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39. *Optimum Distribution of Seismic Observation Points. V —Desirable Location of New Stations in Yugoslavia—*

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Abstract

In order to find the optimum locations for new seismic stations in Yugoslavia, a number of points were provisionally assumed and the calculation of error estimation of seismic focal parameters was carried out. If the location is adequately chosen even a single new station considerably improves the accuracy of the determination of epicenter position and origin time of earthquakes. If two or more stations can be set up the error will decrease as much as 35%. The calculation was based on the Monte Carlo method.

Introduction

The error of epicenter determination and that of origin time of an earthquake depend, on one hand, upon the observation error of wave arrivals. On the other hand, however, the geographical distribution of the stations plays a significant role, too. In the previous papers estimation of the effect of this latter cause was investigated for various geographical distributions of seismic observation points[1,2] including the seismic networks of India[3] and Yugoslavia.[4] Besides, an attempt was made to estimate the amount of the diminution of errors caused by the

1) Y. SATÔ, "Optimum Distribution of Seismic Observation Points," *Zisin*, [ii] **18** (1965), 9. (in Japanese)

2) Y. SATÔ and D. SKOKO, "Optimum Distribution of Seismic Observation Points II," *Bull. Earthq. Res. Inst.*, **43** (1965), 451.

3) D. SKOKO, Y. SATÔ, I. OCHI and T. K. DUTTA, "Accuracy of the Determination of Earthquake Source Parameters as Determined by Monte Carlo Method. Observation on Indian Network," *Bull. Earthq. Res. Inst.*, **44** (1966), 893.

4) Y. SATÔ, I. OCHI and Y. KOTAKE, "Accuracy of the Determination of Earthquake Source Parameters in and around Japan," *Bull. Earthq. Res. Inst.*, **45** (1967), 1.

addition of a single station to the existing network.[5]

In this paper the errors of the earthquake parameters in the territory of Yugoslavia are calculated assuming one or more new stations in addition to the present seismic network. Quantitative study of errors is carried out by use of data from those stations, and in this way we can estimate the desirability or undesirability of the treated networks. Again the Monte Carlo method is applied in the present study.

Procedure

As in the previous papers the error equation for the k-th station is

$$\left(\frac{\partial f}{\partial \Delta}\right)_k \cos\theta_k \cdot \delta R \cos\theta + \left(\frac{\partial f}{\partial \Delta}\right)_k \sin\theta_k \cdot \delta R \sin\theta + \delta T = \varepsilon_k$$

where the notations are

$f(\Delta)$-Travel time,
δR-Distance between the true and calculated epicenters,
δT-Error of the origin time of the earthquake,
θ-Azimuthal angle of calculated epicenter,
θ_k-Azimuthal angle of k-th station,
ε_k-Observation error of the arrival time at k-th station.

The adopted assumptions are as before:

i) Errors δR, δT and ε_k are small,
ii) Observation points are on a flat surface,
iii) Velocity of the wave is constant,
iv) Observation errors ε_k follow Gaussian distribution with mean value 0 and standard deviation ε,
v) The origin of the coordinate system is assumed on the true epicenter,
vi) Depth of the focus is the same all through the calculation.

(I) Suppose, at first, there are a number of fixed seismic stations. (cf. Fig. 1 and Table 1) For a given epicenter position and randomly chosen observation errors ε_k, a set of error equations is prepared. From these observation equations two normal equations are obtained and the same number of unknowns (δR and δT) are calculated.

(II) A similar calculation is repeated for the same seismic network as many as 200 times adopting different sets of random errors at each

5) D. SKOKO, Y. SATÔ and I. OCHI, "Optimum Distribution of Seismic Observation Points. IV," *Bull. Earthq. Res. Inst.*, **45** (1967), 289.

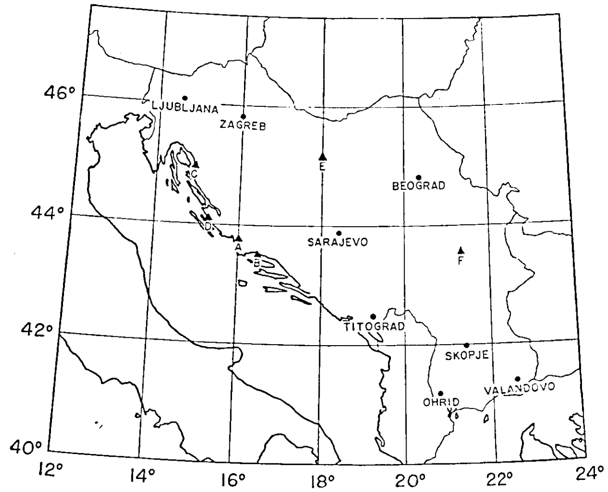

Fig. 1. Eight seismic stations now existing in Yugoslavia and other provisionally chosen stations used for the calculation.

Table 1. Eight seismic stations now existing in Yugoslavia and other provisionally chosen stations used for the calculation.

	STATION	LATITUDE (NORTH) DEG MIN	LONGITUDE (EAST) DEG MIN	INSTRUMENT		
1	LJUBLJANA	46 02.6	14 32.0	1) WIECHERT MECHANICAL	200 KG.	HORIZONTAL
				2) HILLER OPTICAL		VERTICAL
2	ZAGREB	45 49	15 59	1) WIECHERT MECHANICAL	1000 KG.	HORIZONTAL
				2) ID.	1300 KG.	VERTICAL
				3) ID.	80 KG.	HORIZONTAL
3	SARAJEVO	43 52.4	18 25.7	1) MAINKA MECHANICAL	450 KG.	HORIZONTAL
4	BEOGRAD	44 49.3	20 27.3	1) WIECHERT MECHANICAL	1000 KG.	HORIZONTAL
				2) ID.	1300 KG.	VERTICAL
5	TITOGRAD	42 25.8	19 15.6	1) MAINKA MECHANICAL	450 KG.	HORIZONTAL
6	SKOPJE	41 58.3	21 26.4	1) LEHNER-GRIFITH SHORT PERIOD		
				2) PRESS-EWING LONG PERIOD		
				3) WILMORE SHORT PERIOD		
				4) STRONG MOTION RECORDER		
				5) MAINKA MECHANICAL	450 KG.	HORIZONTAL
7	OHRID*	41 08.0	20 50.4	1) LEHNER-GRIFITH SHORT PERIOD		
8	VALANDOVO*	41 20.2	22 35.3	1) LEHNER-GRIFITH SHORT PERIOD		
A**		43 45.0	16 00.0			
B**		43 30.0	16 27.0			
C**		44 59.0	14 54.0			
D**		44 07.0	15 14.0			
E**		45 09.0	18 00.0			
F**		43 34.0	21 20.0			

* UNDER CONSTRUCTION
** STATIONS PROVISIONALLY ASSUMED IN THE CALCULATION

station. Hence we have 200 different δR's and δT's for the given epicenter position.

(III) Then the standard deviations of δR and δT are calculated and are denoted as ΔR and ΔT. The distribution of these quantities

Table 2. Seismic stations included in each network and the result of the calculation thereof.

