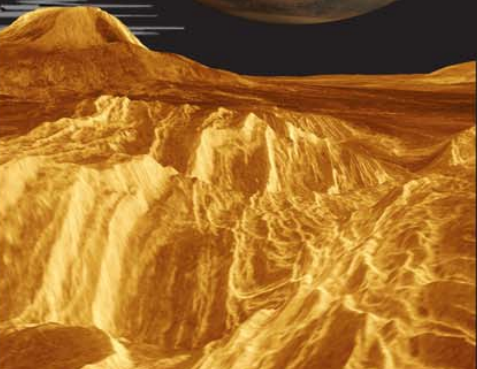
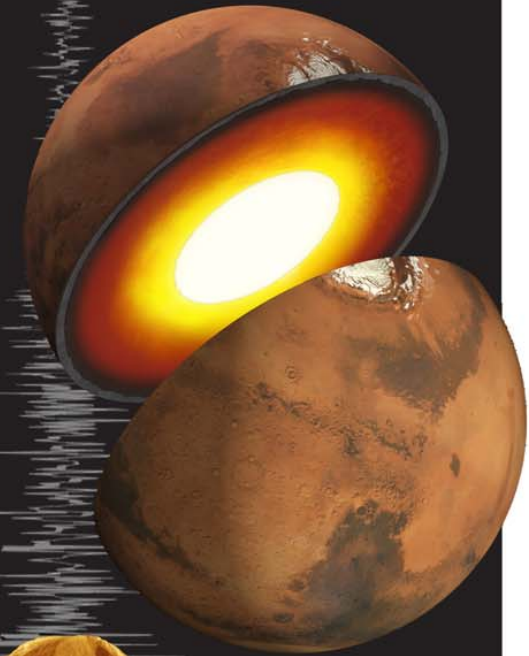


Seismology Tutorial 1: Normal modes of telluric planets

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Tutorial software

- The following tutorial is based on minos normal modes program
- A version of minos is available at CIG
 - <http://geodynamics.org/archive/software/mineos>
- The version used in this tutorial is NOT the CIG one but have been modified in order to compute modes and seismograms for different planets, and also to compute modes for higher order perturbation theories software (HOPT package)
 - <http://www.ipgp.fr/fr/pss/3d-synthetic-seismogram-package>

Mineos

Mineos computes synthetic seismograms in a spherically symmetric non-rotating Earth by summing normal modes.

Attenuation, gravity and transversal anisotropy effects may be optionally taken into account. The package computes mode eigenfrequencies and eigenfunctions, Green's functions and synthetic seismograms for sources with a moment tensor defined in time as a step-function.

| | |
|--------------------|----------------------------|
| Status | Accepting bug reports. |
| Contact | cig-seismo@geodynamics.org |
| Bug reports | Github Issue Tracker |
| License | GNU Public License |

Binaries

Linux

- Mineos-Linux32-1_0_2.tgz - binary for Linux 32 bit
- Mineos-Linux64-1_0_2.tgz - binary for Linux 64 bit

Macintosh

- Mineos-Mac10_4-1_0_2.dmg - dmg for Mac OS X 10.4 (Tiger)
- Mineos-Mac10_6-1_0_2.dmg - dmg for Mac OS X 10.6 (Snow Leopard)

Windows

- Mineos-Win-1_0_2.zip - .zip for Windows (contains .exe in package)

Source Code

mineos-1.0.2.tgz
Latest release.

Documentation



Annuaire | Accès | Contacts | Intranet | Webmail | En | Fr | Rechercher...

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Logiciels et base de données
3D Synthetic Seismogram Package
OPTICLEAR - The database on local optical properties
TOOLS - Tools for computing wave spherical harmonics

3D Synthetic Seismogram Package

Higher Order Perturbation Theory
3D Synthetic Seismogram Package

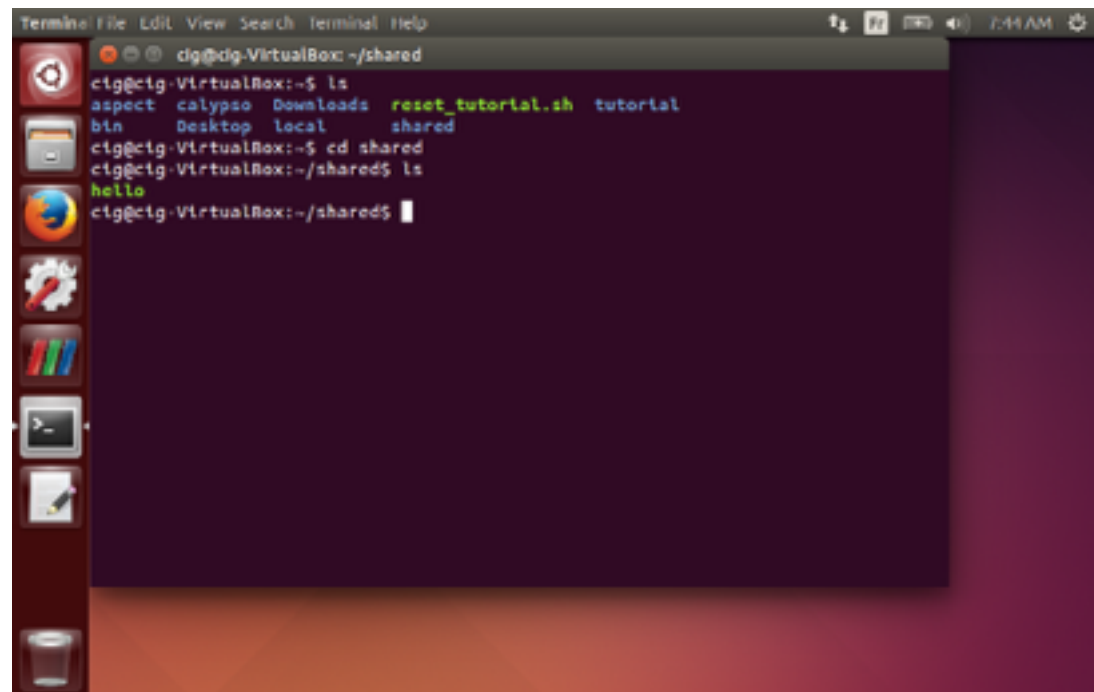
3D Synthetic Seismogram Package is a set of libraries and programs for the computation of normal modes and seismograms for a wide variety of 3D Earth models. This code is based on the higher order perturbation theory in seismology developed by Philippe Lognonné, and requires only a few parameter settings.

The codes runs successfully on several operating systems. Disk space of at least 1 GB and 600 MB of memory are recommended for practical use. The source code is contained in gzip/tar format (17 MB) with an included README file, documentation in postscript and PDF formats, installation scripts, examples, and working directories with input files for the 3D SAW12D and the minos program that is provided in the distribution was written by F. Gilbert, G. Masters

Evénements à venir | Infos pratiques | CNRS

setting up

- Setting up your VM
 - Start the VM
 - create a shared folder CIG_SHARED (to use results for matlab and other application)
 - put a file “hello” inside
 - launch the CIG CIDER_1
 - if green, then put folders inputfortutorial0 and inputfortutorial1
 - make outputtutorial0 and outputtutorial1



```
Terminal File Edit View Search Terminal Help
cig@cig-VirtualBox: ~/shared
cig@cig-VirtualBox:~$ ls
aspect  calypso  Downloads  reset_tutorial.sh  tutorial
bin     Desktop  local      shared
cig@cig-VirtualBox:~$ cd shared
cig@cig-VirtualBox:~/shared$ ls
hello
cig@cig-VirtualBox:~/shared$
```

Tutorial exercise #0: Normal modes for different Mars models

```
cig@cig-VirtualBox:~/tutorial/lognonne$ ls
AH bin Installation_notice.doc Interior_models Normal_modes set_env Sismospher Sismospherd
cig@cig-VirtualBox:~/tutorial/lognonne$ cd Interior_models
cig@cig-VirtualBox:~/tutorial/lognonne/Interior_models$ ls
Earth Mars Moon
cig@cig-VirtualBox:~/tutorial/lognonne/Interior_models$ cd Mars
cig@cig-VirtualBox:~/tutorial/lognonne/Interior_models/Mars$ ls
modeleAR modeleCRUST modeleM10 modeleM2 modeleM4 modeleM7 modeleM9 modeleMO1a modeleMO3 modeleSOHL
modeleCRU modeleM1 modeleM1a modeleM3 modeleM5 modeleM8 modeleMO1 modeleMO2 modeleMO4
cig@cig-VirtualBox:~/tutorial/lognonne/Interior_models/Mars$ cd ../Moon
cig@cig-VirtualBox:~/tutorial/lognonne/Interior_models/Moon$ ls
weber2010
cig@cig-VirtualBox:~/tutorial/lognonne/Interior_models/Moon$ cd ../Earth
cig@cig-VirtualBox:~/tutorial/lognonne/Interior_models/Earth$ ls
ANIPRM
cig@cig-VirtualBox:~/tutorial/lognonne/Interior_models/Earth$
```

```
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ pwd
/home/cig/tutorial/lognonne/Normal_modes/example
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ cp /home/cig/shared/inputfortutorial0/cx_ar .
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ cp /home/cig/shared/inputfortutorial0/cx_m1 .
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ cp /home/cig/shared/inputfortutorial0/cx_sohl .
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ ls
cx_ar cx_prem_out cx_sohl cx_weber cx_weber_tutorial1a prepare_prem test_all
cx_m1 cx_prem_out_test cx_sohl_out cx_weber_out cx_weber_tutorial1b prepare_sohl vi
cx_prem cx_sohl cx_sohl_out_test cx_weber_out_test makefile prepare_weber
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ mkdir ../nodes/marsar
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ mkdir ../nodes/marsm1
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ ls ../nodes
earthprem marsar marsm1 marssohl moonweber
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$
```

We will compute the modes for model AR
for model M1
for model SOHL

Tutorial exercise #0: Normal modes for different Mars models

```

cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ cat cx_ar
cd ../modes/marsar
.././././bin/minos_new << *cnd*
.././././Interior_models/Mars/modeleAR
marsAR
marsAR0
1.e-10 100.
3
2 1000 .3 20. 100 0
*cnd*
#### prepare the output eigenfrequencies for matlab
grep s marsAR | grep -v r | sed -e "1,$ s/s//" > ARfreq
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ cat cx_m1
cd ../modes/marsm1
.././././bin/minos_new << *cnd*
.././././Interior_models/Mars/modeleM1
marsM1
marsM10
1.e-10 100.
3
2 1000 .3 20. 100 0
*cnd*
#### prepare the output eigenfrequencies for matlab
grep s marsM1 | grep -v r | sed -e "1,$ s/s//" > M1freq
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ cat cx_sohl
cd ../modes/marssohl
.././././bin/minos_new << *cnd*
.././././Interior_models/Mars/modeleSOHL
marssohl
marssohl0
1.e-10 100.
3
2 1000 .3 20. 100 0
*cnd*
#### prepare the output eigenfrequencies for matlab
grep s marssohl | grep -v r | sed -e "1,$ s/s//" > sohlfreq
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$

```

Principle:

Modes catalogue is put in a folder

Modes are computed in a frequency bandwidth

in a angular order bandwidth

and up to n overtones are computed

Modes are either spheroidal, radial or toroidal

Command file

go in directory and execute minos_new
input parameters:

catalogue directory name

output file name

catalogue file generic name

error gravity-cutoff (sec-1)

type of mode (3 for S, 1 for R, 2 for T)

