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Modeling Pulse Propagation and Scattering in a Dispersive Medium Using the Cray MTA-2

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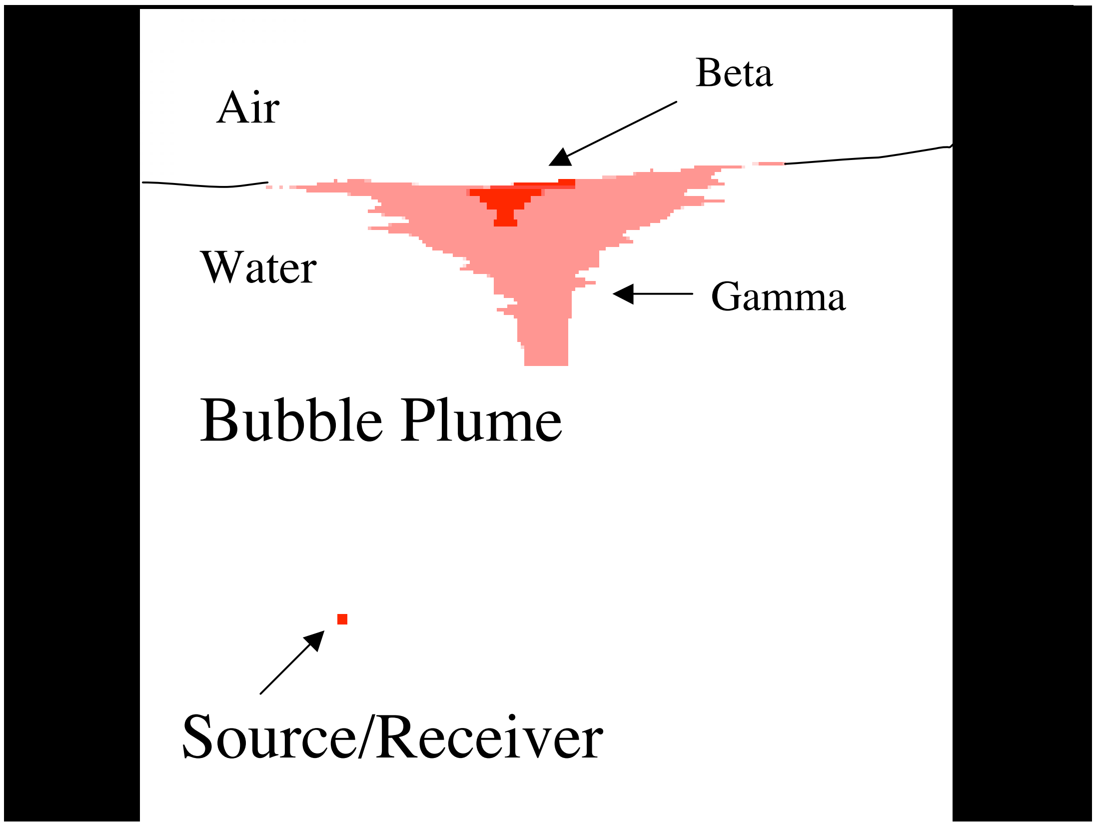
Basic Problem

- Underwater propagation of a signal in ocean
- Signals are short duration pulses (< 1 ms)
- Some regions of the medium may be dispersive (bubble plumes)
- Want to know if and how the signal is distorted

An Example



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The Wave equation

$$\nabla^2 p(r,t) - \frac{1}{c_0^2}\frac{\partial^2 p(r,t)}{\partial t^2} - \frac{1}{c_0}\frac{\partial\left(\Gamma(t) * p(r,t)\right)}{\partial t} = \delta(r - r_s)s(t)$$

First two terms are non-dispersive

Third term accounts for dispersion

Last part deines source location and evolution

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Four parts of update

- Time derivative algorithm
  - Fourth order in time and space
- Causal factor
  - Convolutional Propagation Operator
- Source signal
- Boundary points
  - Complimentary Operators Method

