TUTORIAL

(1) Checklist of input parameters

All of the information below must be specified in the various input files used in VISCO1D.

Earth model

- Viscoelastic stratification: density ρ, bulk modulus κ, shear modulus μ, viscosity η, and long term strength μ' (equation 2 of *Manual*) as a function of radius
- Radius of Earth
- Depth range over which Greens functions will be stored
- Minimum and maximum spherical harmonic degree of deformation field expansion

Fault model

- Number of fault planes
- Strike, dip, rake, slip, length, depths of upper and lower fault edges, latitude and longitude of one fault corner

Observation

- Observation depth
- Number of observation points
- Latitude, longitude of these observation points
- Deformation option:
  (1) Displacement and strain
  (2) Velocity and strain rate
- Time interval with respect to earthquake origin time (start, end times for deformation option #1; single observation time for deformation option #2).

(2) Examples

Before running the examples, compile the needed programs using the Makefile (i.e., ’make all’)

Example 1

This example problem uses a layered Earth model (’earth.modelLP’) with a single viscoelastic layer between depth 16 and 30 km bounded above and below by purely elastic material. The viscoelastic stratification and the fault model are depicted in *Example 1. Figure 1.* It evaluates cumulative displacement and strain at Earth’s surface from the time of the earthquake to a time 5 years after the earthquake, at 54 GPS sites of Bürgmann et al. [1997]. The Marshall et al. [1991] two-plane model is used as the fault model. Viscoelastic relaxation (without gravitational effects) is calculated.

References

Bürgmann, R., P. Segall, M. Lisowski, and J. Svarc, Postseismic strain following the 1989 Loma Prieta earthquake from GPS and leveling measurements, *J. Geophys. Res., 102*, 4933-4955, 1997.

Marshall, G.A., R.S. Stein, and W. Thatcher, Faulting geometry and slip from co-seismic elevation changes: The October 17, 1989 Loma Prieta, California, earth-quake, *Bull. Seism. Soc. Am., 81*, 1660-1693, 1991.

To run this example, run the command file ’go.ex1’, which contains the lines

cp earth.modelLP earth.model	Line 1
nice decay<decay.inLP>/dev/null	Line 2
nice vtordep < dep10 >/dev/null	Line 3
nice decay4<decay.inLP>/dev/null	Line 4
nice vsphdep< dep10 >/dev/null	Line 5
nice strainx<strainx.inLP>/dev/null	Line 6
mv strainx.out strainx.outLP	Line 7

nice strainw<strainx.inLP>/dev/null Line 8

mv strainw.out strainw.outLP Line 9

mv decay.out decay.outLP Line 10

mv vtor.out vtor.outLP Line 11

mv decay4.out decay4.outLP Line 12

mv vsph.out vsph.outLP Line 13

This sequence of commands is typical for calculations of postseismic deformation. The tasks it accomplishes are:

Line 1. Get desired stratification model into 'earth.model'

Line 2. Determine characteristic inverse decay times s_j for toroidal modes (equation (39) of *Manual*).

Line 3. Determine toroidal mode eigenfunction y_1, its radial derivative $\partial_r y_1$, and the associated ε_j (equation (37) of *Manual*) in a form suitable for direct use in equations (32) of *Manual*, to determine the source excitation functions. A subset of this information is re-written at a specified depth level (10 km in this case, as specified in standard input file 'dep10') in order to supply eigenvalue information for use in equation (40) of *Manual*.

Line 4. Determine characteristic inverse decay times s_j for spheroidal modes (equation (24) of *Manual*) and multiplying factors of two independent displacement-stress vector solutions.

Line 5. Determine spheroidal mode eigenfunctions y_1 and y_3, their radial derivatives, and the associated ε_j (equation (21) of *Manual*) in a form suitable for direct use in equations (16) of *Manual*, to determine the source excitation functions. A subset of this information is re-written at a specified depth level (10 km in this case, as specified in standard input file 'dep10') in order to supply eigenvalue information for use in equation (25) of *Manual*.

Line 6. Calculate toroidal mode displacement vector and strain tensor at several observation points for a particular fault model, as specified in ’strainx.inLP’.

Line 7. Move the output file just created by STRAINX into so that it will not be written over by subsequent runs of STRAINX.

Line 8. Calculate spheroidal mode displacement vector and strain tensor at several observation points for a particular fault model, as specified in ’strainx.inLP’.

Line 9. Move the output file just created by STRAINW into so that it will not be written over by subsequent runs of STRAINW.

Lines 10-13. Move the output files created by DECAY, VTORDEP, DECAY4, and VSPHDEP into ’decay.outLP’, etc. so that the Greens functions contained in them can be used again at a later time.

Output files ’strainx.outLP’ and ’strainw.outLP’ will have the calculated deformation. Total deformation is the sum of the deformation which is represented in these two output files.

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Explanation of input files which appear in ’go.ex1’

A) ’earth.model’

47 3 1200.000 0.568

[47 layers, 3 is the specified number of viscoelastic layers. In fact, since we have only a viscoelastic lower crust, this should be a 1, but using a larger value just means that DECAY and DECAY4 will look for additional poles and not find any. Eigenfunctions are evaluated from the surface (depth 0) to depth 28*DEPFAC km, where here DEPFAC=0.568. I did this because I know that my faults will occupy only the top 16 km of the earth model in this example. In fact, you would not want to use a value of

DEPFAC greater than 0.568 because then some eigenfunctions would be evaluated in viscoelastic material (which exists from 16 to 30 km depth), and then subsequent spline interpolations in ’strainx’ and ’strainw’ could behave wildly because the eigen-functions can vary sharply in viscoelastic material itself. This is OK because we assume in any case that the fault is embedded in purely elastic material. The radius of the earth is specified at 1200 km. This is an excellent approximation if only local deformation (within ~150 km of source region) is desired, and it speeds things up a lot compared with using 6371 km for the radius.]

5284.400 5319.100 4.587 15.000 7.000 0.100000E+13

[bottom radius of layer=5284 km, top radius of layer=5319.1 km, density=4.587 g-cm^{-3}, bulk modulus=15 $\times$ 10^{10} Pa, shear modulus=7 $\times$ 10^{10} Pa, viscosity=(0.1E+13) $\times$ 10^{18} Pa s (this is so high that for all practical purposes this layer is purely elastic. DECAY and DECAY4 will not find any relaxation times associated with such a high viscosity]

5319.100	5353.700	4.567	15.000	7.000	0.100000E+13
5353.700	5388.300	4.552	15.000	7.000	0.100000E+13
5388.300	5422.900	4.542	15.000	7.000	0.100000E+13
5422.900	5457.600	4.537	15.000	7.000	0.100000E+13
5457.600	5492.200	4.537	15.000	7.000	0.100000E+13
5492.200	5526.800	4.535	15.000	7.000	0.100000E+13
5526.800	5561.500	4.511	15.000	7.000	0.100000E+13
5561.500	5596.100	4.468	15.000	7.000	0.100000E+13
5596.100	5630.700	4.403	15.000	7.000	0.100000E+13
5630.700	5665.400	4.319	15.000	7.000	0.100000E+13
5665.400	5700.000	4.208	15.000	7.000	0.100000E+13
5700.000	5731.300	4.106	15.000	7.000	0.100000E+13

5731.300	5762.500	4.025	15.000	7.000	0.100000E+13
5762.500	5793.800	3.961	15.000	7.000	0.100000E+13
5793.800	5825.000	3.903	15.000	7.000	0.100000E+13
5825.000	5856.300	3.850	15.000	7.000	0.100000E+13
5856.300	5887.500	3.805	15.000	7.000	0.100000E+13
5887.500	5918.700	3.764	15.000	7.000	0.100000E+13
5918.700	5950.000	3.712	15.000	7.000	0.100000E+13
5950.000	5975.600	3.657	15.000	7.000	0.100000E+13
5975.600	6001.200	3.600	15.000	7.000	0.100000E+13
6001.200	6026.900	3.551	15.000	7.000	0.100000E+13
6026.900	6052.500	3.509	15.000	7.000	0.100000E+13
6052.500	6078.100	3.473	15.000	7.000	0.100000E+13
6078.100	6103.800	3.443	15.000	7.000	0.100000E+13
6103.800	6129.400	3.419	15.000	7.000	0.100000E+13
6129.400	6155.000	3.402	15.000	7.000	0.100000E+13
6155.000	6180.600	3.393	15.000	7.000	0.100000E+13
6180.600	6206.300	3.387	15.000	7.000	0.100000E+13
6206.300	6231.900	3.379	15.000	7.000	0.100000E+13
6231.900	6257.500	3.372	15.000	7.000	0.100000E+13
6257.500	6283.100	3.365	15.000	7.000	0.100000E+13
6283.100	6308.800	3.358	15.000	7.000	0.100000E+13
6308.800	6334.400	3.351	15.000	7.000	0.100000E+13
6334.400	6341.000	3.384	15.000	7.000	0.100000E+13
6341.000	6345.000	3.384	9.510	5.271	3.000000E+00
6345.000	6351.000	3.384	9.510	5.271	3.000000E+00
6351.000	6355.000	3.190	9.510	5.271	3.000000E+00

[bottom radius of layer=6351 km, top radius of layer=6355 km, density=3.190 g-cm^{-3}, bulk modulus=9.51 $\times 10^{10}$ Pa, shear modulus=5.271 $\times 10^{10}$ Pa, viscosity= 3×10^{18} Pa s]

6355.000	6357.000	3.190	7.360	4.080	0.100000E+12
6357.000	6359.000	3.190	7.360	4.080	0.100000E+12
6359.000	6361.000	3.030	7.360	4.080	0.100000E+12
6361.000	6363.000	3.030	7.360	4.080	0.100000E+12
6363.000	6365.000	3.030	7.360	4.080	0.100000E+12
6365.000	6367.000	3.030	7.360	4.080	0.100000E+12
6367.000	6369.000	2.800	6.500	3.600	0.100000E+12
6369.000	6371.000	2.800	6.500	3.600	0.100000E+12

B) 'decay.inLP'

2 475

[minimum and maximum degree of spherical harmonic expansion of def. field. Higher spherical harmonic degrees are strongly attenuated by the 16-km-thick upper elastic plate, which acts as a low bandpass filter. A rule of thumb which I always use is $l_{max} \sim 2 \pi R / H_e$. With Earth radius R=1200 km and upper elastic plate thickness H_e=16 km we get l_{max}=471, close to what appears above. Put another way, I take advantage of the fact that there is very little signal at wavelengths shorter than 16 km.]

C) 'strainx.inLP'

12.45 4.50 62.

