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Network Modeling and An Evaluation of a CD Proposed ISMS

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Sandia National Laboratories
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Network Modeling and An Evaluation of a CD Proposed ISMS

John P. Claassen

The Cooperative Monitoring Technologies Department
Sandia National Laboratories

Abstract

This report briefly describes the improvements and corrections made to a seismic network performance modeling code called NetSim. After expanding its supporting database, the modified code was used to predict the detection and location performances of an International Seismic Monitoring System (ISMS) proposed early in 1995 by the Group of Scientific Experts (GSE) supporting the Comprehensive Test Ban Treaty (CTBT) negotiators. The performance estimates indicated that the primary network achieves or exceeds the GSE goal of detecting a fully coupled 1 kiloton nuclear shot contained in consolidated rock anywhere on the earth. It was also shown that without calibrated regional location models, the primary network alone cannot achieve the GSE location accuracy requirement of 1000 square kilometers at the detection threshold of the primary network, but with the help of 67 auxiliary stations that goal can be achieved in the northern hemisphere. Once the regional location models become better calibrated, the predictions based on these models indicated that the primary network should be able to realize the GSE requirement throughout much of the world. However, the location accuracy requirement is not realized in Central America, on the oceanic islands, on continental margins in the southern hemisphere, and in Antarctica. The introduction of the 67 auxiliary stations into the calibrated network primarily broadens the regions already having good location accuracies. The location performance estimates may be regarded as conservative since the S-wave arrivals were not included. A comprehensive set of scenarios are illustrated in this effort to better understand various influences on network performance.

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Executive Summary

The primary goals of this effort was to evaluate the detection and location capabilities of a primary network as defined early in 1995 by the scientific experts supporting the Comprehensive Test Ban Treaty (CTBT) negotiators and to evaluate the location capability of a combined primary and auxiliary network as tentatively defined at that time. However, before addressing these primary goals, it was necessary to 1) correct and improve the seismic network modeling methods and code appearing in NetSim to produce stable as well as enhanced performance estimates, 2) develop a flexible and user friendly graphical code using locally available graphical tools, and 3) develop a database containing station noise statistics and regional path attenuation for use in the modeling code. As a result of the improvements a new location methodology based on more realistic physical and statistical premises was developed and incorporated into the NetSim code. A simple modification was also introduced to permit location performance estimates of one network conditioned on the detection levels of a another network. The code was specifically corrected to properly estimate regional attenuation across the poles and the international dateline. A search and interpolation routine was also modified to assure convergence to the detection threshold under a large selection of detection criteria to include criteria representative of evasion scenarios. Improvements in the detection model assigned frequency dependent variances to the station noise spectra and the station gain. To better account for the variations in the propagation on a global basis it was also necessary to introduce propagation models which are region dependent. This was accomplished by scaling the regional propagation models for Scandinavia to regions having higher or lower Qs (quality factors).

The improved network simulation software was used to demonstrate that the network as proposed by the Ad Hoc Committee on a Nuclear Test Ban of the Conference on Disarmament in Working Paper (WP) 224 is globally capable of detecting events having magnitudes ranging from under 3.5 to somewhat above 4.0 with a probability of 99%. Since the primary network originally proposed in WP 224 has been upgraded to a 50 station network not significantly different than the original station network, the predicted detection levels for the new network should not differ significantly from those shown here. The location accuracy predictions indicated that in the early years of operation when the regional location models are not well calibrated, the primary network alone cannot achieve the Group of Scientific Experts (GSE)

location accuracy requirement of 1000 square kilometers at the predicted detection thresholds. However, location accuracy estimates based on the primary network when augmented with the 67 auxiliary stations can achieved the GSE accuracy requirement in the northern hemisphere during these early years of operation. Another location accuracy prediction which assumed smaller location model errors as would be indicative of a mature well calibrated network showed that the primary network alone should be able to realize the GSE location requirement at its detection threshold throughout much of the world except in Central America, on some of the oceanic islands, on continental margins in the southern hemisphere, and in Antarctica. The use of the auxiliary stations in the calibrated network primarily broadens the regions already having good location accuracies. The accuracies in those areas not meeting the GSE requirement are not changed significantly. Recent modeling runs introducing even more auxiliary stations have shown that the location findings based on the 67 auxiliary stations are not altered significantly. Since the location performance measures did not include the use of the secondary arrivals, these accuracy estimates may be regarded as conservative.

The reader is urged to review Figures 21 through 26 and their captions to develop a mental picture of the above stated results. In interpreting the detection and location performance results, the reader is fore-warned that the reported performance levels are restricted to the events occurring in consolidated rock as opposed to shots occurring in the oceans. The results, as a consequence, are restricted to the continents and the islands as opposed to the oceans. The detection thresholds for shots contained in the ocean can be approximately estimated from these results by simply lowering the estimates by 0.8 magnitude units. Shots in the oceans were not of a specific concern to this effort since oceanic coverage is to be provided by a hydro-acoustic network with the assistance of a few seismic stations on designated islands.

To validate the predictions made within this effort, future work should focus on validating the modeling methods and parameters using actual network performance measures. The current GSETT-3 (Group of Scientific Experts Technical Test) experiment provides an opportunity to compare predicted and measured performances. Discrepancies between the measured and the modeled performance estimates could be used to determine the adequacy of the predictive models or could possibly be used to flag regions where the

measured performances are different than expected. Predictive insights, therefore, play several important roles. They not only help develop and improve our understanding of the physical and statistical processes which govern the performance of networks but they could also be used to check for anomalous behavior in the actual performance.

There is a continuing need to develop network performance models after networks have been planned. Modeling, when appropriately used, is a discipline which assures that we understand the operation and performance of monitoring networks through comparisons of the actual and measured performances using prediction models which with experience conform more closely to the models which actual process the observations. The obvious application of this process allows one to alter the network for improved performance or for realizing new objectives. Not as obvious, however, is the fact that both measured and predicted performances are required to assess monitoring systems in real-time. In seismically active regions, the actual performance of a global monitoring system can be measured using actual network observations perhaps supplemented by observations from independent stations. For refined performance measures this measured performance could be augmented with the state of the network in the context of a predictive model to infer real-time performance. In areas having insufficient seismicity the performance level of a monitoring system should be estimated using the best available models. The predicted performance could be refined with the few observations available from those regions. Thus the predicted and measured capabilities must be jointly used to assess special situations, isolate the strengths and weakness in the system, and provide insight into modifying or extending the network for new applications or for enhanced performance.

