Optimal distribution of seismological networks: theory and application

Cvetan Sinadinovski[1] and Kevin F.McCue[2]

1. Geophysical Specialist, Saudi Aramco, Dhahran, 31311.
   Email: cvetansin@hotmail.com

2. Adjunct Professor, Central Queensland University, Rockhampton Qld., 4701
   Email: mccue.kevin@gmail.com

Abstract

An accurate determination of the location and origin time of seismic events is of great importance in seismological practice. By designing an optimal station distribution it is possible to locate earthquakes with high accuracy. This may help gain a better understanding of the physical processes that cause them. The theoretically computed uncertainties in the 3-D location and origin time of events are the main criteria in designing networks in Australia and elsewhere. In addition it is important to define the minimal number of stations that is required to detect earth tremors above a selected magnitude, given the signal-to-noise ratio and other instrumental characteristics. The performance of networks also involves choosing feasible geographical locations of stations for the earthquakes and velocity models in a given region. In our approach we show the minimum expected errors in location and origin time of seismic events that can be recorded with specified instrumental networks, both on large and small scales, and discuss these results for existing networks and possible future settings.

Keywords: Seismicity, seismic networks, station distribution

INTRODUCTION

Locating earthquakes accurately with a network of stations depends on the earth models used to generate travel times, the array geometry and the precision of reading the arrival phases. The usual approach is to calculate the errors of the hypocenter parameters for each situation obtained through a least-squares procedure assuming certain errors in the input parameters. Hence those error estimates may be predictive indicators of the accuracy in the solution of real events.

There are a wide variety of sources of error associated with the arrival phases which are of both random and systematic nature. An incorrect velocity model can produce significantly biased solutions not necessarily obvious in the calculated errors. In most cases, such errors are not considered in the calculation of standard errors and default values are used.

This analysis provides error estimation without actually carrying out the inversion calculations. The method uses contour mapping of the solution error onto the array geometry. These presentations are particularly useful, not just for predicting absolute errors which may be subject to unknown model bias, but for displaying relative errors and possible earthquake location as a function of hypocenter position. The method may be applied to networks of arbitrary geometry and in principle for any earth model. Often a plane-layered velocity model is used because of the simplicity and speed of calculating travel times, in spite of the fact that lateral inhomogeneities exist, but errors may appear as random errors in the structure of the simplified model.

The theoretically calculated uncertainties in 3-D location and origin time of the events are then used as criteria in assessing the seismic networks' capabilities. In the particular case of Australia, the Adelaide earthquake of 1954 was selected to determine the accuracy of the solution (Bolt, 1957) with the existing seismographs at the time of the event and again with the current network of seismic stations.

METHOD

Expected errors in the solution of a non-linear least-squares inversion are dependent on the normal equations, which in turn are dependent on the partial derivatives of the travel time function with respect to the solution parameters. Prediction analysis requires the calculation of the normal equations for a set of representative points throughout the array and the inversion of the coefficient matrix after the travel time equations have been suitably weighted according to the assumed accuracy of each parameter.

Then the solution of the event location can be represented as intersection of circles with radii proportional to the P-wave and S-wave velocities. A schematic diagram of two distributions of stations presented by triangles is given in Fig. 1. The top diagram is an undesirable receiver configuration in respect to hypocenter estimation; the probable hypocenter location is shown in red between intersecting lines, with errors (due to velocity or event picking) covering a large area. The bottom case is a better configuration because the probable hypocenter shown in red is confined to a smaller intersection area.