[maximum fault depth=12.45 km, minimum fault depth=4.50 km, dip of fault plane(s)=62 deg. These fault parameters are assumed the same for every fault which is used in one input file. So if you have two or more faults which do not share exactly the same max fault depth / min fault depth / dip, you would need to split things up into two or more separate input files]

1989.88 1989.88 1994.88 1.

[t0; t1 , t2 , VMULT. t0=1989.88 is the origin time of the earthquake. If ISRATE (the second-to-last line of this input file) = 0, then we evaluate cumulative postseismic displacement and strain from time t1 to time t2 from an earthquake occurring at time t0. If ISRATE = 1, then we evaluate velocity and strain rate at time 0.5*(t1+t2) from an earthquake occurring at time t0. In this example, we will get the cumulative displacement and strains for the first 5 years following the Loma Prieta earthquake. VMULT is used if you want to scale all viscosities in the earth model up or down by a constant factor. The current 'earth.modelLP' has viscosity from 16 to 30 km depth $= 3 \times 10^{18}$ Pa s. After the decay times and eigenfunctions have been calculated for this model, if you decide you want to have the deformation with viscosity 6×10^{18} Pa s then use VMULT=2.0. If we want to keep viscosity=3×10^{18} Pa s then use VMULT=1.0, as in this input file. This option allows you to change viscosity without having to recompute the decay times and eigenfunctions all over again.]

2

[2 fault planes with additional parameters given below]

36.928 -121.715 18.5 128. 163.0 210.

[Fault plane #1: (lat,lon) of corner on lower fault edge closest to strike direction; fault length=18.5 km, strike=N128deg.E, rake=163 deg. (combined reverse and right lateral slip), slip=210 cm. Thus (36.928,-121.715) is the lat,lon of the SE corner of the lower fault edge at 12.45 km depth.]

37.031 -121.879 18.5 128. 116.0 210.

[Fault plane #2: explanation similar to fault plane #1. This fault plane connects with fault plane #1 and is the NW continuation of it.]

54

[54 observation points as listed below]

37.10958 -121.845

36.94974 -122.052

36.98226 -121.924

37.04693 -121.938

37.06898 -121.809

37.05006 -121.839

37.10393 -121.909

37.18637 -121.783

37.13713 -121.787

37.21923 -121.738

37.47732 -121.556

37.5083 -121.375

36.58977 -121.773

37.14693 -122.195

37.49892 -121.871

37.18302 -122.395

37.22838 -122.359

37.27371 -122.284

37.31227 -122.216

37.34173 -121.643

37.29016 -122.153

37.36268 -122.123

37.42633 -122.035

37.50671 -121.919

37.75531 -121.566

37.62181 -121.703

37.594 -121.81

37.5413 -121.87

37.69424 -121.675

38.33972 -120.721

36.97977 -121.616

37.11101 -121.844

37.18521 -121.996

37.22893 -121.714

37.18378 -121.706

37.00421 -121.92

37.20571 -121.977

37.0586 -121.994

37.21704 -122.023

36.94609 -121.874

37.28768 -121.866

37.07308 -121.961

36.978 -122.056

37.2472 -121.966

37.0116 -121.833

36.87902 -121.754

37.11029 -121.947

36.99279 -122.052

36.58937 -121.772

37.09934 -122.059

37.16687 -121.926

37.18033 -121.973

37.48012 -121.949

37.58829 -121.385

0

[ISRATE (see explanation above)]

0

[IOBS. If IOBS=0 then surface deformation is evaluated. If IOBS=1 then deformation is at specified depth (that used as input to VTORDEP and VSPHDEP). Thus you could evaluate things at 10 km instead of 0 km depth, at the same 54 observation lat,lon's, by changing this line to a 1]

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Explanation of output files generated by 'go.ex1'

The output file from DECAY and DECAY4 are 'decay.outLP' and 'decay4.outLP', respectively. These contain pairs (l, s_j) for toroidal and spheroidal motion, respectively. These are plotted in *Example 1. Figure 2*. With this viscoelastic structure there are 6 distinct spheroidal mode branches and 2 distinct toroidal mode branches. (This is predicted by equations (46) and (48) of *Manual*, with $M_1 = 2$ and $M_2 = 1$.)

The output file from STRAINX is 'strainx.out', and the output file from STRAINW is 'strainw.out'. (these are moved into 'strainx.outLP' and 'strainw.outLP' by 'go.ex1')

Both 'strainx.outLP' and 'strainw.outLP' will have 54 lines of output each, corresponding to deformation at the 54 observation points in the order in which they appear in ’strainx.inLP’.

A single line of ’strainx.out’ looks like

8.796 5.762 0.307052E+01-0.585062E+00

0.980001E-01-0.980001E-01 0.407049E+00 0.311147E-07-0.363551E-06

[(8.796 , 5.762) are approximations to the Cartesian coordinates of the observation point with respect to a reference point (the (lat,lon) associated with the 1st fault plane corner). 0.307052E+01 -0.585062E+00 are x-displacement u_x and y-displacement u_y in units of cm, where x=local East direction, y=local North direction. Then follow the 5 nontrivial strain components e_{xx}, e_{yy}, e_{xy}, e_{xz}, and e_{yz} in units of 10^{-6}, where z is the local up direction.]

A single line of ’strainw.out’ looks like

8.796 5.763-0.628114E+00-0.403800E-01-0.946508E-01

-0.569254E+00-0.929759E+00-0.990470E-01-0.812605E-08-0.256081E-08

0.543899E+00

[Here, -0.628114E+00 -0.403800E-01 -0.946508E-01 are the x-displacement u_x, y-displacement u_y, and z-displacement u_z, followed by the 6 nontrivial strain components e_{xx}, e_{yy}, e_{xy}, e_{xz}, e_{yz}, and e_{zz}.]

Note that if we had used ISRATE=1 instead of ISRATE=0, then the output would contain velocities in units of cm/yr and strain rates in units of 10^{-6}/yr.

Total deformation is a sum of the deformation in ’strainx.out’ and total e_{xx} is 0.098 + (-0.569) = -0.471 * 10^{-6}, etc.

Spheroidal and toroidal motion horizontal displacement fields are plotted in *Example 1. Figure 3*. The total horizontal displacement field (summed spheroidal and toroidal displacement fields) is plotted in *Example 1. Figure 4*. The deformation is tabulated for observation point #31 of the input file 'strainx.inLP'.

A useful test that the programs are working correctly is that surface strain components e_{xz} and e_{yz} are several orders of magnitude smaller than other strain components (they should be because of stress-free boundary conditions at the surface). e_{zz} is not necessarily zero at the surface!

Example 2

In this example, we repeat Example 1 but calculate deformation according to viscoelastic-gravitational relaxation. Since gravitational effects are manifested only for the spheroidal modes, I omit the toroidal mode part of the calculation, which was done already in Example 1.

To run this example, run the command file 'go.ex2', which contains the lines

```
cp earth.modelLP earth.model                  Line 1
nice decay4m<decay.inLP>/dev/null             Line 2
nice decay4g>/dev/null                        Line 3
nice vsphg< dep10 >/dev/null                  Line 4

nice strainw<strainx.inLP>/dev/null           Line 5
mv strainw.out strainw.outLPg                 Line 6

mv decay4.out decay4.outLPg                   Line 7
mv vsph.out vsph.outLPg                       Line 8
```

This command file accomplishes the same tasks as in Example 1, with differences indicated below.

Line 1. Copy same viscoelastic stratification as in Example 1 onto 'earth.model', except that Earth's radius is now prescribed to be 6371 km. This value (contained in the first line of 'earth.modelLPg') must be used when running the gravitational programs.

Line 2. Determine characteristic inverse decay times s_j for spheroidal modes (equation (24) of *Manual*) with gravitational effects included.

Line 3. Determine corressponding multiplying factors of two independent displacement-stress vector solutions.

Line 4. With program VSPHG, determine spheroidal mode eigenfunctions y_1 and y_3, their radial derivatives, and the associated ε_j just as with VSPH, but with gravitational effects included.

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Explanation of input files which appear in 'go.ex2'

A) 'earth.modelLPg'

This is identical to 'earth.modelLP' of Example 1 except that Earth radius is specified as 6371 km instead of 1200 km:

47 3 6371.000 0.568

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Explanation of output files generated by 'go.ex2'

The output file from DECAY4G is 'decay4.outLPg'. This contains pairs (l, s_j) for spheroidal motion. Corresponding dispersion for toroidal modes was not calculated because it is not affected by the inclusion of gravitational terms, so 'decay4.outLP' is still the dispersion file for toroidal motion. These are plotted in *Example 2. Figure 1*. Comparison with the non-gravitational case in *Example 1. Figure 2* shows little difference except for somewhat faster relaxation times in the gravitational case for the slowest mode branch at wavelengths $>\sim 10^{2.2}$ km.

The output file from STRAINX is ’strainx.out’, and the output file from STRAINW is ’strainw.out’. (these are moved into ’strainx.outLPg’ and ’strainw.outLPg’ by ’go.ex2’)

Both ’strainx.outLPg’ and ’strainw.outLPg’ will have 54 lines of output each, corresponding to deformation at the 54 observation points in the order in which they appear in ’strainx.inLP’.

Spheroidal and toroidal motion horizontal displacement fields are plotted in *Example 2. Figure 2*. The total horizontal displacement field (summed spheroidal and toroidal displacement fields) is plotted in *Example 2. Figure 3*. The deformation is tabulated for observation point #31 of the input file ’strainx.inLP’. It is clear from a comparison with the corresponding Example 1-figures that deformation differs very little from the non-gravitational case.

Example 3

In this example, we repeat Example 1 but calculate the velocity and strain rate field from the 1989 Loma Prieta earthquake evaluated in September, 1999, i.e. nearly 10 years after the earthquake. Following Example 1, we will calculate the non-gravitational deformation field. Since we have already calculated the Greens functions for this case (i.e., for ’earth.modelLP’), we can make use of them and only need to modify two lines of the input file to STRAINX and STRAINW.

To run this example, run the command file ’go.ex3’, which contains the lines

```
#cp earth.modelLP earth.model                         Line 1
#nice decay<decay.inLP>/dev/null                      Line 2
```

```
#nice vtordep < dep10 >/dev/null              Line 3
#nice decay4<decay.inLP>/dev/null             Line 4
#nice vsphdep< dep10 >/dev/null               Line 5

rm decay.out vtor.out decay4.out vsph.out     Line 6
cp decay.outLP decay.out                      Line 7
cp vtor.outLP vtor.out                        Line 8
cp decay4.outLP decay4.out                    Line 9
cp vsph.outLP vsph.out                        Line 10

nice strainx<strainx.inLPa>/dev/null          Line 11
mv strainx.out strainx.outLPa                 Line 12
nice strainw<strainx.inLPa>/dev/null          Line 13
mv strainw.out strainw.outLPa                 Line 14

#mv decay.out decay.outLP                     Line 15
#mv vtor.out vtor.outLP                       Line 16
#mv decay4.out decay4.outLP                   Line 17
#mv vsph.out vsph.outLP                       Line 18
```

This command file accomplishes the same tasks as in Example 1, with differences indicated below.