To provide these high quality performance measures and assessments will require carefully designed models and supporting databases. In an application of such a measurement/prediction system, one can envision tracking and displaying various performance measures in real-time. This would establish confidence in the performance of the monitoring system and provide a global view of the performance. Since doing this on global basis would required considerable resources, it is recommended that an initial effort demonstrate the feasibility of the technique in regions of the world which are currently being studied as part of the CTBT seismic R&D efforts.

1. Introduction

1.1 A Network Modeling Perspective

To place this effort in perspective, recognize that network modeling is a methodology by which to predict and assess the performance of a collection of monitoring stations. As a scientific-engineering-statistical discipline, network modeling brings insight, understanding, and integrity into processes which plan and assess proposed and existing monitoring networks. For modeling to have meaning and significance it is important that the physical and statistical aspects of the source, propagation, detection, location, and discrimination characteristics be appropriately integrated to realize useful predictions or assessments. To confirm or deny the adequacy of either network models or the network processing methods, the predictions must eventually be subjected to the test of actual network observations and the actual network observations to the test of the predictions. This is the primary key to validating both the simulations and the observations. Validated simulation models also permit us to extend performance estimates into new areas of the globe having a similar geology. On the basis of this comparative experience the predictive models or the real-time processing models and their parameters may undergo modification to yield improved predictions or network performance, ultimately bringing light and improvements to the operation of networks. In this regard various GSE working groups are currently evaluating the performance of the GSETT-3 network. These results and additional empirical experience should provide us with significant insight into our current modeling capability. Not as well recognized is the fact that network modeling could also be used to assess changes in the methods by which the network data is processed before actually implementing the changes in the real-time system.

In view of the many anomalies in seismic source and propagation mechanisms network modeling will seldom provide insight and understanding at the microscopic level of network operation. Even though restricted to the macroscopic level, modeling provides useful insight and understanding into the detection, location, and discrimination performances of networks. For

1. Introduction

example, even a simple comparison of the macroscopic predictions with the observed anomalies provides useful information about those portions of the world where the interpretation of the observations may have to be done differently. To provide a view of network performance at the macroscopic level on a global scale requires considerable information. Those who model network performance are very much dependent on those who develop source, propagation, noise, and coda noise models, those that develop and evaluate detection, location, and discrimination algorithms, and those that evaluate actual network performance. Careful collaboration with researchers in these other fields is essential to the development of adequate and meaningful performance models which can effectively assess the performance of actual monitoring systems.

1.2 The Objectives and Overviews of This Work

The primary goals of this effort was to evaluate the detection and location capabilities of a primary network as defined within Working Paper 224 early in 1995 by the scientific experts supporting the CTBT negotiators and to evaluate the location capability of a combined primary and auxiliary network tentatively defined at that time. However, before addressing these primary goals, it was necessary to 1) correct and improve the seismic network modeling methods and code appearing in NetSim to produce stable as well as enhanced performance estimates, 2) develop a flexible and user friendly graphical code using available graphical tools, and 3) develop a database containing station noise statistics and regional path attenuation for use in NetSim. As a result of these latter efforts, a new location methodology based on more realistic physical and statistical premises was developed and incorporated into the NetSim* code. A simple modification was introduced to permit location performance estimates of one network conditioned on the detection levels of a another network. Improvements in the detection model assigned frequency dependent variances to the station noise spectra and the station (array) gain. To more appropriately account for the differences in regional propagation on a global basis and the contributions of the various regional phases, existing regional propagation models were altered to reflect

*Serenio Jr., T. J. A Computer Program for Simulating Detection and Location Capability of Regional Seismic Networks, SAIC 90/1163, Science Application International Corp., March 1990

different qualities in the propagation attributable to tectonic, stable, and very stable geological conditions.

A friendly and versatile graphical interface was developed to plot the performance estimates in various ways. The interface specifically permitted portraying the graphical results in various comparative modes. An option to filter the graphical data was provided to smooth the irregular boundaries often associated with performance levels. The irregularities in the boundaries can adversely impact contour seeking routines.

1.3 Organization of the Report

Section 2 of this report describes the adaptations and improvements made to the detection and location models and code. Section 3 addresses the approach to modeling the performances of the primary and auxiliary networks. The locations of the primary and auxiliary stations are identified within this section. The estimated detection thresholds associated with the primary network are described and discussed in Section 4 and the location capability of the primary and the joint primary and auxiliary networks are described in Section 5. Sections 4 and 5 also introduce and evaluate a more conservative detection criterion that will miss fewer events at its threshold and produces better location accuracies. Section 6 identifies the conclusions produced by these findings, recommends a network detection criteria by which global network performance should be viewed, and suggests future network modeling and performance assessments efforts. All the illustrations supporting the results appear at the end of the report. They are all well annotated should the reader wish to scan them for an overview of the results.

1. Introduction

2. Detection and Location Performance Modeling Enhancements

2.1 Overview of the Detection Model

To produce detection performance estimates a source model is used to convert source intensities such as yield or magnitude to source moment. The source moment is then used to initiate a simulated wave whose signal amplitude is predicted at each station in the network. Several wave propagation models are provided for various regional and teleseismic waves in differing media. With knowledge of 1) the predicted mean and standard deviation of the signal amplitude of each arrival, 2) the mean and standard deviation of the noise or the coda spectrum prior to an arrival, 3) the station's mean (array) gain and standard deviation, and 4) the magnitude bias and uncertainty associated with a station, the SNRs (signal to noise ratios) of the arrivals can be determined as a function of frequency and phase type at each of the observing stations. The frequency (Hz) at which the best SNR occurs for a given phase and station is then determined and the corresponding station detection probability computed for each phase. The collection of station detection probabilities for a given event location is used to compute the network detection probability. A network detection criterion usually requires that a certain number or more of arrival combinations be observed by the network with a given probability so that the observations from a given event can be reasonably associated or will produce a certain location performance level. NetSim in one computational mode determines the network detection probabilities over a global grid of events having identical source intensities. In another computational mode NetSim searches for the event magnitude which realizes the assigned network detection criterion at a given detection probability. This search mode estimates the so-called network detection threshold.

