第七届“地震学算法与程序培训班”

DRadiSurfTomo程序的原理和使用说明

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提纲

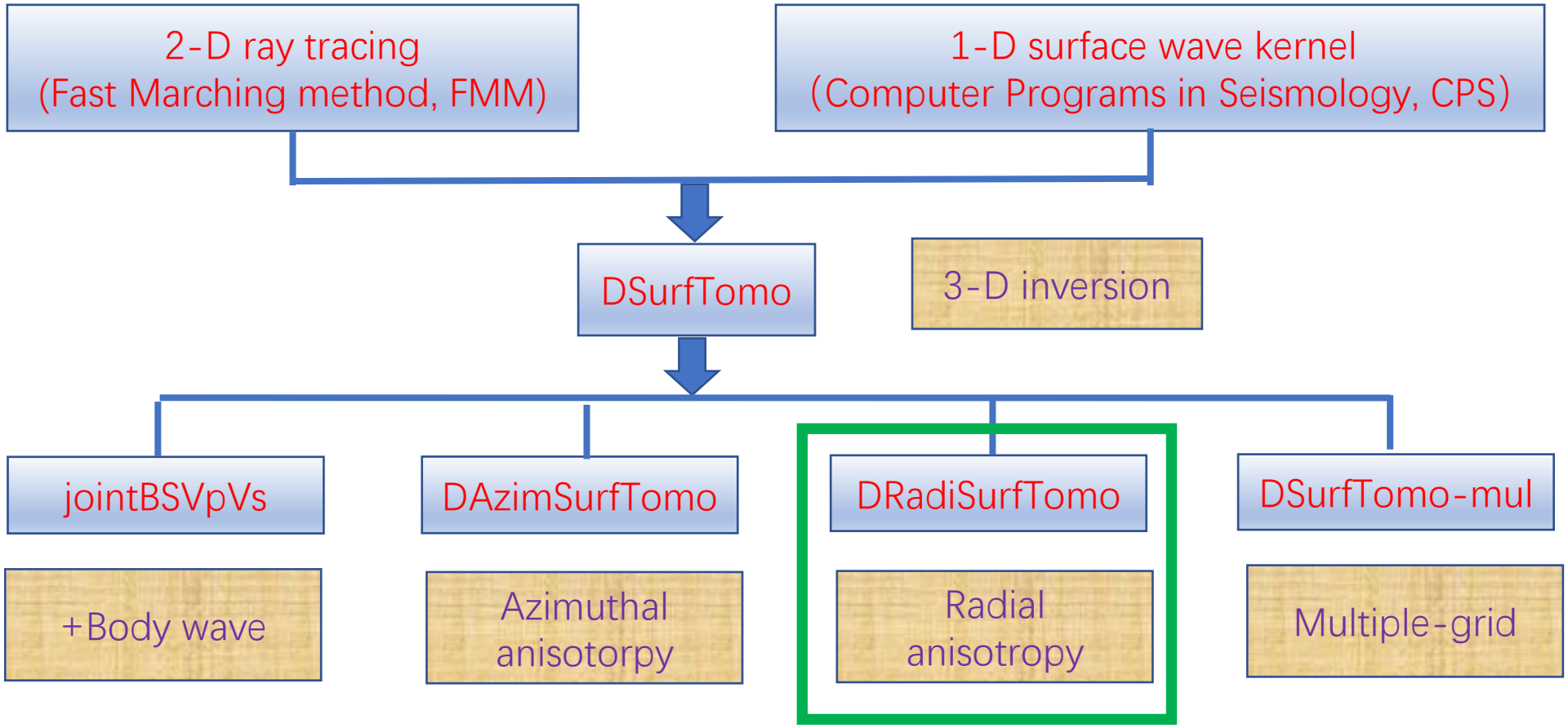
- DRadiSurfTomo程序的简单说明
- DSurfTomo系列程序简单介绍
- 程序原理介绍
- 程序包的安装以及运行
- 程序运行文件准备
- 程序运行示例

简单说明

- DRadiSurfTomo：
  - Direct Radial anisotropy Surface wave Tomography
- 程序的功能：使用Rayleigh/Love波频散计算径向各向异性结构
- 程序的编译：fortran + (openmp)
- 程序的版本和下载：
  - 2021/08/08
  - GitHub - ShaoqianHu/DRadiSurfTomo (https://github.com/ShaoqianHu/DRadiSurfTomo)
  - Or (https://www.researchgate.net/publication/353763440_DRadiSurfTomo)

DSurfTomo程序系列

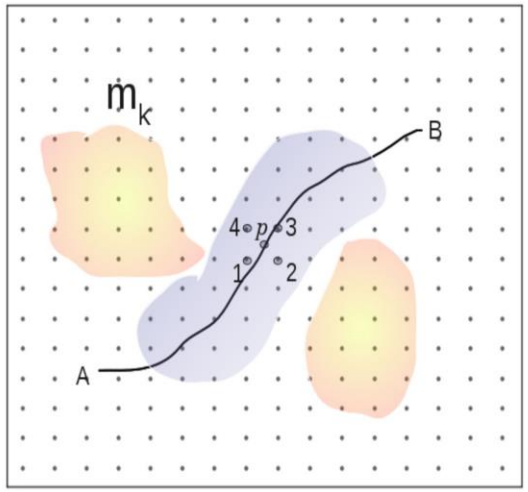
- DSurfTomo: Direct Surface wave Tomography

