

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

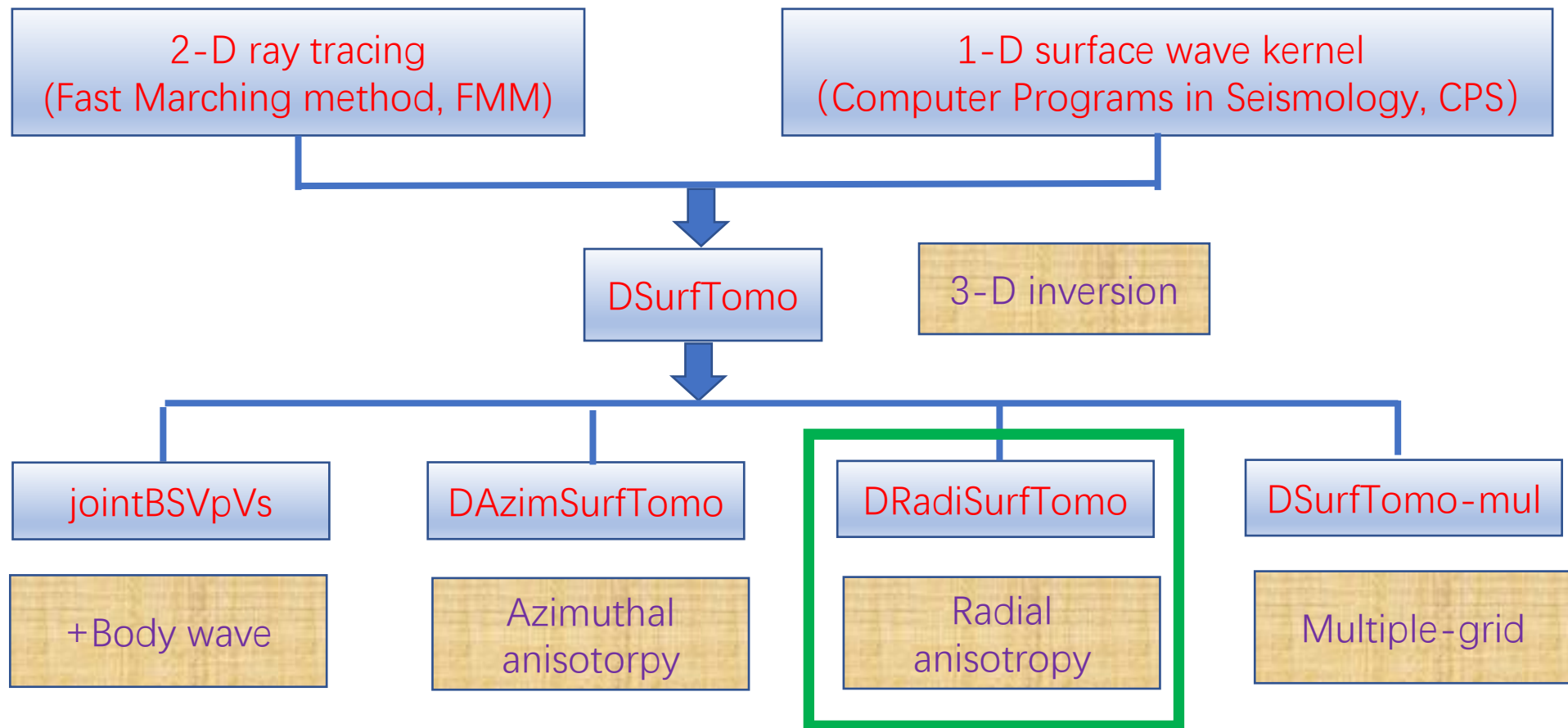
- DRadiSurfTomo程序的简单说明
- DSurfTomo系列程序简单介绍
- 程序原理介绍
- 程序包的安装以及运行
- 程序运行文件准备
- 程序运行示例

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)
(<https://github.com/ShaoqianHu/DRadiSurfTomo>)