Lines 1-5. We make use of the characteristic inverse decay times and Greens functions calculated previously in Example 1. So we comment out/omit the lines the which calculate them.

Lines 6-10. Copy Greens function files obtained from Example 1 onto the appropriate filenames to prepare for running STRAINX and STRAINW on the same earth model ('earth.modelLP' in Example 1).

Lines 11-14. Run STRAINX and STRAINW using input file strainx.inLPa

Output files ’strainx.outLPa’ and ’strainw.outLPa’ will have the calculated deformation. Total deformation is the sum of the deformation which is represented in these two output files.

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Explanation of input files which appear in ’go.ex3’

A) ’strainx.inLPa’

This file is identical to ’strainx.inLP’ except for two lines. The first different line is

1989.79 1999.70 1999.70 1.

[when combined with ISRATE=1 below, this means calculate the postseismic velocity and strain rate fields in 1999.70 from the specified event which occurred in 1989.79]

The last four lines of the input file are

 37.48012 -121.949

 37.58829 -121.385

[points #53 and 54 where deformation is to be calculated]

1

[ISRATE=1 means calculate velocity and strain rate fields at the time indicated above]

0

[IOBS=0, so calculate surface deformation again, as in Example 1]

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Explanation of output files generated by ’go.ex3’

Both ’strainx.outLPa’ and ’strainw.outLPa’ will have 54 lines of output each, corresponding to deformation at the 54 observation points in the order in which they appear in ’strainx.inLPa’.

Dispersion curves for ’earth.modelLP’ are already plotted in *Example 1. Figure 1*. Spheroidal and toroidal motion horizontal displacement fields are plotted in *Example 3. Figure 1*. The total horizontal displacement field (summed spheroidal and toroidal displacement fields) is plotted in *Example 3. Figure 2*. The deformation is tabulated for observation point #31 of the input file ’strainx.inLPa’. Note that the units of deformation are cm/yr for velocity components and $10^{-6}/yr$ for strain rate components.

Example 4

In this example, we repeat Example 3 but calculate deformation at 10 km depth. To put this another way, we repeat Example 1 but calculate the velocity and strain rate field from the 1989 Loma Prieta earthquake evaluated in September, 1999, i.e. nearly 10 years after the earthquake, and we evaluate deformation at 10 km depth. Following Example 1, we will calculate the non-gravitational deformation field. Since we have already calculated the Greens functions for this case (i.e., for ’earth.modelLP’), we can make use of them and only need to modify three lines of the input file to STRAINX and STRAINW.

To run this example, run the command file ’go.ex4’, which contains the lines

```
#cp earth.modelLP earth.model                  Line 1
#nice decay<decay.inLP>/dev/null               Line 2
#nice vtordep < dep10 >/dev/null               Line 3
#nice decay4<decay.inLP>/dev/null              Line 4
#nice vsphdep< dep10 >/dev/null                Line 5

rm decay.out vtor.out decay4.out vsph.out      Line 6
cp decay.outLP decay.out                       Line 7
```

```
cp vtor.outLP vtor.out                      Line 8
cp decay4.outLP decay4.out                  Line 9
cp vsph.outLP vsph.out                      Line 10

nice strainx<strainx.inLPb>/dev/null        Line 11
mv strainx.out strainx.outLPb               Line 12
nice strainw<strainx.inLPb>/dev/null        Line 13
mv strainw.out strainw.outLPb               Line 14

#mv decay.out decay.outLP                   Line 15
#mv vtor.out vtor.outLP                     Line 16
#mv decay4.out decay4.outLP                 Line 17
#mv vsph.out vsph.outLP                     Line 18
```

This command file accomplishes the same tasks as in Example 1, with differences indicated below.

Lines 1-5. We make use of the characteristic inverse decay times and Greens functions calculated previously in Example 1. So we comment out/omit the lines the which calculate them.

Lines 6-10. Copy Greens function files obtained from Example 1 onto the appropriate filenames to prepare for running STRAINX and STRAINW on the same earth model ('earth.modelLP' in Example 1).

Lines 11-14. Run STRAINX and STRAINW using input file strainx.inLPb.

Output files 'strainx.outLPb' and 'strainw.outLPb' will have the calculated deformation. Total deformation is the sum of the deformation which is represented in these two output files.

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```

Explanation of input files which appear in ’go.ex4’

A) ’strainx.inLPb’

This file is identical to ’strainx.inLP’ except for two lines. The first different line is

1989.79 1999.70 1999.70 1.

[when combined with ISRATE=1 below, this means calculate the postseismic velocity and strain rate fields in 1999.70 from the specified event which occurred in 1989.79]

The last four lines of the input file are

37.48012 -121.949

37.58829 -121.385

[points #53 and 54 where deformation is to be calculated]

1

[ISRATE=1 means calculate velocity and strain rate fields at the time indicated above]

1

[IOBS=1, so calculate deformation at depth 10 km, as specified in the input file ’dep10’ used when running VTORDEP and VSPHDEP in Example 1]

\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\

Explanation of output files generated by ’go.ex4’

Both ’strainx.outLPb’ and ’strainw.outLPb’ will have 54 lines of output each, corresponding to deformation at the 54 observation points in the order in which they appear in ’strainx.inLPb’.

Dispersion curves for ’earth.modelLP’ are already plotted in *Example 1. Figure 1*. Spheroidal and toroidal motion horizontal displacement fields are plotted in *Example 4*.

Figure 1. The total horizontal displacement field (summed spheroidal and toroidal displacement fields) is plotted in *Example 4. Figure 2*. The deformation is tabulated for observation point #31 of the input file 'strainx.inLPb'. Note that the units of deformation are cm/yr for velocity components and $10^{-6}/yr$ for strain rate components.

Note that, because deformation is evaluated at 10 km depth, the strain components e_{xz} and e_{yz} are now of comparable magnitude to the other strain components (at the surface they were calculated to be practically zero in previous Examples).

Example 5

This example problem uses a layered Earth model with three distinct viscoelastic layers ('earth.modelLAN') below depth 16 km (*Example 5. Figure 1*). This earth model is considered representative of the central Mojave Desert based on modeling of post-Landers geodetic observations (Pollitz et al., 1999) It evaluates surface cumulative displacement and strain during the time interval 10 – 20 years after a synthetic rifting event at 400 points covering a $2^\circ \times 2^\circ$ area at an observation depth of 4 km.

References

Pollitz, F.F., G. Peltzer, and R. Bürgmann, Mobility of continental mantle: Evidence from postseismic geodetic observations following the 1992 Landers earthquake, *J. Geophys. Res.*, submitted, 1999.

To run this example, run the command file 'go.ex1', which contains the lines

cp earth.modelLAN earth.model	Line 1
nice decay<decay.inLAN>/dev/null	Line 2
nice vtordep < dep04 >/dev/null	Line 3
nice decay4<decay.inLP>/dev/null	Line 4
nice vsphdep< dep04 >/dev/null	Line 5

nice strainx<strainx.inLAN>/dev/null	Line 6
mv strainx.out strainx.outLAN	Line 7
nice strainw<strainx.inLAN>/dev/null	Line 8
mv strainw.out strainw.outLAN	Line 9
mv decay.out decay.outLAN	Line 10
mv vtor.out vtor.outLAN	Line 11
mv decay4.out decay4.outLAN	Line 12
mv vsph.out vsph.outLAN	Line 13

This command file has the same structure as the command file used in Example 1, but uses a different earth model, different limits for the spherical harmonics, a different fault geometry, and different observation points.

Lines 6, 8. Unlike Examples 1-4, which worked with dipping fault planes, this Example uses a vertical fault plane, and thus nmesh1=2 was specifed in the source code of both STRAINX and STRAINW. As remarked in comment #4 of section 4 of the *Manual*, STRAINX and STRAINW are speeded up considerably by using nmesh1=2 when possible.

\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\

Explanation of input files which appear in 'go.ex5'

A) 'earth.model'

43 3 1500.000 0.568

[43 layers, earth's radius=1500 km, eigenfunctions determined from surface down to 28×0.568 = 16 km]

5492.200 5526.800 4.535 15.000 7.000 0.000 0.440000E+00

6308.800	6321.000	3.351	15.000	7.000	0.000	0.440000E+00

[the mantle below 50 km depth has $\mu' = 0$ (equation (2) of *Manual*) and viscosity $\eta_{m\,2} = 4.4 \times 10^{17}$ Pa s (*Example 5. Figure 1*). Note that in Examples 1–4, μ' was not specified in 'earth.model', and a default value of zero was automatically used]

6321.000	6328.000	3.351	15.000	7.000	0.000	3.500000E+00
6328.000	6334.400	3.351	15.000	7.000	0.000	3.500000E+00
6334.400	6339.000	3.351	15.000	7.000	0.000	3.500000E+00

[the mantle between depth 32 and 50 km has $\mu' = 0$ and viscosity $\eta_{m\,1} = 3.5 \times 10^{18}$ Pa s]

6339.000	6345.000	3.190	9.510	5.270	2.400	9.630000E+00
6345.000	6351.000	3.190	9.510	5.270	2.400	9.630000E+00
6351.000	6355.000	3.190	9.510	5.270	2.400	9.630000E+00

[the lower crust between depth 16 and 32 km has $\mu' = 2.4 \times 10^{10}$ Pa, $\eta_c = 9.63 \times 10^{18}$ Pa s]

6355.000	6357.000	3.190	7.360	4.080	0.000	0.100000E+12
6357.000	6359.000	3.190	7.360	4.080	0.000	0.100000E+12
6359.000	6361.000	3.030	7.360	4.080	0.000	0.100000E+12
6361.000	6363.000	3.030	7.360	4.080	0.000	0.100000E+12
6363.000	6365.000	3.030	7.360	4.080	0.000	0.100000E+12
6365.000	6367.000	3.030	7.360	4.080	0.000	0.100000E+12

6367.000 6369.000 2.800 6.500 3.600 0.000 0.100000E+12

6369.000 6371.000 2.800 6.500 3.600 0.000 0.100000E+12

[last 8 lines specify elastic parameters for purely elastic upper crust]

B) ’decay.inLAN’

2 590

[minimum and maximum degree of spherical harmonic expansion of def. field. It was chosen such that $l_{max} \sim 2*\pi*1500\ \mathrm{km}/(16\mathrm{km})$]

C) ’strainx.inLAN’

15.99 8.0 90.

