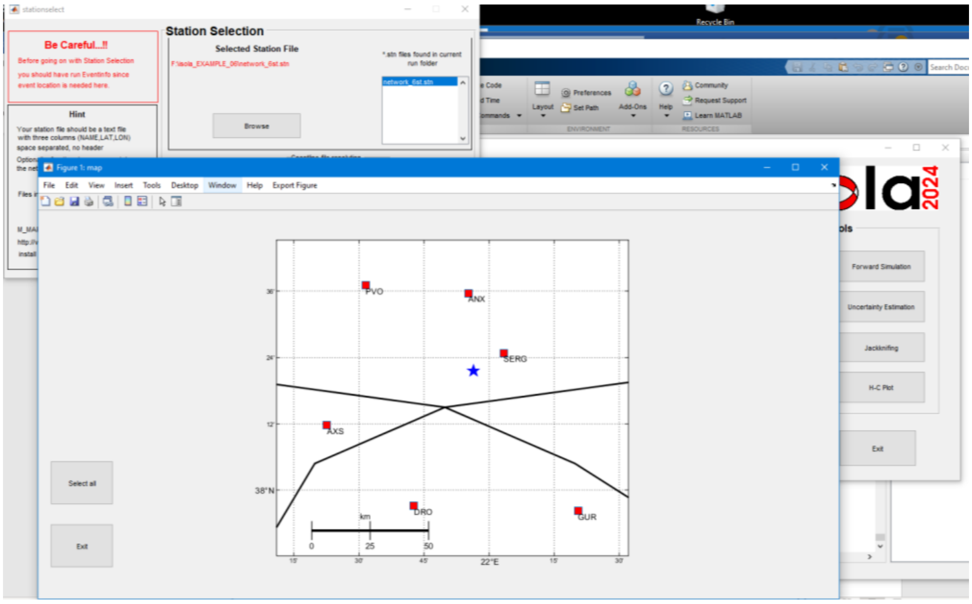
Example 06
Corinth rift, shallow Mw 5.3 earthquake. Hardly resolvable non-DC components.

Before this, see the introductory hints in isola_EXAMPLE_01.

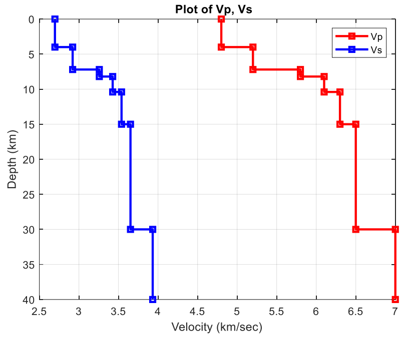
Preparation
Event Info. We study the largest event Mw 5.3 of the earthquake crisis 2020-2021 in the Corinth Gulf: 20210217 at 03:36:06.30 UTC, located by UPSL at Lat 38.36, Lon 21.94, the hypocentral depth 8 km. We choose TWL= 204.8 s, i.e., waveforms will be re-sampled with dt=0.2 s.
Due to some formal reasons, unimportant for this explanation, we set origin time in Event Info at 03:36:00.00 UTC, 6.3 seconds before true one; therefore, when the code will report calculated centroid time CTcalc, the true CT will be CTcalc-6.3.
Station Selection. Taking 6 stations, i.e. all from the file network_6st.stn, saved in the root folder. Epicentral distances 12-59 km.



Data Preparation. Copy into invert folder the *raw.dat from spare folder data_Isola_raw_1024.
Seismic Source Definition. Trial source positions below epicenter, starting at depth 3 km, depth step 1 km, 6 positions at the depth from 3 to 8 km.

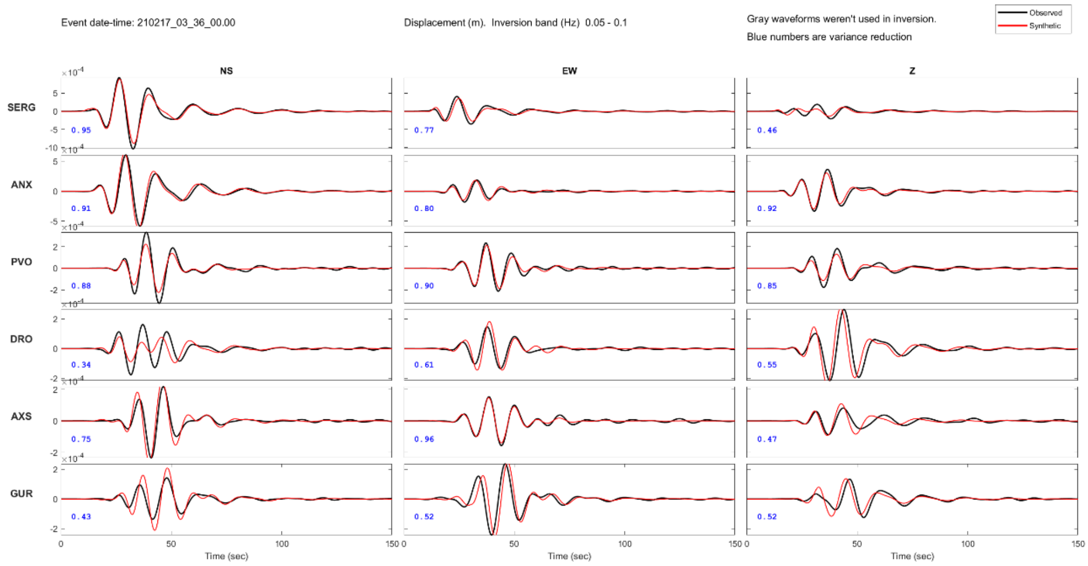
Test 1 Velocity model rigo.cru

Define Crustal Model. We start with the model which is most often used in studies of Corinth Gulf; the model after A. Rigo; rigo.cru taken from the root.