DSurfTomo程序系列

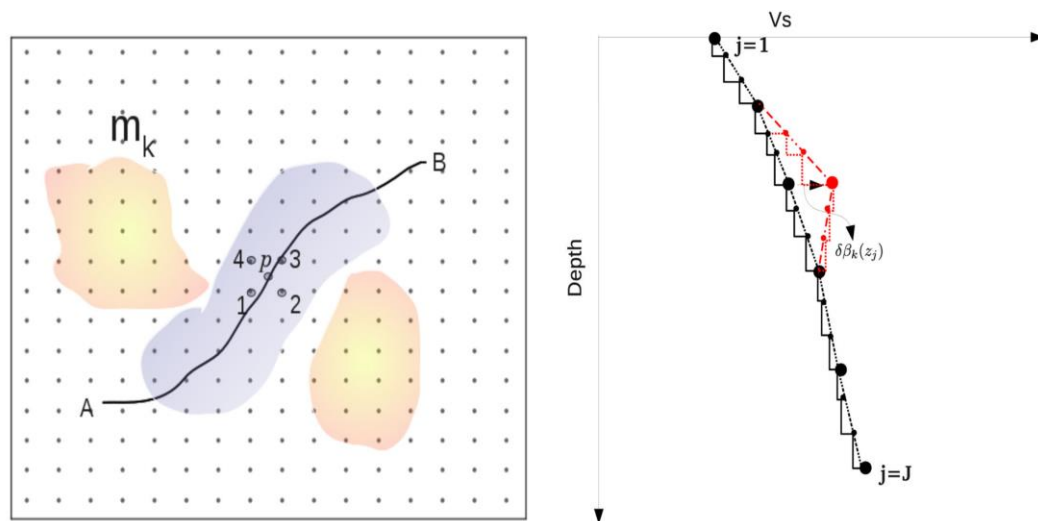
- DSurfTomo: Direct Surface wave Tomography



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 Yunnan, 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