FDTD Discretization

$$
\begin{aligned}
p_{i,j}(t+1)=2.0*p_{i,j}(t)-p_{i,j}(t-1)\\
&+(c_{i,j}*dt*dt/(12*dx*dz)) *\\
&\quad (60*p_{i,j}(t)+\\
&\quad 16*(p_{i+1,j}(t)+p_{i,j+1}(t)+p_{i-1,j}(t)+p_{i,j-1}(t))\\
&\quad -(p_{i+2,j}(t)+p_{i,j+2}(t)+p_{i-2,j}(t)+p_{i,j-2}(t)))\\
&+(c_{i,j}*dt*dt*c_{i,j}*dt*dt/(12*dx*dx*dz*dz)*\\
&\quad (20* p_{i,j}(t)-8*(p_{i+1,j}(t)+p_{i-1,j}(t)+p_{i,j+1}(t)+p_{i,j-1}(t))\\
&\quad +2*(p_{i+1,j+1}(t)+p_{i-1,j+1}(t)+p_{i+1,j-1}(t)+p_{i-1,j-1}(t))\\
&\quad +(p_{i+2,j}(t) +p_{i-2,j}(t)+p_{i,j+2}(t)+p_{i,j-2}(t)))
\end{aligned}
$$

Approximately 40 floating point operations per grid point

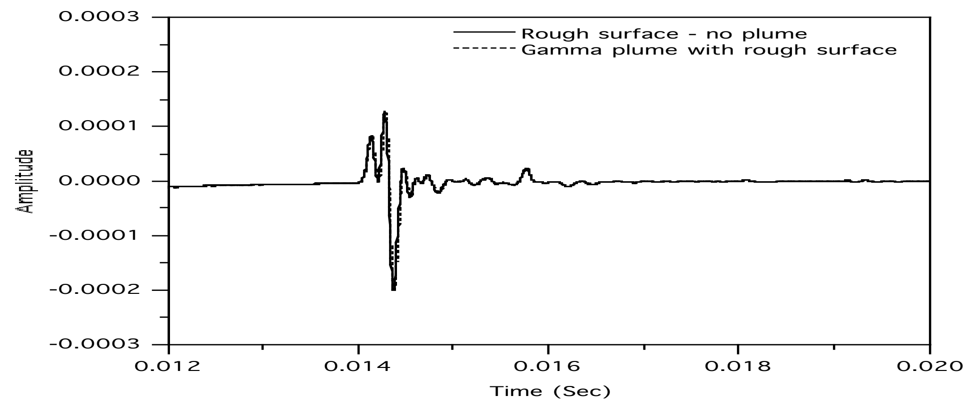
Convolutional Discretization

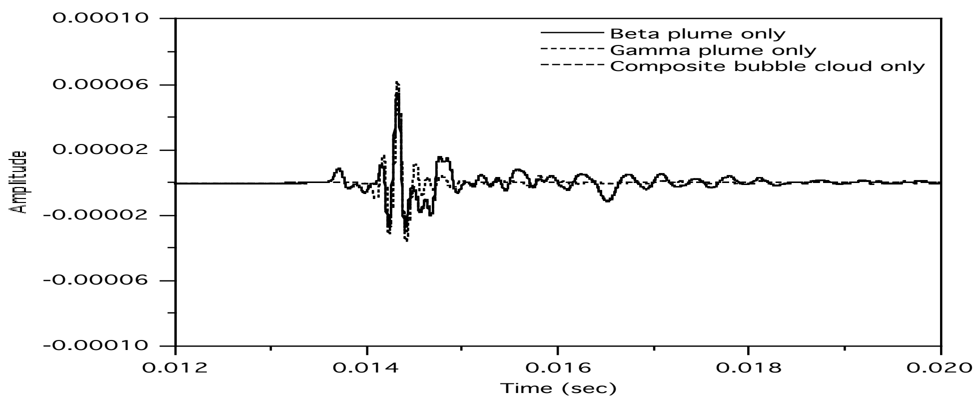
$$cp_{i,j}(t+1) = \sum_{m=1}^{1000} \Gamma_{i,j}(1000-m)\, p_{i,j}(t-1000+m)$$

$$p_{i,j}(t+1) = p_{i,j}(t+1) + \sum_{m=0}^{4} \alpha_{i,j}(m) cp_{i,j}(t-m)$$

Approximately 2000 floating point operations per dispersive grid point

Backscattered Fields





Basic loop

```
for each time step
  for each grid point
    Update FDTD for grid point
    Update convolutional operator
   end
  Update source
  Update boundary points
end
```

