SW4 for Chandan

Kindly do it

Sean R. Ford

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1 Introduction

Chandan asked, "Can you run MZZ, MXX, MYY seismograms for a layered medium in your SW4 and send me the output with the model?"

We obtained SW4 v3.0 from GitHub and compiled on macos with MPICH using the following `make.inc` file:

```
proj = yes
# homebrew version of proj is fine
SW4ROOT = /opt/homebrew
fftw = yes
# homebrew version uses openmpi so installed fftw for mpich
FFTWHOME = /Users/ford17/Applications/fftw-3.3.10
FC = mpif90
CXX = mpicxx
# need Accelerate for blas on macos
EXTRA_LINK_FLAGS = -framework Accelerate -L/opt/homebrew/lib/gcc/current -lgfortran
```

2 Method

The requirements are:

- Station at (x,y,z) = (60, 0, 0)
- Source at (x,y,z) = (10, 0, 10)
- WUS model
- PPW for 5 Hz
- Dirac (delta) source

So we create an SW4 input files for each source. Below is the input file for `mxx.sw4in`:

```
fileio pfs=1 nwriters=16 path=mxx.dir printcycle=1000
grid x=70e3 y=20e3 z=50e3 h=50
time t=45
block vp=7900.0 vs=4620.0 rho=3276.0 qp=60976 qs=27027
block vp=6407.5 vs=3768.0 rho=2822.3 qp=901 qs=402 z2=40000
block vp=6270.8 vs=3739.6 rho=2781.2 qp=658 qs=293 z2=21000
block vp=5544.5 vs=3295.3 rho=2608.9 qp=287 qs=128 z2=8000
block vp=3406.5 vs=2008.9 rho=2215.0 qp=331 qs=147 z2=1900
source x=10e3 y=10e3 z=10e3 mxx=1e18 type=Dirac t0=0
#source x=10e3 y=10e3 z=10e3 mxx=1e18 type=Triangle t0=0 freq=1
#source x=10e3 y=10e3 z=10e3 mxx=1e18 type=C6SmoothBump t0=0 freq=1
rec x=60e3 y=10e3 z=0 file=rec50 sacformat=1
image mode=s y=10e3 cycle=1
```

Note that we could have used refinement at the lowest layer for a more efficient calculation.

And to calculate the results we could use the command:

```
> mpirun -np 16 sw4 mxx.sw4in
```

In practice we used many more processors available on ruby from LC with a slurm script, `runruby.sw4run`:

```
#!/bin/tcsh
#SBATCH -N 50
#SBATCH -J run
#SBATCH -t 500
#SBATCH -p pbatch
#SBATCH --license=lustre1
#SBATCH -A gmp
#SBATCH -o run.sw4out
#SBATCH -e run.sw4err

# Max: 1440 minutes (24 hours) on 520 nodes
# 50 nodes took 15 minutes per run (9 runs = 135 minutes)

# Set CPUS/nodes for RUBY (limit 520 nodes for 24 hours)
@ CPUSPERNODE = 56
```

```
# Compute number of CPUs
@ NCPUS = ( $SLURM_JOB_NUM_NODES * $CPUSPERNODE )

srun -n$NCPUS /usr/workspace/ford17/sw4/optimize_ruby_mp/sw4 mxx.sw4in
srun -n$NCPUS /usr/workspace/ford17/sw4/optimize_ruby_mp/sw4 myy.sw4in
srun -n$NCPUS /usr/workspace/ford17/sw4/optimize_ruby_mp/sw4 mzz.sw4in
srun -n$NCPUS /usr/workspace/ford17/sw4/optimize_ruby_mp/sw4 mxy.sw4in
srun -n$NCPUS /usr/workspace/ford17/sw4/optimize_ruby_mp/sw4 mxz.sw4in
srun -n$NCPUS /usr/workspace/ford17/sw4/optimize_ruby_mp/sw4 myz.sw4in
srun -n$NCPUS /usr/workspace/ford17/sw4/optimize_ruby_mp/sw4 fx.sw4in
srun -n$NCPUS /usr/workspace/ford17/sw4/optimize_ruby_mp/sw4 fy.sw4in
srun -n$NCPUS /usr/workspace/ford17/sw4/optimize_ruby_mp/sw4 fz.sw4in
```

And then we execute the script with:

```
> sbatch runruby.sw4run
```

Our goal for an accurate calculation is to have a minimum points per wavelength (PPW) of between 6 and 10. The PPW is related to the smallest wave velocity v [m/s] divided by the grid spacing h [m] divided by the maximum frequency represented f [1/s]. For the grid used here (v = 2008.9 m/s, h = 50 m) the points per wavelength for a 5 Hz maximum frequency is:

$$\text{PPW} = v/h/f = 2008.9/50/5 \approxeq 8$$

3 Results

The shear wave velocity model is shown in Figure 1.