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

1-D kernel

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

面波传统反演方法

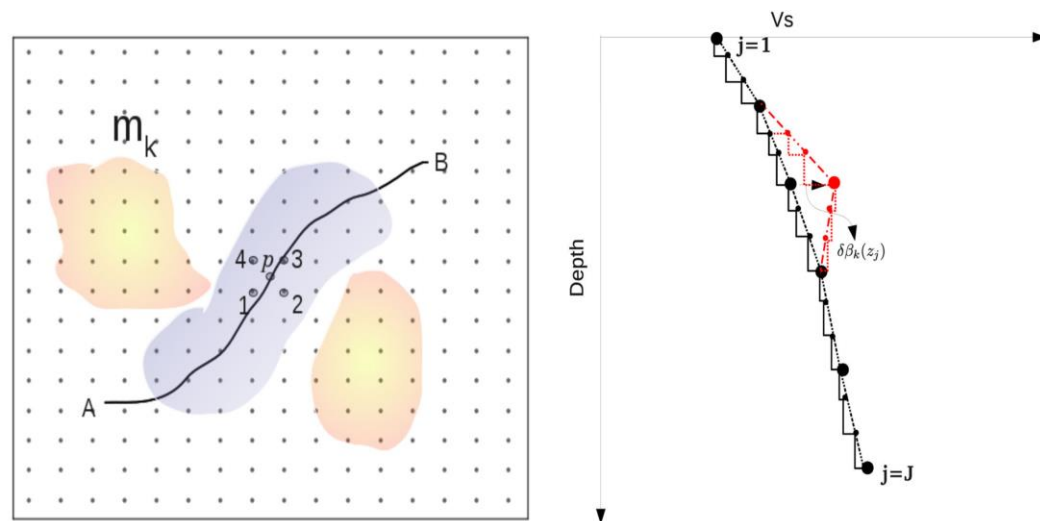
噪声互相关函数 /
地震面波双台法

所有双台路径相 / 群速度频散

2D 相 / 群速度分布

3D 横波速度结构

DSurfTomo程序原理



2-D FMM



