Mausam, (1982), **33**, 4, 427-432

550. 341.4 : 681. 14

Epicentral parameters — A generalised software package

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(*Received 28 February 1980*)

सार – पी एवं एस कलाओं का उपयोग करके नियमित रूप से अधिकेन्द्री को ज्ञात करने के लिए एक कम्प्युटर प्रोग्राम बनाया गया है। दूरभूकंप प्रावस्थाओं के अतिरिक्त समस्त या निकट भूकंप प्रावस्थाओं में से कोई नामत: P_n, P^* एवं P_g के साथ-साथ S_n, S^* एवं S_g^* को सम्मिलित करने का प्रावधान रखा गया है। वर्तमान में 90° की अधिकेन्द्री दूरी के अन्दर शून्य से 280 कि० मी० तक की फोकल गहराइयों के हल ज्ञात किए जा सकते हैं। आंकड़ों में त्रुटियों का मेलजोल के लिए बनाए गए विन्यास जांचें भी प्रोग्राम में सम्मिलित की गई हैं और इस प्रकार स्वीकार योग्य सीमाओं में आने वाले संबंधित प्रेक्षणों की गणना में प्रभावी भार को कम करता है या पूर्णत: हटा देता है।

ये परिणाम सं० रा० भूसर्वेक्षण, अन्तरराष्ट्रीय भूकंप विज्ञान केन्द्र, यू० के० एवं सोवियत रूस को बुलेटिनों में दिए हुए परिणामों से बहुत मिलते-जुलते हैं।

ABSTRACT. A computer programme has been developed for the epicentral determination on routine basis using *P* and *S* phases. In addition to teleseismic phases, provision has been kept for including all or any of the near earthquake phases, namely *Pn*, *P** and *Pg* as well as *Sn*, *S**and *Sg**. Solutions can be obtained at present for focal depths ranging from zero to 280 km within the epicentral distance of 90 degrees. The programme incorporates built-in consistency checks to deal with errors in the data and so discards outright or reduces the effective weightage in the computation of the concerned observations not falling within acceptable limits.

The results agree fairly well with the bulletins of U.S. Geological Survey, International Seismological Centre, U.K. and USSR.

1. Introduction

Epicentral determination of earthquakes occurring in and near India and supply of these parameters to the public and press in the shortest time is one of the principal functions of the India Meteorological Department. Until recently, this work was processed almost manually, but with the increase in the number of seismological stations and improvements in the mode of reception of data from distant Indian stations at the Headquarters, the necessity to use computerised methods has been felt.

In this paper the details of a computer programme for epicentral distances upto 90 deg. have been described in which provision has been kept to use all the near earthquake phases also. The focal depth of earthquakes can be determined upto 280 km which meets the needs of earthquake occurring near India, namely in Hindukush and Manipur Burma regions. The programme has been run on the IBM 360/44 computer in the India Meteorological Department.

2. Scope of the paper

The present network of seismic stations in the country is such that earthquakes of magnitude 5 occurring in the country can be located. In some regions where local network of stations are operating, epicentral parameters can be determined down to magnitude 2 or even less. For such local network, the programmes given by Shaikh *et al.* (1977) and HYPO 71 are successfully being used. As the epicentral distances increase beyond 4° to 5° , the approximations used in the near earthquake programme no longer remain valid. Further, the large differences in the velocity models over the Peninsula, Gangetic basin and the Himalayas suggest that an average velocity model similar to Jeffreys Bullen (1958) or Herrin (1968) can be better suited for epicentral determination over longer distances utilising the data from about 50 observatories in the country. The present programme reads the arrival times of *P* and *S* phases at different stations and computes the tentative origin time and epicentre by solving a set of equations as decribed in the next section.

Since the azimuthal control from Indian stations decreases rapidly with epicentral distance, the errors in the epicentral parameters increase many fold beyond 90°. The programme has, therefore, been restricted to 90° distance only. While the main objective is to determine the epicentral