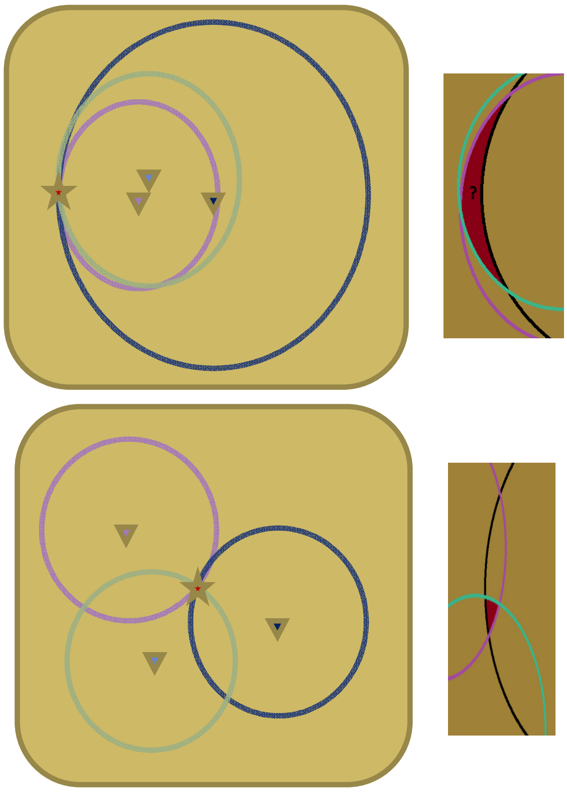


Figure 1: Probable estimate of event location by two networks of stations

Various optimization methods have been used to determine the seismic parameters in respect to the network of stations, (for example Kijko, 1979), and they provide a useful tool for finding the optimal station distribution. We account for the decreasing signal-to-noise ratio due to geometric spreading and follow the procedure to determine network performance the New Manual of Seismological Observatory Practice (Bormann, 1992).

PROGRAM

The station co-ordinates are assumed to be known exactly without error, the P and S arrival phases are picked with a known *a priori* precision and the travel times are computed for a flat Earth model consisting of homogeneous layers. The P and S velocities within the layers are defined with approximately 10% uncertainty and the positions of layer boundaries are known with same accuracy in percentage.

The RMS value of noise in a frequency band within which STA/LTA algorithms operate (for digital stations) or a frequency band of the recording equipment (for analogue stations) is also assumed known. Both station types have a flat response in a frequency band of interest usually in a range of 1 to 10 Hz. The size of the area containing the array of stations has to be such that Earth model approximation is valid to a certain degree.

The input files are named after particular projects and basically can be separated into velocity modeling, seismic station distribution and discretization parameters files. The output files contain the predicted location errors for P-wave and combined P- and S-wave cases. They are given as the 3 semi-axes of an error ellipsoid represented as square root values of the x-,y-,z-axis of cross section of the hypocenter error ellipsoid with the horizontal plane through the hypocenter.

In more detail the input file for velocity modeling designed for layered earth model is defined as:

- P wave velocity, in km/s;
- S wave velocity, in km/s;
- depth to top of layer, in km;
- error of P velocity estimate for the layer, in km/s;
- error estimate for S wave velocity in the layer, in km/s;
- error estimate of the layer thickness in km, and
- an indicator for the first mantle layer.

The seismic station info for each station is given in a separate line containing:

- name (usually 4 characters);
- latitude in decimal degrees;
- longitude in decimal degrees;
- elevation above mean sea level in meters;
- type of station (digital or analogue);
- flag to use P- and/or S-arrival time;
- accuracy of P- and/or S-arrival time readings in seconds;
- amplification at frequency where maximum amplitude is expected;
- noise level as RMS value in a pass band for STA/LTA trigger, and
- minimal trace amplitude in millimeters to detect the earthquake with standard instruments.

The last input is a list that contains discretization parameters that drive the analysis:

- latitude range in decimal degrees;
- longitude range in decimal degrees;
- hypocentral depth in kilometers;
- trigger type and STA/LTA ratio;
- minimal number of stations needed to trigger for detection of an event;
- attenuation function;
- coefficients for locally derived magnitude;
- criteria used to sort the stations, and
- number of sorted stations to be used in modeling.

It is well known that in an ideal case the best location results can be achieved with a network that is equally distributed in azimuthal space and preferably has at least one station above the hypocenter zone. However, in reality, there is always a good number of other considerations that have to be taken into account when deploying seismic station such as: political and administrative borders, coastlines and landscapes, climate, exposure of bedrock at the surface, noise from roads or industrial plants, equipment safety in remote and unpopulated areas, access to power, servicing costs etc. These constraints put limitations on station installation that often makes the final positioning of any seismic station challenging. In spite of this, knowing the expected errors in location due to station geometry is always useful.

APPLICATION

In the early hours of 1st March 1954, (3.40am local time), the city of Adelaide experienced one of the South Australian severest earthquakes. The strong shaking woke most residents, cracked walls and loosened plaster from many buildings. Southern suburbs sustained the worst damage, with fallen chimneys and partial wall collapse of some dwellings. Other hills areas especially south of the city centre, along the Burnside fault, also reported damage (Kerr-Grant, 1956; Malpas, 1993; Sinadinovski et al., 2006).

