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Empirical criteria for the accuracy of earthquake locations on the Croatian territory

Tena Belinić and Snježana Markušić

Department of Geophysics, Faculty of Science, University of Zagreb, Zagreb, Croatia

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This paper presents the empirically based ground truth criteria, or shorter GT criteria, for the estimation of the epicentral location accuracy of the seismic events recorded at network stations within 400 km around the city of Zagreb. The criteria are based only on the network coverage metrics and the GT5 level represents an absolute location error lower than 5 km. They have been developed using a bootstrap resampling method: same earthquakes have been relocated many times but with different, randomly selected seismic stations. We used 330 reference events taken from the pages of ISC (ISC Reference Event Bulletin, 2008) and showed that the location accuracy is most affected by the distance to the farthest station in the seismic network, while not at all influenced by the distance to the nearest. The developed GT criteria for $GT5_{95\%}$ level of accuracy require 10 or more network stations, all within 125 km from the epicentre, and the secondary azimuthal gap (the largest gap when any given station is removed from the network) less than 200°, or the network quality metric (the deviation between the optimal uniformly distributed network and the actual network) less than 0.41. The obtained results revealed that the global criteria are too restrictive and unsuitable for the studied area since they require more regular networks. With our criteria, it is possible to achieve higher accuracy for the networks with a bigger secondary azimuthal gap or greater network quality metric. In addition, our criteria limitations are shown for the areas with simpler geological structure.

Keywords: GT criteria, epicentral location accuracy, bootstrap method, Croatia

1. Introduction

One of the most important tasks in seismology is to determine the position of any source that radiates seismic energy. The exact hypocentral locations are necessary for the calculation of seismic hazard and the development of 3D seismic velocity models in the Earth's interior. Almost all earthquake catalogues are produced by using iterative linear inversion schemes and 1D seismic velocity models to estimate hypocentral locations and uncertainty parameters, although there are efforts to develop non-linear inversion methods (Sambridge and Kennett, 2001; Kennett, 2006) and 3D models (Levshin and Ritzwoller, 2003; Ritzwoller et al., 2003; Nicholson, 2006) that could be used in routine supplementation of earthquake catalogues. Usually, the main goal is to achieve catalogue completeness to the lowest possible magnitude and the goal to maintain equal accuracy for all events is generally overlooked. Therefore, the catalogues inevitably contain a mixture of accurate, good and bad locations and the data from earthquake catalogues should be always used with caution. In fact, published bulletins provide hardly any information about the accuracy of the hypocentral location.

The common practice of seismic location accuracy analysis is to calculate the formal uncertainties (error ellipses, elapsed time and unreliability of depth). According to Pavlis (1986), they are dominated by three factors: measurement errors of the seismic arrival times, modelling errors of the calculated traveltimes and non-linearity of the earthquake location problem. The majority of the location algorithms rely on one of the following two methods to determine uncertainties: the first, which is based on the F-statistic, where the *a posteriori* residual distribution is defined with a location confidence ellipsoid which is estimated by scaling the partial derivatives of traveltime with respect to the hypocentre coordinates (Flinn, 1965); or the second, which is based on the χ^2 - statistic, where the *a priori* phase picking and traveltime uncertainties are obtained through the location algorithm to produce a coverage ellipsoid (Evernden, 1969). The correct calculation of formal uncertainties demands the following assumption fulfilled: Gaussian uncorrelated error processes with zero mean; although proved in practice as non-viable for most seismic locations. The most critical assumption is that traveltime prediction errors are unbiased due to the use of a 1D model for traveltime prediction in the 3D Earth, which results in tendency along specific paths. Currently, the most popular approach to the evaluation of location uncertainties is the use of th e probabilistic Bayesian formulation (Husen and Smith, 2004; Gesret et al., 2015). Its final solution is the complete posterior probability density function of the event location and it essentially depends on the accuracy of the used velocity model.

Therefore, the ground truth criteria were introduced to specify the accuracy of epicentral location only by network geometry, while the quality of phase picking can be uneven and the used velocity model does not need to be optimal. Bondár et al. (2001) and Bondár et al. (2004) developed the GTXC% criteria, where X is the location accuracy in kilometres with a confidence level of C%, respectively, the exact epicentre is within X km from the estimated one. All events recorded on the regional networks are directly approved as the $\mathrm{GT20}_{90\%}$ level events. Bondár et al. (2004) and Bondár and McLaughlin (2009) extended the criteria using the global bulletin's data, while Boomer et al. (2010, 2013) tested the existing global criteria against the reference GT0 explosions and

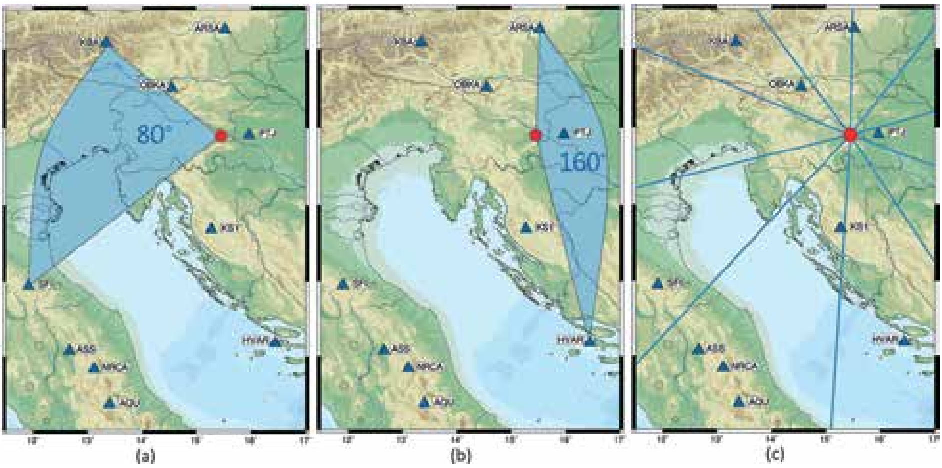

Figure 1. Example of: (*a*) primary azimuthal gap; (*b*) secondary azimuthal gap; (*c*) real and optimal network for the earthquake that happened 4.16.2000 at 20:29 on location (45.9° N, 15.45° E). The primary azimuthal gap is 80° and the secondary 160°, they are marked with blue. Real stations are displayed with blue triangles, while the possible positions of the optimal network stations are represented by blue lines. The network quality metric for the real network is $\Delta U = 0.35$ and for the optimal $\Delta U = 0$.

