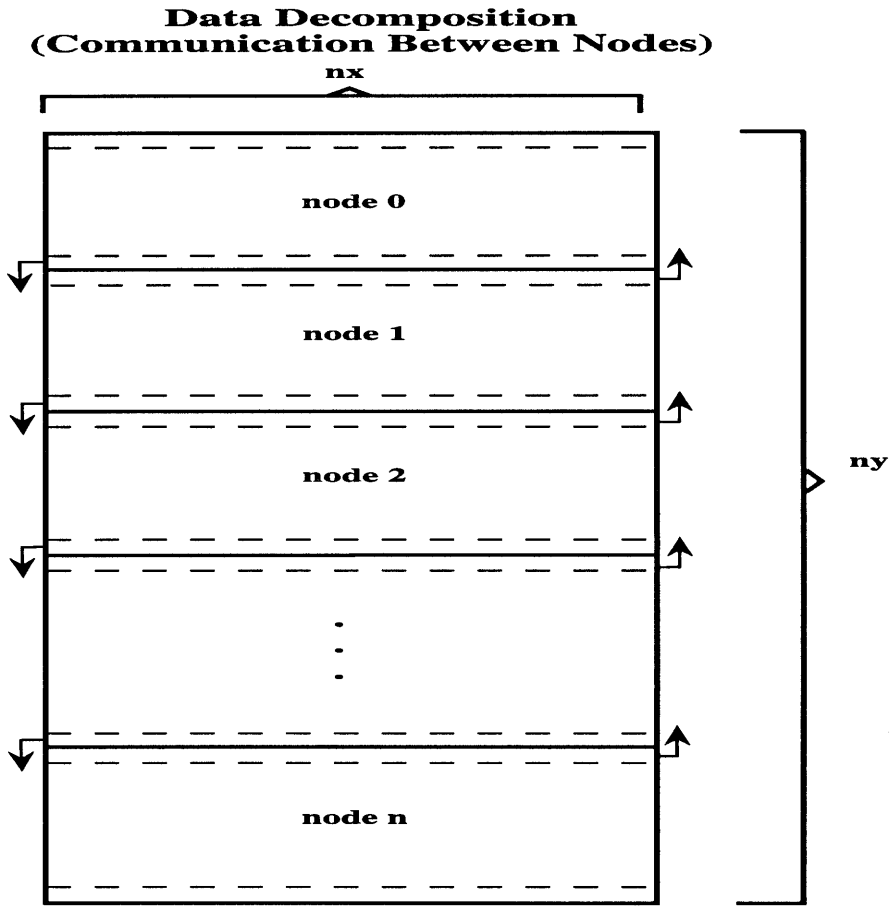


Figure 2-7: Data Decomposition - Communication Scheme Between Nodes

1. all nodes have the same number of rows, or

2. the first nodes [**0**,i] have one more row than the last nodes [$i+1$,$last$].

Figure (2-1) gives an example of a data decomposition and load distribution when we use 8 processors. Even though we are using a physical hypercube of *dimension 3* (8 processors), they are logically configured as a linear array of *size 8*. This is possible because the *nCUBE 2* supercomputer lets you send and receive messages between any pair of nodes in a subcube, using very sophisticated routing algorithms. The *ny* rows

are decomposed between the 8 processors and they communicate during the computations only with its *north* and *south* neighbors. The system was developed such that, communication between processors overlaps in time with computations, in order to minimize the waiting time due to communication — communication overhead.

2.6.2 Memory Management

In every *nCUBE 2* node the memory map is a little bit different to the one in a conventional computer, because the *nCUBE 2* is an hypercubic architecture that uses *message passing* as a communication and synchronization mechanism. Figure (2-8) shows this configuration. The main difference with a conventional processor is that every nCUBE node has an additional area called the **Communication Buffer Area**. This area can be defined the same way as you define the size for the *heap* and the *stack* areas, when you submit a job to the nCUBE supercomputer. This area is primarily used by every node for communication and I/O, and can be managed by the user in a similar way as the *heap* area — allocating and deallocating memory blocks. Every time a user wants to send a message from one node to another, the message is copied from the user area to the *communication buffer*, before the transmission. In a similar way, every message received by a node is stored in the *communication buffer* and a pointer to the message is returned to the user program to access that message. Moreover, an nCUBE node uses this area as a temporal buffer during I/O operations. Therefore, the main difference between the *heap* and the *communication buffer* area is that the later can be used by the system or the user, while the *heap* is only used by the user. That is why is so important to define an adequate size for the *communication buffer* area, leaving enough free space to be used by the OS activities.

We define a very small space for the *heap* (128KB) and the *stack* (128KB) areas, because we are not using neither recursive functions nor too many levels of nested

function calls. Instead, in order to improve the efficiency we manage almost all dynamic data structures in the *communication buffer*, so that we do not need to move data around memory every time we need to send, or receive messages.

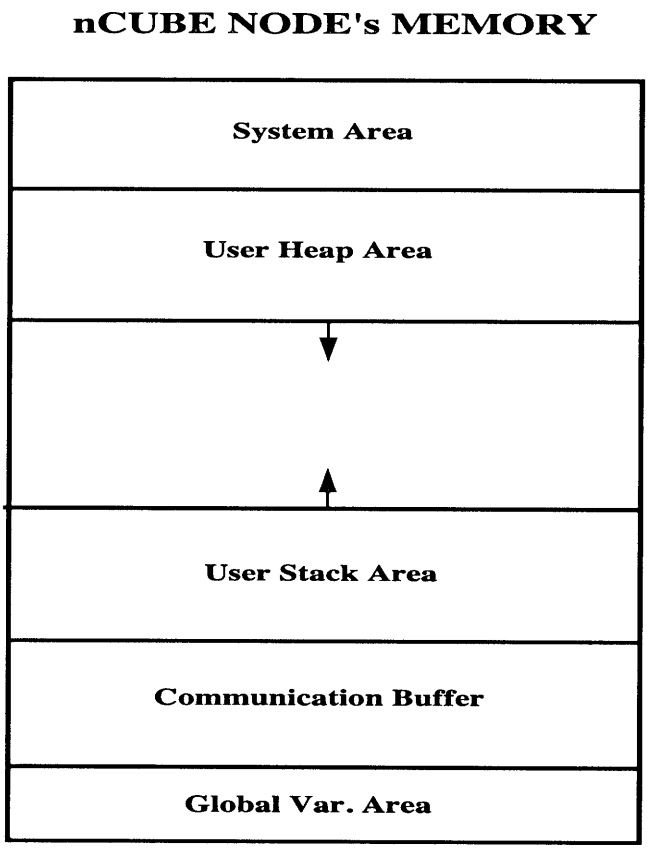


Figure 2-8: nCUBE Node's Memory Map

In addition, when the input matrix has been distributed between the processors there is still the possibility that the problem cannot be solved in main memory, and we need to decompose even more the submatrix managed by every processor. We use again a *1D-data decomposition* algorithm to divide every submatrix in blocks that can be managed in main memory. Our goal here, is to try to keep the largest possible

data block in main memory in order to obtain the best results. Therefore, we divide the submatrix in n blocks, so that the block size is the largest possible, considering the available memory and the number of blocks we must keep simultaneously in main memory in order to solve the problem *out-of-core* memory. Again, there are also only two cases:

1. every block has the same number of rows, or
2. blocks $[0,n-1]$ have the same size, and block n is smaller.

Figure (2-9) shows the block decomposition in any *node i*.

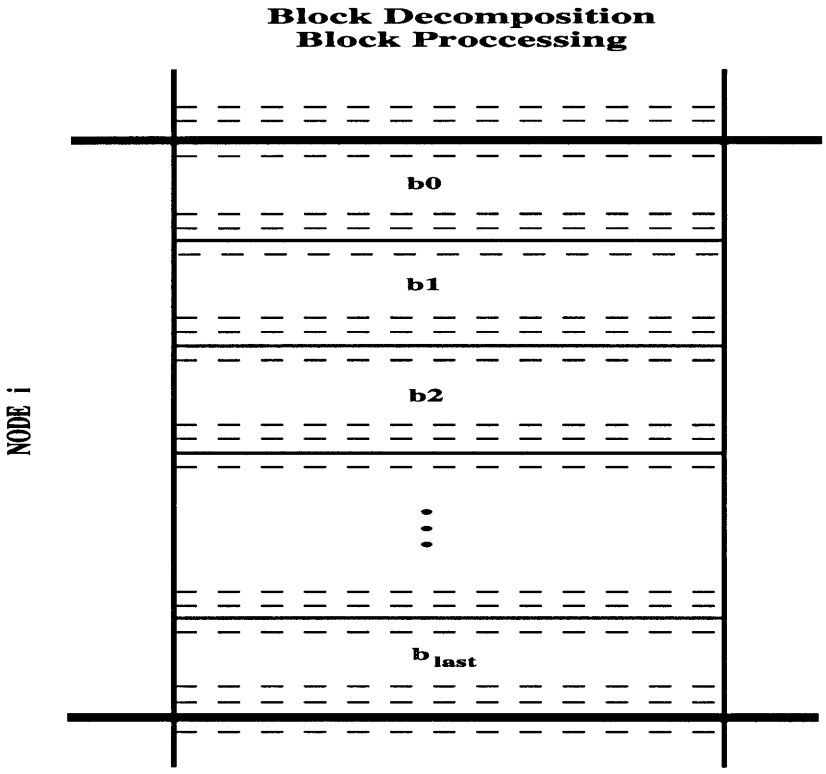


Figure 2-9: Block Decomposition and Processing

In summary, what we are trying to do is, to emulate in "some way" a virtual memory manager that let us solve very large wave propagation problems which do not fit in main memory, by the use of secondary storage (disks) to process the data set using smaller blocks. Of course, our system is not as complex and versatile as a *virtual memory manager*, but it is enough for our practical purpose.

2.6.3 Asynchronous I/O

When the problem to be solved does not fit in main memory, our problem of *seismic wave propagation* is not *cpu-bound* anymore, and becomes an *I/O-bound* problem. We are going to need to, read large data blocks from disk to be processed in main memory, and to, write back to disk the modified data blocks. The use of synchronous I/O would be crazy, because the time spent waiting for blocks to be read and written would not be acceptable. Therefore, we decided to use the asynchronous I/O features of the nCUBE in order to overlap I/O operations with computations. By *asynchronous I/O*, we mean that, we can initiate or request an I/O operation — read or write —, and continue the execution without having to wait for the operation to be completed. Of course, that means that we do not need the data requested until some time in the future.

Basically, our approach is request a read for the next block to be processed, request a write for the last block processed, and proceed to compute the current block. After we finish the processing, we need to wait for the read and write operations to be completed, in order to continue. The advantage was that we did not have to wait for the I/O operations to be completed in order to proceed with the computations, overlapping in time I/O operations with computations.

If we want to do this overlapping, we must keep simultaneously in main memory

the previous, current, and next data block. Figure (2-10) shows that the minimum number of data blocks that have to be kept in main memory in order to overlap the I/O operations with computations is seven (7). When we request to read the next block to be processed, it is necessary to read the *SPEED block*, the *NEW pressure block* (at time t), and the *OLD pressure block* (at time $t-1$). When we request to write the previous block, it is necessary to write only the *NEW pressure block* (at time t). And, when we want to process the current block, it is necessary to keep in main memory, the *SPEED block*, the *NEW pressure block* (at time t), and the *OLD pressure block* (at time $t-1$). We compute the maximum possible size for a data block based on this information, and leaving enough space for the OS in the *communication buffer*.

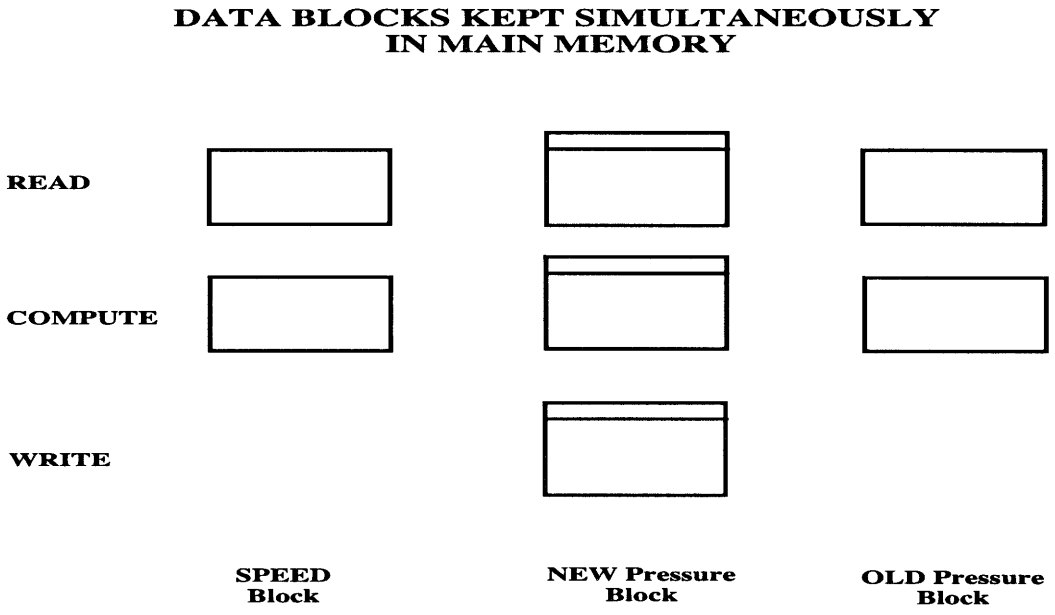


Figure 2-10: Data Blocks Kept Simultaneously in Memory

Given this explanation, now figure (2-11) shows a time diagram of a block processing sequence in a particular node. Suppose that, the submatrix corresponding

to a particular node was subdivided in $(last + 1)$ blocks. At the beginning, we read *block 0*, an wait until the I/O operation is finished. Then we request to read *block 1*, and compute *block 0* simultaneously. When we finish to compute *block 0*, we request to read *block 2* and write *block 0*, while we compute *block 1*. From now on, we request to read the next block, to write the previous block, and to compute the current block while the I/O operations are in progress.

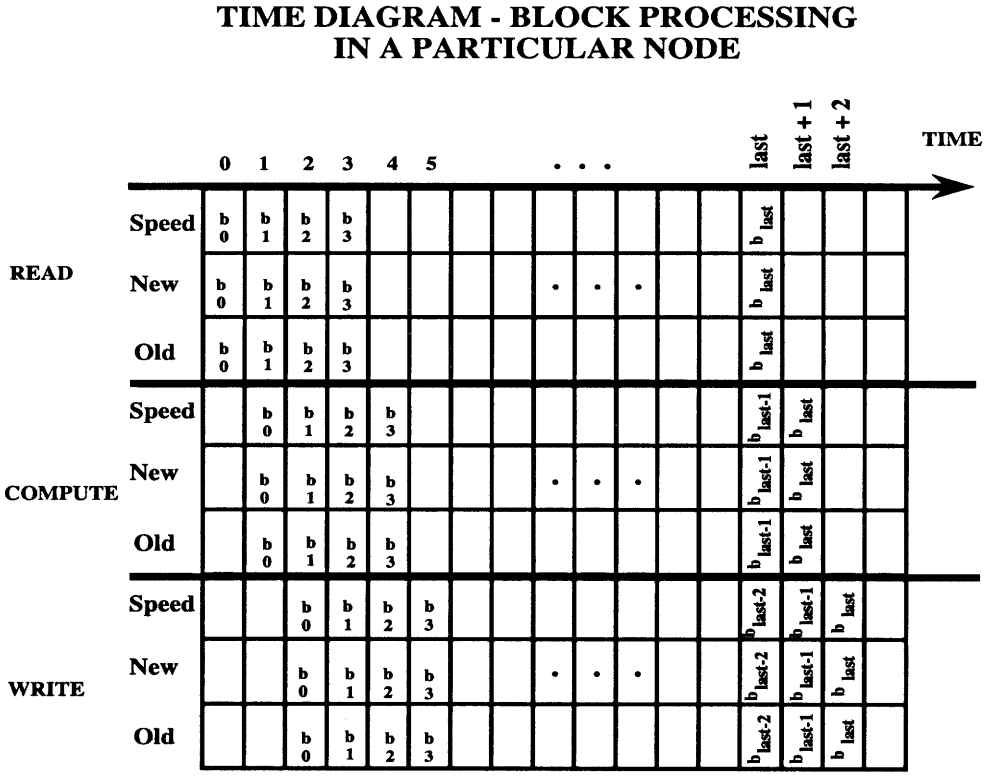


Figure 2-11: Time Diagram Showing How blocks are processed in time in a particular node

Chapter 3

Results/Test Cases

In this chapter we present the results obtained after evaluating our system with two test cases. We also show the parameters used for the runs and how waves are propagated through the medium, and we analyze and interpret the results obtained. We test our system with two models: a *Constant* velocity model of 256×256 grid points (256KB), and the *Marmousi* model (EAEG, 1990; Versteeg, 1994) of 751×2301 grid points (6.6MB). The goal of the first model is to show how the system behaves over hundreds of iterations, even though this is a very small test case. The goal of the second model is to give an idea of the system's behavior with large data files using *asynchronous I/O* operations. Although we could not test the system using *asynchronous I/O* with a disk array, we were able to perform several tests using PFS (Parallel File System) with *synchronous I/O*. These tests allow us to predict the behavior when using *asynchronous I/O*. We also present an analysis of the expected system performance and a comparison with the synchronous version. In addition we give a bound for the *in-core* version in the sequential and parallel case.

3.1 Description of Test Cases

3.1.1 Constant Velocity Model

We used a simple and very small constant velocity model to test the correctness of our solution. This model is of 256 × 256 grid points ($nx = ny = 256$), and the constant velocity used was $10000 ft/msec$. We used $dx = dy = 2.1 ft$, and $dt = 0.15 msec$ as the size of the discretization in space and time. We used a Ricker wavelet ($ichoix = 6$) as a source function, with $t0 = 0$ as the start time for the seismogram, and $f0 = 250 Hz$ as the center frequency of the wavelet. We defined $psi = 0.0$, and $gamma = 0.0$ because they are not used by the Ricker wavelet. In addition, we used an explosive source ($itype = 0$), and the source is positioned in the center of the grid ($isx = 128$, and $isy = 128$). The width of the source smoothing function is selected as $sdev = 2.1$. The basic purpose of this test was to see the behavior of the system with a large number of iterations ($nt = 150$), and to make sure that the wave propagation was correctly modeled. Figures (3-1)-(3-3) show how the wave is propagated after 500 iterations. It is important to mention that we are using free-surface boundaries.