In the absence of any instrumental records under a distance of 600km, the isoseismal maps become crucial evidence in deciding the epicentral location (34.93^{o}S and 138.69^{o}E), while the depth was estimated at less than 10km. The maximum intensity of the earthquake has been established as MM VIII. Seismograms of this earthquake were obtained at Melbourne, Riverview, Perth and Brisbane, though it was not large enough to be recorded in New Zealand nor Manila. Apparently the Adelaide seismograph was still in operation, but had problems with the time marks and the instrument thrown off scale at the first onset due to the proximity of the epicenter. The initially assigned local magnitude was 5.4, although this has been reviewed a few times (McCue, 1980).

Our analysis based on only four stations mentioned above (MEL, RIV, PER and BRS) predicted that the expected errors in the epicenter determination would be at least in the order of 35km in x-y direction and about 65km in z-direction depth for an event occurring at a shallow depth. The precision of the seismogram readings was assumed as +/-0.5s (with a rotation rate of 15mm/min) for the standard velocity IASPEI94 model. These calculations should be considered as the minimum values in expected errors of earthquake location.

Today the existent South Australian earthquake monitoring network is used to measure State seismic activity as well as record events from all around the world

http://www.pir.sa.gov.au/minerals/earthquakes/earthquake_monitoring_network

There are 24 stations located all around the State that record seismic activity which can be used to determine the location, magnitude, depth and duration of the events. The network displayed on Fig. 2 is a combination of digital and analogue instruments that work in continuous and triggered mode.

Some of the instruments are the weak motion devices (seismometers) that can record small earthquakes at great distance, but may go off scale if a large event happens nearby. Since those devices are extremely sensitive, the sensor is usually placed away from roads and human activities, and the signal may be sent to a manned site by a low power UHF radio link. Other instruments are the strong motion devices (accelerometers) that usually do not record small or distant earthquakes and rarely go off scale when a large event happens. Their information is very valuable for structural engineers.

