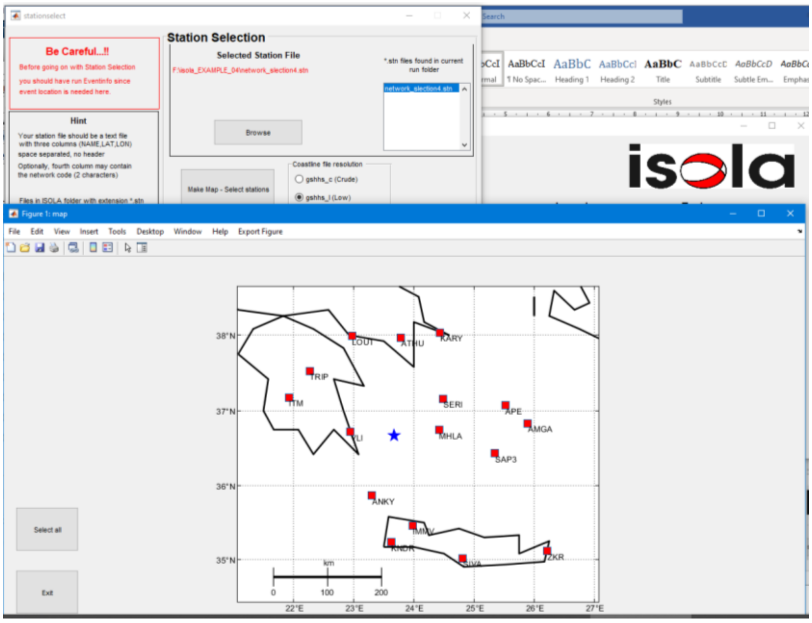
Example 04
Peloponnese, intermediate-depth Mw 5.9 earthquake. Behavior of different covariance matrices. Well-resolvable non-DC components.

Before this, see the introductory hints in isola_EXAMPLE_01.

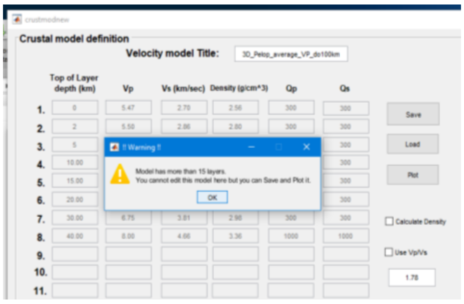
Preparation

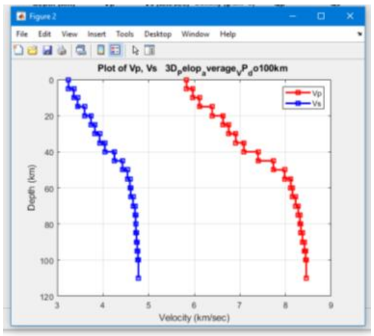
Event Info. We study a real event of 20140829, Mw 5.9, located by NOA at Lat 36.67, Lon 23.6715, at 03:45:05.00 UTC, depth 97 km (an intermediate-depth event). We choose TWL= 409.6 s, implying waveform sampling with dt= TWL/1024= 0.4 s.

Station Selection. Taking 16 stations, all from the file network_slection4.stn, saved in the root folder. Select all. The station selection tool requires to confirm each station because *stime.isl data are absent. [This data, i.e., start times, for all stations *, were used in the preprocessing, which is not the subject of the present example, and that is why they are missing here]. Then Exit.



Define Crustal Model. Load the model from file 1Dfrom3D_averaged.cru from the root. This is an average 1D velocity model derived from a 3D model of the region. The model has more than 15 layers; the tool issues a warning, but the user can make Plot and Save. So, make Save and Exit.





Data Preparation. No need to do anything. Real waveforms have been instrumentally corrected and resampled with dt=0.4 s before this test and appear in folder invert as *raw.dat for all selected stations *,are also stored (backup) in folder data_RAW_Isola_real_PelopNo5.

Test 1 Vertical Grid Search

Seismic Source Definition. Trial source positions below epicenter, starting at depth 80 km, depth step 5 km, 8 sources. Calculate and Exit. Data files src*.dat appear in folder green.

Green function calculation. GF is calculated up to the Nyquist frequency 1.25 Hz, assuming delta-function moment rate (default values); 8 trial sources, 16 stations.

Inversion, frequency range 0.02-0.10 Hz (common to all stations). Time search -10 to +10 s, step 0.4 s (which is the minimum possible step, given by dt). Choosing Full MT.

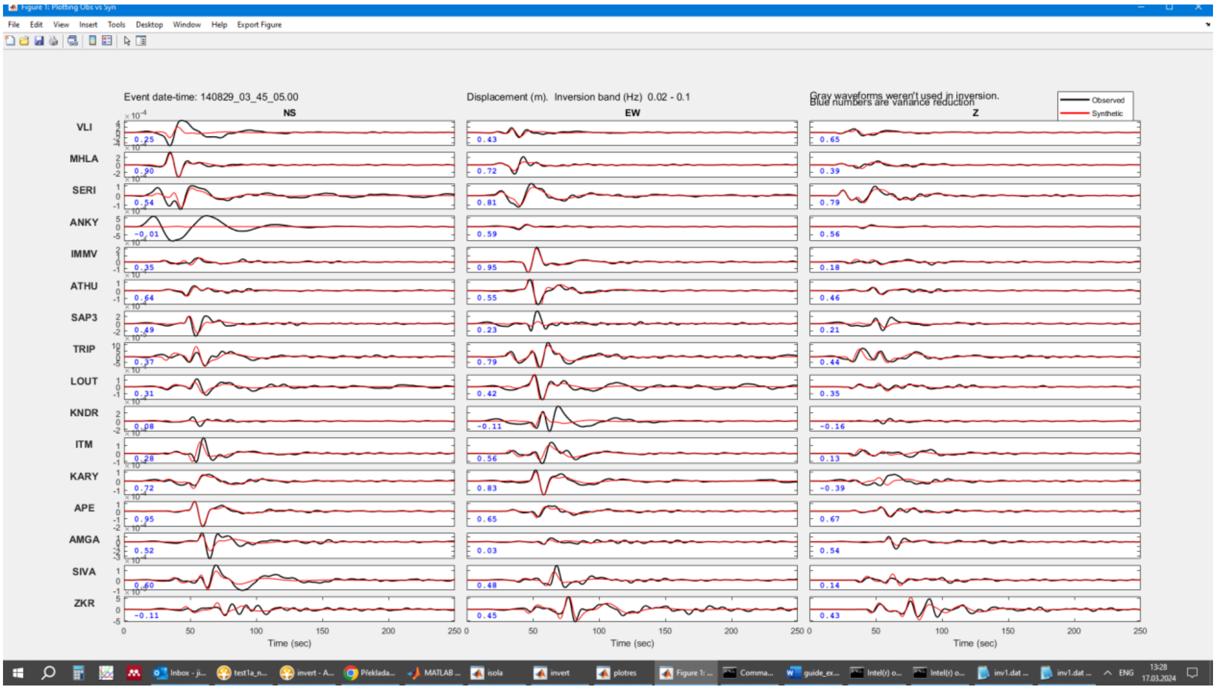
a) Without covariance matrix, “no-cova” (better speaking with Cd= const I). Results are saved in invert\test1a. Optimal position no. 4, depth 95 km. From inv1.dat file in the invert folder:

moment (Nm): 7.0099694E+17
moment magnitude: 5.9
VOL % : -23.3
DC % : 58.7
CLVD % : -18.1

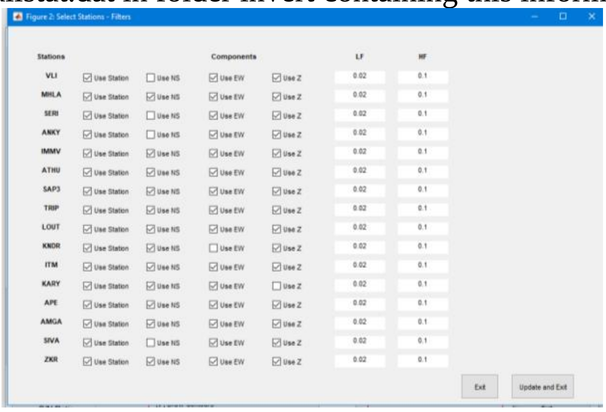
strike,dip,rake:	263	63	161
strike,dip,rake:	2	73	27
strike,dip,rake:	2	73	27

varred= 0.1818448

Waveform fit is visibly bad at several components. A closer investigation of integrated original broad-band records in Seisgram software indicated instrumental disturbances (‘mice’) responsible for poor fit, e.g. at VLI-N.



b) Again 0.02-0.10 Hz but deselecting wrong components; you may check also file allstat.dat in folder invert containing this information.