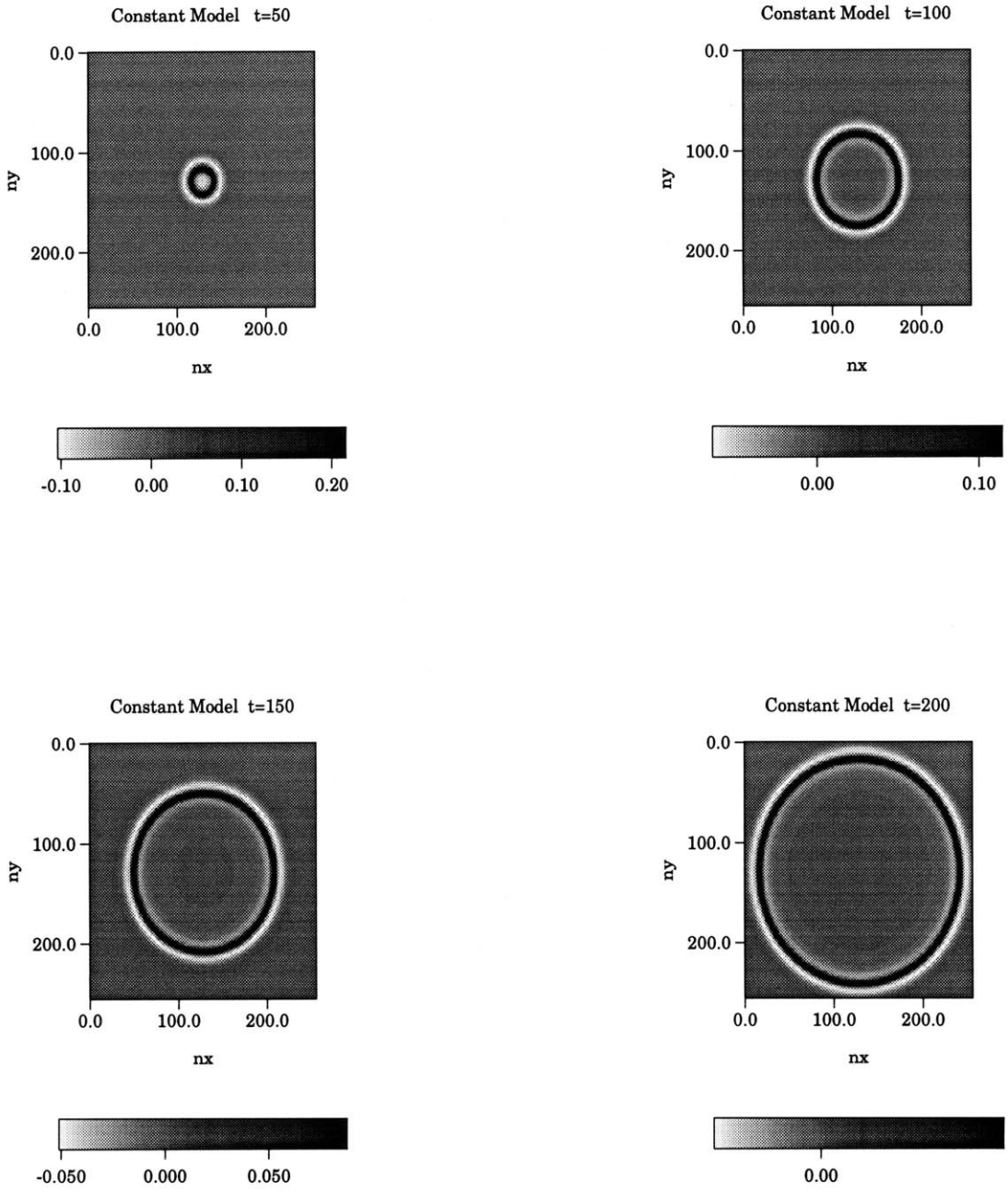


Figure 3-1: Propagated Wave after 50, 100, 150, and 200 iterations.

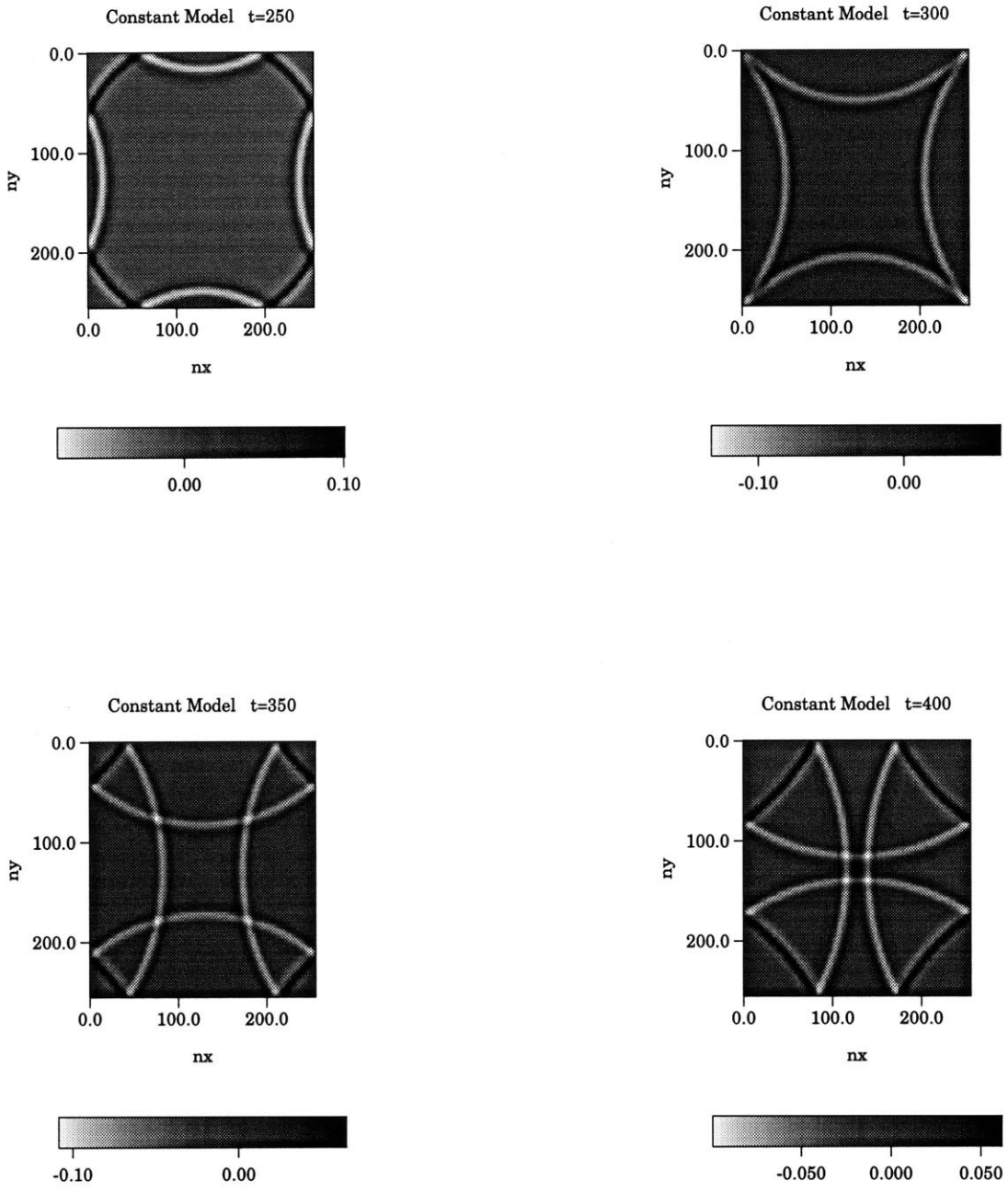


Figure 3-2: Propagated Wave after 250, 300, 350, and 400 iterations.

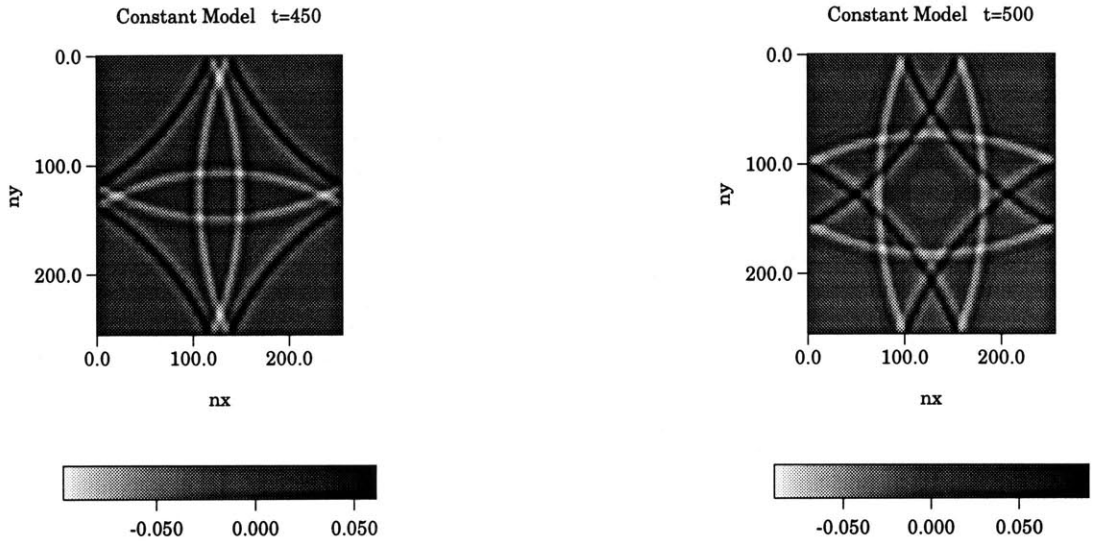


Figure 3-3: Propagated Wave after 450, and 500 iterations.

3.1.2 Marmousi Velocity Model

Figure (3-4) shows the *Marmousi* velocity model (EAEG, 1990; Versteeg, 1994), which is a complex synthetic 2-D acoustic data set, based on a profile of the North Quenguela Trough in the Cuanza Basin in Angola. Because the model underlying *Marmousi* was based on a real situation it is very complex, meaning that it contains many reflectors, steep dips and strong velocity gradients in both directions.

This model is of 751 $\times$ 2301 grid points ($nx = 2301$, $ny = 751$). We used $dx = dy = 333.0ft$, and $dt = 0.04msec$ as the size of the discretization in space and time. We used a Ricker wavelet ($ichoix = 6$) as a source function, with $t0 = 0$ as the start time for the seismogram, and $f0 = 250Hz$ as the center frequency of the wavelet. We defined $psi = 0.0$, and $gamma = 0.0$ because they are not used by the Ricker wavelet. In addition, we used an explosive source ($itype = 0$), and the source is positioned in the top center of the grid ($isx = 1150$, and $isy = 0$). The width of the source smoothing function was selected as $sdev = 333.0$. The basic purpose of this test was to see the behavior of the system with large data files, and few iterations ($nt = 5$). Figures (3-5), (3-6), and (3-7) show how the wave is propagated after 2500 iterations for the Marmousi model. At the bottom of figure (3-6) we can see the reflections of high-contrast boundaries (see figure (3-4)).

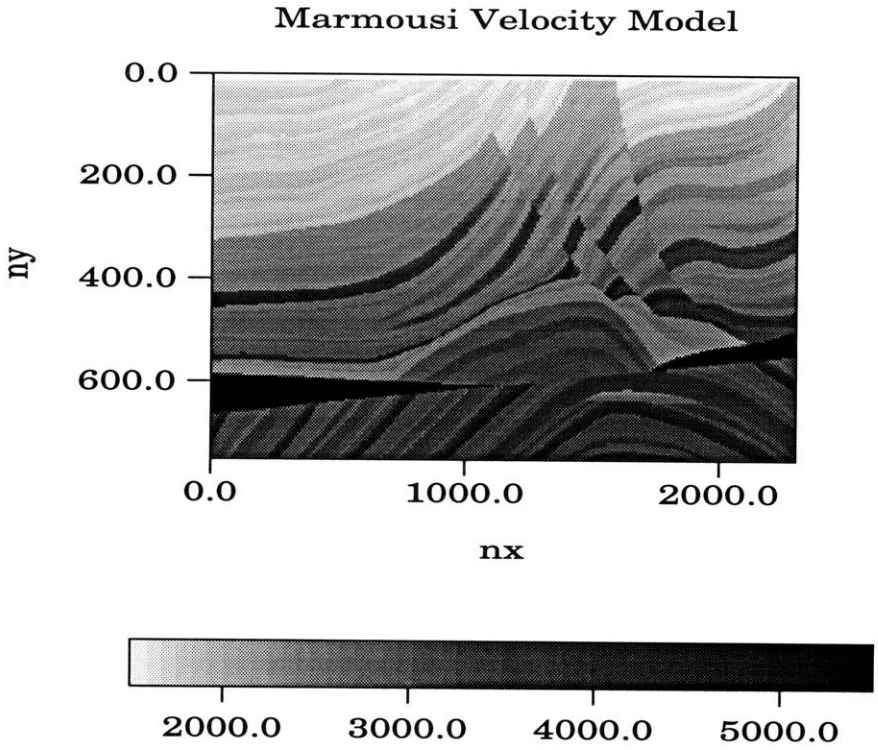


Figure 3-4: *Velocity Model for the MARMOUSI data set*: The grid size is 751×2301.

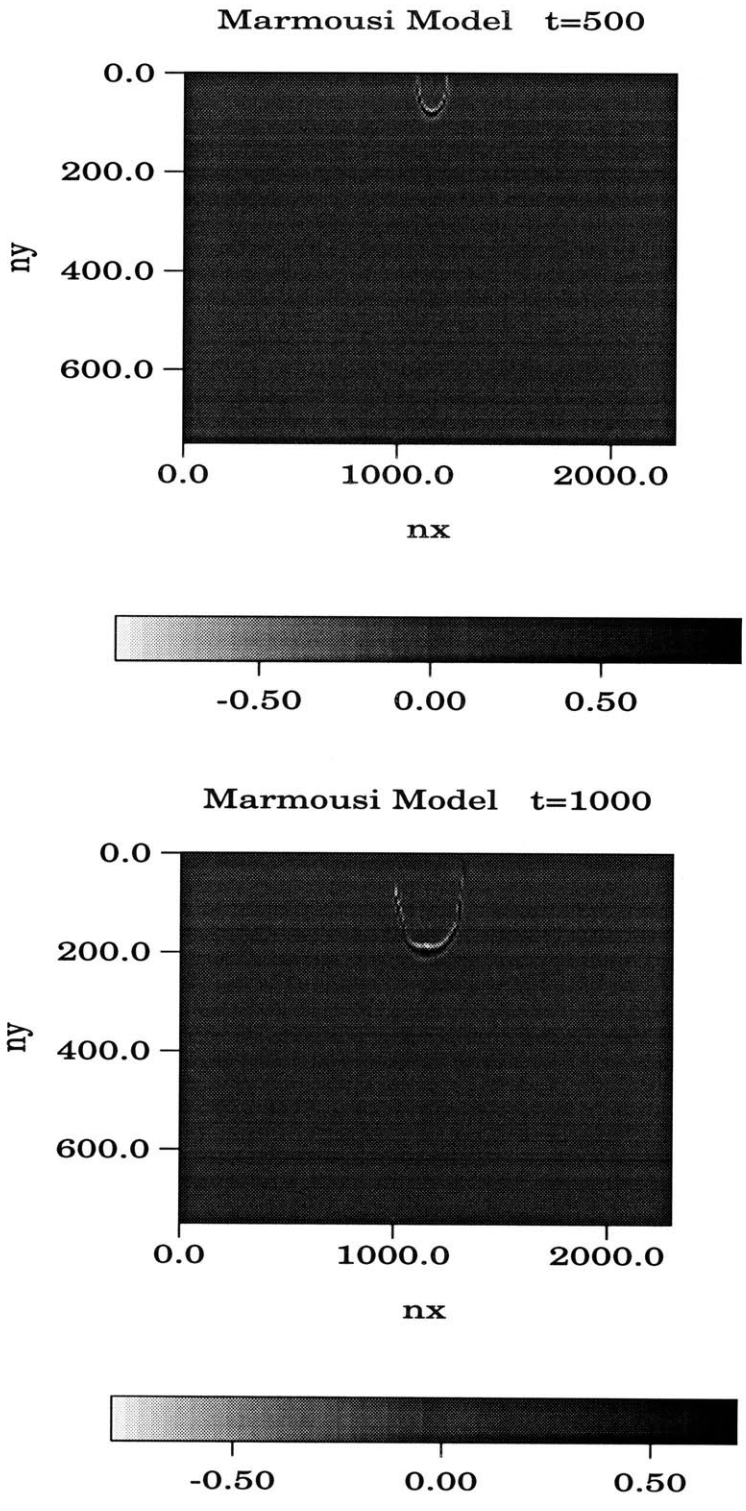


Figure 3-5: Propagated Wave after 500 and 1000 iterations.

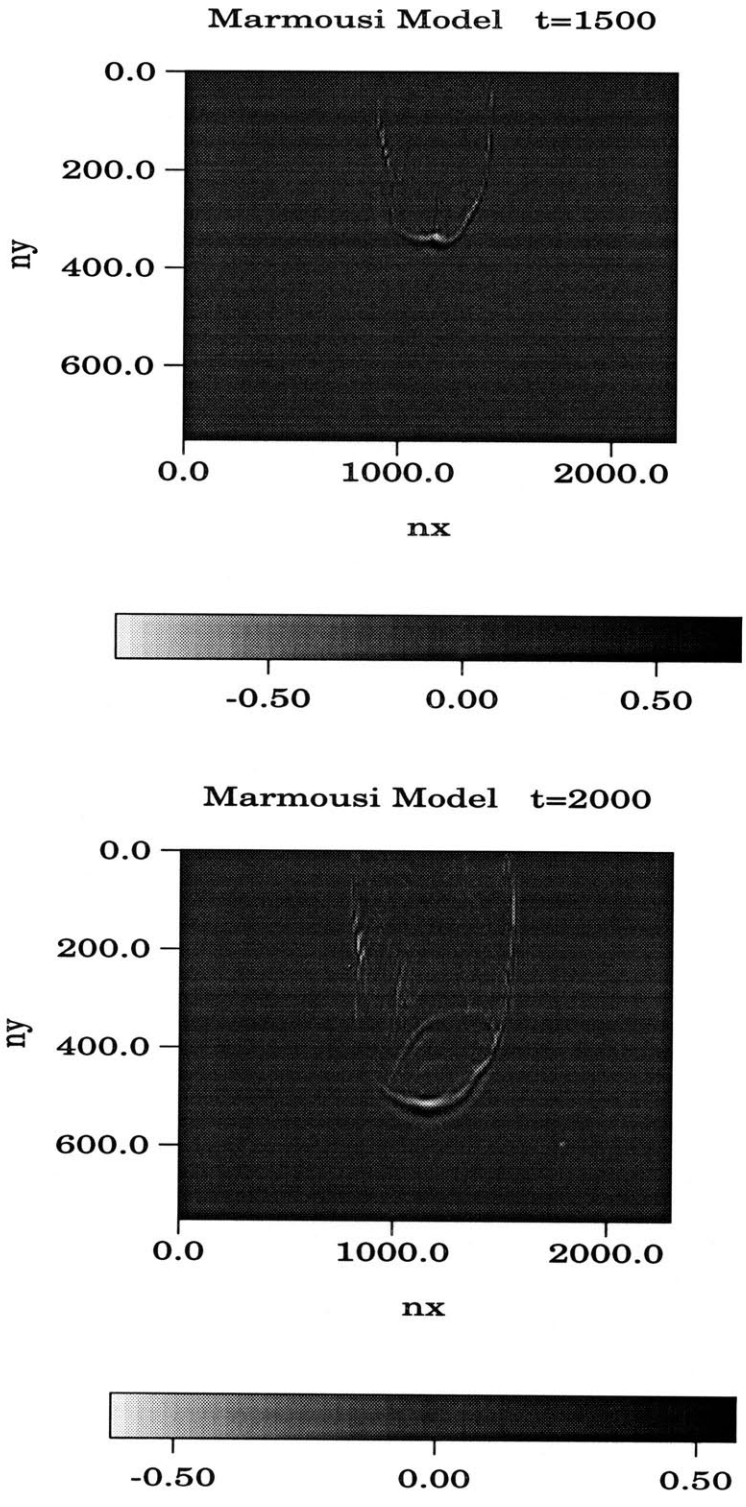


Figure 3-6: Propagated Wave after 1500, and 2000 iterations.