Lmin Lmax fmin fmax 0

last command is to prepare the output for
figures

Tutorial exercise #0: Frequencies with gnu plot

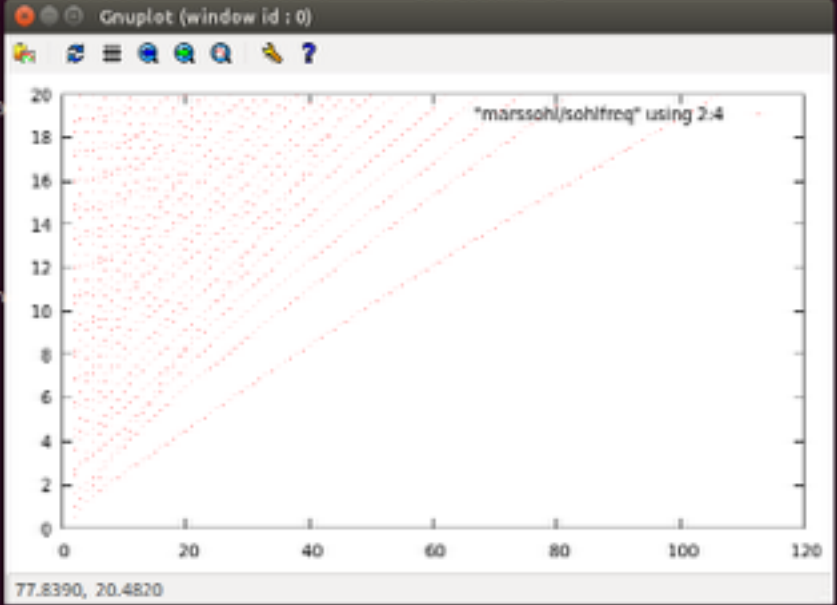
```
Gnuplot (window id : 0)
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_nodes/nodes$ pwd
/home/cig/tutorial/lognonne/Normal_nodes/nodes
Gnuplot (window id : 0)
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_nodes/nodes$ pwd
/home/cig/tutorial/lognonne/Normal_nodes/nodes
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_nodes/nodes$ ls
earthpren marsar marsmi marssohl moonweber
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_nodes/nodes$ ls mars+/*freq
marsar/ARfreq marsmi/Mifreq marssohl/sohlfreq
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_nodes/nodes$ head -5 marsar/ARfreq
0 2 0.2670744E-02 0.4250622 2352.597 5.426685 374.0890 -0.6532190E-10
1 2 0.5960623E-02 0.9486626 1054.116 7.308533 362.7884 0.1571550E-10
2 2 0.9255110E-02 1.472997 678.8882 5.661913 644.0574 -0.4001531E-10
3 2 0.1437285E-01 2.287510 437.1565 9.881943 534.6102 0.1763805E-10
4 2 0.1665023E-01 2.649966 377.3633 3.729011 572.7487 0.2341188E-10
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_nodes/nodes$
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_nodes/nodes$

G N U P L O T
Version 4.6 patchlevel 4 last modified 2013-10-0
Build System: Linux x86_64

Copyright (C) 1986-1993, 1998, 2004, 2007-2013
Thomas Williams, Colin Kelley and many others

gnuplot home: http://www.gnuplot.info
faq, bugs, etc: type "help FAQ"
immediate help: type "help" (plot window: hit 'h')

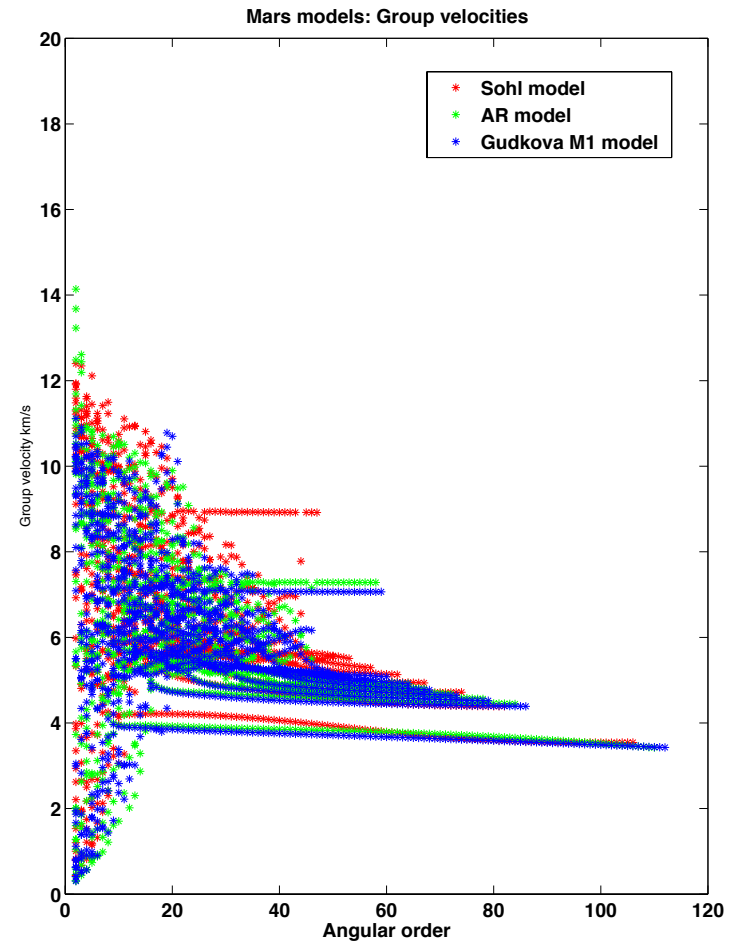
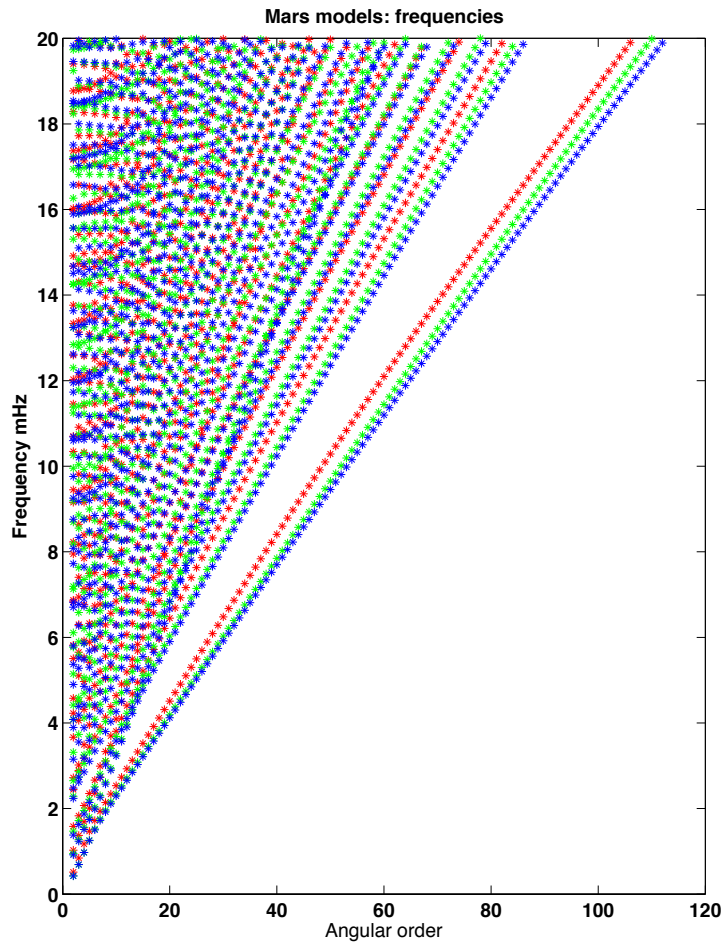
Terminal type set to 'wxt'
gnuplot> plot "marsar/ARfreq" using 2:4 with dots
gnuplot> plot "marsmi/Mifreq" using 2:4 with dots
gnuplot> plot "marssohl/sohlfreq" using 2:4 with dots
gnuplot> █
```



order in *freq files

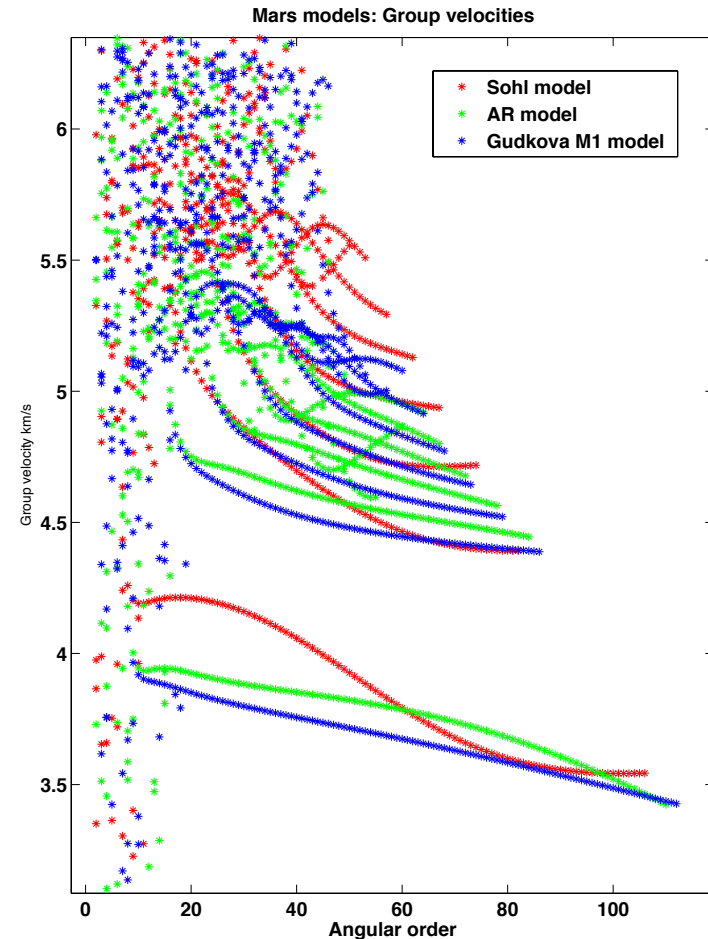
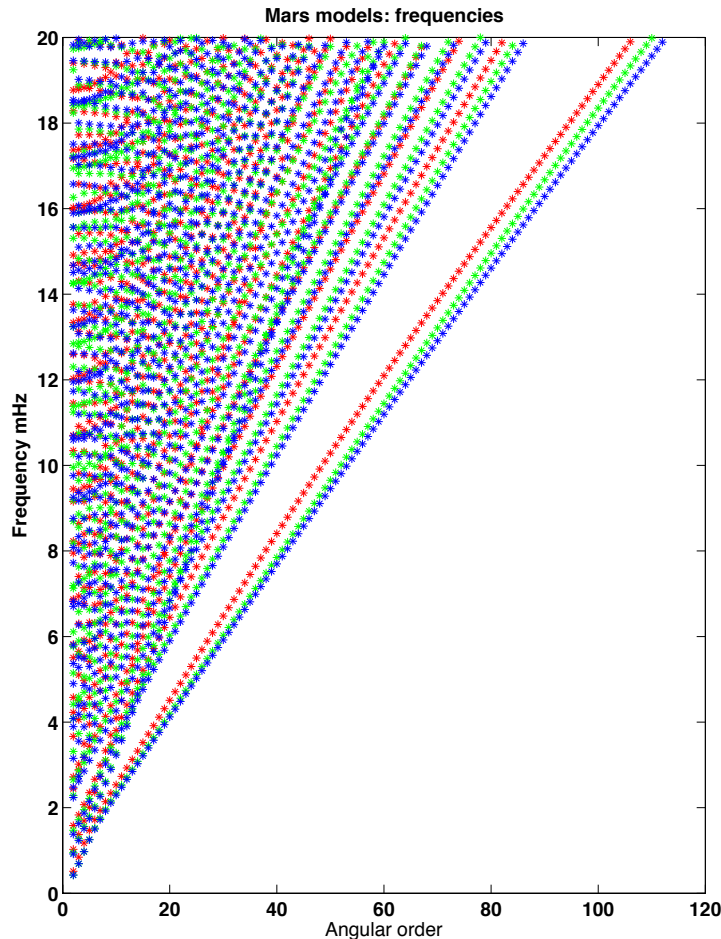
| N | L | omega (Hz) | f (mHz) | T(sec) | vg (km/s) | Q | error |
|---|---|------------|---------|--------|-----------|---|-------|
|---|---|------------|---------|--------|-----------|---|-------|

Tutorial exercise #0: Frequencies with matlab (1/2)



Tutorial exercise #0: Frequencies with matlab (1/2)

- Both frequencies and group velocities shows large sensitivity to the model used...