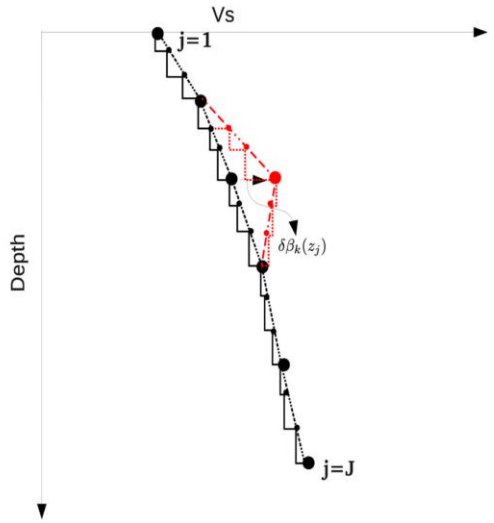


Related references

- N. Rawlinson and M. Sambridge, 2004, Wave front evolution in strongly heterogeneous layered media using the fast marching method, GJI, 156(3), 631-647 (FMM)
- R. B. Herrmann, 2013, Computer programs in seismology: An evolving tool for instruction and research, SRL, 84(6), 1081-1088 (CPS)
- H. Fang, H. Yao, H. Zhang, Y-C Huang, and R. D. van der Hilst, 2015, Direct inversion of surface wave dispersion for three-dimensional shallow crustal structure based on ray tracing: methodology and application, GJI, 201, 1251-1263 (DSurfTomo)
- H. Fang, H. Zhang, H. Yao, A. Allam, D. Zigone, Y. Ben-Zion, C. Thurber, and R. D. van der Hilst, 2016, A new algorithm for three-dimensional joint inversion of body wave and surface wave data and its application to the Southern California plate boundary region, JGR, 121, 3557-3569 (jointBSVpVs)
- C. Liu, H. Yao, H.-Y. Yang and W. Shen, H. Fang, S. Hu, and L. Qiao, 2019, Direct inversion for three-dimensional shear wave speed azimuthal anisotropy based on surface wave ray tracing: methodology and application to Yunnnan, Southwest China, JGR, 124. (DAzimSurfTomo)
- S. Hu, H. Yao, and H. Huang, 2020, Direct surface wave radial anisotropy tomography in the crust of the eastern Himalayan syntaxis, JGR, 125. (DRadiSurfTomo)
- S. Luo, H. Yao, J. Wang, K. Wang, and B. Liu, 2021, Direct inversion of surface wave dispersion data with multiple-grid parameterizations and its application to a dense array in Chao Lake, eastern China, GJI, 225(2), 1432-1452. (DSurfTomo-mul)