[maximum fault depth=15.99 km, minimum fault depth=8.0 km, dip of fault plane(s)=90 deg.]

1989.88 1989.88 1994.88 1. 1975. 1985. 1995. 1.

[combined with ISRATE=0 as specified below, evaluate cumulative postseismic displacement and strain field over the period 1985 to 1995 due to the seismic event which occurred in 1975]

1

[2 fault planes with additional parameters given below]

0.899361 0.000000 200. 0. 190. 500.
36.928 -121.715 18.5 128. 163.0 210.

[Fault plane #1: lat=0.899361° N, lon=0° E are the coordinates of the lowermost corner of the fault plane closest to the specified strike direction of N0E. With fault length = 200 km, this corresponds to a north-striking fault extending from lat=+0.899361˚ N to lat=-0.899361˚ N along the arc lon=0˚ E. Rake is specifed as 190 deg. According to the conventions of STRAINX and STRAINW, when rake > 181 deg., then the source is no longer a shear dislocation but rather a rift (tensile opening) along the specified fault plane with the given magnitude (here 210 cm). When rake < -181 deg., then those programs will prescribe the opposite of a rifr -- a crack closing of the given magnitude]

400

[400 points filling up a 2˚ × 2˚ area centered on lat=0˚ N, lon=0˚ E]

```
 -2.000000   -2.000000
  2.000000    2.000000
```

[1st and 400th observation points, with 398 observation points in between]

0

[ISRATE=0, so evaluate displacement and strain fields]

1

[IOBS=1, so calculate deformation at depth 4 km, as specified in the input file ’dep04’ used when running VTORDEP and VSPHDEP in **Lines 3** and **5** of ’go.ex5’]

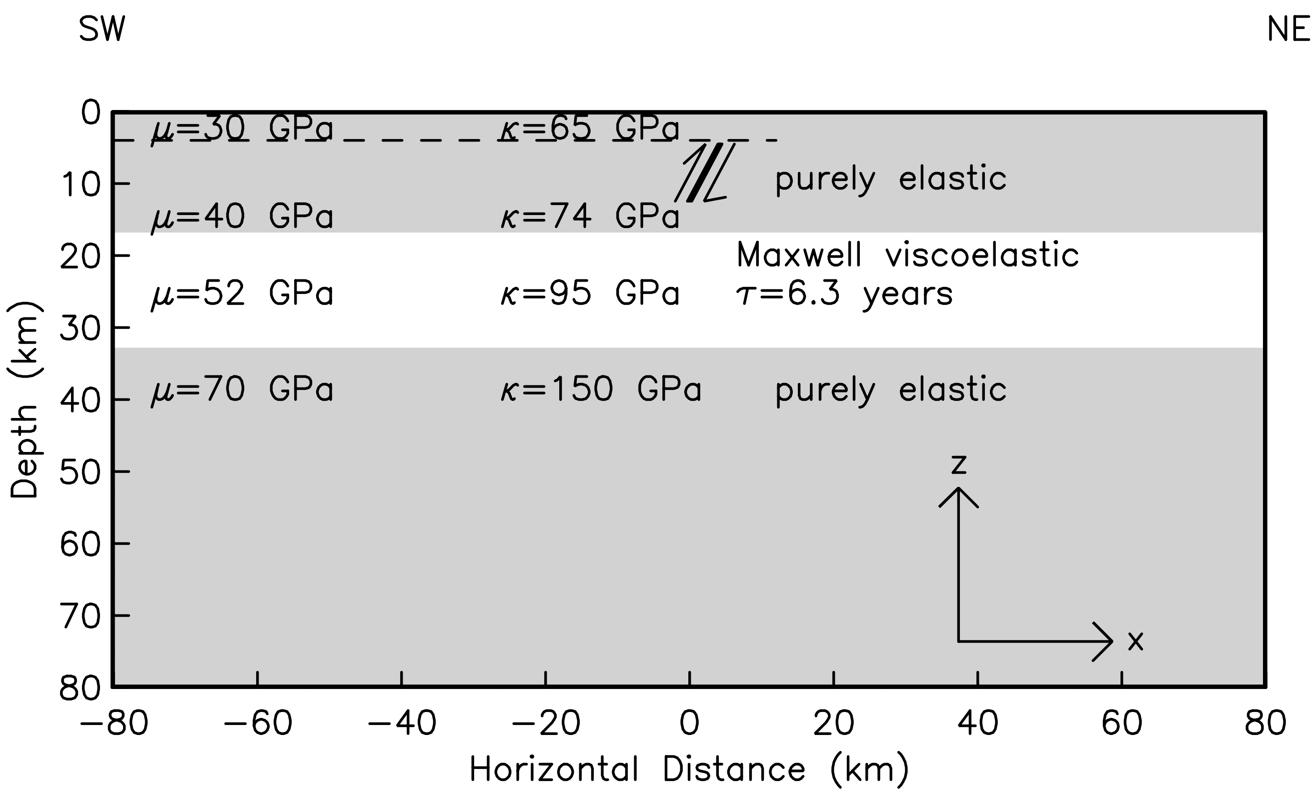
Explanation of output files generated by ’go.ex5’

Both ’strainx.outLAN’ and ’strainw.outLAN’ will have 400 lines of output each, corresponding to deformation at the 400 observation points in the order in which they appear in ’strainx.inLAN’.

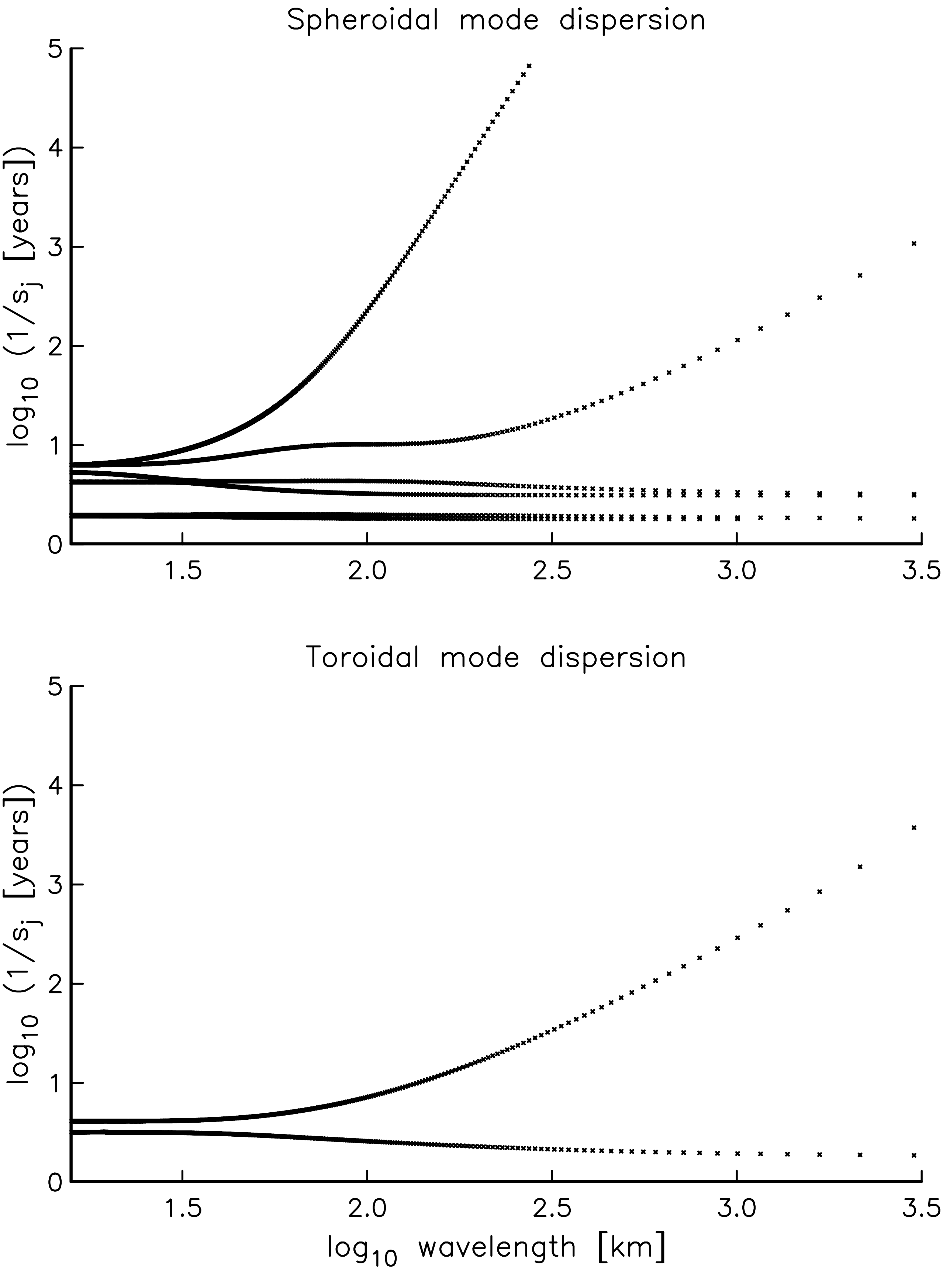
Dispersion curves for ’earth.modelLAN’ are plotted in *Example 5. Figure 2*. With this viscoelastic structure there are 13 distinct spheroidal mode branches and 4 distinct toroidal mode branches. (This is predicted by equations (47) and (49) of *Manual*, with $M_1 = 1$, $M_2 = 3$, $M_3 = 1$, and $M_4 = 1$.) Spheroidal and toroidal motion horizontal displacement fields are plotted in *Example 5. Figure 3*. The total horizontal displacement field (summed spheroidal and toroidal displacement fields) is plotted in *Example 5. Figure 4*.

EXAMPLE 1. Figure 1

Viscoelastic stratification and faulting geometry for calculation of postseismic displacements following the 1989 Loma Prieta earthquake.