Calculated velocities bandpassed between 20 s and 5 Hz are shown in Figure 2.

4 Comparison with CPS

Dispalcements are also calculated using CPS and shown in Figure 3.

Bob Herrmann produced an excellent tutorial that guided our work here. In that tutorial, Bob found "execellent agreement" between SW4 and CPS.

We use the script `DOIT.sh` to run the CPS codes:

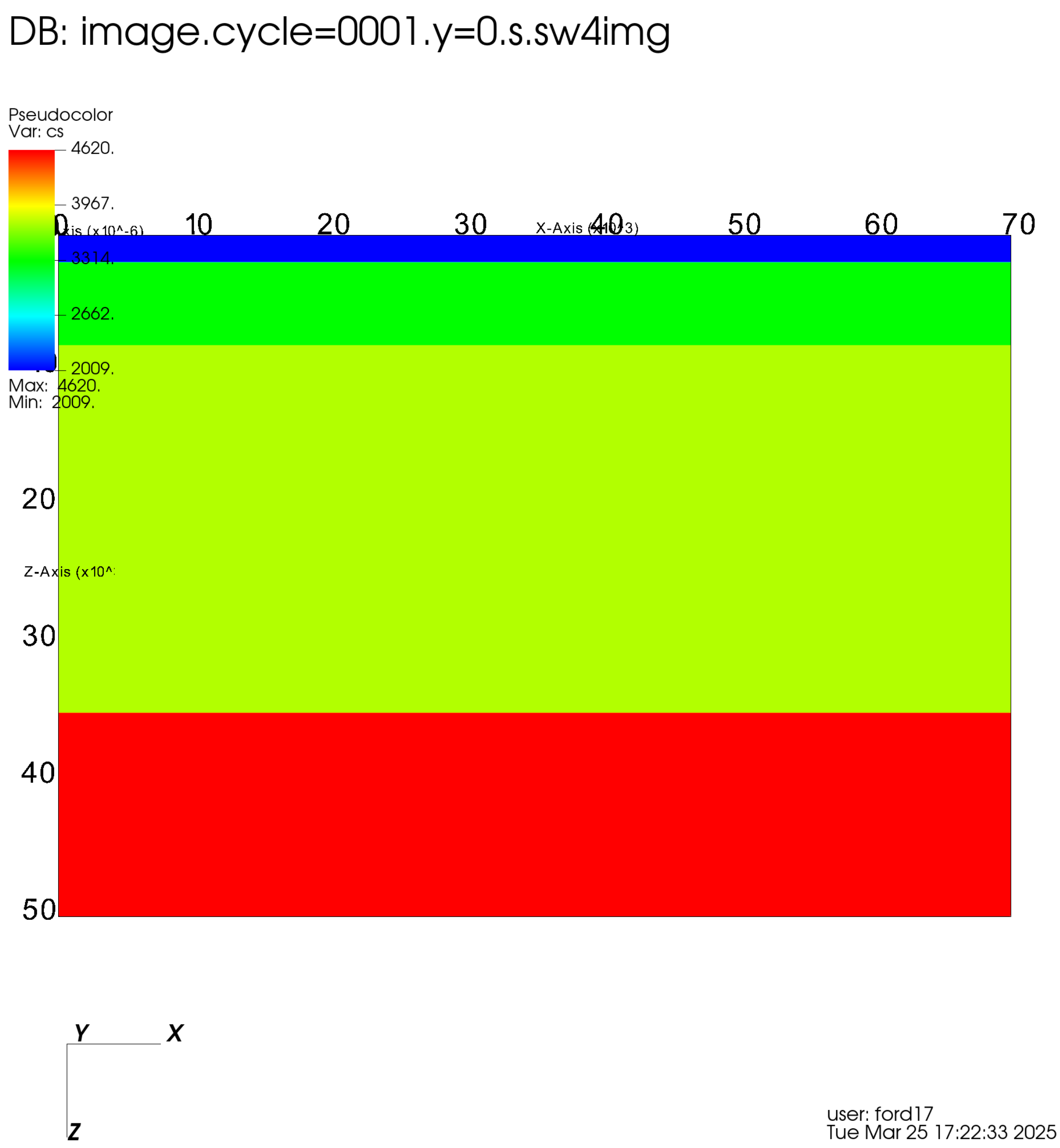

Figure 1: Shear wave velocity model plotted with VisIt

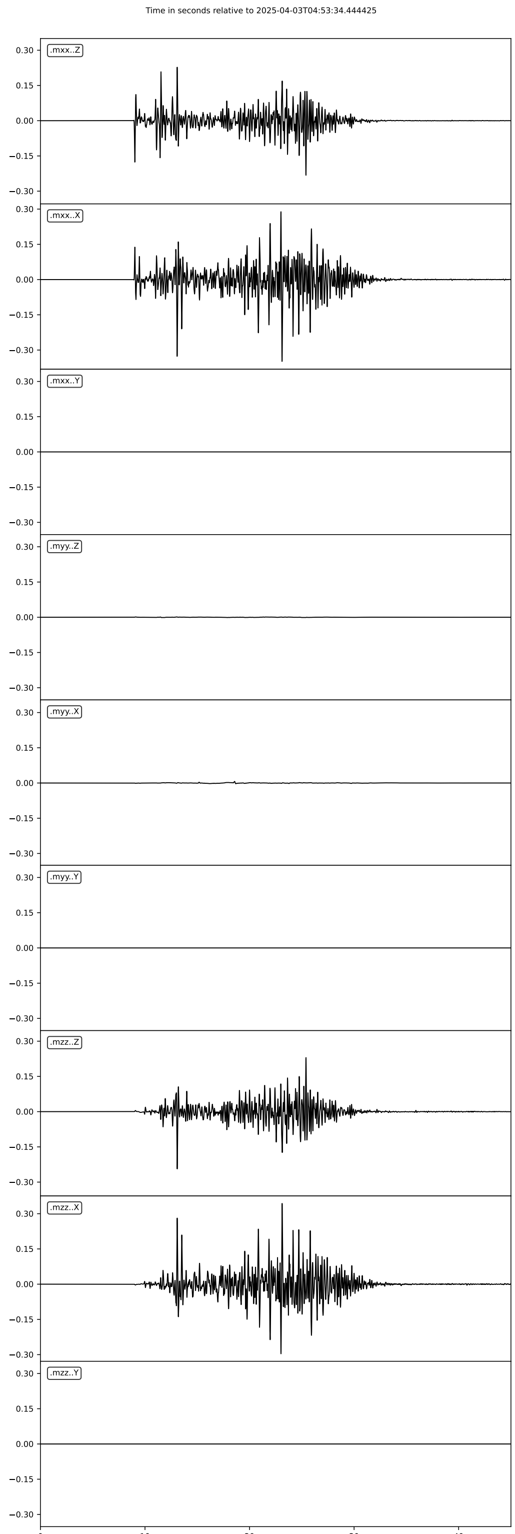

Figure 2: Calculated displacements low passed at 5 Hz plotted with ObsPy.

```
#!/usr/bin/env bash

## Any layered model
cat > WUSnoQ.mod << FIN
MODEL.01
Model after     8 iterations
ISOTROPIC
KGS
FLAT EARTH
1-D
CONSTANT VELOCITY
LINE08
LINE09
LINE10
LINE11
  H(KM) VP(KM/S) VS(KM/S) RHO(GM/CC) QP QS ETAP ETAS FREFP FREFS
 1.9000   3.4065   2.0089     2.2150  0  0 0.00 0.00  1.00  1.00
 6.1000   5.5445   3.2953     2.6089  0  0 0.00 0.00  1.00  1.00