CASE	EIGHT FIXED STATIONS	ADDITIONAL STATIONS A	B	C	D	E	F	NUMBER OF STATIONS	MEAN VALUE OF $\Delta R^{\cdot}$ (SIMPLE)	$\Delta T^{\cdot\cdot}$ (SIMPLE)	$\Delta R^{\cdot}$ (WEIGHTED)	$\Delta T^{\cdot\cdot}$ (WEIGHTED)	FIGURE
0)	*							8	29	76	26	69	3
1)	*				*			9	22	60	20	56	4A
2)	*	*						9	23	62	20	56	4B
3)	*					*		9	28	68	25	62	4C
4)	*						*	9	27	65	24	60	4D
5)	*		*	*				10	19	52	18	49	5A
6)	*				*	*		10	20	49	18	47	5B
7)	*				*		*	10	19	47	18	46	5C
8)	*				*	*	*	11	20	48	18	46	6A
9)	*		*	*			*	11	19	48	18	45	6B
10)	*		*	*	*	*		12	18	47	17	44	7

. UNIT: 100 m
.. UNIT: 10 msec

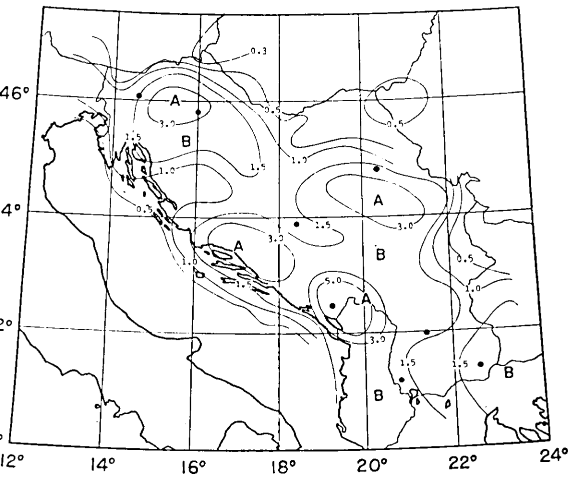

Fig. 2. Seismicity map of Yugoslavia.
Weighted frequency of the earthquakes with the intensity I=VII° MCS on the area 1000 km² within 50 years, drawn on the basis of the data of the earthquakes with intensities VI, VII and VIII° MCS (from: V. V. Beloussov, A. A. Sorsky, Tectonic Map of Europe, Moscow, 1962; original scale 1:2,500,000). There are macroseismic data for the territory of Yugoslavia since 361 A.D. and microseismic ones since 1908. A is the area with the seismicity larger than 3.0 and B is the area for 1.5~3.0.

all over the territory gives a general idea of the error caused by that specific network and enables us to make conclusions about the quality of the network. (cf. Fig. 3)

(IV) Sometimes a single parameter is desirable as the measure of the suitability of the network. For that purpose the arithmetic means of ΔR and ΔT are calculated. In this case, however, seismic active areas should be considered more heavily than other quiet areas. According to the seismicity of each area, therefore, the weight for the calculation of the arithmetic mean is decided. (Simple means are also calculated. cf. Table 2 and Fig. 2.)

(V) In order to see the effect of the addition of extra stations, a number of new stations are chosen and a similar calculation is repeatedly carried out for the network with an increased number of stations. (cf. Table 2)

(VI) Again the mean values of ΔR and ΔT are calculated so that the effect of the increase of station(s) may be evaluated.

Parameters and data adopted

For the actual numerical calculation of the errors, the following values are assumed:

Velocity of the waves in the medium $=7.0$ km/sec
Standard deviation of the observation errors $=0.1$ sec
Depth of the focus $=25$ km

For the weighted mean of ΔR and ΔT, 3 and 2 are adopted as the weight for the areas A and B respectively, and for the remaining part the weight 1 is used. Classification of the seismic area in Fig. 2 is done on a large scale map.

The epicenters are placed at intervals of 30′ both in longitude and in latitude, and there are 200 points altogether for which the calculation is performed.

Along with the case where eight existing stations are assumed, several other calculations are carried out in which one, two, three or four observation points are added to the present Yugoslav seismic network. In accordance with the results of the previous paper[5] the given positions in Table 1 and in Fig. 1 are chosen as new favorable locations of new stations, which are listed in Table 1 and are also shown in Fig. 2.

Result of calculation

(I) No additional station*—case 0)**

The amount of errors ΔR and ΔT are shown in Fig. 3. One can see that a large area of the central part is characterised by rather small errors, while the periphery has larger values. Comparison between Fig. 3 and Fig. 2 shows that some areas of higher seismicity have large errors, which fact is especially true at the southwestern coastal area and the central eastern and northwestern parts. Those are the weak points of the existing network, even if we assume that all the stations are supplied with highly sensitive seismographs.

(II) One additional station—cases 1)-4)

The results of calculations are plotted in Fig. 4. From the comparison of the values ΔR with the above-mentioned case (case 0) Fig. 3) it is easily understood that the continental area with small errors ($\Delta R<10(=1000\,\mathrm{m})$) is considerably increased. The increase is more than 10% for the cases 1), 2) and 4), and for the case 3) about 6%. On the other hand cases 1) and 2) don't have the region with the errors larger than 200(=20 km). The areas with larger errors for all the four cases are less than the case 0).

As the result of the calculation of cases 1) and 2) one can see considerable decrease of the errors ΔR in the most active seismic areas (A in Fig. 1) and slightly less diminution for the cases 3) and 4) compared with the case 0). Particularly we can notice that there is no difference between the cases 1) and 2). This may be natural because the added stations A and B are close by. It follows that among all the experiments where only one new station is added cases 1) and 2) have advantage in regard to the accuracy of epicenter location.

Again, the continental areas with small errors of ΔT are larger for the networks with one additional station than the original case. If we take the regions where the errors ΔT are less than 50(=500 m sec) the increase of the area for all the four cases is more than 13%. The territory covered by large errors $\Delta T>200(=2\,\mathrm{sec})$, on the contrary, decreases greatly except for case 4).

Generally speaking, cases 1) and 2), namely

15.2°E, 44.1°N and 16.0°E, 43.3/4°N (D and A)

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* Though the stations of the existing Yugoslav seismic network (altogether 8 stations) are supplied with different kinds of instruments there is a plan to provide seismographs of the same quality.