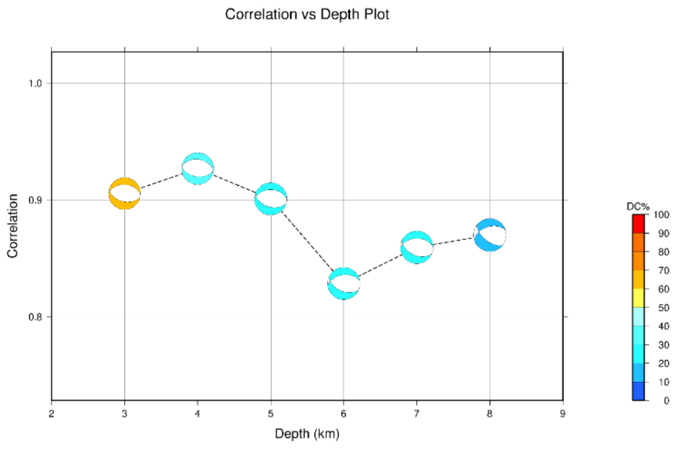


Green function calculation. GF is calculated up to the Nyquist frequency 2.5 Hz, assuming delta-function moment rate (default values); 6 trial sources, 6 stations.
Inversion, frequency range 0.05-0.10 Hz (common to all 6 stations). Time search -4 to +15 s, step 0.2 s. Choosing Full MT. Inversion standard (no_cova).

VR = 0.86 (read form the screen) is high, waveform fit is very good:



The formally optimal source position is no. 2 (depth 4 km), but the depth resolution 3-5 km is low.



From inv1.dat file in invert folder we read:

All trial positions and shifts for subevent# 1
(isour = source position,ishift*dt=time shift)

isour,ishift,corr,			moment,	DC%,	str,dip,rak,str,dip,rak					
1	38	0.905382	0.8348E+17	66.591	102	48	-84	274	41	-96
2	39	0.926849	0.9166E+17	35.530	97	48	-91	280	41	-88
3	38	0.900911	0.1049E+18	20.092	106	48	-80	272	41	-100
4	37	0.828404	0.1151E+18	22.191	261	45	-114	115	49	-66
5	36	0.859488	0.1313E+18	23.377	114	48	-73	270	43	-107
6	37	0.869951	0.1513E+18	12.556	253	48	-134	128	57	-51

Here I marked in yellow the column showing DC%, which is strongly varying with trial depth (partially seen also in colored beachballs of the above plot), i.e., we obtain a relatively high DC% only at the shallowest depth (no.1, depth 3 km).

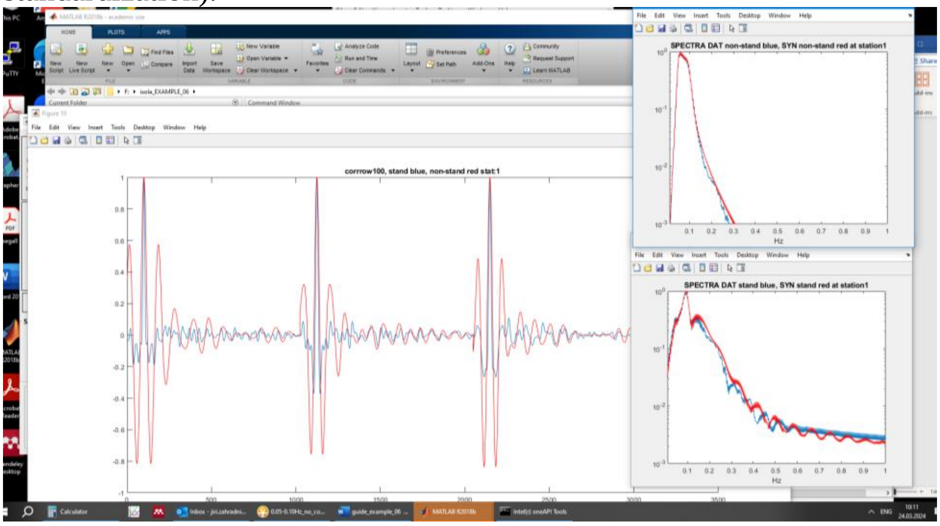
The best-fit solution:
Selected source position for subevent # 1
isour,ishift 2 39 ….. optimal position No, 2 (depth 4 km), time 39 dt

moment (Nm): 9.1663673E+16
moment magnitude: 5.3
VOL % : 35.7
DC % : 35.5
CLVD % : 28.8
strike,dip,rake: 97 48 -91
strike,dip,rake: 280 41 -88
varred= 0.8590469

A notable result are considerable values of VOL% [also known as ISO%] and CLVD%, hence a relatively low DC%.

Inversion, again frequency range 0.05-0.10 Hz (common to all 6 stations). Again choosing Full MT, but now inversion **with cova Toeplitz type** (formerly in our materials also called cova_FULL).

From Matlab command window:
varred_classical = 0.85757; varred_standardized = 0.86877
(increase of VR is null, but standardized residuals are less correlated than before standardization).



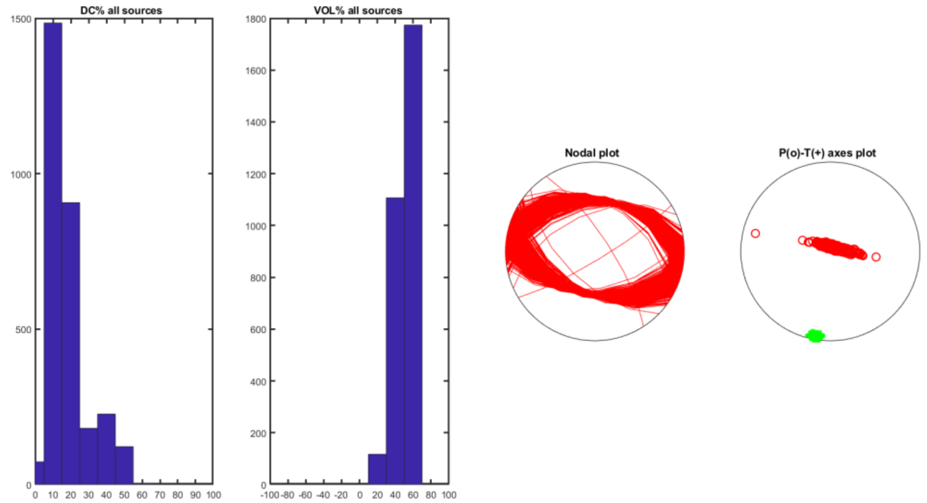
Iteration1

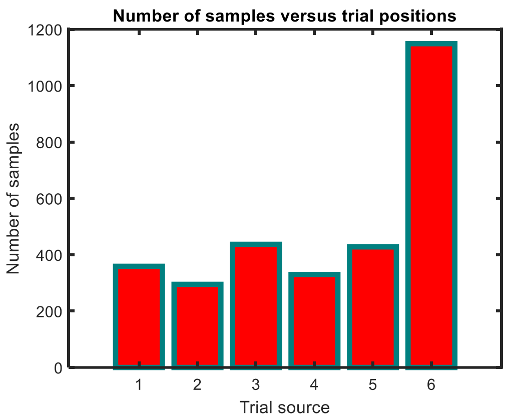
From inv1.dat:
moment (Nm): 9.5198551E+16
moment magnitude: 5.3
VOL % : 38.4
DC % : 29.9
CLVD % : 31.7
strike,dip,rake: 96 49 -92
strike,dip,rake: 280 41 -87
varred= 0.8575677