The NO COVA mode with deselected components yields inv1.dat like this:

moment (Nm): 6.5262523E+17
moment magnitude: 5.8
VOL % : -9.7
DC % : 62.7
CLVD % : -27.6
strike,dip,rake: 260 65 164
strike,dip,rake: 357 75 25
varred= 0.5483028

Note a significant decrease in VOL% (=ISO%). Thus, this is a good example of how sensitive and vulnerable to various data errors is this parameter (and equally the DC% and CLVD%)! Variance reduction has increased, and Mo and Mw have also changed. Typically, the s/d/r angles remained almost unaffected, these are relatively stable parameters. Optimal centroid depth is again 95 km (better speaking 90-100 km with almost identical correlation), see Plot Results and Plot Correlation versus Source, or the file *inv1.png in invert\test1b_no_cova and waveform fit in *wave.png in the same folder.

c) Again 0.02-0.10 Hz. Set the same deselected components as in Test 1d. Now we invert with covariance matrix ("cova"), with the most commonly used cova type "Toeplitz" (previously in my codes and tests also called cova_FULL). The covariance matrix for this run is calculated from residuals (observed minus synthetic waveforms) obtained in the no_cova run. This is iteration 1.

In inv1.dat (in invert folder) we find:

```
moment (Nm):  6.3461763E+17
  moment magnitude:   5.8
         VOL % :  -8.9
          DC % :  71.6
        CLVD % : -19.5
 strike,dip,rake:       261        65       165
 strike,dip,rake:       357        76        25
varred=  0.5464264
```

In the Matlab command window we read:
varred_classical = 0.17867, varred_standardized = 0.79218

indicating the efficiency of the cova approach, even though varred =0.546 is now lower than before (0.548). If we trust this cova approach, we obtain a considerably increased DC%, compared to Test 1b (i.e., from 63% to 72%), along with the decrease of the |CLVD%|.

[As a rule, varred classical (0.178 here) on the output of Matlab, and varred on the last line of inv1.dat (0.546 above) do not differ much. Here, the particularly low value of the varred_classical in Matlab is because the Matlab code also includes the low-fit removed components.]

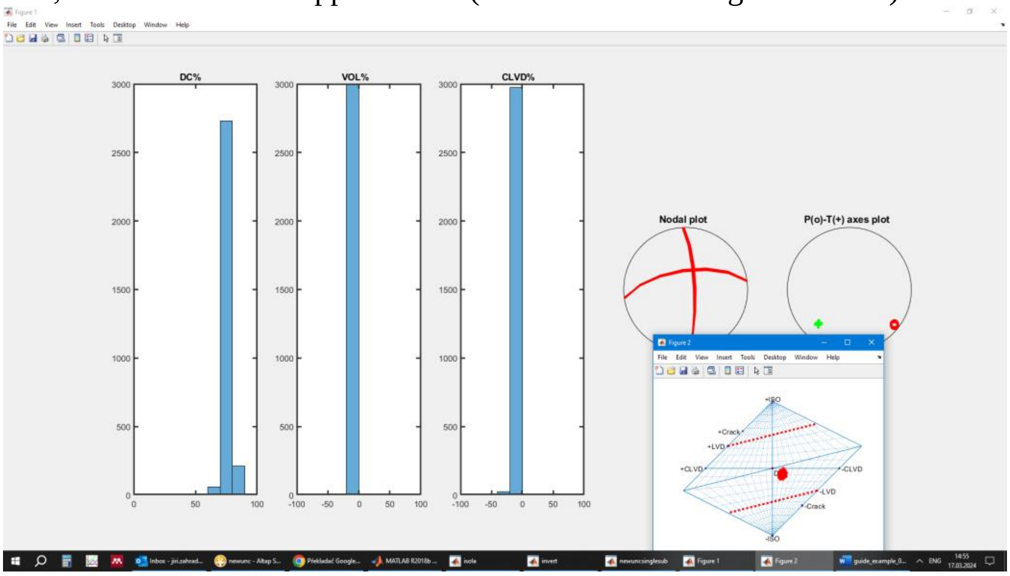
Now again 0.02-0.10 Hz, inverting with the same (Toeplitz) cova type, iteration 2:

```
moment (Nm):  6.0067007E+17
  moment magnitude:   5.8
```

VOL % : -9.6
DC % : 75.7
CLVD % : -14.8
strike,dip,rake: 357   77   25
strike,dip,rake: 261   65   166
varred= 0.5416536

We observe a relatively small change from iteration 1 to 2 (smaller than between iteration 0 and 1), with the trend to slightly increase |VOL%|, increase DC%, and decrease |CLVD%|.

It is probably not very important to further iterate. Instead, now we proceed to the Uncertainty tool, and start with the upper button (Method 1 - selecting 1 subevent).



Plots are generated and, in the Matlab command window, we find the error statistics from 3000 random draws of MT based on the best-fit source position (the 3rd position, 90 km depth) and the posterior covariance matrix of MT for that position. The spread, quantified by standard deviation, is small; the source is close to pure shear (100% DC):

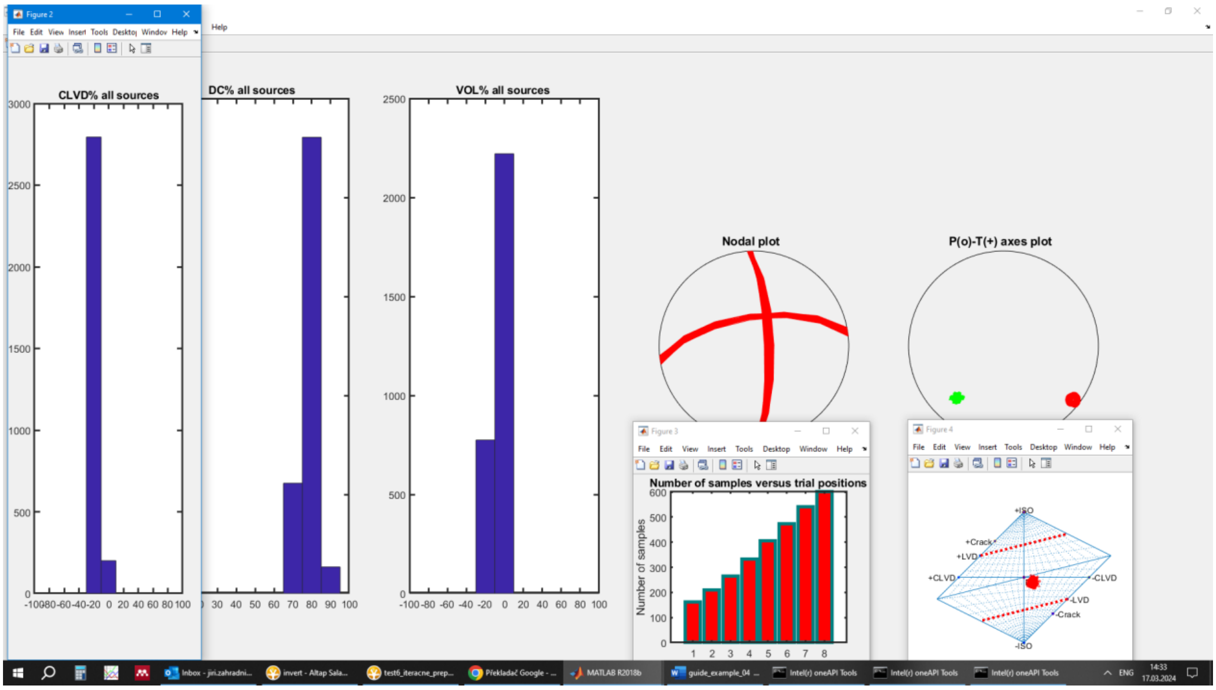
Mean of DC% is : 75.8, STD of DC% is : 2.8
Mean of CLVD% is : -14.8, STD of CLVD% is : 2.1
Mean of ISO% is : -9.4, STD of ISO% is : 2.5

(The user can obtain slightly different values and plots because the used random number generator has no repeatability.)