** Cases 0) and 1) were studied before.[5]

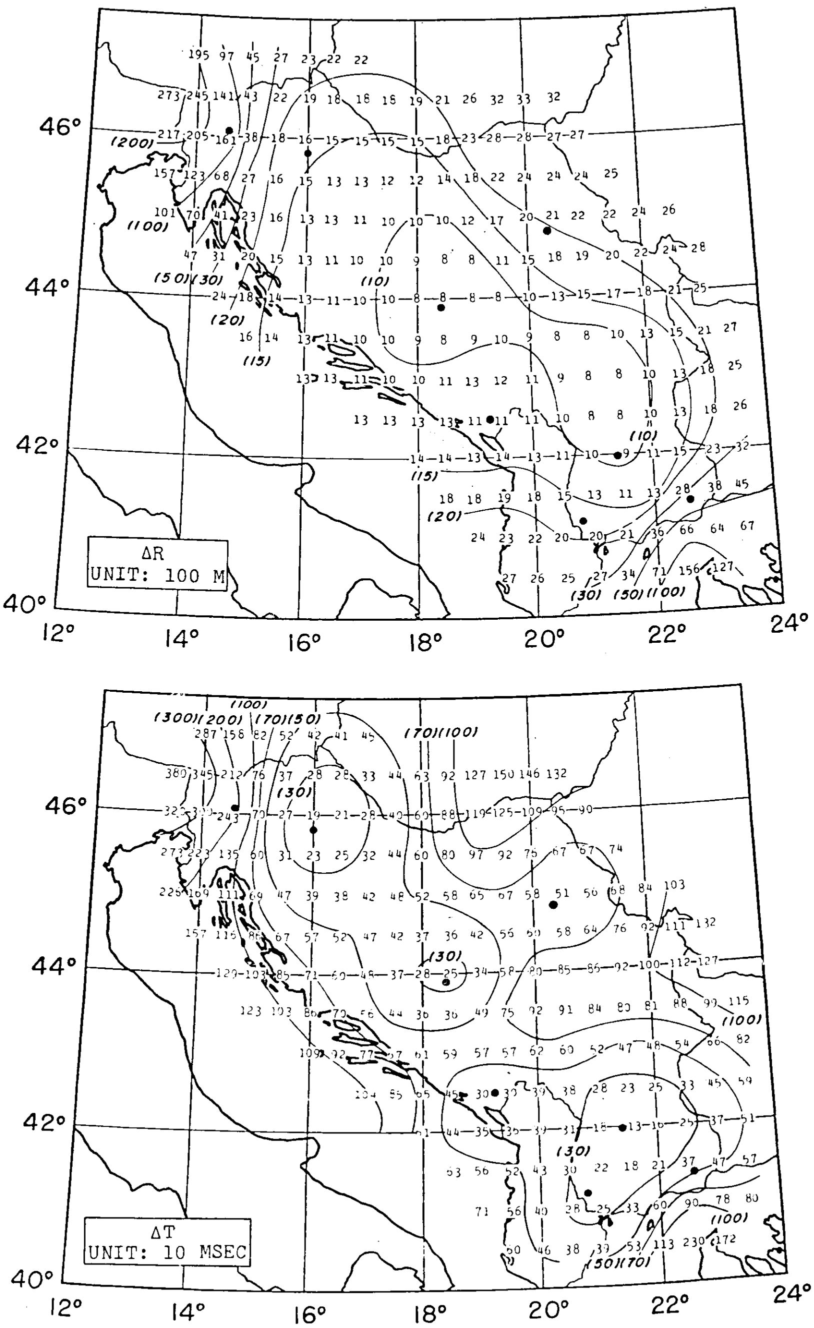
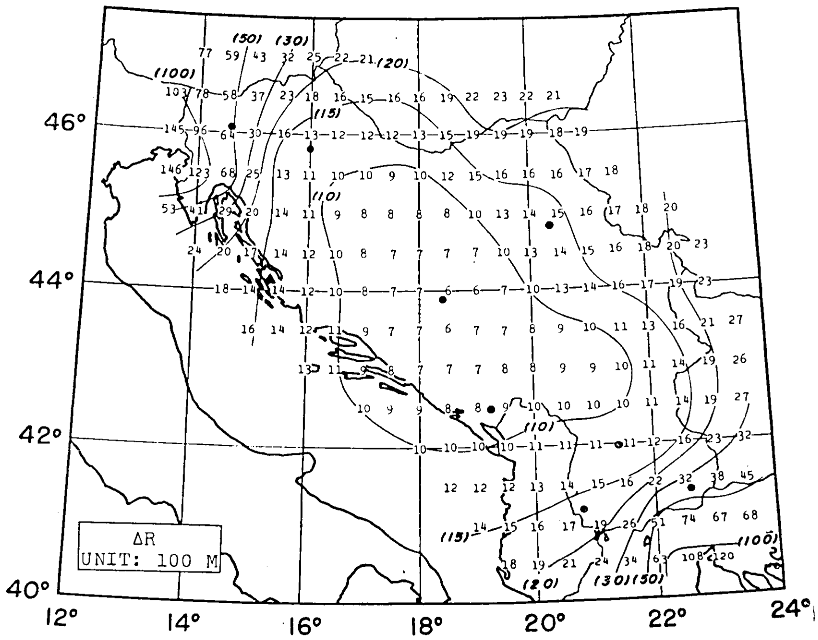


Fig. 3. Case 0) 8 fixed stations.



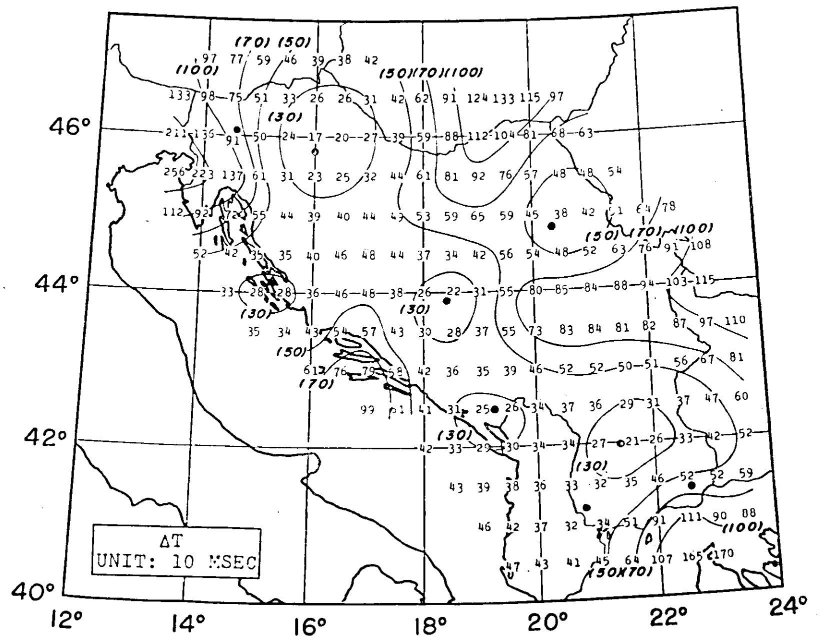


Fig. 4A. Case 1) (8 fixed+D) stations.