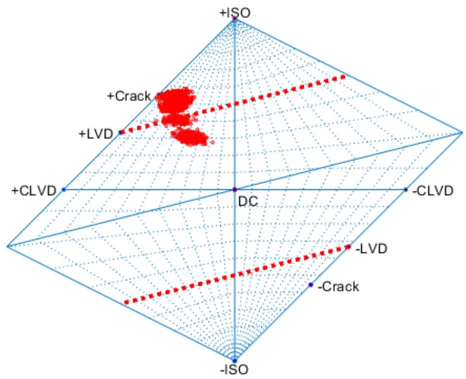
Iteration 2:

moment (Nm): 9.7459113E+16
moment magnitude: 5.3
VOL % : 40.6
DC % : 25.9
CLVD % : 33.5
strike,dip,rake: 95 49 -94
strike,dip,rake: 282 40 -84
varred= 0.8553417

After second iteration which shows almost the same VOL% as the first iteration, or as no_cova, we go to the main panel and choose Uncertainty (the lower button – including uncertain depth):







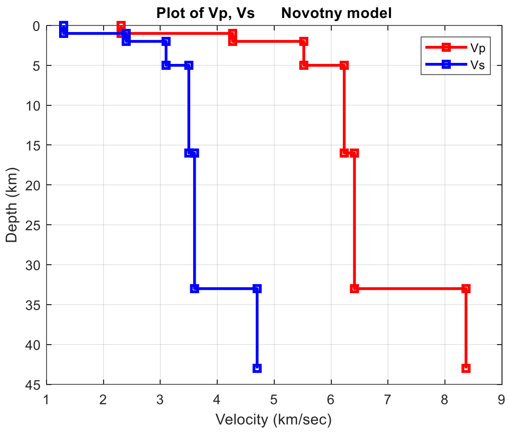
Strike/dip/rake angles are relatively stable. Perhaps only the P-axis (red circles) is less well resolved than the T-axis (green pluses). The DC, CLVD and ISO vary considerably with depth, thus in the source-type plot we observe three "red clouds". There is no single "cloud" preferred because of the best waveform fit. Therefore, overall, the standard deviations of the percentages are large:

Mean of DC% is : 17.6; STD of DC% is : 11.2
Mean of CLVD% is : 33.6; STD of CLVD% is : 4.4
Mean of ISO% is : 48.8; STD of ISO% is : 8.1

If we stop here, we should accept a significant deviation of the earthquake from 100% DC, the source type being close to an opening crack (ISO>0, CLVD>0). Anyway, we continue, and will further consider the effect of the assumed velocity model upon the non-DC components.

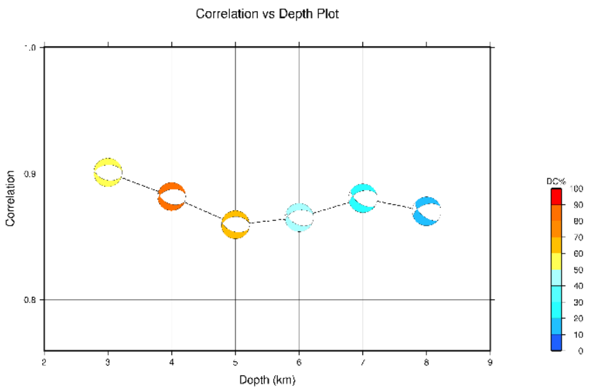
Test 2 Velocity model novotny.cru

Define Crustal Model. We continue with another model, that by O. Novotny, the model which often well fits waveforms in Greece: see file novotny.cru, taken from the root.

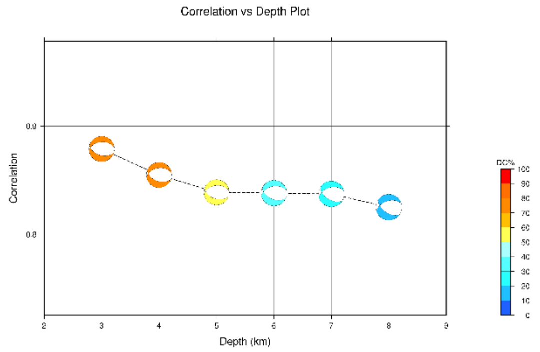


Inversion, frequency range 0.05-0.10 Hz (common to all 6 stations). Time search -4 to +15 s, step 0.2 s. Choosing Full MT. Inversion standard (no_cova).

From inv1.dat
Selected source position for subevent #   1
 isour,ishift   1   39
moment (Nm): 1.5595863E+17
   moment magnitude: 5.4
            VOL % : -24.3 ….. in model Rigo we had VOL= +35.7, a huge difference
            DC % : 55.9
           CLVD % : -19.8
 strike,dip,rake: 104   45   -77
 strike,dip,rake: 266   46   -102
varred= 0.8116943