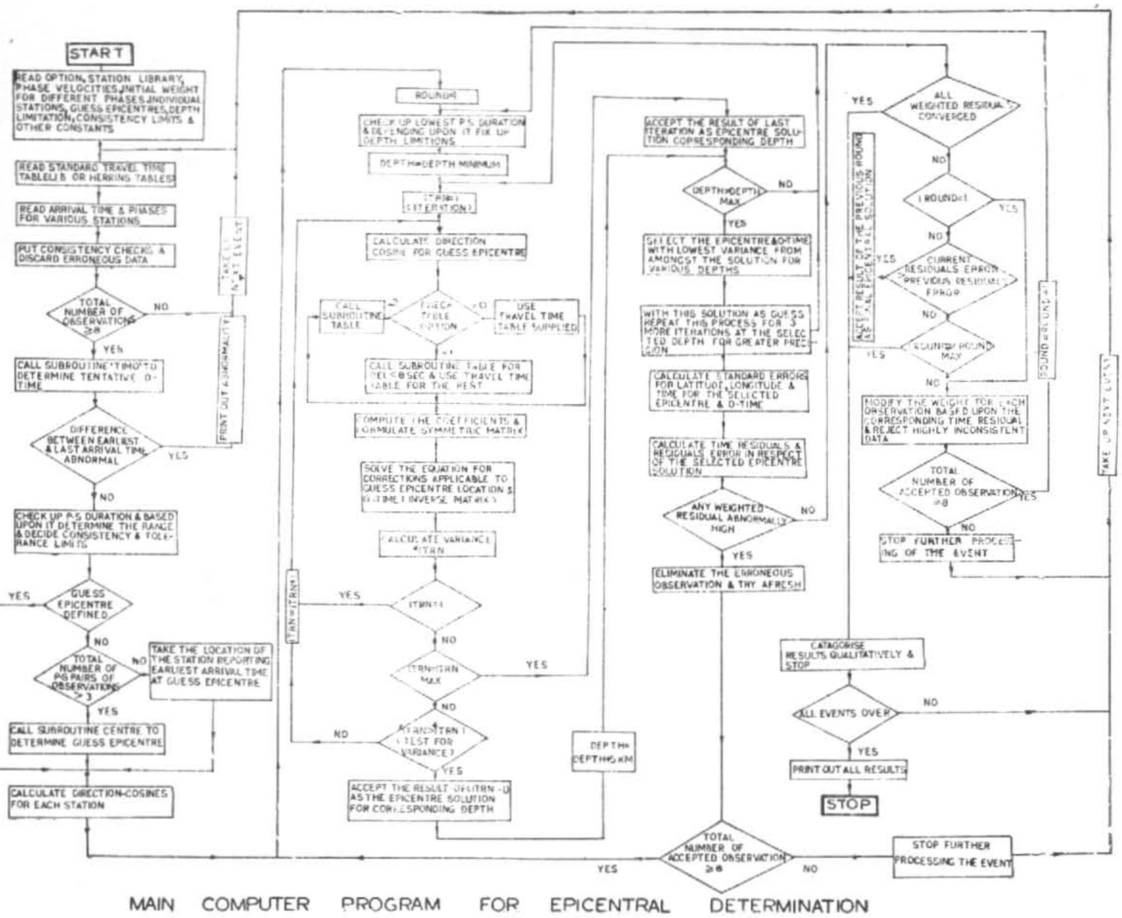

Fig. 1. Main computer program for epicentral determination

parameters for earthquakes around in and near India for which better azimuthal control is available, the provision for using the same programme upto 90° has been kept so that it can be used on operational basis for stronger events of significance in the neighbouring countries. The programme, therefore, makes use of only *P* and *S* phases and does not include core phases like *PKP*, *SKS* and others.

2.1. *Tentative origin time*

Computation of tentative O-time is based upon the ratio of *P* to *S* wave velocities which is generally taken as $\sqrt{3}$. If the arrival times of *P* and *S* waves are t_p and t_s respectively and t the tentative origin time :

$$(t_s - t)/(t_p - t) = \sqrt{3}$$

$$\text{or } t = (\sqrt{3}\, t_p - t_s)/(\sqrt{3} - 1)$$

From this equation origin time is determined for all the stations for which both *P* and *S* observations are available. Now if t_0 is the approximate origin time and dt_0 its error,

$$dt_0 = W_L\,[\sqrt{3}\,(t_p - t_0) - (t_s - t_0)/(\sqrt{3} - 1)]$$

where W_L is the weight assigned to the individual observational pair. For *N* pairs of *P* and *S* observations, a set of *N* linear equations are obtained which are solved by the least squares method. The details are published in an earlier paper (Shaikh *et al.* 1977) and is called TIMO.