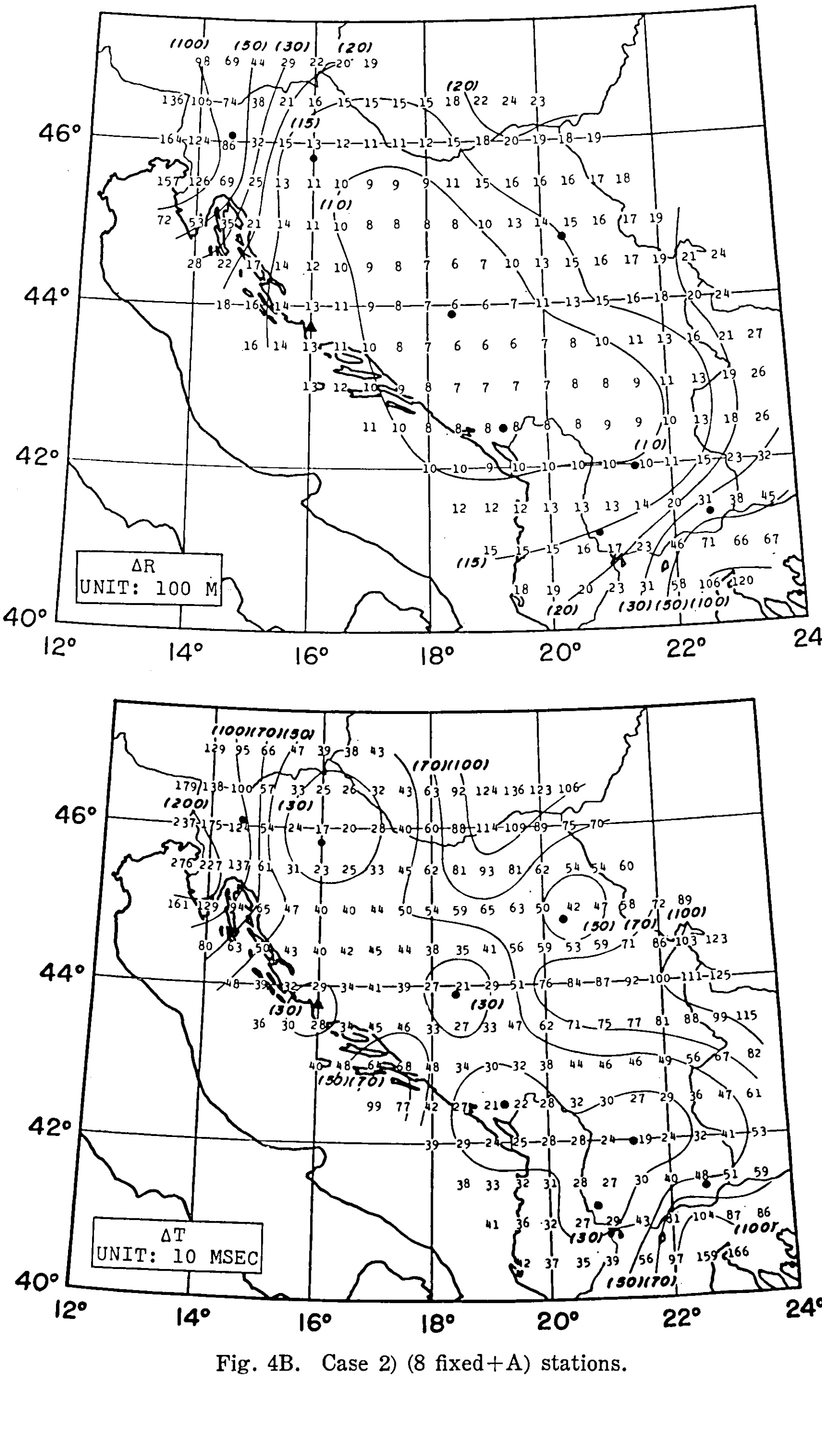


Fig. 4B. Case 2) (8 fixed+A) stations.

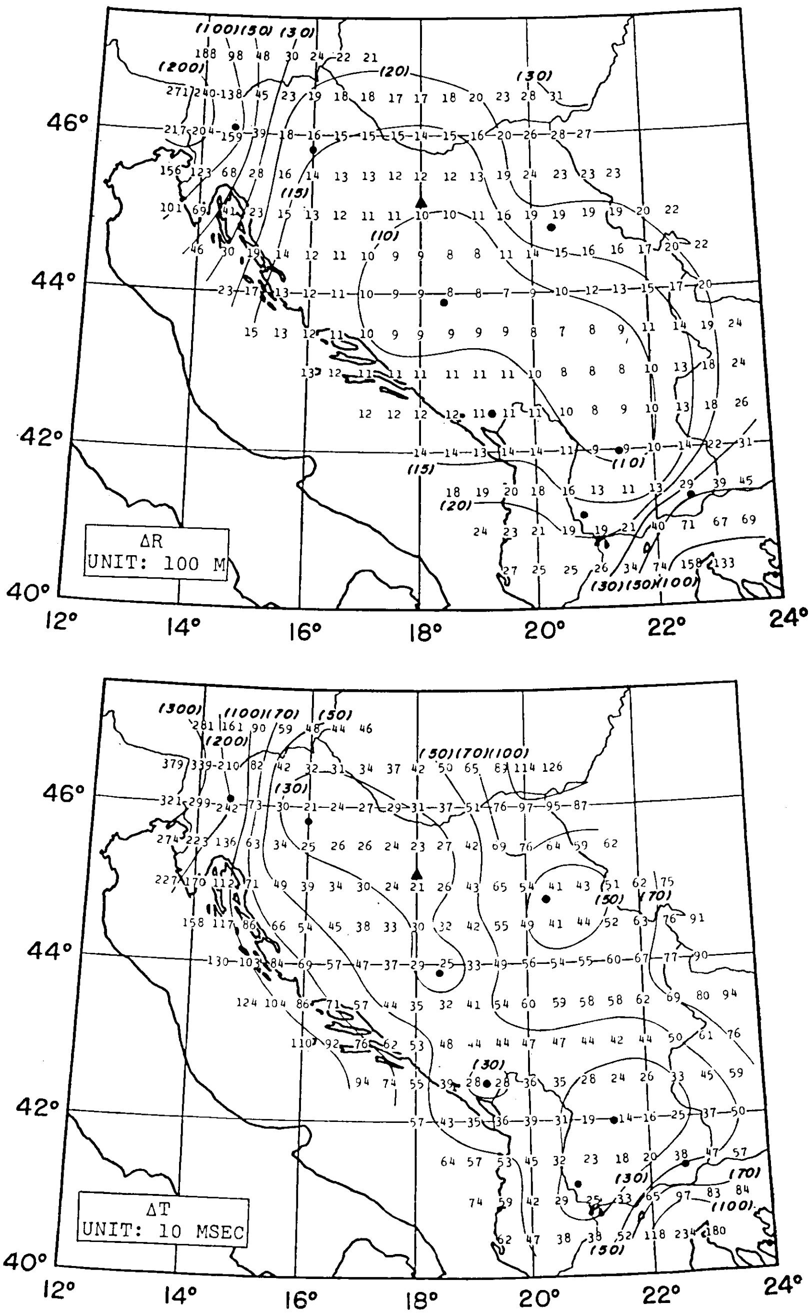


Fig. 4C. Case 3) (8 fixed+E) stations.