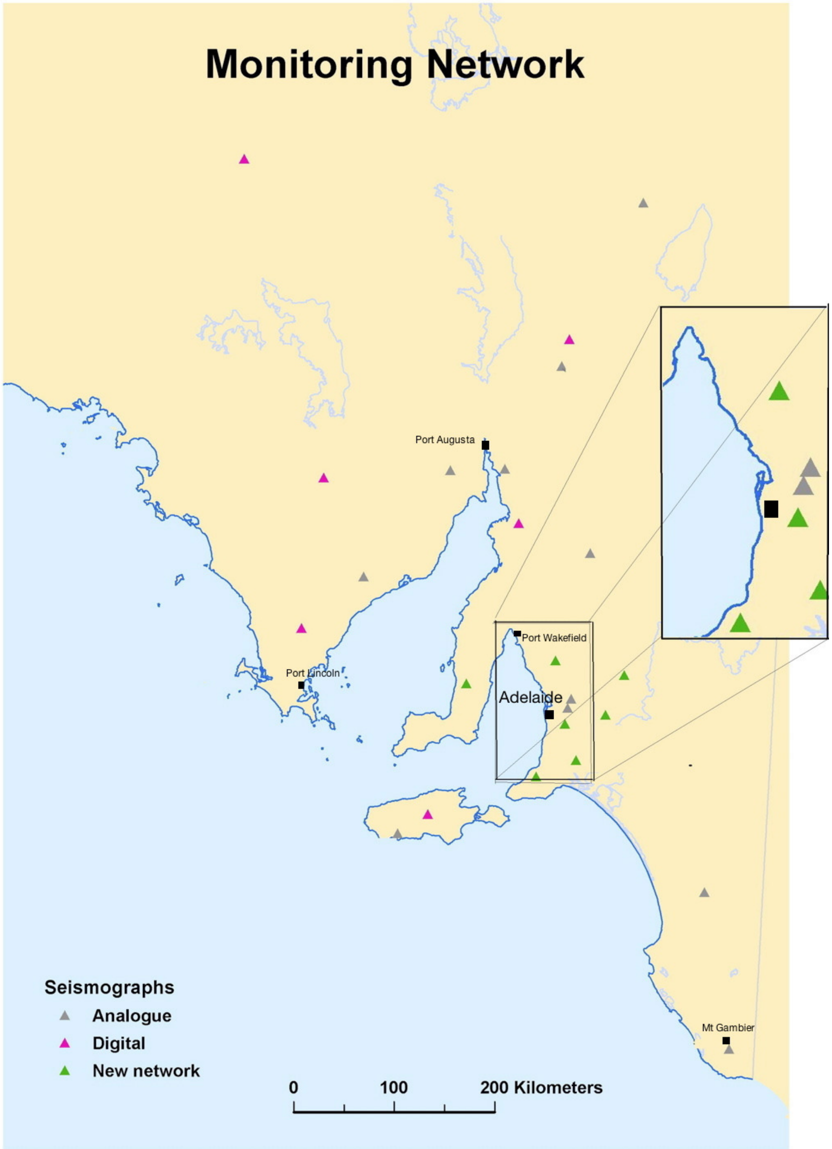


Figure 2: Present earthquake monitoring network of South Australia

The two array configurations considered here are firstly, the whole network of 24 seismic stations represented by triangles and secondly, the case of 22 seismic stations (without the two analogue stations in the central Adelaide region), as displayed in the enlarged window inlet. The window is chosen to cover the area of interest, which is the most densely populated region of the State.

Prediction analysis was carried out for many different combinations of event depth and earth models using P- and S-wave arrivals at each station in the network with a given precision. To test the accuracy of the estimated standard errors, actual least-squares solutions were performed a large number of times for the grid points over the windowed area using either fixed precision or randomly-generated noise added to the data and to the model parameters. The probable estimate errors for a 5x5km grid model in x-y direction and depth (z-direction) for shallow events in the top 5km and deeper events of 20km for the two cases is displayed in figures 3 and 4.

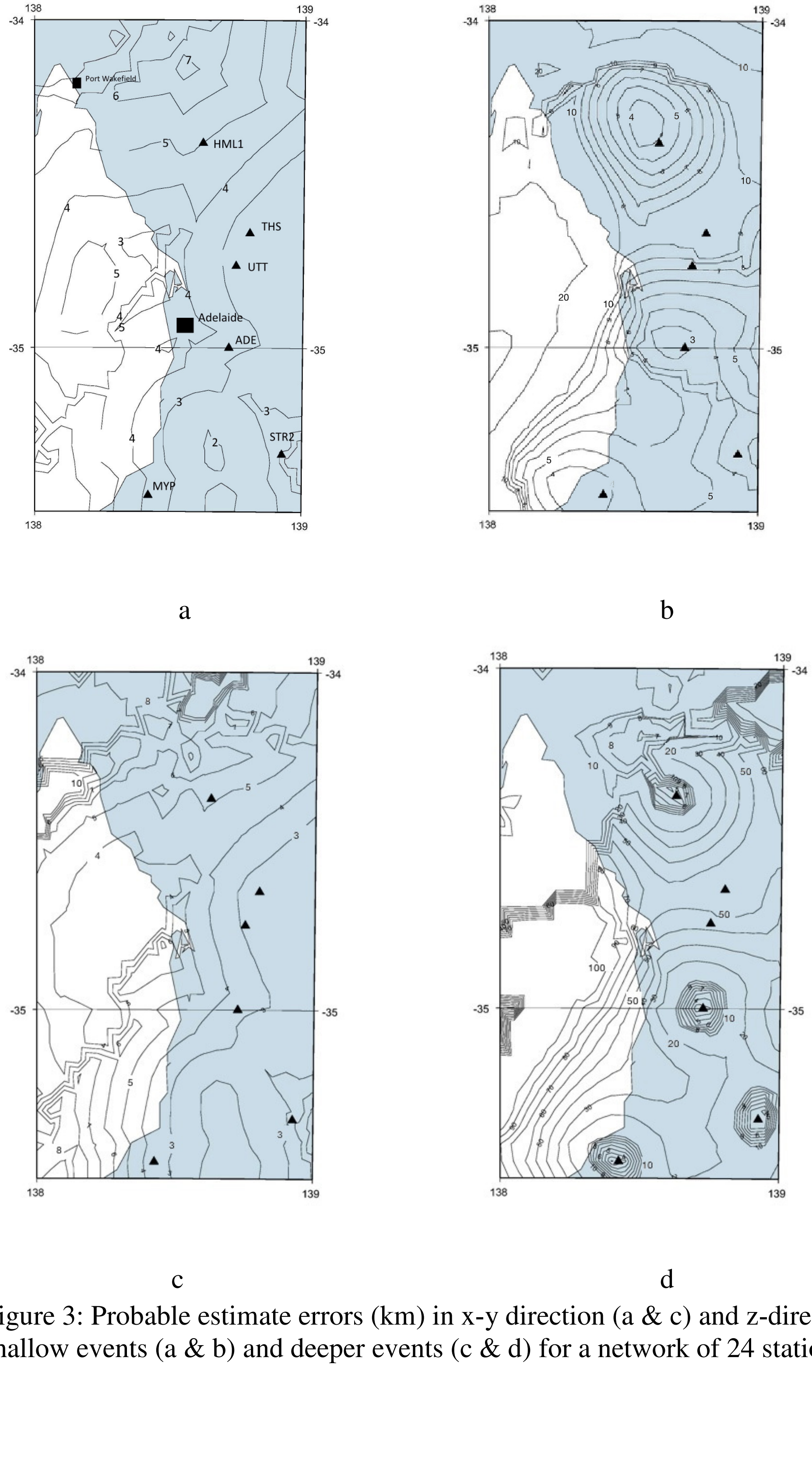
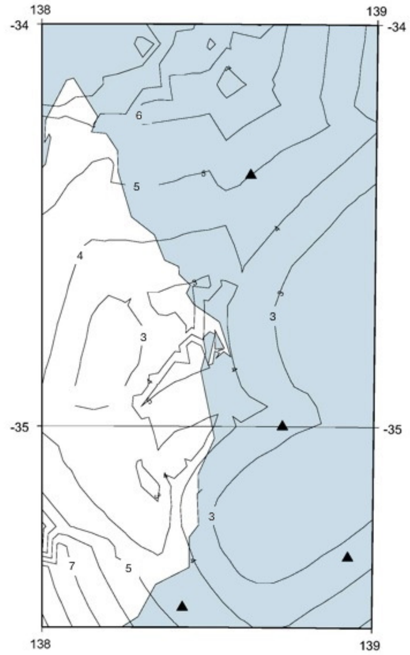
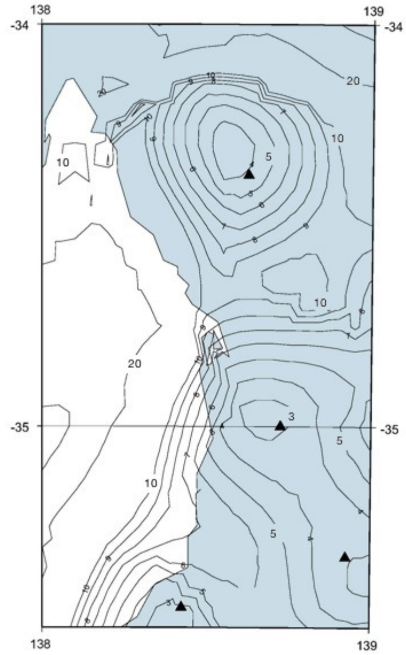