2.2. *Tentative epicentre*

The epicentral distance at any one station may be computed from the well known relation :

$$\cos \triangle = aA + bB + cC$$

where, $a = \cos \phi \cos \lambda$,

$b = \cos \phi \sin \lambda$,

$c = \sin \phi$,

$A = \cos \phi_s \cos \lambda_s$,

$B = \cos \phi_s \sin \lambda_s$ and

$C = \sin \phi_s$

ϕ and λ are the latitude and longitude of the epicentre, and ϕ_s and λ_s are the latitude and longitude of the stations respectively. Similar equations hold good for other stations. Weights are to be assigned to observations depending upon the epicentral distances of the obserational stations. The *n* weighted equations derived from

Eqn. (1) for n data may be written in the normal equation form as :

$$(W\ AA)\, a + (W\ AB)\, b + (W\ AC)\ c = (W\ AL)$$
$$(W\ BA)\, a + (W\ BB)\, b + (W\ BC)\ c = (W\ BL)$$
$$(W\ CA)\, a + (W\ CB)\, b + (W\ CC)\ c = (W\ CL) \qquad (2)$$

where $L = \cos\triangle$

For practical purposes accuracy of observations is assumed to be equal ; W can be empirically chosen depending upon the epicentral distances. This is incorporated in a sub-routine 'Centre'.

Jeffreys Bullen travel time tables were used to compute the epicentral distances for assigned focal depth by interpolation. Tentative epicentre is determined by calling sub-routine Centre, if the total number of P and S pairs is three or more by solving for a, b and c, otherwise the coordinates of the station reporting earliest arrival time are taken as trial epicentre. In the above equation, therefore, $\cos\triangle$ or L is calculated by computing the epicentral distance from the J.B. Tables after subtracting the origin time from the arrival time of P and S phases. Provision has also been kept to accept an externally introduced guess epicentre. The sub-routine Centre when called upon reads the J. B. Tables for various specified focal depths and interpolates P-S intervals for the assigned initial depths. It then checks up for the observed P-S interval to be non-zero, and computes the coefficients of the normal Eqn. (2) above. A solution of these equations gives the direction cosines a, b and c of the epicentre and using these, the variance is calculated for the corresponding assigned depth. For observations greater than 3, least squares method is employed to solve for a, b and c. The depth is then steadily incremented, and the respective variance is calculated. The process can be repeated for focal depths upto 280 km. From amongst the various depths, the solution with least variance is picked up as the tentative epicentre. The flow diagram is given in Fig. 1.

3. Revision of origin time and location of an earthquake .

The observed arrived time of P or S phase at a station, the epicentre and origin time of the event can be computed from :

$$t = T\,(\lambda_s, \phi_s, \lambda, \phi, h, t_0) \qquad (3)$$

where, t = arrival time of P or S

λ_s, ϕ_s = longitude and latitude of the station,

λ, ϕ = longitude and latitude of epicentre,

h = focal depth,

t_0 = origin time

If $t_0 + dt_0$, $\lambda + d\lambda$, $\phi + d\phi$ and h are the most probable origin time and location of an earthquake, then the corresponding probable arrival time t, for a station at a distance from the provisional epicentre, can be obtained by substituting these values in Eqn. (3).

Thus

$$t_1 = T_1\,(\lambda_s, \phi_s, \lambda + d\lambda, \phi + d\phi, h, t_0 + dt_0) \qquad (4)$$

Expanding and linearising we obtain :

$$t_1 = T\,(\lambda s, \phi s, \lambda, \phi, h, t_0) + \frac{\partial T}{\partial\triangle}\frac{\partial\triangle}{\partial\lambda}\, d\lambda + \frac{\partial T}{\partial\triangle}\frac{\partial\triangle}{\partial\phi}\, d\phi + \frac{\partial T}{\partial t_0}\, dT_0$$

The error E introduced is thus given by :

$$E = t_1 - T = \frac{\partial T}{\partial\triangle}\frac{\partial\triangle}{\partial\lambda}\, d\lambda + \frac{\partial T}{\partial\triangle}\frac{\partial\triangle}{\partial\phi}\, d\phi + \frac{\partial T}{\partial t_0}\, dT_0 \qquad (5)$$

Since t_0 is the origin time, we have $\partial T/\partial t_0 = 1$

Eqn. (5), therefore, can be written as :

$$\alpha\, d\lambda + \beta\, d\phi + dt_0 = E \qquad (6)$$

or

$$F = E - (\alpha\, d\,\lambda + \beta\, d\,\phi + dt_0) \qquad (7)$$

where, $$\alpha = \frac{\partial T}{\partial\triangle}\frac{\partial\triangle}{\partial\lambda} \text{ and } \beta = \frac{\partial T}{\partial\triangle}\frac{\partial\triangle}{\partial\phi} \qquad (8)$$

