ISSN 1069-3513, Izvestiya, Physics of the Solid Earth, 2019, Vol. 55, No. 2, pp. 250–255. © Pleiades Publishing, Ltd., 2019.
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The Use of Parallel Computing for the High-Resolution Determination of Earthquake Source Parameters

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Received June 29, 2017; revised February 20, 2018; accepted May 28, 2018

Abstract—Determination of the focal mechanism and source depth of an earthquake by the direct examination of their probable values on a grid in the parameter space also makes it possible to estimate their resolution. However, a detailed search is time consuming. As an example of a source that requires the use of a detailed grid, we consider a special case of a shallow earthquake whose one nodal plane is subhorizontal. Studying these events from the records of long-period surface waves requires a grid that has a high degree of detail for the angles of the focal mechanism. We discuss the application of the methods of parallel computing for speeding up the calculation of earthquake parameters and present the results of the application of this approach for studying the strongest aftershock of the earthquake in Tohoku.

Keywords: focal mechanism, shallow earthquake, parallel calculations

DOI: 10.1134/S1069351319020046

INTRODUCTION

The study of the peculiarities of long-period surface waves emitted by a shallow earthquake (Bukchin, 2006; Bukchin et al., 2010) shows that in the case when one of the nodal planes of the source is subhorizontal, small variations in its dip angle significantly alter the surface wave's radiation pattern of this source and change the estimate of the moment magnitude of the event. An example of the change in the radiation pattern of the fundamental Love mode at a period of 200 s as a function of the dip angle δ is presented in Fig. 1. The sources are strike-slip faults with different values of the dip angle and fixed values of the strike angle ($\psi = 0°$), rake angle ($\lambda = 0°$), and the depth of the source ($h = 30$ km). The top row shows the current values of the dip angle, the middle row shows the corresponding focal mechanisms, and the bottom row shows the corresponding radiation patterns of the Love wave. As can be seen from the figure, when the dip angle varies from 90° to 15°, the radiation pattern of the Love wave barely changes, and the small changes in the focal mechanism significantly alter the surface wave's radiation pattern only over the last ten degrees when one of the nodal planes becomes subhorizontal. As a result, the methods for estimating the angles of the focal mechanism applied to these events must ensure a sufficiently high level of their resolution.

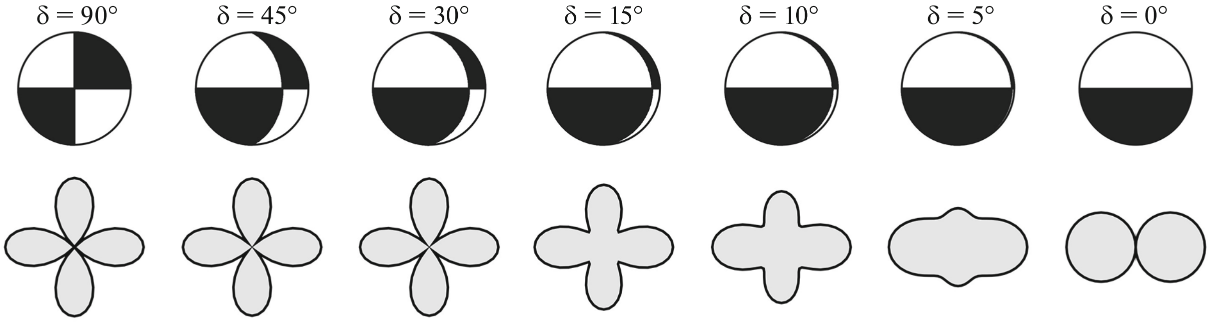

Fig. 1. Radiation patterns of fundamental Love mode emitted by shallow source in form of strike-slip fault for different values of dip angle δ.

