

NON-LINEAR FOCAL MECHANISM SOLUTIONS:
A PARAMETRIC STUDY OF THE EARTHQUAKE
NEAR PLOVDIV (BULGARIA) ON FEBRUARY 21, 2018

Reneta Raykova[✉], Lyuba Dimova

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Abstract

The focal mechanism of the M_W 4.4 earthquake that struck on February 21, 2018, near the city of Plovdiv (Bulgaria) was investigated by using the INPAR method. INPAR is a non-linear inversion approach that estimates a moment tensor by comparing observed and synthetic seismograms. Waveform data from multiple seismic data centres were collected and processed to ensure consistency in the sampling rate and time window. Synthetic seismograms were computed using various parameters, such as velocity structure, origin time, location, depth, and rupture duration. The impact of the above parameters on the reliability of the obtained moment tensor was evaluated by conducting numerous tests. The final focal mechanism, computed with INPAR, was determined in two steps: a linear search and a non-linear search in the parameter space. The computed rupture mechanism was then compared with the parameters of the known seismogenic faults in the region. The study establishes a set of parameters suitable for exploring the rupture characteristics of the moderate earthquake near Plovdiv and contributes to a better understanding of the faulting processes in the Maritsa fault zone.

Key words: focal mechanism, structure models, localization, source time function, INPAR

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Introduction. Focal mechanism (FM) solutions are crucial for understanding earthquake rupture processes and the geodynamic behaviour of seismically active regions. The traditional methods for determining FMs have primarily been designed for strong earthquakes (magnitude $M > 5.0$) and have relied on data from globally distributed seismic stations and long-period seismic waves (greater than 30 s, in GCMT [1] and RCMT [2]).

The recent seismicity in Bulgaria has been typically low to moderate, with magnitudes rarely exceeding 5.0 [3]. In the region, FMs have previously been determined by using the first-motion polarity of seismic waves [4]. However, this approach can be affected by various factors, including seismic noise, station orientation errors, and uneven station distribution, which may lead to inaccurate results.

This study presents the application of the non-linear INdirect PARametrization (INPAR) inversion method [5] for determining the focal mechanisms (FMs) of moderate earthquakes ($4.0 < M < 5.0$) in Bulgaria and the adjacent areas. While INPAR has been successfully applied in various tectonic settings worldwide, its application to moderate events in Bulgaria has not yet been systematically investigated. In this work, we analyze the earthquake that occurred on February 21, 2018, and assess the influence of different parameters, such as velocity models, event localization, and source time function, on the derived FM and using data from a limited number of seismic stations. The event had a moment magnitude of M_W 4.4 (MED_RCMT, <https://rcmt2.bo.ingv.it>).

Geologic and tectonic settings. The studied earthquake occurred near Plovdiv, within the Upper Thracian Lowland according to the geomorphological zonation of Bulgaria [6]. This basin is primarily shaped by the Maritsa river, which flows east-southeast between the Sredna Gora and the Rhodope Mountains. The formation and evolution of the basin are closely linked to the tectonic activity of the Maritsa Fault Zone, which has influenced both the sediment deposition and the landscape development in the area. KOUNOV and GERDJIKOV [7] critically examine the proposed wrench tectonic model for the central Sredna Gora Zone, which also includes the Maritsa Fault Zone, where predominantly strike-slip movements are suggested. They claim that, although strike-slip and oblique-slip structures are present, their timing and contribution to the deformation of the region are not yet fully understood.

The regional context is illustrated in Fig. 1a, which shows the seismicity ($M > 4$), the reference location of the studied event (ISC estimates, [8]), and location of the seismic stations used in this study. Figure 1b presents the seismogenic faults according to the European Database of Seismogenic Faults (EDSF) [9], along with the epicentre of the event as determined by various data centres [8] and the previously reported FMs [8, 10].