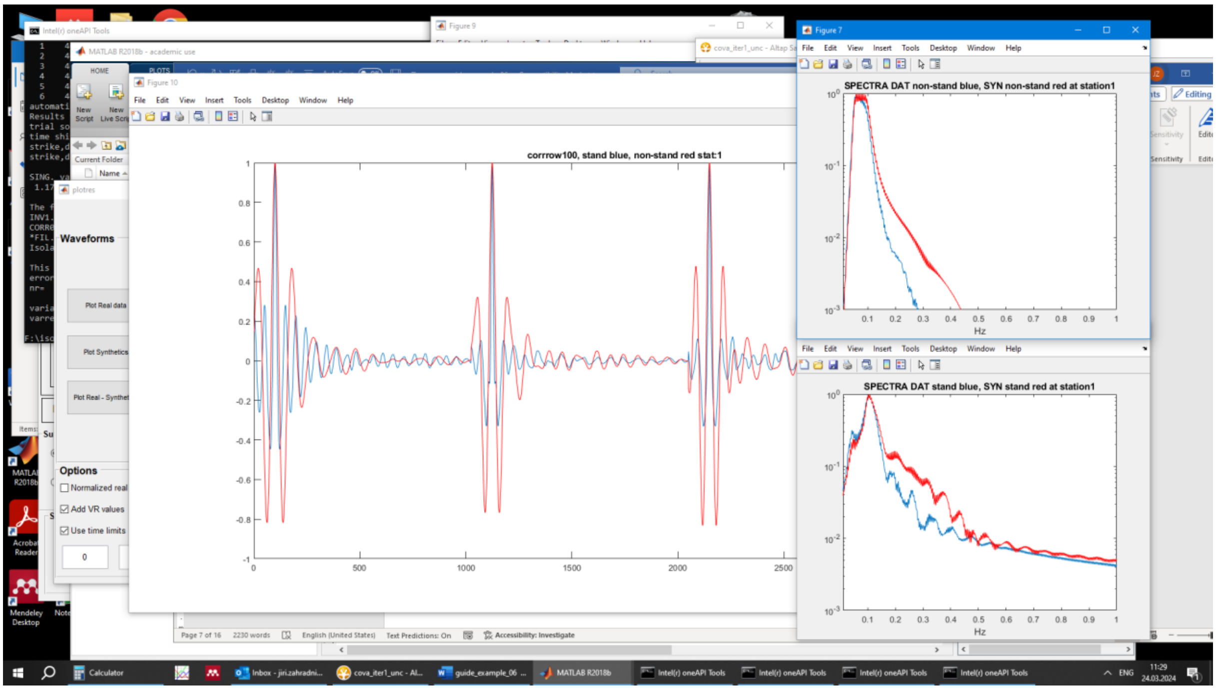
Inversion, frequency range 0.05-0.10 Hz (common to all 6 stations). Time search -4 to +15 s, step 0.2 s. Choosing Full MT. Inversion with cova (Toeplitz), formerly called FULL, the 1st iteration. See Test2 subfolder.



Position 1 is preferred (depth 3 km).

From inv1.dat in invert folder:
Preferred position no 1.
moment (Nm): 1.1569188E+17
moment magnitude: 5.3
VOL % : -13.0
DC % : 79.4
CLVD % : -7.6
strike,dip,rake: 265 44 -106
strike,dip,rake: 107 47 -74
varred= 0.7875482

From Matlab command window
varred_classical = 0.78755; varred_standardized = 0.85764

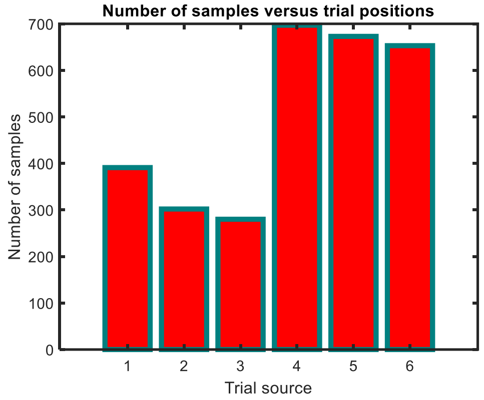


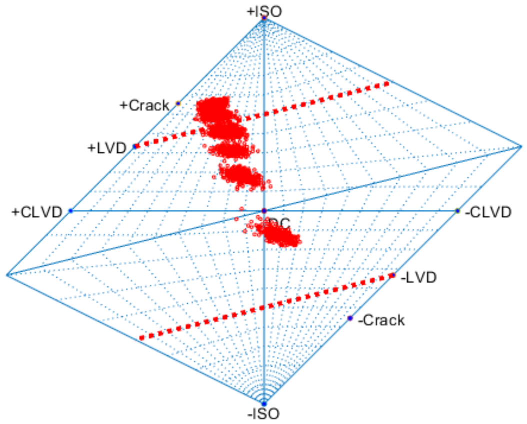
We observe a very different result compared to Test 1, the source is not far from 100% DC if considering the best-fit solution (preferred position No 1, depth 3 km).

The Uncertainty tool (its lower button, considering all trial positions, i.e., uncertain depth) applied after iteration 1, provides a mean DC% of 41.5, lower than in the preferred position above (where we encountered DC% of 79.4). The standard deviation of DC% = 22% is large due to many "clouds" in the source type plot. For this earthquake and velocity model, the method cannot prefer a single depth, and different depths provide different non-DC components.

Mean of DC% is : 41.5; STD of DC% is : 21.8
Mean of CLVD% is : 17.5; STD of CLVD% is : 11.3
Mean of ISO% is : 35.7; STD of ISO% is : 21.8

The MT cluster in the source-type plot, near the center of the graph, i.e., near the 100% DC, is just the above solution at the best-fit depth of 3 km (position 1), but the remaining clusters point to source type ranging from DC to an opening (+)crack.





Now let us inspect the variation of the solution **(with cova)** when doing **more iterations**. In each iteration, but not shown here, position 1 is the best-fit position regarding the waveform fit.