Tutorial exercise #1

- **WHAT ARE THE AMPLITUDE OF 15 sec SEISMIC WAVES GENERATED BY A SHALLOW MOONQUAKE ON THE MOON ?**
 - Choose a Lunar Model
 - Compute Normal modes: **Why ?**
 - Define a seismic source, i.e. moonquake with
 - position (including depth)
 - Magnitude
 - Compute seismograms at different stations...
 - Estimate the amplitude

Tutorial exercise #1: background

- Why computing normal modes....?
- Reason is mathematical...
- Normal modes are a complete basis of ALL solutions of the seismic equation with given boundary limits, which practically means that ANY solution of the seismic equation (such as our solution for a deep moonquake) can be expressed in this basis

3D Basis (our 3D space)

Constant Position and 3D coordinates

$$\vec{u} = x\vec{i} + y\vec{j} + z\vec{k}$$

Time dependent Position and 3D coordinates

$$\vec{u}(t) = x(t)\vec{i} + y(t)\vec{j} + z(t)\vec{k}$$

Coordinates depends on time


unit vector does not depend on time

Tutorial exercise #1: background


- Why computing normal modes....?
- Reason is mathematical...
- Normal modes are a complete basis of ALL solutions of the seismic equation with given boundary limits, which practically means that ANY solution of the seismic equation (such as our solution for a deep moonquake) can be expressed in this basis

Normal mode Basis (the space of seismic waves)

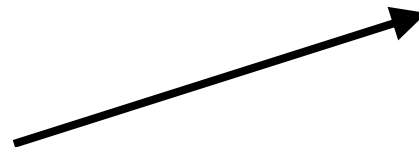
3D field of position, including surface displacement


$$\vec{u}(t, r, \theta, \varphi) = \sum_k c(t) \vec{U}_k(r, \theta, \varphi)$$

Time dependent Position and 3D coordinates


$$k = (\ell \quad m \quad n)$$

Coordinates depends on time



unit vector does not depend on time



Tutorial exercise #1: background

The response of the Earth to an impulsive equivalent body force is obtained from the summation over all positive and negative indices, i.e., positive frequencies as well as negative frequencies. This finally allows recovery of a real amplitude for the Green tensor, equal to

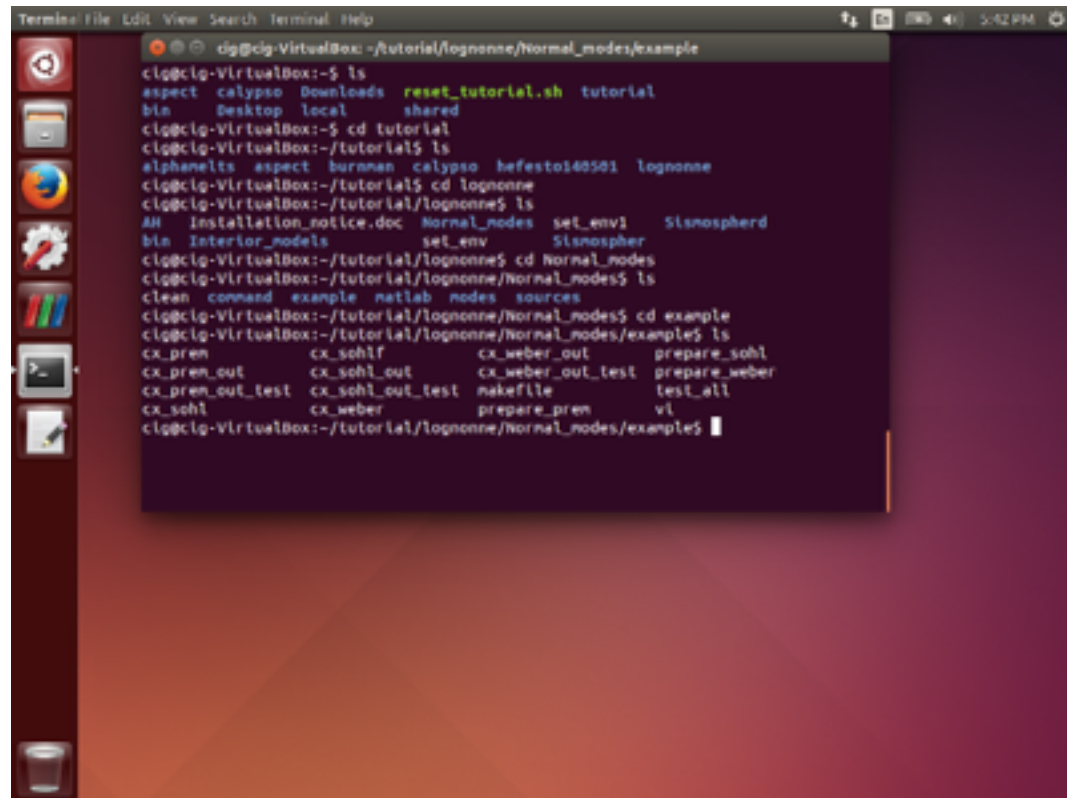
$$|\mathbf{u}(t)\rangle = H(t) \sum_{k>0} \Re e \left(\frac{1}{i\sigma_k} \langle \mathbf{v}_k | \mathbf{f} \rangle e^{i\sigma_k t} | \mathbf{u}_k \rangle \right) \quad (43)$$

TABLE 4 Amplitude of the ground displacement as described by a summation of normal modes for a local double couple. The index s denotes the position of the source

| Source Function | Displacement Expression |
|--|--|
| Seismic tensor with general source function $ \mathbf{f}(t)\rangle = -\mathbf{M}(t)\nabla\delta(\mathbf{r} - \mathbf{r}_s)$ | $ \mathbf{u}(t)\rangle = \sum_{k>0} \Re e \left(\frac{1}{i\sigma_k} \int_0^t dt' \mathbf{M}(t') : \nabla \mathbf{v}_k(\mathbf{r}_s) e^{i\sigma_k(t-t')} \mathbf{u}_k \rangle \right)$ |
| Seismic tensor with Heaviside source function $ \mathbf{f}(t)\rangle = -\mathbf{M}_0 H(t)\nabla\delta(\mathbf{r} - \mathbf{r}_s)$ | $ \mathbf{u}(t)\rangle = H(t) \sum_{k>0} \Re e \left(\frac{1}{\sigma_k^2} \mathbf{M}_0 : \nabla \mathbf{v}_k(\mathbf{r}_s) (1 - e^{i\sigma_k t}) \mathbf{u}_k \rangle \right)$ |

Tutorial exercise #1

- go and update the command file for normal modes computations
- cx_prem (Prem model for Earth)
- cx_sohl (Sohl model for Mars)
- cx_weber (Weber model for Moon)



```
Terminal: File Edit View Search Terminal Help
dg@clg-VirtualBox: ~/tutorial/lognonne/Normal_modes/example
clg@clg-VirtualBox:~$ ls
aspect calypso Downloads reset_tutorial.sh tutorial
bin Desktop local shared
clg@clg-VirtualBox:~$ cd tutorial
clg@clg-VirtualBox:~/tutorial$ ls
alphanelts aspect burnnan calypso hefesto140501 lognonne
clg@clg-VirtualBox:~/tutorial$ cd lognonne
clg@clg-VirtualBox:~/tutorial/lognonne$ ls
AH Installation_notice.doc Normal_modes set_env1 Sismospher
bin Interior_models set_env Sismospher
clg@clg-VirtualBox:~/tutorial/lognonne$ cd Normal_modes
clg@clg-VirtualBox:~/tutorial/lognonne/Normal_modes$ ls
clean command example matlab nodes sources
clg@clg-VirtualBox:~/tutorial/lognonne/Normal_modes$ cd example
clg@clg-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ ls
cx_prem cx_sohl cx_weber_out prepare_sohl
cx_prem_out cx_sohl_out cx_weber_out_test prepare_weber
cx_prem_out_test cx_sohl_out_test makefile test_all
cx_sohl cx_weber prepare_prem vl
clg@clg-VirtualBox:~/tutorial/lognonne/Normal_modes/example$
```


Tutorial exercise #1 : update in VM

- update the `cx_weber` into two tutorial for S modes between 0.1 and 67 mHz (`cx_weber_tutorial1a`) and radial modes (`cx_weber_tutorial1b`) *both are in inputfortutorial1*

folder where the modes will be stored and file describing the model

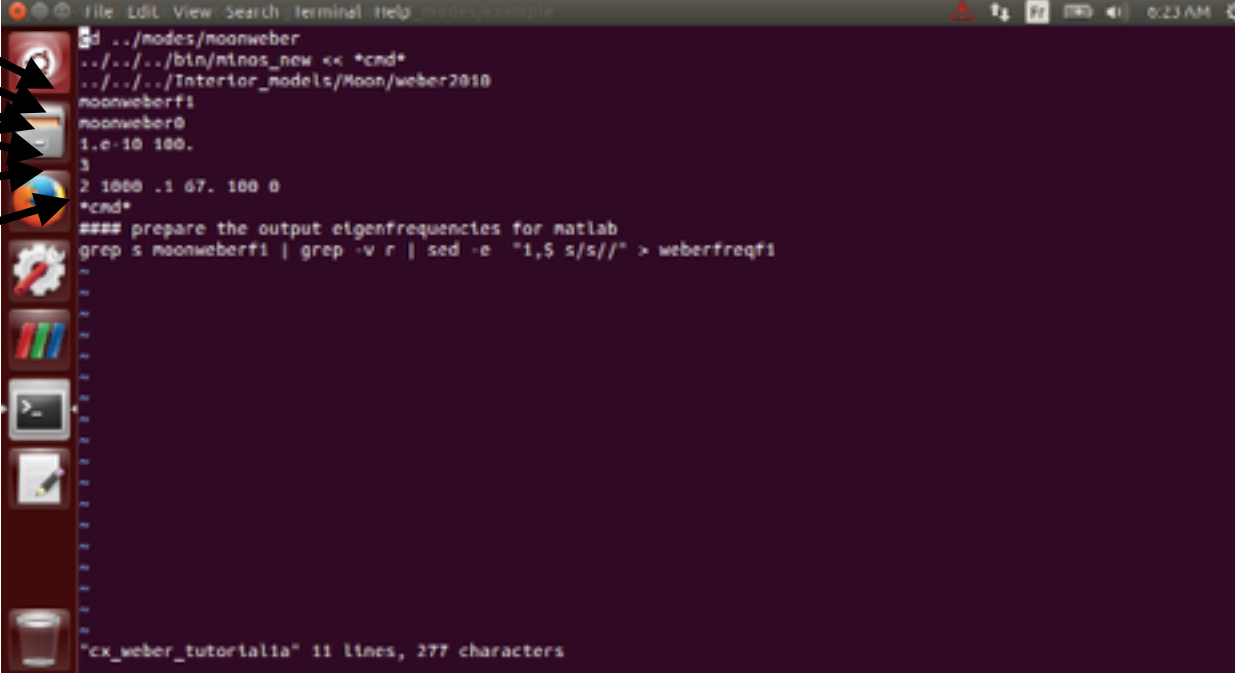
output file

Generic name for model
error and angular
frequency above which
gravity is neglected

Spheroidal (3), Toroidal (2)
Radial(1)