Data and method. The earthquake selected for this study occurred near the city of Plovdiv, Bulgaria, with the following reference parameters (ISC so-

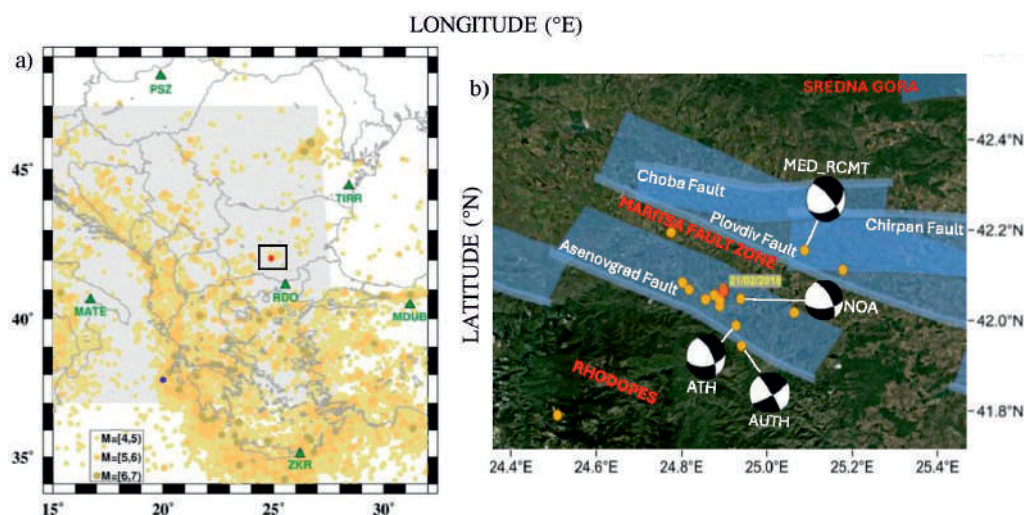


Fig. 1. (a) Map of the region shows: the observed seismicity by yellow, orange, and beige dots, scaled to magnitude and indicating earthquake epicentres ($M > 4$) from 1970 to 2020 [8]; the location of the selected seismic stations – green triangles; the studied earthquake epicentre – red dot; the gray area is covered by velocity models “cell” from [11] and the white area – by models “EurID” extracted from [12]. The black rectangle zooms the region around the studied event. (b) Seismogenic faults according to EDSF [9]; the reference location of the studied event as ISC solution (red dot [8]); the locations obtained by different seismological data centres (given in [8]) are shown by orange dots; the FMs according to different data centres [8, 10]) for the studied event are shown as beach balls, connected to the relevant epicentre. Seismogenic EDSF faults are shown as upper fault boundary (thick blue lines) and fault projection on the surface (blue area)

lution [8]): M_W 4.4 (MED_RCMT), origin time 2018/02/21 23:41:58.82 UTC, location at 42.066°N 24.900°E, and depth of 9.3 km. Published FMs [8, 10] indicate different types of rupture, ranging from predominantly normal faulting to nearly strike-slip faulting, with M_W between 4.2 and 4.4.

A range of parameters were tested to select the most suitable configuration for the INPAR procedure used to calculate the FM of this event. Freely available seismograms were collected from SAGE (<https://www.iris.edu>), GEOFON (<https://www.geofon.de>), and the Romanian EIDA node (<https://eida-sc3.infp.ro>) for 21 stations. The 30-min mseed data were decimated to 5 sps and aligned to a common time window. The data were then converted to SAC format, required for analysis by the INPAR software. The seismograms were filtered using a low-pass filter, with a corner frequency that varied by station (0.1 Hz is generally used). After several preliminary iterations with different sets of station components, we selected records from only six stations due to the low signal-to-noise ratio ($SNR < 2$) and the presence of a second, nearly simultaneous, event in the region that altered some waveforms. Only station RDO has good correlation (> 0.5) for all three components and only Z component is used at other stations.

The INPAR method is an inversion technique designed to retrieve the moment tensors, particularly for moderate-to-low magnitude earthquakes ($M_W < 5$). Developed and refined at the University of Trieste [5], INPAR employs a point source approximation and utilizes waveform data from seismic stations at epicentral distances up to 2500 km. The method systematically computes theoretical seismograms for varying depths and epicentral locations, allowing for a flexible and accurate representation of the earthquake source [13]. INPAR iteratively compares theoretical seismograms with observed data, analyzing waveforms of relatively short periods (generally ≥ 10 s, using a low-pass filter with a 0.1 Hz corner frequency), making it particularly suitable for shallow earthquakes. The correlation coefficient is calculated as an average of all samples of observed and synthetic seismograms for all selected station components, filtered with the low-pass filter, to define the best-fitting moment tensor (MT). Additionally, INPAR performs a non-linear genetic search to assess the robustness of the solution and selects a final set of source parameters, including seismic moment and temporal rupture function.