Since,

$$\cos\triangle = A\cos\phi\cos\lambda + B\cos\phi\sin\lambda + C\sin\phi$$

Obtaining the partial derivatives from the above equation, we get :

$$-\sin\triangle\,\frac{\partial\triangle}{\partial\lambda} = -A\cos\phi\sin\lambda + B\cos\phi\cos\lambda$$

or $$\frac{\partial\triangle}{\partial\phi} = \frac{Ab - Ba}{\sin\triangle}$$

Likewise,

$$-\sin\triangle\,\frac{\partial\triangle}{\partial\phi} = -A\cos\lambda\sin\phi - B\sin\lambda\sin\phi + C\cos\phi$$

or

$$\frac{\partial\triangle}{\partial\phi} = \frac{(A\cos\lambda + B\sin\lambda)\sin\phi + C\cos\phi}{\sin\triangle}$$

TABLE 1

Comparison of epicentral parameters determined by different agencies

Date	Origin time (GMT) h	m	s	Epicentre (°N)	(°E)	Focal depth (km)	Region	Agency
6 Nov 1975	00	11	26.9	30.23	77.98	77		Computer (IMD)
	00	11	30	29.8	78.3	00		Manual (IMD)
	00	11	38	30.04	77.9	—	Himachal Pradesh	Moscow
	00	11	30.4	29.61	77.87	16		ISC
16 Apr 1976	16	51	22.1	6.62	95.37	40		Computer (IMD)
	16	51	26	7.5	95.0	00		Manual (IMD)
	16	51	31.2	7.5	94.4	22	Nicobar Island	USAS
	16	51	32.2	7.42	94.35	38		ISC
29 Sep 1976	02	51	24.1	29.46	81.72	50		Computer (IMD)
	02	51	27	28.7	81.7	00	India-Nepal border	Manual (IMD)
	02	51	30	30.1	81.3	—		Moscow
	02	51	24.9	29.50	81.51	33		ISC
5 Oct 1976	18	02	12.3	5.58(S)	153.36	5		Computer (IMD)
	18	02	12	4.8(S)	153.6	00	New Britain Islands	Manual (IMD)
	18	02	15.4	6.45(S)	153.0	22		USGS
6 Nov 1976	18	04	6.6	28.17	100.69	00	Szechwan China	Computer (IMD)
	18	04	8	28.0	100.7	00		Manual (IMD)
	18	04	10	27.7	101.1	—		Moscow
	18	04	06	27.66	101.04	5		ISC

TABLE 2

Epicentral parameters of near earthquake

Date (Jan '75)	Origin time (GMT) h	m	s	Epicentre Lat. (°N)	Long. (°E)	Focal depth (km)	Programmes
19	08	00	20.6	32.18	78.45	0.0	II
	08	00	21.3	32.11	78.44	0.0	I
20	03	42	38.0	32.31	78.05	0.0	II
	03	42	38.7	32.28	77.85	0.0	I
20	09	17	19.1	31.98	78.20	0.0	II
	09	17	20.3	32.06	77.92	0.0	I
20	13	24	9.8	32.07	78.65	20.0	II
	13	24	8.6	32.13	78.54	0.0	I
21	12	33	10.6	31.92	78.41	0.0	II
	12	33	11.5	31.86	78.29	0.0	I
22	09	38	10.4	31.98	78.59	0.0	II
	09	38	12.3	31.84	78.55	20.0	I

II — Present computer programme   I — Programme by Shaikh *et al.* (1977)

Substituting them into Eqn. (8) we get :

$$\alpha = \frac{\partial T}{\partial \triangle} \frac{(A\,b - B\,a)}{\sin \triangle}$$

$$\beta = \frac{\partial T}{\partial \triangle} \left[\frac{(A\cos\lambda + B\sin\lambda)\sin\phi - C\cos\phi}{\sin \triangle} \right]$$

The n weighted eqns. of observations, derived from Eqn. (6) for n data, may be transformed into normal equations as given below after multiplying Eqn. (6) on both sides by α then by β and finally by t_0 :

$$(W\alpha\alpha)\,d\lambda + (W\alpha\beta)\,d\phi + (Wt_0\,\alpha)\,dt_0 = (W\alpha E)$$

$$(W\beta\alpha)\,d\lambda + (W\beta\beta)\,d\phi + (Wt_0\beta)\,dt_0 = (W\beta E)$$

$$(Wt_0\,\alpha)\,d\lambda + (Wt_0\beta)\,d\phi + (Wt_0t_0)\,dt_0 = (Wt_0E) \quad (9)$$

The weight W depends upon the observational errors in respect of the epicentral distances from the corresponding observational stations.

For practical purposes, however, W can be empirically chosen depending upon the class of the observational station, its epicentral distances and on the type of phase (*viz.*, P_g, S_g, P^*, S^*, P_n, S_n etc).