2. Detection and Location Performance Modeling Enhancements

2.2 Improvements in the Detection Model

An improvement was introduced into the NetSim detection model by assigning frequency dependent noise variances to the station noise spectra. The noise variance is strongly frequency dependent and can significantly influence detection probabilities at low frequencies as a result of micro-seismic variations and at high frequencies ($f > 2$ Hz) as a result of cultural noise fluctuations. The prototype IDC (International Data Center) now routinely estimates the noise variance as well as mean noise levels of the GSETT-3 stations on a frequency dependent basis to support network modeling efforts.

In additional efforts the gain variance for the array stations was made frequency dependent. Since the gain variance for regional arrays is small, this change at present appears not to be significant but may become significant when and if the large teleseismic arrays are used for regional monitoring. The mean gain and variance for the regional NORESS (Norwegian Regional Experimental Seismic Station) array had been reported in a previously reported effort.* However, the regional gain statistics for the new 9 element arrays to be deployed in the primary network and some of the older teleseismic arrays have not been documented as part of this effort. This has been left as a future exercise. In the interim the gain characteristics for the NORESS array were used to estimate the gain of the new smaller regional arrays. Also the gain of teleseismic arrays was assumed to be larger than the square root of N (no. of elements) at SP (short period) frequencies less than 2 Hz, at the square root of N between 2 and 4 Hz, and the quadratic root of N (the non-coherent gain) at frequencies above 4 Hz. The use of the non-coherent gain at the high frequencies is simply an admission that the spatial coherence of these very large arrays deteriorates at higher frequencies.

To appropriately account for the differences in propagation on a global basis it is necessary to use propagation models which are region dependent. In previous unreported efforts variations in the quality of regional propagation were assigned on a global basis by using the Q variations of L_g propagation as an indicator of the quality of propagation of the other regional phases. This

*Claassen., J. P., The Application of Multiply Constrained Minimum-Variance Adaptive Beam-forming to Regional Monitoring, BSSA, Vol. 82, No.5, pp2191-2212, Oct 1992

assumption may be overly simplistic but does permit implementing region dependent propagation models because $L_g Q$ is almost known worldwide, primarily as a result of efforts by researchers at St. Louis University.* It was therefore possible to scale the Scandinavian L_g model developed by workers at SAIC† to other regions of the world. The Scandinavian propagation models for the remaining regional phases were also scaled in an ad hoc manner assuming that the mechanisms which affect the quality of L_g propagation also affect the remaining regional waves. The Scandinavian models were scaled to low ($L_g Q = 900$) and high ($L_g Q = 300$) attenuation regions assuming that the Scandinavian craton represented a medium attenuation ($L_g Q = 600$) region. These regional attenuation assignments on a global basis are shown in Figures 1 and 2. This scaling approach was used in the interim because frequency dependent regional models for propagation in distinct geologies of the world, other than L_g , have not been addressed or when addressed have not been developed in a manner compatible with NetSim. These propagation models must be frequency dependent and must be coupled to a viable source model if they are to have utility within the NetSim code.

It may be assumed that the Scandinavian models are applicable to many other cratons of the world with reasonable accuracy. Whether it is reasonable to extrapolate the models to active tectonic regions or to more efficient cratons based on measured $L_g Q$ remains to be seen. The DOE research efforts in regional propagation should help shed light on these assumptions and will eventually provide refinements to the propagation models used within NetSim. The model for teleseismic P propagation is based on the classical Veith and Clawson model‡ as extended to include PKP arrivals at ranges greater than 140 degrees. These core refracted arrivals (PKP) provide enhanced detections by stations at distances greater than 140 degrees from the event. The frequency dependence of the P waves had been extrapolated by SAIC to higher frequencies by assuming $T^* = 1$. The propagation model for teleseismic S is an extrapolation of the Scandinavian regional model for S_n .

*For example, J. Xie and B. J. Mitchell, A back-projection method for imaging large-scale lateral variations of L_g coda Q with application to continental Africa, *Geophys. J. Int.* (1990) 100, 161-181

†Serenio Jr., Thomas J., Attenuation of Regional Phases in Fennoscandia and Estimates of Arrival Time and Azimuth Uncertainty Using Data Recorded by Regional Arrays, Report SAIC 90/1492, Science Applications International Corporation, September 1990

‡Veith, Karl F. and G. E. Clawson, Magnitude From Short-Period P-Wave Data, *BSSA*, Vol. 62, No. 2, pp435-452, April 1972

2. Detection and Location Performance Modeling Enhancements

Whether this is a viable model for teleseismic S remains to be determined. Clauser* of the NDC/AFTAC has reported that teleseismic S appears to produce overly optimistic detections. Whether this optimism occurs as a result of the extrapolation, an inadequate teleseismic P coda noise model, or through a empirical model primarily based on earthquake sources must be determined.

NetSim also has provisions to include barriers within the database of propagation models. It is becoming strongly evident that barriers to Lg propagation appear throughout the world. In earlier years it was largely known that the ocean basins formed significant barriers to Lg propagation. More recently we have come to understand that the Caspian Sea, the Ural mountains, the southern boundary of the Tibetan plateau, the Red Sea, and many other geologic features serve as Lg barriers. Of these only the ocean basins were modeled as Lg barriers in the current effort. Future efforts will attempt to identify these barriers more carefully and include them in the NetSim database. In addition to Lg barriers some recent work† indicates that Sn propagation isn't supported by some lower crustal and upper mantle structures. This effect can be modeled as a region dependent Sn barrier or as a probability that Sn will not propagate in a given region. Additional empirical knowledge regarding this phase on a global basis is required to more fully understand the impact of regional Sn on network performance.

The NetSim regional attenuation accumulation model was corrected to properly estimate the attenuation across the polar regions and the international dateline. This coding error frequently contaminated the numerical results and not only affected the detection performance estimates but also severely impacted location performance estimates. The code was also inherently limited to networks having fewer than 129 stations. Considerable effort was applied to extend the capability of the code to 256 stations since some of the code was "hard wired" for a maximum of 128 stations. In addition extensive portions of the code were re-written using more conservative FORTRAN structures to permit the compiler to improve the computational speed without altering the answers achieved without optimization. Finally, a search and interpolation routine was modified to assure convergence to the correct

*Private communication

†Koch, Karl and Brian Stump, Implications for Upper Mantle Structure in the Western United States from Complete Far-Regional Seismograms, BSSA, Vol. 85, No. 5, pp1432-1444, October 1995

detection threshold under diverse detection criteria to include criteria representative of evasion scenarios.