1-D kernel

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

面波直接反演方法

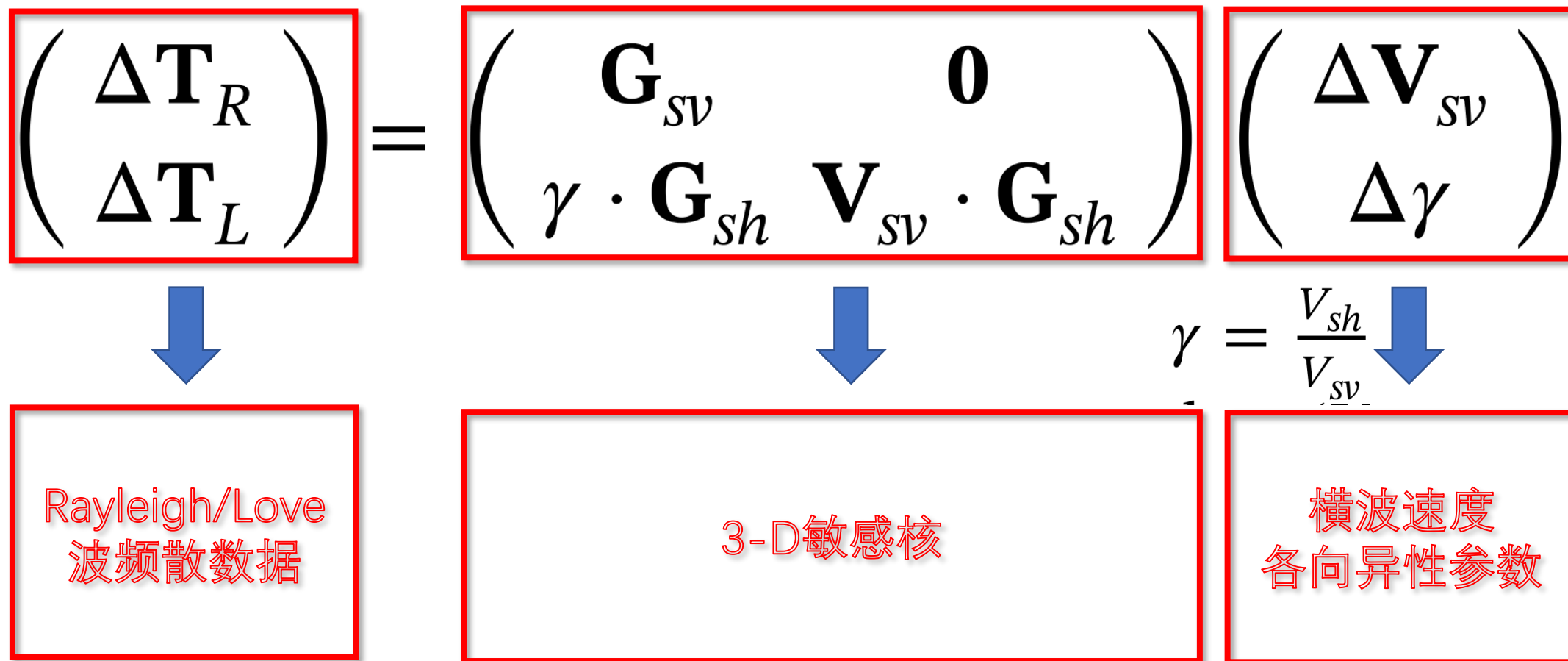
噪声互相关函数 /
地震面波双台法

所有频率双台路径面波走时

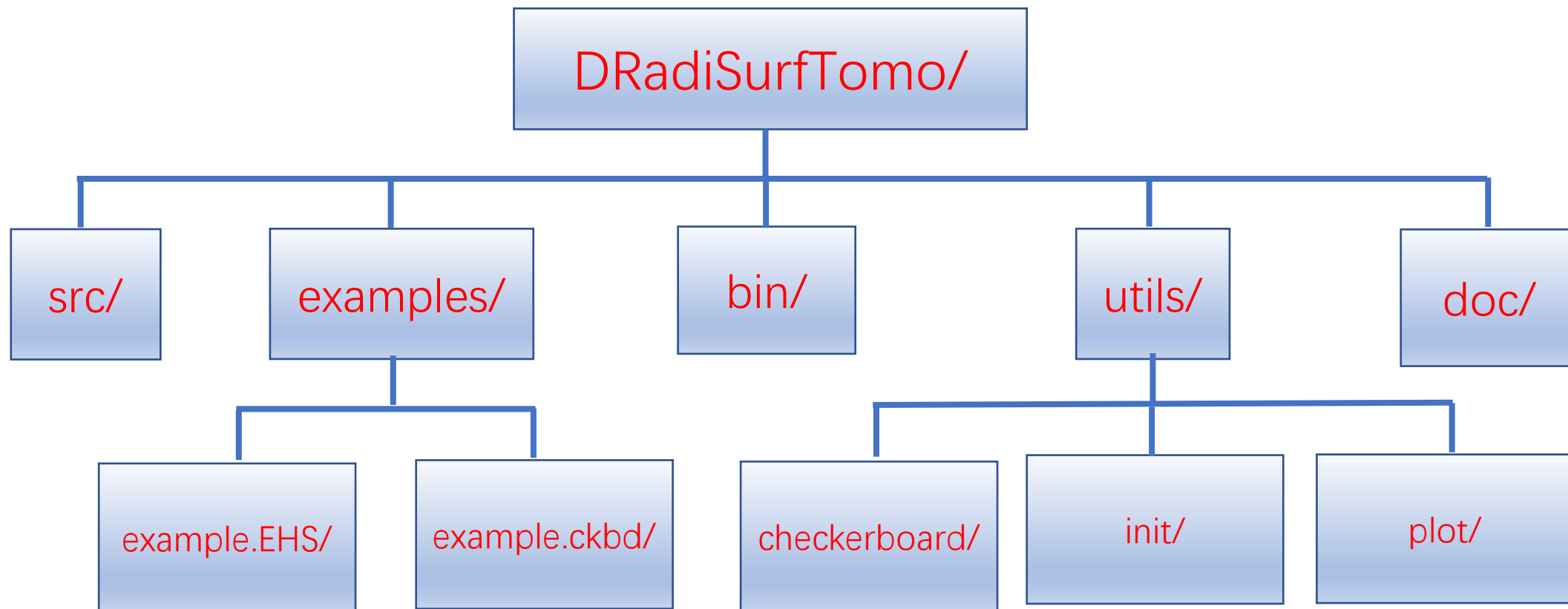
不同频率面波的路
径不同：面波路径
射线追踪 (fast
marching
method)
(Rawlinson, 2004)