Now we use the lower button, Method 2 in the Uncertainty tool. It needs a considerably longer calculation time; in fact, we repeat inversion as many times as is the number of trial positions, i.e., 8-times. The result, reported in Matlab command window, is this:

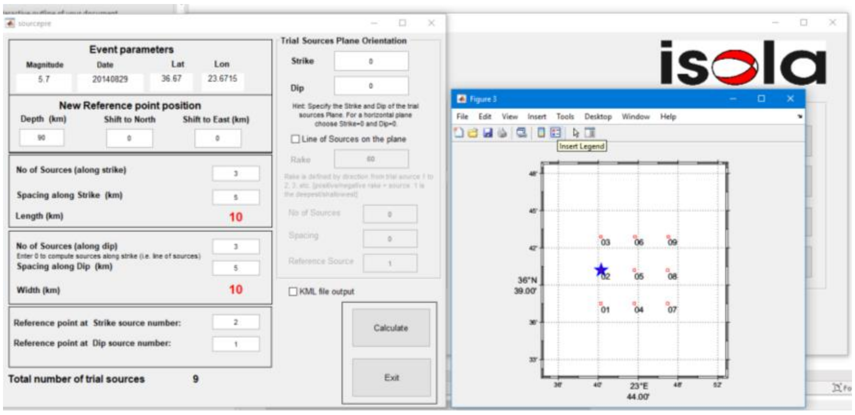
Mean of DC% is : 78.4, STD of DC% is : 3.8
Mean of CLVD% is : -13.6, STD of CLVD% is : 2.4
Mean of ISO% is : -8.0, STD of ISO% is : 3.0
Running with 8 trial source positions

This is an MT-error estimate also considering the uncertain trial position (depth), not only the best-fit depth as above. Although the best-fit solution depth was in the 3rd position, this estimate, considering uncertain depth, as a whole, prefers the deepest trial position. For that position, it creates most random samples, as seen from the red-color histogram below. This is due to a relatively complex interplay between the posterior covariance matrix of MT and waveform fit [see file newunc_log.dat in folder newunc]. Nevertheless, in this particular case, the two error estimates do not differ much between the best-fit position 1 (above) and the overall preferred position 3 (here). The similarity is because MT in this example is weakly varying with source position. [Very different are examples 03 and 06.] The source type plot remains almost equally focused as above. Both estimates in Test 1d indicate that the source type is close to pure DC, and here (with cova, DC=78%) the source is even closer to DC than initially estimated in Test 1b (no_cova, DC=63%).



Test 2 Horizontal Grid Search of Centroid

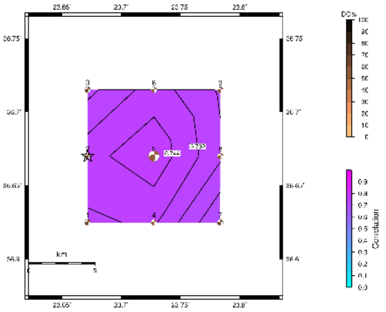
a) Calculating Green functions for 9 trial source positions in a horizontal plane at a depth 90 km. Star is the epicenter. This test is based on preliminary calculations in a broader vicinity of the hypocenter, here reduced to 9 positions just for speed of demonstration.



Now we must be sure that invert window from previous tests was closed. We re-open it and check in the upper left corner that now we use 9 trial positions. Inversion is now made again for 0.02-0.10 Hz, full MT mode, no_cova.

Without covariance matrix, “no-cova” means that the data covariance matrix is Cd= const I, where I is the identity matrix; i.e. the matrix has a constant diagonal, the values are the same for all components and all stations, const = A^2 where A is maximum amplitude of the displacement at the most distant used station in the 0.02-0.10 Hz range, in this case station ZKR, const = 3.18e-9 m^2. It means that the inverted covariance matrix is again purely constant-diagonal, with values Cdinv =1./const=3.14e8. The Cd matrix has no effect upon the inversion [because it appears in the least squares formula twice and the terms cancel out], better speaking, the best-fit solution is exactly the same as when Cd is totally absent. That is why this method is often called “no-cova”. All station components have the same weight. Nevertheless, Cd has an effect upon the uncertainty, it determines the MT spread around the best-fit solution, and this spread also includes the effect of uncertain trial source position. This is the simplest and fastest uncertainty assessment method, sometimes criticized because it does not comprise “standardization”, i.e., the data error is not Gaussian and no attempt is made to make it closer to Gaussian (the spectrum is not whitened).

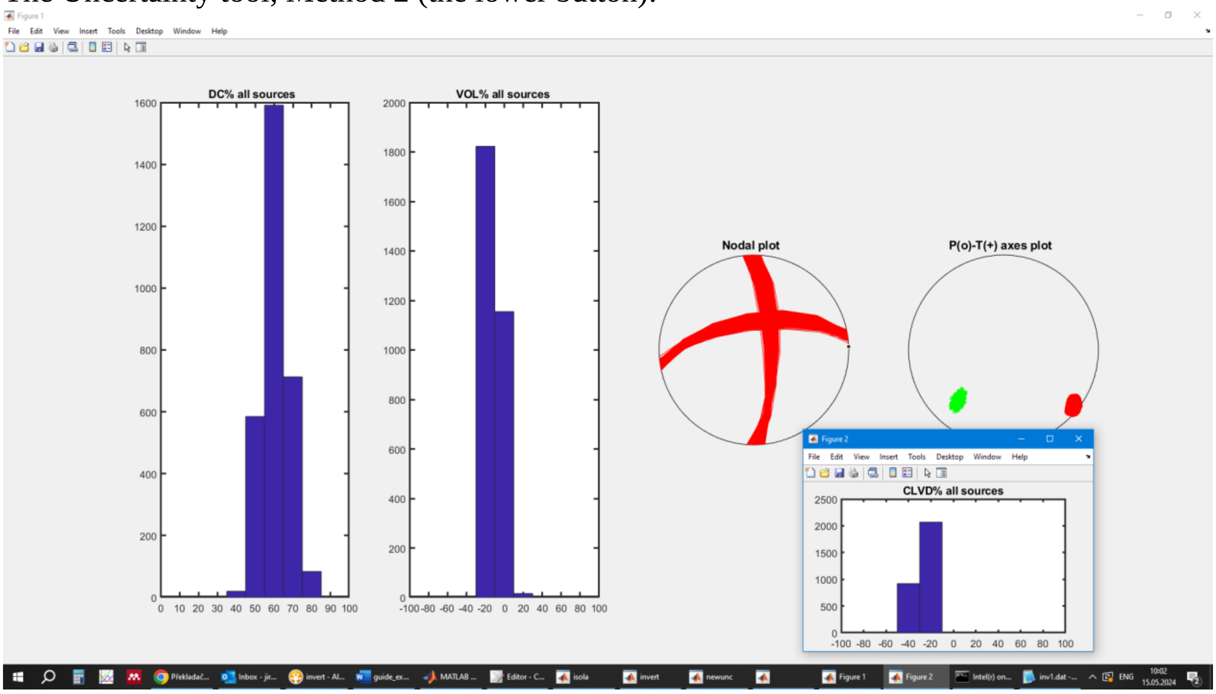
The same deselected components as in Test 1d. We obtain a weak preference for centroid position shifted 5 km eastward from the epicenter (trial point no. 5), with a little change in MT. See \invert\test2a_no_cova. The following plot is from invert tool, the button Plot correlation on map:

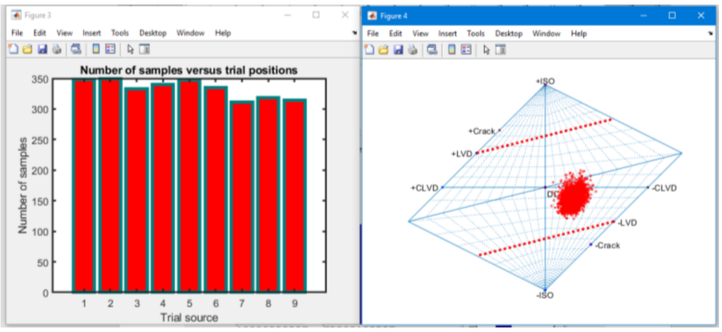


From file inv1.dat we find

isour,ishift 5 8
moment (Nm): 6.3998332E+17
moment magnitude: 5.8
VOL % : -12.6
DC % : 57.5
CLVD % : -29.9
strike,dip,rake: 261 65 163
strike,dip,rake: 358 74 25
varred= 0.5662458

The Uncertainty tool, Method 2 (the lower button):





Mean of DC% is : 60.9; STD of DC% is : 7.0
Mean of CLVD% is : -27.3; STD of CLVD% is : 5.7
Mean of ISO% is : -11.3; STD of ISO% is : 6.9

At the same time, keeping the same frequency range, no_cova inversion, but requesting **two subevents**, we obtain inv2.dat:

Position, Time, Moment, Strike Dip Rake ………………………………..DC%, VR

5	3.20	0.63998E+18	261.	66.	163.	358.	75.	25.	128.	6.	222.	28.	28.	61.	57.5	0.56625E+00
3	5.20	0.92301E+17	17.	84.	-110.	272.	21.	-16.	266.	47.	125.	36.	19.	20.	39.3	0.57598E+00

The second subevent is rather formal, and insignificant because its moment 0.92301E+17 is lower than 1/6 of subevent 1. It says that, in the considered frequency range, the earthquake is a single-point source.