2.3 Improvements to the Location Model

The probability weighted location model embedded within NetSim has been questioned for more than a decade by the verification community. An attempt by SAIC* had been made to produce a more plausible model but the bases for these modifications are not completely tenable. The new model developed in this effort is based on a Monte Carlo estimation technique having more realistic physical and statistical premises. The new location performance model is summarized by the steps identified in Table 1. The new model permits the use of detections having a usable SNR beneath the station threshold to help locate events. This particular feature simulates the ability of an analyst to draw additional observations from stations not reporting detections. A related feature makes the arrival time uncertainty dependent on the SNR of the arrival. In developing the new location performance estimation routine, the type of statistic on which location performance is based was also corrected and was permitted to assume different confidence levels at the discretion of the user. A simple modification was also introduced to permit location performance estimates of the combined primary and auxiliary stations at the detection level of the primary network. Finally, better real-time reporting of the location performance estimates was also included in the modified code, particularly to help identify areas of the world where the distribution of stations produces ill-conditioned estimates.

2.4 Station Noise Estimation and Database

In earlier efforts methods were developed to estimate the station noise statistics using actual station data. In view of the log normal statistics of noise and the NetSim adaptation of those statistics, the noise statistics must be estimated in a special way to be consistent with the observed noise statistics. Over a period of several years station noise statistics to support network modeling were estimated on a continuing basis using various sources of noise data as they became available. Station noise statistics are now available for

*Sereno Jr., Thomas J., Steven R. Bratt, and Gaymond Yee, NetSim: A Computer Program for Simulating Detection and Location Performance of Regional Seismic Networks, Report SAIC 90/1163, Science Applications International Corporation, March 1990

2. Detection and Location Performance Modeling Enhancements

approximately 230 stations. In the past year the station noise estimation method was shared with the CMR/ARPA. Now the noise statistics for the GSETT-3 stations are routinely estimated at the prototype IDC.

3. The Approach

The detection and location performance estimates were based on 46 primary (declared in the WP-224) and 67 auxiliary stations, whose locations are shown in Figure 3. The performance estimates were based on the final network configuration having all the upgrades as recommended by the experts to the CTBT negotiators. The improved version of NetSim was used to estimate the detection threshold performance of this primary network on a global basis for four different detection criterion, each having a network detection probability of 90%. Four criteria were selected to show a range of possible detection performance levels as may occur in the actual operation of the primary network. Weak detection criteria were included simply because limited observations of a suspicious event are sometimes carefully studied in practice. It is useful to know at what level such a suspicious event may be detected. The utility of using secondary arrivals in the detection criterion is also investigated. Recognize that the prototype IDC currently requires that three or more P arrivals be detected at distinct stations $[(P+Pg)/3]$ as an admission that a network detection has occurred. This criterion is among the four criteria investigated. Special evaluations of the prototype IDC criterion were also performed at a 99% detection probability requirement to determine the impact on the threshold when fewer missed detections are permitted.

The location performances at the detection threshold of the primary network with and without the use of auxiliary stations were also estimated using the new Monte Carlo method. As will be seen it is also important to investigate the location performance of the primary network alone since on occasion the analyst is unable to call for correct auxiliary station data because an event cannot be properly located. This condition is, of course, integrally tied to the detection capability. The location capability at the threshold associated with the $(P+Pg)/3$ criterion with 99% probability is also evaluated under two different travel-time error conditions to show the location capability of the networks on start-up and after having more carefully documented the location models and their corrections.

3. The Approach

To account for the different station noise levels, the performance estimates were based on the actual station noise statistics when available. For those primary stations for which noise data were not available, noise statistics similar to those of the GTSN (Global Telemetered Seismic Network) stations, which are recognized as very low noise stations, were assigned. The noise spectrum of a GTSN-like station is shown in the graph of Figure 4 where the NORESS noise spectrum is also shown for comparison purposes. For those auxiliary stations whose noise data were not available, the noise statistics were assumed to be similar to those of the GTSN stations after raising them by 10 dB to reflect the noisier characteristics usually associated with the auxiliary stations. The location performance results were based on arrival and bearing statistics shown in Table 2. The arrival time statistics are based on the average travel time residuals for the events defined by GSETT-3 network during the first three months of its operation. These error characteristics appear to be somewhat optimistic based on historical experience; so these values will be regarded as error residuals achievable under more carefully documented location models. In some special studies the model error associated with the P arrival is assumed to be twice that shown in Table 2 in order to simulate the case where regional location models are not calibrated. The bearing statistics are based on the empirically determined bearing errors observed by various investigators in recent years. It has been assumed that any biases in the bearing estimates have been applied. At the stated accuracy the bearings contribute little to the location accuracy except under conditions where location of an event is marginally possible.

The contour plots of Figures 5 through 16 illustrate the detection and location performance results associated with four detection criteria. The illustrations are grouped by the following detection criteria: 1) 2 or more P arrivals criterion [specifically stated as $(P+Pg)/2$], 2) 3 or more P arrivals criterion [$(P+Pg)/3$], 3) 4 or more P arrivals criterion [$(P+Pg)/4$], and 4) 4 or more arrivals (P or S) criterion where at least 2 of the arrivals must be P arrivals [$(P+Pg)/4 + ((P+Pg)/3 * (S+Lg)/1) + ((P+Pg)/2 * (S+Lg)/2$]. A minimum of 2 P arrivals was retained in the latter criterion since P arrivals are important to associating arrivals and locating events. Within each group of three illustrations the first documents the detection performance, the second illustrates the location performance of the primary network, and the third shows the location performance when the auxiliary stations are added.

To assist in interpreting the contour graphs, the contours have not only been labeled but also filled with differing color/gray tones to make interpretation easier. The darker tones depict larger values. For further assistance in interpreting the contours, a pair of numbers appear in upper right-hand parentheses of the plot to disclose the minimum contour level and the contour increment, respectively. In some of the plots the minimum level is not always observed on the plot because the area it encloses is too small. The contours are actually based on partially smoothed performance measures so as to assure that the contouring process is not subjected to the spatial irregularities in the performance estimates. The captions beneath each illustration provide a comprehensive interpretation of the network performance result. The detection threshold levels are provided in magnitude units in the Scandinavian $m_b(Lg)$ measure. The location performance accuracy is given in square kilometers at the 90% confidence level. The area of uncertainty is, of course, elliptical in shape. In portraying the performance, the events were assumed to be shallow buried explosions contained in hard rock. Containment in hard rock produces a larger seismic signal than had the shot been contained in alluvium.