Lmin, Lmax, fmin, fmax, N 0

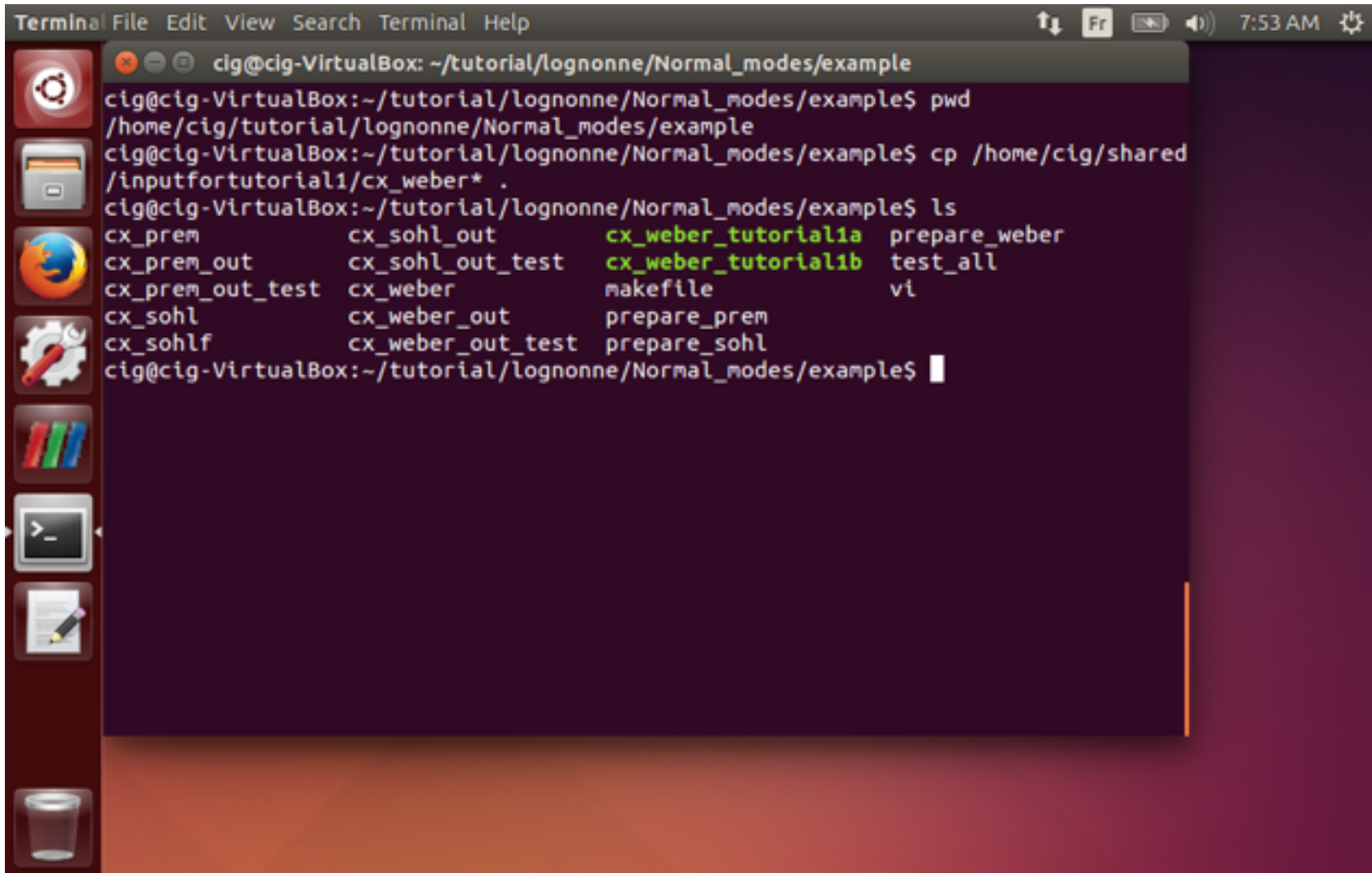
Lmin: minimum angular number
Lmax: maximum angular number
fmin : minimum frequency
fmax: maximum frequency
Number of overtones computed



```
cd ../nodes/noonweber
../../../../bin/mkns_new << *cmd*
../../../../Interior_models/Moon/weber2010
noonweber1
noonweber0
1.e-10 100.
3
2 1000 .1 67. 100 0
*cmd*
### prepare the output eigenfrequencies for matlab
grep s noonweberf1 | grep -v r | sed -e "1,5 s/s//" > weberfreqf1
```

for 50 mHz, Lmax = 500
for 100 mHz, Lmax = 1000

Tutorial exercice #1 : update through shared folder



The image shows a terminal window titled "Terminal" with a menu bar (File, Edit, View, Search, Terminal, Help) and a system tray (7:53 AM, settings, volume, network). The terminal prompt is "cig@cig-VirtualBox: ~/tutorial/lognonne/Normal_modes/example". The user enters "pwd", which returns "/home/cig/tutorial/lognonne/Normal_modes/example". Then, the user enters "cp /home/cig/shared/inputfortutorial1/cx_weber* .", which copies files from a shared folder. Finally, the user enters "ls", which lists the files in the current directory. The output of "ls" is as follows:

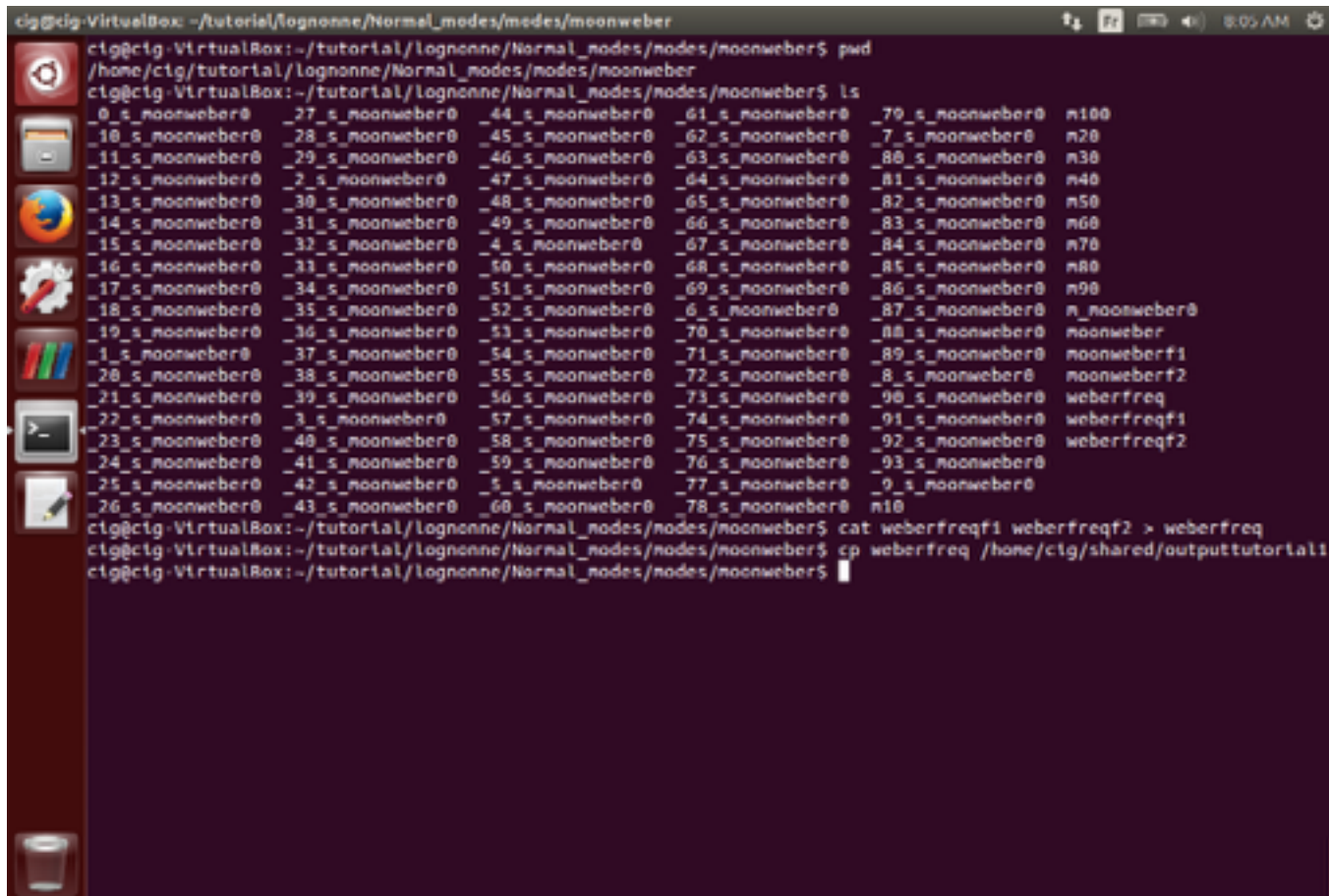
```
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ pwd
/home/cig/tutorial/lognonne/Normal_modes/example
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ cp /home/cig/shared
/inputfortutorial1/cx_weber* .
cig@cig-VirtualBox:~/tutorial/lognonne/Normal_modes/example$ ls
cx_prem          cx_sohl_out      cx_weber_tutorial1a  prepare_weber
cx_prem_out      cx_sohl_out_test cx_weber_tutorial1b  test_all
cx_prem_out_test cx_weber         makefile             vi
cx_sohl          cx_weber_out     prepare_prem
cx_sohlf         cx_weber_out_test prepare_sohl
```

Tutorial exercise #1 : compute normal modes

- execute the script by typing
 - `./cx_weber_tutorial1a`
 - `./cx_weber_tutorial1b`
- Normal modes can be computed to higher frequencies
- This will however need a vertical model with a thinner mesh
- The key in the computation is to check the error, which must never be larger than $1e-3$ (which is already large, precise computation must have errors of at least $1e-6$)

Tutorial exercise #1

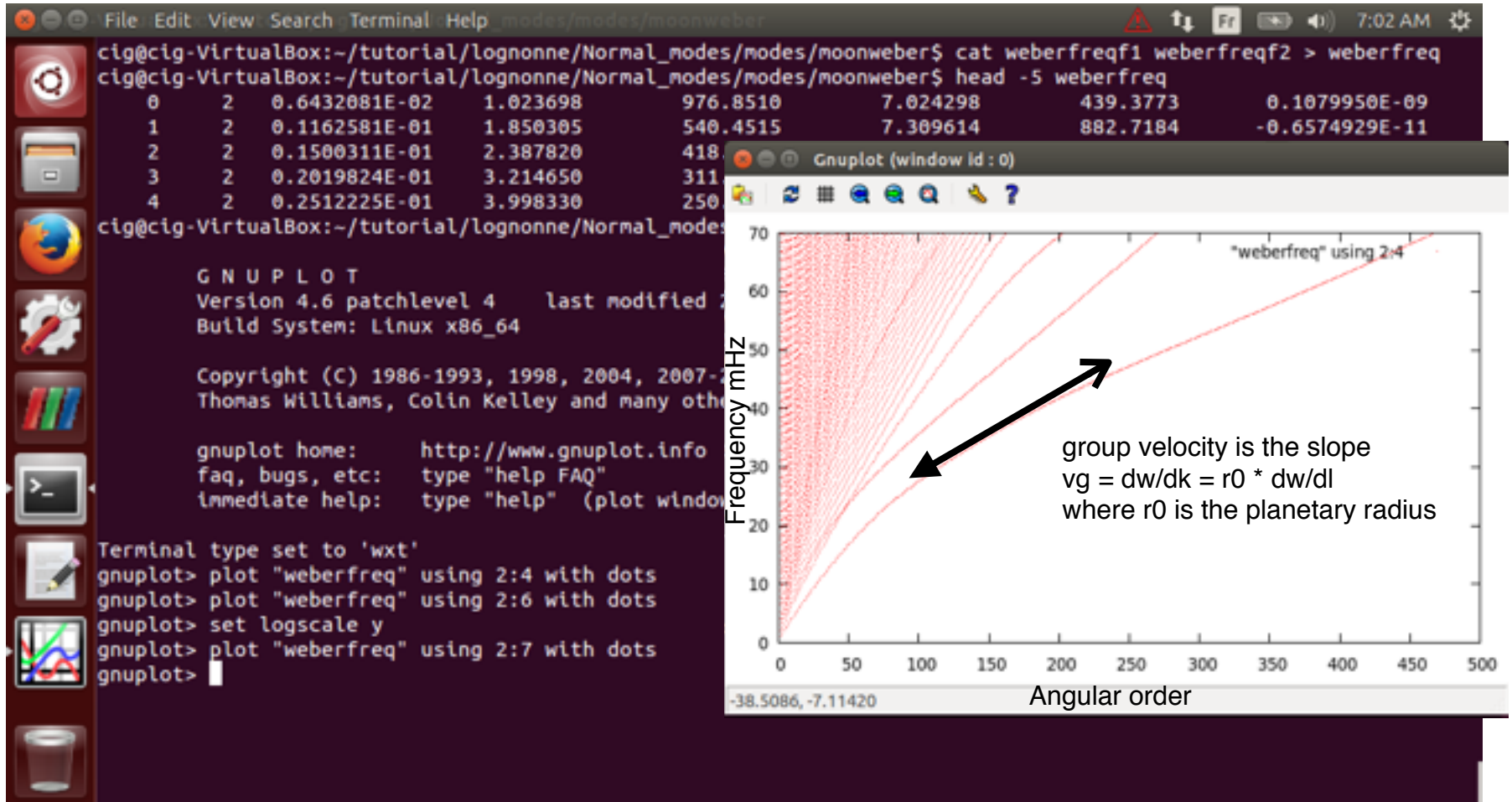
- Results are in Normal_modes/modes/moonweber
- These are files for all n orders, in which the normal modes functions and frequencies are stored
- create a frequency file with the two runs
- The results can be exported in the shared outputtutorial1



```
ctg@ctg-VirtualBox: ~/tutorial/lognonne/Normal_modes/modes/moonweber
ctg@ctg-VirtualBox:~/tutorial/lognonne/Normal_modes/modes/moonweber$ pwd
/home/ctg/tutorial/lognonne/Normal_modes/modes/moonweber
ctg@ctg-VirtualBox:~/tutorial/lognonne/Normal_modes/modes/moonweber$ ls
_0_s_moonweber0  _27_s_moonweber0  _44_s_moonweber0  _61_s_moonweber0  _79_s_moonweber0  n100
_10_s_moonweber0  _28_s_moonweber0  _45_s_moonweber0  _62_s_moonweber0  _7_s_moonweber0  n20
_11_s_moonweber0  _29_s_moonweber0  _46_s_moonweber0  _63_s_moonweber0  _80_s_moonweber0  n30
_12_s_moonweber0  _2_s_moonweber0  _47_s_moonweber0  _64_s_moonweber0  _81_s_moonweber0  n40
_13_s_moonweber0  _30_s_moonweber0  _48_s_moonweber0  _65_s_moonweber0  _82_s_moonweber0  n50
_14_s_moonweber0  _31_s_moonweber0  _49_s_moonweber0  _66_s_moonweber0  _83_s_moonweber0  n60
_15_s_moonweber0  _32_s_moonweber0  _4_s_moonweber0  _67_s_moonweber0  _84_s_moonweber0  n70
_16_s_moonweber0  _33_s_moonweber0  _50_s_moonweber0  _68_s_moonweber0  _85_s_moonweber0  n80
_17_s_moonweber0  _34_s_moonweber0  _51_s_moonweber0  _69_s_moonweber0  _86_s_moonweber0  n90
_18_s_moonweber0  _35_s_moonweber0  _52_s_moonweber0  _6_s_moonweber0  _87_s_moonweber0  n_moonweber0
_19_s_moonweber0  _36_s_moonweber0  _53_s_moonweber0  _70_s_moonweber0  _88_s_moonweber0  moonweber
_1_s_moonweber0  _37_s_moonweber0  _54_s_moonweber0  _71_s_moonweber0  _89_s_moonweber0  moonweberf1
_20_s_moonweber0  _38_s_moonweber0  _55_s_moonweber0  _72_s_moonweber0  _8_s_moonweber0  moonweberf2
_21_s_moonweber0  _39_s_moonweber0  _56_s_moonweber0  _73_s_moonweber0  _90_s_moonweber0  weberfreq
_22_s_moonweber0  _3_s_moonweber0  _57_s_moonweber0  _74_s_moonweber0  _91_s_moonweber0  weberfreqf1
_23_s_moonweber0  _40_s_moonweber0  _58_s_moonweber0  _75_s_moonweber0  _92_s_moonweber0  weberfreqf2
_24_s_moonweber0  _41_s_moonweber0  _59_s_moonweber0  _76_s_moonweber0  _93_s_moonweber0
_25_s_moonweber0  _42_s_moonweber0  _5_s_moonweber0  _77_s_moonweber0  _9_s_moonweber0
_26_s_moonweber0  _43_s_moonweber0  _60_s_moonweber0  _78_s_moonweber0  n10
ctg@ctg-VirtualBox:~/tutorial/lognonne/Normal_modes/modes/moonweber$ cat weberfreqf1 weberfreqf2 > weberfreq
ctg@ctg-VirtualBox:~/tutorial/lognonne/Normal_modes/modes/moonweber$ cp weberfreq /home/ctg/shared/outputtutorial1
ctg@ctg-VirtualBox:~/tutorial/lognonne/Normal_modes/modes/moonweber$
```