13.0000   6.2708   3.7396     2.7812  0  0 0.00 0.00  1.00  1.00
19.0000   6.4075   3.7680     2.8223  0  0 0.00 0.00  1.00  1.00
 0.0000   7.9000   4.6200     3.2760  0  0 0.00 0.00  1.00  1.00
FIN

## Recording at 50 km with Nyquist above 5 Hz
# DIST DT NPTS T0 VRED
echo "50 0.01 4096 0 0" > dfile

## Run
rm -fr hspec96.*
hprep96 -M WUSnoQ.mod -d dfile -HS 10
hspec96

## Output
# Triangle is 2 * L * dt = 2 * 25 * 0.02 = 1
# hpulse96 -V -t -l 25 | f96tosac -G
# Impulse
hpulse96 -V -i | f96tosac -G

## Put in mechanism
# 1e18 nt-m = 1e25 dyne-cm
MOM=1.0e+25
ZSSFILE=`ls *.ZSS | head -1`
PROTO=`basename $ZSSFILE .ZSS`
```

```
for MIJ in MXX MXY MXZ MYY MYZ MZZ
do
gsac << EOF
mt to ZNE AZ 0 BAZ 180 ${MIJ} ${MOM} FILE ${PROTO}
w
mv T.Z ${MIJ}_${PROTO}_Z
mv T.N ${MIJ}_${PROTO}_N
mv T.E ${MIJ}_${PROTO}_E
q
EOF
done
FORCE=1.0e+20
for F in FN FE FD
do
gsac << EOF
mt to ZNE AZ 0 BAZ 180 ${F} ${FORCE} FILE ${PROTO}
w
mv T.Z ${F}_${PROTO}_Z
mv T.N ${F}_${PROTO}_N
mv T.E ${F}_${PROTO}_E
q
EOF
done
```