3D 横波速度结构

DRadiSurfTomo程序原理



软件包



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

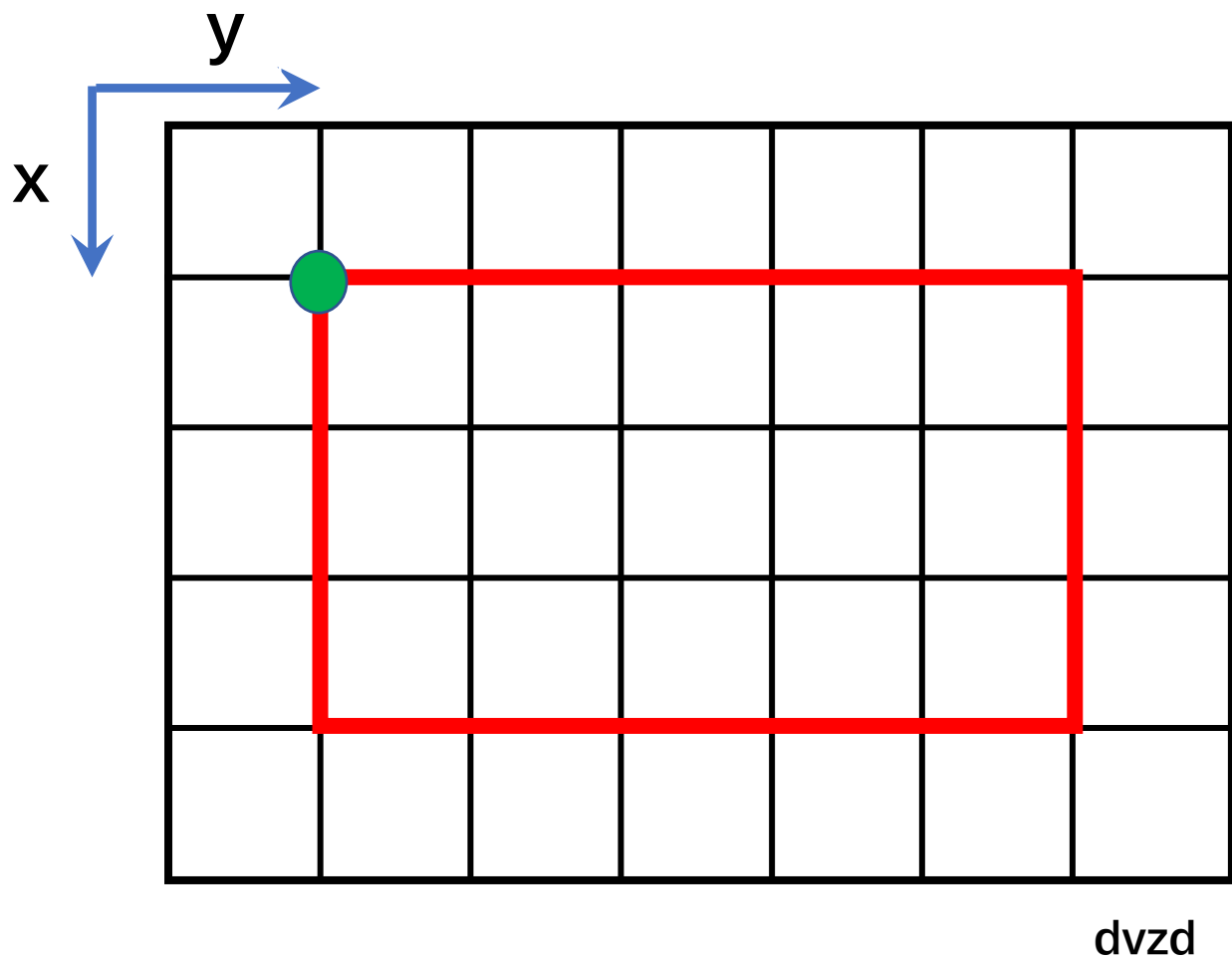
程序输入文件

- 参数设置
- 输入初始模型
- 输入数据

输入参数文件 (默认DRadiSurfTomo.in)

CC	
C INPUT PARAMETERS	前3行：注释
CC	
AllR.dat c: Rayleigh wave data file	4~5行：数据文件名称
AllL.dat c: Love wave data file	
12 19 18 c: nx ny nz (grid number in lat lon)	6~8行：模型位置和大小
32.5 90.50 c: goxd gozd (upper left point,[lat,lon])	
0.5 0.5 c: dvxd dvzd (grid interval in lat and lon)	
5000 c: nsr*c*maxf	
20.0 20.0 0.0 c: lambda1 lambda2 damp	
2 c: nsublayer (numbers of sublayers for each layer)	11行：深度方向上次级节点
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 (大)速度(反演)	
0 c: synthetic flag(0:real data,1:synthetic)	
0.02 c: noiselevel (反演)	
2.5 c: threshold	