In interpreting the following detection and location performance results, the reader is fore-warned that the reported performance levels are restricted to the events occurring in consolidated rock as opposed to shots occurring in the oceans. So the results are applicable to the continents and the islands as opposed to the oceans. The detection thresholds for shots in the ocean can be estimated from these results by simply lowering the estimates shown here by approximately 0.8 magnitude units*. The location performance for events in the ocean as opposed to the islands may also be better than shown here.

*Private communication for Keith McLaughlin, S-Cubed, a division of Maxwell Industries

3. The Approach

4. Discussion of the Detection Results

4.1 General

An examination of the network detection thresholds under the four detection criteria as shown in Figures 5, 8, 11, and 14 indicates that the detection magnitudes vary from under 2.75 to above 4.0. The threshold levels are very much dependent on the station density and the detection criterion used by the network. The best (lowest) thresholds are associated with the minimal criteria $(P+Pg)/2$ and $(P+Pg)/4 + ((P+Pg)/3*(S+Lg)/1) + ((P+Pg)/2*(S+Lg)/2)$ (Figures 5 and 14, respectively) and the highest thresholds are associated with the historical $(P+Pg)/4$ criterion (Figure 11). The lowest thresholds typically occur in regions having the higher station densities or having more array stations. The detection thresholds computed in these contour plots are not adjusted for station biases as induced by source and receiver structures. If the source and propagation models contributing to these estimates are assumed to be correct, the estimated threshold is thought to be somewhat higher than report here if the source or station is located on a tectonic province.

It is interesting to compare the detection thresholds among the various network detection criterion. The increase in the detection threshold in going from a $(P+Pg)/2$ criterion to a $(P+Pg)/4$ criterion, both at 90%, is illustrated in Figure 17. In going to a more stringent criterion, the threshold rises by 0.25 magnitude units on most landmasses with some significantly larger increases in those regions having an inadequate density of stations to achieve the 4 P criterion. The increase in the detection threshold in going from a $(P+Pg)/3$ criterion to a $(P+Pg)/4$ criterion, both at 90%, is illustrated in Figure 18. Here the thresholds differ typically by 0.125 magnitude units on most landmasses with again some large differentials in isolated regions not having an adequate density of stations to achieve the 4 P criterion. Recognize that those areas experiencing a significant change in threshold have a high station density or are well endowed with array stations. This enables the network to achieve low thresholds at relaxed detection criterion in these areas but the station density is inadequate to achieve a similar threshold at a more stringent criterion, such as 4 P at 90% or 3 P at 99%.

4. Discussion of the Detection Results

The lowest detection thresholds, when the detection criterion is restricted to the P arrivals only, appear in North America and Eurasia primarily as result of higher station densities and the number of array stations there. However, as the number of arrivals in the detection criterion increases the lowest levels are restricted to central Eurasia probably because more stations appear across a larger landmass. The poorest (highest) detection thresholds occur on the continents and islands appearing in the southern hemisphere and across Central America. The thresholds in these locations can exceed 3.75 or 4.0 magnitude units depending on the detection criterion. Even when the secondary arrivals are available to contribute to the detections, the thresholds remain above 3.5 magnitude units along the coastal margins of the southern continents, within Antarctica, on the oceanic islands, and within Central America as shown in Figure 14.

A careful examination of the performance levels associated with the $(P+Pg)/2$ criterion as shown in Figure 5 and the $(P+Pg)/4 + ((P+Pg)/3*(S+Lg)/1) + ((P+Pg)/2*(S+Lg)/2)$ criterion as shown in Figure 14 indicates that they produce almost identical detection levels. A comparative examination of the difference thresholds in Figures 17 with 19 further demonstrates the similarity of the thresholds associated with these two criteria. This suggests that the secondary arrivals (through the Scandinavian models) are usually detected when the primaries are detected. In reality one can not always be assured that the secondary arrivals accompany the primary arrivals as a result of the source dynamics, propagation barriers, and "hot spots" which severely attenuate the shear arrivals. However, the importance of the secondary arrivals to network detection can be appreciated by comparing the performance levels of two criteria requiring the same minimal number of arrivals, viz., the $(P+Pg)/4$ criterion and the $(P+Pg)/4 + ((P+Pg)/3*(S+Lg)/1) + ((P+Pg)/2*(S+Lg)/2)$ criterion. This difference in the threshold is illustrated in the contour graph of Figure 19 which shows that when the secondary arrivals are available, the thresholds can be reduced by at least 0.25 magnitude units with significantly larger improvement in many regions.

The minimal $(P+Pg)/2$ detection criterion is not a robust criterion in practice since it is susceptible to frequent bogus events as a result of station noise combining with a real detection at another station to form an apparent network detection. So the thresholds appearing in Figure 5 are seldom achieved in practice. These detection levels become more important, however, when array

stations observe several arrivals and when secondary arrivals augment the P detections as discussed above. Under these circumstances an adequate number of time picks and bearings will more likely be available to associate arrivals and locate events within the primary network. If lower thresholds become important to global monitoring, then the inclusion of the secondary arrivals in the network detection criterion is more important to detecting as well as locating events. Automated detection and association schemes now under investigation may help realize these lower threshold levels with fewer false alarms.

The above observations and a comparison of thresholds within the northern and southern hemispheres indicate that as the landmass becomes smaller increased station density is required to monitor at the same levels as on the larger landmasses. The implication is that events must be well "surrounded" by stations to satisfy the detection criterion in a robust manner. This requirement becomes even more acute when attempting to locate events.

4.2 Special Detection Results

A particular concern is that when 90% is used as the network detection probability, 10% of the events are permitted to escape detection at the desired threshold. Although it is not realistic to impose extremely high detection probabilities, like 99.99%, because of the very high station density and operational costs to do so, it is interesting to consider 99% and determine the impact on the detection threshold. Figure 20 illustrates that under the 3 P criterion at 99% the threshold is only increased by approximately 0.125 magnitude units as compared to the same criterion at 90% probability. Admittedly, there are some large changes in thresholds in Australia and North America; however, the station distributions are thought not to be as robust there as elsewhere. When you consider the possibility of including the secondary arrivals in the detection criterion, it appears that the use of 99% detection probability will not become costly in either missed detections or additional stations.