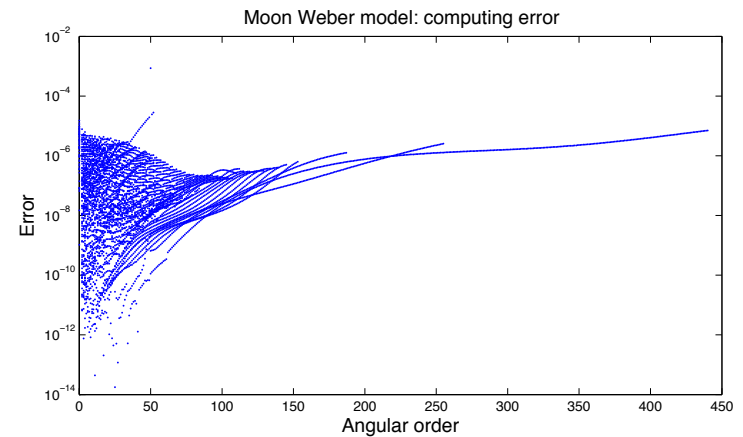
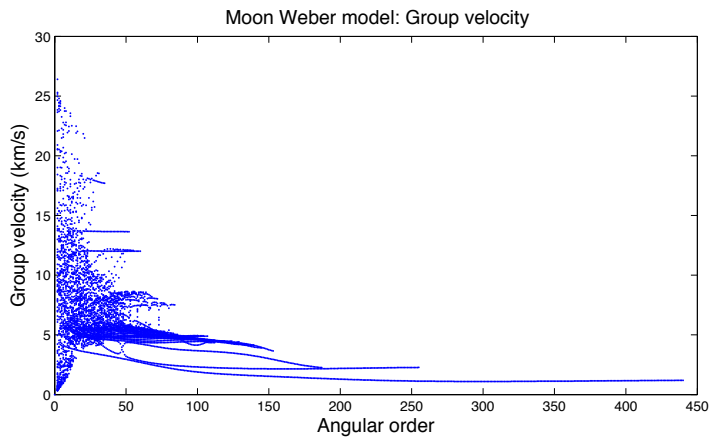
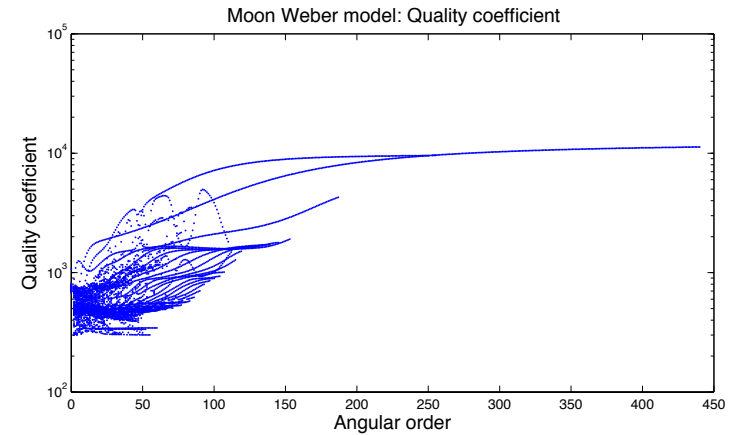
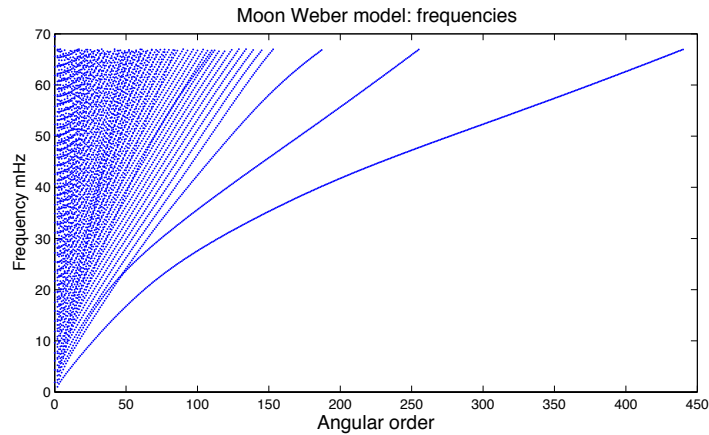
Tutorial exercise #1 : plotting results with gnu plot

| N | L | omega (Hz) | f (mHz) | T(sec) | vg (km/s) | Q | error |
|---|---|------------|---------|--------|-----------|---|-------|
|---|---|------------|---------|--------|-----------|---|-------|



Tutorial exercice #1 : plotting results with matlab

- matlab alternative (`plot_weber.m` in `inputfortutorial1` folder)