DSurfTomo程序原理



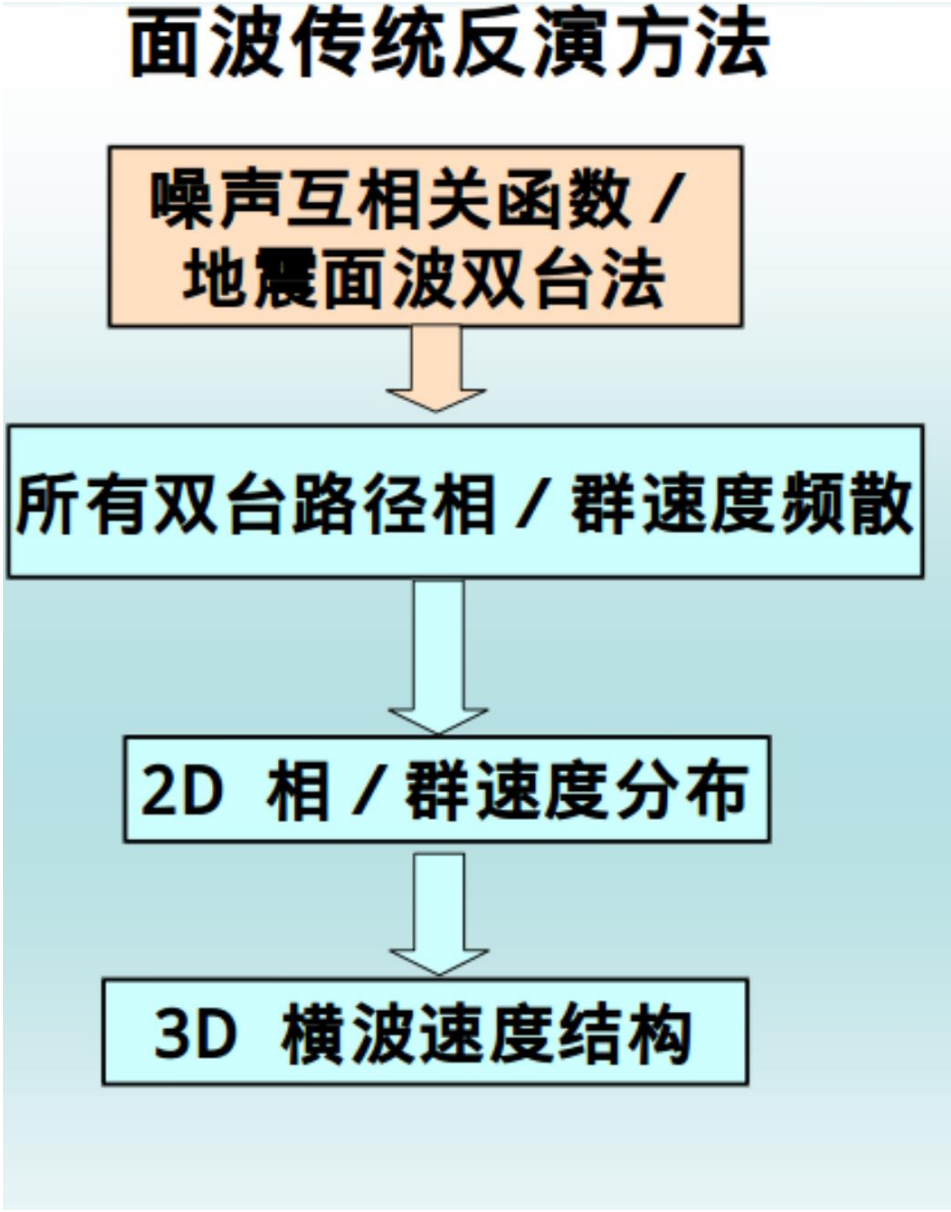


2-D FMM

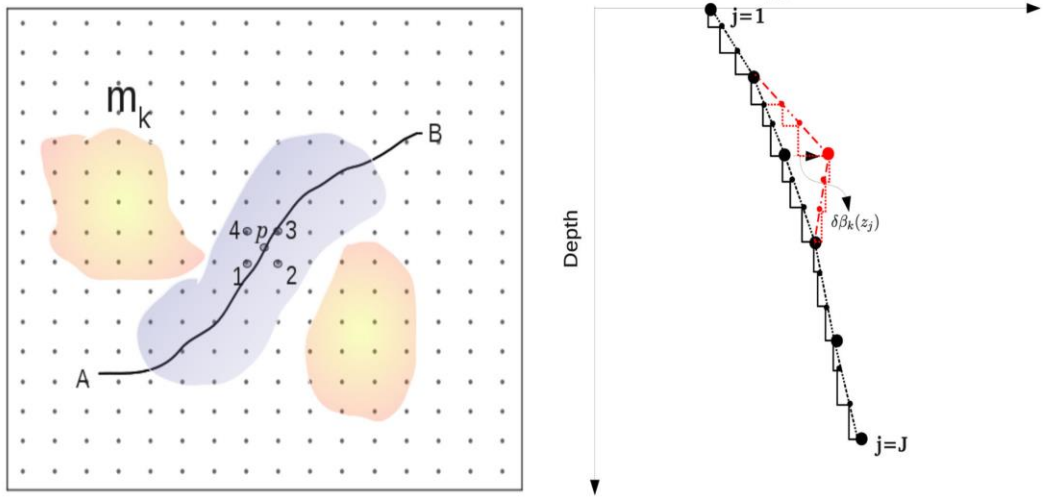
1-D kernel

$$d = G_{2D} m_c$$

$$m_c = G_{1D} V_s$$



DSurfTomo程序原理



2-D FMM ✖ 1-D kernel

$$d = G_{3D}V_s$$

面波直接反演方法

噪声互相关函数 / 地震面波双台法

所有频率双台路径面波走时

不同频率面波的路径不同：面波路径射线追踪（ fast marching method ）(Rawlinson, 2004)

3D 横波速度结构

DRadiSurfTomo程序原理

$$\begin{pmatrix} \Delta \mathbf{T}_R \\ \Delta \mathbf{T}_L \end{pmatrix} = \begin{pmatrix} \mathbf{G}_{sv} & \mathbf{0} \\ \gamma \cdot \mathbf{G}_{sh} & \mathbf{V}_{sv} \cdot \mathbf{G}_{sh} \end{pmatrix} \begin{pmatrix} \Delta \mathbf{V}_{sv} \\ \Delta \gamma \end{pmatrix}$$