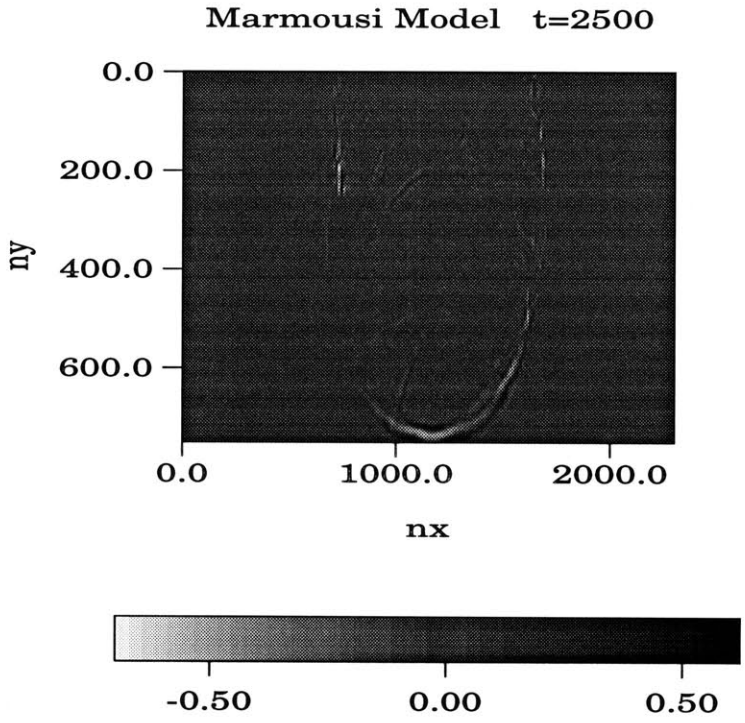


Figure 3-7: Propagated Wave after 2500 iterations.

3.2 Test Results

In this section we present the results for both the *Constant* velocity model and the *Marmousi* velocity model. We plotted four kind of graphs:

1. total execution time as a function of the number of nodes — keeping the communication buffer size constant,
2. total I/O time as a function of the number of nodes — keeping the communication buffer size constant,
3. total execution time as a function of the communication buffer size — keeping the number of nodes constant, and
4. total I/O time as a function of the communication buffer size — keeping the number of nodes constant.

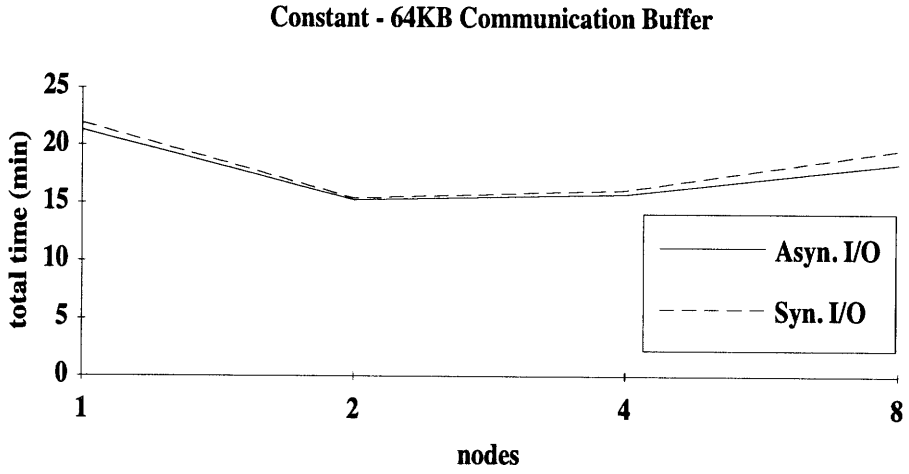
In order to understand and interpret the results correctly, it is important to notice that all input and output files used during the tests were stored in a local UNIX disk on the *front-end* — SUN SparcStation — and, therefore, all I/O requests were directed to the *front-end* computer. This was a bottleneck (e.g., see Patt, 1994) for our application, but it was necessary because there are still problems in using *asynchronous I/O* with PFS (Parallel File System). Furthermore, the *front-end* computer is a shared machine in the network, and is used as a Web and file server. This causes fluctuations in the I/O times between runs, and affects the performance of the system. Figure (3-16) shows the I/O time fluctuations for a communication buffer size of $80KB$ with only one node. In addition, at the end of this section, we present several results showing total and I/O times when using PFS, but with *synchronous I/O*. These results give us an idea of the expected performance when using PFS with *asynchronous I/O*.

3.2.1 Constant Velocity Model

Using the *Constant* velocity model, we made tests with different *communication buffer* sizes — $64KB$, $80KB$, $144KB$, and $160KB$ — and nodes — 1, 2, 4, and 8. Figures (3-8) and (3-9) present four graphics showing total execution and I/O time versus the number of nodes, and Figures (3-10) and (3-11) present another four graphics showing total execution and I/O time versus the *communication buffer* size.

3.2.2 Marmousi Velocity Model

Using the *Marmousi* velocity model, we made tests with different *communication buffer* sizes — $448KB$, $512KB$, $576KB$, and $2048KB$ — and nodes — 1, 2, 4, 8, and 32. Figures (3-12) and (3-13) present four graphics showing total execution and I/O time versus the number of nodes, and figures (3-14) and (3-15) present another four graphics showing total execution and I/O times versus the *communication buffer* size.



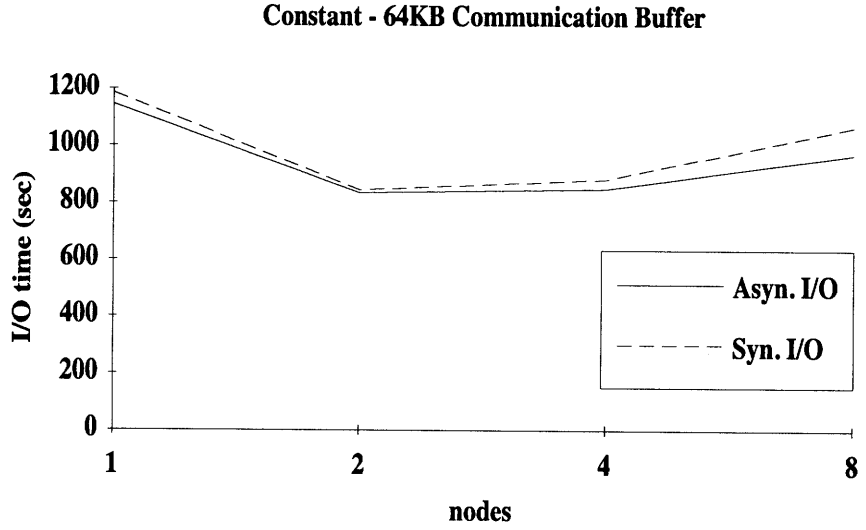


Figure 3-8: *Constant Model with 64KB for the Communication Buffer*: As we increase the number of processors, the total execution time and the total I/O time decrease, but, when we use four or more nodes, time increases because there are more processors accessing only one disk. Note also that in both cases the results using *asynchronous I/O* were better than those using *synchronous I/O*.

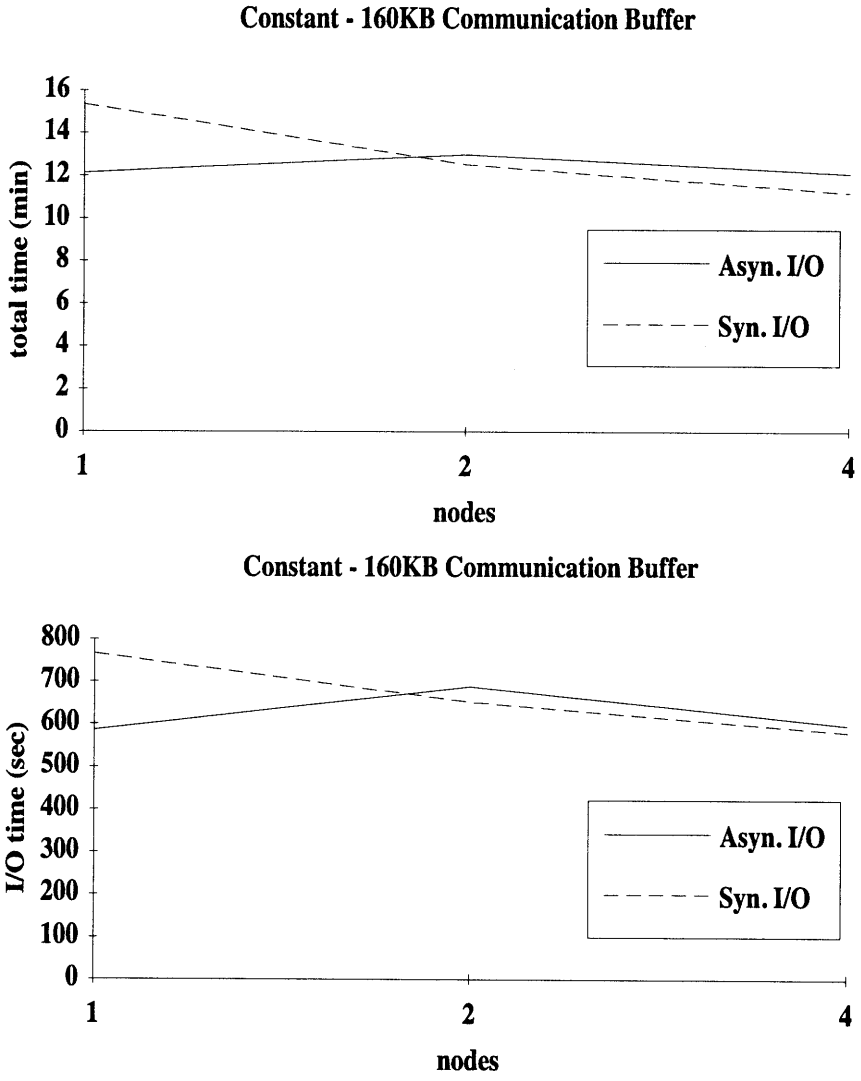


Figure 3-9: *Constant Model with 160KB for the Communication Buffer*: In this case the asynchronous version is better than the synchronous version when only one node is used. When we use more than one node, the synchronous version is a little bit better. We see that as we increase the number of nodes, the execution and I/O time also increase. It is important to notice that we obtained better results when using 144KB rather than 160KB for the communication buffer. In addition, when the I/O overhead begins to grow and the only disk used becomes a bottleneck, the synchronous version can be a bit better than the asynchronous version.

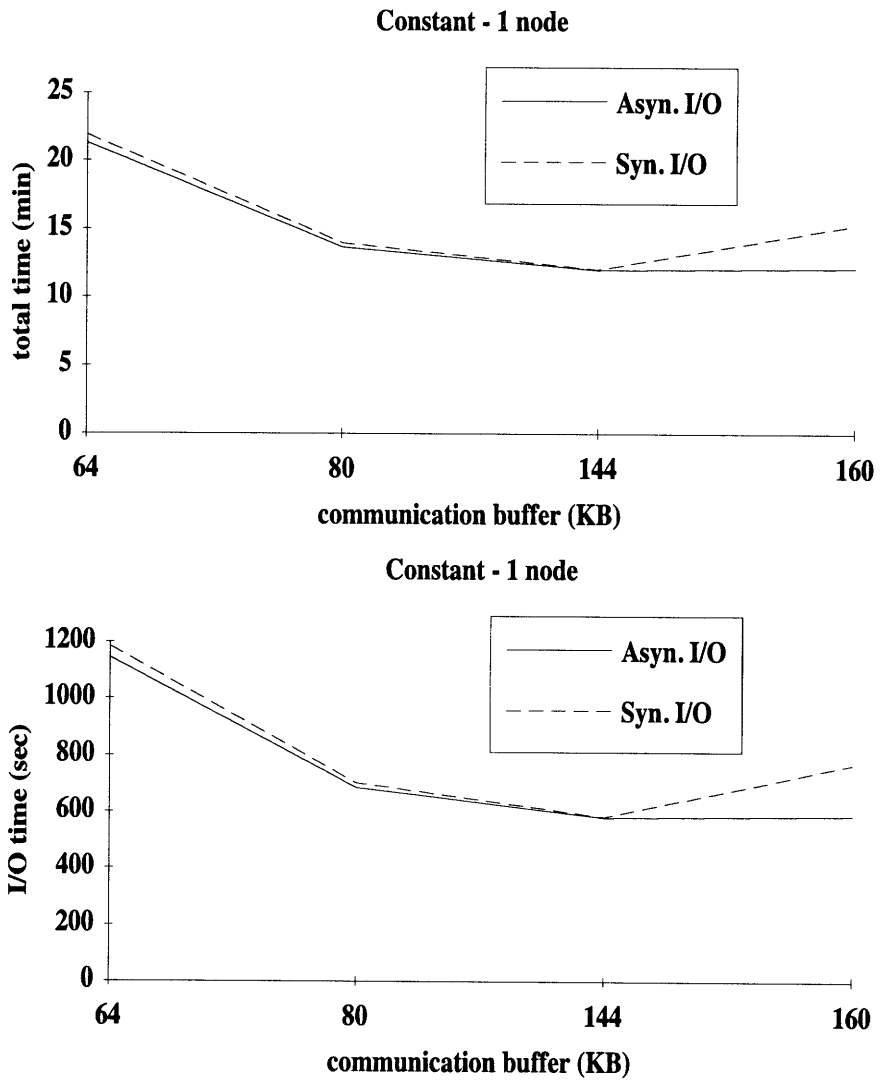


Figure 3-10: *Constant Model with 1 node*: We notice that as we increase the communication buffer size, the total execution time and the total I/O time decrease. In the synchronous version, times begin to increase again when the communication buffer size is greater than 144KB, while in the asynchronous version times keep decreasing. It is very clear that the asynchronous version is preferable to the synchronous one.

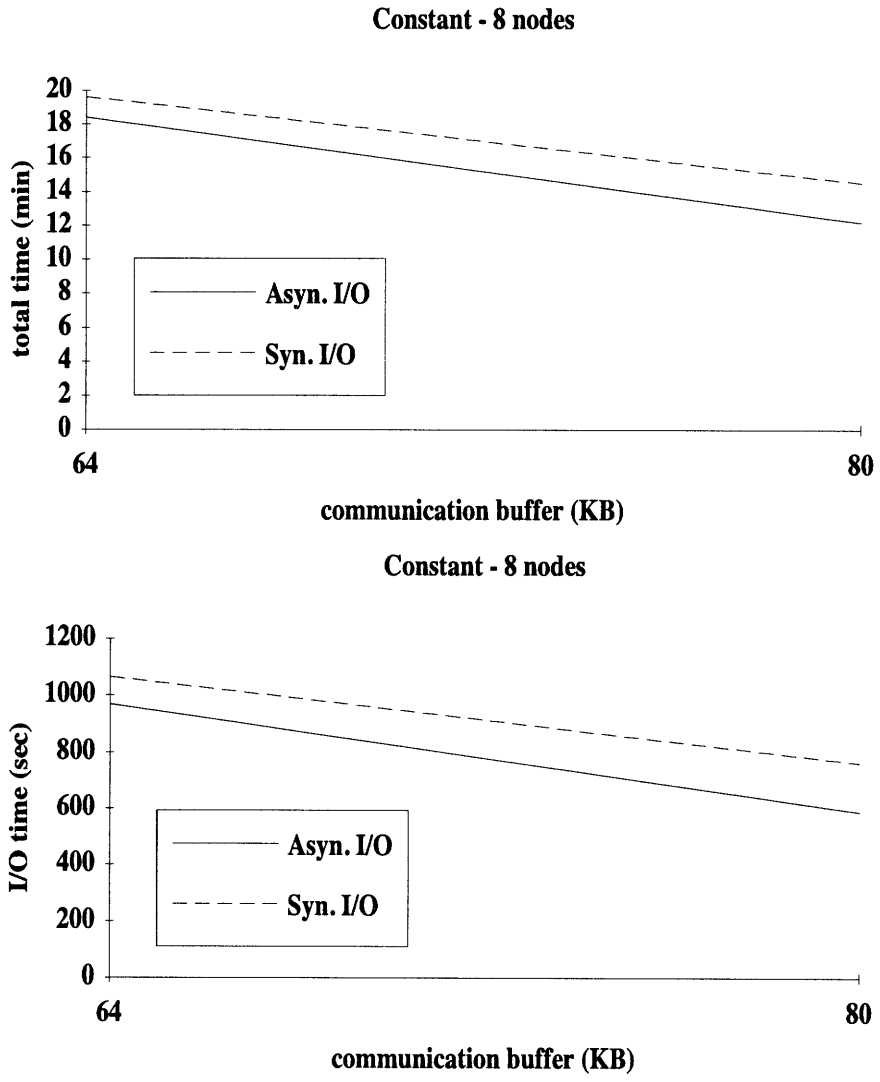


Figure 3-11: *Constant Model with 8 nodes*: In this case it is pretty clear that the asynchronous version is better than the synchronous version, and, as in the previous cases, as we increase the communication buffer size, times decrease. The interesting thing here is that the total execution and I/O times are greater than the ones obtained with 4 nodes. This is due to the I/O overhead, because there are too many processors requesting I/O operations on only one disk. We would obtain better results if we were using a disk array.

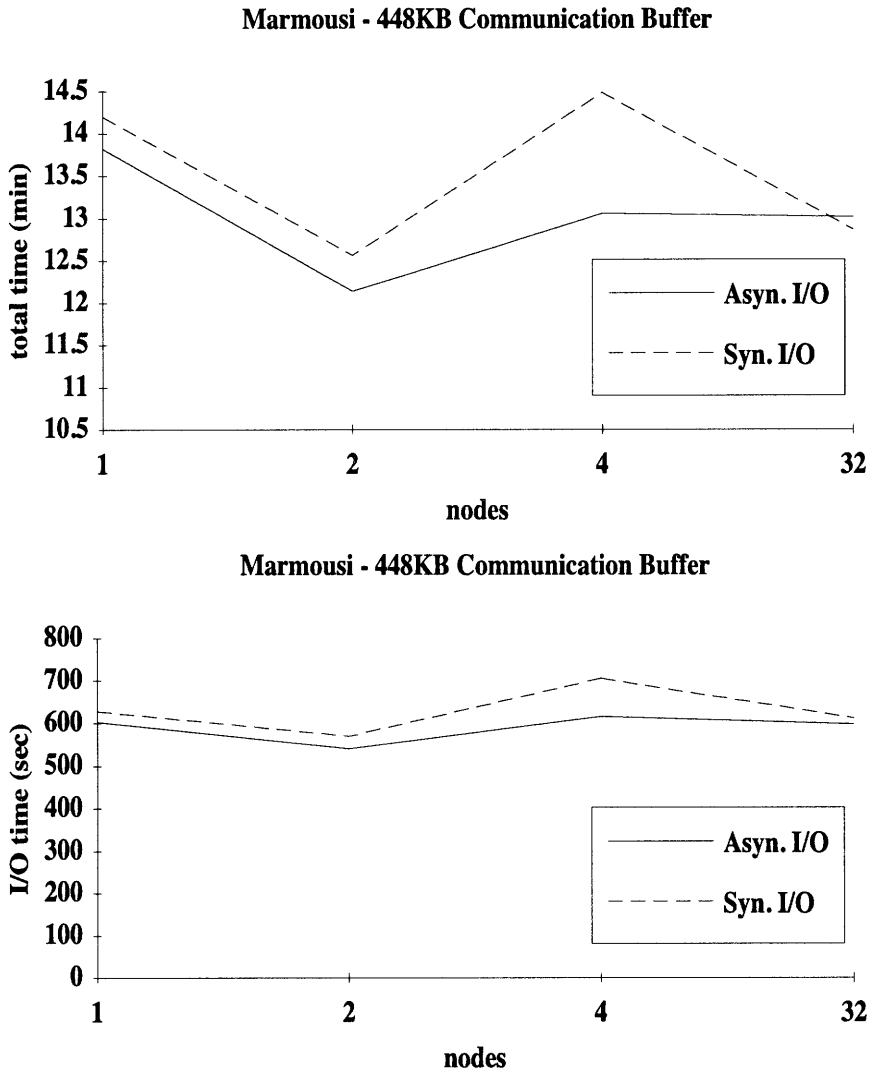


Figure 3-12: *Marmousi Model with 448KB for the Communication Buffer*: We notice that as we increase the number of processors, the total execution time and I/O times decrease, but, when using four or more nodes, time increases because there are more processors accessing only one disk. Note also that in both cases the results using *asynchronous I/O* were better than the *synchronous I/O*. These are the same results as the ones obtained with the small *Constant Model*.