DETERMINING THE FOCAL MECHANISM, DEPTH, AND SEISMIC MOMENT OF AN EARTHQUAKE FROM THE LONG-PERIOD AMPLITUDE SPECTRA OF SURFACE WAVES

The most intense surface displacements recorded by seismic stations are observed in surface waves. Each of these waves is the result of the convolution of the corresponding Green function, which is determined by the structure of the medium along the wave's propagation path, and the seismic moment density tensor which characterizes the inelastic processes taking place in the earthquake's source (Backus and Mulcahy, 1976). For calculating the Green function, we use the model of a medium with weak horizontal heterogeneity (Woodhouse, 1974; Babich et al., 1976). Green's surface-wave function for this model depends on the parameters of the medium in the vicinity of the source and in the vicinity of the recording point, on the average phase velocity of the wave along the ray, on its geometric spreading, and attenuation. At the same time, the amplitude spectrum of particle displacements in a surface wave does not depend on its phase velocity. The velocities of surface waves in the real Earth are not known with sufficient accuracy. Therefore, for determining the source parameters of the earthquakes, we typically use only the amplitude spectra of the surface waves. The method and examples of practical applications are described in (Bukchin et al., 1992; 2015; Lasserre et al., 2001).

For describing the source in the moment tensor approximation , we consider the instant point shear dislocation (double couple) at a depth h. This source is defined by five parameters: the depth, the focal mechanism determined by three angles (strike ψ, fall δ, and rake λ), and seismic moment M_0. The first four parameters are determined by direct examination of (searching through) their possible values on the grid in the parameter space, and the fifth parameter M_0 is found by the minimization of the differences (residual ε) of the observed amplitude spectra from their predictions for each current combination of the values of the other parameters. The degree of detail of the grid for the angles of the focal mechanism can reach one degree. The parameter values that minimize the residual are considered as the estimates of these parameters. For estimating the degree of resolution of each of these four parameters, we construct four partial residual functions: $\varepsilon_h(h)$, $\varepsilon_\psi(\psi)$, $\varepsilon_\delta(\delta)$, and $\varepsilon_\lambda(\lambda)$. When examining the possible values of the parameters, of the two nodal planes we consider only the steeper one. Its dip angle cannot be less than 45°, and its range of values is determined by the inequalities $45° \le \delta \le 90°$.

As is known, the focal mechanism cannot be unambiguously determined from the amplitude spectra of the surface waves. For each double couple there are three equivalent double couples that emit surface waves with the same amplitude spectrum. These four equivalent solutions represent two pairs of mechanisms that are rotated relative to each other by 180° around the vertical axis and differ from each other in each pair by the opposite direction of the displacement. Therefore, the partial residual functions of the amplitude spectra for the strike and rake angles are periodic with a period of 180°. For choosing one of the four equivalent focal mechanisms, we compare the synthetic phase spectra of the surface waves at very long periods (typically 100 s at the shortest) calculated for each of these four solutions with the observed phase spectra. The focal mechanism for which these spectra are closest is accepted as the optimal focal mechanism.

THE USE OF PARALLEL COMPUTING FOR SPEEDING UP CALCULATIONS OF THE SOURCE PARAMETERS OF AN EARTHQUAKE

The described algorithm was implemented in the MomTens_omp program with parallel computations (this program can be downloaded from the website of the Institute of Earthquake Prediction Theory and Mathematical Geophysics http://mitp.ru/en/soft). The OpenMP technology is currently one of the most popular instruments of parallel programming for computers with a shared memory. This technology is based on the traditional programming languages such as C, C++, and Fortran. The sequential program is used as the base, and the set of directives, functions, and environment variables is used for creating its parallel version. It is assumed that the parallel program will be portable between different shared-memory computers supporting OpenMP. The OpenMP technology is aimed at providing the user with a single version of the program for parallel and sequential computing (Antonov, 2009). In this paper, we consider the possibility of using this technology for speeding up the calculation of the parameters of the earthquake's source from the surface wave spectra. In the general form, the program flowchart is presented in Fig. 2. The depth cycle is the outermost loop. The parallellism is performed at the level of this cycle. As described above, the OpenMP technology parallelizes the applications on multiprocessor systems with a shared memory, in our case on the cores of a single processor. The program starts with a sequential area: initially, one process (thread) is operating; at the entry to the parallel area, a few more processes are generated between which the parts of the program are subsequently allocated. The iterations in the depth cycle are distributed between as many cores as possible and are performed independently of each core except for the critical sections. A critical section is understood as a part of the program that cannot be executed by more than one thread. If a critical section is already being executed by some thread, then all the other threads that have executed the directive for the section with the given name will be blocked until the entered thread finishes the execution of this critical section. As soon as the working thread leaves the critical section, one of the threads that were blocked at the entry will enter it. If there were several threads at the entry to the critical section, one of them is selected at random, whereas the other blocked threads continue waiting (Antonov, 2009). We use critical sections for working with the global (common for all cores) minima of the residuals. This is necessary for preventing the simultaneous rewriting of the global minima by multiple threads when several current local minima are smaller than the current global minimum.