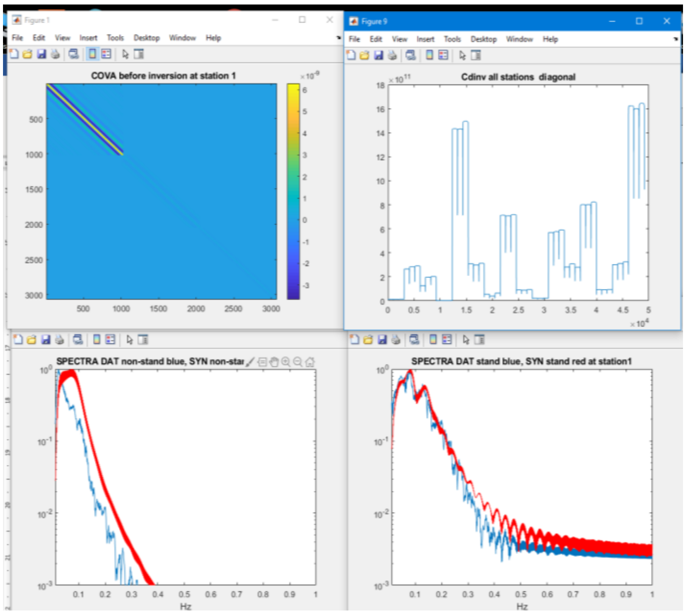
b) We repeat a single-subevent inversion without cova (to obtain residual waveforms), and then switch to inversion with cova Toeplitz (also called FULL); iteration 1. The same deselected components as in Test 1d. Analogously to Test 1, now in trial position 5 (=5 km east of epicenter), we obtain a slightly greater DC% compared to the no_cova result.

Iteration 1
isour,ishift 5 8
moment (Nm): 6.1992390E+17
moment magnitude: 5.8
VOL % : -12.7
DC % : 62.7
CLVD % : -24.6
strike,dip,rake: 261 65 164
strike,dip,rake: 358 75 25
varred= 0.5644639

Itaration 2
moment (Nm): 6.0742224E+17
moment magnitude: 5.8
VOL % : -12.8
DC % : 66.1
CLVD % : -21.0
strike,dip,rake: 262 65 165
strike,dip,rake: 358 76 25
varred= 0.5613745

Iteration 3
moment (Nm): 5.9948707E+17
moment magnitude: 5.8
VOL % : -13.0
DC % : 68.4
CLVD % : -18.6
strike,dip,rake: 358 77 24
strike,dip,rake: 262 65 166
varred= 0.5585070

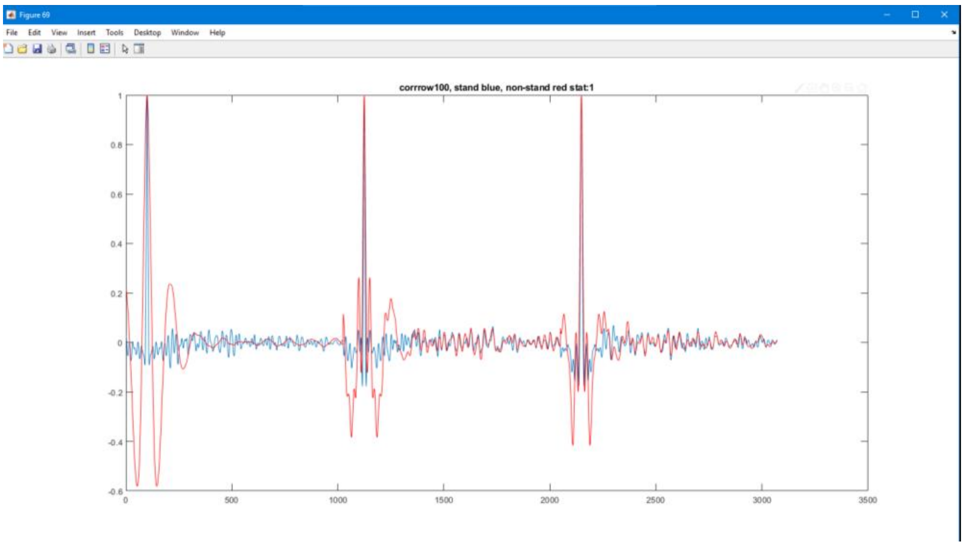
The next plots are after iteration 1.



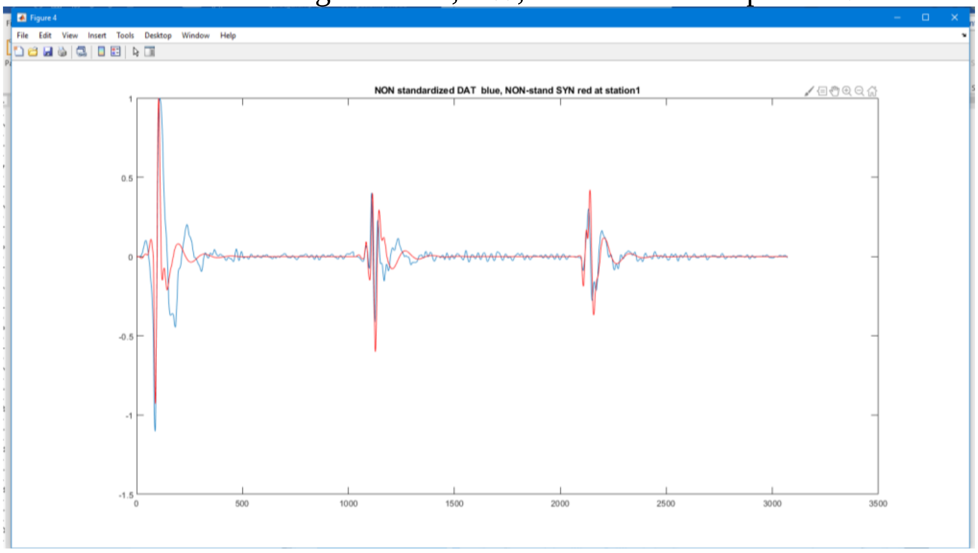
Low diagonal values of the inverted cova matrix at some stations indicate how the cova approach sets low weights to those stations; note the range of the Cdinv diagonal elements from ~1 to ~20.

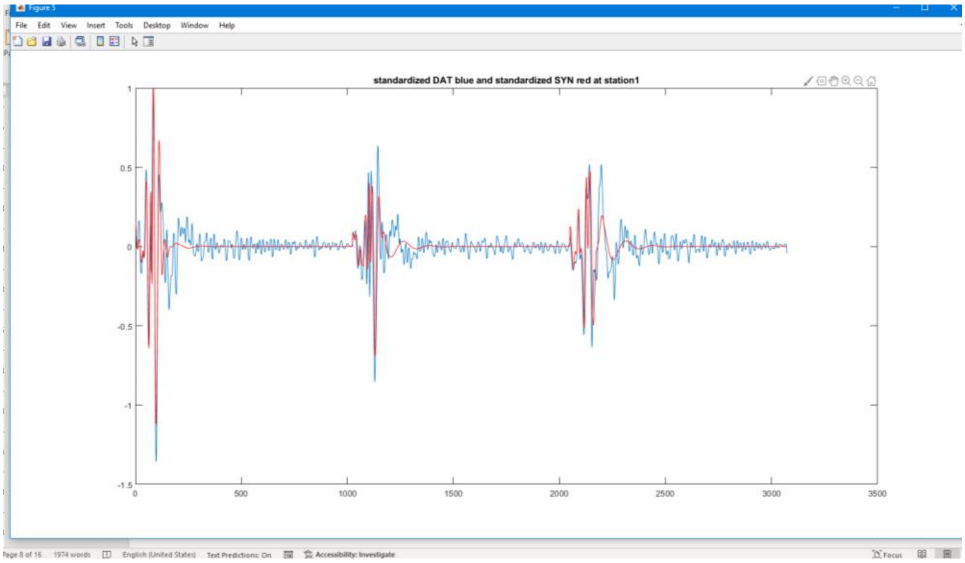
As an example, see the upper right panel, and the almost zero height of the first "column" for the values between 0 and 0.3 on the horizontal axis) – this "column" is the first station (that with a "mouse"). The user might erroneously infer that the cova technique will automatically suppress that disturbance. However, this is not the case. If we invert with cova and include the disturbed components (not shown here), we still get similarly large ISO values as in Test 1a. The cova method does not substitute the careful data quality check.