EXAMPLE 1. Figure 2



EXAMPLE 1. Figure 3

Spheroidal motion deformation of point #31

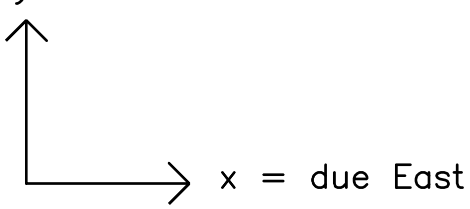
8.796 5.763 -0.628114E+00 -0.403800E-01 -0.946508E-01 -0.569254E+00
-0.929759E+00 -0.990470E-01 -0.812605E-08 -0.256081E-08 0.543899E+00

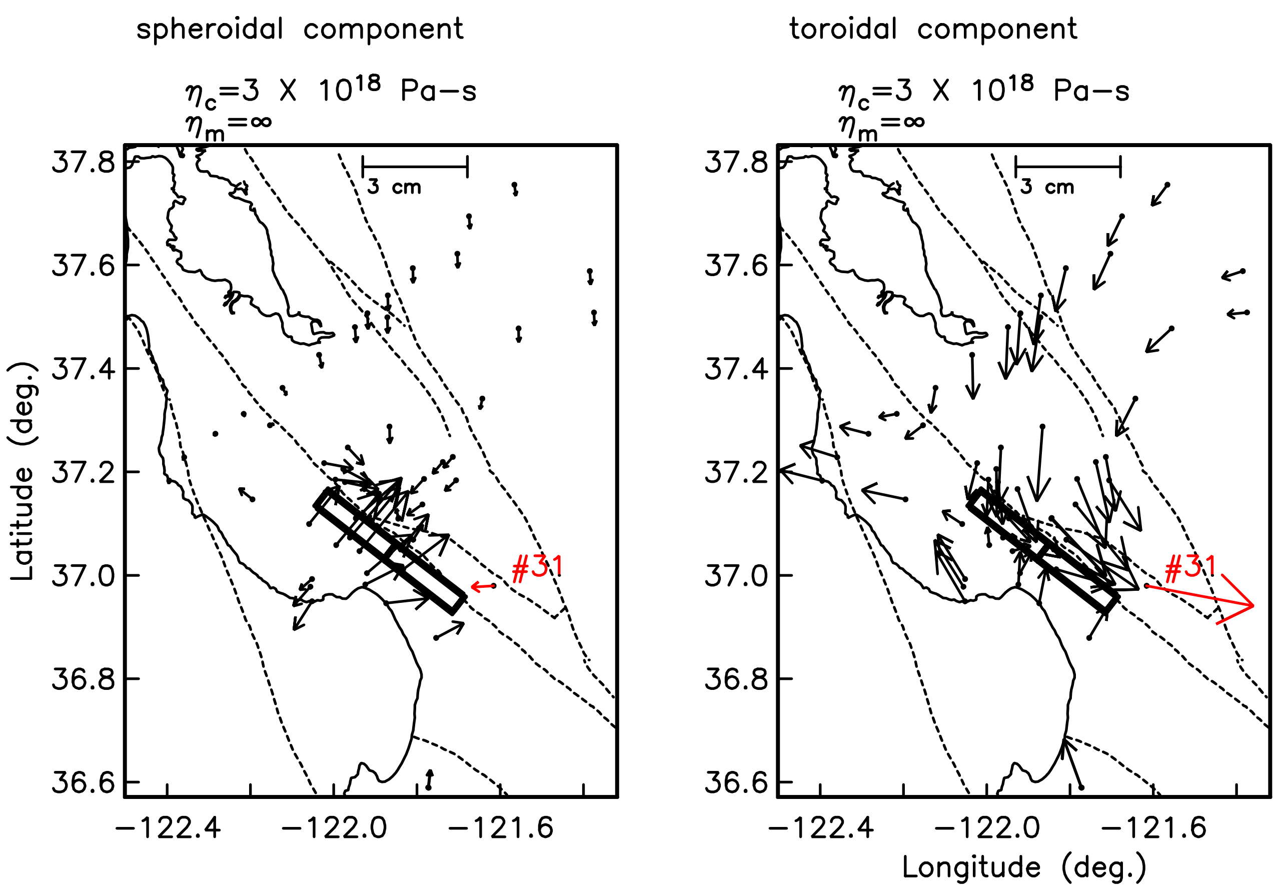
x_{31}(km) y_{31}(km) u_x(cm) u_y(cm) u_z(cm) $e_{xx}(10^{-6})$
$e_{yy}(10^{-6})$ $e_{xy}(10^{-6})$ $e_{xz}(10^{-6})$ $e_{yz}(10^{-6})$ $e_{zz}(10^{-6})$

Toroidal motion deformation of point #31

8.796 5.762 0.307052E+01 -0.585062E+00 0.980001E-01 -0.980001E-01
0.407049E+00 0.311147E-07-0.363551E-06

x_{31}(km) y_{31}(km) u_x(cm) u_y(cm) $e_{xx}(10^{-6})$ $e_{yy}(10^{-6})$
$e_{xy}(10^{-6})$ $e_{xz}(10^{-6})$ $e_{yz}(10^{-6})$



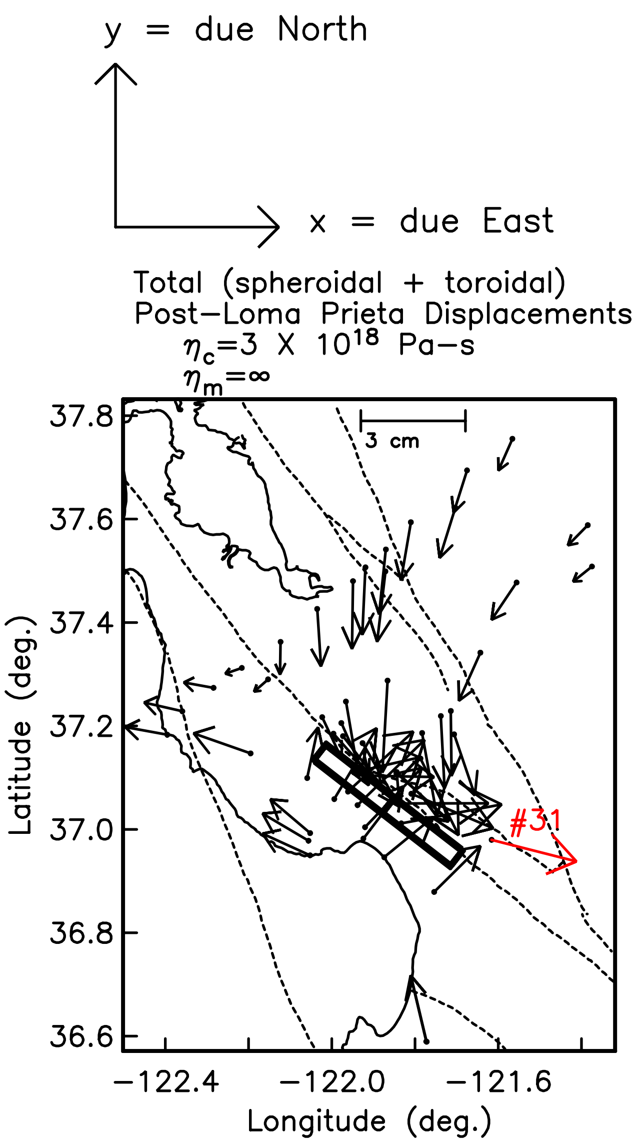


EXAMPLE 1.   Figure 4

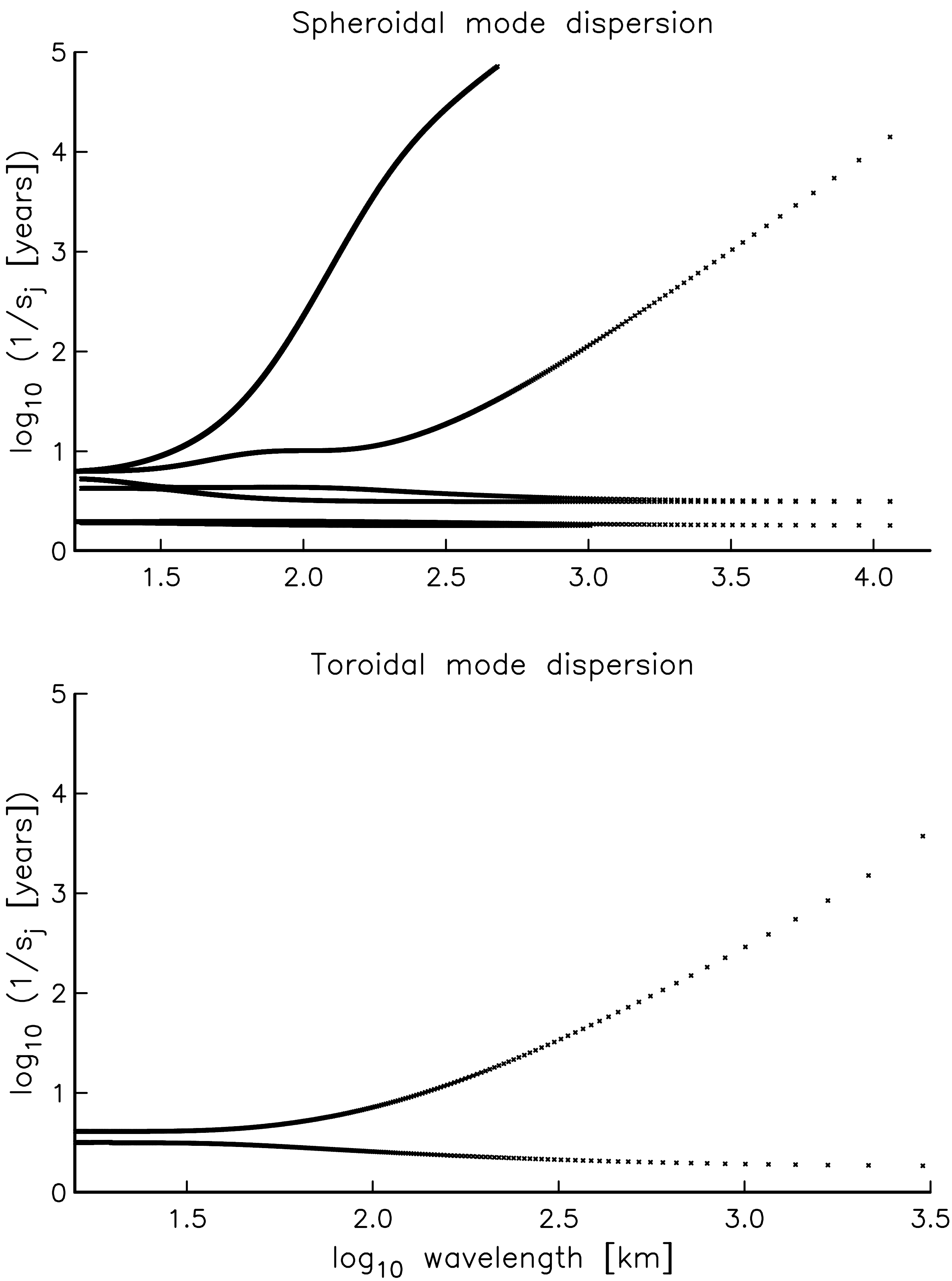
Total (spheroidal + toroidal) motion deformation of point #31