THE STRONGEST AFTERSHOCK OF THE EARTHQUAKE IN TOHOKU, JAPAN, MARCH 11, 2011, $M_w = 8.4$

The described approach was used for studying the strongest aftershock of the Tohoku earthquake that occurred half an hour after the main shock. As a result, the records of this aftershock were strongly contaminated by the radiation of the preceding main event. With the use of the FTAN spectral–time analysis program, we filtered the Love and Rayleigh fundamental modes recorded by 13 stations of the IRIS, GEOSCOPE and GEOFON networks in the period ranging from 100 to 200 s and used these data for determining the parameters of the studied event. The layout of the stations is shown in Fig. 3a. The grid step for the angles of the focal mechanism was 1°. Table 1 presents the focal mechanisms and phase residuals for the four equivalent solutions obtained from the analysis of the amplitude spectra of the surface waves. As can be seen from the table, solution 1 illustrated in Fig. 3b is optimal. The obtained values of the strike, dip, and rake angles are 33°, 89°, and 91°, respectively, and the seismic moment is 0.46×10^{22} N m. This value corresponds to the moment magnitude $M_w = 8.4$. Our estimate of the depth of the best point source is 10 km. The partial residual functions for the depth of the source and for the angles of the focal mechanism, which characterize their resolution, are shown in Fig. 4.

Table 1. Focal mechanisms and phase residuals for four equivalent solutions obtained from analysis of surface wave amplitude spectra

Solution no.	Dip	Strike	Rake	Normalized phase residual
1	89°	33°	91°	0.345
2	89°	213°	91°	0.483
3	89°	213°	–89°	0.621
4	89°	33°	–89°	0.717

Both versions of the program (without and with parallelization) were timed on the records of the strongest Tohoku aftershock that were used in our analysis. The running time of the program without parallelization was 99 min in the case of with parallelization into 2 cores (each core was 2 threads) it was 41 min. Thus, the program runtime was more than halved (inverse to the number of cores (2)) but it was more than quarter the runtime of the program without parallelization (inverse to the number of threads (4)). This is due to several factors. Firstly, besides the parallel part, the program also has the sequential parts associated with data reading, critical sections, and writing and outputting the results. Secondly, it is worth noting that threads are not equivalent to cores. In contrast to the "real" cores which are full and independent copies, in the case of multithreading in a single processor, only part of the internal nodes are duplicated, primarily the ones that are responsible for storing and preparing the data. The executive nodes responsible for the organization and processing of the data remain single and at any given time they are used by at most one of the threads.

COMPARISON WITH THE CMT SOLUTION

Let us compare the obtained solution with the solution presented in the Global CMT catalog (GCMT solution). Prior to this, let us consider the problem of selecting the spectral range of the observations. When this range is moved from the interval of the periods that are insufficiently long for the use of the approximation of a point instant source to the interval of the longer periods, the estimates of the source parameters change significantly. As the periods become sufficiently long and this approximation becomes adequate, the parameter estimates take on their limiting values and cease to change with the further increase of the periods. The illustration for the strongest aftershock of the Tohoku earthquake is shown in Figs. 5a–5c. These graphics show the solutions that were obtained from the same set of the records of surface waves and filtered in the three different spectral bands.