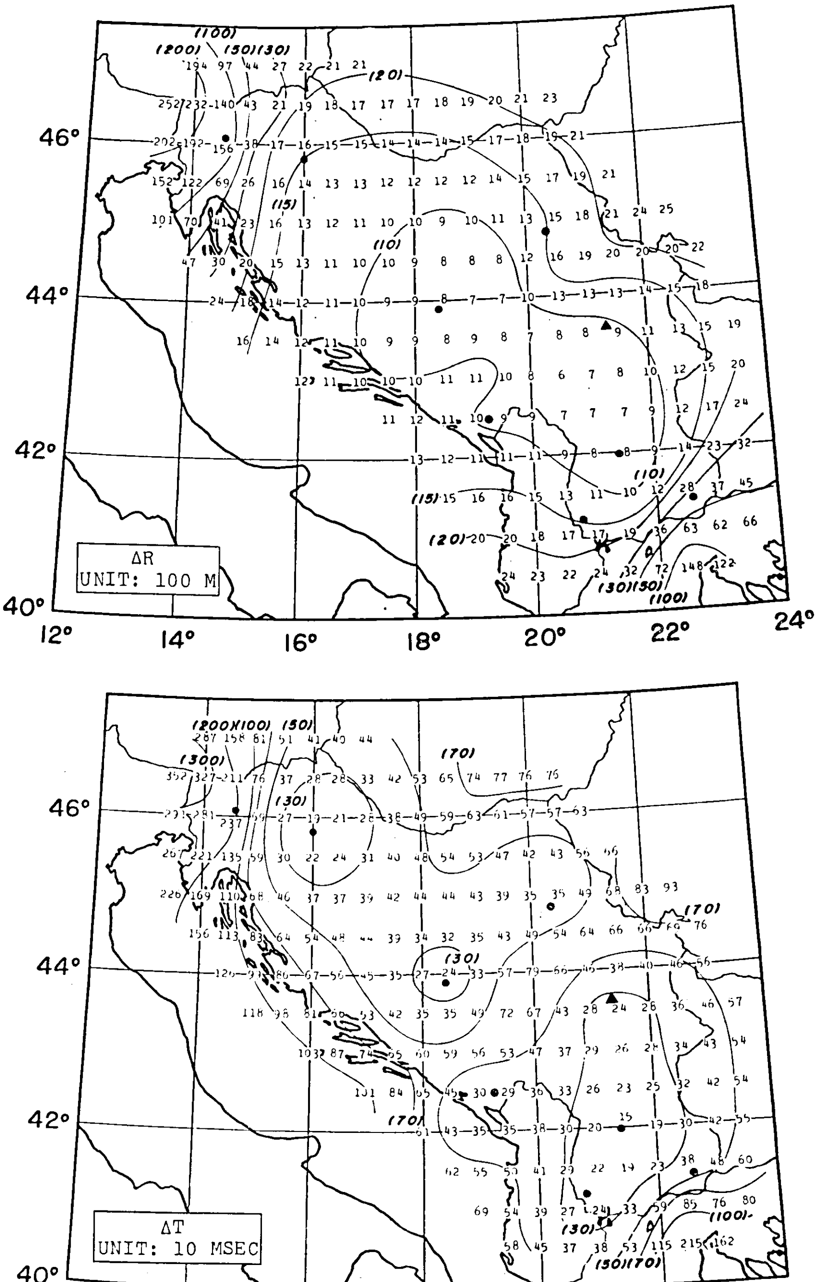


Fig. 4D. Case 4) (8 fixed+F) stations.

are far better than the cases 3) and 4), which can be seen especially in the Adriatic coastal region. There is no essential difference between cases 1) and 2) though we can find minor differences if we compare the two figures very carefully.

(III) Two additional stations—cases 5)-7)

The cases 5) (B and C added), 6) (D and E added) and 7) (D and F added) are treated here and the results of the calculation are shown in Fig. 5.

The area covered by small $\Delta R(<10(=1000\ \mathrm{m}))$ is even larger by about 10-13% in the above cases than the favorable ones with one extra station. Among the above three cases, however, no significant difference is seen and any of them can be treated as equally good for the epicenter determination.

As for the origin time errors also, these cases have a large area with good accuracy $(\Delta T<30(=300\ \mathrm{m\,sec}))$, besides, the area with poor accuracy $(\Delta T>200(=2\ \mathrm{sec}))$ is much restricted compared with the cases treated before. In the seismic active region around 17.5°E, 43.5°N case 5) has advantage over other cases, but in another active region around 20.5°E, 44.5°N this is not so. For case 7) one can find an area with very small errors $(\Delta T=19(=190\ \mathrm{m\,sec}))$, while at the active zone around 20.5°E, 44.5°N rather large values are found. It will be worth mentioning that the mean values of ΔT for coastal region in these cases (cases 5), 6) and 7)), have the following amounts 48, 43 and 41($\times 10$ m sec) respectively. Because of these error amounts we can conclude that the cases 6) and 7) are preferable.

(IV) Three additional stations—cases 8) and 9)

Only two examples of this kind are treated, namely, case 8) (D, E and F added) and case 9) (B, C and F added). The results are given in Fig. 6. It is curious to find that these cases scarcely improve the epicenter determination compared with the cases of two additional stations. There is no special advantage in either of the above two, except minor points which could be found in figures.

With regard to the errors of origin time, however, both of the cases give slightly smaller ΔT than previous cases. Here case 9) has a small advantage in the area around 17.5°E, 43.5°N, while case 8) is preferable in the area around 20.5°E, 44.5°N. Otherwise there is no essential difference between these two.

(V) Four additional stations—case 10)

Results of calculations for this case (B, C, D and E added) are drawn

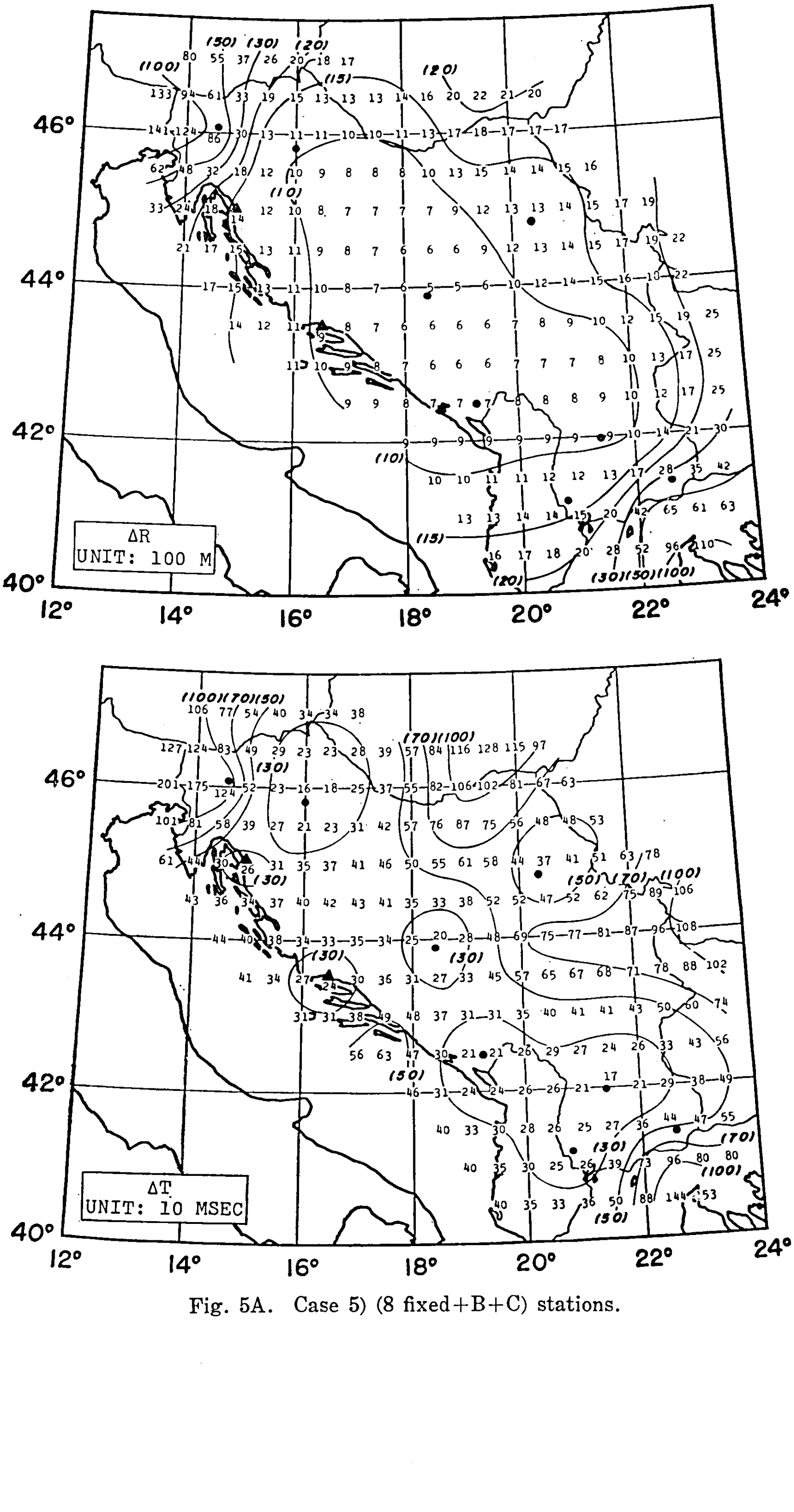


Fig. 5A. Case 5) (8 fixed+B+C) stations.

