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Abstract

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GEOPHYSICS

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DETERMINATION OF EARTHQUAKE EPICENTERS ON AN ELECTRONIC COMPUTER

(Presented by Academician E. K. Fedorov on 26 XII 1962)

1. The present work is devoted to a method for determining epicenters on a universal digital computer. This method is suitable for the case when the initial approximation is unknown and some observations contain large errors (which corresponds to the problem of providing an operational seismic service). Judging from fairly long experience in using our program, provided that the necessary minimum of data is available, failures (cases in which no solution is found) are unlikely (fractions of a percent), and significant errors are practically excluded.

A similar problem is treated in work ([1]), which describes a program for determining the epicenter and focal depth from P, PKP_1, and pP waves, if an initial approximation is known and the pP waves have already been identified.

In the present work, the initial data used are the arrival times of P waves at epicentral distances up to 105° and of PKP_1 waves at distances greater than 110°. If they are erroneously identified, they are rejected in the course of the computation. Arrivals in the shadow zone (from 105 to 110°) are regarded as unreliable and are not used. The hodograph is taken to be the same for the entire Earth. Allowance for the nonsphericity of the Earth is limited to the fact that the calculations are carried out in geocentric coordinates.

The program that has been compiled makes it possible to use, for each earthquake, data from no more than 150 stations out of a total of 1006 stations of the world, whose coordinates are stored on tape.

2. Statement of the problem: given the times t_k of arrival of a P or PKP_1 wave at m_0 seismic stations (k is the number of the station in the general list of stations used) and the coordinates of these stations (λ_k, φ_k), where λ_k is longitude and φ_k is latitude; the hodograph is known, $g = g(\Delta, h)$,

the dependence of travel time g on epicentral distance Δ and focal depth h. It is required to find the time of occurrence of the earthquake t and the hypocenter coordinates λ (longitude), φ (latitude), h.

We shall seek (t, h, λ, φ) from the condition that the mean square residual be sufficiently small:

$$\bar{\psi} = \left\{ \frac{1}{m'} \sum_{i=1}^{m'} f_{k_i}^2 \right\}^{1/2}, \qquad (1)$$

where $f_k = t + \psi_k$; $\psi_k = g(\Delta_k, h) - t_k$; Δ_k is the epicentral distance for the k-th station. From the summation in (1) there are excluded those stations for which, during the computation, excessively large $|f_k|$ are obtained, as well as stations in the shadow zone.

The method of solution is as follows: first we seek the minimum of the function $\bar{\psi}$, constructed using all stations (except those falling in the shadow zone). The method of finding the minimum for a given set of stations k

is set out below. At the point of the minimum all f_{k_i} and Δ_{k_i} are computed. After this we seek the minimum of a new function $\overline{\psi}$; it is still defined by formula (1), but only $\max(m_0/C_4, C_1)$ stations with the smallest $|f_{k_i}|$ are included in the summation, as well as stations for which

$$|f_{k_i}| < C_2 + C_3\overline{\psi} \qquad (2)$$

(C_i are prescribed constants).

If the minimum of the new function $\overline{\psi}$ is smaller than the preceding minimum, we compute new f_{k_i}, again determine which stations should be excluded from the summation,* and again seek the minimum of $\overline{\psi}$. This process continues as long as the successive minima of $\overline{\psi}$ decrease. If the smallest $\overline{\psi}$ obtained is less than the prescribed number A, then we assume that the solution has been found. Otherwise we assume that a local minimum of $\overline{\psi}$ has been found which does not coincide with the hypocenter; then we add to the latitude and longitude of this minimum prescribed sufficiently large numbers and, from the point thus obtained (essentially arbitrary), begin the search for the minimum anew. The number of repetitions of this procedure is limited. The coordinates of the minimum thus found are used as the initial approximation for repeating the entire process described above with reduced constants C_2, C_3 (i.e., with a stricter requirement on the residuals f_{k_i}).