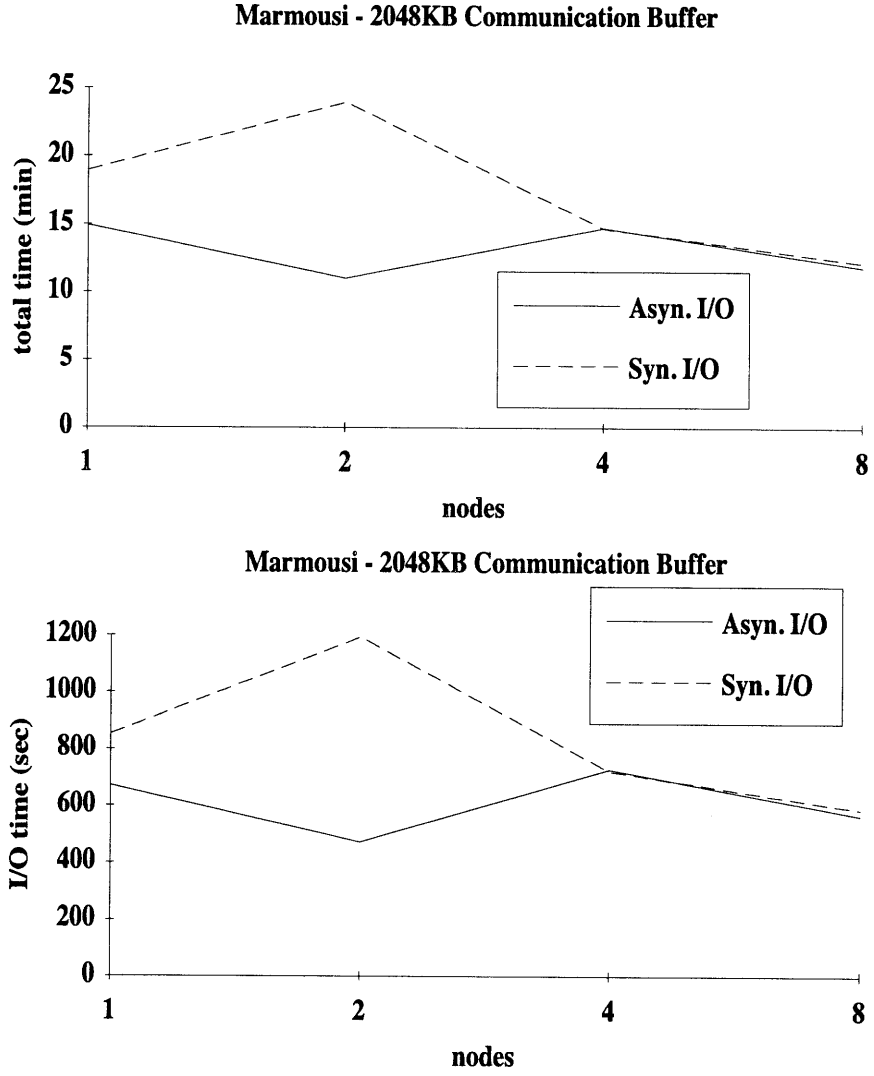


Figure 3-13: *Marmousi Model with 2048KB for the Communication Buffer*: In this case it is very clear that the asynchronous version is better than the synchronous one, but, when we begin to use more than four nodes, the behavior of both versions is very similar. It is also clear that the memory requirements for synchronous and asynchronous I/O are different. It is important to note that we obtained better results when using 576KB rather than 2048KB for the communication buffer.

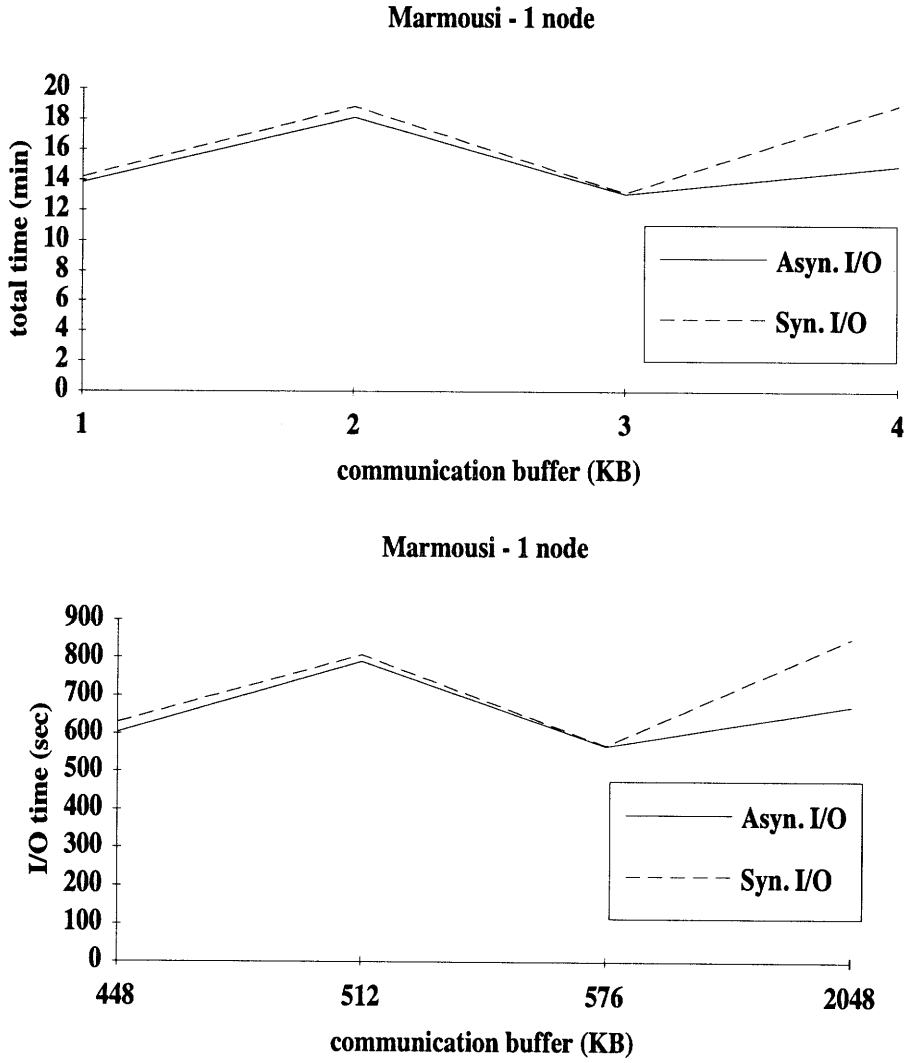


Figure 3-14: *Marmousi Model with 1 node*: We notice that execution and I/O times are better with some communication buffer sizes than with others. It is also clear that the asynchronous version is better than the synchronous one.

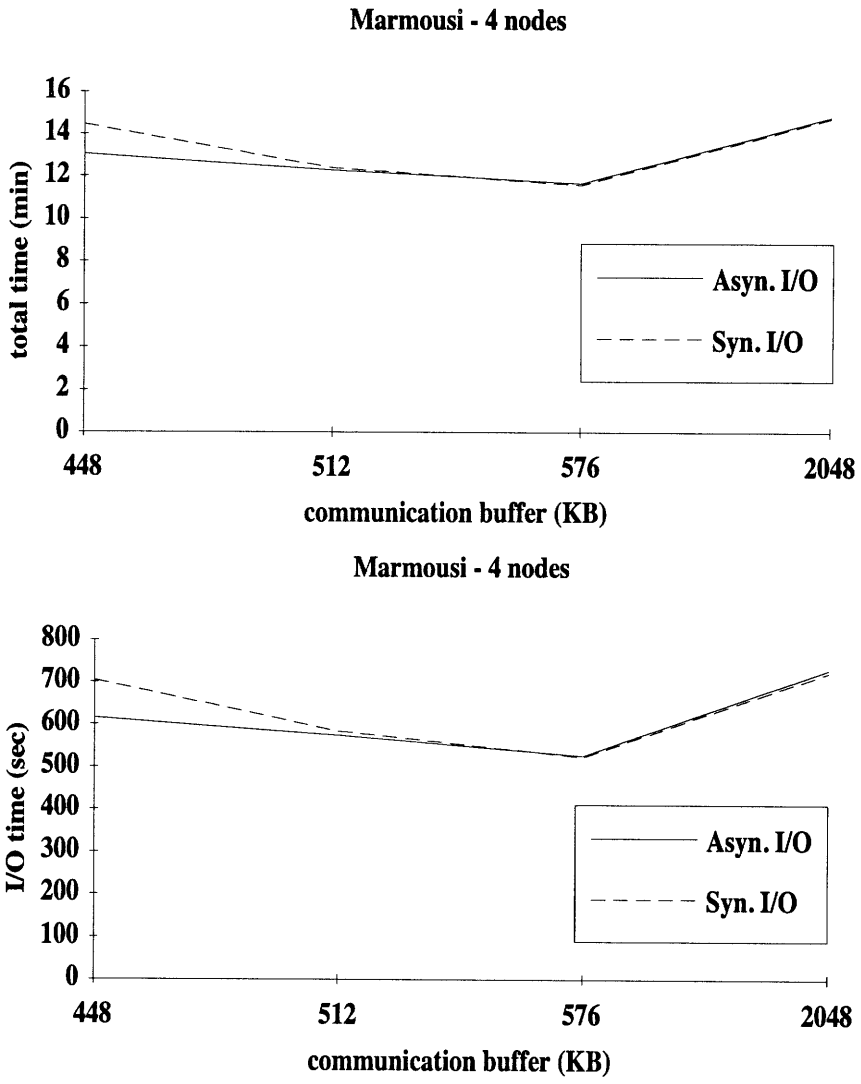


Figure 3-15: *Marmousi Model with 4 nodes*: The behavior here is similar to the case with two nodes. Times — execution and I/O — decrease as we increase the communication buffer size, but after 576KB times begin to grow again. Times for the synchronous and asynchronous version are very similar, but the asynchronous version is a little bit better. We can also notice that the times are very similar to the ones obtained when we use only two nodes, which means that the *I/O-subsystem* is becoming a bottleneck again.

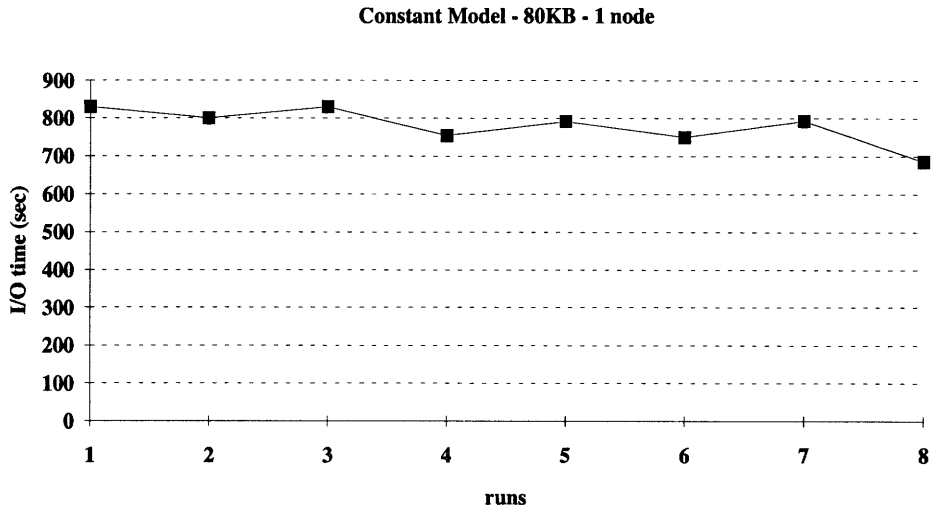


Figure 3-16: *I/O Time Fluctuation*: Total I/O time from 8 runs of the constant velocity model using *asynchronous I/O*, and a communication buffer size of 80KB on 1 node. We can see the time fluctuations, because the *front-end* computer is operating as a Web and file server.

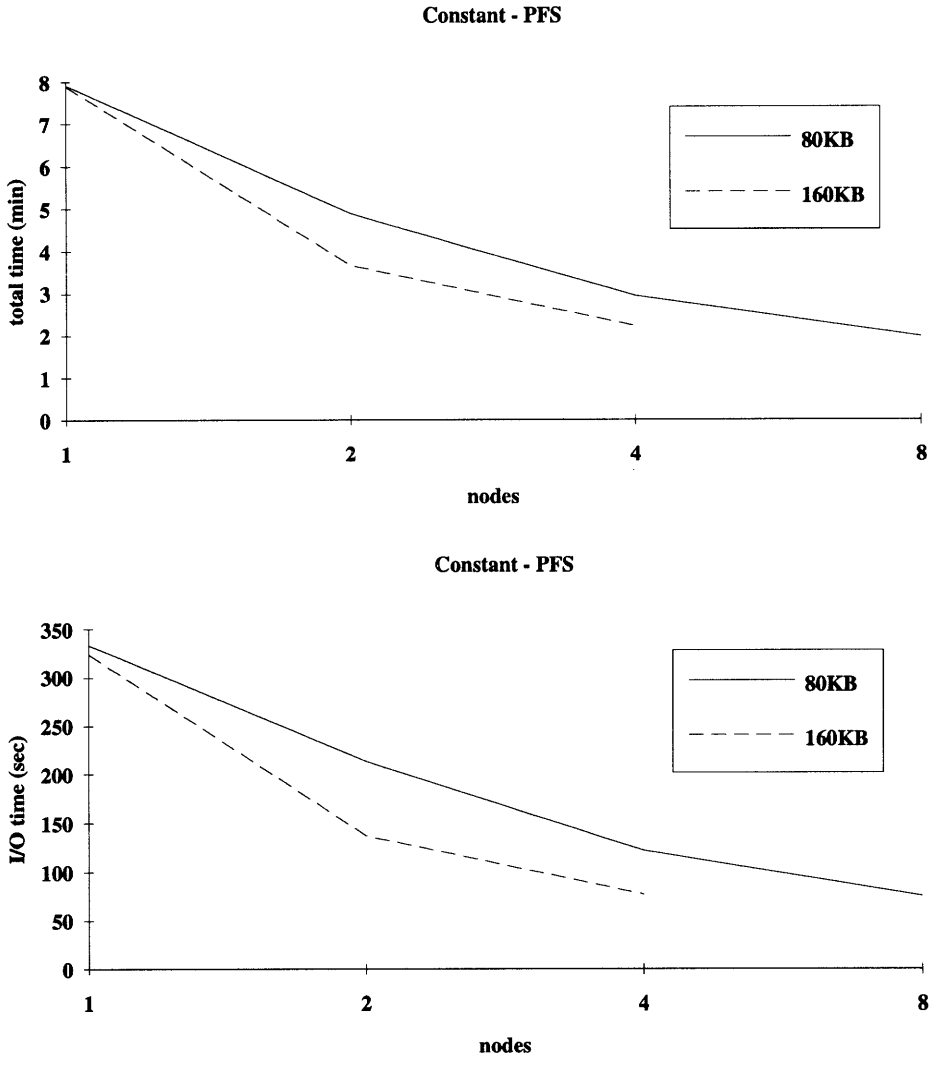


Figure 3-17: *SYNCHRONOUS I/O + PFS — Constant Model (Comm. buffer = 80KB, and 160KB)*: As we can see, increasing the size of the communication buffer reduces the total and I/O times. The difference is evident, because we are using very small memory sizes. Comparing these results with the ones presented in figures 3-8 and 3-9, total and I/O times were reduced in more than half using PFS with *synchronous I/O.*

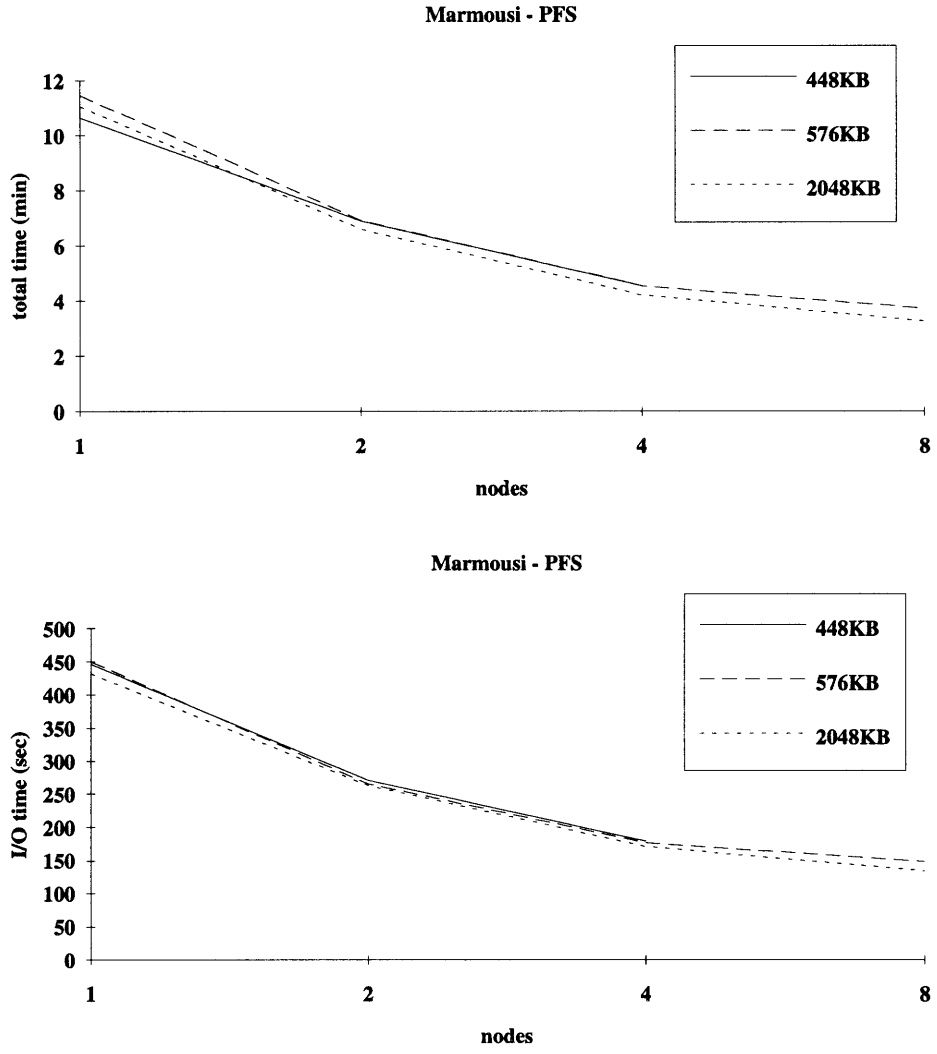


Figure 3-18: *SYNCHRONOUS I/O + PFS — Marmousi Model (Comm. buffer = 448KB, 576KB, and 2048KB)*: In this case, we notice that increasing the size of the communication buffer does not affect significatively the total and I/O times. However, we can see the same behavior that in figure 3-17, increasing the number of nodes decreases the total and I/O times. In this case, the difference is not relevant, because we are using very large data blocks. Comparing these results with the ones presented in figures 3-12 and 3-13, total and I/O times were reduced approximately between 25% and 50% using PFS with *synchronous I/O*.

3.3 Performance Analysis

In this section we present a performance analysis of our system by comparing it with a sequential version, and with a parallel version using synchronous I/O. We also show the order of the algorithm used when the problem is solved *in-core* memory. For this section let us assume that:

- nx: is the number of columns of the grid,
- ny: is the number of rows of the grid,
- nt: is the number of time steps,
- *blk-size*: is the size in bytes of every data block kept in main memory,
- N: is the number of processors used.