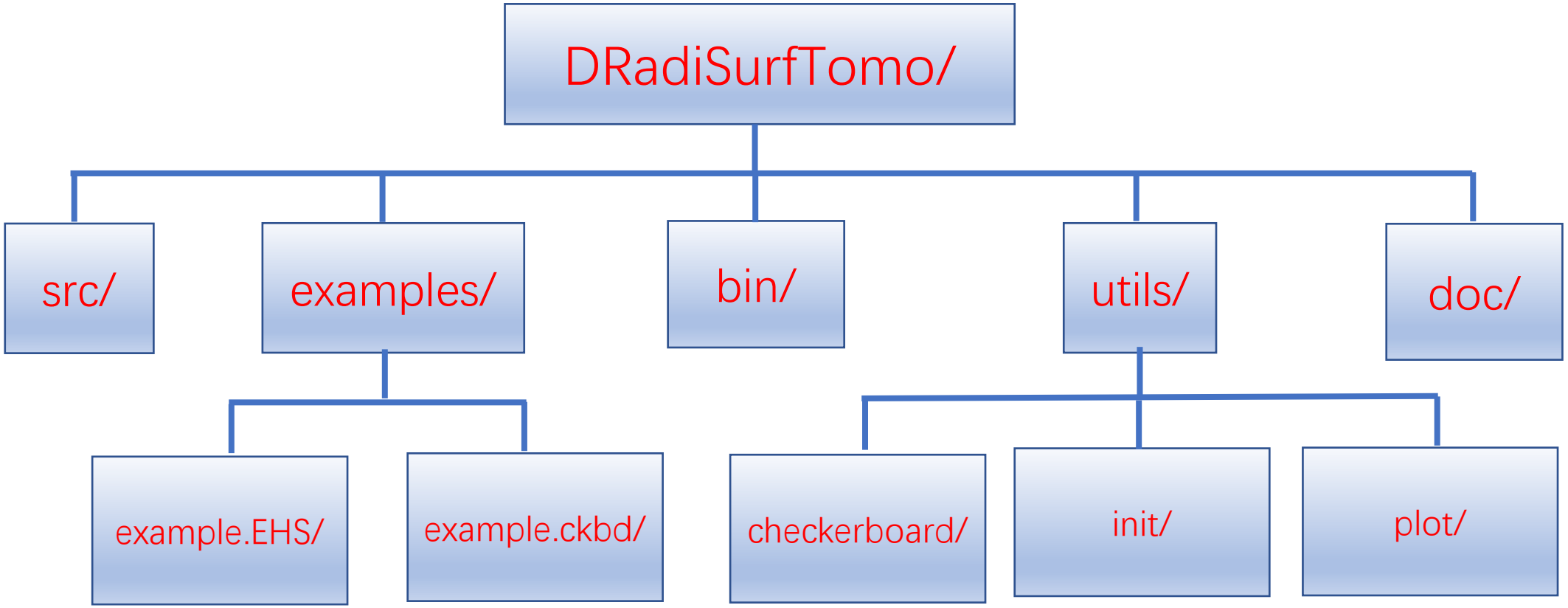
$$\gamma = \frac{V_{sh}}{V_{sv}}$$

Rayleigh/Love
波频散数据

3-D敏感核

横波速度
各向异性参数

软件包


DRadiSurfTomo/
src/
examples/
bin/
utils/
doc/
example.EHS/
example.ckbd/
checkerboard/
init/
plot/

软件包安装和运行

- 安装：
  - cd src/
  - In Makefile, 第3行： 修改 FC=(your fortran compiler)
  - In Makefile, 第5行：32位机删除 –m64
  - Type : make clean; make

- 运行：
  - cd ../example/example_EHS/;
  - Type: ../../bin/DRadiSurfTomo DRadiSurfTomo.in

软件包

- src/
  - main.f90　　主程序
  - CalRadAniG.f90　　3-D面波敏感核
  - lsmrModule.f90　　最小二乘法子程序
  - surfdisp.f　　1-D面波频散正演程序

- examples/
  - examples_EHS:　　喜马拉雅东构造结的数据和配置文件
  - Example_ckbd:　　喜马拉雅东构造结检测版测试相关配置文件

软件包

- utils/init/ 生成初始模型
  - 输入： mod.1d
  - 输出： MOD.gam 和 MOD.Vsv
- utils/plot/ 绘制反演结果
  - 输入： DRadiSurfTomo输出模型文件
  - 输出： 模型文件横剖面图像
- utils/checkerboard/ 进行检测版测试
  - 输入： mod.1d
  - 输出： MOD.gam, MOD.Vsv, MOD.true.gam, 和MOD.true.Vsv

程序输入文件

- 参数设置
- 输入初始模型
- 输入数据

输入参数文件（默认DRadiSurfTomo.in）

```
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c INPUT PARAMETERS
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
AllR.dat                          c: Rayleigh wave data file
AllL.dat                          c: Love wave data file
12 19 18                          c: nx ny nz (grid number in lat lon a
32.5  90.50                      c: goxd gozd (upper left point,[lat,lo
0.5 0.5                        c: dvxd dvzd (grid interval in lat and lo
5000                               c: nsrc*maxf
20.0  20.0  0.0                   c: lambda1 lambda2 damp
2                                 c: nsublayer (numbers of sublayers fo
1.5 5.5                           c: minimum velocity, maximum velocity
0.85 1.15                          c: minimum gamma, maximum gamma
10                                c: maxiter (iteration number)
0.1                               c: sparsity fraction
36                                c: kmaxRc (followed by periods)
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
0                                  c: kmaxRg
36                                 c: kmaxLc
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
0                                 c: kmaxLg
0                                 c: synthetic flag(0:real data,1:synthetic)
0.02                              c: noiselevel
2.5                               c: threshold
```