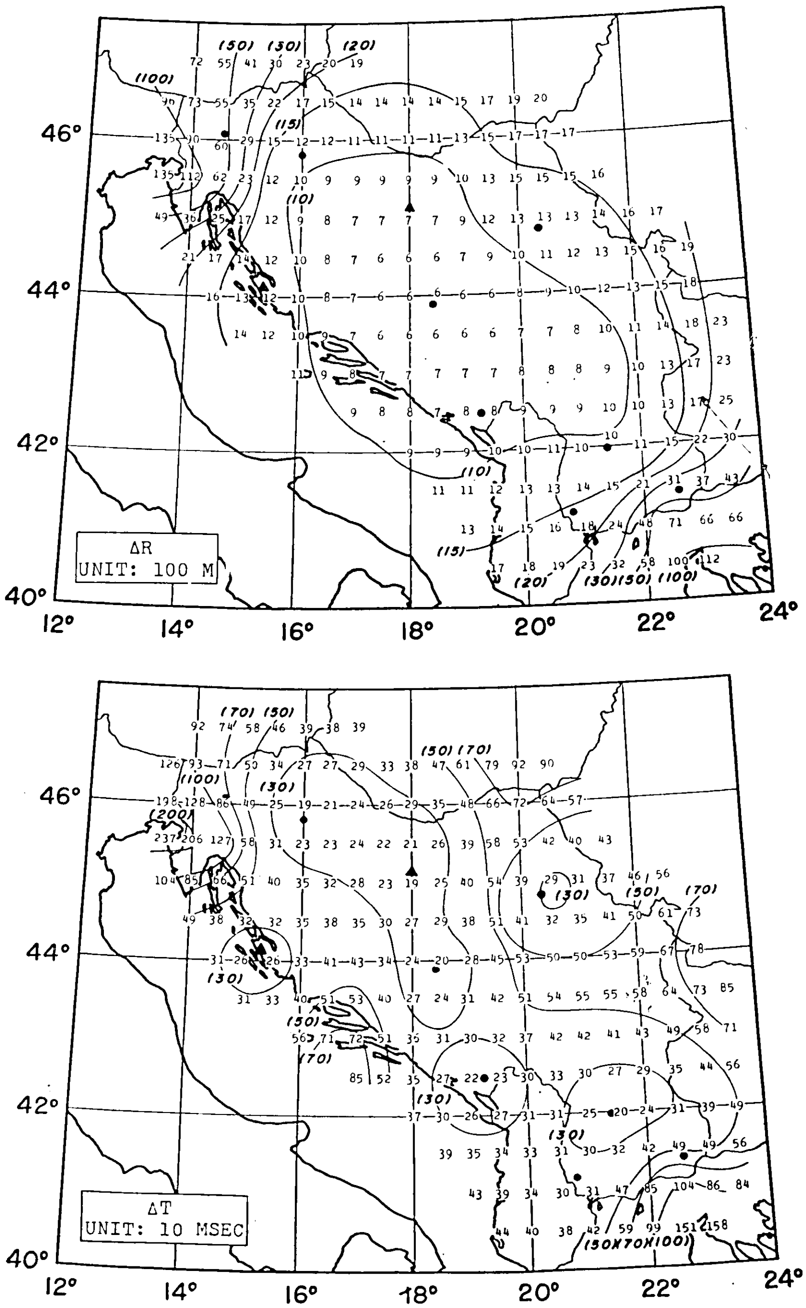


Fig. 5B. Case 6) (8 fixed+D+E) stations.

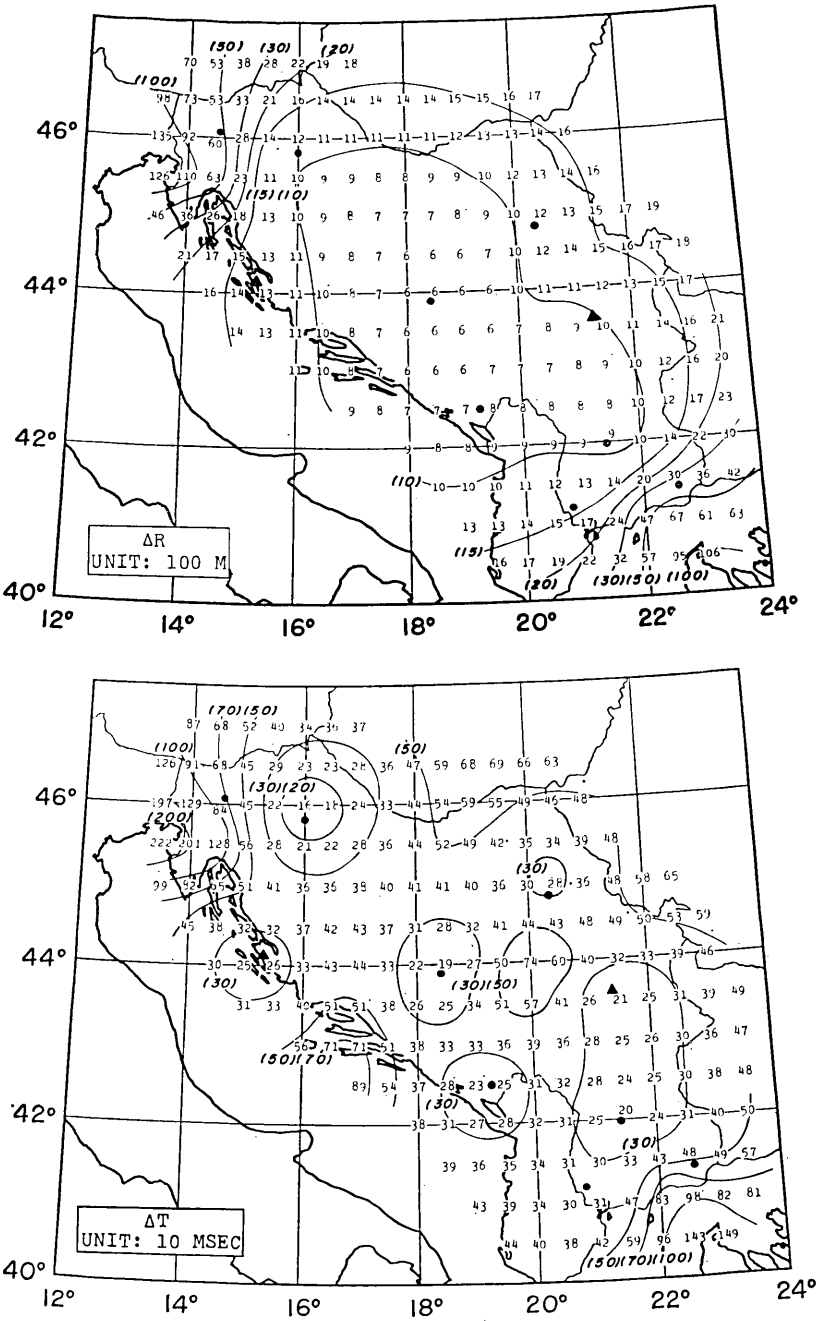


Fig. 5C. Case 7) (8 fixed+D+F) stations.