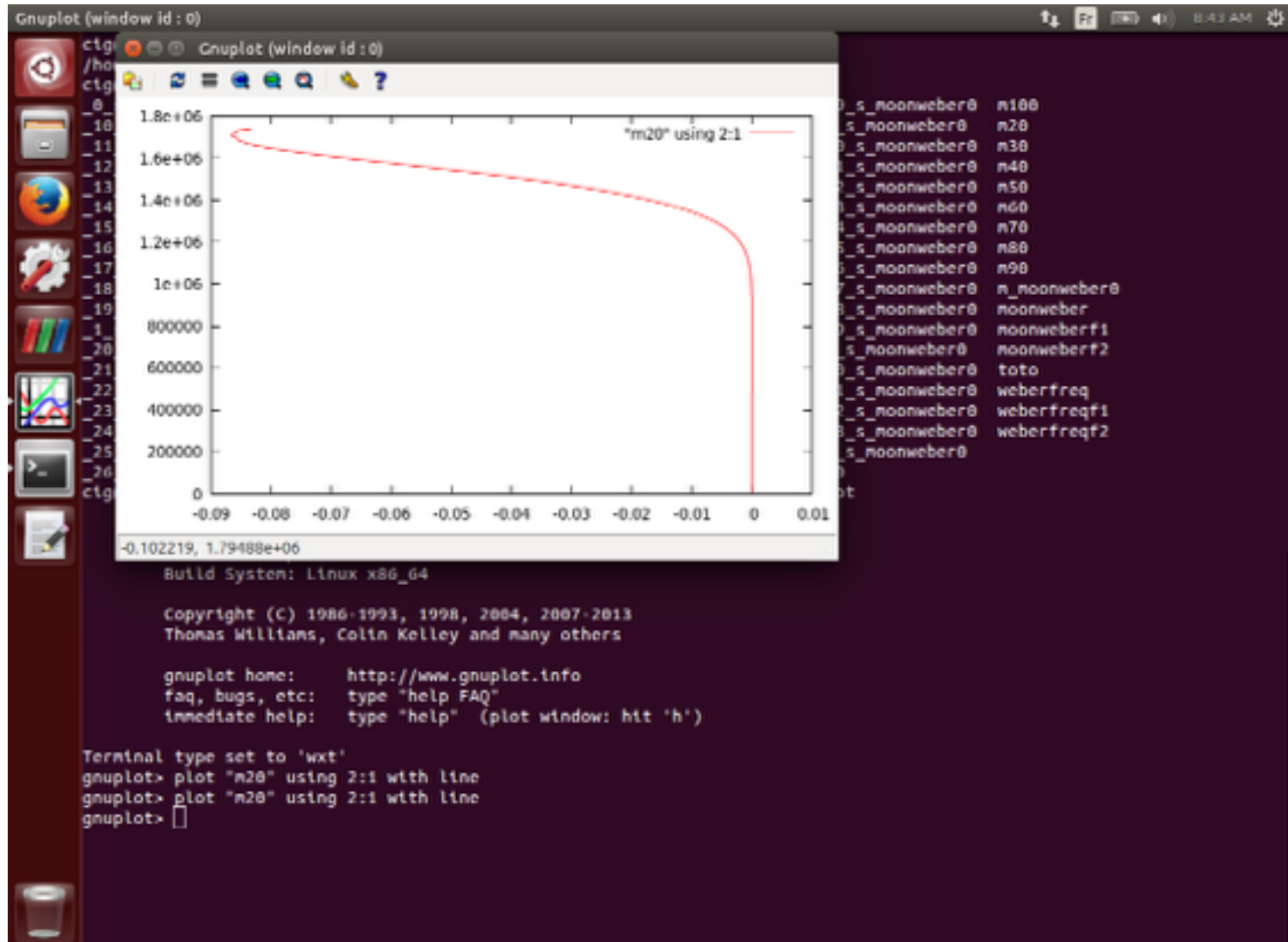


Tutorial exercice #1 : plotting mode amplitudes with matlab

- Transfert modes amplitudes (m10,m20... files) in shared folder

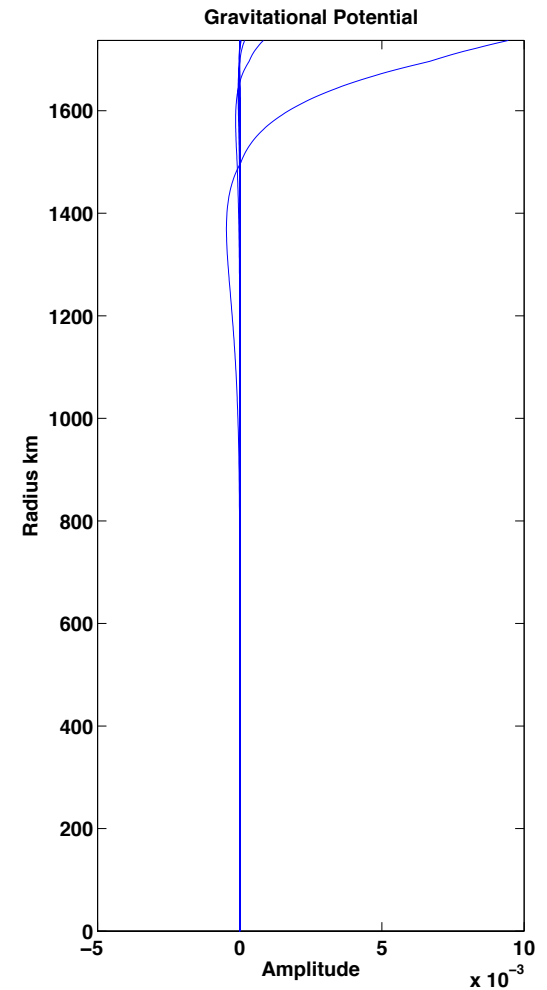
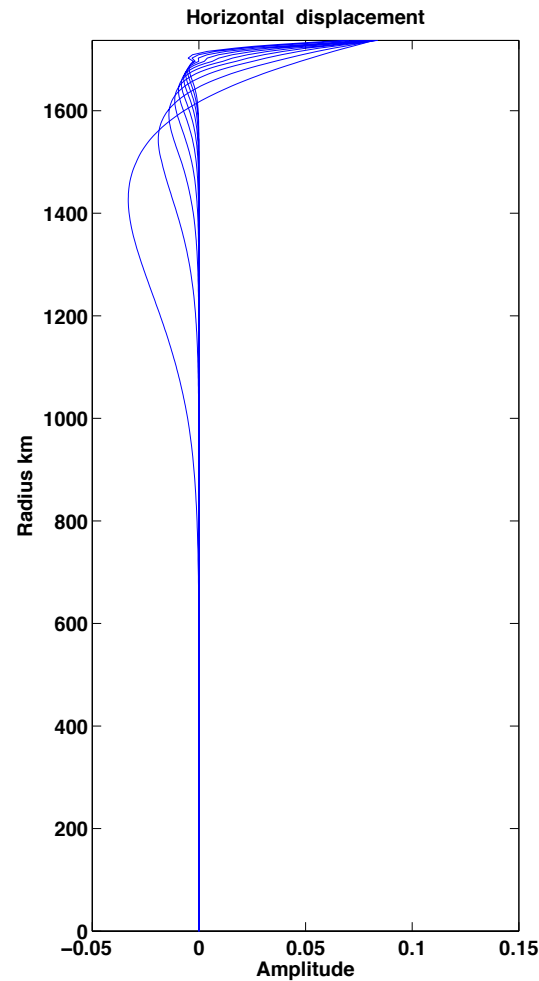
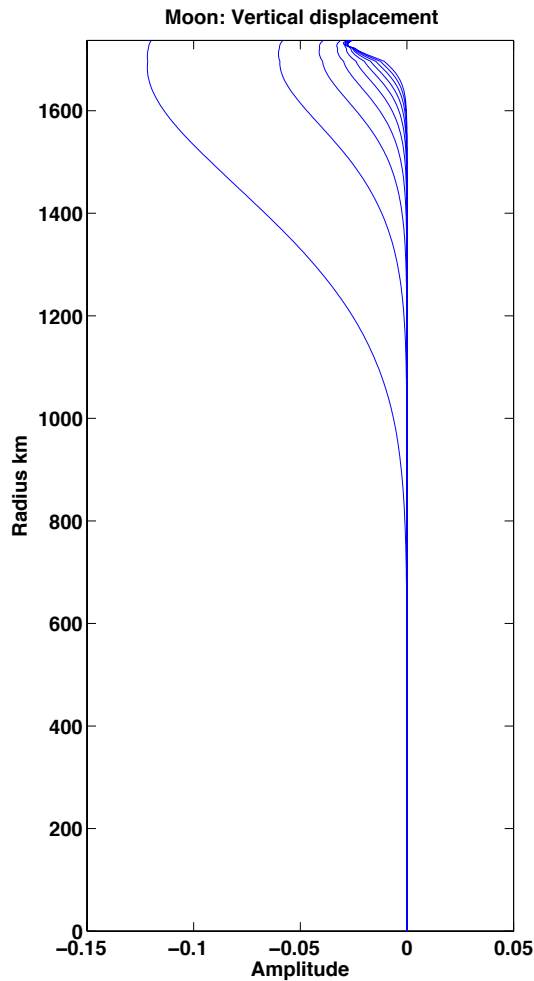
```
clg@clg-VirtualBox: ~/tutorial/lognonne/Normal_modes/modes/moonweber
clg@clg-VirtualBox:~/tutorial/lognonne/Normal_modes/modes/moonweber$ pwd
/home/clg/tutorial/lognonne/Normal_modes/modes/moonweber
clg@clg-VirtualBox:~/tutorial/lognonne/Normal_modes/modes/moonweber$ ls
_0_s_moonweber0  _27_s_moonweber0  _44_s_moonweber0  _61_s_moonweber0  _79_s_moonweber0  m100
_10_s_moonweber0  _28_s_moonweber0  _45_s_moonweber0  _62_s_moonweber0  _7_s_moonweber0  m20
_11_s_moonweber0  _29_s_moonweber0  _46_s_moonweber0  _63_s_moonweber0  _80_s_moonweber0  m30
_12_s_moonweber0  _2_s_moonweber0  _47_s_moonweber0  _64_s_moonweber0  _81_s_moonweber0  m40
_13_s_moonweber0  _30_s_moonweber0  _48_s_moonweber0  _65_s_moonweber0  _82_s_moonweber0  m50
_14_s_moonweber0  _31_s_moonweber0  _49_s_moonweber0  _66_s_moonweber0  _83_s_moonweber0  m60
_15_s_moonweber0  _32_s_moonweber0  _4_s_moonweber0  _67_s_moonweber0  _84_s_moonweber0  m70
_16_s_moonweber0  _33_s_moonweber0  _50_s_moonweber0  _68_s_moonweber0  _85_s_moonweber0  m80
_17_s_moonweber0  _34_s_moonweber0  _51_s_moonweber0  _69_s_moonweber0  _86_s_moonweber0  m90
_18_s_moonweber0  _35_s_moonweber0  _52_s_moonweber0  _6_s_moonweber0  _87_s_moonweber0  m_moonweber0
_19_s_moonweber0  _36_s_moonweber0  _53_s_moonweber0  _70_s_moonweber0  _88_s_moonweber0  moonweber
_1_s_moonweber0  _37_s_moonweber0  _54_s_moonweber0  _71_s_moonweber0  _89_s_moonweber0  moonweberf1
_20_s_moonweber0  _38_s_moonweber0  _55_s_moonweber0  _72_s_moonweber0  _8_s_moonweber0  moonweberf2
_21_s_moonweber0  _39_s_moonweber0  _56_s_moonweber0  _73_s_moonweber0  _90_s_moonweber0  toto
_22_s_moonweber0  _3_s_moonweber0  _57_s_moonweber0  _74_s_moonweber0  _91_s_moonweber0  weberfreq
_23_s_moonweber0  _40_s_moonweber0  _58_s_moonweber0  _75_s_moonweber0  _92_s_moonweber0  weberfreqf1
_24_s_moonweber0  _41_s_moonweber0  _59_s_moonweber0  _76_s_moonweber0  _93_s_moonweber0  weberfreqf2
_25_s_moonweber0  _42_s_moonweber0  _5_s_moonweber0  _77_s_moonweber0  _9_s_moonweber0
_26_s_moonweber0  _43_s_moonweber0  _60_s_moonweber0  _78_s_moonweber0  m10
clg@clg-VirtualBox:~/tutorial/lognonne/Normal_modes/modes/moonweber$ cp m*0 /home/clg/shared/outputtutorial1
clg@clg-VirtualBox:~/tutorial/lognonne/Normal_modes/modes/moonweber$
```

Tutorial exercise #1 : plotting mode amplitudes with gnu plot



Tutorial exercise #1 : plotting mode amplitudes with matlab

- plotmode_weber.m

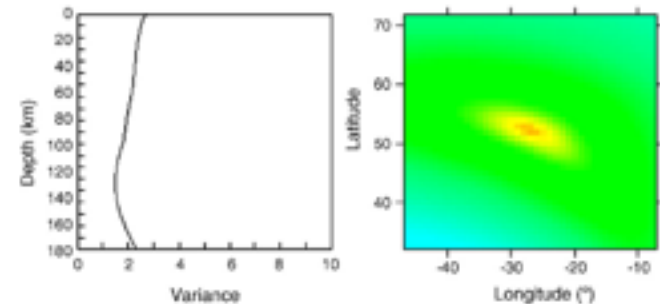
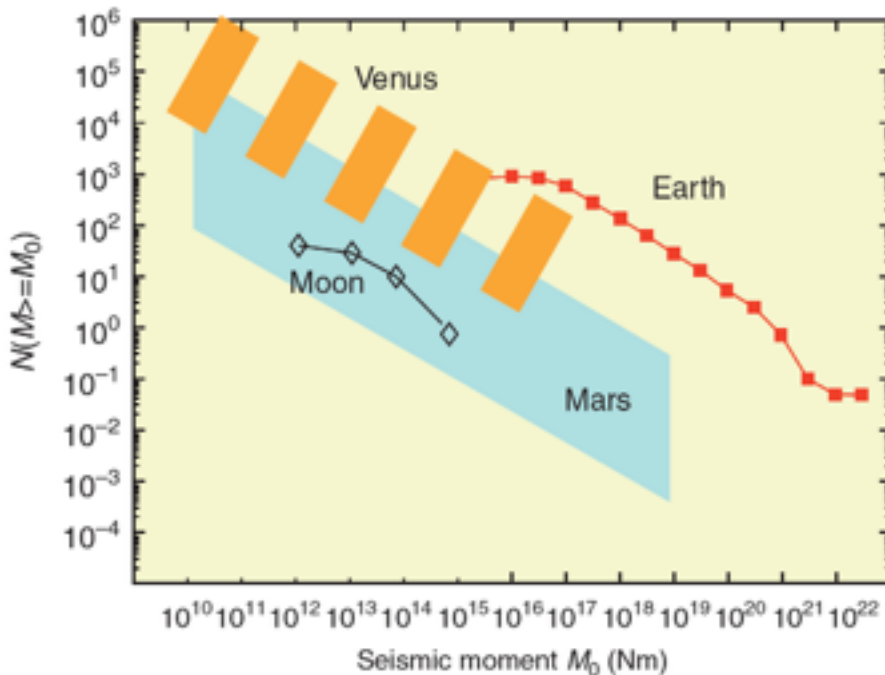


Tutorial exercise #1

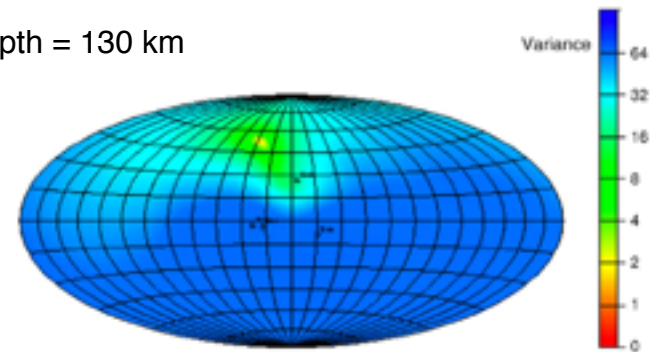
- **WHAT ARE THE AMPLITUDE OF 10 sec CORE PHASE, 20 sec SURFACE WAVES AND NORMAL MODES GENERATED BY A SHALLOW MOONQUAKE ON THE MOON ?**
 - Choose a Lunar Model
 - Compute Normal modes: Why ?
 - **Define a seismic source, i.e. moonquake with**
 - **position (including depth)**
 - **Magnitude**
 - Compute seismograms at different stations...
 - Estimate the amplitude

Tutorial exercise #1 : Seismic moment for Moonquake

- Largest deep Moonquake $\sim 5 \cdot 10^{13}$ Nm
- Largest Shallow Moonquake $3 \cdot 10^{14}$ Nm- $1.6 \cdot 10^{14}$ Nm
- Tohoku Earthquake $\sim 5.3 \cdot 10^{22}$ Nm
 - Moon DMQ moments are 10^9 smaller than the largest Earth quakes...
- We take a 10^{14} Nm quake (10^{21} dyne cm)