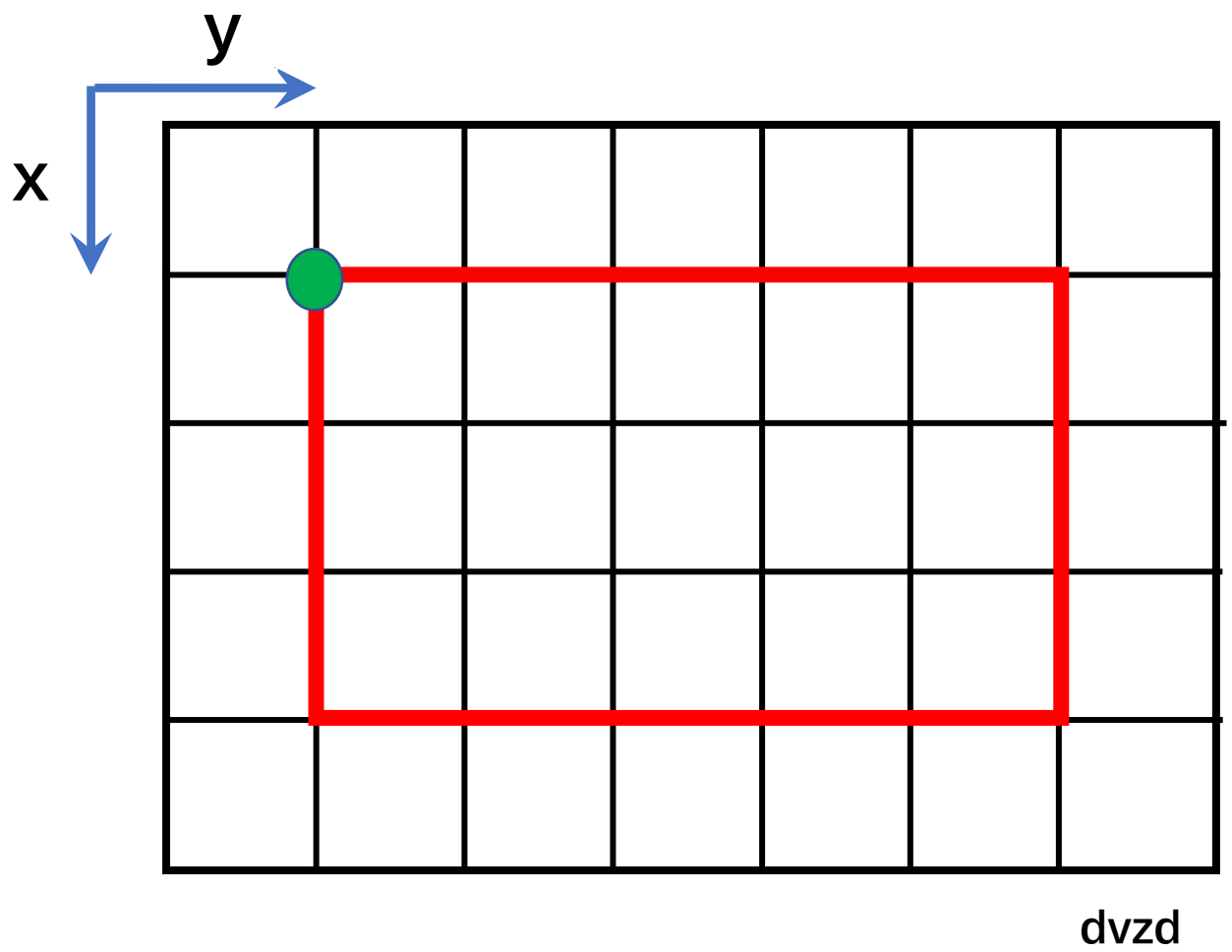
前3行：注释

4~5行：数据文件名称

6~8行：模型位置和大小

11行：深度方向上次级节点

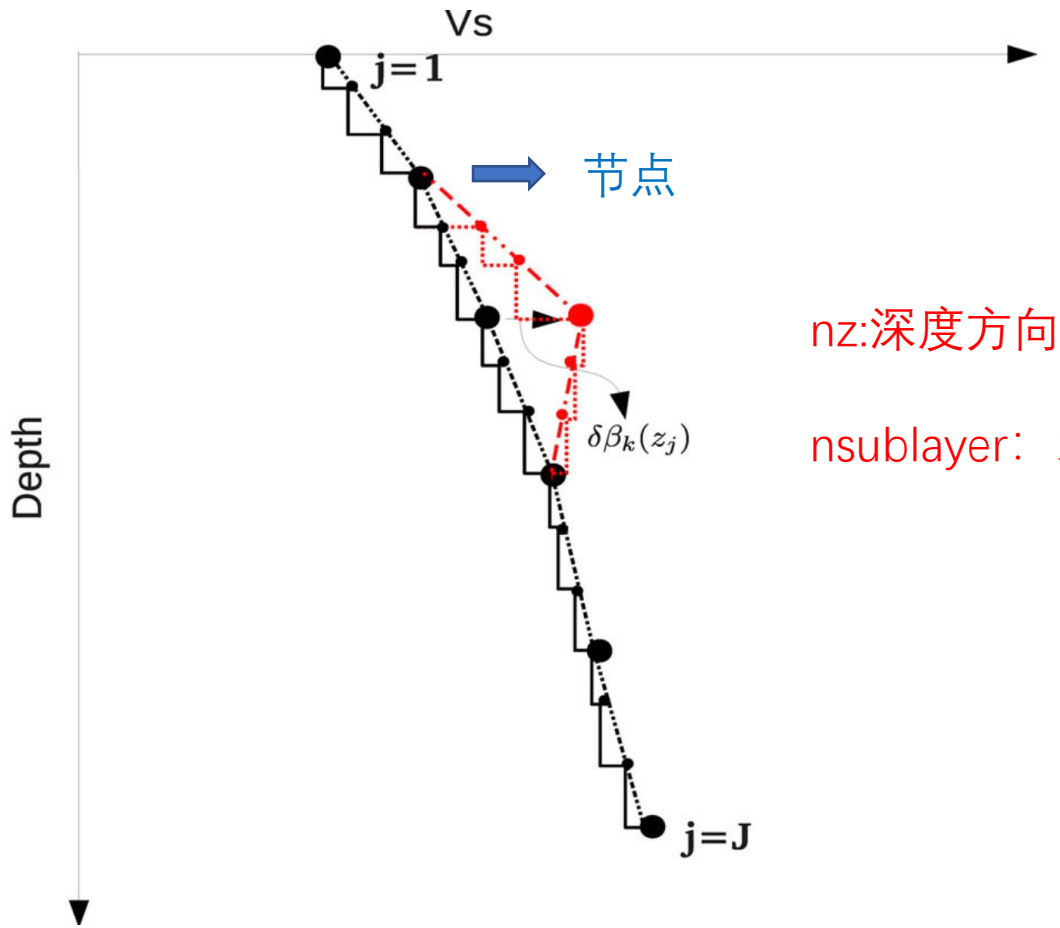
模型设置（水平方向）



绿色原点：(goxd, gozd)
黑色方框：输入模型
红色方框：输出模型

左侧模型
nx=6； ny=8;

模型设置（深度方向）



nz:深度方向上的节点，左侧模型nz=6

nsublayer：左侧模型nsublayer=3

输入参数文件（默认DRadiSurfTomo.in）

```
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c INPUT PARAMETERS
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
AllR.dat                          c: Rayleigh wave data file
AllL.dat                          c: Love wave data file
12 19 18                          c: nx ny nz (grid number in lat lon a
32.5  90.50                       c: goxd gozd (upper left point,[lat,lo
0.5 0.5                           c: dvxd dvzd (grid interval in lat and lo
5000                               c: nsrc*maxf
20.0  20.0  0.0                   c: lambda1 lambda2 damp
2                                 c: nsublayer (numbers of sublayers fo
1.5 5.5                           c: minimum velocity, maximum velocity
0.85 1.15                          c: minimum gamma, maximum gamma
10                                c: maxiter (iteration number)
0.1                               c: sparsity fraction
36                                c: kmaxRc (followed by periods)
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
0                                  c: kmaxRg
36                                 c: kmaxLc
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
0                                 c: kmaxLg
0                                 c: synthetic flag(0:real data,1:synthetic)