We also calculated the Green's functions using the `strains` calculation from SW4. This is obtained via reciprocity where strains at the source location are calculated due to a unit force at the surface. Such an input file for the vertical component can be calculated using the following input file:

```
fileio pfs=1 nwriters=16 path=fz.dir printcycle=1000
grid x=70e3 y=20e3 z=50e3 h=50
time t=45
block vp=7900.0 vs=4620.0 rho=3276.0 qp=60976 qs=27027
block vp=6407.5 vs=3768.0 rho=2822.3 qp=901 qs=402 z2=40000
block vp=6270.8 vs=3739.6 rho=2781.2 qp=658 qs=293 z2=21000
block vp=5544.5 vs=3295.3 rho=2608.9 qp=287 qs=128 z2=8000
block vp=3406.5 vs=2008.9 rho=2215.0 qp=331 qs=147 z2=1900
source x=60e3 y=10e3 z=0 fz=1e15 type=Dirac t0=0
#source x=60e3 y=10e3 z=0 fz=1e15 type=Triangle t0=0 freq=1
#source x=60e3 y=10e3 z=0 fz=1e15 type=C6SmoothBump t0=0 freq=1
rec x=10e3 y=10e3 z=10e3 file=rec50 sacformat=1 variables=strains
image mode=s y=10e3 cycle=1
```

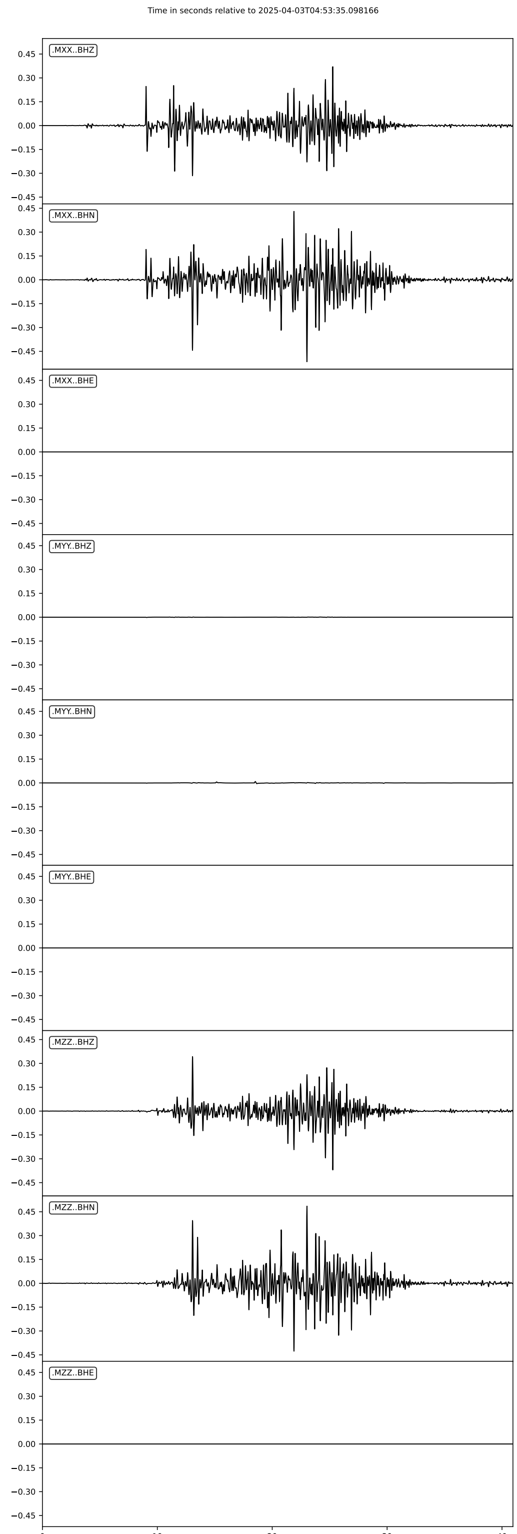

Figure 3: Calculated displacements using CPS low passed at 5 Hz plotted with ObsPy.

5 Conclusions

SW4 and CPS are excellent tools for wavefield calculations.