demonstrated that the global criteria may be overly restrictive for the relatively simple geological structures.

The aim of this study was to determine the GT criteria for the local network within a radius of 400 km around the city of Zagreb in order to achieve the $GT5_{95\%}$ level of accuracy for epicentral locations. The GT5 level represents an absolute location error lower than 5 km. We used the network coverage as a metric for location accuracy evaluation, which is defined by the primary and the secondary azimuthal gap measurements. Also, we researched the influence of event-network distances on the location accuracy. The used resampling method ensured the independence of the locations of the same earthquakes due to randomly selected networks. The studied area has a relatively complex structure, thus the resulting criteria should be similar to those obtained by Bondár et al. (2004, 2009).

2. GT criteria parameters

As previously mentioned, it is common to use network coverage as the measure of location accuracy. It is quantified by the primary and the secondary azimuthal gap (Figs. 1a and 1b) defined as:

- primary azimuthal gap – the largest gap between a network's event-station azimuths,
- secondary azimuthal gap – the largest gap that results when any given station is removed from the network.

The primary azimuthal gap is directly linked to the network geometry and represents a quantitative measure of how well the epicentre is surrounded by the stations. However, this metric is sensitive to reading errors, thus the use of the secondary azimuthal gap is more standardly accepted. The secondary azimuthal gap is the more robust measure of the network geometry, as it reduces the vulnerability to phase picking and traveltime prediction errors, and implicitly invokes the constrains on the primary azimuthal gap and the minimum number of stations.

To provide the best azimuthal coverage for the event location, intuitively, the stations in a local network should be uniformly distributed among the azimuths. The more the network deviates from this optimal geometry, the more prone it becomes to location uncertainties. The network quality metric introduced by Bondár and McLaughlin (2009) is defined as the mean absolute deviation between the optimal uniformly distributed network and the actual network. The metric is given by the expression:

$$\Delta U = \frac{4\sum|esaz_i - (unif_i + b)|}{360N} \tag{1}$$

where N is the number of stations, $esaz_i$ is the ith event-to-station azimuth, $unif_i = \frac{360\,i}{N}$ for $i = 1, ..., N$ and $b = avg(esaz_i) - avg(unif_i)$. Event-to-station azimuths must be sorted by increasing values. The network quality metric is normalized, thus ΔU values range from 0 to 1. $\Delta U = 0$ when the stations are uniformly distributed and $\Delta U = 1$ when all the stations are at the same azimuth (Fig. 1c). The metric is sensitive to large azimuthal gaps and potentially correlated stations, *i.e.* unbalanced networks with stations at similar azimuths. Although related to the non-parametric Kolmogorov-Smirnov statistic, D (which represents the maximum absolute deviation between two distributions), the ΔU metric is defined as the normalized area between the (best fitting) uniform network and the actual one.

The location accuracy can be influenced by event-station distances, *e.g.* distances to the nearest and the farthest network station, number of used phases etc. To locate the events, the seismological surveys use either all phases recorded on the seismic stations or just the first arrivals, because of their higher accuracy. The determination of the S-phase arrival time is more difficult because of the larger signal-to-noise ratio (considering that the arrival of the S-wave is during the P-wave coda and that it can be preceded by the converted phases) and it introduces larger uncertainties (Husen and Hardebeck, 2010).

3. Review of GT criteria

Earthquake location accuracy has been the subject of numerous studies during the last decades with the purpose of increasing the effectiveness of nuclear explosion monitoring and collecting high accuracy data. Kennett and Engdahl (1991) were the first who determined the global location accuracy and found an average error of 14 km for a data set of 104 events.

Sweeney (1996) defined ‘reference events’ and explored the option of choosing them from the global bulletins, *e.g.* the International Seismological Center (onward ISC) and the National Earthquake Information Center (NEIC). Reference events are earthquakes and explosions whose hypocentres have high accuracy, better than 5 km. The location accuracy for these catalogues was evaluated as 10–15 km, when the azimuthal gap is less than 200° and at least 50 phases are used. For teleseismic networks with azimuthal gap lower than 90°, Sweeney (1998) found an accuracy of 15 km when using at least 50 phases.

Engdahl et al. (1998) provided a new catalogue, named EHB, using a newer global velocity model (*ak135*), the arrival times of later phases and special station traveltime corrections. They relocated a data set of 1166 nuclear explosions and 83 earthquakes, and found an average error of 9.4 ± 5.7 km, for an azimuthal gap of less than 180°.

Bondár et al. (2001) introduced ’ground truth’ categories (GTX, where *X* represents the epicentre location accuracy in kilometres). They described the event location accuracy for the Ground Truth data set assembled at the Centre for Monitoring Research (CMR). The events that satisfied Sweeney’s (1998) criteria were accepted as GT25, while for the GT10 level, the events required at least five stations within 2° distance and an azimuthal gap of less than 180° for stations within 5° distance.