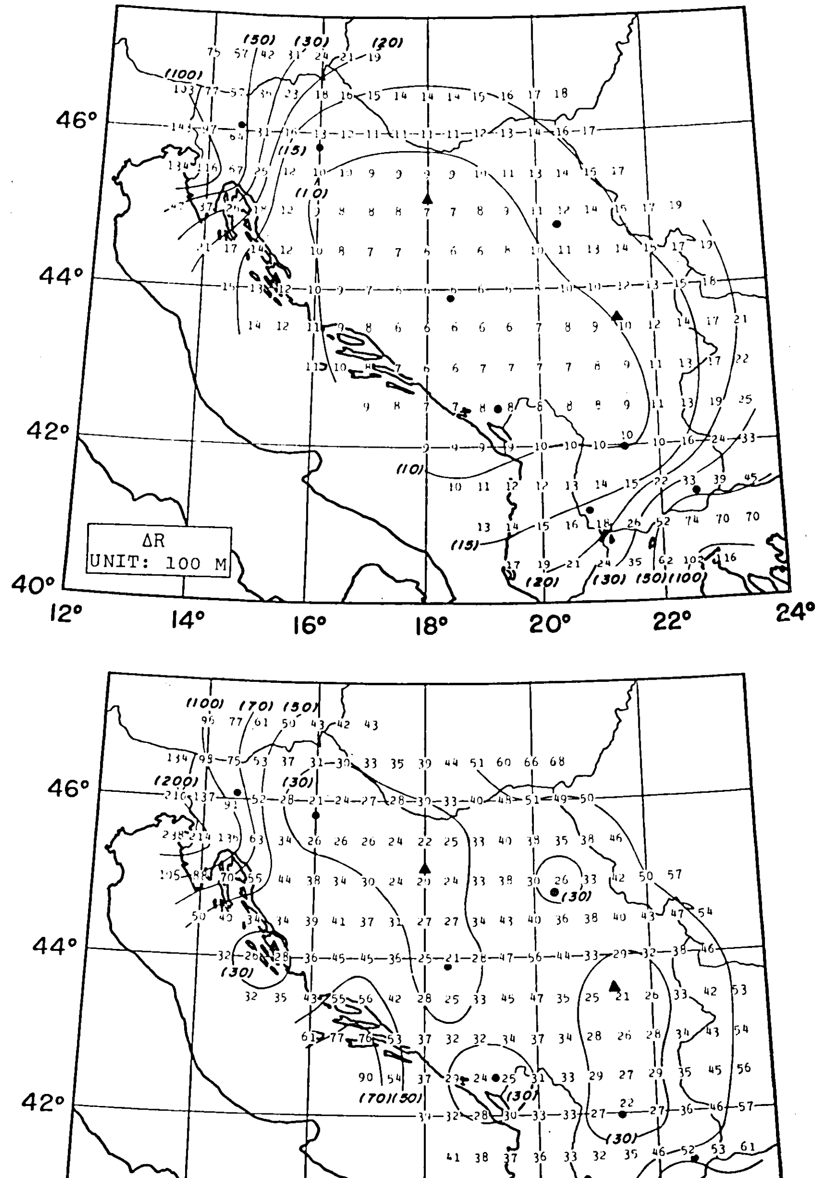


Fig. 6A. Case 8) (8 fixed+D+E+F) stations.

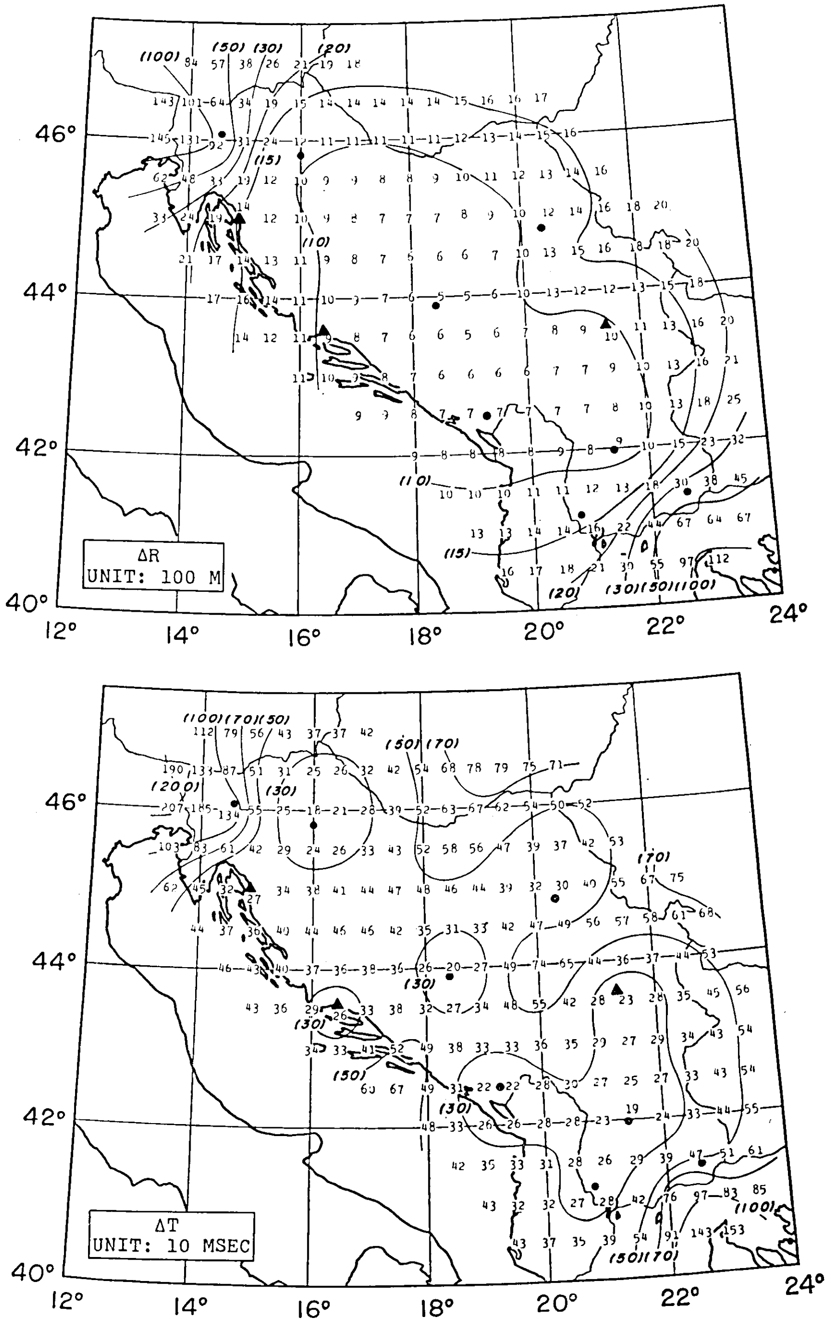


Fig. 6B. Case 9) (8 fixed+B+C+F) stations.