Iteration 2
VOL % : -9.3
DC % : 90.2
CLVD % : 0.5

Iteration 3
VOL % : -2.6
DC % : 88.4
CLVD % : 9.0

Iteration 4
VOL % : 1.6
DC % : 81.6
CLVD % : 16.7

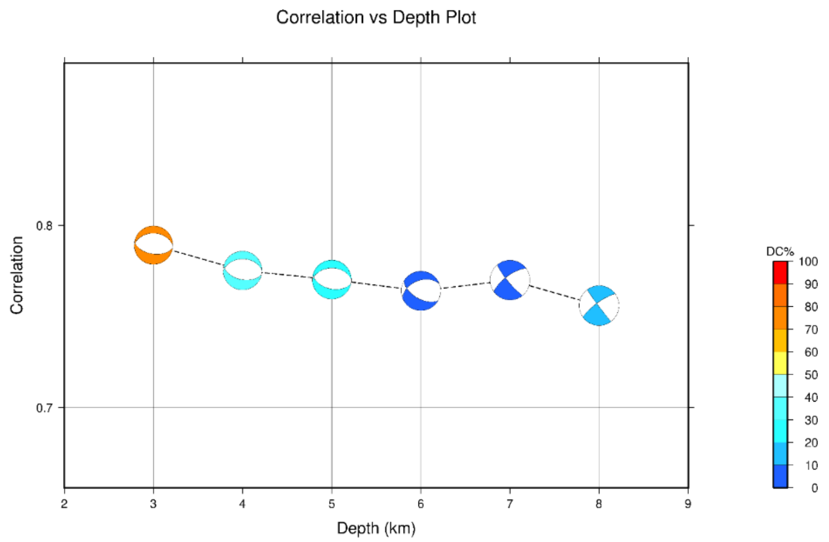
Iteration 5

VOL % : 4.0

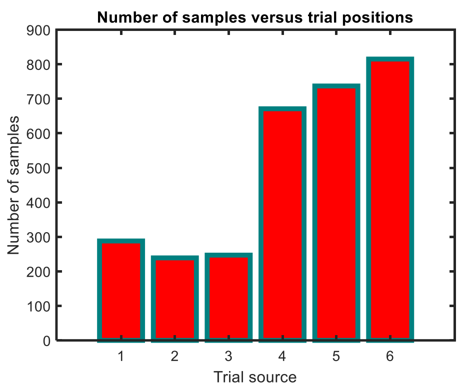
DC % : 77.6

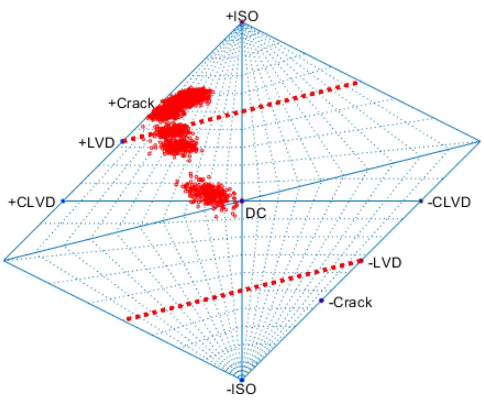
CLVD % : 18.4

At iteration 5, position no 1 is still (weakly) preferred, but we observe an even greater variation of focal mechanism and DC% with depth than in the 1st iteration.



The number of random samples (at each depth) is jointly determined by the waveform misfit and the posterior covariance matrix of MT; see file newunc_log.dat in the newunc folder. Since waveform misfit varies just a little with trial depth, the dept-variation of the covariance matrix has the dominant effect on the MT probability density: trial positions 4-6 (depths 6-8 km) have a greater number of random samples (those near the +crack), although the misfit is optimal at the trial position 1 (depth 3 km, near 100% DC).





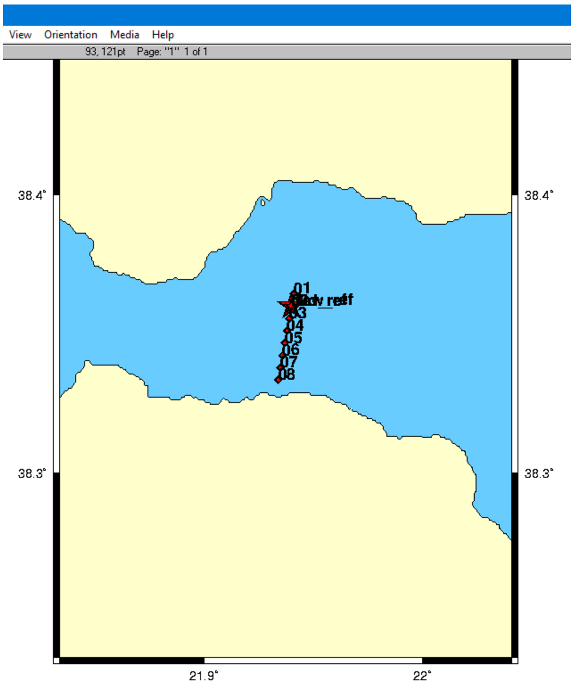
The most significant effect (indicated already after iteration 1) is that DC% strongly varies with depth. The shallowest depth provides a solution closest to 100% DC. Note that with velocity model Rigo we observed a similar trend, but never obtained so high DC% as here in model Novotny.

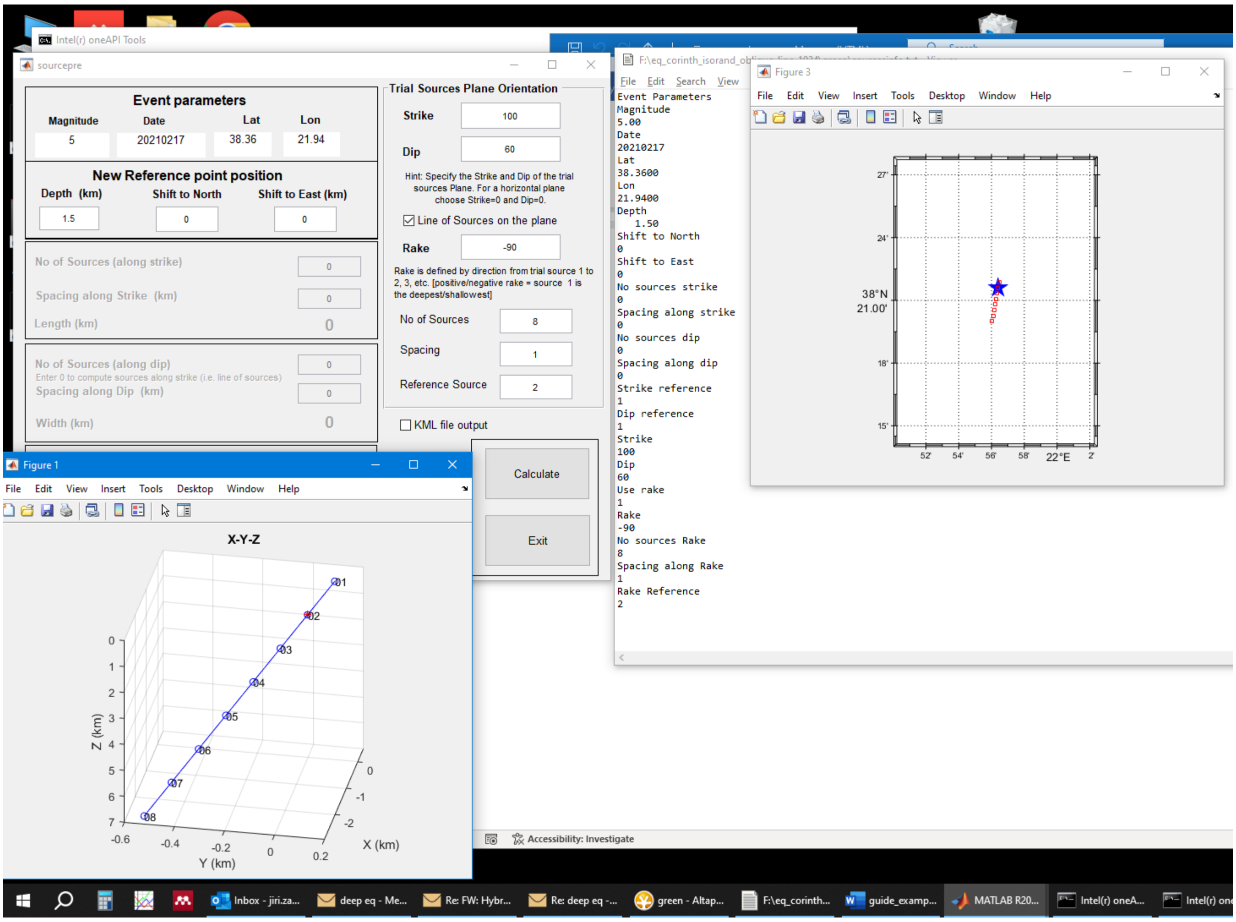
The major conclusion *for this particular earthquake* is that: (i) waveform fit varies just little with trial depth, hence we cannot robustly prefer the best-fit (shallowest) depth, (ii) DC% varies very strongly with trial depth, so – due to (i) – we cannot quite safely prefer the shallowest depth with the largest DC% (~80% in model Novotny), and (iii) velocity model has great effect on non-DC (in model Rigo, even when adopting the shallowest best-fit depth, DC% would be still quite low, definitely < 50%).