The Matlab generated plot shows that standardized residuals (blue) are closer to delta functions than the non-standardized residuals (red), i.e. the adopted cova approach method makes the data error less correlated, as desired in the theory of inverse problems.

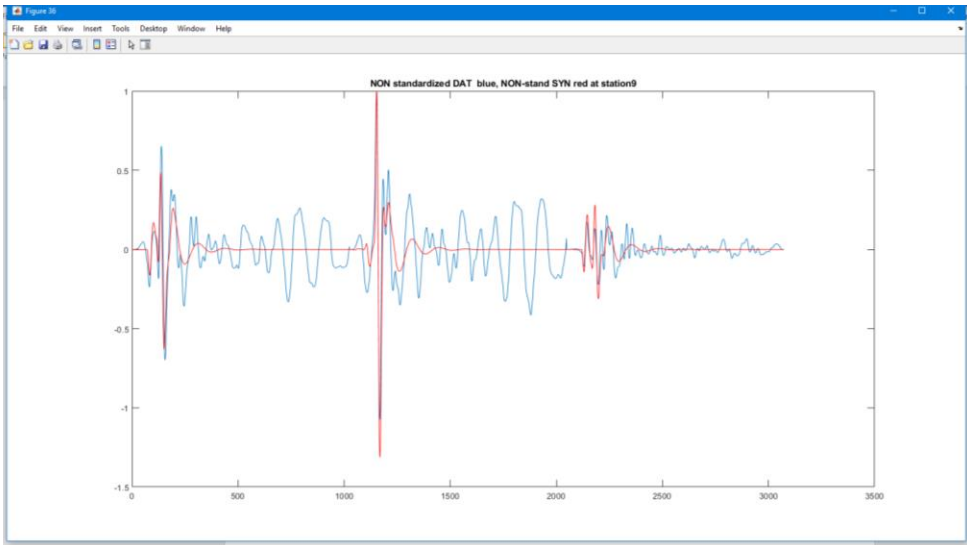


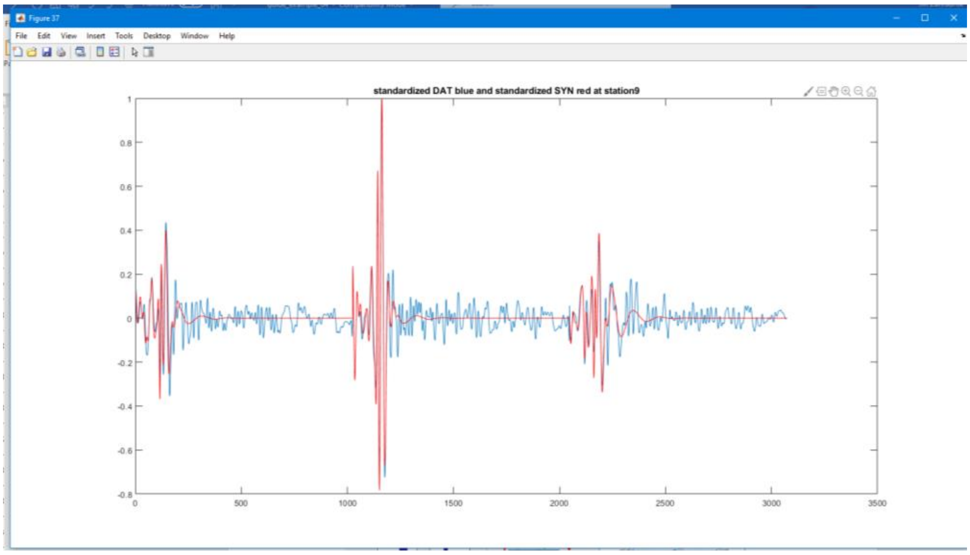
The non-standardized data at station 1 are less well fitted than standardized. The three curves from the left to right are NS, EW, and vertical components.



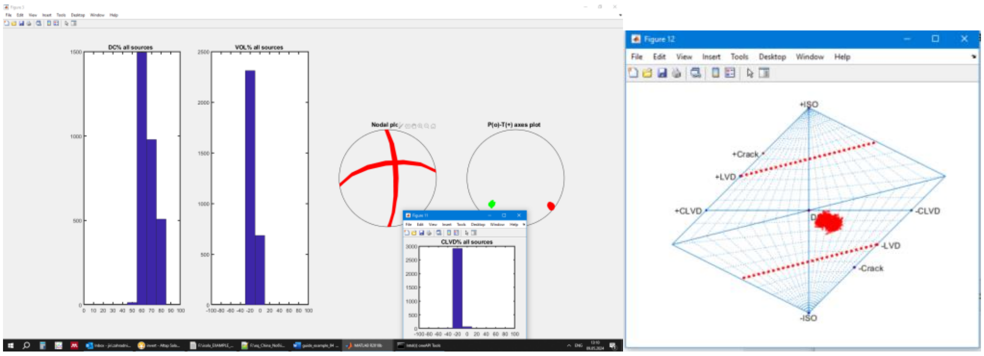


Here we show a nice standardization at station 9 (compare the presence and absence of low-frequency noise in the non-standardized and standardized waveforms, respectively, i.e., a suppression of the low-frequency noise).





The uncertainty assessment (after iteration 1), as in the second part of Test 1d:

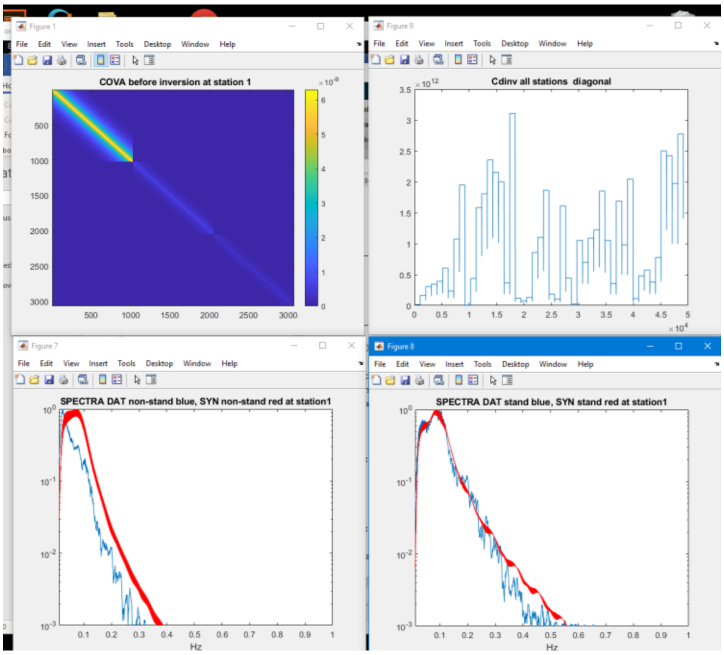


Mean of DC% is : 66.9; STD of DC% is : 6.8
Mean of CLVD% is : -20.8; STD of CLVD% is : 5.0
Mean of ISO% is : -12.3; STD of ISO% is : 3.0

Although we allowed for an uncertain source position, the scatter of MTs in the source-type plot is low, with a small negative CLVD and negative ISO, not far from the DC solution.

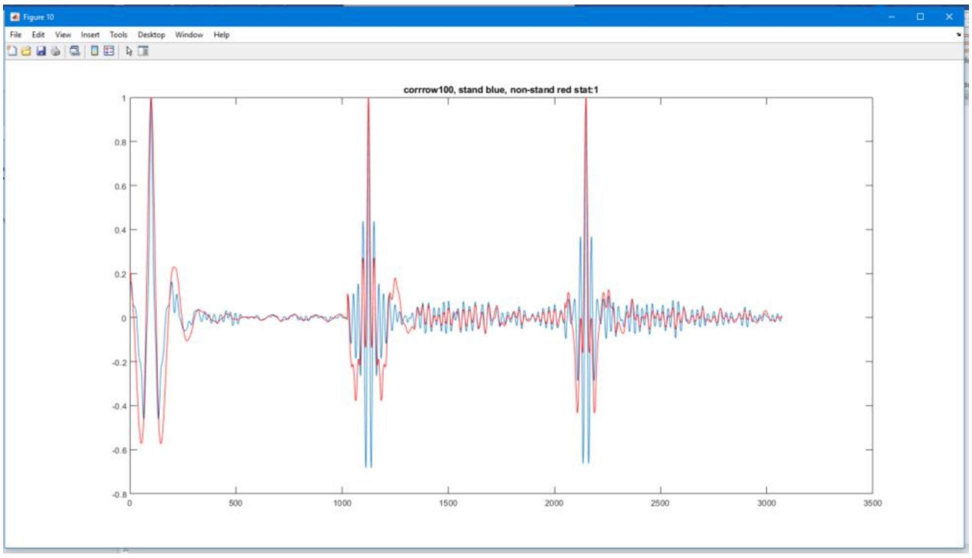
c) Here we again first repeat a single-subevent inversion without cova [such a step produces residuals from which we calculate data covariance matrix], and then switch to inversion with another type of covariance matrix, called Variances, formerly and in some files also called COMPVAR; iteration 1; See \invert\test2c_cova_COMPVAR_iteration1