In the development of the 2004 criteria (Bondár et al., 2004, see Tab. 1), events from regions with complex crustal structure were used and an average global P_g /

Table 1. Global GT (Bondár et al., 2004) and EBGT criteria for the Kaapvaal Craton (Boomer et al., 2010).

					Number of stations within specified distance			
Network	Distance [°]	P_g / P_n crossover distance [km]	Primary azimuthal gap [°]	Secondary azimuthal gap [°]	Between P_g / P_n crossover distance and 1000 km	< P_g / P_n crossover distance	Minimal distance	GT level
Local	0–2.5	250	110	160	–	10	1 between 30 km	$GT5_{95\%}$
Near regional	2.5–10	250	–	120	10	–	–	$GT20_{90\%}$
Regional	2.5–20	250	–	120	–	–	–	$GT25_{90\%}$
Teleseismic	28–91	–	–	120	–	–	–	$GT25_{90\%}$
Kaapval EBGT	0–1.9	215	202	–	–	10	1 between 79 km	$GT3_{95\%}$

P_n crossover distance of 250 km was considered. Using the bootstrap resampling method, they relocated two GT0 events repeatedly due to the density of the network coverage in the local distances; there where 3 stations within 30 km, and at least 40 stations within 250 km of each event. On account of the used global crossover P_g / P_n distance of 250 km, the criteria may not always be representative of the local velocity structures and can lead to phase identification errors.

Bai et al. (2006) modified the $GTX_{C\%}$ classification to $REXC_{\%}$, which represents a reference error (the epicentre lies within the *X* km from the reference epicentre). They showed that the relative hypocentral error achieves a $RE1_{95\%}$ level, and the relative epicentral error $RE0.5_{95\%}$ if the seismic network meets following requirements: (1) a minimum of 15 ± 2 station within 100 km around the epicentre and (2) primary azimuthal gap lower than 210°.

Boomer et al. (2010) for the Kaapvaal Craton in South Africa specified the criteria to achieve an empirically based ground truth level EBGT3 with 95% confidence. The conditions are: (1) an event should be recorded at 8 or more stations within the P_g / P_n crossover distance of 215 km and (2) the primary azimuthal gap must be lower than 202°. Furthermore, if an event is recorded at 9 or more stations where one is within 79 km from the epicentre, focal depth accuracy is 4 km with 95% confidence. Similarly, if an event is recorded at 8 stations, focal depth accuracy is 6 km. Using the new criteria, (Tab. 1) they have identified 10 new GT5 events which had previously failed the restrictive criteria from 2004 or 2009.

Also, Boomer et al. (2013) determined the EBGT criteria for the Main Ethiopian Rift and the Tibetan Plateau (Tab. 2). In a region of the Main Ethiopian Rift, an event must be recorded at at least 8 stations within the local P_g / P_n crossover distance and the network must have a quality metric less than 0.43 to be classified as EBGT5 with 95% confidence. The criteria for the Tibetan Plateau are similar, although slightly less restrictive; the quality metric must be less than 0.45. They identified 34 new GT5 events in Ethiopia and 27 in Tibet.

The IASPEI[1] catalogue of reference GT events (ISC Reference Event Bulletin, 2008) consists of: nuclear explosions with GT0-5 levels (Bennett et al., 2010);

Table 2. Global GT (Bondár & McLaughlin, 2009) and EBGT criteria for the Main Ethiopian Rift and the Tibetan Plateau (Boomer et al., 2013).

Network	Distance [°]	P_g / P_n crossover distance [km]	Network quality metric	Number of stations within specified distance			GT level
				Between P_g / P_n crossover distance and 1000 km	< P_g / P_n crossover distance	Minimal distance	
Local	0–1.35	150	≤ 0.35	–	10	1 between 10 km	$GT5_{95\%}$
Ethiopia EBGT	0–1.6/1.9	178/211	<0.43	–	8	–	$GT5_{95\%}$
Tibet EBGT	0–1.5	167	<0.45	–	8	1 between 65 km	$GT5_{95\%}$

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[1] *International Association of Seismology and Physics of the Earth's Interior*

chemical explosions and explosions caused by mines with GT0-5 levels (Bondár et al., 2004); and earthquakes with GT5 levels (Bondár et al., 2008; Bondár and McLaughlin, 2009; regularly updating from the ISC bulletin). There is total of 8816 events.

4. Data and methods

For the evaluation of the GT criteria, we studied the local network within a radius of 400 km around the city of Zagreb (45.81° N, 15.98° E). We used 330 reference events from the IASPEI GT catalogue (ISC Reference Event Bulletin, 2008) downloaded from the pages of the International Seismological Center. They have been recorded at 315 seismic stations (Fig. 2), each at more than 10 station in the period from January 1980 to July 2012. Almost all of events had depth smaller than 20 km, and 29 of the used events were explosions that