8.796 5.763 0.244241E+01 -0.625442E+00 -0.946508E-01 -0.471254E+00
-0.102776E+01 0.308002E+00 0.229886E-07 -0.366112E-06 0.543899E+00

x_{31}(km) y_{31}(km) u_x(cm) u_y(cm) u_z(cm) $e_{xx}(10^{-6})$
$e_{yy}(10^{-6})$ $e_{xy}(10^{-6})$ $e_{xz}(10^{-6})$ $e_{yz}(10^{-6})$ $e_{zz}(10^{-6})$



EXAMPLE 2. Figure 1



EXAMPLE 2. Figure 2

Spheroidal motion deformation of point #31

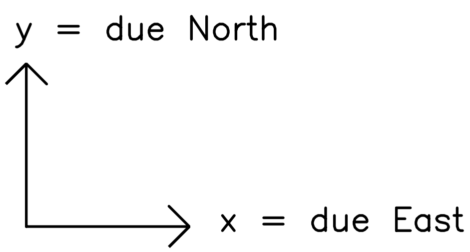
8.796 5.763 -0.616663E+00 -0.390487E-01 -0.143094E+00 -0.581457E+00
-0.948081E+00 -0.953838E-01 -0.445124E-08 -0.288863E-08 0.554959E+00

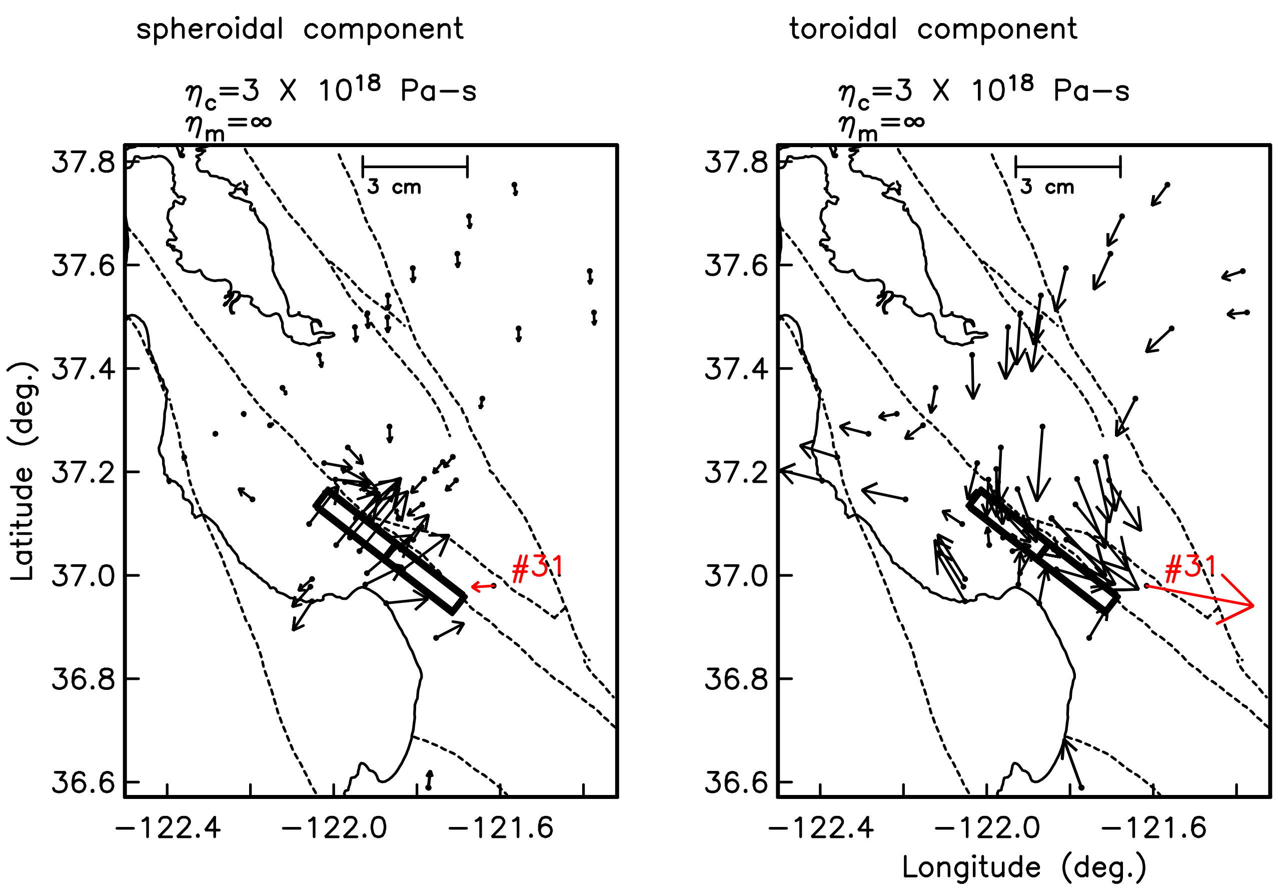
x_{31}(km) y_{31}(km) u_x(cm) u_y(cm) u_z(cm) $e_{xx}(10^{\square 6})$
$e_{yy}(10^{\square 6})$ $e_{xy}(10^{\square 6})$ $e_{xz}(10^{\square 6})$ $e_{yz}(10^{\square 6})$ $e_{zz}(10^{\square 6})$

Toroidal motion deformation of point #31

8.796 5.762 0.307052E+01 -0.585062E+00 0.980001E-01 -0.980001E-01
0.407049E+00 0.311147E-07-0.363551E-06

x_{31}(km) y_{31}(km) u_x(cm) u_y(cm) $e_{xx}(10^{\square 6})$ $e_{yy}(10^{\square 6})$
$e_{xy}(10^{\square 6})$ $e_{xz}(10^{\square 6})$ $e_{yz}(10^{\square 6})$





EXAMPLE 2. Figure 3

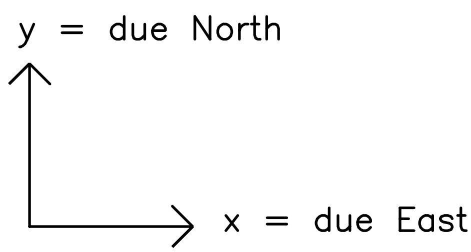
Total (spheroidal + toroidal) motion deformation of point #31

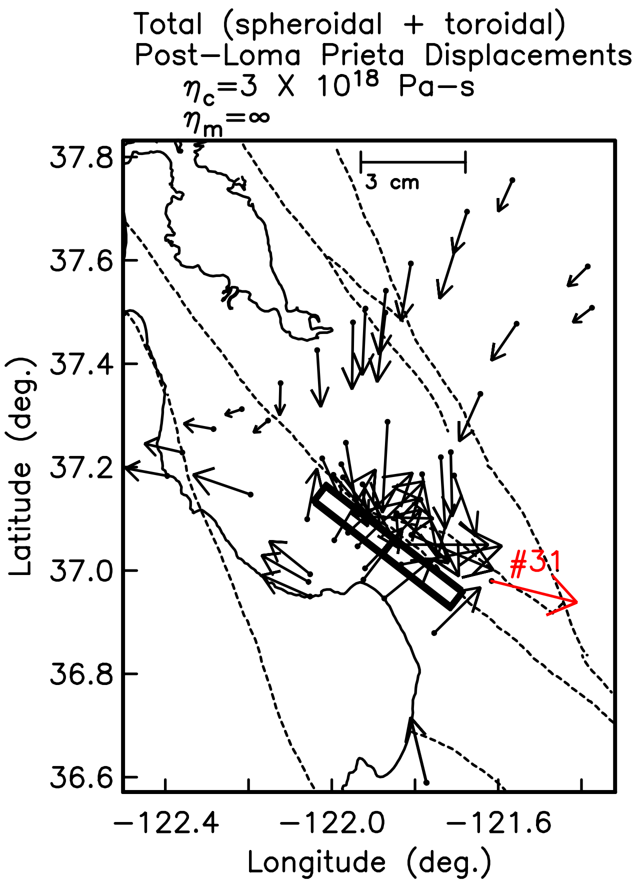
8.796 5.763 0.245386E+01 -0.624111E+00 -0.143094E+00 -0.483457E+00

-0.104608E+01 0.311665E+00 0.266635E-07 -0.366440E-06 0.554959E+00

x_{31}(km) y_{31}(km) u_x(cm) u_y(cm) u_z(cm) e_{xx}(10^{-6})

e_{yy}(10^{-6}) e_{xy}(10^{-6}) e_{xz}(10^{-6}) e_{yz}(10^{-6}) e_{zz}(10^{-6})





EXAMPLE 3. Figure 1

Spheroidal motion deformation of point #31

8.796 5.763 -0.494032E-01 0.376045E-02 -0.217260E-01 -0.597056E-01

-0.735816E-01 -0.144263E-01 -0.259865E-09 -0.787407E-10 0.483615E-01

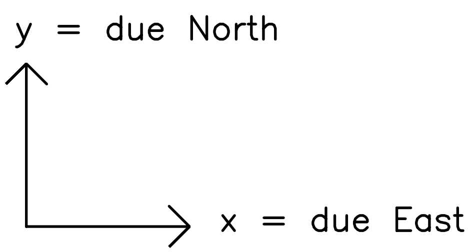
x_{31}(km) y_{31}(km) u_x (cm yr) u_y (cm yr) u_z (cm yr) e_{xx} (10^{-6} yr)
e_{yy} (10^{-6} yr) e_{xy} (10^{-6} yr) e_{xz} (10^{-6} yr) e_{yz} (10^{-6} yr) e_{zz} (10^{-6} yr)