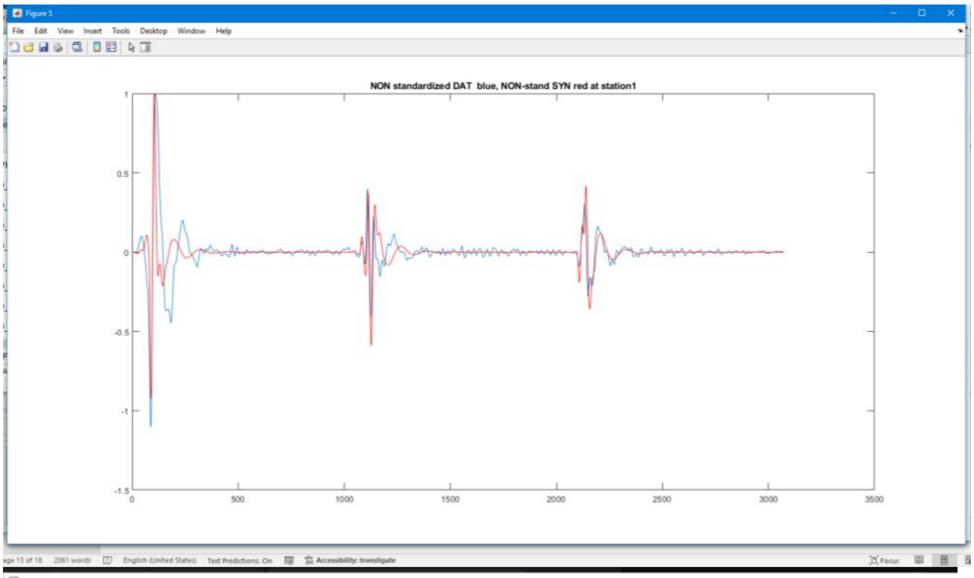
From inv1.dat file:
isour,ishift 5 8
moment (Nm): 5.9019290E+17
moment magnitude: 5.8
VOL % : -12.0
DC % : 69.3 …….. quite a large
CLVD % : -18.7
strike,dip,rake: 261 66 164
strike,dip,rake: 358 76 23
varred= 0.5602056

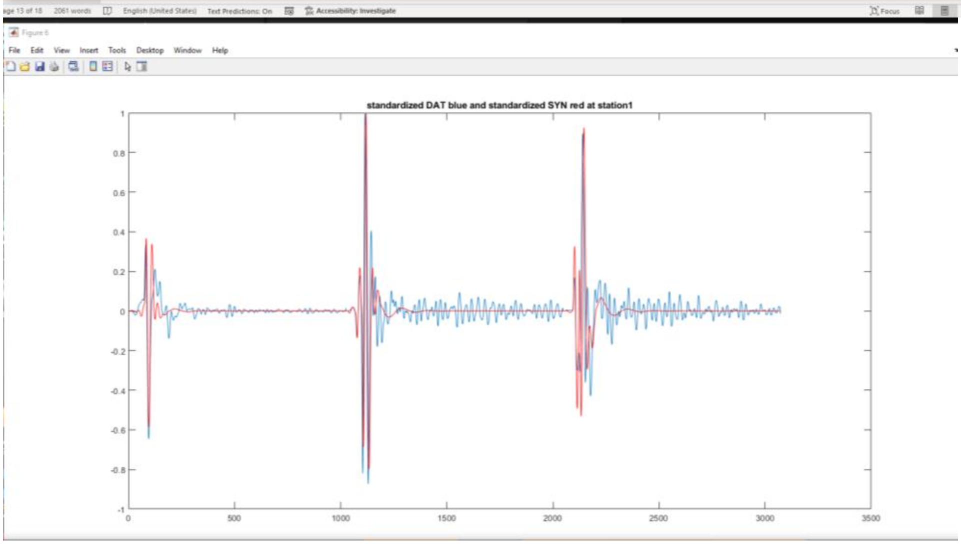


This covariance matrix has dominant diagonal terms and exponentially decreases out of the diagonal. The diagonal term of each station component is given by the variance of residual waveform of that component. Although this type of covariance matrix represents another type of data weighting, the results (above) are similar to those of Test 2b, not only in terms of the optimal ISO%, CLVD%, but also in terms of the uncertainty.

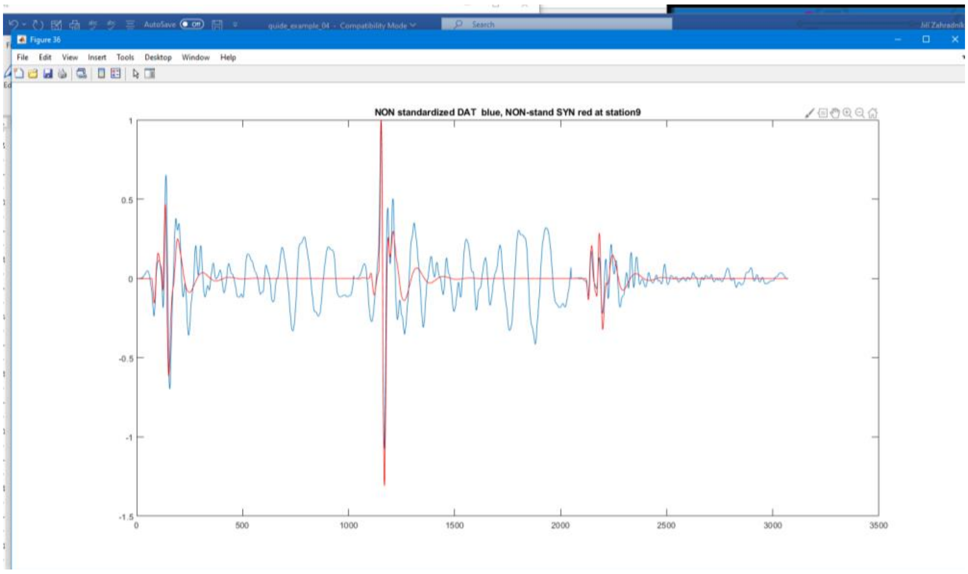
Note a smaller range of the Cdinv elements compared to Test 2b. Also note that this type of cova produces less strong whitening of spectra and it does not produce non-causal arrivals in the standardized seismograms. It may be useful in some applications and needs more investigation.

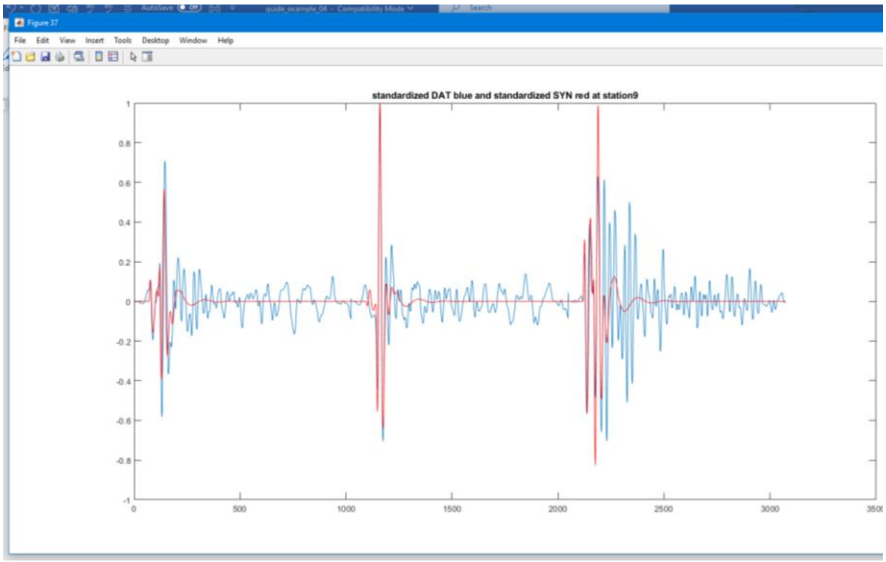




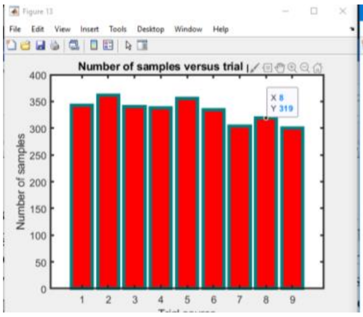


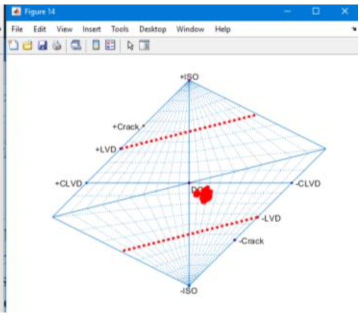
The same for station 9:





The uncertainty is similar to the previous cova type (Toeplitz):





Mean of DC% is : 72.5; STD of DC% is : 4.7
Mean of CLVD% is : -15.8; STD of CLVD% is : 3.6
Mean of ISO% is : -11.7; STD of ISO% is : 3.0

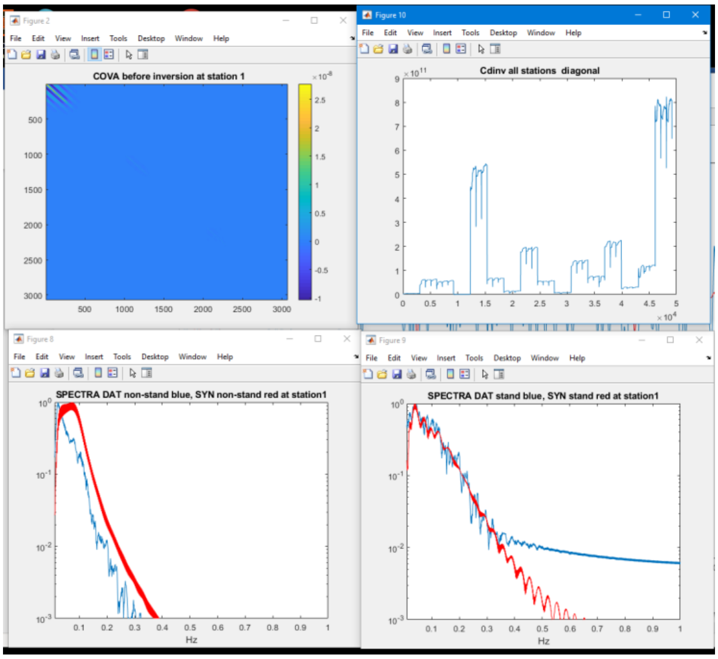
The 'MT cloud' (measuring the uncertainty, or MT scatter) is somewhat smaller than in Tests 2a,b which by no means implies that real uncertainty is smaller and/or that MT is better retrieved than in the previous (and following) methods.

d) Now again first no-cova and then the non-Toepplitz matrix [also in our tests somewhere called cova_FULLMOV]. The data error is greatly whitened (see delta-like correlation functions below). However, this method strongly enhances high frequencies in standardized seismograms (above 0.4 Hz) which do not contribute to fit improvement in standardized seismograms. Although time varying, nonstationary covariance is generally advantage, the strong enhancement of high frequencies in standardized seismograms may not always be welcome. To be further investigated…

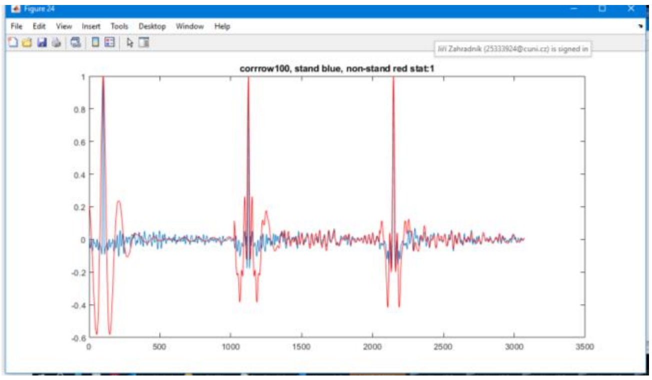
moment (Nm): 6.0362020E+17
moment magnitude: 5.8
VOL % : -11.3
DC % : 63.7
CLVD % : -25.1

strike,dip,rake:	262	65	163
strike,dip,rake:	358	75	25

varred= 0.5636913



Station 1:



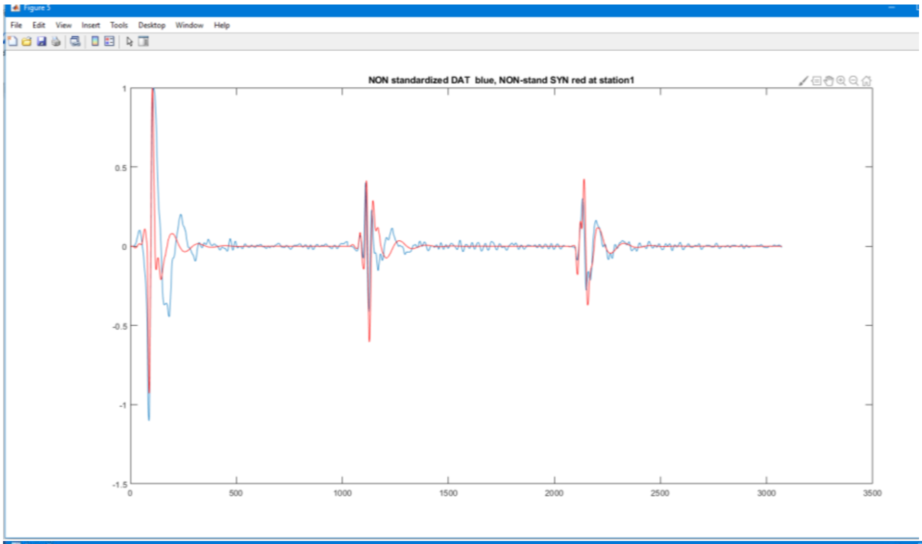


Figure 5
File Edit View Insert Tools Desktop Window Help
NON standardized DAT blue, NON-stand SYN red at station1