3.3.1 In-Core Memory Version

Solving the problem *in-core* memory is very easy because we only have to read the input files, make the respective initializations, and compute the new pressures the specified time steps nt. Therefore, the general algorithm for solving the problem *in-core* memory in a sequential machine is shown in figure (3-19):

In the algorithm of figure (3-19), $INITIALIZATION()$ takes time $\Theta(nx \times ny)$, the $UPDATE()$ takes constant time $\Theta(1)$, and the *COMPUTE - IN - CORE - MODEL()* also takes time $\Theta(nx \times ny)$. An because the outer loop is executed nt times, the order of the sequential *in-core* memory version is:

```
2D-AWE_IN_CORE_MEMORY_SEQUENTIAL()
{
INITIALIZATIONS();
FOR (every time step) DO
  UPDATE value in source position;
  COMPUTE-IN-CORE-MODEL();
END-DO;
};
```

Figure 3-19: Sequential Algorithm for Solving the Acoustic Wave Equation In-Core Memory

$$\begin{aligned} \Theta(SEC.IN.CORE) &= \Theta(nx \times ny) + \Theta(nx \times ny \times nt) \\ &= \Theta(nx \times ny \times nt) \end{aligned} \tag{3.1}$$

A parallel version of this algorithm is presented in figure (3-20) based on a *"distributed-memory/message-passing"* model:

Assuming that we have N processors, and that the data set is divided between the processors using a *1D-data decomposition* algorithm which produces subproblems of about the same size for each processor, in algorithm (3-20) the $INITIALIZATION()$ takes time $\Theta(\frac{nx \times ny}{N})$ in each processor, the $UPDATE$ takes constant time $\Theta(1)$, and the *COMPUTE - IN - CORE - MODEL()* takes time $\Theta(\frac{nx \times ny}{N})$. The $SEND()$ of edges takes time $\Theta(nx)$, but the communication overlaps with the computation of the model, and we can be almost sure — if the communication overhead is small — that we will not have to wait for communication. The $RECEIVE()$ and $COMPUTE - EDGE()$ operations take time $\Theta(nx)$. And because the outer loop is executed nt times, the order of the parallel *in-core* memory version is:

```
M2D-AWE_IN_CORE_MEMORY_PARALLEL()
{
FOR (every time step) DO
  UPDATE value in source position;
  IF (I am not NODE 0) THEN
     SEND upper edge TO up neighbor;
  IF (I am not the last NODE) THEN
     SEND lower edge TO down neighbor;
  COMPUTE-IN-CORE-MODEL();
  IF (I am not NODE 0) THEN
     RECEIVE upper edge FROM up neighbor;
     COMPUTE upper edge;
  END-IF;
  IF (I am not the last NODE) THEN
     RECEIVE lower edge FROM down neighbor;
     COMPUTE lower edge;
  END-IF;
END-DO;
};
```

Figure 3-20: Parallel Algorithm for Solving the Acoustic Wave Equation In-Core Memory

$$\begin{aligned} \Theta(PAR.IN.CORE) &= \max\left(\Theta\left(\frac{nx \times ny}{N}\right) + \Theta\left(\frac{nx \times ny \times nt}{N}\right)\right) \\ &= \max\left(\Theta\left(\frac{nx \times ny \times nt}{N}\right)\right) \end{aligned} \tag{3.2}$$

As you can see in equation (3.2), the order of the parallel version is better than the sequential version while we increase the number of processors, but we have to be very careful because there is a point when the communication overhead due to the large number of processors surpasses the computing time and, from that point on, increasing the number of processors increases also the turnaround of the program and it is possible to reach a point where the sequential version is even better than the parallel version using thousands of processors (e.g., see Kwang, 84; Del Rosario and Choudhary, 94).

3.3.2 Out-of-Core Memory Version

The *out-of-core* version of the system is basically the most important part of this thesis, because with it we have the ability to solve very large scale wave propagation problems with the available resources. Our version was developed using the ideas of asynchronous I/O, but we also developed a version of the system that uses synchronous I/O for comparison purposes. Unfortunately, we could not test our system using asynchronous I/O with the nCUBE 2's PFS (Parallel File System), because it was impossible to put them to work together. However, we are planning to keep working on the implementation of the system using the *Parallel File System*, because we know that this is a bottleneck in any massively-parallel *I/O-bound* application like ours. Therefore, we were able to test the system with data files in only "one" local disk at the front-end, and we tried to project the behavior with a disk array (e.g., see Ganger *et al.*, 1994) with file-stripping facilities.

In the *out-of-core* memory version of the system, every node decomposes its own subproblem in data blocks that can be kept simultaneously in the main memory to optimize the block size. The asynchronous and synchronous I/O versions are very similar in structure, but the main difference is that in the synchronous I/O version we repeat the sequence READ-COMPUTE-WRITE block without any kind of overlapping between I/O and computations. However, in the asynchronous I/O version we use a technique of pre-fetching blocks from a disk, so that the waiting time is reduced by the overlapping of I/O operations with computations. Thus, while we are computing the block (b), we are simultaneously reading in advance — pre-fetching — the next block ($b+1$) and we are writing the previous block ($b-1$). So that, after we finish the computation of a block (b), the next block can be in the main memory, and the previous block can be saved on a disk.

All these features make the asynchronous I/O approach faster than the syn-

chronous one in a computer environment where the I/O subsystem is not a bottleneck. Unfortunately, in the environment where we perform our tests, the use of only one local disk without the help of a parallel file system yields very similar results for both versions. However, our intuition tell us that it is possible to obtain very good results when using a *parallel file system* with the asynchronous version.

3.4 Conclusions

Before drawing any conclusion, it is important to understand the environment in which all tests were done. All data files — input and output — were stored in only one of the front-end's local disks, because it was impossible to test the asynchronous version of the system using the nCUBE 2's PFS (Parallel File System). This disk is connected to the front-end's SCSI controller with two other disks in the chain. Therefore, as we increase the number of nodes in our test, this disk becomes the bottleneck of the system. The SCSI controller will enqueue all requests (e.g., see Ruemmler and Wilkes, 1994; Hennessy and Patterson, 1990), and there will be a contention in the disk. When the number of requests is too high, I/O operations will be sequentialized because we are using only one disk. Unfortunately, this was the only working environment in which we were able to test our system, and, of course, it affects the results dramatically. Furthermore, as it was shown in figure (3-16), there are fluctuations in the total I/O time, because the *front-end* is been used as a Web and network file server.

As shown by the results in this chapter, the application of ideas like *asynchronous I/O*, overlapping, pipelining, and parallel processing to solve very large scale wave propagation problems using the approach outlined in this thesis, is not only possible but also practical. Even though the method was only implemented for a 2-D case,

all these ideas can be used and applied to 3-D cases. Although we were able to perform tests with only one disk, from these results it is possible to make the following conclusions:

- We have proved that the use of *Asynchronous I/O* yields better results than *Synchronous I/O*, and we can expect even better results using PFS with disk arrays (e.g., see Ganger *et al.*, 1994).
- In *I/O-bound* applications like ours the *I/O-subsystem* is the bottleneck which sets the limit for the maximum speedup that can be reached.
- In *I/O-bound* applications, as we increase the number of nodes, execution and I/O times decrease until we reach the saturation point. This point is defined by the *I/O-Bandwidth* of the system, and not by the *Communication-Bandwidth.*
- Memory requirements are very different when using *Asynchronous I/O* or *Synchronous I/O.*
- The size of the *communication buffer* is directly related to the number of nodes used, and affects the scaling of the system.
- When using *Synchronous I/O*, the *I/O overhead* increases as we increase the number of nodes because there is only one available disk. We expect better results when using PFS.
- It is expected that using PFS with a disk array will produce better results with *Asynchronous I/O*, but we will always be limited by the *I/O-Bandwidth* — which will be determined by the maximum number of disks that can be accessed in parallel, and by the transfer rate between the main memory and the disks.

- The size of the *communication buffer* is directly related to the number of disks that can be accessed in parallel, the *I/O-Bandwidth*, number of nodes, data block size, and the buffering capacity.

- When solving large models with only one disk, we usually reach the best results with no more than four nodes due to the *I/O-Bandwidth* limitations.

- Using PFS (a four disk array) together with *Synchronous I/O* has proven to be more effective than using *Asynchronous I/O* with only one disk. In all cases times were decreased between 25% and 50%. However, we expect even better results when using PFS together with *Asynchronous I/O*.

- We also obtained very good I/O transfer rates using PFS with *synchronous I/O*. For example, with a communication buffer size of $160KB$ and two nodes we reach a transfer rate of 0.55 $Mbytes/sec$.

Chapter 4

Discussion and Conclusions

The principal achievement of this thesis is to demonstrate that very large scale seismic wave propagation problems can be solved using *out-of-core* memory finite difference methods on a parallel supercomputer. We do this by using special memory management techniques based on *pipelining*, *asynchronous I/O*, and *dynamic memory allocation*. We optimized the memory use by keeping to a minimum the number of data blocks needed simultaneously.

In this thesis we developed a two-dimensional finite difference method to simulate very large scale seismic wave propagation problems. As a case study we worked with two-dimensional *acoustic* waves, but this method can be easily extended to the cases of 2-D and 3-D *elastic* waves. We developed an *out-of-core* memory system using a *distributed-memory/message-passing* approach to solve problems that could not be processed in the past using conventional *in-core* memory systems, and we implemented our system using the *ANSI C* programming language on an *nCUBE 2* parallel computer.

We tested our system with a small *Constant* velocity model — 256×256 —, and

the large *Marmousi* velocity model — 751×2301 — using 1, 2, 4, 8, and 32 processors, and several memory sizes. Even though our *nCUBE 2* has 4 parallel disks, we were only able to make tests on a single *front-end* (SUN) disk, because the nCUBE 2's PFS — Parallel File System — did not work properly with the *asynchronous I/O* functions.

Our experience in developing this new approach for very large scale *finite difference* modeling, along with the results of our performance tests allow us to reach the following conclusions:

1. The use of an *out-of-core* memory technique is feasible and suitable for solving very large scale seismic wave propagation problems.

2. Utilization of *asynchronous I/O* operations yields better results, namely a decrease in the run time, compared with the use of *synchronous I/O* operations for very large scale wave propagation problems due to the overlapping of I/O with computations.

3. In *I/O-bound* applications the speedup is limited by the *I/O-bandwidth* of the *I/O-subsystem*, and owing to the speed difference between the CPU and I/O devices the *I/O-subsystem* becomes the system "bottleneck".

4. Increasing the number of processors in *I/O-bound* applications can reduce the response time, but, in order to obtain significant improvements, we must increase the *I/O-bandwidth* as we increase the number of processors in order not to saturate the *I/O-subsystem.*

5. Even though we were able to perform tests only with one disk, the results were very promising and we expect even better results when using the PFS (Parallel File System) with a disk array and file striping capabilities.

6. The choice of memory and block size is directly related to the number of parallel disks available, *I/O-bandwidth*, number of nodes, and buffering capacity of the *I/O-subsystem.*

A tangible result of this work is that the *Marmousi* velocity model — 751×2301 — can be solved with *out-of-core* memory using a parallel computer with less than 8 nodes (with $4MB$ memory per node). When an *in-core* memory method is used, one would need more than 8 nodes to solve the problem. Extrapolating from these results, we can conclude that very large problems can be solved using *out-of-core* memory.

4.1 Future work

Although we implemented our system for a two-dimensional *acoustic* wave propagation problem to show the feasibility of our approach, this method is more useful when applied to *three-dimensional acoustic* or *elastic* wave propagation problems. In three-dimensional problems memory limitations confine applications to very small models, e.g., a model of size $400 \times 100 \times 80$ points on an *nCUBE 2* with 128 nodes and $4MB$ per node (Cheng, 1994).

For the system to be practical it is necessary to implement it using the PFS (Parallel File System) with a disk array in order to balance the *I/O-bandwidth* with the number of processors used. The use of PFS together with *asynchronous I/O* and *pipelining* should produce greatly improved results.

When solving three-dimensional problems, it may be useful to experiment with different network configurations and different data decomposition algorithms. We used a one-dimensional data decomposition algorithm for solving the two-dimensional acoustic wave propagation problem. It is important to analyze the impact of other

data decomposition strategies — 2-D and 3-D — on the *communication* and I/O bandwidth.

We were only able to perform tests on an *nCUBE 2* parallel supercomputer, which has a MIMD hypercube architecture. It may be useful to migrate the code to other parallel machines in order to test the portability and general applicability of our algorithms.

Finally, it will be useful to generalize our approach and develop a library of function calls to facilitate the implementation of other, *finite difference* problems in science and engineering.

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Appendix A

The Source Code

In this appendix we present the source code for the main routines used for our implementation of the *Very Large Scale 2-D Acoustic Waves Propagation* program using 1-D data decomposition and *message-passing*, *asynchronous I/O*, and *pipelining*. Source files are written using ANSI C standard on an *nCUBE 2* hypercube computer.