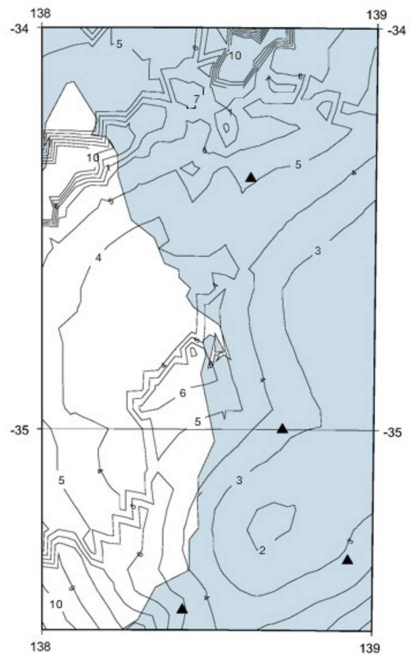
Figure 3: Probable estimate errors (km) in x-y direction (a & c) and z-direction (b & d) for shallow events (a & b) and deeper events (c & d) for a network of 24 stations



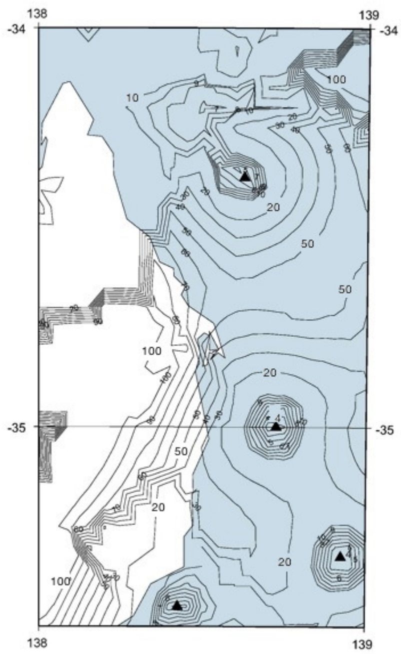
a



b



c



d

Figure 4: Probable estimate errors (km) in x-y direction (a & c) and z-direction (b & d) for shallow events (a & b) and deeper events (c & d) for a network of 22 stations