0.02                              c: noiselevel
2.5                               c: threshold
```

前3行：注释

4~5行：数据文件名称

6~8行：模型位置和大小

9行：内存相关

11行：深度方向上次级节点

15行：内存相关

输入参数文件（默认DRadiSurfTomo.in）

```
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c INPUT PARAMETERS
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
AllR.dat                          c: Rayleigh wave data file
AllL.dat                          c: Love wave data file
12 19 18                          c: nx ny nz (grid number in lat lon a
32.5  90.50                       c: goxd gozd (upper left point,[lat,lo
0.5 0.5                         c: dvxd dvzd (grid interval in lat and lo
5000                               c: nsrc*maxf
20.0  20.0  0.0                   c: lambda1 lambda2 damp
2                                 c: nsublayer (numbers of sublayers fo
1.5 5.5                           c: minimum velocity, maximum velocity
0.85 1.15                          c: minimum gamma, maximum gamma
10                                c: maxiter (iteration number)
0.1                               c: sparsity fraction
36                                c: kmaxRc (followed by periods)
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
0                                  c: kmaxRg
36                                 c: kmaxLc
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
0                                 c: kmaxLg
0                                 c: synthetic flag(0:real data,1:synthetic)
0.02                              c: noiselevel
2.5                               c: threshold
```