Let us now compare the solution shown in Fig. 5c with the GCMT solution illustrated in Fig. 5d. These solutions strongly differ. For example, our M_w estimate is 8.4, whereas the GCMT estimate for M_w is 7.9. We note, however, that the compared solutions were obtained from the records of surface waves that were filtered in different spectral bands. If we compare the GCMT solution ($T > 75$ s) with the solution shown in Fig. 5a (75 s $< T <$ 120 s), we see that these solutions are fairly close to each other. At the same time, as was noted above, the periods in the band of 75 s $< T <$ 120 s are insufficiently long for the event under study. This gives us grounds to construe the significant difference of our solution from the GCMT solution as probably being associated with the inadequately selected spectral range of the observations for calculating the GCMT solution.

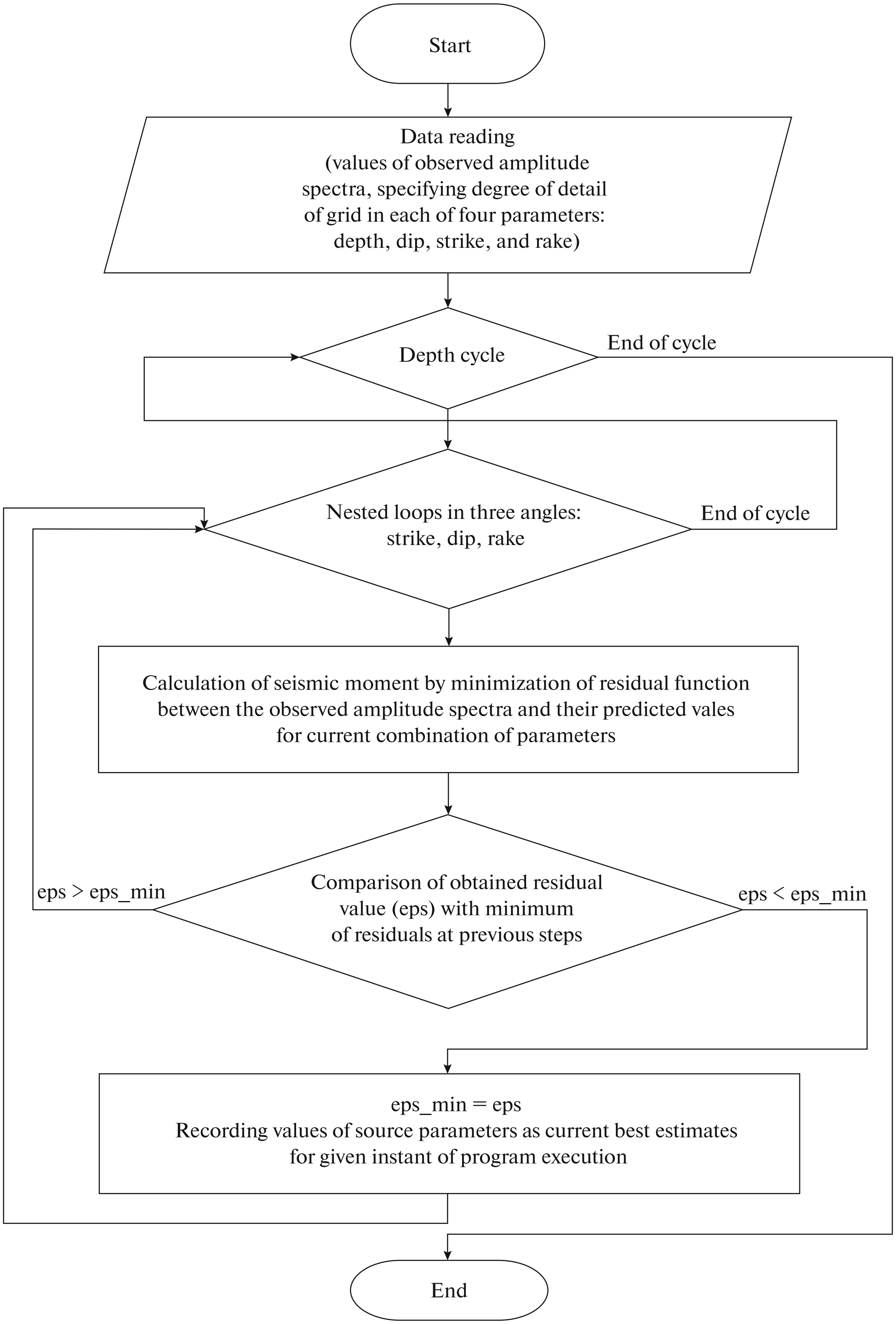

Fig. 2. Program flowchart.