Reliable event detection is important in mining regions where frequent events, some of which exceed 3.5 magnitude, occur. Figure 21 indicates that under this more stringent 99% criterion the primary network only achieves a threshold at or beneath 3.5 in a small portion of the globe. Since mining events

4. Discussion of the Detection Results

in many regions of world are to be detected and located down to magnitude 3.5, many of these events will not be regularly observed nor located when the detection threshold in that region is considerably above 3.5 magnitude units. As a consequence, those auxiliary stations assigned to locating mining events should really be part of the primary network to reduce the detection threshold in those regions. It may take several stations in the vicinity of the mines if the detection threshold is to be reduced by 0.5 magnitude units to achieve the desired 3.5 threshold.

5. Discussion of the Location Results

5.1 The Location Accuracies Associated with the Primary Stations

The location accuracies for the primary stations when the locations are restricted to P arrivals appear in Figures 6, 9, and 12. This series of location performance estimates indicates that as the detection thresholds of primary network rises at a particular point on the earth as a result of the detection criterion becoming more stringent, the accuracy by which the events are located improves. The improvement simply occurs because the location estimates are performed at a higher SNR as a results of the higher thresholds. An increase in detection threshold by a nominal 0.25 magnitude unit (see Figures 11 and 5) results in considerable improvement in the location accuracy as attested by the accuracies improving from 500 to 250 square kilometers in the areas having the best accuracies and by improving from nominally 4500 to 2000 square kilometers along the continental margins (compare Figures 6 and 12). The use of the primary arrivals alone results in location accuracies considerably poorer than 2400 square kilometers in western Greenland, "western" Antarctica, the coastal margins of Australia, the southern tips of Africa and South America, Indonesia, New Zealand, Central America, and on the oceanic islands as shown in Figure 9 for the 3 P criterion. When the accuracy is plotted at a coarser scale (10,000 sq. km. minimum with 10,000 sq. km. increments) to illustrate the accuracies in these remote areas, the very dark areas of Figure 22 show the areas where events more likely cannot be located as a result of missed detections and poor accuracies. These areas include many of the oceanic islands, Western Greenland, and western Antarctica. When it is possible to locate event in these areas, the accuracy will be poor, primarily as a result of the low density of primary stations in these remote areas.

Fortunately, when the secondaries are permitted to contribute to the location estimates, the location accuracies improved substantially as attested by the estimates appearing in Figure 15. These results may be overly optimistic,

5. Discussion of the Location Results

particularly in the oceanic areas, since the teleseismic S model tends to produce overly optimistic results. Further, since regional S and Lg do not always propagate or are highly attenuated (“blocked”) in some areas, the estimates should also be cautiously considered on the continents. The results on the larger landmasses simply show what could be possible under ideal conditions. Other “secondary” arrivals such as PP, PCP, pP, SCS, etc, not modeled here, are thought by some investigators to be helpful in improving the location performance. Recognize, however, that some of these phases are only effective at larger event magnitudes.

Since secondary arrivals do not always propagate or do not provide definitive arrival times, the inability to locate in these more remote regions based on P waves alone could be a serious matter on some occasions. Figure 22 illustrates the likely regions where the location performance by the primary network will be poor. This network will require assistance from the secondary arrivals and additional seismic and hydro-acoustic stations to achieve the GSE location requirement in these areas.

5.2 The Location Improvements Provided by the Auxiliary Stations

The graphs of Figures 7, 10, 13, and 16 illustrate location accuracies when the observations of the auxiliary stations are used to improve the locations. Recall that these location accuracies are based on event magnitudes detectable 90% of the time by the primary network for the stated detection criterion. In many areas of the world the addition of the auxiliary stations substantially enlarges the region in which exceptionally high location accuracies of 250 to 300 square kilometers are achieved. However, in other regions the improvements remain unacceptable (greater than 1000 square kilometers by GSE standards) even at the higher detection thresholds when the locations are simply based on the primary arrivals alone. These areas include “western” Antarctica, Indonesia, Central America, southern Africa, New Zealand, many of the coastal margins, and the oceanic islands. The use of the secondary arrivals, when available, improves the location accuracy considerably. However as stated above, caution is warranted when interpreting the results which include the S arrivals.

5.3 Special Location Results

Be mindful that the above location accuracy estimates assumed that the propagation paths are well calibrated. When not calibrated it is reasonable to assume that the location model error is approximately 1.5 seconds for P waves. Under this assumption the location accuracy of the primary network at the threshold of the 3 or more P detection criterion at 99% probability is illustrated in the results of Figure 23. This result indicates that the primary network alone in its uncalibrated years of operation should be able to achieve location accuracies ranging from under 750 square kilometers in central Eurasia to well above 7500 square kilometers elsewhere, both with 90% confidence. These poorer accuracies predicted here are still superior to the global accuracies reported for the GSETT-3 network by several GSE investigators* who identified average accuracies of 15,382 sq. km. at the 90% confidence level when they compared the GSETT-3 locations with the NEIC locations. The poor GSETT-3 accuracy may be attributable to the very low station density associated with this network over very large portions of the globe. Locations on islands of the southern oceans and in portions of Antarctica at or below the network detection threshold may not be possible since the accuracies greatly exceeds 10,000 square kilometers in these areas (not shown but similar to Figure 22).

As operational experience of the networks provides the necessary corrections to the location models and the modeling error reduces to 0.75 seconds for the P wave, the location accuracies improve to beneath 300 square kilometers over much of the northern hemisphere with poorer accuracies elsewhere as illustrated in Figure 24. The areas of uncertainty in some of the oceanic areas are well over 2700 square kilometers. This result demonstrates that with calibrated regional location models, the primary network can largely achieve the GSE requirement of 1000 square kilometers over most of the major landmasses but not along the continental margins, on the oceanic islands, Antarctica, and a portion of Greenland. Some additional location improvement should, however, be realized through the use of the S arrivals when they are observed.