Results. All tested parameters for the selected earthquake, along with the obtained FM planes and the MT magnitudes (derived by INPAR method application), are summarized in Table 1. We initially fixed a set of parameters and performed INPAR varying only the event depth. The solution showed relatively good waveform correlation between observed and synthetic seismograms (0.77) and relatively small error in depth estimation. However, the MT magnitude was underestimated in the linear INPAR inversion ($M_W = 3.9$) and overestimated in the subsequent genetic non-linear inversion ($M_W = 5.1$). In the following tests, only one parameter was varied at a time to reduce uncertainty in the results.

In Test 1, we employed specific epicentre-to-station averaged velocity structures based on the $1^\circ \times 1^\circ$ “cell” models from [11] (grey area in Fig. 1a) and $1^\circ \times 1^\circ$ “EurID” models from [12] for regions not covered by [11] (white area in Fig. 1a). In Tests 2, 3 and 4, different velocity models were applied: Test 2 – general epicentre-to-station averaged “EurID” model [12]; Test 3 – common model for the study area (averaged “cell” models [11]) applied to all epicentre-to-station paths; Test 4 – variable models interpolated between models in Test 1 and in Test 2 for each epicentre-to-station path. Test 3 yielded the highest waveform correlation (0.79) and the smallest depth error (± 0.3 km). FM plane parameters varied by a few degrees relative to Test 1, while the estimated magnitudes remained unchanged.

The velocity model strongly influences travel times and, consequently, the event origin time. In Tests 5 and 6, time-shifts of 0 s and 3 s from the origin time (2 s in Test 1) were applied. Test 5 resulted in a magnitude M_W 4.9 closer to published estimates, and the strike of the first plane was about 40° smaller. Waveform correlation in Test 6 matched that in Test 1, but depth resolution was improved. The event depth was found to be highly sensitive to the velocity model.

T a b l e 1

Tested parameters and resulting FMs

Test No	Parameter	Value	WfCor; Depth [km] ¹	FM planes ² – linear; M_w	FM planes ² – genetic; M_w
1	Initial set	³	0.77 25.3–3.3	168 72 –165/ 73 76 –19; 3.9	 168 70 –168/ 74 78 –20; 5.1 
2	Model	EurID	0.42 14.7±0.7	154 74 –167/ 60 77 –16; 3.7	 156 72 –169/ 63 80 –18; 4.9 
3	Model	Common	0.57 20.7±0.5	166 80 –178/ 75 88 –10; 3.9	 165 76 177/ 256 87 14; 5.1 
4	Model	Cells- EurID	0.79 23.6±0.3	164 69 –167/ 69 77 –21; 3.9	 165 69 –169/ 71 80 –21; 5.1 
5	Time- shift	0 s	0.45 25.0–15.0	131 64 –163/ 33 75 –27; 3.6	 130 64 –163 33 75 –27; 4.9 
6	Time- shift	3 s	0.77 21.3±0.4	171 77 –169/ 79 80 –13; 3.9	 172 77 –171/ 80 81 13; 5.1 
7	Depth step	1.5 km	0.75 25.0–24.0	169 72 –166/ 74 76 –18; 3.9	 170 71 –168/ 76 79 –19; 5.1 
8	Depth step	2 km	0.71; 25.0–21.0	168 73 –164/ 73 75 –17; 3.9	 168 71 –167/ 74 78 –19; 5.1 
9	Depth and location step	2 km; 0.1°	0.74 20.7±1.1 42.05±0.02 24.95±0.00	75 71 –8/ 168 83 –161; 3.9	 171 81 –166/ 79 76 –9; 5.1 
10	STFTs ⁴	3	0.71 24.0–11.0	169 70 177/ 260 87 20; 3.8	 169 68 168/ 264 79 22; 4.7 
11	STFTs ⁴	4	0.73 25.0–17.0	169 70 –173/ 77 83 –20; 3.8	 170 70 –172/ 77 82 –20; 5.0 
12	Low-pass frequency	0.12 Hz	0.51 20.8±4.0	155 71 –174/ 63 84 –19; 3.8	 156 70 –175/ 64 85 –20; 4.9 
13	Low-pass frequency	0.15 Hz	0.36 25.0–17.0	146 64 –176/ 54 86 –26; 3.9	 51 83 –32/ 146 58 –171; 4.9 
14	Final set	⁵	0.71 21.3±3.4 42.08±0.02 24.90±0.02	177 74 177/ 268 87 16; 3.8	 177 74 178/ 267 88 16; 4.9 

¹ Depth error is given by “±error” when the estimated depth is inside the explored depth interval; the symbol “–error” is used when the estimated depth is close to the maximal possible value and “+error” exceeded the maximal depth in the explored depth interval.