A.1 FD_1D.c

The main source file for the *2-D Acoustic Waves Propagation* program.

```
/*****************************************************************************
*                                                                            *
*       File: fd_1D.c                                                        *
*                                                                            *
*       Purpose: 2D-Finite Difference Seismic Wave Propagation program with  *
*                1D Data Decomposition                                       *
*                                                                            *
*****************************************************************************/

#include "include.common.h"    /* System Header Files                      */
#include "defines.h"           /* Constant and Macro definitions           */
#include "fd_1D.h"             /* Function and Global Var. definitions     */
#include "err.h"        /* Macros for Error Handling                  */

/*---------------------------------------------------------------------------*/
/* Initialization of global variables                                        */
/*---------------------------------------------------------------------------*/

void initialize(void)
{
                          SEE  SOURCE  FILE
}

/*---------------------------------------------------------------------------*/
/* Read Global Parameters from input file                                    */
/*---------------------------------------------------------------------------*/

void read_global(void)
{
                          SEE  SOURCE  FILE
}

/*---------------------------------------------------------------------------*/
/* Read global parameters in the local memory of every node. Every node has  */
/* the same values, which are read from <root>.input data file               */
/*---------------------------------------------------------------------------*/
```

```
void read_local(void)
{
                          SEE  SOURCE  FILE
}

/*------------------------------------------------------------------------*/
/* Returns the number of bytes of available memory in the Communication   */
/* Buffer, using a bisection method (binary search)                       */
/*------------------------------------------------------------------------*/

int mem_avail(void)
{
  int error_mem = 1024, min_mem = 0, max_mem, med_mem;
  char *ptr;

  max_mem = MAX_MEM_AVAIL * MB;
  do {
    med_mem = (min_mem + max_mem) / 2;
    if ((ptr = (char *)ngetp(med_mem)) == (void *)-1)
      max_mem = med_mem;
    else {
      min_mem = med_mem;
      NRELP(ptr);
    };
  } while ((max_mem - min_mem) > error_mem);
  return (min_mem);
}

/*------------------------------------------------------------------------*/
/* Init parameters needed during the whole computation:                   */
/*                                                                        */
/* Transmission Parameters: node to send edge to, node to receive edge from. */
/* The edges are sent/received in a linear way:                           */
/* 0 -> 1 -> 2 -> ... -> k -> (k+1) -> ... -> (num_nodes-1)               */
/*------------------------------------------------------------------------*/

void init_parameters(void)
{
  /* Transmission Parameters */
  mflag        = calloc(1, sizeof(int));                    /* not used */
  send_to_down = rcv_from_down = (mynode + 1) % num_nodes;
  send_to_up   = rcv_from_up   = (mynode + num_nodes - 1) % num_nodes;
  edge_size    = ELEM_SIZE * nx;
```

```
  /* I/O Parameters */
  first_offset   = (long)ylo * (long)edge_size;
  cbuf_size = mem_avail();            /* bytes available in the Comm. Buffer */
  cbuf_rows = cbuf_size / edge_size;  /* rows     "      "   "   "      "    */
}

/*--------------------------------------------------------------------------*/
/* Decompose data between processors. The decomposition assign the same     */
/* amount of rows to every node except possible the last ones which can have */
/* one less row. Therefore:                                                 */
/*                                                                          */
/* 0   <= node <= k              will have (ypts+1) rows                    */
/* k+1 <= node <= (num_nodes-1)   "    "   (ypts)    "                       */
/*                                                                          */
/* rows_left = number of rows left after dividing the number of rows in the  */
/*             data set in equal parts. Then each one of this rows will be   */
/*             assigned to nodes 0 to (rows_left-1), such that these nodes   */
/*             are going to process one more row than the last ones          */
/*--------------------------------------------------------------------------*/

void decompose_data(void)
{
  int rows_left;

  rows_left = ny % num_nodes;
  ypts      = ny / num_nodes;
  if (mynode < rows_left) {
     ypts++;
     ylo = mynode * ypts;
  }
  else
     ylo = rows_left*(ypts+1) + (mynode - rows_left)*ypts;
  yhi  = ylo + ypts - 1;
}

/*--------------------------------------------------------------------------*/
/* Returns 1 if the source is in this node                                  */
/*--------------------------------------------------------------------------*/

int ishere_source(int ix, int iy)
{
  if (ylo <= iy && iy <= yhi) {
     printf("Source is on node %d\n", mynode);
```

```
    wavlet(ichoix, 0, LENF, f, f0, psi, gamma, t0, dt);
    return (1);
  }
  else
    return (0);
}

/*-------------------------------------------------------------------------*/
/* Returs 1 if the problem its in RAM (0 otherwise). It also omputes size of */
/* every data block to be READ-COMPUTE-WRITE, based on the maximun number of */
/* data blocks that are going to be simultaneously in RAM memory at a given. */
/* When the problem fits in RAM there is only one block and the size of the  */
/* the last data block is the same block size (there is only one block).     */
/*-------------------------------------------------------------------------*/

int problem_fits(void)
{
  if (ypts <= max_blk_size) {
    blk_size      = last_blk_size = ypts * edge_size;              /* bytes */
    last_blk_size = blk_size;                        /* it is not necessary */
    num_blks      = 1;                                /* it is not necessary */
    return (1);
   }
  else
    return (0);
}

/*-------------------------------------------------------------------------*/
/* Computes size of every data sub-block to be READ-COMPUTE-WRITE, based on  */
/* the maximun number of data blocks that are going to be simultaneously in  */
/* RAM memory at a given time. It also computes the size every data block    */
/* (including the last data block). When the problem is too large to fit in  */
/* memory "blk_size" and "last_blk_size" are ZERO. It is always true that:   */
/* ypts > max_blk_size                                                       */
/*-------------------------------------------------------------------------*/

void num_blocks_and_size(void)
{
  int rows;

  blk_size = last_blk_size = num_blks = 0;
  rows     = max_blk_size;
  while ((rows >= MINIMUN_ROWS) && (blk_size == 0)) {
```

```
    last_blk_rows = ypts % rows;
    if (last_blk_rows == 0) {
      blk_size      = last_blk_size = rows * edge_size;
      num_blks      = ypts / rows;
      last_blk_rows = rows;
    }
    else if (last_blk_rows >= MINIMUN_ROWS) {
      blk_size      = rows * edge_size;
      last_blk_size = last_blk_rows * edge_size;
      num_blks      = ypts / rows + 1;
    }
    else                        /* last_blk_rows < MINIMUN_ROWS */
      rows--;
  };
  rows_per_block = rows;
}

/*-------------------------------------------------------------------------*/
/* Computes the number of blocks in which data should be divided, taking   */
/* into account the amount of memory available, and the size of every block */
/*-------------------------------------------------------------------------*/

int num_blocks(void)
{
  int blks = 1, rows;

  if (ypts > max_blk_size) {
     rows = blk_size / edge_size;                  /*  rows in a data block */
     blks = ypts / rows;                      /* number of data blocks */
     if ((ypts % rows) != 0) blks++;
  };
  return (blks);
}

/*-------------------------------------------------------------------------*/
/* Read SPEED file and generate a new file where all elements are          */
/* multiplied by dt/dx. It also creates the two initial pressure files:    */
/* OLD and NEW with all zeroes.                                            */
/*-------------------------------------------------------------------------*/

void modi_speed(void)
{
                          SEE  SOURCE  FILE
```

```
}

/*-------------------------------------------------------------------------*/
/* Open Working data files: spm_fn (read only), old_fn (read/write), and   */
/* new_fn (read/write)                                                     */
/*-------------------------------------------------------------------------*/

void open_data_files(void)
{
  OPEN(spm_fd, spm_fn, O_RDONLY, R_MODE);              /* read only  */
  OPEN(new_fd, new_fn, O_RDWR,   RW_MODE);              /* read/write */
  OPEN(old_fd, old_fn, O_RDWR,   RW_MODE);              /* read/write */
}

/*-------------------------------------------------------------------------*/
/* Allocate memory in the communication buffer for the: block to be read,  */
/* block to be computed, and block to be written, dependig if the problem is */
/* going to be solved in core or out of core memory                        */
/*-------------------------------------------------------------------------*/

void allocate_memory(void)
{
                          SEE  SOURCE  FILE
}

/*-------------------------------------------------------------------------*/
/* Send the OLD upper edge to the node above. This function is only called */
/* after reading block 0 in every node, except in node 0                   */
/*-------------------------------------------------------------------------*/

void send_upper_edge(int send_to)
{
  /* b=0 & mynode<>0 */
  char *old_edgep;
  int  mtype = UP_EDGE_MTYPE;

  start_comm = amicclk();                    /* start time comm. req. */
  old_edgep = old_blkp;
  NWRITE(old_edgep, edge_size, send_to, mtype, &mflag);
  node_t.comm_req += (amicclk()-start_comm);        /* end time comm. req.   */
}

/*-------------------------------------------------------------------------*/
```

```
/* Send the OLD lower edge to the node below. This function is only called   */
/* after reading the last data block in every node, except in the            */
/* last node                                                                 */
/*---------------------------------------------------------------------------*/

void send_lower_edge(int send_to)
{
  /* b=last block & mynode<>(num_nodes-1) */
  char *old_edgep;
  int  mtype = LOW_EDGE_MTYPE;

  start_comm = amicclk();                    /* start time comm. req. */
  old_edgep = old_blkp + last_blk_size - edge_size;
  NWRITE(old_edgep, edge_size, send_to, mtype, &mflag);
  node_t.comm_req += (amicclk()-start_comm);        /* end time comm. req.   */
}

/*---------------------------------------------------------------------------*/
/* Receive the upper edge from the node above. This function is only         */
/* called after reading the last data block in every node, except in         */
/* node 0. Returns a pointer to the edge received                            */
/*---------------------------------------------------------------------------*/

char *rcv_upper_edge(int rcv_from)
{
  /* mynode <> 0 */
  char *old_edgep = 0;
  int  mtype = LOW_EDGE_MTYPE;

  start_comm = amicclk();                    /* start time comm. wait */
  NREADP(&old_edgep, edge_size, &rcv_from, &mtype, &mflag);
  node_t.comm_wait += (amicclk()-start_comm);       /* end time comm. wait   */
  return (old_edgep);
}

/*---------------------------------------------------------------------------*/
/* Receive the lower edge from the node below. This function is only         */
/* called after reading the last data block in every node, except in         */
/* the last node. Returns a pointer to the edge received                     */
/*---------------------------------------------------------------------------*/

char *rcv_lower_edge(int rcv_from)
{
```

```
  /* mynode <> (num_nodes - 1) */
  char *old_edgep = 0;
  int  mtype = UP_EDGE_MTYPE;

  start_comm = amicclk();                    /* start time comm. wait */
  NREADP(&old_edgep, edge_size, &rcv_from, &mtype, &mflag);
  node_t.comm_wait += (amicclk()-start_comm);       /* end time comm. wait   */
  return (old_edgep);
}

/*-------------------------------------------------------------------------*/
/* Read a Block from MODI SPEED, NEW, and OLD disk files asynchronously    */
/*-------------------------------------------------------------------------*/

void read_block(int b, int nbytes, char *spm_ptr, char *new_ptr, char *old_ptr)
{
  start_aio = amicclk();                     /* start time aio req. */
  if (b == 0) read_offset = first_offset;
  /* Init result structures for asynchronous I/O */
  *res_read_speedp = init_res_aio;
  *res_read_newp   = init_res_aio;
  *res_read_oldp   = init_res_aio;
  /* Read block (b) from MODI SPEED, NEW, and OLD File */
  AIOREAD(spm_fd, spm_ptr, nbytes, read_offset, SEEK_SET, res_read_speedp);
  AIOREAD(new_fd, new_ptr, nbytes, read_offset, SEEK_SET, res_read_newp);
  AIOREAD(old_fd, old_ptr, nbytes, read_offset, SEEK_SET, res_read_oldp);
  read_offset = read_offset + (long)nbytes;
  node_t.aio_req_read += (amicclk()-start_aio);         /* end time aio req. */
}

/*-------------------------------------------------------------------------*/
/* Write a Block to disk asynchronously                                    */
/*-------------------------------------------------------------------------*/

void write_block(int b, int nbytes, char *blkp)
{
  long offset;
  char *ptr;
  int  num_bytes;

  start_aio = amicclk();                    /* start time aio req.   */
  if (b == 0) {                                   /* Block = 0             */
    write_offset = first_offset;
```

```
    if (mynode == 0) {                    /* Block = 0 in NODE = 0 */
      offset     = write_offset;
      ptr        = blkp   + edge_size;
      num_bytes  = nbytes - edge_size;
    }
    else {                                          /* Block = 0 in NODE > 0 */
      offset     = write_offset + (long)edge_size;
      ptr        = blkp         + 2*edge_size;
      num_bytes  = nbytes       - 2*edge_size;
    };
  }
  else {                                                      /* Block > 0  */
    offset    = write_offset - (long)edge_size;
    ptr       = blkp;
    num_bytes = nbytes + (((b == (num_blks-1)) && (mynode == (num_nodes-1))) ?
         edge_size : 0);
  };
  if (b == (num_blks-1)) {
    *res_last_writep = init_res_aio;
    AIOWRITE(new_fd, ptr, num_bytes, offset, SEEK_SET, res_last_writep);
  }
  else {
    *res_writep = init_res_aio;
    AIOWRITE(new_fd, ptr, num_bytes, offset, SEEK_SET, res_writep);
  };
  write_offset = write_offset + (long)nbytes;
  node_t.aio_req_write += (amicclk()-start_aio);        /* end time aio req. */
}

/*-------------------------------------------------------------------------*/
/* Wait for ending of one, two, three, or four asynchronous operations.    */
/* If n_aio = 1, waits for the culmination of                              */
/* If n_aio = 2,   "    "   "       "      "                                */
/* If n_aio = 3,   "    "   "       "      "                                */
/* If n_aio = 4,   "    "   "       "      "                                */
/* If n_aio = 5,   "    "   "       "      "                                */
/*-------------------------------------------------------------------------*/

void wait_aio(int n_aio)
{
  int aio;
  aio_result_t *res_aiop[5];
```

```
  start_aio = amicclk();                        /* start time aio wait */

  for (aio=0; aio<n_aio; aio++) {
    if ((res_aiop[aio] = aiowait(timeout)) == (aio_result_t *)-1) {
       sprintf(estring,"%s:%d:%d: Error in %d aiowait",
       __FILE__,__LINE__,npid(),aio);
       perror(estring); kill(-1,SIGKILL); exit(1);
    };
  };

  node_t.aio_wait += (amicclk()-start_aio);           /* end time aio wait   */
}

/*-------------------------------------------------------------------------*/
/* Modify the value in the source position, iff the source is in this      */
/* node, and t<LENF. It checks if the source is in the current block       */
/*-------------------------------------------------------------------------*/

void update_source(int isy, int isx)
{
  char  *source_ptr;
  float  source_val;
  long   offset;

  source_ptr = (char *)&source_val;
  offset     =  ((long)isy * (long)nx + (long)isx) * (long)ELEM_SIZE;
  LSEEK(old_fd, offset,     SEEK_SET);
  READ(old_fd,  source_ptr, ELEM_SIZE);
  source_val += f[t];
  LSEEK(old_fd, offset,     SEEK_SET);
  WRITE(old_fd, source_ptr, ELEM_SIZE);
}

/*-------------------------------------------------------------------------*/
/* Compute a Block. This procedure assume that the data was divided in more */
/* than one block (num_blocks > 1).                                        */
/* all points in a block: (i,j), i=[0,ny1+1], j=[0,nx1+1]                  */
/* internal points:       (i,j), i=[1,ny1],   j=[1,nx1]                    */
/*-------------------------------------------------------------------------*/

void compute_block(int b)
{
  int nx1, ny1, i, j, last;
```

```
  float speed2, speed2_1, speed2_2;

  start_cpu    = amicclk();              /* start time for computations */
  nx1          = nx - 2;
  ny1          = (b == (num_blks-1)) ?
                 (last_blk_size/edge_size-2) : (rows_per_block-2);
  last         = ny1 + 1;
  speed        = (float *)speed_blkp;
  old          = (float *)old_blkp;
  new          = (float *)(new_blkp+edge_size);
  new_prev_row = (float *)new_blkp;
  if (b == 0) {                                  /* First Block: b = 0    */
     if (mynode == 0) {                          /* First Block in NODE 0 */
        /* Compute the 1st row: i=0 */
        for (j=1; j<=nx1; j++) {
  speed2   = SPEED(0,j); speed2 *= speed2;
  NEW(0,j) = (2.0 - 4.0*speed2)*OLD(0,j) - NEW(0,j) +
             speed2*(OLD(0,j+1) + OLD(0,j-1) + OLD(1,j));
};
/* Compute the upper left and upper right corners */
speed2_1    = SPEED(0,0);    speed2_1 *= speed2_1;
speed2_2    = SPEED(0,nx-1); speed2_2 *= speed2_2;
NEW(0,0)    = (2.0 - 4.0*speed2_1)*OLD(0,0) - NEW(0,0) +
              speed2_1*(OLD(0,1) + OLD(1,0));
NEW(0,nx-1) = (2.0 - 4.0*speed2_2)*OLD(0,nx-1) - NEW(0,nx-1) +
              speed2_2*(OLD(0,nx1) + OLD(1,nx-1));
      }
      else {                   /* First Block in every node except in NODE 0 */
/* Copy the first two OLD rows, first SPEED row, and first NEW row   */
/* of block 0, in order to use them when computing the first row of  */
/* block 0 after receiving the lower edge (OLD) from node (i-1)      */
memcpy(speed_upper_edgep, &SPEED(0,0), edge_size);
memcpy(new_upper_edgep,   &NEW(0,0),   edge_size);
memcpy(old_upper_edgep,   &OLD(0,0),   2*edge_size);
      };

      /* Copy the last two OLD rows, the last SPEED row, and the last NEW    */
      /* row of this block, in order to use them when computing the last row */
      /* of this block and the first row of the next block. The last row of  */
      /* NEW is copied to the first row of read_newp, because this is the    */
      /* next block to be processed                                          */
      memcpy(speed_prev_rowp, &SPEED(last,0), edge_size);
      memcpy(old_prev_rowp,   &OLD(ny1,0),  2*edge_size);
```

```
    memcpy(read_newp,       &NEW(last,0),   edge_size);
 }
 else {                 /* It is not the first block */
   /* Compute 1st row of the block */
   for (j=1; j<=nx1; j++) {
     speed2   = SPEED(0,j); speed2 *= speed2;
     NEW(0,j) = (2.0 - 4.0*speed2)*OLD(0,j) - NEW(0,j) + speed2 *
                (OLD(0,j+1) + OLD(0,j-1) + OLD(1,j) + OLD_PREV(1,j));
   };
   /* Compute the upper left and upper right corners */
   speed2_1    = SPEED(0,0);    speed2_1 *= speed2_1;
   speed2_2    = SPEED(0,nx-1); speed2_2 *= speed2_2;
   NEW(0,0)    = (2.0 - 4.0*speed2_1)*OLD(0,0) - NEW(0,0) +
                 speed2_1*(OLD(0,1) + OLD(1,0) + OLD_PREV(1,0));
   NEW(0,nx-1) = (2.0 - 4.0*speed2_2)*OLD(0,nx-1) - NEW(0,nx-1) +
         speed2_2*(OLD(0,nx1) + OLD(1,nx-1) + OLD_PREV(1,nx-1));

   /* Compute the last NEW row of previous block */
   for (j=1; j<=nx1; j++) {
     speed2      = SPEED_PREV(j); speed2 *= speed2;
     NEW_PREV(j) = (2.0 - 4.0*speed2)*OLD_PREV(1,j) - NEW_PREV(j) + speed2
                   *(OLD_PREV(1,j+1) + OLD_PREV(1,j-1)
                   + OLD(0,j)        + OLD_PREV(0,j));
   };
   /* Compute the upper left and upper right corners of the last NEW */
   /* row of previous block                                          */
   speed2_1       = SPEED_PREV(0);    speed2_1 *= speed2_1;
   speed2_2       = SPEED_PREV(nx-1); speed2_2 *= speed2_2;
   NEW_PREV(0)    = (2.0 - 4.0*speed2_1)*OLD_PREV(1,0) - NEW_PREV(0) +
                    speed2_1*(OLD_PREV(1,1) + OLD(0,0) + OLD_PREV(0,0));
   NEW_PREV(nx-1) = (2.0 - 4.0*speed2_2)*OLD_PREV(1,nx-1) - NEW_PREV(nx-1) +
            speed2_2*(OLD_PREV(1,nx1)+OLD(0,nx-1)+OLD_PREV(0,nx-1));

   if ((b == (num_blks-1)) && (mynode == (num_nodes-1))) {
      /* Last block of last Node */
      /* Compute the last row    */
      for (j=1; j<=nx1; j++) {
speed2      = SPEED(last,j); speed2 *= speed2;
NEW(last,j) = (2.0 - 4.0*speed2)*OLD(last,j) - NEW(last,j) +
              speed2*(OLD(last,j+1) + OLD(last,j-1) + OLD(ny1,j));
      };
      /* Compute the lower left and lower right corners */
      speed2_1       = SPEED(last,0);    speed2_1 *= speed2_1;
```

```
      speed2_2       = SPEED(last,nx-1); speed2_2 *= speed2_2;
      NEW(last,0)    = (2.0 - 4.0*speed2_1)*OLD(last,0) - NEW(last,0) +
                       speed2_1*(OLD(last,1) + OLD(ny1,0));
      NEW(last,nx-1) = (2.0 - 4.0*speed2_2)*OLD(last,nx-1) - NEW(last,nx-1) +
               speed2_2*(OLD(last,nx1) + OLD(ny1,nx-1));
    }
    else if (b != (num_blks-1)) {                /* it isn't the last block */
      /* Copy the last two OLD rows, the last SPEED row, and the last NEW   */
      /* row of this block, in order to use them when computing the last    */
      /* row of this block and the first row of the next block. The last    */
      /* row of NEW is copied to the first row of read_newp, because this   */
      /* is the next block to be processed                                  */
      memcpy(speed_prev_rowp, &SPEED(last,0), edge_size);
      memcpy(old_prev_rowp,   &OLD(ny1,0),  2*edge_size);
      memcpy(read_newp,       &NEW(last,0),   edge_size);
    };
  };

  /* Compute the internal points */
  for (i=1; i<=ny1; i++)
    for (j=1; j<=nx1; j++) {
      speed2   = SPEED(i,j); speed2 *= speed2;
      NEW(i,j) = (2.0 - 4.0*speed2)*OLD(i,j) - NEW(i,j) +
         speed2*(OLD(i,j+1) + OLD(i,j-1) + OLD(i+1,j) + OLD(i-1,j));
    };
  /* Compute vertical borders: j=0 and j=nx-1 */
  for (i=1; i<=ny1; i++) {
    speed2_1    = SPEED(i,0);    speed2_1 *= speed2_1;            /* j=0    */
    speed2_2    = SPEED(i,nx-1); speed2_2 *= speed2_2;            /* j=nx-1 */
    NEW(i,0)    = (2.0 - 4.0*speed2_1)*OLD(i,0) - NEW(i,0) +
                  speed2_1 * (OLD(i,1) + OLD(i+1,0) + OLD(i-1,0));
    NEW(i,nx-1) = (2.0 - 4.0*speed2_2)*OLD(i,nx-1) - NEW(i,nx-1) +
                  speed2_2 * (OLD(i,nx1) + OLD(i+1,nx-1) + OLD(i-1,nx-1));
  };
  node_t.cpu_comp += (amicclk()-start_cpu);     /* end time for computations */
}

/*-------------------------------------------------------------------------*/
/* Compute lower edge in node (i) using the edge received from node (i+1).  */
/* This is executed in every node except in the last node                   */
/*-------------------------------------------------------------------------*/

void compute_lower_edge(void)
```

```
{
  /* b = (num_blks-1), NODE != (num_nodes-1) */
  int nx1, ny1, last;
  float speed2, speed2_1, speed2_2;

  start_cpu    = amicclk();              /* start time for computations */
  nx1          = nx - 2;
  ny1          = last_blk_size/edge_size - 2;
  last         = ny1 + 1;
  speed        = (float *)speed_blkp;
  old          = (float *)old_blkp;
  low_edge_rcv = (float *)low_edge_rcvp;
  /* Compute the internal points for last row of last block */
  for (j=1; j<=nx1; j++) {
    speed2      = SPEED(last,j); speed2 *= speed2;
    NEW(last,j) = (2.0 - 4.0*speed2)*OLD(last,j) - NEW(last,j) + speed2 *
                  (OLD(last,j+1) + OLD(last,j-1) + OLD_NEXT(j) + OLD(ny1,j));
  };
  /* Compute the lower left and lower right corners */
  speed2_1       = SPEED(last,0);    speed2_1 *= speed2_1;
  speed2_2       = SPEED(last,nx-1); speed2_2 *= speed2_2;
  NEW(last,0)    = (2.0 - 4.0*speed2_1)*OLD(last,0) - NEW(last,0) +
                     speed2_1*(OLD(last,1) + OLD(ny1,0) + OLD_NEXT(0));
  NEW(last,nx-1) = (2.0 - 4.0*speed2_2)*OLD(last,nx-1) - NEW(last,nx-1) +
           speed2_2*(OLD(last,nx1) + OLD(ny1,nx-1) + OLD_NEXT(nx-1));
  node_t.cpu_comp += (amicclk()-start_cpu);  /* end time for computations */
}

/*-------------------------------------------------------------------------*/
/* Compute upper edge in node (i) using the edge received from node (i-1).  */
/* This is executed in every node except in the node 0                      */
/*-------------------------------------------------------------------------*/

void compute_upper_edge(void)
{
  /* b = (num_blks-1), NODE != 0 */
  int nx1;
  float speed2, speed2_1, speed2_2;

  start_cpu   = amicclk();              /* start time for computations */
  nx1         = nx - 2;
  speed       = (float *)speed_blkp;
  old         = (float *)old_blkp;
```

```
  up_edge_rcv = (float *)up_edge_rcvp;
  /* Compute the internal points for 1st row of 1st block */
  for (j=1; j<=nx1; j++) {
    speed2    = SPEED_UP(j); speed2 *= speed2;
    NEW_UP(j) = (2.0 - 4.0*speed2)*OLD_UP(0,j) - NEW_UP(j) + speed2 *
                (OLD_UP(0,j+1) + OLD_UP(0,j-1) + OLD_UP(1,j) + OLD_LOW(j));
  };
  /* Compute the lower left and lower right corners */
  speed2_1     = SPEED_UP(0);    speed2_1 *= speed2_1;
  speed2_2     = SPEED_UP(nx-1); speed2_2 *= speed2_2;
  NEW_UP(0)    = (2.0 - 4.0*speed2_1)*OLD_UP(0,0) - NEW_UP(0) + speed2_1 *
                 (OLD_UP(0,1) + OLD_UP(1,0) + OLD_LOW(0));
  NEW_UP(nx-1) = (2.0 - 4.0*speed2_2)*OLD_UP(0,nx-1)-NEW_UP(nx-1) + speed2_2 *
                 (OLD_UP(0,nx1) + OLD_UP(1,nx-1) + OLD_LOW(nx-1));
  node_t.cpu_comp += (amicclk()-start_cpu);     /* end time for computations */
}

/*-------------------------------------------------------------------------*/
/* Write lower edge of node (i) to disk using asyncronous I/O. This        */
/* function is called after the last block of data has been processed, and */
/* only if this is not the last node                                       */
/*-------------------------------------------------------------------------*/

void write_lower_edge()
{
  long offset;
  int  last_row;

  start_aio = amicclk();                       /* start time aio req. */
  new       = (float *)(new_blkp+edge_size);
  *res_lowp = init_res_aio;
  last_row  = (last_blk_size / edge_size) - 1;
  offset    = (long)yhi * (long)edge_size;
  AIOWRITE(new_fd, &NEW(last_row,0), edge_size, offset, SEEK_SET, res_lowp);
  node_t.aio_req += (amicclk()-start_aio);            /* end time aio req.   */
}

/*-------------------------------------------------------------------------*/
/* Write upper edge (1st row) of block 0 in node (i) to disk using         */
/* asyncronous I/O. This function is called after the last block of data has */
/* been processed, and only if this is not node 0                          */
/*-------------------------------------------------------------------------*/
```

```
void write_upper_edge(void)
{
  start_aio = amicclk();                        /* start time aio req. */
  *res_upp = init_res_aio;
  AIOWRITE(new_fd, &NEW_UP(0), edge_size, first_offset, SEEK_SET, res_upp);
  node_t.aio_req += (amicclk()-start_aio);            /* end time aio req.   */
}

/*-------------------------------------------------------------------------*/
/* Takes a snapshot of the actual NEW file                                 */
/*-------------------------------------------------------------------------*/

void take_snapshot(int time_step)
{
                              SEE  SOURCE  FILE
}

/*-------------------------------------------------------------------------*/
/* Deallocate from the HEAP and from the Communication Buffer all memory   */
/* used during by the program                                              */
/*-------------------------------------------------------------------------*/

void deallocate_memory(int problem)
{
                              SEE  SOURCE  FILE
}

/*-------------------------------------------------------------------------*/
/* Close all data files, and removing unnecessary files                    */
/*-------------------------------------------------------------------------*/

void close_files(void)
{
                              SEE  SOURCE  FILE
}

/*-------------------------------------------------------------------------*/
/* Gather times from every node, compute maximun, minimun, and average time */
/* and generate a file with the results                                    */
/*-------------------------------------------------------------------------*/

void report_times(void)
{
```

```
                        SEE  SOURCE  FILE
}

/*************************************************************************/
/*******************************          ********************************/
/*******************************   MAIN   ********************************/
/*******************************          ********************************/
/*************************************************************************/

main()
{
  initialize();
  whoami(&mynode, &mypid, &myhid, &ncubedim);
  num_nodes = ncubesize();
  read_global();
  read_local();
  decompose_data();
  init_parameters();
  /* Compute Maximum block size (rows) when the problem fits in RAM */
  max_blk_size = (cbuf_rows - SPARE_ROWS - USED_ROWS_IN) / DATA_BLKS_IN;
  if (max_blk_size < MINIMUN_ROWS) {
     SHOW("Not enough space in Comm. Buffer (in core)"); exit(1);
  };
  incore = problem_fits();              /* == 1 iff problem fits in RAM */
  incore = imin(incore, ALL_NODES, MIN_MTYPE, ALL_NODES);
  if (incore == 1) {          /* problem fits in RAM in all nodes */
     SHOW("Problem Fits in RAM");
     incore_model();
     return (0);                         /* END program, there was no error  */
  };
  /* At this point we know that the problem doesn't fit in RAM and we have   */
  /* to check if data has can be divided in blocks to be processed           */
  /* asynchronously.                                                         */

  /* Compute Maximum block size (rows) when the problem doen't fit in RAM    */
  max_blk_size = (cbuf_rows - SPARE_ROWS - USED_ROWS_OUT) / DATA_BLKS_OUT;
  if (max_blk_size < MINIMUN_ROWS) {
     SHOW("Not enough space in Comm. Buffer (out of core)"); exit(1);
  };
  num_blocks_and_size();     /* blk_size == 0 iff problem doesn't fit in RAM */
  min_blk_size = imin(blk_size, ALL_NODES, MIN_MTYPE, ALL_NODES);
  if (min_blk_size == 0) {
     SHOW("Problem cannot be decomposed using this CUBE dimension"); exit(1);
```

```
};
/* At this point we know that the problem doesn't fit in RAM and data was  */
/* divided in blocks to be processed asynchronously. Therefore:            */
/*                                                                         */
/* num_blks > 1                                                            */
SHOW("Problem Doesn't Fit in RAM");
source_node = ishere_source(isx, isy);
modi_speed();
open_data_files();
allocate_memory();
start_cpu = amicclk();                    /* start time other comp. */
/* Main loop for executing every time step */
for (t=0; t <= nt; t++) {
  if (mynode == 0) printf("Iteration t=%d\n", t);
  if (source_node && t<LENF)
     update_source(isy, isx);           /* Update value in source position */
  node_t.cpu_other += (amicclk()-start_cpu);       /* end time other comp. */
  /* Processing of the first data blocks */
  /* Read B0 */
  read_block(0, blk_size, read_speedp, read_newp+edge_size, read_oldp);
  wait_aio(3);                                    /* wait until B0 is read  */
  start_cpu = amicclk();                    /* start time other comp. */
  /* Update pointers */
  SWAP(char *, read_speedp, speed_blkp);         /* B0 has to be processed */
  SWAP(char *, read_newp,   new_blkp);
  SWAP(char *, read_oldp,   old_blkp);
  node_t.cpu_other += (amicclk()-start_cpu);     /* end time other comp.   */
  if (mynode != 0)                    /* Send upper OLD edge if not node 0 */
     send_upper_edge(send_to_up);
  /* Read B1 */
  read_block(1, blk_size, read_speedp, read_newp+edge_size, read_oldp);
  compute_block(0);                                /* compute B0 */
  wait_aio(3);                              /* wait until B1 is read  */
  start_cpu = amicclk();                    /* start time other comp. */
  /* Update pointers */
  SWAP(char *, new_blkp,    write_newp);   /* B0 has to be written to disk */
  SWAP(char *, read_speedp, speed_blkp);   /* B1 has to be processed       */
  SWAP(char *, read_newp,   new_blkp);
  SWAP(char *, read_oldp,   old_blkp);
  node_t.cpu_other += (amicclk()-start_cpu);       /* end time other comp. */
  /* Main loop for processing (read-compute-write) all data blocks */
  for (b=1; b <= num_blks-2; b++) {
    /* read B(b+1) */
```

```
      read_block(b+1, blk_size, read_speedp, read_newp+edge_size, read_oldp);
      write_block(b-1, blk_size, write_newp);                /* write B(b-1) */
      compute_block(b);                                      /* compute B(b) */
      start_cpu = amicclk();                    /* start time other comp. */
      /* Update pointers */
      SWAP(char *, new_blkp, write_newp);  /* B(b) has to be written to disk */
      SWAP(char *, read_speedp, speed_blkp);   /* B(b+1) has to be processed */
      SWAP(char *, read_newp,   new_blkp);
      SWAP(char *, read_oldp,   old_blkp);
      node_t.cpu_other += (amicclk()-start_cpu);     /* end time other comp. */
      wait_aio(4);  /* Wait until B(b+1) is read and block B(b-1) is written */
   }; /* END LOOP b */
   /* Processing the last two data blocks */
   write_block(num_blks-2, blk_size, write_newp);   /* write  B(num_blks-2) */
   compute_block(num_blks-1);                      /* compute B(num_blks-1) */
   write_block(num_blks-1,last_blk_size,new_blkp); /* write   B(num_blks-1) */
   wait_aio(2);    /* wait until B(num_blks-2) and B(num_blks-1) is written */
   if (num_nodes > 1) {  /* program is running in more than one node */
      /* After reading last block, compute the lower edge if not last node  */
      if (mynode != (num_nodes-1)) {
send_lower_edge(send_to_down);
low_edge_rcvp = rcv_lower_edge(rcv_from_down);
new           = (float *)(new_blkp+edge_size);
compute_lower_edge();
write_lower_edge();
NRELP(low_edge_rcvp);
      };
      /* After reading last block, compute the upper edge if not first node */
      if (mynode != 0) {
up_edge_rcvp = rcv_upper_edge(rcv_from_up);
new          = (float *)(new_blkp+edge_size);
compute_upper_edge();
write_upper_edge();
NRELP(up_edge_rcvp);
      };
      if ((mynode == 0) || (mynode == (num_nodes-1)))
wait_aio(1);        /* wait for the upper or lower edge written  */
      else
wait_aio(2);           /* wait for the upper and lower edge written */
   };
   if (((t+1) % isnap) == 0) take_snapshot(t+1);
   start_cpu = amicclk();                    /* start time other comp. */
   SWAP(int, old_fd, new_fd);                     /* Swap File Descriptors  */
```

```
  }; /* END LOOP t  */
  start_init = amicclk();                    /* start time initia.     */
  deallocate_memory(NO_FIT);
  close_files();
  node_t.init += (amicclk()-start_init);           /* end time initia.       */
  report_times();         /* gather and report execution times */
  return (0);         /* END program, there was no error   */
} /***************************** END  main ***********************************/
```