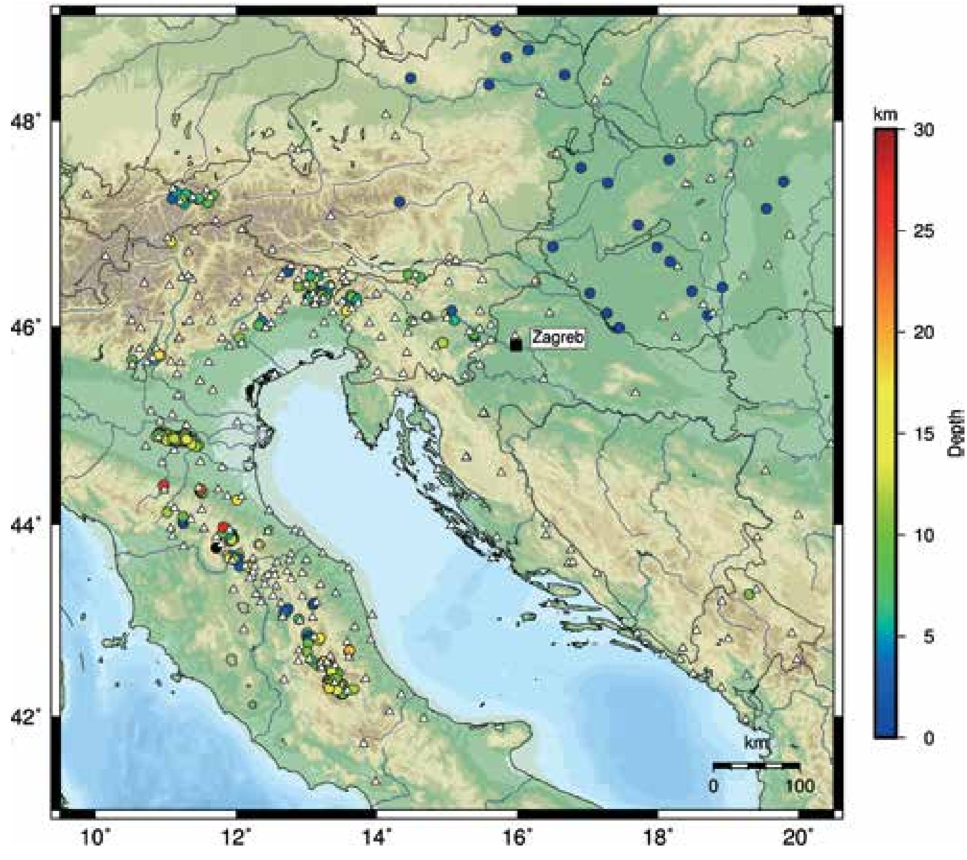

Figure 2. Map shows the locations of used reference events (the colour of the dot depends on the depth of the event) and seismic stations (white triangles).

happened near the ground along the seismic profiles in the Hungary. Also, there were nine earthquakes with the magnitude larger than 5, and the strongest one with a magnitude of 5.6 occurred on 26 September 1997 near the town Foligno (43.02° N, 12.89° E) in central Italy.

We used the bootstrap resampling method, which estimates generalized errors based on resampling with a completely random selection of samples. To ensure independent samples, the easiest approach is to use sampling with replacement, especially when there is large number of possible elements (*e.g.* arrival

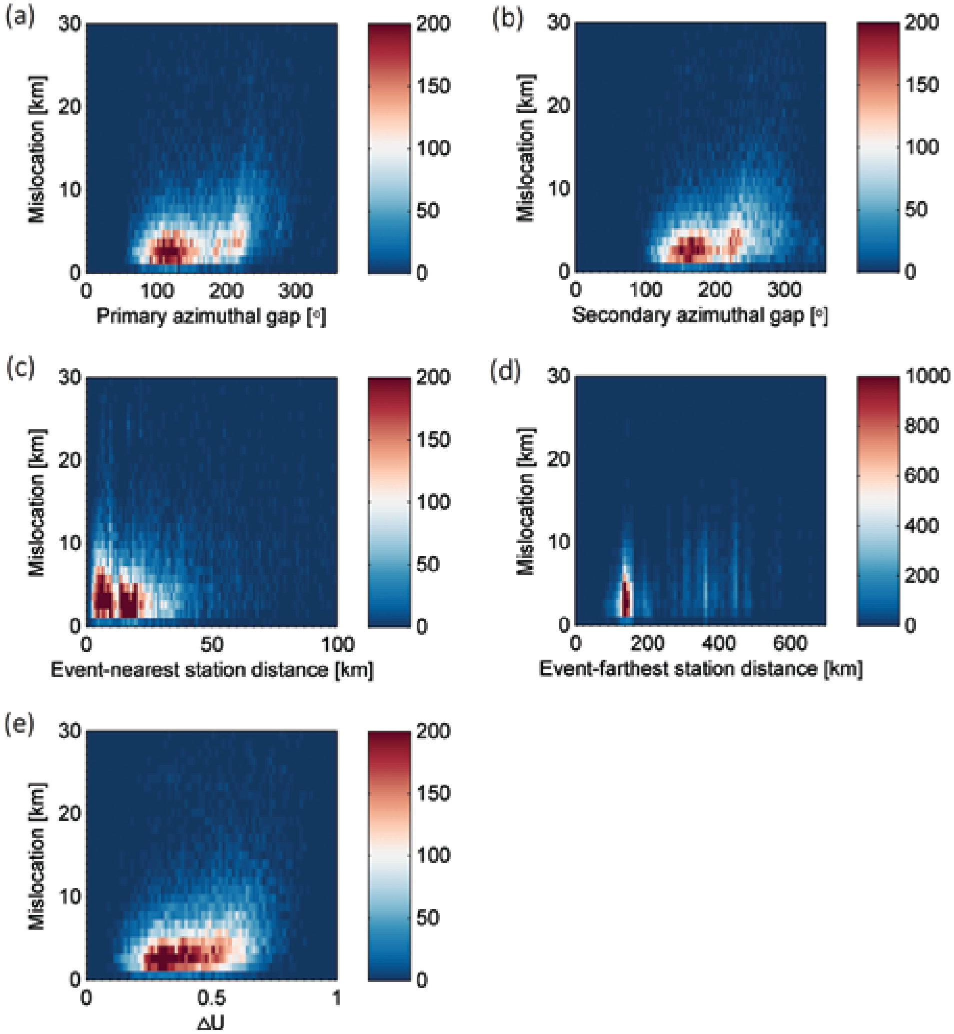

Figure 3. 2D histogram of epicentral mislocation versus: (*a*) primary azimuthal gap; (*b*) secondary azimuthal gap; (*c*) event-nearest station distance; (*d*) event-farthest station distance and (*e*) network quality metric obtained with 100 Monte-Carlo realisations for all phases recorded at 10 station networks.