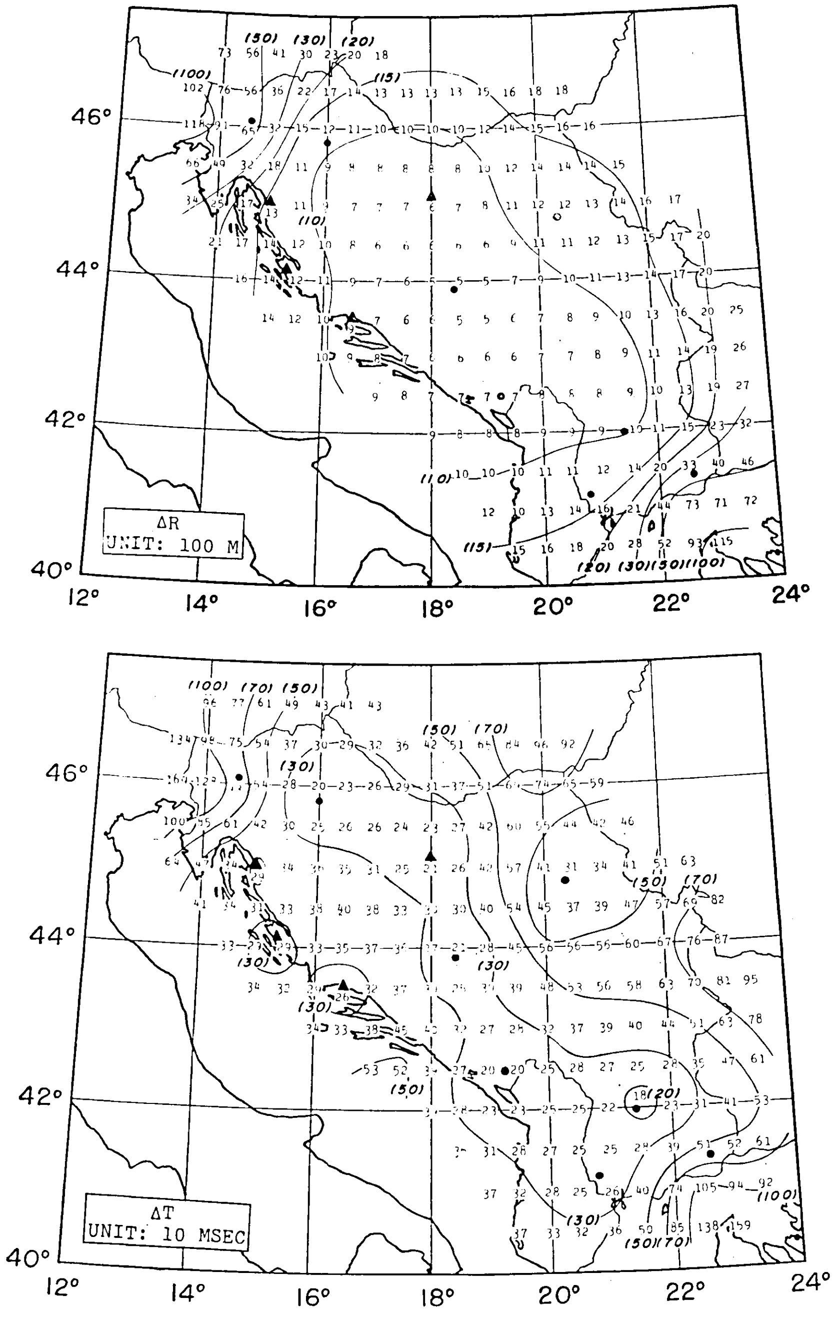


Fig. 7. Case 10) (8 fixed+B+C+D+E) stations.

in Fig. 7, from which one can see that the area with small errors of epicenter location ($\Delta R<10(=1000\,\mathrm{m})$) is the largest and that the high error region is the smallest in all the cases given in this paper. The mean value of ΔR in the continental region is 15($=1500$ m) for the cases 8) and 9), and 13 for the present case. In the seismic active areas also, we can find smaller errors of origin time in Fig. 6 than in other cases.

From the above-mentioned fact we can see the advantage of the distribution with four new stations in comparison with any other networks investigated in the present study.

Conclusion

From the calculations shown here the necessity of setting up new seismic observation points in Yugoslavia is concluded. The addition of a small number of extra stations will improve the weak points of the existing network, particularly the accuracy of epicenter location and of origin time in the seismic active areas of the territory. Smaller errors of epicenter location for a given observation network are generally associated with smaller errors of origin time.

It is noticed that even a small change in the position of an extra station (compare the cases 1) and 2)) is followed by an appreciable change in the accuracy of seismic source parameters if we treat some specific area rather than the territory as a whole.

Only one new station added to the existing Yugoslav seismic network has significant effect in the decrease of the errors of both epicenter location and origin time. If only one station is to be added its recommendable position is the region between

15.2°E, 44.1°N and 16.0°E, 43.3/4°N (D and A) .

In case two stations can be added the diminution of errors ΔR and ΔT is great if we make comparison with analogous values for the cases with one new station. Desirable combinations of the two additional stations are either

15.2°E, 44.1°N and 18.0°E, 45.1°N (D and E)

or 15.2°E, 44.1°N and 21.3°E, 43.6°N (D and F) .

From the comparison between the cases with three additional stations and those with two it is concluded that the former has little advantage.

Four extra stations, however, bring further improvements and rather homogeneous space distribution of the errors ΔR and ΔT, and the distribution tested here is worth recommending.

The numerical calculation was carried out at the Computer Center, University of Tokyo.

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39. 地震観測点の最良分布 V
続　ユーゴスラヴィア新観測所の最適地

ザグレブ大学 Dragutin SKOKO

地震研究所 小竹美子 佐藤泰夫

ユーゴスラヴィアはさきにスコピエの地震に見まわれ，1967 年にも破壊的地震があるなど，その対策が真剣に考えられているが，地震観測の向上も一つの重要課題となつている．それで現存する 8 個所の観測所に加えて，新しく 1 観測所を建設するならば震央及び発震時の決定精度がどのようになるかについてさきに計算を行ない，概略の結果はすでに得られている．今回はこれに下に記すような改良を加えて計算を行なつた．(モンテ·カルロ法を使用する基本的な方針と計算手続は前と全く同様である.)

1. 観測所建設のための実際的適地数個所をえらび，これらの点について前回よりも詳細な計算を行なつたこと．(第 1 図および第 1 表参照)

2. 新観測所は 1 個所と限定せず，2, 3, 4 個所に設けた場合をも扱つたこと．(第 2 表参照)

3. 観測網の良否を定めるためのパラメーターとしては，ユーゴスラヴィア全土に震央を仮定し (緯度，経度とも 30′ おき)，これらに対する誤差の期待値 δR, δT の平均値 ΔR, ΔT を従来用いて来た．しかし地震の発生はユーゴスラヴィア全体について一様ではないので，サイスミシティに準じて 3 段階の重みをつけ，これを用いた重荷平均をとることにより，地域的にことなる頻度を考慮に入れた．(第 2 図参照)

以上の方針に基づいて計算した結果は第 3~7 図に示されているが，これによつて次のような結論を下すことが可能であろう．

1. 観測点 1 個所を加えるのならば，アドリア海沿岸の A または D 点 (第 1 図参照) がよいであろう．これにより ΔR<1 Km の地域は 10% 以上まし，最大誤差は半分以下となる．

2. 2 点を加えうるのならば，1 点はアドリア海岸の D 点に，他は内陸の E または F 点が，計算結果からも，実際的考慮からも適地と思われる．

3. 第 2 表に示すような 3 点をえらんだのでは，2 点の場合にくらべ，さほどの改良はみられないが，4 点 B, C, D, E を加えうるならば，その効果は少なくない．