A.2 FD_1D.h

This is the primary include file used by the main program **fd_1D.c**.

```
/*****************************************************************************
*                                                                            *
*       File: fd_1D.h                                                        *
*                                                                            *
*       Purpose: Constant definitions to be used by the                      *
*                Finite Difference 1D program                                *
*                                                                            *
*       Included By: fd_1D.c                                                 *
*                                                                            *
*****************************************************************************
*
*
* Memory Management:
*
*   NODE_MEM      = KBytes of Memory per node.
*   1KB           = bytes in 1KB.
*   DATA_BLKS_OUT = number of data blocks simultaneously in memory (Com.
*                   Buff.) when the problem doesn't fit in RAM memory.
*   DATA_BLKS_IN  = number of data blocks simultaneously in memory (Com.
*                   Buff.) when the problem does fit in RAM memory.
*
*
* Global Parameters (node independent):
*
*   num_nodes = number of nodes in the N-cube (2^ncubedim).
*   nx, ny, nt                = grid dimensions.
*   dx, dy, dt, dtodx         = see documment.
*   ichoix, t0, f0, psi, gamma = wavelet parameters.
*   itype, isx, isy, sdev     = source position and type in grid coordinates.
*   isnap = number of time steps between every snapshot of the pressure field.
*   pfs   = 1 iff working files are going to be opened in the nCUBE Parallel
*           File System (default = 0).
*   source_node               = 1 iff the source is located in this node.
*   root                      = root name for every file used in this run.
*
*
* I/O Files Used:
```

```
*
*   root_fn  = input parameters file name.
*   root_fd  =   "       "       "   descriptor.
*   speed_fn = velocity file name.
*   speed_fd =    "      "   descriptor.
*   spm_fn   = speed file name with every component multiplied by dt/dx.
*   spm_fd   = modified velocity file descriptor (speed * dtodx).
*   old_fn   = pressure file name       in iteration (t-1).
*   old_fd   =    "      "   descriptor "     "      (t-1).
*   new_fn   =    "      "   name       "     "      (t).
*   new_fd   =    "      "   descriptor "     "      (t).
*   tmp_fd   = temporal file descriptor for swaping old_fd and new_fd.
*
*
* Local Parameters (node dependent):
*
*   ylo            = lowest value in y-axis for processor (i).
*   yhi            = highest value in y-axis for processor (i).
*   ypts           = # of pts in the y-axis (rows) for processor (i).
*   blk_size       = Size of every data block to be Read-Computed-Writed.
*   min_blk_size   = min data block size between every node.
*   last_blk_size  =  "   " last data block associated to this node.
*   last_blk_rows  = rows "  "    "     "       "      "   "    "  .
*   rows_per_block = rows per block in [0,num_blks-2] except last block.
*   min_rows       = minimun number of rows per block of every node.
*   num_blks       = # of data blocks to be Read-Computed-Written.
*   incore         = 1 iff the problem fits in RAM (0 otherwise).
*   b              = block being processed [0,num_blks-1].
*   t              = time [0,nt-1] (number of iterations).
*
*
* Memory Management:
*
*   CODE_SIZE     = ~bytes reserved for code and static variables.
*   HEAP_SIZE     =    "      "      "  the Heap.
*   cbuf_size     =    "      "      "   "  Communication Buffer.
*   cbuf_rows     = Communication Buffer size in number of rows (edge_size).
*   SPARE_ROWS    = free rows (edge_size) in the Communication Buffer.
*   USED_ROWS_OUT = used  "   (edge_size) "   "       "          "    when the
*                   problem doesn't fit in RAM memory.
*   USED_ROWS_IN  = used rows (edge_size) in the Communication Buffer  "    "
*                   problem does fit in RAM memory.
*   DATA_BLKS_OUT = number of data blocks simultaneously in memory (Com.
```

```
*                  Buff.) when the problem doesn't fit in RAM memory.
*   DATA_BLKS_IN  = number of data blocks simultaneously in memory (Com.
*                  Buff.) when the problem does fit in RAM memory.
*   max_blk_size  = max. possible size for a data block (in rows of edge_size).
*   FIT           = indicates if the problem does    fit in RAM memory.
*   NO_FIT        =     "     "   "     "    doesn't  "  "   "    "   .
*   MINIMUN_ROWS  = minimun number of rows per block in order for the
*                  decomposition to be efficient.
*
*
* Data Blocks:
*
*   read_speedp   = pointer to the SPEED data block to be read from disk.
*   read_oldp     =   "     "   "  OLD    "     "   "  "   "    "    "  .
*   read_newp     =   "     "   "  NEW    "     "   "  "   "    "    "  .
*   write_newp    =   "     "   "   "     "     "   "  "  written to disk.
*   new_blkp      =   "     "   "  NEW    "     "   being processed.
*   old_blkp      =   "     "   "  OLD    "     "     "       "    .
*   speed_blkp    =   "     "   "  SPEED  "     "     "       "    .
*   tmp_blkp      = temp. var. to switch read_speedp, write_newp, and new_blkp.
*   new           = float pointer to new_blkp.
*   old           =   "     "     "  old_blkp.
*   speed         =   "     "     "  speed_blkp.
*
*
* Edges Manipulation (inside the same node, between blocks):
*
*   old_prev_rowp   = last two rows OLD from previous block. (copy)
*   speed_prev_rowp =  "   row SPEED     "      "       "      "
*   old_prev_row    = pointer to float.
*   speed_prev_row  =    "    "    "  .
*   new_prev_row    = float ptr (last NEW row from previous block).
*
*
* Edges Manipulation (between nodes):
*
*   low_edge_rcvp     = pointer to the lower edge received from node (i+1).
*   up_edge_rcvp      =   "     "   "  upper  "       "     "    "   (i-1).
*   new_upper_edgep   =   "     "   "  NEW upper edge in node (i).
*   old_upper_edgep   =   "     "   "  OLD two upper edges in node (i).
*   speed_upper_edgep =   "     "   "  SPEED upper edge in node (i).
*   low_edge_rcv      =   "     "  float.
*   up_edge_rcv       =   "     "    "  .
```

```
*   new_upper_edge    =   "     "    "  .
*   old_upper_edge    =   "     "    "  .
*   speed_upper_edge  =   "     "    "  .
*
*
* Controlling Asynchronous I/O:
*
*   res_lowp        = used for writing  lower edge from last  block.
*   res_upp         =  "    "     "     upper  "    "   first   "  .
*   res_writep      =  "    "     "     current NEW block.
*   res_last_writep =  "    "     "     last     "    "  .
*
*
* I/O Parameters:
*
*   RW_MODE      = READ/WRITE mode.
*   R_MODE       = READ ONLY  mode.
*   W_MODE       = WRITE ONLY mode.
*   isnap        = indicates how many time steps (t) between every snapshot
*                  of NEW file.
*   first_offset = initial position of the fp for data in node (i).
*   read_offset  = fp position for data block to be read in node (i).
*   write_offset = fp position for data block to be written in node (i).
*
*
* Transmission Parameters:
*
*   send_to_up     = send edge to node above (not valid for node 0).
*   send_to_down   = send edge to node below (not valid for last node).
*   rcv_from_up    = rcv. edge from node above (not valid for node 0).
*   rcv_from_down  = rcv. edge from node below (not valid for last node).
*   edge_size      = size in bytes of the edge to be sent/received.
*   ALL_NODES      = specify all nodes in a subcube when performing a
*                    global minimun computation.
*   LOW_EDGE_MTYPE = message type for send/rcv lower OLD edge.
*   UP_EDGE_MTYPE  = message type for send/rcv upper OLD edge.
*   MIN_MTYPE      = message type used for computing a global minimun.
*
*
* Time Measurements:
*
*   time_type  = type definition for a structure to keep the total time
*                consumed by the program.
```

```
*   total_time = total itemized time consumed by the program.
*   SYNC_MTYPE = message type used for synchronizing the subcube before
*                timing the program.
*   TMIN_MTYPE = message type used for computing minimun executing time.
*   TMAX_MTYPE =    "     "    "    "      "     maximun     "      "  .
*   TAVG_MTYPE =    "     "    "    "      "     average     "      "  .
*
*
*************************************************************************/
/*****************    DECLARTATION   OF  FUNCTIONS   ***********************/

void initialize(void);
void read_global(void);
void read_local(void);
void decompose_data(void);
int  mem_avail(void);
void init_parameters(void);
int  ishere_source(int ix, int iy);
int  problem_fits(void);
void num_blocks_and_size(void);
void modi_speed(void);
void open_data_files(void);
void allocate_memory(void);
void send_upper_edge(int send_to);
void send_lower_edge(int send_to);
char *rcv_upper_edge(int rcv_from);
char *rcv_lower_edge(int rcv_from);
void read_block(int b,int nbytes,char *spm_ptr,char *new_ptr,char *old_ptr);
void write_block(int b, int nbytes, char *blkp);
void wait_aio(int n_aio);
void update_source(int isy, int isx);
void compute_block(int b);
void compute_lower_edge(void);
void compute_upper_edge(void);
void write_lower_edge(void);
void write_upper_edge(void);
void take_snapshot(int time_step);
void deallocate_memory(int problem);
void close_files(void);
void report_times(void);

/************************    EXTERNAL  FUNCTIONS   ************************/
```

```
extern void incore_model(void);

/*****************    DECLARATION  OF  GLOBAL VARIABLES  *********************/

  char errstr[512], root[256];
  int mynode, mypid, myhid, ncubedim, status;
  int nx, ny, nt;
  float dx, dy, dt, dtodx;
  float t0, f0, psi, gamma, sdev, f[LENF];
  int ichoix, itype, isx, isy, isnap, pfs = 0;
  int ylo, yhi, ypts;
  int source_node;
  int num_nodes, edge_size;
  int blk_size, last_blk_size, num_blks, rows_per_block;
  int           last_blk_rows;
  int min_blk_size, min_rows, incore;

  /* Memory Management */
  int cbuf_size, cbuf_rows, max_blk_size;

  /* Control variables */
  int i, j, t, b;

  /* Data Block pointers */
  char  *read_speedp, *read_newp, *read_oldp;
  char  *speed_blkp,  *new_blkp,  *old_blkp, *write_newp;
  float *speed,       *new,       *old;

  /* To manage I/O */
  char root_fn[256], speed_fn[256], spm_fn[256];
  char new_fn[256], old_fn[256], tmp_fn[256];
  FILE *root_fd;
  int  speed_fd, spm_fd, old_fd, new_fd, tmp_fd;
  long first_offset, read_offset, write_offset;

  /* To control Asynchronous I/O */
  aio_result_t *res_read_speedp, *res_read_newp, *res_read_oldp;
  aio_result_t *res_writep, *res_last_writep, *res_lowp, *res_upp;
  aio_result_t init_res_aio = { AIO_INPROGRESS, 0 } ;
  struct timeval *timeout;
  struct timeval init_timeout = { 0, 0 };

  /* Edge Manipulation (between blocks) */
```

```
char  *speed_prev_rowp, *old_prev_rowp;
float *speed_prev_row,  *old_prev_row,  *new_prev_row;

/* Edge Manipulation (between nodes) */
char  *low_edge_rcvp,   *up_edge_rcvp;
float *low_edge_rcv,    *up_edge_rcv;
char  *new_upper_edgep, *old_upper_edgep, *speed_upper_edgep;
float *new_upper_edge,  *old_upper_edge,  *speed_upper_edge;

/* To control message passing */
int mtype, *mflag, send_to_up, send_to_down, rcv_from_up, rcv_from_down;

/* Time Measurements */
struct time_type {
  double init;
  double snap;
  double comm;   /* comm     = comm_wait    + comm_req      */
  double comm_wait;
  double comm_req;
  double cpu;   /* cpu      = cpu_comp     + cpu_other     */
  double cpu_comp;
  double cpu_other;
  double aio;   /* aio      = aio_wait     + aio_req       */
  double aio_wait;
  double aio_req;               /* aio_req  = aio_req_read + aio_req_write */
  double aio_req_read;
  double aio_req_write;
} node_t;

struct time_type zero_time = { 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
       0.0, 0.0, 0.0, 0.0, 0.0, 0.0 };

double start_init, start_snap, start_comm, start_cpu, start_aio;
```