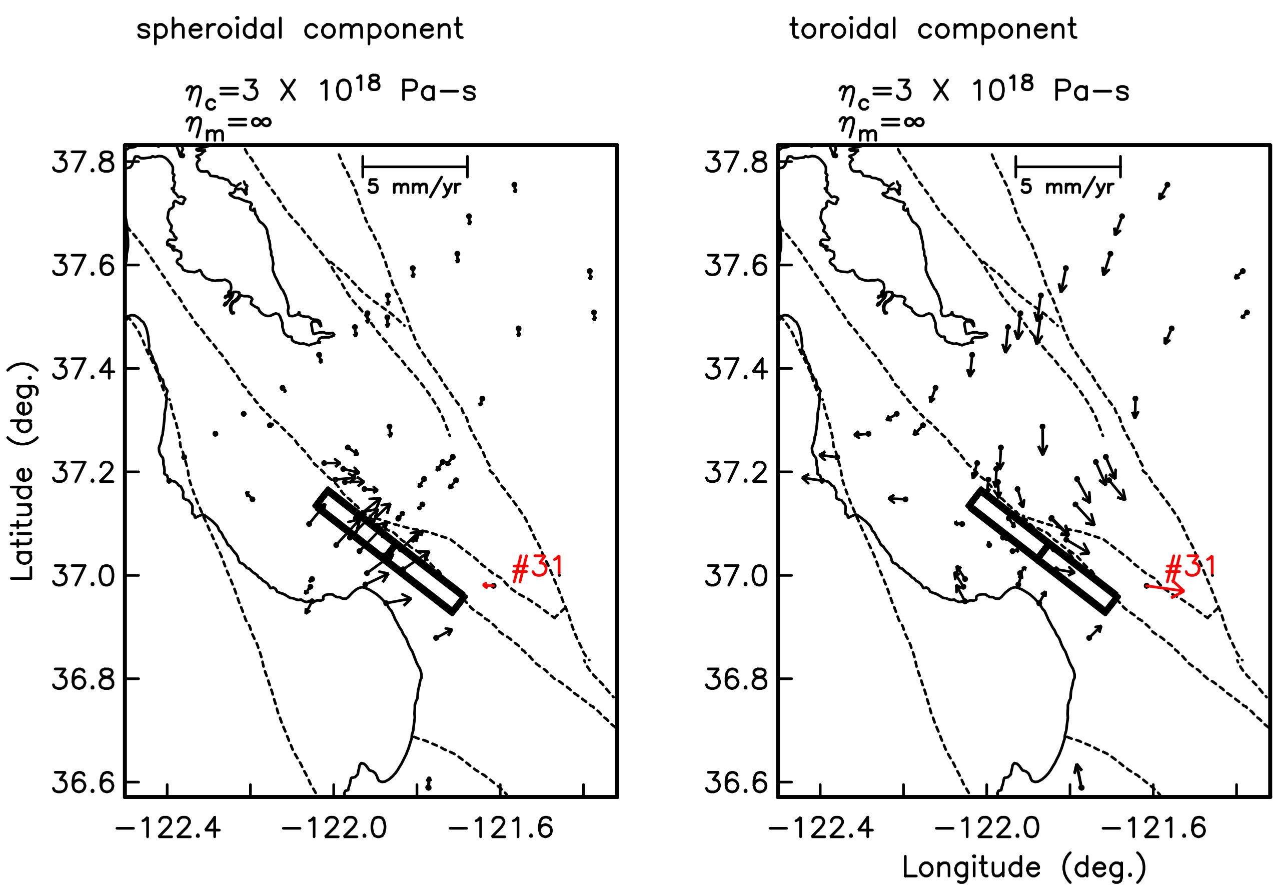
Toroidal motion deformation of point #31

8.796 5.762 0.178704E+00 -0.251833E-01 0.199062E-01 -0.199062E-01

0.140605E-01 -0.372318E-10 -0.616475E-08

x_{31}(km) y_{31}(km) u_x (cm yr) u_y (cm yr) e_{xx} (10^{-6} yr) e_{yy} (10^{-6} yr)
e_{xy} (10^{-6} yr) e_{xz} (10^{-6} yr) e_{yz} (10^{-6} yr)



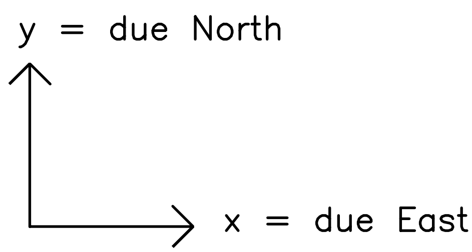


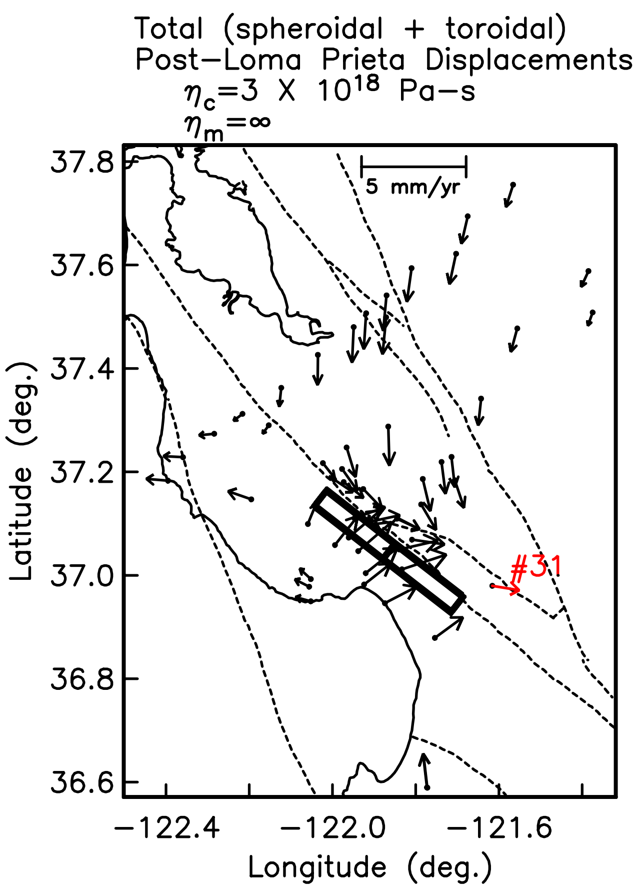
EXAMPLE 3. Figure 2

Total (spheroidal + toroidal) motion deformation of point #31

8.796 5.763 0.129301E+00 -0.214228E-01 -0.217260E-01 -0.397994E-01
-0.934878E-01 -0.365800E-03 -0.297097E-09 -0.624349E-08 0.483615E-01

x_{31}(km) y_{31}(km) u_x(cm yr) u_y(cm yr) u_z(cm yr) $e_{xx}(10^{-6}\,yr)$
$e_{yy}(10^{-6}\,yr)$ $e_{xy}(10^{-6}\,yr)$ $e_{xz}(10^{-6}\,yr)$ $e_{yz}(10^{-6}\,yr)$ $e_{zz}(10^{-6}\,yr)$





EXAMPLE 4. Figure 1

Spheroidal motion deformation of point #31

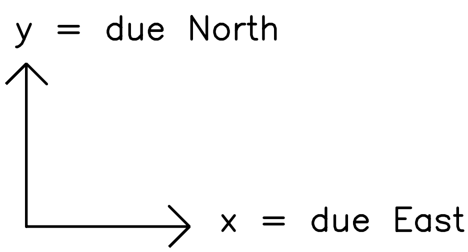
8.796 5.763 -0.829742E-02 0.184421E-01 -0.799669E-01 0.442155E-02
-0.732833E-01 0.396851E-03 0.111806E+00 0.264494E-01 0.919847E-01

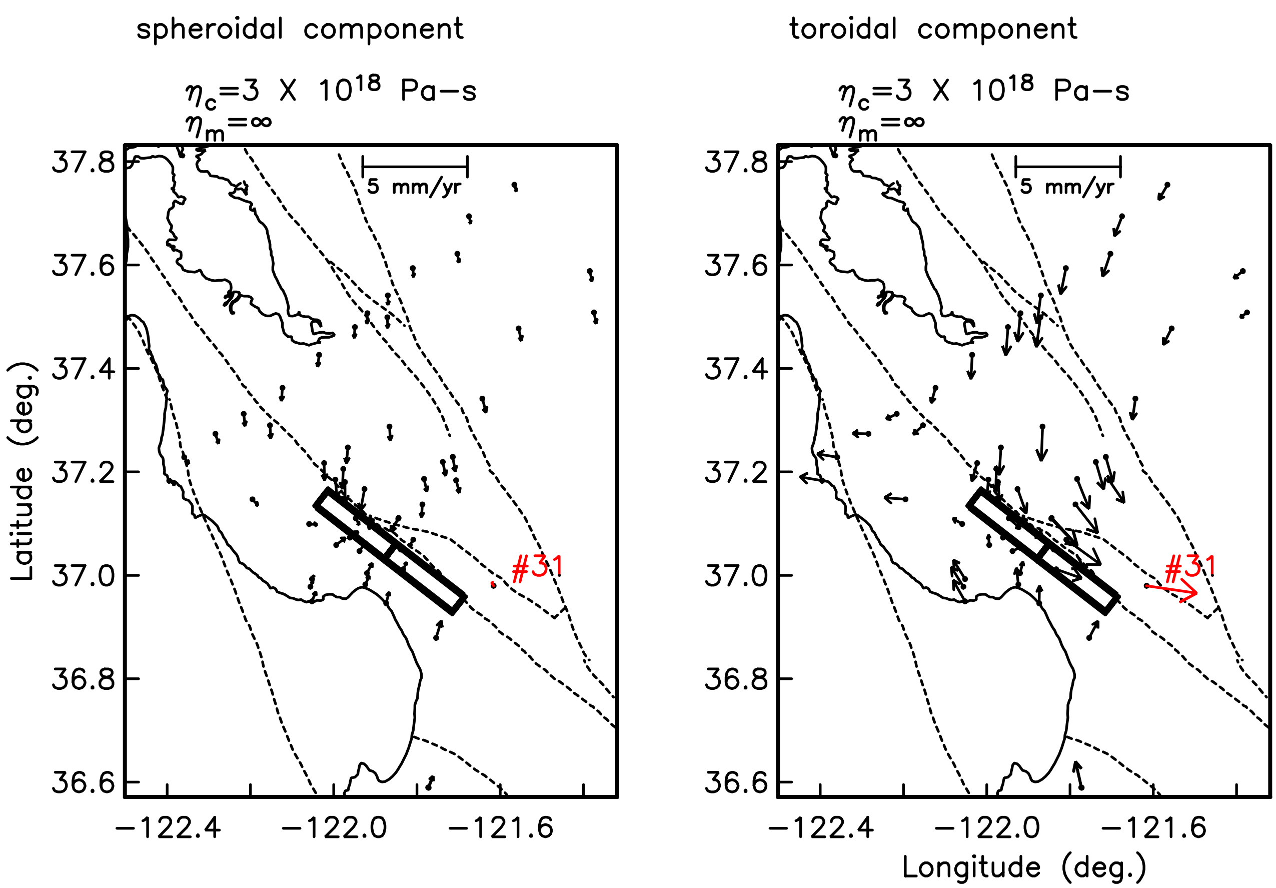
x_{31}(km) y_{31}(km) u_x (cm yr) u_y (cm yr) u_z (cm yr) e_{xx} (10^{-6} yr)
e_{yy} (10^{-6} yr) e_{xy} (10^{-6} yr) e_{xz} (10^{-6} yr) e_{yz} (10^{-6} yr) e_{zz} (10^{-6} yr)