Depth = 130 km



Tutorial exercise #1 : preparing the input files (1/2)

```
cig@cig-VirtualBox: ~/tutorial/lognonne/Sismospherd/exemple_moon
cig@cig-VirtualBox:~/tutorial/lognonne/Sismospherd/exemple_moon$ pwd
/home/cig/tutorial/lognonne/Sismospherd/exemple_moon
cig@cig-VirtualBox:~/tutorial/lognonne/Sismospherd/exemple_moon$ ls
cx_sismo  data2.ah  data2.asc  README  results.n  sphericDIST10  sphericDIST100  sphericDIST20  sphericDIST50
cig@cig-VirtualBox:~/tutorial/lognonne/Sismospherd/exemple_moon$ cp /home/cig/shared/inputfortutorial1/cx_sismo_tutorial1* .
cig@cig-VirtualBox:~/tutorial/lognonne/Sismospherd/exemple_moon$
```

```
File Edit View Search Terminal Help
7.07160810E-05 -8.53553356E-05 1.46446619E-05 -3.53553332E-05 3.53553405E-05 -3.53553405E-05 (*e27 dyne.cn)
year ,month, hour, minute, second for the event:
2011 3 11 5 47 32.7999992
position of the source ( geographic): 0.000000000000000 0.000000000000000
year ,month, hour, minute, second for the seismogram:
1995 7 30 0 0 0.00000000
length of the seismogram (in hours), sampling:
0.99972222222222218 1.000000000000000
pole & zero: 10.0000000 3.00000000
32.7999992 0.00000000
number of points for the output 10800
number of points for the input 3600
stat: MUSchan: z
1727.099999999999 1734.0900000095367
11 3 2011 2011 70 1
11 3 2011 2011 70 1
calendar julien(event): 70 2011
calendar julien(seismo): 70 2011
2011 3 11 5 47 32.7999992
2011 3 11 5 47 32.7999992
position of the source ( geocentric) 0.000000000000000 0.000000000000000
time between the beginning of the seismogram and the beginning of the source: 0.000000000000000
delta t at the beginning : 1.000000000000000
dtc : 1.000000000000000
number of samples in the record : 10800
number of samples to skip at the beginning : 0
number of samples to compute : 10801
power of 2 : 10384
the seismogram is computed for a duration of 4.550833333333333 hours
position of the station ( geocentric)
lat: 0.000000000000000 lon: 100.0000000000000
position of the station ( geographic)
lat: 0.000000000000000 lon: 100.0000000000000
channel 0
recquisition: 1
maximum amplitude modeled in z: 9.66219773E-07
record length: 3600 zsyn
cig@cig-VirtualBox:~/tutorial/lognonne/Sismospherd/exemple_moon$ ls
cx_sismo cx_sismo_tutorial1a data.ah data2.asc README sphericDIST10 sphericDIST100F sphericDIST20 sphericDIST50
cx_sismo_tutorial1b data2.ah data2.asc results.n sphericDIST100 sphericDIST100F sphericDIST20F sphericDIST50F
cig@cig-VirtualBox:~/tutorial/lognonne/Sismospherd/exemple_moon$ cp spheric* /home/cig/shared/outputtutorial1
cig@cig-VirtualBox:~/tutorial/lognonne/Sismospherd/exemple_moon$
```

Tutorial exercise #1 : preparing the input files (2/2)

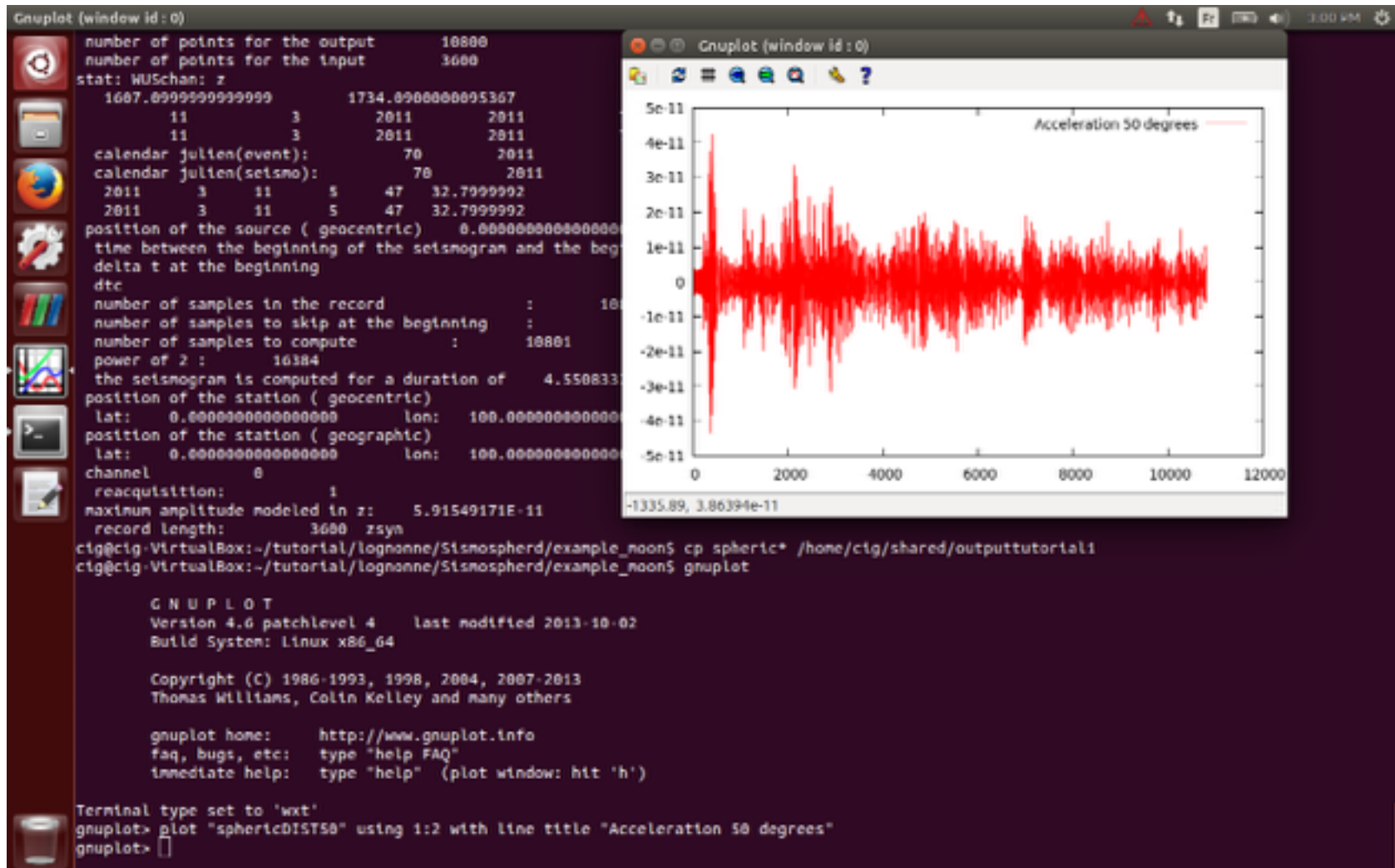
```
File Edit View Search Terminal Help
sed -e "1,$ s/DIST/10./g" < dataZ.asc | ../../bin/asc2ah >data.ah
../../bin/ahmodhead -e 0. 0. 10. 2011 3 11 05 47 32.8 -m 45. 45. 45. 1e-6 1. 1. -l data.ah > data2.ah # reference
../../bin/sismospherd0 << *cmd*
noonweber0
../../Normal_nodes/nodes/noonweber
0 0 0 -1 1. 66.
1
2 0 0 1
sphericDIST10F
2 0
data2.ah
-1 -1
3
*cmd*
sed -e "1,$ s/DIST/20./g" < dataZ.asc | ../../bin/asc2ah >d
../../bin/ahmodhead -e 0. 0. 10. 2011 3 11 05 47 32.8 -m 45
../../bin/sismospherd0 << *cmd*
noonweber0
../../Normal_nodes/nodes/noonweber
0 0 0 -1 1. 66.
1
2 0 0 1
sphericDIST20F
2 0
data2.ah
-1 -1
3
*cmd*
sed -e "1,$ s/DIST/50./g" < dataZ.asc | ../../bin/asc2ah >d
../../bin/ahmodhead -e 0. 0. 10. 2011 3 11 05 47 32.8 -m 45
../../bin/sismospherd0 << *cmd*
noonweber0
../../Normal_nodes/nodes/noonweber
0 0 0 -1 1. 66.
1
2 0 0 1
sphericDIST50F
2 0
data2.ah
-1 -1
3
"cx_sismo_tutorial1a" 56 lines, 1314 characters
```

Folder with the mode
generic name
NSmin NSmax NTmin NTmax fmin fmax
Number of seismograms (*here 1*)
ivit igrav isec ioutput (*ivit 0,1,2 for displacement, velocity, acceleration; igrav=0,1 for gravity or not, ised =1,0 for static term or not, output =1,0 for output or not*)
input output (*input 0 (hand input), 1 through ah, 2 change duration, output 0 (only synthetics), 1 data and synthetics*)
output file
depth altitude (*if -1 -1, those of the input file*)
time of seismogram in hr

Tutorial exercise #1 : compute seismograms

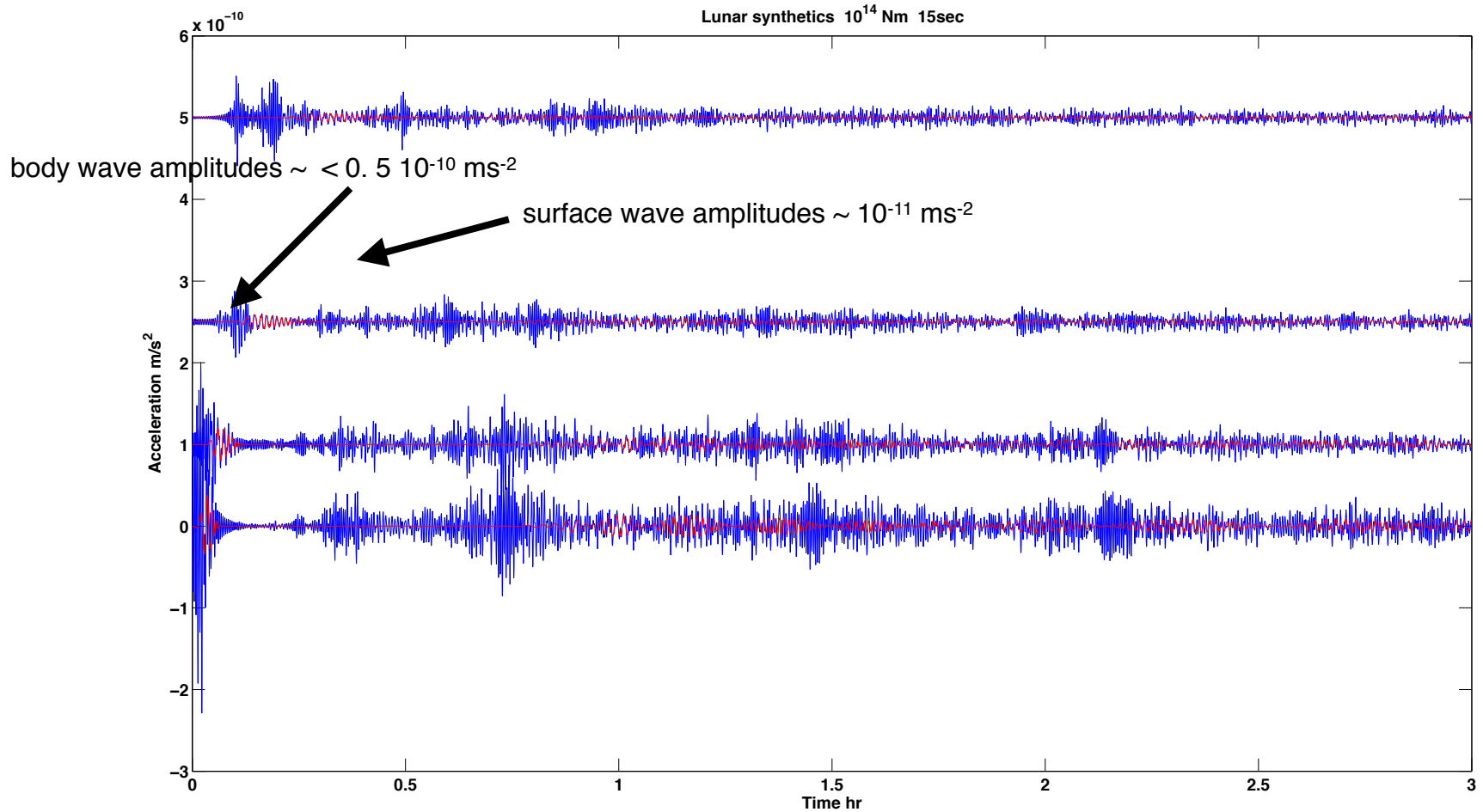
- type
 - `./cx_sismo_tutorial1a` (for fundamental only)
 - `./cx_sismo_tutorial1b` (for all modes)