As hypocenter of this earthquake was near the largest trial depth, we can speculate whether event has started at the 8-km depth as a non-DC small shock which has later evolved into a major shallow moment release of the DC type. In Corinth Gulf, at the 6-10 km depth, there is a detachment zone characterized by common occurrence of swarms and fluid flows, where a small non-DC event would be possible.

Test 3 Inclined line of trial positions

The line inspired by the paper Zahradnik et al., JGR 2022. Again, model of Novotny is used.





Trial sources can be found in sources.gmt file, saved in Test3\green

Lon	Lat	depth
21.9409934559	38.3644359332	0.6339745962 01
21.9400000000	38.3600000000	1.5000000000 02
21.9390066654	38.3555640550	2.3660254038 03
21.9380134520	38.3511280983	3.2320508076 04
21.9370203597	38.3466921297	4.0980762114 05
21.9360273886	38.3422561494	4.9641016151 06
21.9350345386	38.3378201573	5.8301270189 07
21.9340418097	38.3333841535	6.6961524227 08

Points 1 and 8 are the shallowest and deepest, respectively.

<u>Define Crustal Model</u>. We continue with novotny.cru.
<u>Inversion, frequency range 0.05-0.10 Hz (</u>common to all 6 stations). Choosing Full MT. First we try Inversion standard (no_cova)

From inv2.dat in invert folder

```
 Point time moment                                                        DC% cummulVR
 4  7.60  0.15373E+18  266.  43.  -103.  103.  49.  -78.  76.  81.  185.  3.  276.  9.  58.8  0.84093E+00
 1  5.00  0.24620E+17  275.  60.  86.  102.  30.  96.  8.  15.  175.  75.  277.  3.  85.4  0.89716E+00
```

Since we invert only low frequencies < 0.1 Hz, we obtain effectively a single-source model, the second subevent (in point 1) has its moment 10-times smaller than subevent 1, so it is non-physical (thus shaded).

Then continuing with cova – iteration 1.

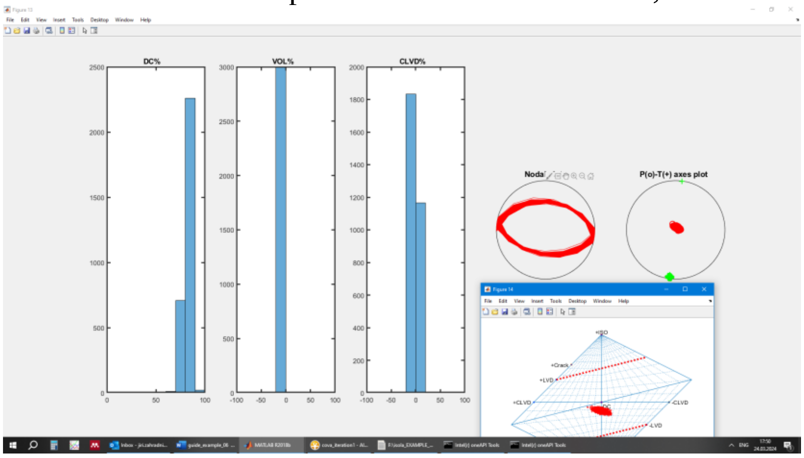
From inv2.dat in invert folder

Point time moment DC% cummulVR

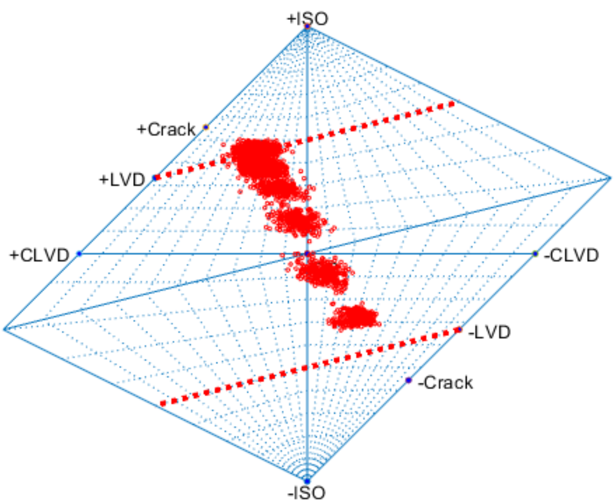
4 7.80 0.11262E+18 99. 49. -88. 276. 41. -93. 32. 86. 187. 4. 278. 2. 85.4 0.81715E+00