* French and Swedish Delegations, "Observed Global and Regional Detection and Location Capability of the EISMS During the First Half of 1995", GSE/FR,SW/1, August 14, 1995

5. Discussion of the Location Results

The use of the auxiliary stations will, of course, improve the location accuracies above that produced by the primary network alone. Figure 25 illustrates the location accuracy on a global basis when observations by both the primary and auxiliary networks are available. The location accuracies are specified at the 90% confidence level and at the detection threshold of the 3 P criterion with 99% probability. The underlying modeling errors assumed a one sigma error of 1.5 seconds for the P wave model, again a value more representative of a network not having well calibrated location models. The accuracies range from beneath 300 square kilometers in a portion of Eurasia to above 4500 square kilometers primarily in the ocean basins and "western" Antarctica. This result demonstrates that with the help of the auxiliary stations, the GSE location requirement can be achieved in the northern hemisphere in comparison to the use of the primary network alone under the uncalibrated assumption.

As the operational experience matures within the joint primary and auxiliary networks and the modeling errors reduce to approximately 0.75 seconds, the accuracies will improve to areas under 250 square kilometers over a very large portion of the northern hemisphere and to areas over 2250 square kilometer primarily within the ocean basins as shown in Figure 26. The introduction of 67 auxiliary stations into the calibrated network primarily broadens the regions already having good location accuracies. The combined networks still do not develop the required accuracy on some continental margins, on oceanic islands, and a major portion of Antarctica. The location improvements in square kilometers for the mature network modeling case as provided by the auxiliary stations are illustrated in Figure 27. The auxiliary network produces improvements ranging up to 400 square kilometers. Again since these accuracies were based on P arrivals alone, one should expect some additional improvement in the accuracies when S arrivals contribute to the location estimates.

6. Conclusions and Recommendations

The primary network originally proposed in WP-224 has been recently enhanced to a 50 station network. Since the 50 station network is not significantly different than the WP-224 network analyzed here, the performance levels for the new network should not differ significantly from those predicted here. Therefore focusing on the stringent detection criterion of 3 or more P at 99%, we may conclude that the currently proposed primary network is capable of establishing detection thresholds ranging from beneath 3.5 to over 4.0 (see Figure 21). In general the detection capability in the northern hemisphere is superior to that found in the southern hemisphere. The best detection levels appear in central Eurasia with higher thresholds appearing elsewhere. The highest (poorest) thresholds appear primarily on the oceanic islands with some major landmasses such as Antarctica, Central America, southern South America, and New Zealand also experiencing higher thresholds. Since the estimated thresholds are beneath magnitude 4.25, the expert's goal of achieving a network monitoring capability of detecting 1 kiloton shots fully coupled in hard rock appears to have been realized or exceeded on a global basis.

Although a plot at a global scale will not portray localized pockets of superior detection capability, it is safe to further assert that some of the mining regions of the world will not be monitored to a threshold of 3.5 magnitude units as recommended by the GSE. As a consequence, it is suggested that the auxiliary stations which are assigned the task of assisting in the location of the larger mining events be upgraded to primary stations in those mining regions having an insufficient threshold.

The results of Figures 5, 8, 11, and 14 generally indicate that the network detection level in those regions having the higher network thresholds are not greatly affected by the number or kinds of arrivals observed by the stations (i.e., the number of arrivals appearing in the detection criterion). The detection levels primarily change by 0.25 magnitude units in going from a weak to a strong detection criterion. However, in those regions having lower thresholds, say 3.5 under the weaker network detection criteria (Figures 5 and 14), the

6. Conclusions and Recommendations

detection threshold becomes sensitive to changes in the detection criterion as illustrated by Figures 17, 18, 19, and 20. These sensitive areas appear in Australia, North America, southern Africa, and several smaller regions. This implies that the lower thresholds are being realized at station spacings which cannot maintain the low thresholds under the more stringent criteria.

Detection criteria with 90% probability have been historically used as the basis for judging network detection performance. What is not often discussed is that 10% of the time events will not be observed/detected at the network threshold. Since the detection task is restricted to the primary network, this number of missed detections may be unacceptable. Unless this limitation is addressed, the prototype IDC may have to depend on detections volunteered by the open networks. It is, therefore, recommended that the 3 or more P criterion at 99% probability be accepted as the standard network detection criterion. This choice would be consistent with the 3 or more P criterion currently used by the prototype IDC to define an event in the GSETT-3 test and produces a threshold comparable to that associated with the historic 4 P criterion at 90%. In the context of global monitoring as opposed to test site monitoring, it is preferable to state that the network misses only 1% of the detections at the required network threshold as opposed to 10% of the events. Detections by at least three primary stations is sufficient to establish an approximate location.

A comparison of the results of Figures 23 and 24 indicates that the primary network will not be able to achieve the GSE location accuracy requirement 90% of the time in much of the world until the regional location models become calibrated. Even with the help of the auxiliary stations in an uncalibrated state, the location requirement is realized only in the northern hemisphere as illustrated in Figure 25. Once the regional location models become well calibrated, the primary network alone, as illustrated in Figure 24, should be able to achieve the accuracy requirement on almost all major landmasses. However, even with the help of 67 auxiliary stations as illustrated in Figure 26, the accuracy requirement will not always be realized on the coastal margins of southern hemisphere continents, on much of Antarctica, Central America, and on many of the oceanic islands. The seismic networks will, therefore, require assistance from the secondary arrivals and hydro-acoustic stations to assure an acceptable location capability in these areas. Recent modeling runs with the use of even more auxiliary stations have shown

that these additional auxiliary stations contribute in much the same way as the 67 stations do here and do not alter these findings significantly.

Recognize that even though the primary network could possibly detect and locate events alone, this does not preclude the use of the auxiliary stations. The role of auxiliary stations extends well beyond the refinement of the location. First, they are very much needed to calibrate the location capability of the entire network. Second, they play an even more important role in the discrimination of events where much higher SNRs than that required by detection and location are necessary. This implies that a higher station density, as provided by the combined networks, is required to achieve the higher SNR. Third, they can also voluntarily submit suspicious events not observed by the primary network

Network modeling as a discipline is a powerful tool for portraying the performance of global networks. However, in its current state of development, the performance estimates for regional networks are primarily restricted to cratons because propagation models have only been validated for that geology. Additional regional propagation models are required if more viable predictions are to be made in a larger variety of geologies. Of particular importance are regional propagation models for tectonic areas such as found in the western portions of the Americas and the southern parts Eurasia. Modeling of propagation at teleseismic distances is largely restricted to the initial P wave as results of the classical work of Veith and Clawson. However, a validated propagation model appears to be lacking for teleseismic S.