A.3 defines.h

Include file with all constant definitions used by the main program **fd_1D.c**.

```
/*****************************************************************************
*                                                                            *
*       File: defines.h                                                      *
*                                                                            *
*       Purpose: Constant definitions to be used by the                      *
*                Finite Difference 1D program                                *
*                                                                            *
*       Included By: fd_1D.c, fd_1D.incore.c                                 *
*                                                                            *
*****************************************************************************/

/*****************   C O N S T A N T     D E F I N I T I O N S   *************/

/* Memory Management */
/* #define NODE_MEM       4096          4 MB */

#define MAX_MEM_AVAIL    32                                  /*  32 MB */
#define NODE_MEM        512                                     /* 512 KB */
#define KB             1024                                     /*   1 KB */
#define MB             1024*KB                                  /*   1 MB */
#define CODE_SIZE    131072                                  /* 128 KB */
#define HEAP_SIZE    131072                                     /* 128 KB */
#define SPARE_ROWS        5
#define USED_ROWS_OUT    12               /* the problem doesn't fit in RAM */
#define DATA_BLKS_OUT     8            /*  "     "      "      "  "   "  */
#define USED_ROWS_IN      2               /*  "     "    does     "  "   "  */
#define DATA_BLKS_IN      3               /*  "     "     "       "  "   "  */
#define FIT               0
#define NO_FIT            1
#define MINIMUN_ROWS      3

#define ELEM_SIZE sizeof(float)                  /* Bytes/element in Arrays */

#define SPD_FN "/pfs/tonysena/speed"
#define SPM_FN "/pfs/tonysena/modi.speed"
#define NEW_FN "/pfs/tonysena/new.press"
#define OLD_FN "/pfs/tonysena/old.press"
```

```
#define RW_MODE  0666
#define R_MODE   0444
#define W_MODE   0222

#define LENF 500

/* Message Passing */
#define LOW_EDGE_MTYPE  1
#define UP_EDGE_MTYPE   2
#define MIN_MTYPE       3
#define SYNC_MTYPE      4
#define TMIN_MTYPE      5
#define TMAX_MTYPE      6
#define TAVG_MTYPE      7
#define ALL_NODES      -1
#define NODE_ZERO       0

/******************   ACCESING 1D-ARRAYS AS MATRICES   **********************/

/* SPEED, OLD, and NEW for current block in memory */
#define SPEED(i,j)    speed[(i)*nx + (j)]
#define OLD(i,j)      old[(i)*nx + (j)]
#define NEW(i,j)      new[(i)*nx + (j)]

/* Lower SPEED, OLD, and NEW edges from previous block */
#define SPEED_PREV(j) speed_prev_row[j]
#define NEW_PREV(j)   new_prev_row[j]
#define OLD_PREV(i,j) old_prev_row[(i)*nx + (j)]

/* Upper NEW, SPEED, and OLD edges of block 0 in every node */
#define NEW_UP(j)   new_upper_edge[j]
#define SPEED_UP(j) speed_upper_edge[j]
#define OLD_UP(i,j) old_upper_edge[(i)*nx + (j)]

/* Upper OLD edge from next node (i+1) */
#define OLD_NEXT(j) low_edge_rcv[j]

/* Lower OLD edge of last block from previous node (i-1) */
#define OLD_LOW(j) up_edge_rcv[j]

/**********************   DECLARATION  OF  MACROS    ***********************/
```

```
#define SWAP(t,x,y) \
  { t tmp; \
    tmp = x; x = y; y = tmp; \
  }

#define SHOW(msg) \
  if (mynode == 0) \
     printf("%s\n", msg)
```

A.4 err.h

Include file with all macro definitions used by the main program **fd_1D.c**.

```
/*****************************************************************************
*                                                                            *
*       File: err.h                                                          *
*                                                                            *
*       Purpose: Macros to manage error messages                             *
*                                                                            *
*****************************************************************************
*
*  w = number of bytes written.
*
*****************************************************************************/

#include <sys/types.h>
#include <signal.h>

char estring[512];
int error, w;

/*-------------------------  ASYNCHRONOUS  I/O  ---------------------------*/

#define AIOREAD(ifd,bufp,bytes,offset,whence,resultp) \
  if (aioread(ifd,bufp,bytes,offset,whence,resultp) < 0) { \
     sprintf(estring,"%s:%d:%d: Error in aioread",__FILE__,__LINE__,npid()); \
     perror(estring); kill(-1,SIGKILL); exit(1); \
  }

#define AIOWRITE(ifd,bufp,bytes,offset,whence,resultp) \
  if (aiowrite(ifd,bufp,bytes,offset,whence,resultp) < 0) { \
     sprintf(estring,"%s:%d:%d: Error in aiowrite",__FILE__,__LINE__,npid()); \
     perror(estring); kill(-1,SIGKILL); exit(1); \
  }


/*-------------------------  MESSAGE  PASSING  ---------------------------*/

#define NWRITE(buf,blen,dest,mtype,not_used) \
  if (nwrite(buf, blen, dest, mtype, not_used) < 0) { \
```

```
    sprintf(estring,"%s:%d:%d: Error in nwrite",__FILE__,__LINE__,npid()); \
    perror(estring); kill(-1,SIGKILL); exit(1); \
  }

#define NWRITEP(buf,blen,dest,mtype,not_used) \
  if (nwritep(buf, blen, dest, mtype, not_used) < 0) { \
    sprintf(estring,"%s:%d:%d: Error in nwritep",__FILE__,__LINE__,npid()); \
    perror(estring); kill(-1,SIGKILL); exit(1); \
  }

#define NREAD(buf,blen,src,mtype,not_used) \
  if (nread(buf, blen, src, mtype, not_used) != blen) { \
    sprintf(estring,"%s:%d:%d: Error in nread",__FILE__,__LINE__,npid()); \
    perror(estring); kill(-1,SIGKILL); exit(1); \
  }

#define NREADP(buf,blen,src,mtype,not_used) \
  if ((blen = nreadp(buf, blen, src, mtype, not_used)) < 0) { \
    sprintf(estring,"%s:%d:%d: Error in nreadp",__FILE__,__LINE__,npid()); \
    perror(estring); kill(-1,SIGKILL); exit(1); \
  }

#define NSYNC(mtype) \
  if (nsync(mtype) != 0) { \
    sprintf(estring,"%s:%d:%d: Unable to Synchronize Nodes", \
    __FILE__,__LINE__,npid()); perror(estring); kill(-1,SIGKILL); exit(1); \
  }


/*-------------------------  MEMORY  ALLOCATION  -------------------------*/
/*--------------------------------  HEAP  --------------------------------*/

#define MALLOC(ptr,ptr_t,nbytes) \
  if ((ptr = (ptr_t *)ngetp(nbytes)) == NULL) { \
    sprintf(errstr,"%s:%d:%d: Error in ngetp", \
    __FILE__,__LINE__,npid()); perror(errstr); exit(1); \
  }


/*-------------------------  MEMORY  ALLOCATION  -------------------------*/
/*------------------------  COMMUNICATION  BUFFER  ------------------------*/

#define NGETP(ptr,ptr_t,nbytes) \
```

```
  if ((ptr = (ptr_t *)ngetp(nbytes)) == (void *)-1) { \
     sprintf(errstr,"%s:%d:%d: Error in ngetp", \
     __FILE__,__LINE__,npid()); perror(errstr); exit(1); \
  }

#define NRELP(ptr) \
  if (nrelp(ptr) < 0) { \
     sprintf(estring,"%s:%d:%d: Error in nrelp",__FILE__,__LINE__,npid()); \
     perror(estring); kill(-1,SIGKILL); exit(1); \
  }


/*--------------------------  SYNCHRONOUS  I/O  ---------------------------*/

#define READ(ifd, buf, blen) \
  if ((error=read(ifd, buf, blen)) != blen) { \
     fprintf(stderr,"#bytes expected=%d, #read=%d\n",blen,error); \
     sprintf(estring,"%s:%d:%d: Error in read",__FILE__,__LINE__,npid()); \
     perror(estring); kill(-1,SIGKILL); exit(1); \
  }

#define WRITE(ifd, buf, blen) \
  if ((w=write(ifd, buf, blen)) != blen) { \
     sprintf(estring,"%s:%d:%d: Error in write",__FILE__,__LINE__,npid()); \
     perror(estring); kill(-1,SIGKILL); exit(1); \
  }

#define LSEEK(ifd,offset,whence) \
  if (lseek(ifd,offset,whence) < 0) { \
     sprintf(estring,"%s:%d:%d: Error in lseek",__FILE__,__LINE__,npid()); \
     perror(estring); kill(-1,SIGKILL); exit(1); \
  }

#define OPEN(ifd,ifn,flags,mode) \
  if ((ifd = open(ifn, flags, mode) ) < 0) { \
     sprintf(errstr,"%s:%d:%d: Error opening %s", \
     __FILE__,__LINE__,npid(),ifn); perror(errstr); exit(1); \
  }

#define FOPEN(ifd,ifn,flags) \
  if ((ifd = fopen(ifn, flags)) == NULL) { \
     sprintf(errstr,"%s:%d:%d: Error opening %s", \
     __FILE__,__LINE__,npid(),ifn); perror(errstr); exit(1); \
```

```
  }

#define CLOSE(ifd) \
  if (close(ifd) < 0) { \
     sprintf(estring,"%s:%d:%d: Error in close",__FILE__,__LINE__,npid()); \
     perror(estring); kill(-1,SIGKILL); exit(1); \
  }

#define FCLOSE(ifd) \
  if (fclose(ifd) != 0) { \
     sprintf(estring,"%s:%d:%d: Error in fclose",__FILE__,__LINE__,npid()); \
     perror(estring); kill(-1,SIGKILL); exit(1); \
  }

#define CREAT(ifd,ifn,mode) \
  if ((ifd = creat(ifn, mode)) < 0) { \
     sprintf(errstr,"%s:%d:%d: Error creating file %s", \
     __FILE__,__LINE__,npid(),ifn); perror(errstr); exit(1); \
  }

#define REMOVE(ifn) \
  if (remove(ifn) != 0) { \
     sprintf(errstr,"%s:%d:%d: Error removing file %s", \
     __FILE__,__LINE__,npid(),ifn); perror(errstr); exit(1); \
  }
```

A.5 include.common.h

Include file with all includes used by sevral programs developed.

```
/*****************************************************************************
*                                                                            *
*       File: include.common.h                                               *
*                                                                            *
*       Purpose: Include ofsystem header files common to all sources files   *
*                                                                            *
*****************************************************************************/

#include <errno.h>
#include <fcntl.h>
#include <ntime.h>
#include <npara_prt.h>
#include <sys/uio.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <sys/async.h>
#include <sys/stat.h>
#include <sys/time.h>
#include <sys/types.h>
#include <swap.h>
#include <unistd.h>
```

Appendix B

Hardware & Software Platform Used

In this appendix we present the hardware and software platform used during the design, development, and test phases of the project for our *2D-Acoustic Wave Propagation* system.

B.1 Hardware Platform

Programs were written in SUN SparcStations and DECstations 5000, and compiled to be executed in an *nCUBE 2* parallel computer. These machines are part of the ERL-MIT (Earth Resources Laboratory) network, and the *nCUBE 2* with 512 processors is the property of the *ERL Center for Advanced Geophysical Computing.* Figure (B-1) shows the ERL-MIT data network configuration. We have several DECstations and SUN WS, the *nCUBE 2* supercomputer uses a SUN WS as Front-End and it has 4 parallel disks with a total capacity of 4 Gbytes. In addition, the ERL network is

connected to the MIT data network and also to the internet.

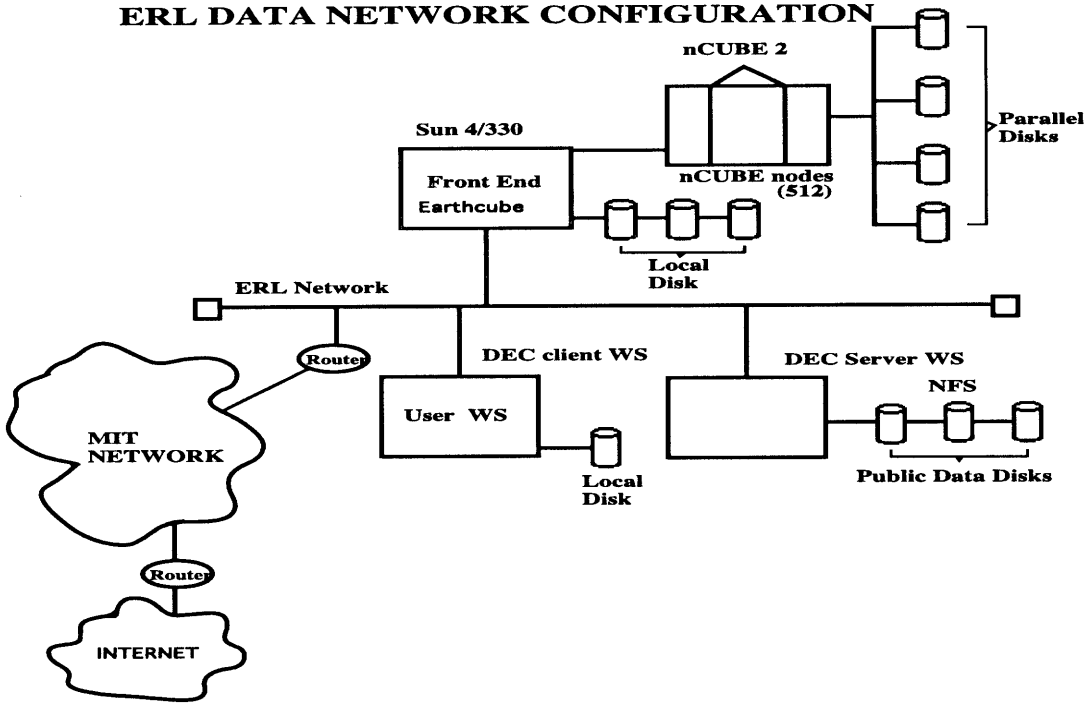

Figure B-1: ERL Data Network Configuration

B.2 Software Platform

The system was developed completely under the UNIX OS, using the C programming language (Kernighan and Ritchie, 1988). We used 100% ANSI C (Harbison and Guy L. Steele, 1991), specifically, we used a C compiler to generate an executable code for the *nCUBE 2* supercomputer called *ncc*, which is ANSI C compatible and has some extensions to support *message-passing*. In addition to the nCUBE C compiler (*ncc*), we also use its C preprocessor (*nccom*), the assembler (*nas*), and the link editor (*nld*). All of them are part of the nCUBE Development Environment, version 3.2 (07/01/93).

The system was debugged using *ndb* — the nCUBE version of the well known *dbx* UNIX debugger. We also used *ngdb* (nCUBE, 1992; Stallman and Pesch, 1992), the GNU version of the well known *gdb* UNIX debugger. In addition, the project was managed using the UNIX *make* utility (e.g., see Oram and Talbot, 1994).

In order to prepare the documentation and the edition of source files we used the GNU Emacs (e.g., see Cameron and Rosenblatt, 1992) editor, and the LaTeX Documentation System (Lamport, 1985; Lamport, 1994; Goossens *et al.*, 1994; Kopka and Daly, 1993).

Appendix C

Input/Output Data Files

In this appendix we describe the I/O data files needed to execute the program. The system requires that the user specifies a root file name in order to access all I/O data files. There are two input files:

- $<$ *root name* $>$*.input*: which contains the input parameters that define the problem.
- $<$ *root name* $>$*.alpha*: which is the velocity file. This file should be a floating point binary file written row by row. nCUBE floating point numbers are IEEE byte swapped (i.e. like in the DEC stations, but inverse of that in the SUN workstations).

The < *root name* >.*input* has the following parameters:

```
(int)nx       (int)ny     (int)nt
(float)dx     (float)dy   (float)dt
(int)ichoix   (float)t0   (float)f0   (float)psi (float)gamma
(int)itype    (int)isx    (int)isy    (float)sdev
(int)isnap    (int)pfs
```

Where:

- *(nx, ny, nt)*: nx is the number of columns and ny is the number of rows of the grid, and nt is the number of time steps in the simulation.
- *(dx, dy, dt)*: are the size of the discretization in space and time.
- *(ichoix, t0, f0, psi, gamma)*: *ichoix* define the wavelet used as a source function (i.e. *ichoix*=6 means the Ricker wavelet, $t0$ is the start time for the seismogram, $f0$ is the center frequency of the wavelet, and *psi* and *gamma* are parameters used by some wavelets, but not by the Ricker wavelet.
- *(itype, isx, isy, sdev)*: *itype* defines the source type (i.e. *itype*=0 means explosive source), *isx* and *isy* are the source positions in the grid coordinates, and *sdev* is the width of the source smoothing function.
- *(isnap, pfs)*: *isnap* is the frequency (in time steps) in which snapshots of the pressure field are saved to disk, and pfs is **zero** if the data files are going to be used via NFS (Network File System), or **one** if it is via PFS (Parallel File System).

There are five output files:

- $<$ *root name* $>$*.modi.speed*: which is the same velocity file but with every velocity multiplied by dt/dx. It is used during the computations (same format as the velocity file).
- $<$ *root name* $>$*.new.data*: which is the pressure file at time (t) (same format as the velocity file).
- $<$ *root name* $>$*.old.data*: which is the pressure file at time $(t-1)$ (same format as the velocity file).
- $<$ *root name* $>$*.total.AIO.time*: which contains all the information about the actual run: problem size, number of processors, parameters of the problem, memory used, timing information, etc.
- $<$ *root name* $>$*.snap.AIO.*$<$ *iterations* $>$: which contains a snapshot of the pressure file at the time specified. An input parameter defines the snapshot step.