The contoured maps on figures 3 and 4 have very similar shape especially in the offshore parts of the selected window centered over Adelaide city. Generally the expected errors in the x-y direction in the offshore part are almost twice as large than in the inland part and vary between 6 to 7km for shallow events, while the expected errors in the onshore area are mostly between 2 to 4km. The main difference between the 22 and 24 station network configuration is underneath the central zone when the two stations are removed from calculation and where minimal horizontal resolution drops from 2 to 3km. Also, the southern edge on Fig. 4 has larger expected errors due to lower signal detection on the three neighboring stations criteria, which can be of importance for precise detection of the earthquakes on the Burnside fault.

A comparison of the top and the bottom images on Figures 3 and 4 shows the effects of the increased depth on the event resolution. The basic error form is not greatly changed by increasing the depth of the event from shallow (2km) to a deeper (22km) event. The errors in x-, y-, and z-direction are generally increased due to smaller relative curvature of the wave-front surface. Intersection area for all circles of errors becomes bigger with increasing depth as was discussed earlier on Fig. 1. The contours in the z-direction (figures d) for the deeper events practically reflect the stations' position. Events on the southern side for the 24 station network have better resolution in the z-direction since the farther stations are somewhat more sensitive to depth variations. The expected errors in the z-direction in the offshore part are almost ten times larger than in the inland part and vary between 10 to 50km for deeper events.

These contoured maps represent only two cases of a series of analysis to demonstrate the application of the prediction program to a likely scenario and the output can change depending on the selection of input parameters.

SUMMARY

This prediction analysis applied to the problem of hypocenter determination using a network of seismic stations allows fast and accurate calculation of errors to be expected in the event solutions as a result of the accuracy of the input parameters. The *a priori* nature of these error calculations makes them particularly useful in analyzing the resolving power of a seismic network over a region of interest. Such theoretical analysis is helpful both for the design of a new array over a particular region or in the optimal addition of stations to an existing network. By designing the optimal station distribution in terms of hypocenter and timing parameters, it is possible to locate these events with higher accuracy that may help better understanding of the physical processes that cause them.

By 1957 most of Adelaide Plains had been urbanized with expansion of low density housing after World War II and the growth of outer centers north and southwards along the coast. With the southerly development of Adelaide's suburbs, an event of similar size recurring today might be expected to cause significantly higher loss than the 1954 earthquake, so precise determination of its location would be of a paramount importance for planning purposes.

Since the errors in all input parameters are held fixed during our calculations, the variation in predicted error is solely a function of the geometric position of the event in respect to the network. Thus these output results should be interpreted in a relative manner because the real errors in input parameters are unknown and only estimated. In particular, the model velocities may have unknown bias which would in turn produce a biased picture. The results presented here in the form of error contour maps provide a visual way of array detection and can be applied in improving network capabilities.

REFERENCES

Bolt, B.A., 1957. The Epicentre of the Adelaide Earthquake of 1954 March 1. Journal and Proceedings of the Royal Society New South Wales, Vol. 90, pp. 39-43.

Bormann, P., (Ed.) 2002. IASPEI, New Manual of Seismological Observatory Practice, GeoForschungsZentrum, Potsdam, Germany.

Kerr-Grant, C., 1956. The Adelaide earthquake of 1st March 1954, Trans. R Soc. South Australia 79, pp. 177-185.

Kijko, A., 1977, An algorithm for the optimum distribution of a regional seismic network-I, Pageoph, 115, pp. 999-1009.

Malpas, K., 1993. Historical earthquakes in South Australia vols 1-5. Flinders University of South Australia, School of Earth Sciences, unpublished report.

McCue, K.F., 1980. Magnitudes of Some Early Earthquakes in Southeastern Australia, Search 11, No. 3, pp. 78-80.

Sinadinovski, C., Greenhalgh, S.A. and Love, D., 2006. Historical earthquakes: a case study for the Adelaide 1954 earthquake. Australian Earthquake Engineering Society Conference Proceedings, pp. 151-157, Canberra.