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Remove operations on zero

- FDTD not performed on points where signal could not have propagated
- Do not include values of zero in calculation of convolutional operator
- Speed up only occurs for early time steps and decreases as time progresses

Unoptimized MTA Time	2564 seconds
Orig MTA Time	1468 seconds

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Convolutional Improvement

Original Code

```
do m=1,ntau
 k=mod(nloc+m-1,nc)
 indx=nloc+kount+multi-1
 if (indx.gt.nc)indx=indx-nc
 s=s+c(m)*u(indx-1,i,j)
end do
```

Orig MTA time 1468 secs
Improved MTA time 391 secs

Modified Code

```
if (indx+ntau-1 .le. nc) then
  do m=1,ntau
   s=s+c(m)*u(indx+m-1,i,j)
  endo
else
 do m=1,nc-indx+1
   s=s+c(m)*u(indx+m-1,i,j)
 end do
 do m=ncpo1-indx+2, ntau
   s=s+c(m)*u(indx-nc+m-1,i,j)
 end do
endif
```

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Futures Improvement

Original Code

```
!$MTA PARALLEL
  do j=1,nz-1
    do i=1, nx-1
 !$MTA PARALLEL OFF
        ……..
!$MTA PARALLEL ON
     enddo
  enddo
```

MTA improved 391 seconds
MTA future 131seconds

Modified Code

```
!$MTA PARALLEL
!$MTA LOOP FUTURE
      do j=1, nz-1
!$MTA LOOP FUTURE
       do  i=1,nx-1
!$MTA PARALLEL OFF
       …..
!$MTA PARALLEL ON
        enddo
      enddo
```

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Split Loops

```
for each grid point
  Update FDTD for grid point
end
for each dispersive grid point
  Update convolutional operator for grid point
 end
```

MTA futures	131 seconds
MTA Split	93 seconds

Old Kernel Canal Analysis

```
fsq=cvelsq(i,j)*dx*dx
 grad=fsq*(-60.0*u(i,j,i1)+16.0*(u(i+1,j,i1)+u(i,j+1,i1)
                  +u(i-1,j,i1)+u(i,j-1,i1))-(u(i+2,j,i1)+u(i,j+2,i1)
                  +u(i-2,j,i1)+u(i,j-2,i1)))/(12.0*dx*dz)
         +fsq*fsq*(20.0*u(i,j,i1)-8.0*(u(i+1,j,i1)+u(i-1,j,i1)
                         +u(i,j+1,i1)+u(i,j-1,i1))+2.0*(u(i+1,j+1,i1)
                         +u(i-1,j+1,i1)+u(i+1,j-1,i1)+u(i-1,j-1,i1))
                         +u(i+2,j,i1)+u(i-2,j,i1)+u(i,j+2,i1)+u(i,j-2,i1))
                         /(12.0*dx*dx*dz*dz)
  u(i,j,i0)=2.*u(i,j,i1)-u(i,j,i2)+grad
```

Loop summary: 44 instructions, 40 floating point operations

16 loads, 2 stores, 15 reloads

New Kernel Canal Analysis

```
grad=e1(i,j)*u(i,j,i1)
     +e2(i,j)*(u(i+1,j,i1)+u(i,j+1,i1)+u(i-1,j,i1)+u(i,j-1,i1))
     + e3(i,j)*(u(i+2,j,i1)+u(i,j+2,i1)+u(i-2,j,i1)+u(i,j-2,i1))
     +e4(i,j)*(u(i+1,j+1,i1)+u(i-1,j+1,i1)
     +u(i+1,j-1,i1)+u(i-1,j-1,i1))
   u(i,j,i0)=2.0*u(i,j,i1)-u(i,j,i2)+grad
```

Loop summary: 21 instructions, 19 floating point operations,
19 memory operations

MTA split 95 seconds   MTA new kernel 83 seconds

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Summary of Running Times

No Optimization Code	2564 seconds
Original Code	1468 seconds
Improved Code	391 seconds
Future Code	131 seconds
Split Code	95 seconds
New Kernel Code	83 seconds

MTA Capabilities

40 220 Megahertz processors

3 floating point operations per second (26.4GF)

8 Byte memory transfer per cycle (70.4GB)

25 cycle latency

128 hardware threads per processor.