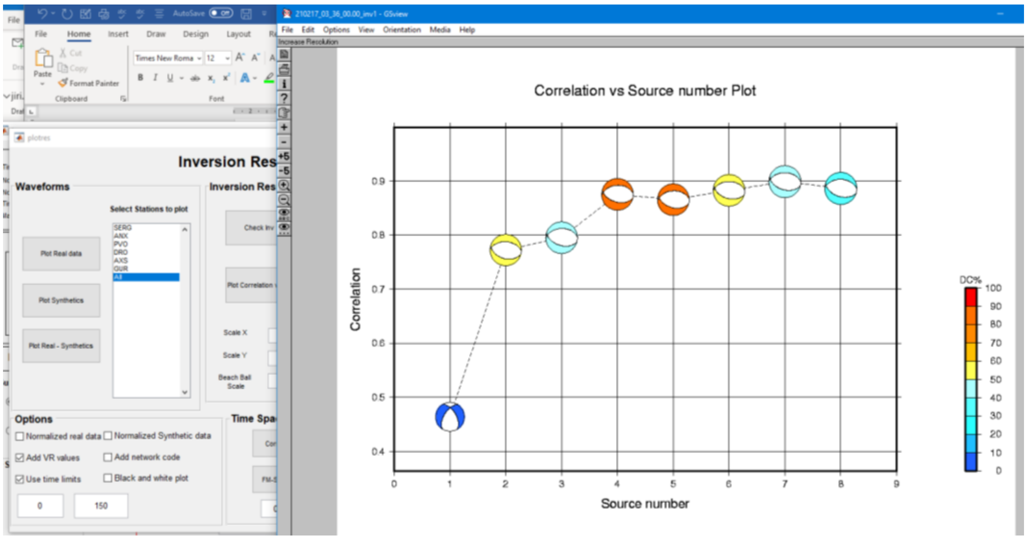
1 8.00 0.67532E+16 78. 80. 82. 299. 13. 130. 175. 35. 338. 54. 80. 8. 29.4 0.85661E+00

We observe a similar result as in Test 2, now on the inclined line, the dominant subevent 1 is at trial point No. 4, is shallow (depth 3.2 km), and its DC% is large. Uncertainty estimate at the best-fit position No. 4 (using the upper button of the Uncertainty tool, i.e. Method 1) shows that MT at this position is near to 100% DC, and is well resolved.



However, when involving position in the uncertainty estimate (the lower button, Method 2), then after inversion with cova, iteration 1, we again find a strong tradeoff between non-DC component and depth.