² FM planes: plane I (strike° dip° rake°)/ plane II (strike° dip° rake°).

³ Reference parameters: cellular structures (cells, [11]); time-shift 2 s; source time function triangles – 5; fixed geographical coordinates (42.066°N; 24.900°E), depth between 1.3–25.3 km with a step of 4 km; low-pass corner frequency 0.1 Hz.

⁴ STFTs – Source Time Function Triangles with 10 s width and half width overlapping.

⁵ Final parameters: scaling between two models (cells [11] and EurID [12]), time-shift 3 s, source time function triangles – 3; epicentral geographical coordinate step ±0.05°; depth between 5.3 and 25.3 km with a step of 4 km, low-pass corner frequency of 0.1 Hz.

Depth steps were varied in Test 7 and Test 8 (1.5 km and 2 km, respectively), compared to 4 km in Test 1. Although waveform correlations were slightly lower than in Test 1, depth errors were large, nearly comparable to the depth of the event. The focal plane parameters and magnitudes remained largely unchanged.

Some uncertainties in the velocity model can be compensated by small adjustments in the event location and depth. In Test 9, we varied both geographic coordinates (epicentre step 0.05°) and depth (step 4 km). The resulting event depth was 20.7 ± 1.1 km, and the epicentre coordinates were $42.05 \pm 0.02^\circ\text{N}$ and $24.95 \pm 0.001^\circ\text{E}$. The waveform correlation was 0.74, nearly equal to the highest correlation of 0.79 in Test 3. No significant changes in the FM plane parameters and magnitude were observed compared to Test 1.

Another investigated parameter was the source time function, which was modelled using several half-overlapping triangles. The width of each triangle corresponds to the shortest period in the signal, as defined by the low-pass filter corner frequency (10 s, corresponding to a corner frequency of 0.1 Hz). The number of the triangles determines the maximum rupture duration and is closely related to the true origin time, applied time-shift, low-pass filtering, and indirectly, to the velocity model and event depth. In the initial Test 1, five triangles were used, defining the maximum rupture duration of approximately 30 s. In Tests 10 and 11, three and four triangles were employed, respectively. These changes resulted in decreased waveform correlation (0.71 and 0.73), larger errors in the estimated depth, focal planes parameters like in Test 1, and magnitudes of M_W 4.7 in Test 10 and M_W 5.0 in Test 11.

The low-pass corner frequency is crucial for the waveform shape, as it also determines the width of STFTs and the estimated rupture duration. In Tests 1 to 11, a cut-off frequency of 0.1 Hz was used for low-pass filtering of the seismograms. In Tests 12 and 13, cut-off frequencies of 0.12 Hz and 0.15 Hz were applied, respectively. Increasing the cut-off frequency resulted in more complex waveforms, making it difficult to identify the main wave package for some stations. These tests showed a significant decrease in waveform correlation. The resulting M_W was 4.9 for both tests.

Based on the results of all tests, we selected the final set of parameters (listed in Table 1). The MT inversion using this parameter set yielded a good waveform correlation (0.71), an epicentral location error of 0.02° , a depth of approximately 21.3 km with an error of 3.4 km, and a final magnitude $M_W = 4.9$. The focal planes parameters are $267^\circ/88^\circ/16^\circ$ (Plane I) and $177^\circ/74^\circ/178^\circ$ (Plane II). The INPAR inversion results with the final parameter set are illustrated in Fig. 2. The solution is consistent with the one from AUTH (<https://seismo.auth.gr/>), and the plane parameters are close to those of the Chirpan fault (EDSF, [9]).

Parametric tests are critical in studies of complex geographic regions, as default parameters often do not capture the specific seismicity characteristics or geological and geophysical peculiarities. Careful selection of inversion parameters significantly improves the reliability and accuracy of the obtained results.