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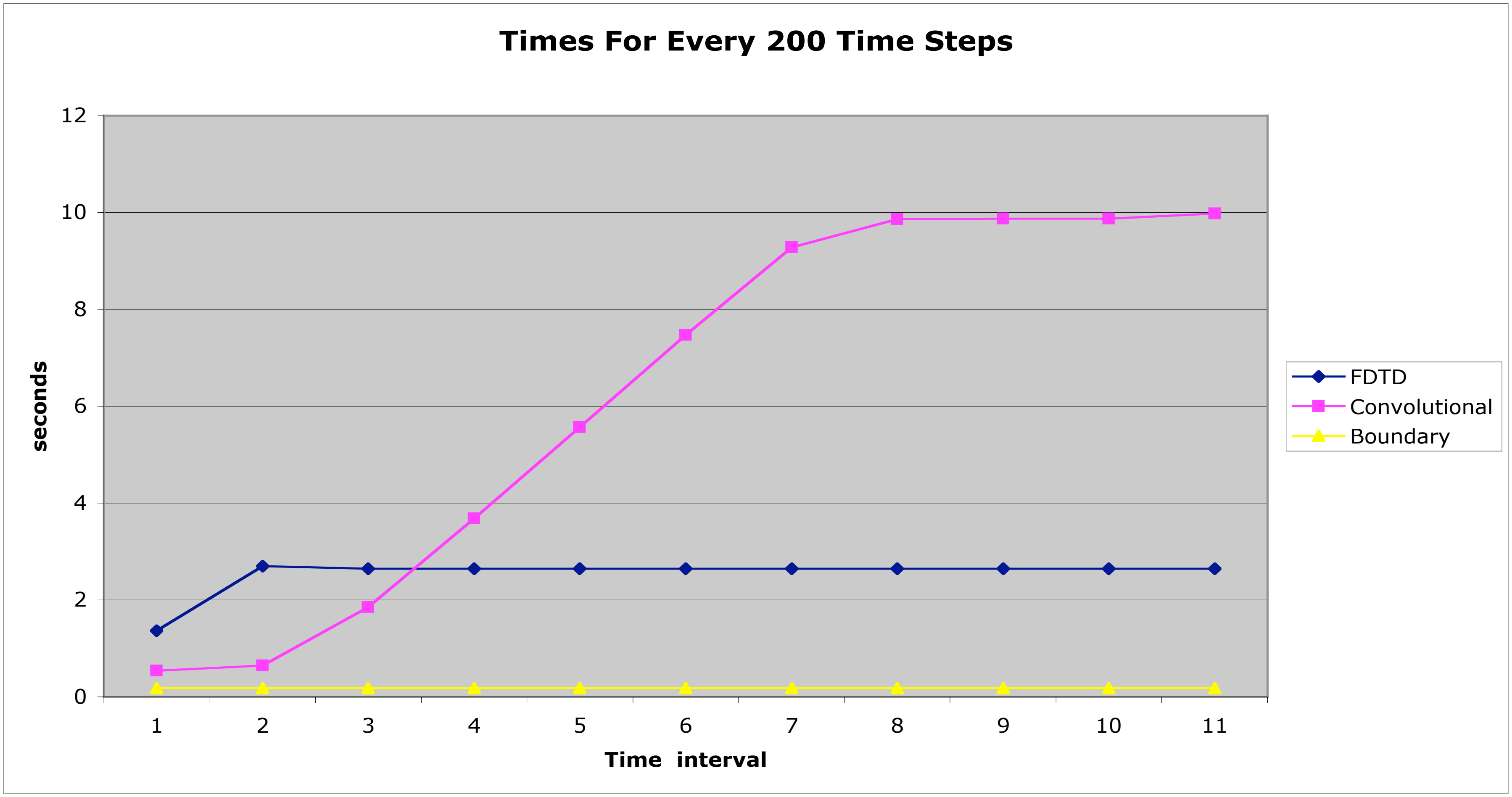
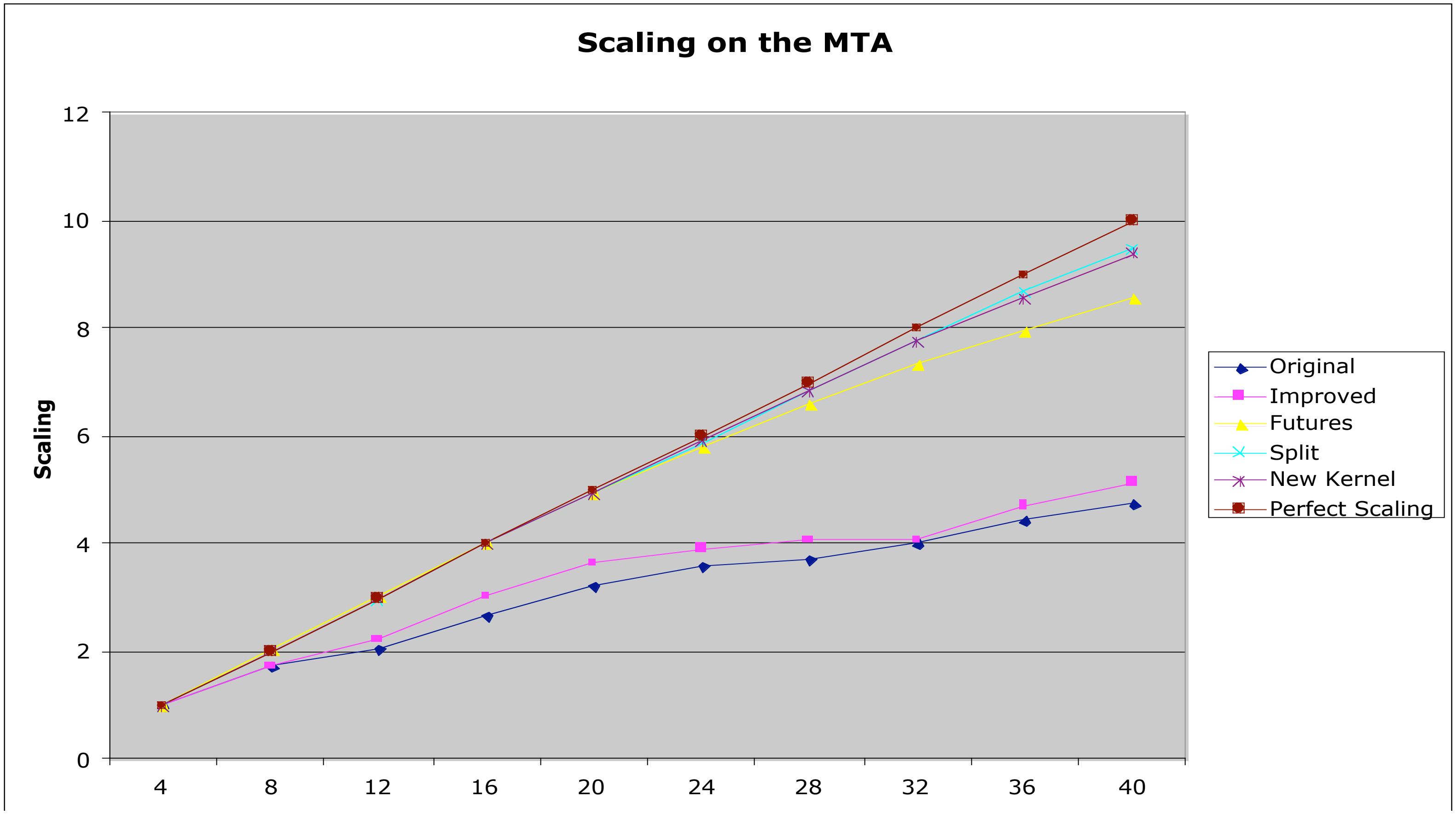
MTA Performance Peak %

Code	CPU Util	Memory	FP Ops
Original	25	8	2
Improved	28	22	7
future	84	75	20
split	95	77	31
New kernel	89	85	27

Work Over Time



Scaling on the MTA



Future Work

- Convert code to MPI
  - Arrays need to be cache friendly
  - Problem needs to be split up among processors to balance load
  - Communication costs need to be considered

Future Work

Heterogeneous Wave equation

3D problem.

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