Toroidal motion deformation of point #31

8.796 5.762 0.240072E+00 -0.353467E-01 -0.230824E-02 0.230824E-02
0.255259E-01 -0.712311E-01 0.988352E-02

x_{31}(km) y_{31}(km) u_x (cm yr) u_y (cm yr) e_{xx} (10^{-6} yr) e_{yy} (10^{-6} yr)
e_{xy} (10^{-6} yr) e_{xz} (10^{-6} yr) e_{yz} (10^{-6} yr)



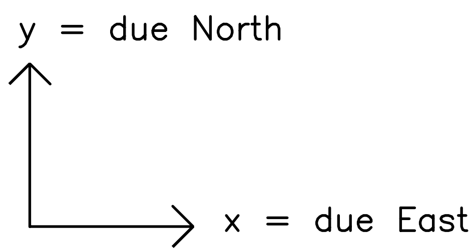


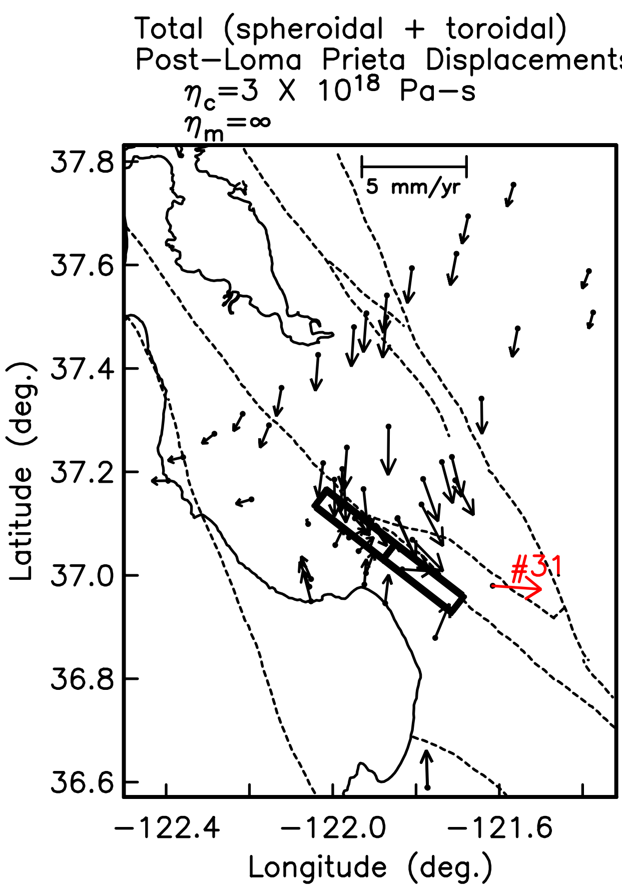
EXAMPLE 4. Figure 2

Total (spheroidal + toroidal) motion deformation of point #31

8.796 5.763 0.231775E+00 -0.169046E-01 -0.799669E-01 0.211331E-02
-0.709751E-01 0.259228E-01 0.405749E-01 0.363329E-01 0.919847E-01

x_{31}(km) y_{31}(km) u_x (cm yr) u_y (cm yr) u_z (cm yr) e_{xx} (10^{-6} yr)
e_{yy} (10^{-6} yr) e_{xy} (10^{-6} yr) e_{xz} (10^{-6} yr) e_{yz} (10^{-6} yr) e_{zz} (10^{-6} yr)





EXAMPLE 5. Figure 1

Viscoelastic stratification used to model postseismic deformation in the Landers epicentral area. A purely elastic upper crust (base at 16 km depth) is underlain by a standard linear solid lower crust (base at 30 km depth) and Maxwell viscoelastic fluid upper mantle. Parameters κ, μ, and η are the bulk modulus, shear modulus, and viscosity, respectively, and μ' is the long term strength of the lower crust ($\mu' = 0$ would correspond to a Maxwell viscoelastic fluid). Elastic stratification is prescribed by values κ_{c1} = 65 GPa, μ_{c1} = 36 GPa, κ_{c2} = 95 GPa, μ_{c2} = 53 GPa, and κ_m = 150 GPa, μ_m = 70 GPa.

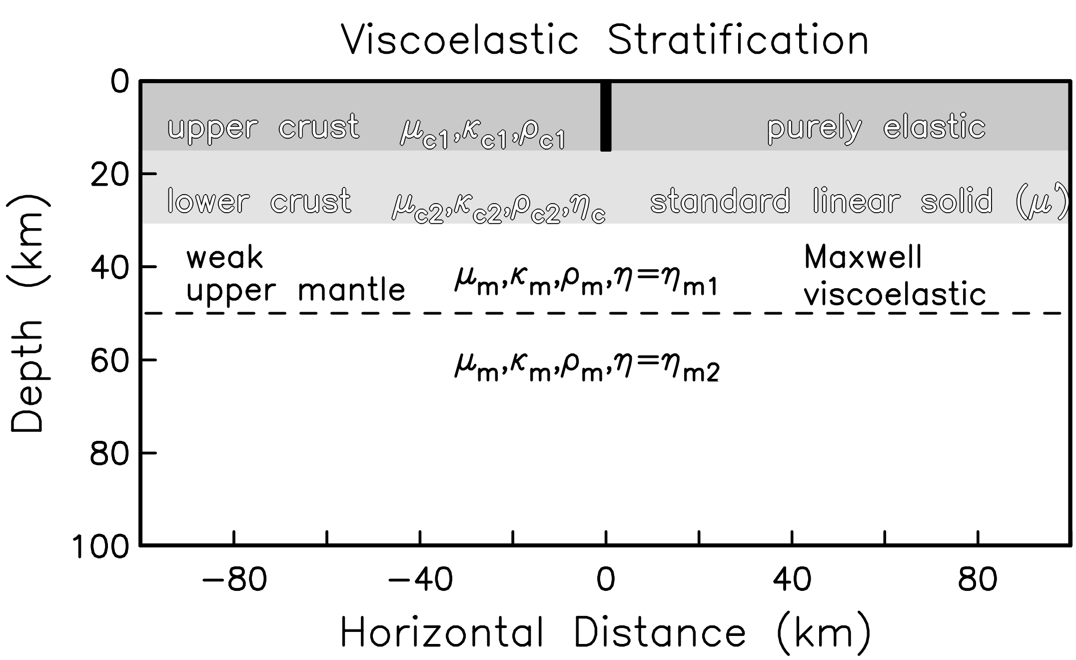
Viscoelastic material properties are specified as:

$\mu' = 2.4 \times 10^{10}$ Pa

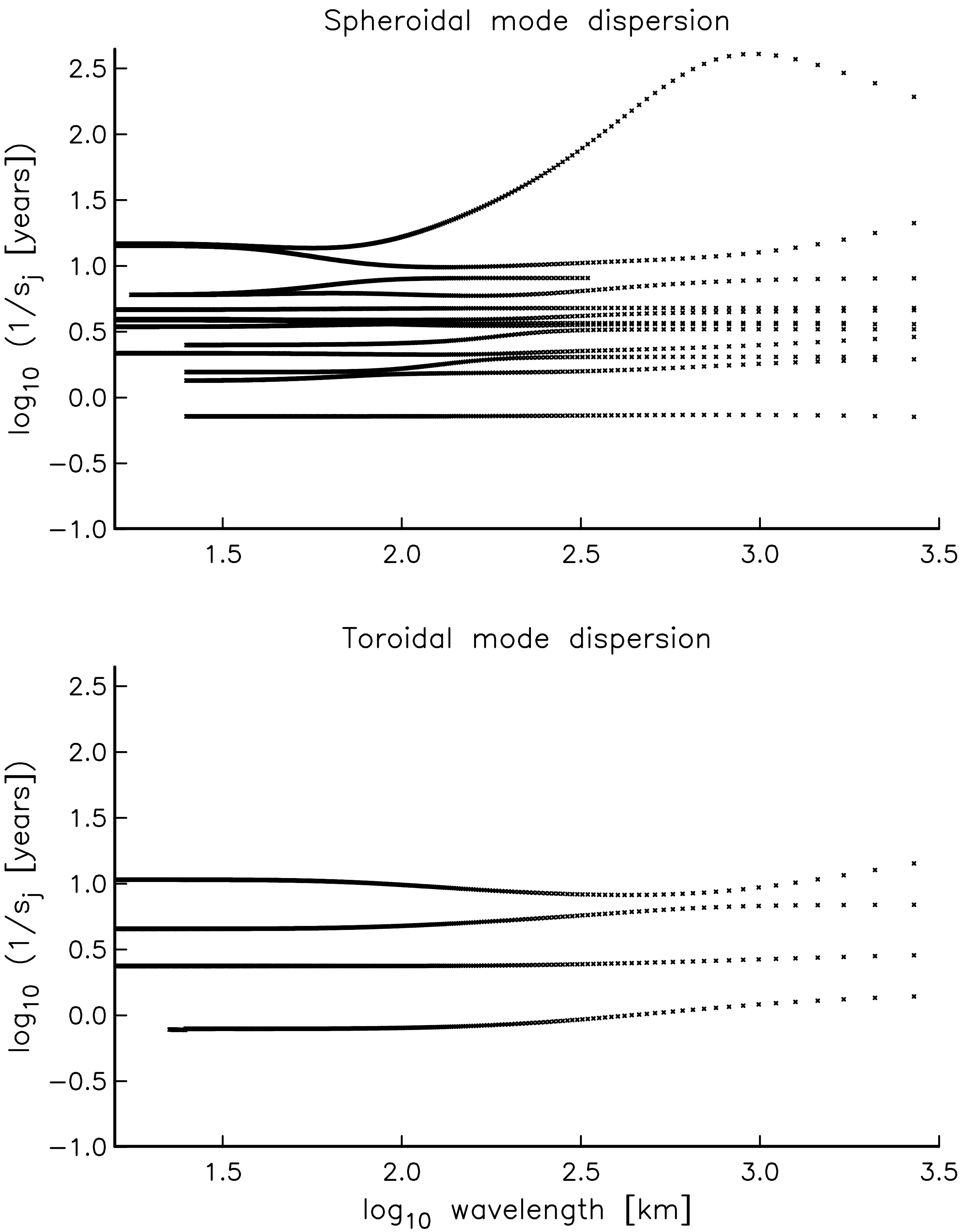
$\eta_c = 11.25 \times 10^{18}$ Pa s

$\eta_{m1} = 4.5 \times 10^{18}$ Pa s

$\eta_{m2} = 1.5 \times 10^{18}$ Pa s



EXAMPLE 5. Figure 2



EXAMPLE 5.   Figure 3