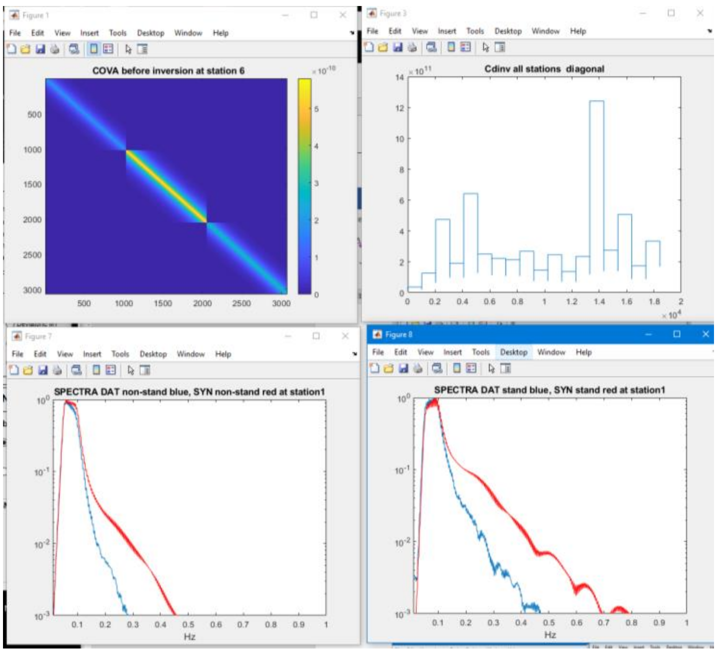


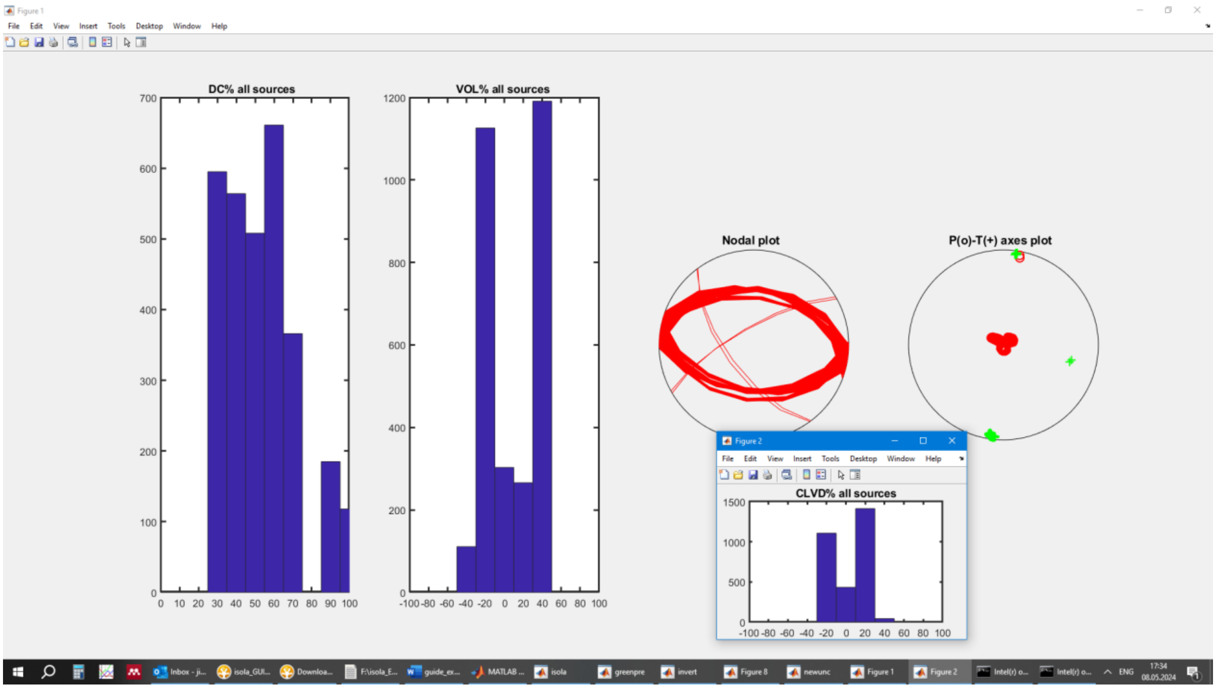


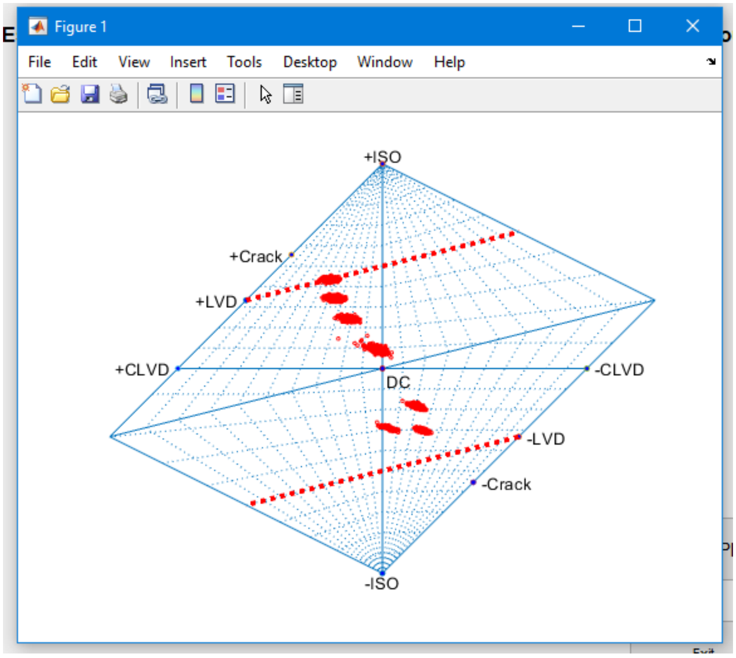
It would be interesting to increase the maximum frequency of inversion Fmax beyond 0.1 Hz, so that the source model would have at least two subevents, and to study whether perhaps the deep one can be non-DC, and the shallow one closer to DC. However, I obtained no stable results of this kind because for Fmax ~ 0.3 Hz the waveform fit was already poor due to the imprecise velocity model. Thus, I was unable to prove the hypothesis that the event started as a non-DC deep subevent, followed by a major DC shallow subevent.

The rest of this tutorial is less important. It focuses on the alternative cova matrices without any qualitatively new result.

We return to Fmax 0.1.
<u>Inversion, frequency range 0.05-0.10 Hz (</u>common to all 6 stations). Choosing Full MT. We calculate a singe subevent, first with inversion standard (no_cova), then with cova_Variences [formerly during creation of these examples also called COMPVAR].

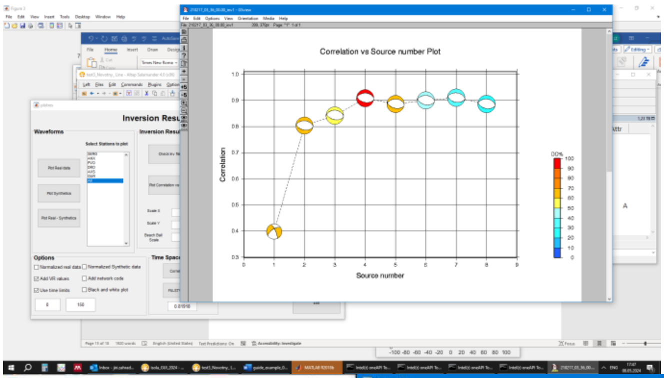


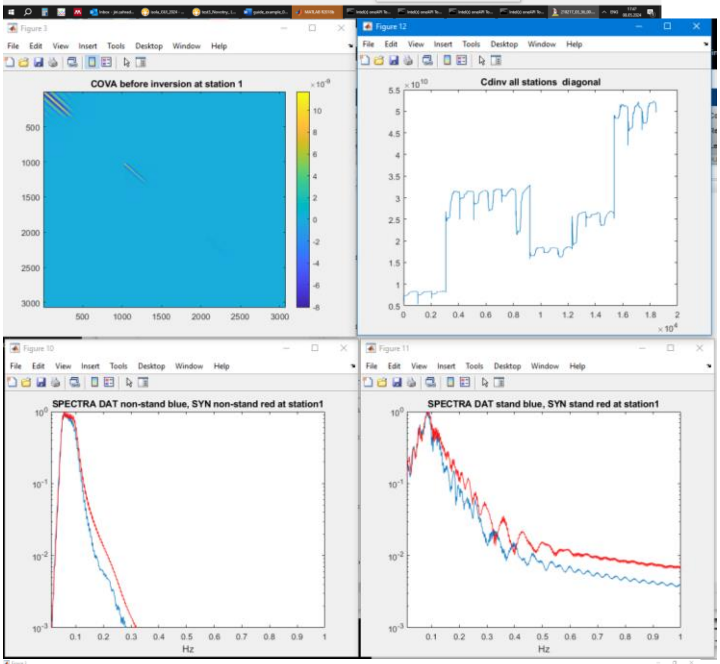


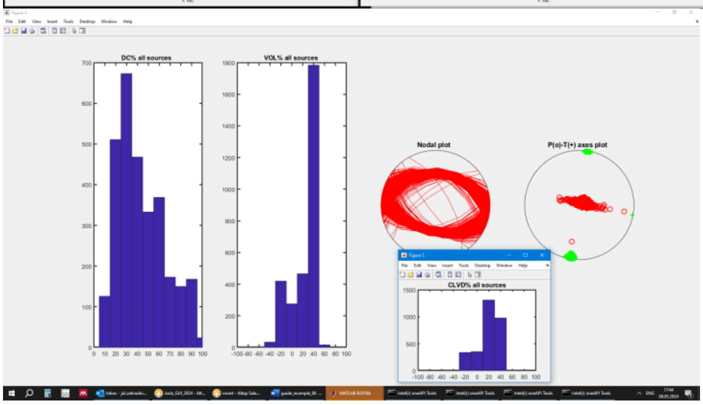


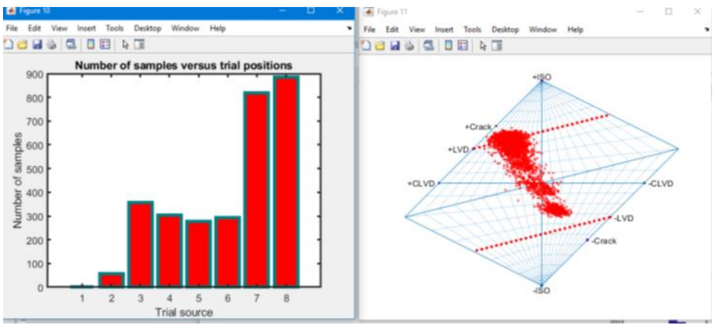
Analogical result with Non-Toeplitz matrix [formerly called in these examples also FULL_MOV]: First no-cova, then this…)

7 7.60 0.13882E+18 103. 48. -86. 276. 42. -95. 58. 86. 189. 3. 280. 3. 33.1 0.79395E+00









The Isola users should learn that sometimes they must conclude that **full MT cannot be reliably retrieved**, and only strike/dip/rake angles are relatively robust. This is the situation of this earthquake.