前3行：注释

4~5行：数据文件名称

6~8行：模型位置和大小

9行：内存相关

11行：深度方向上次级节点

12~13行：控制输出模型参数范围

15行：内存相关

输入参数文件（默认DRadiSurfTomo.in）

```
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c INPUT PARAMETERS
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
AllR.dat                          c: Rayleigh wave data file
AllL.dat                          c: Love wave data file
12 19 18                          c: nx ny nz (grid number in lat lon a
32.5  90.50                      c: goxd gozd (upper left point,[lat,lo
0.5 0.5                        c: dvxd dvzd (grid interval in lat and lo
5000                               c: nsrc*maxf
20.0  20.0  0.0                   c: lambda1 lambda2 damp
2                                 c: nsublayer (numbers of sublayers fo
1.5 5.5                           c: minimum velocity, maximum velocity
0.85 1.15                          c: minimum gamma, maximum gamma
10                                c: maxiter (iteration number)
0.1                               c: sparsity fraction
36                                c: kmaxRc (followed by periods)
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
0                                  c: kmaxRg
36                                 c: kmaxLc
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
0                                 c: kmaxLg
0                                 c: synthetic flag(0:real data,1:synthetic)
0.02                              c: noiselevel
2.5                               c: threshold
```

前3行：注释

4~5行：数据文件名称

6~8行：模型位置和大小

9行：内存相关

11行：深度方向上次级节点

12~13行：控制输出模型参数范围

14行：线性反演迭代次数

15行：内存相关

输入参数文件（默认DRadiSurfTomo.in）

```
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c INPUT PARAMETERS
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
AllR.dat                          c: Rayleigh wave data file
AllL.dat                          c: Love wave data file
12 19 18                          c: nx ny nz (grid number in lat lon a
32.5  90.50                      c: goxd gozd (upper left point,[lat,lo
0.5 0.5                        c: dvxd dvzd (grid interval in lat and lo
5000                             c: nsrc*maxf
20.0  20.0  0.0                   c: lambda1 lambda2 damp
2                                 c: nsublayer (numbers of sublayers fo
1.5 5.5                           c: minimum velocity, maximum velocity
0.85 1.15                          c: minimum gamma, maximum gamma
10                                c: maxiter (iteration number)
0.1                               c: sparsity fraction
36                                c: kmaxRc (followed by periods)
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
0                                 c: kmaxRg
36                                c: kmaxLc
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
0                                 c: kmaxLg
0                                 c: synthetic flag(0:real data,1:synthetic)
0.02                              c: noiselevel
2.5                               c: threshold
```

前3行：注释

4~5行：数据文件名称

6~8行：模型位置和大小

9行：内存相关

11行：深度方向上次级节点

12~13行：控制输出模型参数范围

14行：线性反演迭代次数

15行：内存相关

16~21行：输入频散数据参数

频散数据参数

- kmaxRc：Rayleigh波相速度（c)的周期个数
- kmaxRg：Rayleigh波群速度（g)的周期个数
- kmaxRc：Love波相速度（c)的周期个数
- kmaxRc：Love波群速度（g)的周期个数

- 注意：需要跟datafile一致

输入参数文件（默认DRadiSurfTomo.in）

```
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c INPUT PARAMETERS
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
AllR.dat                          c: Rayleigh wave data file
AllL.dat                          c: Love wave data file
12 19 18                          c: nx ny nz (grid number in lat lon a
32.5  90.50                       c: goxd gozd (upper left point,[lat,lo
0.5 0.5                           c: dvxd dvzd (grid interval in lat and lo
5000                               c: nsrc*maxf
20.0  20.0  0.0                   c: lambda1 lambda2 damp
2                                 c: nsublayer (numbers of sublayers fo
1.5 5.5                           c: minimum velocity, maximum velocity
0.85 1.15                          c: minimum gamma, maximum gamma
10                                c: maxiter (iteration number)
0.1                               c: sparsity fraction
36                                c: kmaxRc (followed by periods)
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
0                                  c: kmaxRg
36                                 c: kmaxLc
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
0                                 c: kmaxLg
0                                 c: synthetic flag(0:real data,1:synt
0.02                              c: noiselevel
2.5                               c: threshold
```

前3行：注释

4~5行：数据文件名称

6~8行：模型位置和大小

9行：内存相关

11行：深度方向上次级节点

12~13行：控制输出模型参数范围

14行：线性反演迭代次数

15行：内存相关

16~21行：输入频散数据参数

23~24行：理论测试相关

输入参数文件（默认DRadiSurfTomo.in）

```
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c INPUT PARAMETERS
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
AllR.dat                          c: Rayleigh wave data file
AllL.dat                          c: Love wave data file
12 19 18                          c: nx ny nz (grid number in lat lon a
32.5  90.50                      c: goxd gozd (upper left point,[lat,lo
0.5 0.5                        c: dvxd dvzd (grid interval in lat and lo
5000                             c: nsrc*maxf
20.0  20.0  0.0                   c: lambda1 lambda2 damp
2                                 c: nsublayer (numbers of sublayers fo
1.5 5.5                           c: minimum velocity, maximum velocity
0.85 1.15                          c: minimum gamma, maximum gamma
10                                c: maxiter (iteration number)
0.1                               c: sparsity fraction
36                                c: kmaxRc (followed by periods)
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
0                                 c: kmaxRg
36                                c: kmaxLc
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
0                                 c: kmaxLg
0                                 c: synthetic flag(0:real data,1:synt
0.02                              c: noiselevel
2.5                               c: threshold
```