times), thus a large number of realisations can be easily achieved. The method is quick and easy with no assumptions on the model type and does not rely on asymptotic results. The Rather arbitrary choice of 10 stations is typical for dense local networks. A request for a larger number of stations would eliminate too many small networks, because networks with fewer stations can not satisfy the constraints on the azimuthal gap to achieve GT5 levels of accuracy. When data from regional networks are used to determine the GT level, there is often the problem of a small number of stations. Sometimes the events that should be included in GT catalogues do not pass the global criteria due to their network geometry or the limited number of stations, although perhaps their locations are accurate within 5 km.

In this paper, for each of 330 reference events, we made 100 Monte-Carlo realisations. In every realisation, the event was relocated with 10 randomly chosen different stations that recorded the event. There were not any conditions on the number and type of used phases. We made a total of 33 000 realisations. For each of them, we calculated the primary and secondary azimuthal gap, the distance to the nearest and farthest station and the network quality metric (by eq. 1). Events were located with the program HYPOSEARCH (Herak, 1989). Reference events have locations with high accuracy, thus locating errors were calculated as differences between those locations and locations determined in each realisation.

5. Results and discussion

5.1. Dependency of epicentral mislocation on the GT criteria parameters

The 2D histograms of scattered epicentral mislocation versus mentioned parameters are shown on Fig. 3. We can see that the mislocation error increases with a larger primary or secondary azimuthal gap, *i.e.* there is a greater error range, which was expected. Networks with larger azimuthal gaps are biased in the locating of the epicentral position as they have a tendency to “pull” locations to themselves. The error range increases for networks with the primary azimuthal gap larger than 150° or with the secondary one larger than 220°. Mislocations are up to 10 km for networks with a smaller gap, while for those with bigger gaps, they margin up to 30 km. There is a smaller range of secondary azimuthal gaps (220°–360°) within which errors reach larger values (the range of primary gaps is from 150° to 360°), which proves the premise that the secondary azimuthal gap is the more robust measure of network geometry. Also, we can see that the event-nearest station distance does not affect the mislocation range (*i.e.* it remains practically the same for all distances) and that most of the used networks have one station within 30 km. Furthermore, the mislocation error increases with larger event-farthest station distance (> 300 km) or with a larger network quality metric (> 0.4). On all histograms, the errors mostly do not exceed 10 km.

5.2. GT criteria

With results from bootstrapping, we made empirical cumulative distribution plots of mislocation errors that provided data-based probability distributions. Ninety-fifth percentile can be obtained to form a one-sided 95% confidence interval for the true epicentre location. The correct interpretation of confidence intervals (asymptotic or empirical) is that 95% of such intervals contain the exact location, and 5% do not. We found out that the biggest influence on epicentral accuracy is the distance to the farthest network station, *i.e.* the empirical cumulative distribution has the fastest growth, and the influence of the distance to the nearest network station is negligible. Limiting or necessary, the maximum distance for all network stations is 125 km. We estimated it by trial-and-error to reach 95% confidence, which for the greater distances was not possible. According to the work of Di Stefano et al. (2006), the local P_g / P_n crossover distance for Italy is 130 km, while for our area it is estimated between 100 and 150 km (Brückl et al., 2007). The distance of 125 km is evidently almost equal to the local P_g / P_n crossover distance for this area, which was expected, and it represents valuable metric to avoid lateral heterogeneity.

To achieve an accuracy of 5 km with 95% confidence, numerous variations of the criteria were made and the best was chosen. Therefore, it is possible to use either the primary or secondary azimuthal gap or the network quality metric, but the network must be within 125 km.

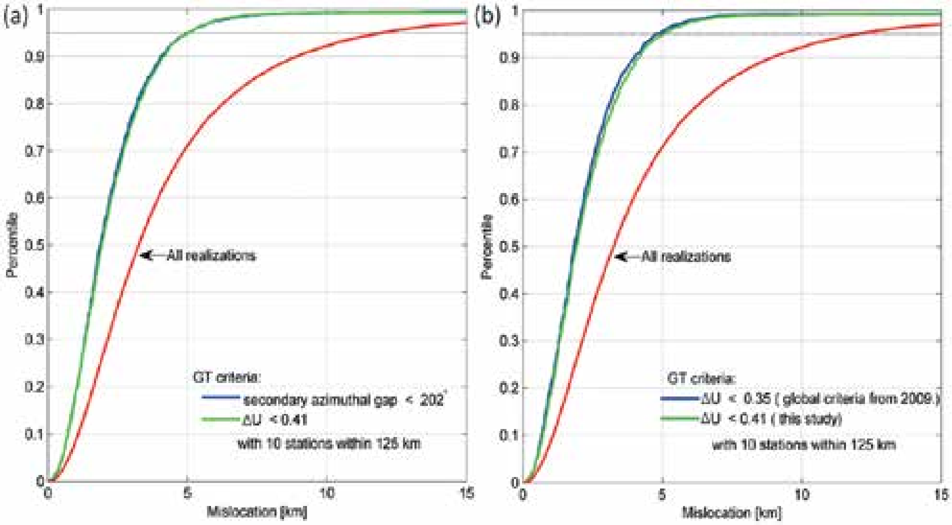

Figure 4. The cumulative percentile of mislocations for: (*a*) two criteria developed by this study (the blue line represents restriction on the secondary azimuthal gap, the green one on network quality metrics); (*b*) this study (*green line*) versus the criteria by Bondár and McLaughlin (2009) (*blue line*). All realizations without any use of criteria are shown with a red line.