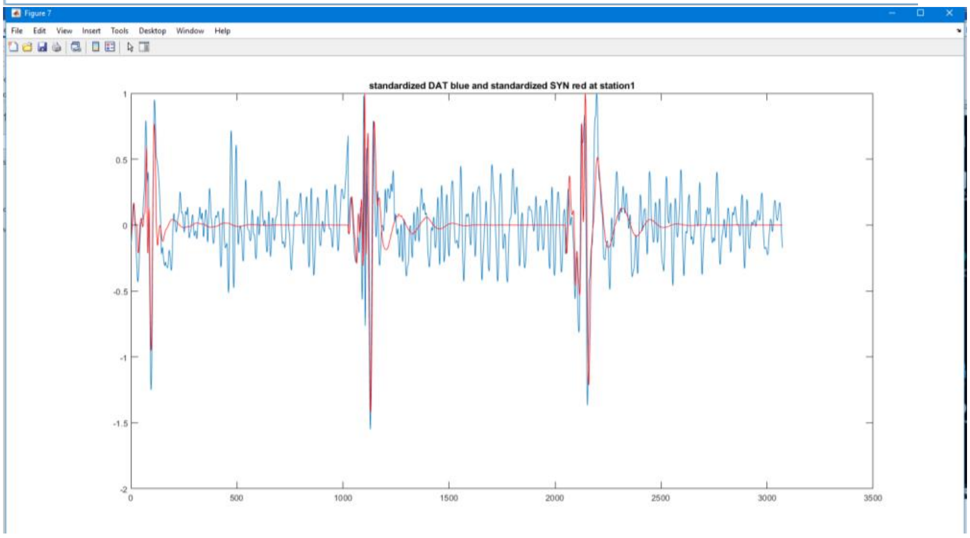
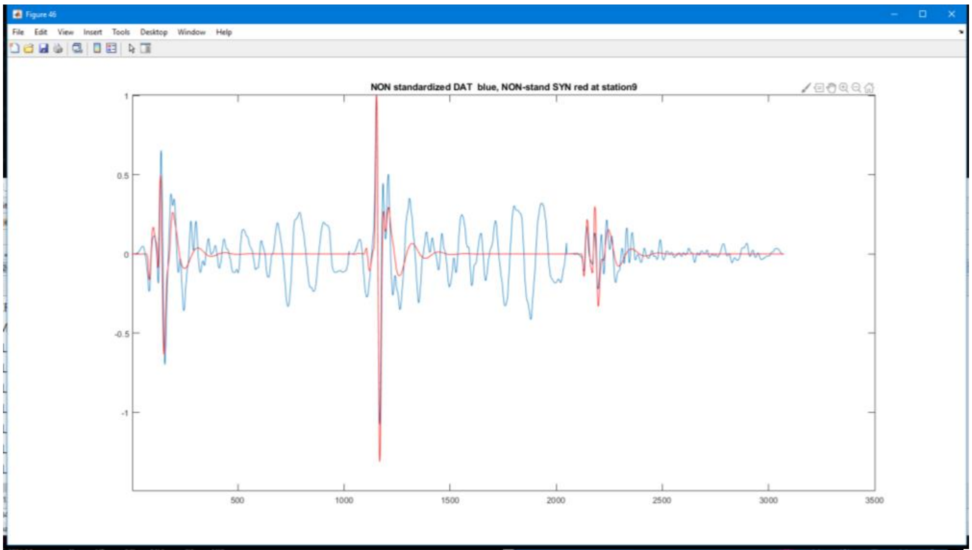
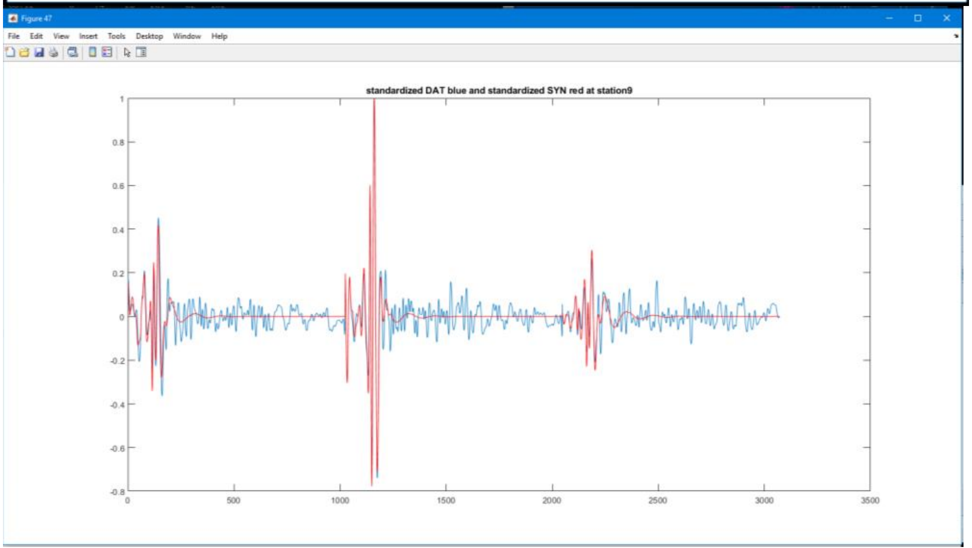


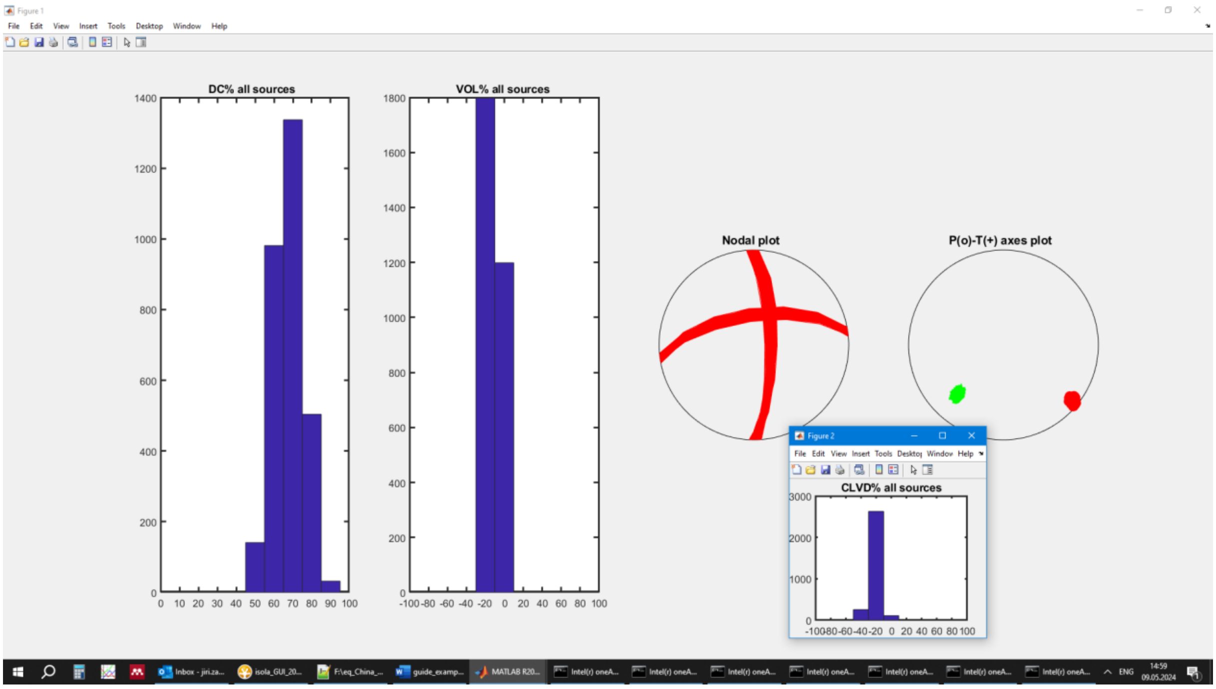
Figure 7
File Edit View Insert Tools Desktop Window Help
standardized DAT blue and standardized SYN red at station1

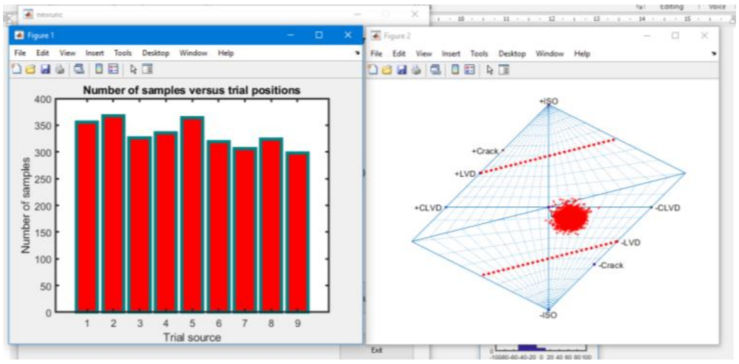
Station 9:





Note that the ratio of the components is similar in non-standardized and standardized waveforms (which was not the case with the previous methods).





Mean of DC% is : 67.7; STD of DC% is : 7.8
Mean of CLVD% is : -21.2; STD of CLVD% is : 6.4
Mean of ISO% is : -11.0; STD of ISO% is : 5.0

Summary:
The table compares the performance of the individual cova matrices with focus on non-DC.

The velocity model is 1D average from 3D
All provide Mw 5.8
All provide an increase of DC% and a decrease of |CLVD | compared to no-cova result. The no-cova result is outside the uncertainty range of the cova result.

Method	ISO% best	DC% best	CLVD% best	ISO% $[\mu/\sigma]$	DC% $[\mu/\sigma]$	CLVD% $[\mu/\sigma]$	VR
No cova	-13	57	-30	-11/7	61/7	-27/6	0.566
Variances (+exp)	-12	69	-19	-12/3	72/5	-16/4	0.560
Toeplitz	-13	63	-24	-12/3	67/7	-21/5	0.564
Non-Toeplitz	-11	64	-25	-11/5	68/8	-21/6	0.563
Ranges	-13, -11	54, 69	-31,-19	-12, -11	58, 72	-16, -31	

The above ranges are relatively broad which is a warning demonstrating how the same data can provide varying estimates of the non-DC components, solely due to different assumptions about data error.

Interestingly, if we adopt another velocity model (model Novotny) we can obtain the non-DC values even outside the above ranges, but with a slightly lower VR.

Method	ISO best	DC best	CLVD best	ISO $[\mu/\sigma]$	DC $[\mu/\sigma]$	CLVD $[\mu/\sigma]$	VR
No cova	-7	65	-28	-6/8	67/7	-25/6	0.546
Toeplitz	-8	73	-19	-7/4	78/6	-15/5	0.541

This demonstrates importance of an independent check that velocity model is appropriate.

These results can be discouraging. However, in Example 6 we shall demonstrate a physical situation in which non-DC components are even much less well resolvable than here. In the present example, we were luckier, at least we are sure that this earthquake had its DC > 60%.