Table 1

Iteration number	ψ	λ	φ	m'
Counting from the equator	**Counting from the equator**	**Counting from the equator**	**Counting from the equator**	**Counting from the equator**
0	431.3	0.1° E	0.1° N	64
1	360.7	171.4° E	73.2° S	64
2	311.7	75.2° W	70.4° S	56
3	260.9	78.7° W	59.2° S	66
4	281.5	157.8° W	42° S	65
5	268.4	75.9° W	10.2° S	66
6	199.1	140.9° W	10.9° S	66
7	66.5	118.4° W	26.1° S	67
8	15.6	121.8° W	32.5° N	65
9	3.5	119.5° W	34.67° N	66
10	2.8	119.2° W	34.9° N	66
16	1.16	119.02° W	34.98° N	58
17*	1.02	119.0° W	34.9° N	55
21	0.903	118.9° W	34.95° N	52
Counting from the station nearest the epicenter	**Counting from the station nearest the epicenter**	**Counting from the station nearest the epicenter**	**Counting from the station nearest the epicenter**	**Counting from the station nearest the epicenter**
0	10.8	119.7° W	34.4° N	66
1	3.12	119.4° W	34.7° N	66
2	2.8	119.15° W	34.9° N	66
3	2.79	119.16° W	34.9° N	66
6	1.16	119.0° W	34.9° N	58
8*	1.02	119.0° W	34.9° N	55
9	0.938	118.9° W	34.9° N	53
12	0.903	118.9° W	34.9° N	52

* Reduction of C_3

The minimum of the function $\overline{\psi}$, for a fixed set of stations, is found by iterations: we replace $\overline{\psi}$ in the neighborhood of the n-th approximation by a quadratic form and take the minimum of this form as the $(n+1)$-st approximation.

Despite the seeming locality of this method, it made it possible to find the epicenter coordinates accurately for arbitrarily poor initial approximations. It is interesting that the time expended depended little on the accuracy of the initial approximation. This is evident from the results of computing several hundred epicenters from two initial approximations: from a conventional point near the equator ($h = 0$; $\lambda = \varphi = 0.1°$) and from the neighborhood of the true epicenter; the initial data were the usual ones for the seismic service of the USSR. In this case the difference in the number of iterations for 55% of earthquakes was less than 10 and almost always less than 100. For about 15% of earthquakes this difference was even negative, because of gross errors in t_k and the unfavorable distribution of stations (in these cases the iterations move away from the true solution until the erroneous t_k are discarded).

As an example of the convergence of the iterative process, Table 1 gives successive iterations in determining the epicenter of the earthquake in California on 21 VII 1952 ($h = 0$-18 km; $\lambda = 119°$ W; $\varphi = 35°$ N).

* In this case, stations excluded earlier may be included in the subsequent calculation if their residuals are sufficiently small.

3. The accuracy of the results is characterized as follows. On the material of the USSR seismic service, as a rule, it was possible to obtain $\bar{\psi} < 1.5$—2, so that the internal consistency of the computations was substantially higher than expected (according to (7)–about 6 sec). The accuracy of determining the true hypocenter is characterized indirectly by the distance of the epicenters found by us from those indicated in the USCGS and JSS bulletins. In 55% of cases this distance is less than 0.3°, and in 92% of cases less than 1°. The difference is explained mainly by the use of different sets of stations.

The experience of computation has shown the possibility of localizing very distant epicenters from data of a small number of stations, if t_k are sufficiently (but within reasonable limits) accurate. For example, the epicenter of the "Blanca" explosion in Nevada was determined with an error of 10 km from observations at only 7 stations.

The focal depth is determined with an error of up to 50 km for 60–70% of earthquakes; this percentage is unexpectedly high, but still insufficient for dispensing with the pP, sP phases.

The experience of applying the program described in the practice of the USSR seismic service will be analyzed separately. We shall note only that by the present time $\sim$ 2000 epicenters have been determined. The average computation time (from two initial approximations–the equator and the station nearest to the epicenter) is 1-2 min. The percentage of failures is about 5 (they are explained mainly by insufficient data). The total number of epicenters determined operationally after the transition to the machine increased by 30–50%, owing to the fact that the need for a good initial approximation or for the S phase disappeared.

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Note: Figure translations are in progress. See original paper for figures.