Finally, the developed GT criteria for the studied area are as follows:

- primary azimuthal gap < 170° or
- secondary azimuthal gap < 200° or
- network quality metric < 0.41

for networks with stations within the local P_g / P_n crossover distance of 125 km.

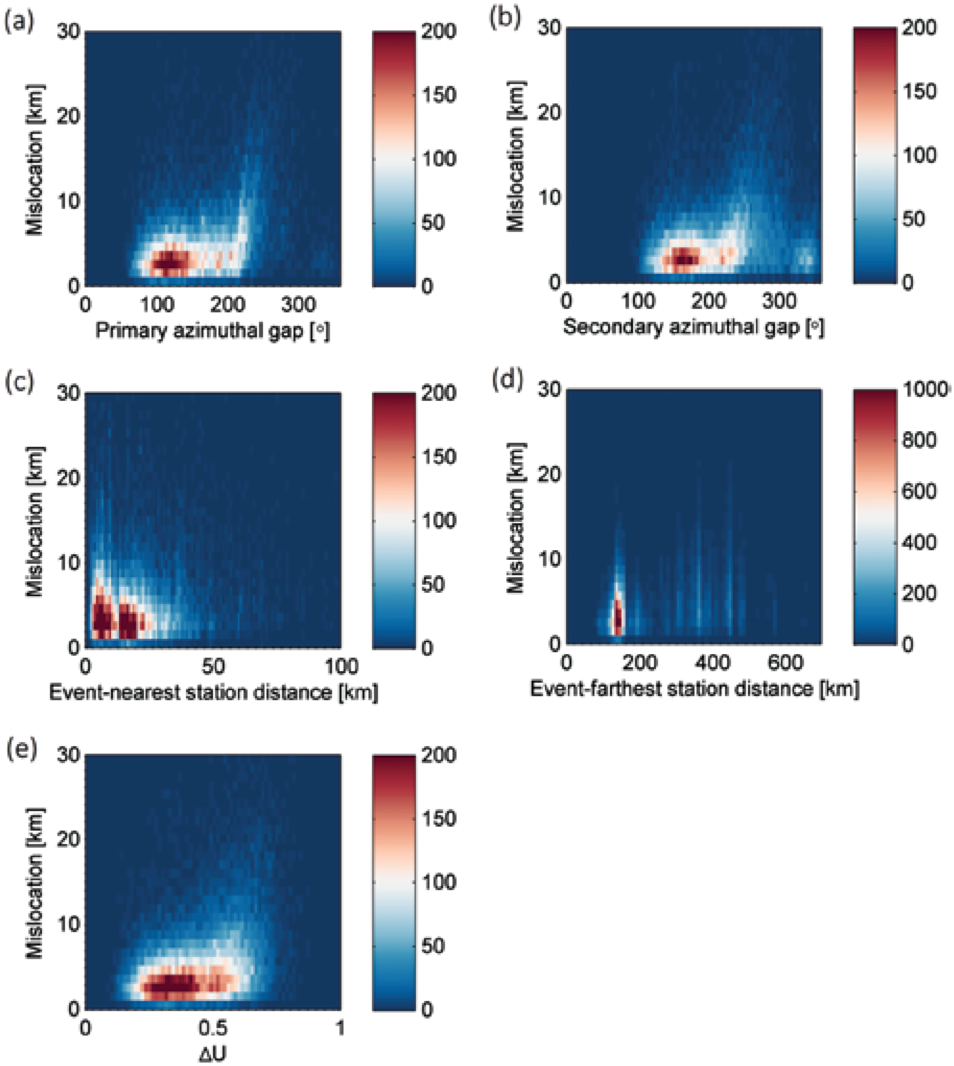

Figure 5. The 2D histogram of epicentral mislocation versus: (*a*) primary azimuthal gap; (*b*) secondary azimuthal gap; (*c*) event-nearest station distance; (*d*) event-farthest station distance and (*e*) network quality metric obtained with 100 Monte-Carlo realizations just for the first arrivals recorded at 10 station networks.

The empirical cumulative distribution of mislocations with the resulting criteria for the $GT5_{95\%}$ level of accuracy is shown on Fig. 4a. Without any criteria, the determined location accuracy is 5 km with 70%, 9 km with 90% and 12 km with 95%.confidence. However, with the use of any criterion, it is possible to achieve an accuracy of 4 km with 90% and 5 km with 95% confidence, which is a great accuracy improvement with not so restrictive criteria. We recommend the use of a criterion for the secondary, instead of primary azimuthal gap, since it is the more robust network coverage measure.