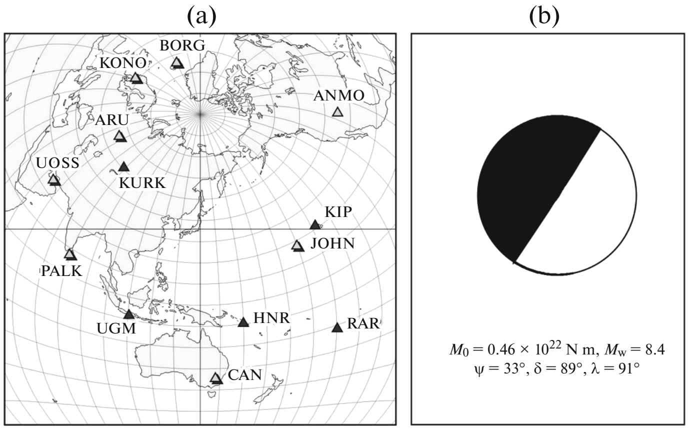

Fig. 3. (a) Distribution of points of surface wave recording and (b) best solution of four equivalent solutions obtained from amplitude spectra of surface waves. Dark and light triangles correspond to Rayleigh and Love waves, respectively.

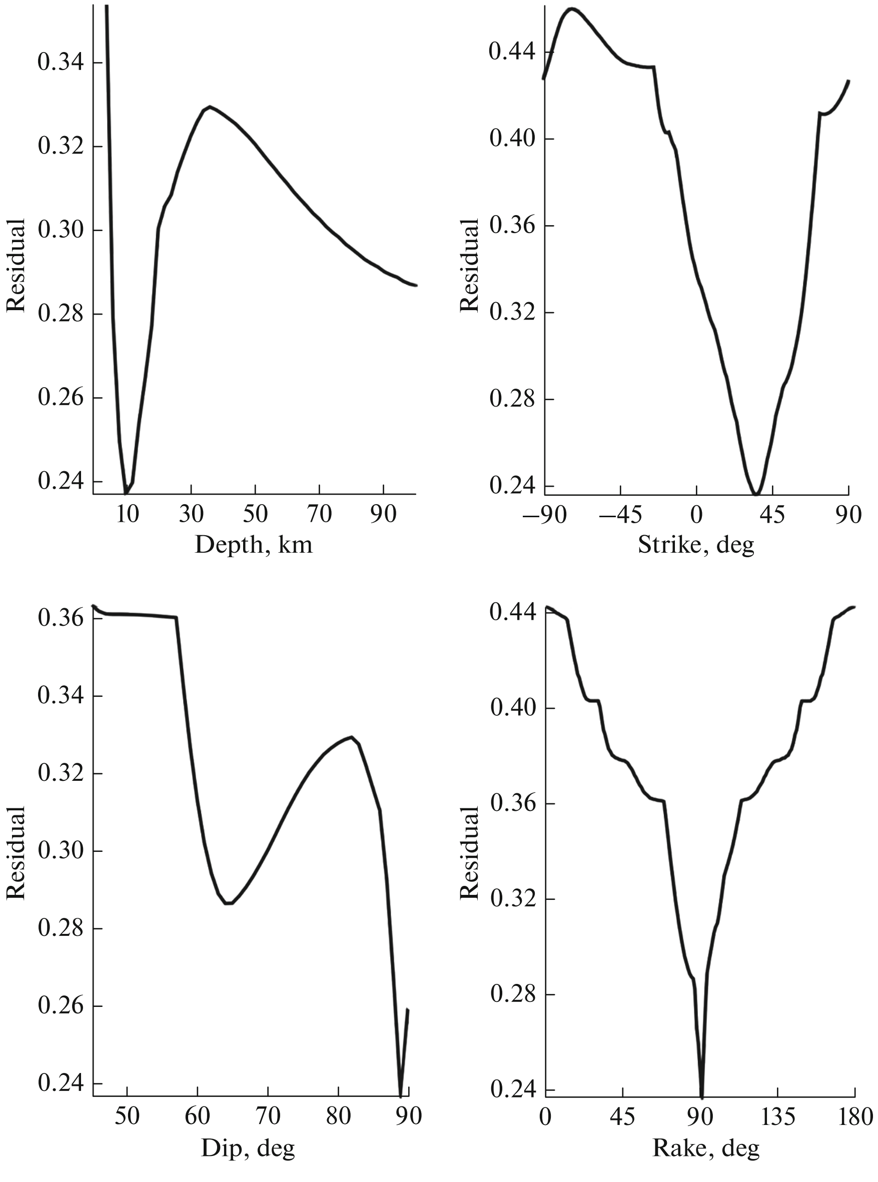

Fig. 4. Partial residual functions for source depth and angles of focal mechanism.

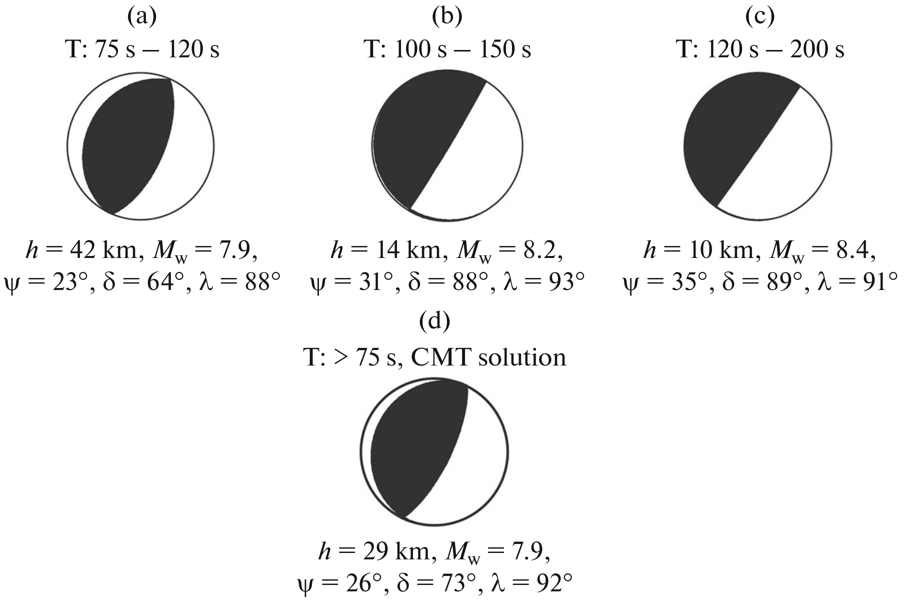

Fig. 5. Results of surface wave spectra inversion in three spectral bands. Comparison with GCMT solution.

CONCLUSIONS

Determining the focal mechanism and source depth of an earthquake by a direct search through their possible values on a grid in the parameter space in the case of a sufficiently detailed search requires considerable computing time. As an example of a source that requires the use of a detailed grid, we consider a special case of a shallow earthquake one of whose nodal planes is subhorizontal. This is the strongest aftershock of the Tohoku earthquake, which is discussed in detail in this paper. The results obtained for this event significantly differ from the solution presented in the Global CMT catalog. It is shown that this difference can be explained by the inadequately selected spectral range of the observations for obtaining the CMT solution. The use of parallel computing for speeding up the calculation of earthquake parameters is discussed. The OpenMP technology is currently one of the most popular parallel programming techniques for computers with a shared memory. The results of using this method for studying the strongest aftershock of the Tohoku earthquake are presented.

ACKNOWLEDGMENTS

We thank the IRIS, GEOSCOPE, and GEOFON networks for providing the seismic records.

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Translated by M. Nazarenko