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

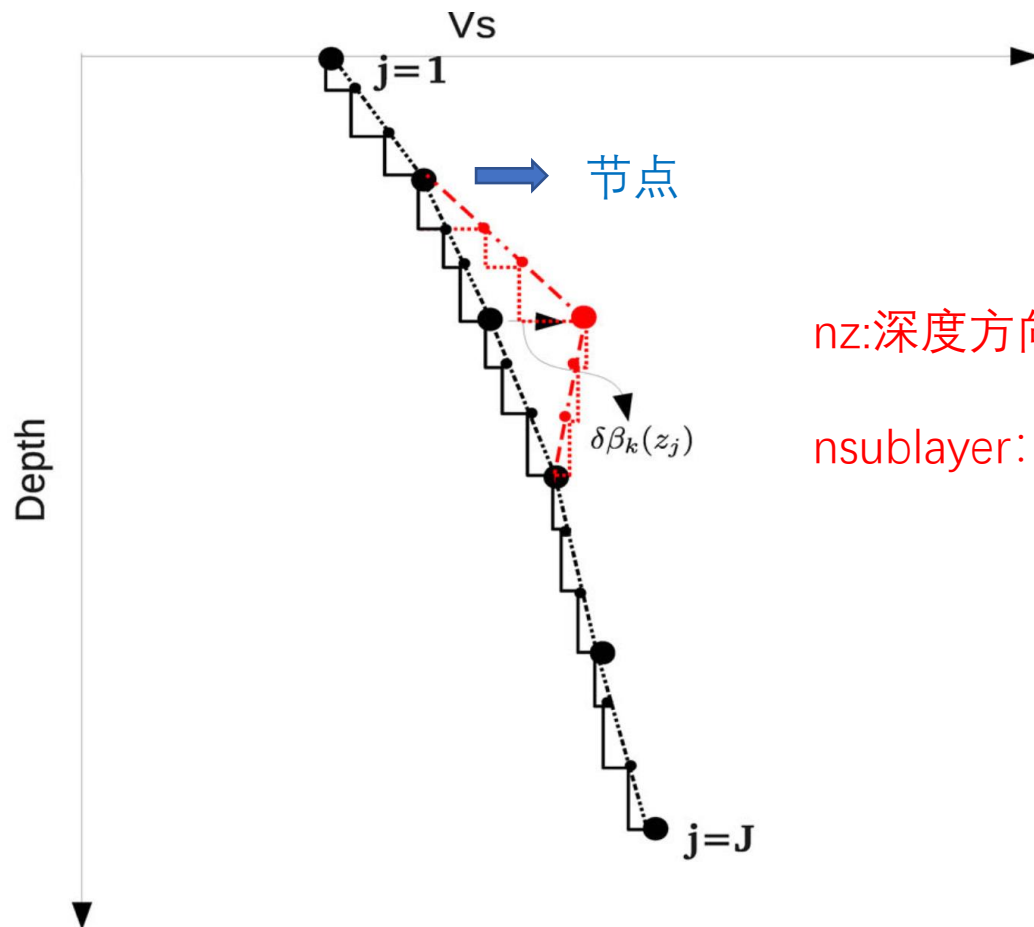
左侧模型

$nx=5; ny=7;$

dvxd

dvzd

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)

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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,lon]	6~8行：模型位置和大小
0.5 0.5 c: dvxd dvzd (grid interval in lat and lon)	
5000 c: nsrc*maxf	9行：内存相关
20.0 20.0 0.0 c: lambda1 lambda2 damp	
2 c: nsublayer (numbers of sublayers for each node)	11行：深度方向上次级节点
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	15行：内存相关
36 weight 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 damp 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 min(max) vel c: kmaxLg (大)速度(反演)	
0 c: synthetic flag(0:real data,1:synthetic)	
0.02 maxiter c: noiselevel (反演)	
2.5 c: threshold	

输入参数文件 (默认DRadiSurfTomo.in)

CC	
C INPUT PARAMETERS	前3行：注释
CC	
AllR.dat c: Rayleigh wave data file	4~5行：数据文件名称
AllL.dat c: Love wave data file	
12 19 18 c: nx ny nz (grid number in lat lon a	6~8行：模型位置和大小
32.5 90.50 c: goxd gozd (upper left point,[lat,l	
0.5 0.5 c: dvxd dvzd (grid interval in lat and lo	
5000 c: nsrc*maxf	9行：内存相关
20.0 20.0 0.0 c: lambda1 lambda2 damp	
2 c: nsublayer (numbers of sublayers fo	11行：深度方向上次级节点
1.5 5.5 c: minimum velocity, maximum velocity)	12~13行：控制输出模型参数范围
0.85 1.15 c: minimum gamma, maximum gamma	
10 c: maxiter (iteration number)	
0.1 c: sparsity fraction	15行：内存相关
36 weight 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	

输入参数文件 (默认DRadiSurfTomo.in)

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32.5 90.50 c: goxd gozd (upper left point,[lat,lon]	
0.5 0.5 c: dvxd dvzd (grid interval in lat and lon)	
5000 c: nsrc*maxf	9行：内存相关
20.0 20.0 0.0 c: lambda1 lambda2 damp	
2 c: nsublayer (numbers of sublayers for each node)	11行：深度方向上次级节点
1.5 5.5 c: minimum velocity, maximum velocity	12~13行：控制输出模型参数范围
0.85 1.15 c: minimum gamma, maximum gamma	
10 c: maxiter (iteration number)	14行：线性反演迭代次数
0.1 c: sparsity fraction	15行：内存相关
36 weight 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 damp 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 min(max) vel c: kmaxLg (大)速度(反演)	
0 c: synthetic flag(0:real data,1:synthetic)	
0.02 maxiter c: noiselevel (反演)	
2.5 c: threshold	

输入参数文件 (默认DRadiSurfTomo.in)

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC  
C INPUT PARAMETERS  
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC  
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,l  
0.5 0.5 c: dvxd dvzd (grid interval in lat and lo  
5000 c: nsr*c*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 weight 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 damp 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 min(max) vel c: kmaxLg  
0 c: synthetic flag(0:real data,1:synthetic)  
0.02 noiselevel  
2.5 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)

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC  
c INPUT PARAMETERS  
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC  
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 d) [lat,lon,d]  
32.5 90.50 c: goxd gozd (upper left point,[lat,lon,d])  
0.5 0.5 c: dvxd dvzd (grid interval in lat and lon)  
5000 c: nsrc*maxf  
20.0 20.0 0.0 c: lambda1 lambda2 damp  
2 c: nsublayer (numbers of sublayers for each layer)  
1.5 5.5 c: minimum velocity, maximum velocity (km/sec)  
0.85 1.15 c: minimum gamma, maximum gamma  
10 c: maxiter (iteration number)  
0.1 c: sparsity fraction  
36 weight 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 damp 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 min(max) vel c: kmaxLg  
0 c: synthetic flag(0:real data,1:synthetic data)  
0.02 noiselevel  
2.5 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)