Furthermore, the whole procedure was performed two times. In the first case, the events were relocated with the first recorded arrivals of both P and S waves, and in the second with the first arrivals of only P waves. Actually, both cases presented a bigger dispersion for all parameters (Fig. 5) and the criteria

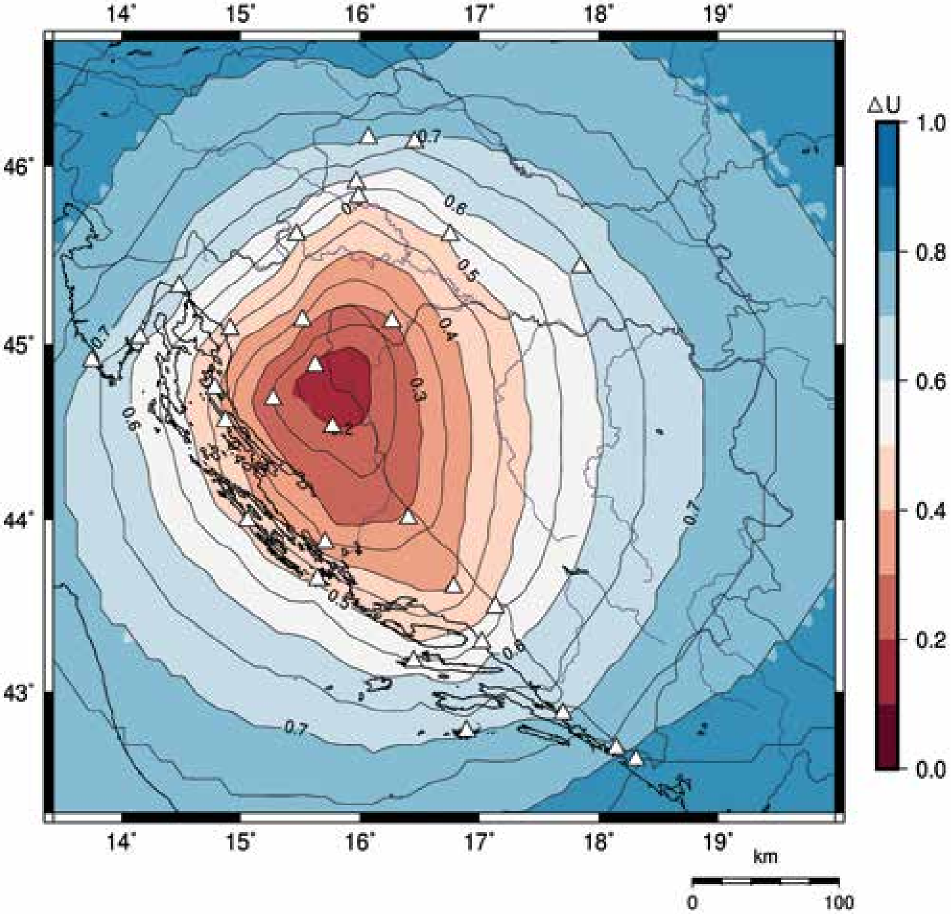

Figure 6. Map of calculated network quality metric for Croatian seismological network. Seismic stations are represented by white triangles.

are stricter than those for all the recorded phases because if you use less data on almost every station, the epicentral mislocation should be greater. With the use of the previously presented criteria, in this case, the same accuracy is given with a 5% smaller confidence (*e.g.* 90%), thus we recommend the use of every recorded phase on every station.

The Croatian seismological network currently consists of 30 stations spread all over the country. On account of the country's irregular shape and its deviation from any geometrical figure, the network quality metric variates between 0.1 and 0.75 (Fig. 6). The central part has the best seismic coverage with an average of around 0.4 and its events could achieve the GT5 level of accuracy without adding additional stations from the surrounding countries.

Generally, the criteria were developed to assess the epicentral accuracy and do not require additional adjustments or the use of the latest algorithms, although the use of the optimal 1D or 3D speed model could significantly improve location accuracy. Better models may improve the accuracy of traveltime prediction or more precisely satisfy the assumption of unbiased errors. Still, our aim was to establish the criteria for routine epicentral locating which do not require any additional research and that was achieved.

5.3. Comparison with previous GT criteria

If we take a look at the global criteria from 2004 (see Tab. 1) for local networks, to achieve a $GT5_{95\%}$ level it is necessary to have: 10 stations within 250 km, one station 30 km from the epicentre, the primary azimuthal gap of less than 110° and the secondary of less than 160°. Our criteria only require the secondary azimuthal gap to be of less than 200° and 10 stations located within 125 km. Both criteria are displayed on Fig. 7. It is important to have in mind that the global criteria do not give the $GT5_{95\%}$ level of accuracy for the studied area and that we cannot use a distance of 250 km. Our criteria limit only the secondary azimuthal gap, while the global criteria limit also the primary azimuthal gap, which makes our criteria less restrictive and better for rather dense networks, with large azimuthal gaps. The criteria for the Kaapvaal Craton only limit the primary azimuthal gap (< 202°) to achieve an $EBGT3_{95\%}$ level. These criteria, in comparison to ours, provide a higher level of accuracy, which is probably the consequence of a simpler geological structure.

The global criteria from 2009 (Tab. 2) limit the network quality metric with 0.35 and require having 5 stations within the local crossover distance and one at 10 km from the epicentre. Again, the criteria are more restrictive than ours (limit to $\Delta U < 0.41$) and that is shown on Fig. 4b. Ours allow quite dense networks, but with a less regular geometrical arrangement to achieve better accuracy. In addition, the criteria for the Tibetan Plateau and the Great Rift Valley are less restrictive, limiting the metric to 0.45 and 0.43.