Tutorial exercise #1 : plotting the seismograms on gnuplot



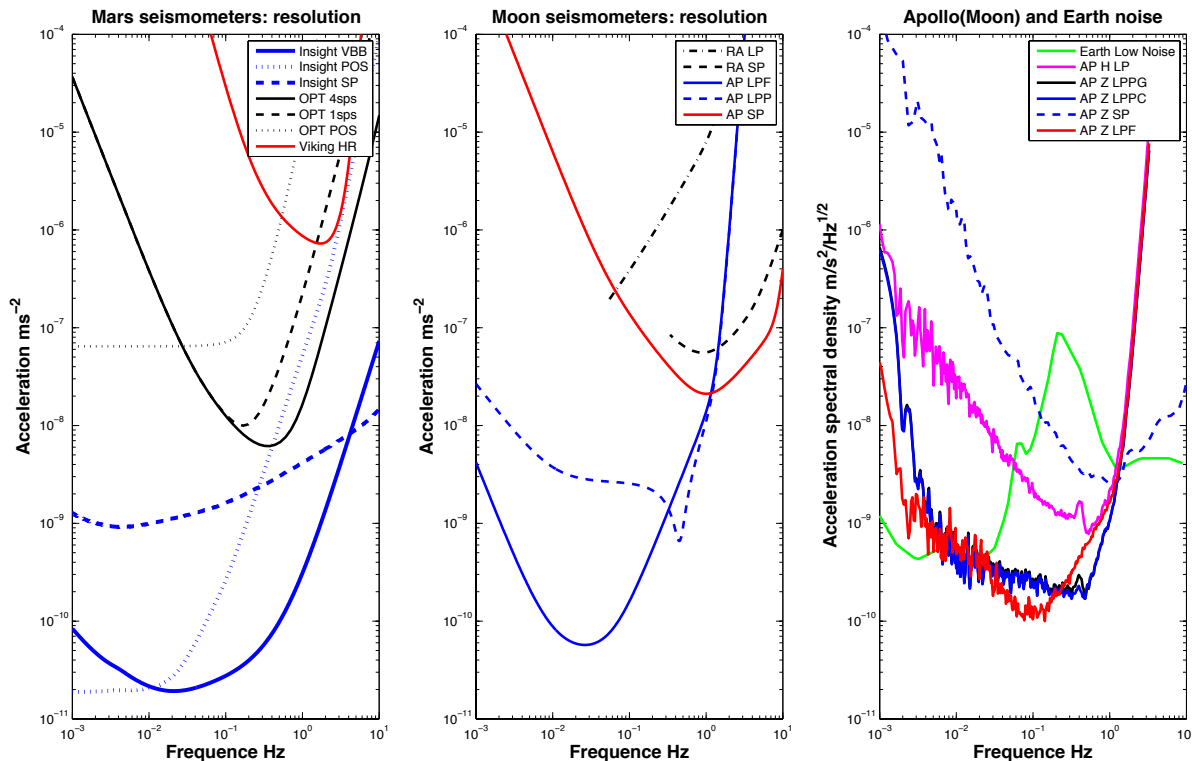
Tutorial exercice #1 : plotting the seismograms on matlab

- plot_sismo.m



Tutorial exercise #1 : did Apollo get this signal ?

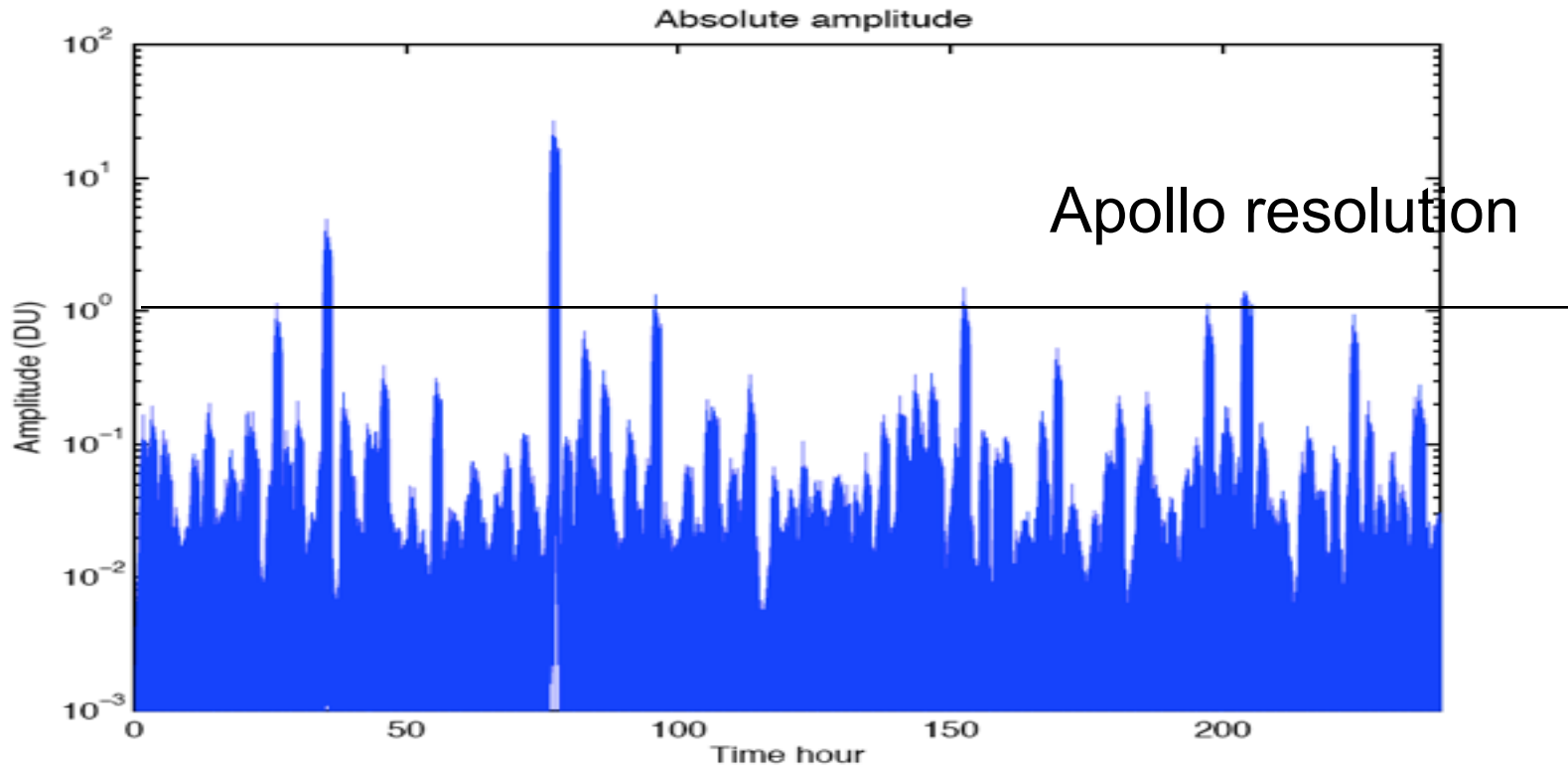
- Apollo noise at 20 sec (0.05 Hz) : $ASD = 4 \times 10^{-10} \text{ ms}^{-2}/\text{Hz}^{1/2}$
- Equivalent noise in the 0.01 Hz-0.06 Hz (15sec-100sec):
 - $ASD \cdot \sqrt{Df} = 0.9 \cdot 10^{-10} \text{ ms}^{-2} \text{ rms}$
- Apollo was not able to detect these long period waves... and practically, no waves below ~ 5 sec are detected...



Seismic noise estimations

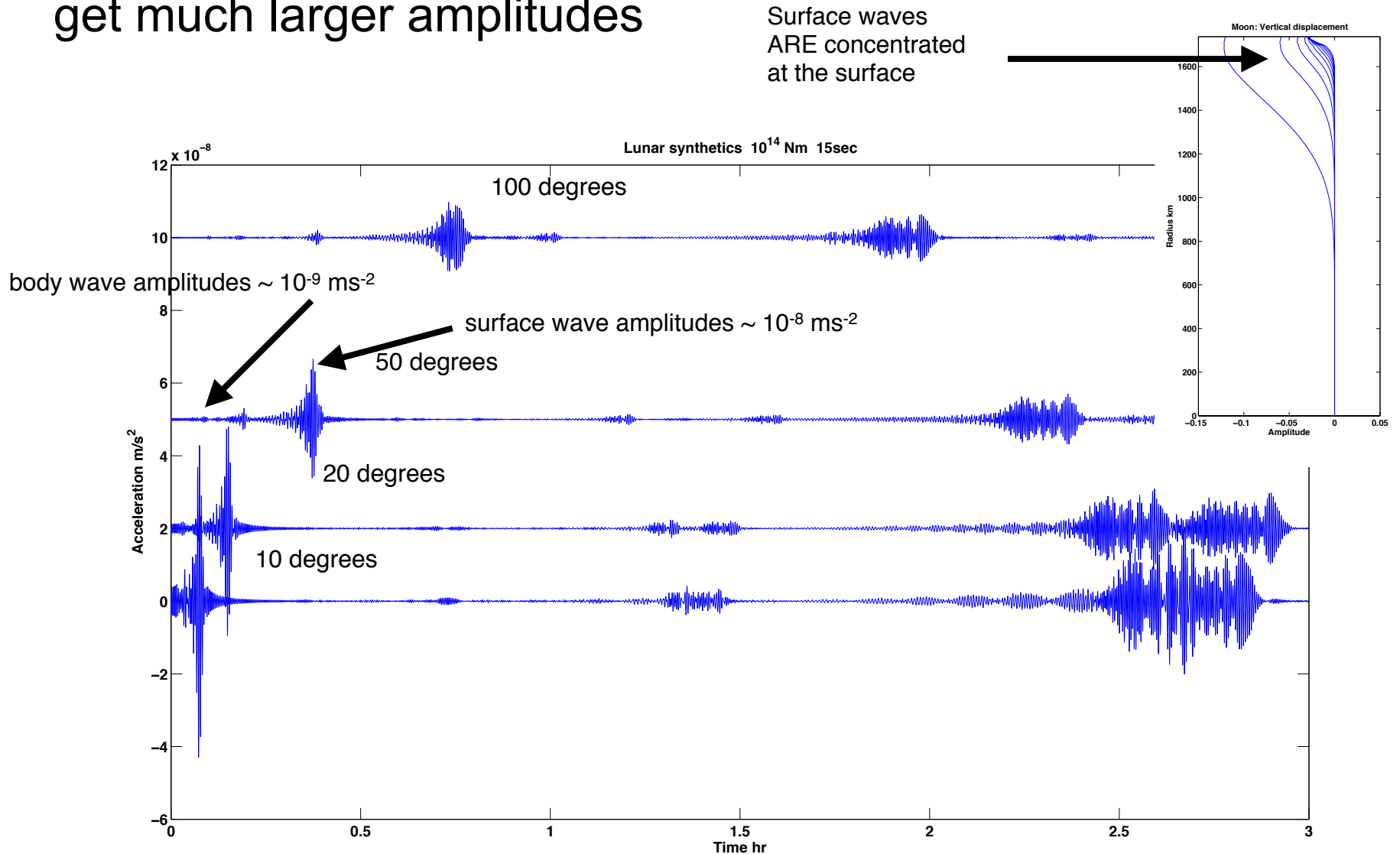


- A continuous source of noise on the Moon can be related to the continuous impacts of micro-meteorites (Lognonné et al., 2009)
- We find a seismic background continuous noise in the range of 10^{-2} - 10^{-1} Apollo DU at 0.5 Hz, corresponding to amplitudes of 5×10^{-11} to 5×10^{-12} ms^{-2}



Tutorial exercise #1 : source depth

- Home work... re compute a seismograms for 10 km depth and get much larger amplitudes



Tutorial exercise #1 : Displacement seismograms

- type
 - ./cx_sismo_tutorial1c (for fundamental only)
 - ./cx_sismo_tutorial1d (for all modes)