前3行：注释

4~5行：数据文件名称

6~8行：模型位置和大小

9行：内存相关

10行：光滑及阻尼参数

11行：深度方向上次级节点

12~13行：控制输出模型参数范围

14行：线性反演迭代次数

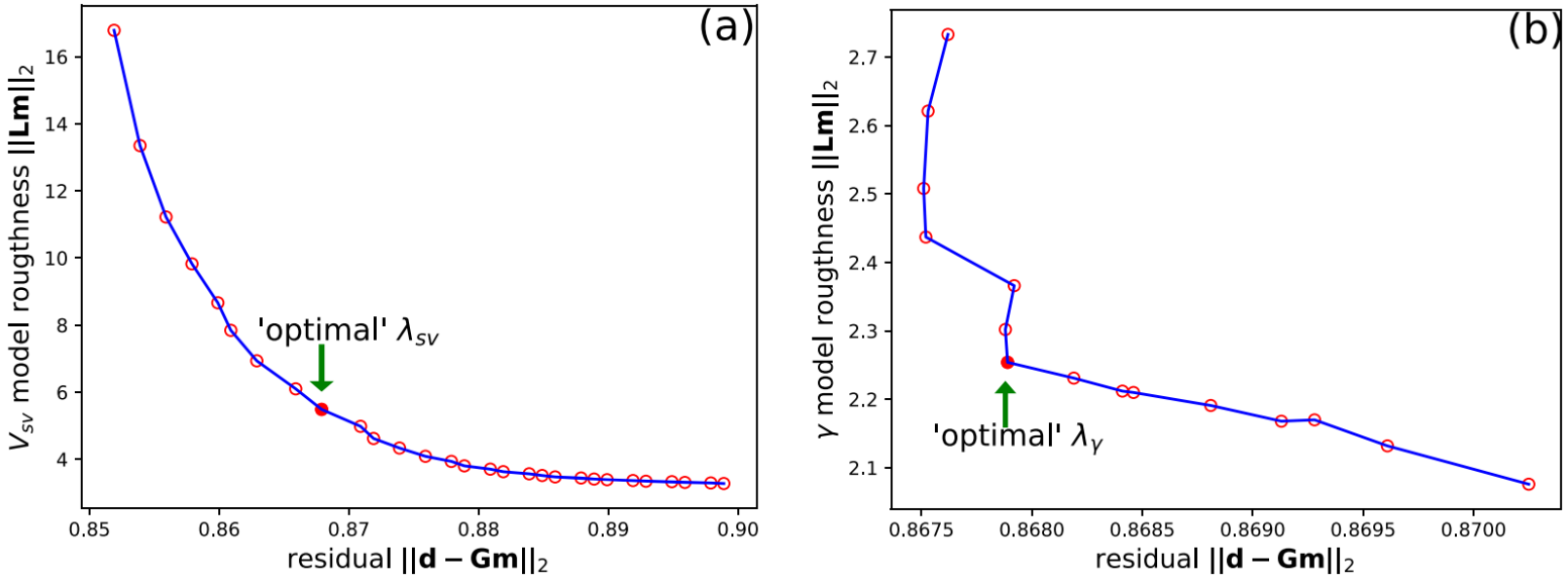
15行：内存相关

16~21行：输入频散数据参数

23~24行：理论测试相关

光滑及阻尼参数

- 光滑参数(*lambda1, lambda2*):
  - $e = residual + lambda1 * |Lm_{SV}|_2 + lambda2 * |Lm_{\gamma}|_2$
- 阻尼参数(*damp*):
  - inv(M)~inv(M+ *damp**I)



输入初始模型（MOD.gam和MOD.Vsv）

depth(nz)

```
for iz=1:nz
    for iy=1:ny
        for ix=1:nx
            output(vs(ix,iy,iz));
        end
        output('\n');
    end
end
```

输入数据文件

```
#    29.190    91.759 1 2 0
   29.117    93.782     3.156
   29.488    94.579     3.124
#    29.318    97.186 1 2 0
   29.072    93.386     3.066
   29.117    93.782     3.054
   29.247    94.258     3.034
   29.488    94.579     3.068
   29.707    92.149     3.082
   29.808    93.907     3.032
   29.875    92.621     3.096
   29.897    93.515     3.088
   29.909    95.472     3.122
   30.023    92.965     3.072
#    29.506    96.756 1 2 0
   29.117    93.782     3.058
   29.190    91.759     3.070
   29.488    94.579     3.050
   29.707    92.149     3.054
   29.875    92.621     3.120
   29.909    95.472     3.114
   30.023    92.965     3.054
#    29.641    97.896 1 2 0
   28.898    91.943     3.084
   29.117    93.782     3.078
   29.488    94.579     3.086
   29.506    96.756     3.082
   29.758    96.102     3.092
   29.773    95.700     3.056
   29.808    93.907     3.068
   29.875    92.621     3.078
   29.897    93.515     3.104
   29.909    95.472     3.068
   29.961    94.780     3.082
   30.009    96.691     3.020
```

格式:

#（震源） 纬度 经度 index R/L U/C

（台站） 纬度 经度 观测相（群）速度

 # 。。。

Index：跟*.in文件中对应

R/L: Rayleigh/Love; R: 2, L:1

U/C: group/phase velocity; U: 1, C: 0