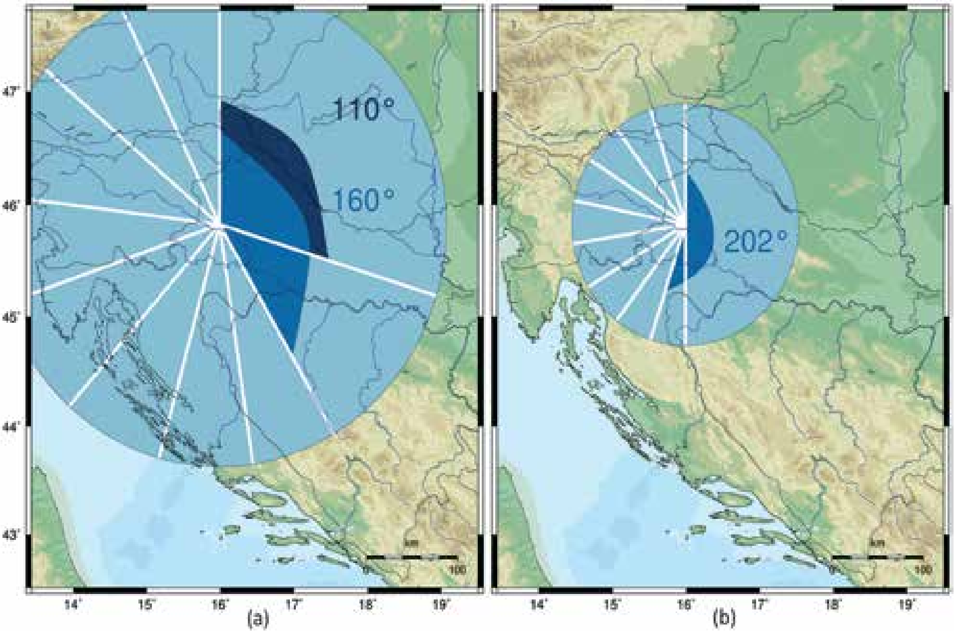

Figure 7. An example of a seismic network which meets the criteria: (*a*) from 2004; (*b*) determined by this paper. The white lines represent the possible station locations and the light blue area is the area within which all network stations must be. The crossover P_g / P_n distance is: (*a*) 250 km, which is too large for the studied area; (*b*) 125 km. The darker blue colours mark the limits on the primary and secondary azimuthal gaps.

To sum up, we can see that our criteria for a relatively complex area are less restrictive than the global ones, but more restrictive for areas of relatively simple structures. The criteria require only the use of the network within the local crossover distance with a quite large secondary azimuthal gap or network quality metric. The application of these criteria may contribute to the improvement of speed models and better understanding of the Earth's interior.

6. Conclusions

We present the GT criteria for the area within a radius of 400 km around the city of Zagreb. The GT criteria allow the determination of earthquake location with a high accuracy and confidence level.

Here, we applied the bootstrap resampling method and relocated 330 reference events but with different randomly picked seismic networks. The event location accuracy is mostly affected by the distance to the farthest network station, while not at all influenced by the distance to the nearest. The GT criteria for the studied area to achieve the $GT5_{95\%}$ accuracy level demand that: (1) at least 10 network stations be within 125 km from the epicentre; (2) the secondary azimuthal gap be smaller than 200°, or the network quality metric less than 0.41. The use of just the first arrivals, rather than all the recorded ones, can downgrade the accuracy confidence up to 5%. Events from the Central part of Croatia have the best chance to achieve the $GT5_{95\%}$ accuracy level due to an average ΔU of 0.4. Also, the obtained results show that the global criteria are too restrictive for our area since they require more regular networks. With our criteria, higher accuracy can be achieved by rather dense networks with larger secondary azimuthal gap or greater network quality metric. Still, the limitations of our criteria are shown for the areas with simpler geological structures.

The estimated GT criteria determined only the accuracy of the epicentral location, but not at all the accuracy of origin time or the hypocentral location. These parameters strongly depend on the used seismic velocity model and prevent the development of criteria based only on network coverage, thus they require a different approach. However, the obtained criteria provide a simple method to subsequently control the epicentral location accuracy, as well as guidance for its improvement.

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SAŽETAK

Empirijski kriterij za određivanje točnosti lokacije epicentra potresa na području Hrvatske

Tena Belinić i Snježana Markušić

U ovom radu određen je empirijski GT kriterij (engl. *ground truth)* za područje definirano polumjerom od 400 km oko grada Zagreba. Kriterij koristi mrežnu pokrivenost kao mjeru točnosti lokacije epicentra, a GT5 razina predstavlja apsolutnu pogrešku lokacije manju od 5 km. Primijenjena je metoda ponovnog uzorkovanja, gdje su Monte-Carlo postupkom velik broj puta relocirani isti potresi, ali s različitim slučajno odabranim seizmološkim postajama. Korišteno je 330 referentnih događaja preuzetih sa stranica ISC-a (ISC Reference Event Bulletin, 2008). Pokazali smo da na točnost lokacije najviše utječe udaljenost do najudaljenije postaje mreže, dok uopće ne utječe udaljenost do najbliže. Određeni GT kriterij proučavanog područja za postizanje $GT5_{95\%}$ razine točnosti zahtjeva da se mreža seizmoloških postaja mora nalaziti unutar 125 km od epicentra i da sekundarna azimutalna razlika (*tj*. najveća razlika između azimuta dviju postaja koja se dobiva uklanjanjem bilo koje postaje iz mreže) mora biti manja od 200° ili mjera kvalitete mreže (tj. srednje apsolutno odstupanje između optimalne uniformno distribuirane mreže postaja i stvarne mreže) manja od 0,41. Dobiveni rezultati pokazuju da su globalni kriteriji previše restriktivni za naše područje budući da zahtijevaju pravilnije mreže. Našim kriterijem je moguće postići višu točnost za mreže s većom sekundarnom azimutalnom razlikom i većom mjerom kvalitete mreže. Također, pokazali smo ograničenost našeg kriterija za područja jednostavnije građe.

Ključne riječi: GT kriterij, točnost lokacije epicentra, metoda ponovnog uzorkovanja, Hrvatska

Corresponding authors address: Snježana Markušić, Department of Geophysics, Faculty of Science, University of Zagreb, Horvatovac 95, HR-10000 Zagreb, Croatia; tel: +385 1460 5913, e-mail: markusic@irb.hr