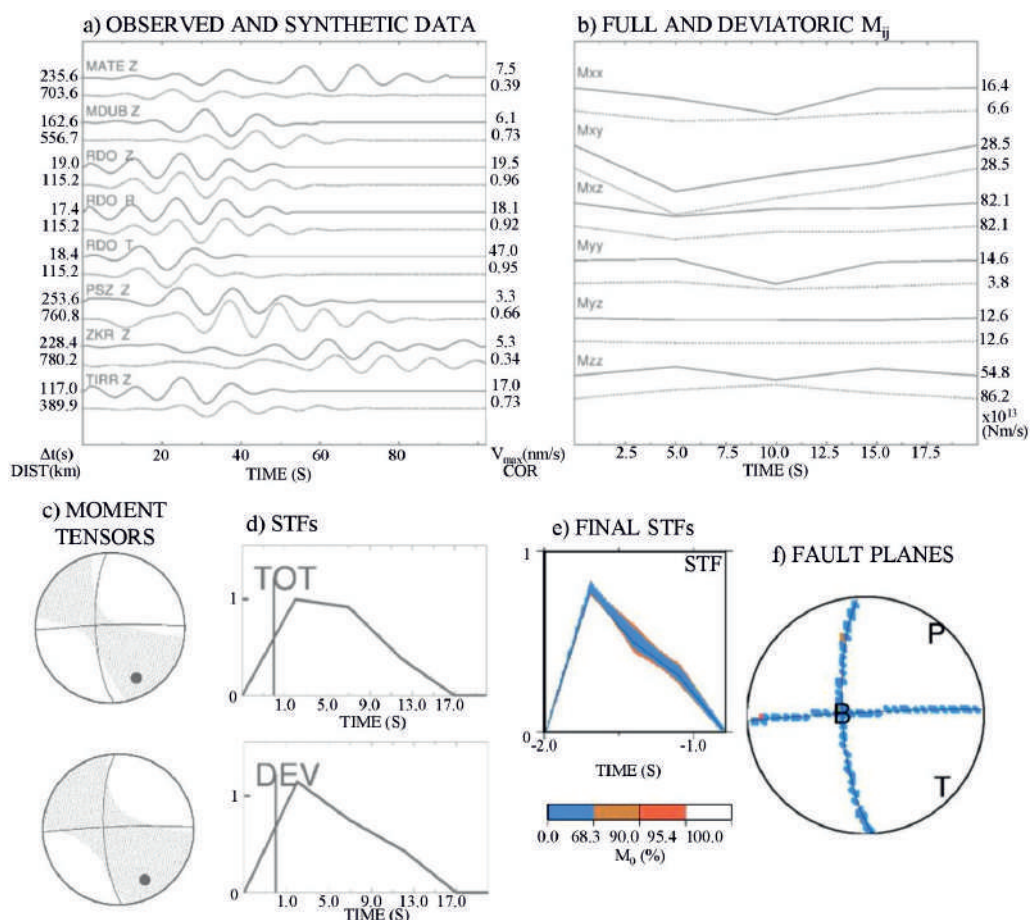


Fig. 2. Results of the inversion. (a) Waveform fit between synthetic (thin line) and observed (thick line) seismograms, where for each station the numbers on the left indicate the time after the origin time Δt and epicentral distance DIST, and the numbers on the right give the maximum velocity amplitude V_{max} in nm/s and correlation COR. (b) Calculated MT components M_{ij} ($i, j = x, y, z$) as total (thick lines) and deviatoric parts (dotted lines); the numbers on the right indicate the maximum value of each component. (c) Total and deviatoric MT with beachball representation; the black point indicates the positive polarity of the first P-wave arrival at station RDO. (d) Source time functions for total and deviatoric MT. Non-linear solution for the analyzed events: (e) source time function and scalar seismic moment value, and (f) fault plane solution with noted pressure (P) and tension (T) sections as well as null axis B

Conclusion. Parametric tests of the INPAR method for the February 21, 2018 earthquake near Plovdiv (M_W 4.4) indicate that optimal results are obtained using an interpolation between two velocity models in the inversion, joint parametrization of location and depth, application of a time-shift in the origin time, a small number of source time function (STF) triangles, and, where possible, a higher corner frequency for low-pass filtering of the seismograms. The obtained event depth and focal planes parameters suggest that the earthquake most likely occurred along the Chirpan Fault. The magnitude estimation may

have been influenced by the waveform of a nearly contemporaneous event elsewhere on the Balkan Peninsula with a similar magnitude.

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*Department of Meteorology and Geophysics,
Faculty of Physics, Sofia University “St. Kliment Ohridski”,
5 James Bourchier Blvd, 1164 Sofia, Bulgaria
e-mails: rraykova@phys.uni-sofia.bg, lyuba_dimova@phys.uni-sofia.bg*