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC  
c INPUT PARAMETERS  
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC  
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,lon]  
0.5 0.5 c: dvxd dvzd (grid interval in lat and lon)  
5000 c: nsrc*maxf  
20.0 20.0 0.0 c: lambda1 lambda2 damp  
2 c: nsublayer (numbers of sublayers for  
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 weight 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 damp 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 min(max) vel c: kmaxLg  
0 c: synthetic flag(0:real data,1:synthetic)  
0.02 noiselevel  
2.5 threshold
```

前3行： 注释

4~5行: 数据文件名称

6~8行：模型位置 and 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

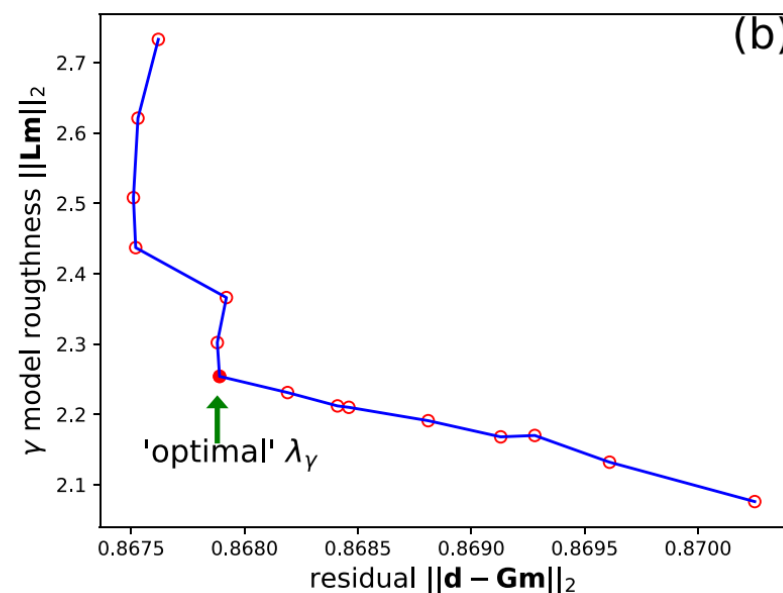
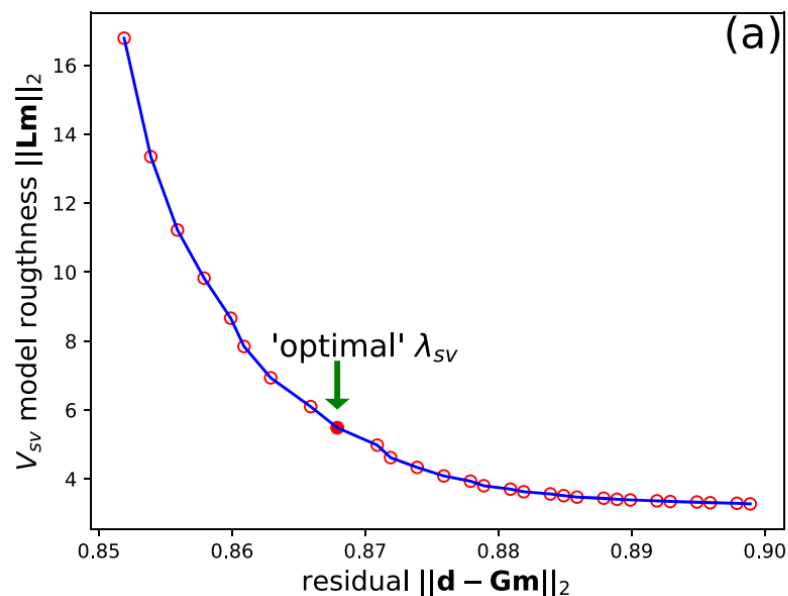
15行：内存相关

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*):
 - $e = residual + \lambda_1 * |Lm_{SV}|_2 + \lambda_2 * |Lm_\gamma|_2$
- 阻尼参数(*damp*):
 - $inv(M) \sim inv(M + damp * I)$



输入初始模型 (MOD.gam和MOD.Vsv)

```
0.0  5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0 60.0
70.0 80.0 90.0 100.0 120.0
```



depth(**nz**)

[illegible]

```
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