The set of n equations are solved for $d\lambda$, $d\phi$ and dt_0 from which the epicentral coordinates and origin time are determined for zero focal depth. The variance are again determined by using the observed calculated (J. B. Tables) travel times. The process is repeated by increasing the focal depth to 5 km giving another set of epicentre and origin time. The iteration is repeated for focal depths upto 280 km and the solution with the minimum variance is taken as the final result.

4. Salient features of the computer programme

(*i*) Each observational data card is scrutinised and incomplete messages, wrong name of stations punched on the cards or outside the library are discarded. The library can be augumented externally upto 50 stations.

(*ii*) Provision has been kept for not proceeding with an event at all in case the number of observations is less than 8. If the time difference between earliest reported time and the last reported arrival time exceeds a certain acceptable limit depending upon the range, a message is printed out. This criterion is useful to eliminate widely discrepant data.

If any highly inconsistent data is rejected at any stage, the whole process is repeated again with the remaining observations.

(*iii*) Weights are assigned as discussed in the earlier programme for near earthquakes (Shaikh *et al.* 1977). Initial weights assigned to P and S phases are 1 and 1/2 respectively. These can be externally controlled depending upon the quality of records at a particular station.

(*iv*) Maximum and minimum focal depths can be restricted externally. For example, if any evidence (geophysical or otherwise) for depths is found, the focal depth may be restrained accordingly.

(*v*) The programme has 3 options for solutions :

(*a*) Using the J. B. Tables provided for computation of epicentral distances which may be used for distant earthquakes ($\triangle = 10°$). At present we can compute epicentral parameter with focal depths upto 280 km which is sufficient for earthquakes occurring near India including Hindukush and Burmese-Andaman regions. However, it is being further modified to include deeper earthquakes as well.

(*b*) If the crustal structure of a particular region is known and the intercepts and the wave velocities have been fed initially, the tables are computed for determining epicentral parameter of near earthquakes (upto $\triangle = 10°$). The programme then becomes more or less similar to that reported for near earthquakes (Shaikh *et al.* 1977) but has the advantage of using generalised equations.

(*c*) For $\triangle = 10°$, provision has also been kept to use regional travel time tables for near stations and utilize J. B. Tables for distant stations. This, of course, may create some problems due to the difference of structures between the two models and may be used only in special situations.

Residual error is calculated along with travel time residuals from the equation :

$$\text{Residual error} = \sqrt{\sum_{i=1}^{n} \frac{W_i\,R_{ei}^2}{n-4}}$$

where W_i is the weight and R_e is the residuals.

After every round of weight modification, residual error is checked up with that of the previous round and if it is found to be greater than that in the earlier round, the solution is discarded. In that case, the solution of the previous round is accepted as the final solution.

(*vi*) The final check in data consistency is applied by comparing the origin time of the event with the arrival time at all the observations. If any arrival time is found to be earlier than the origin time which, of course, is attributed to serious error in the observations, the programme is run again after removing the doubtful observations.

5. Results & Discussion

The epicentral parameters of some earthquakes determined from Indian stations manually and using the present programme are given in Table 1. The epicentral parameters computed from world-wide stations data as reported by U.S. Geological Survey, International Seismological Centre, U.K. and operational bulletin of USSR (from USSR network only) have also been given in the table. Comparison shows that the epicentral parameters determined with our programme are in fairly good agreement with the results of other agencies in the world. As expected the accuracy in the epicentral parameters decreases with distance because of narrow azimuthal control from Indian stations.

Table 2 gives the results of near earthquakes using J. B. Tables and the crustal model for Kinnaur region (Chaudhury & Srivastava 1977). Results obtained using the earlier programme based on cartesian coordinates (Shaikh *et al.* 1977) have also been given in the same tables. The agreement is quite good.

Situations may arise, however, when *S* phase cannot be reliably determined for any of the Indian stations particularly if a great earthquake occurs near India, making all the records almost white soon after the onset of *P* waves. In such situations manual determination is difficult since 0-time cannot be fixed. The present computer programme may be useful on such situations since provision has been kept to start the iterative process by taking the arrival time of *P* phase at the nearest station as the origin time. This, however, works only if sufficient number of observations are available. However, the timing accuracy of the stations for any epicentral programme cannot be over emphasized which sets the limitation in obtaining the desired results.

References

Chaudhury, H.M. and Srivastava, H.N., 1977, Proc. Sixth World Conf. Earthquake Engng., New Delhi, 1-55.

Ichikawa, M., 1965, Papers in Meteor. & Geophys. (Tokyo), **26**, 90.

Shaikh, Z. E., Srivastava, H.N. and Chaudhury, H.M., 1977, *Indian J. Met. Hydrol. Geophys.*, **28**, 467.