The Veith-Clawson model for P waves used within this effort is an average over many source and receiver geologies and will not predict the consistent deviations from that average other than through the use of station biases. Station biases will eventually emerge as the operation of a network matures and should be included in future modeling efforts to account for differing crustal geologies. It is interesting to speculate as to whether the stations biases can be reduced through use of the tectonic attenuation models in the future. It appears that current research efforts may yield such an improvement for some regions.

Since Lg barriers are important factors in regional modeling and since knowledge of these barrier locations are emerging from the current research,

6. Conclusions and Recommendations

future efforts should include the effects of these barriers. The use of these barriers will play a very important role in modeling the discrimination capability in some regions. Future efforts should model the discrimination performance to include determining the thresholds for various combinations of discriminants.

The current location model is based on travel-time characteristics and bearing estimates. There are other location models that could have been developed, but the one used in producing these results is consistent with the one currently used by the prototype IDC. Among these other models is the master event method which can produce better accuracies than those estimated here but which requires the use of well located reference events. Such reference events may not always be available in all regions of the world. Location estimation is currently an important research topic as we seek to improve and automate the location estimates. If any breakthroughs are made, NetSim should also be modified to model the new location methods. The new approaches can then be evaluated on a comparative basis with the current method. NetSim can be also be used to estimate the levels at which an evader may wish to test with confidence.

As continuing GSETT-3 (Group of Scientific Experts Technical Test No. 3) performance estimates are made from actual network detections and locations, future efforts could validate the predicted performance estimates using the GSETT-3 observations. Discrepancies between the measured and the modeled estimates could determine the adequacy of the predictive models and could possibly be used to flag regions where the measured performance could be different than expected. As a consequence, the predictive insight could play several important roles. It not only could help develop understanding and refinement of the physical processes which govern the performance of networks but it could also be used to check for anomalous behavior in the actual performance.

It is important to recognize that both measured and predicted performances are required to assess monitoring systems in real-time. In seismically active regions, the actual performance of a global monitoring system can be measured using actual network observations perhaps supplemented by observations from independent stations. For refined performance measures this measured performance could be augmented with the state of the network

in the context of a predictive model to infer real-time performance. In areas having insufficient seismicity the performance level of a monitoring system should be estimated using the best available models. The predicted performance could be refined with the few observations available from those regions. Thus the predicted and measured capabilities must be jointly used to assess special situations, isolate the strengths and weakness in the system, and provide insight into modifying or extending the network for new applications or for enhanced performance.

To provide these high quality performance measures and assessments will require carefully designed models and supporting databases. In an application of such a measurement/prediction system, one can envision tracking and displaying various performance measures in real-time. This would establish confidence in the performance of the monitoring system and provide a global view of the performance. Since doing this on global basis would required considerable resources, it is recommended that the initial demonstration concentrate on the regions of the world which are currently being studied as part of the CTBT seismic R&D efforts.

6. Conclusions and Recommendations

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Table 1. The Monte Carlo Method

1. For N very large perform N network location realizations
2. For each realization do the following:
 - a. If a gaussian distributed random outcome with mean log SNR and variance $\vartheta^2 = \vartheta_{signal}^2 + \vartheta_{noise}^2 + \vartheta_{gain}^2$ exceeds 0 dB for a given arrival and station and if a uniformly distributed outcome on [0,1] is less than the data availability, then admit that station's observations
 - b. From the set of all observations create a weighted least squares (WLS) system of observations with weights given by

$$\sigma_T^2 = \sigma_{model}^2 + \left(\frac{\sigma_{time}}{SNR - 1} \right)^2$$
 - c. Solve the resulting WLS system
 - d. Determine the location uncertainties from the error covariance matrix. For realizations in which the event is not locatable, simply assign very large errors to the outcome
3. Repeat 2 until the realizations are exhausted
4. From the N outcomes determine the location uncertainties at several percentile levels

Assumptions Governing the Location Performance

Table 1: Arrival Time and Bearing Statistics

Phase	Model Error (seconds)	Arrival Error (seconds)	Bearing Error for Simple Stations (degrees)	Bearing Error for Array Stations (degrees)
P, Pg, or Pn	0.75/1.5	0.15	20	15
S or Sn	2.0	0.30	-	25
Lg	1.5	0.50	-	15

Figure 1. Regional Propagation Assignments for the Eastern Hemisphere. Cream colored regions correspond to low attenuation cratons, beige to medium attenuation cratons, and brown to high attenuation tectonics.

Figure 2. Regional Propagation Assignments for the Western Hemisphere. Cream colored regions correspond to low attenuation cratons, beige to medium attenuation cratons, and brown to high attenuation tectonics.

Figure 4. The average daytime noise spectrum associated with four GTSN stations is compared with the daytime noise spectrum at the NORESS array. This noise characteristic was assigned to all the primary stations whose noise spectrum was not available. For those auxiliary stations whose noise spectrum was not available 10 dB of noise was added to this spectrum.

Figure 5. The event magnitude (the so-called the detection threshold) at which 2 or more P arrivals are detected 90% of the time are estimated here for the primary network. The PKP waves were included among the P arrivals so as to enhance station detection at distances larger than 140 degrees. Actual station noise statistics were used when available and GTSN like noise statistics were used for those stations whose noise characteristics were not available. This result shows that this network detection criterion achieves its best threshold levels in central Australia as a results of the two large arrays there. Elsewhere higher detection thresholds are estimated. For example, levels beneath 3.0 are estimated in portions of Eurasia, northern Africa, and central North America and magnitudes under 3.5 are estimated on major portions of most landmasses with some exceptions. Realize that this minimal network detection criterion, when implemented in practice, is subject to frequent bogus events as a result of fictitious detections but becomes more meaningful when the network is augmented with array stations and when secondary arrivals are also observed.

Figure 6. This contour plot illustrates the location accuracy of the primary network at the detection threshold shown in Figure 5. The location accuracies were based on P waves only and are stated in square kilometers at a confidence level of 90%. Only contained shallow events were assumed to occur. This result shows that the primary network alone can locate events with accuracies better than 500 square kilometers in a large portion of central Eurasia. The good accuracies there are thought to be attributable to the density of array stations designated for this region. The accuracies elsewhere are poorer than 500 square kilometers. Events in the darkest portions of the contour plot are locatable within epicentral areas much greater than 4500 square kilometers. These areas include northern North America, Greenland, "western" Antarctica, Australia, Indonesia, Central America, southern Africa, southern South America, and most of the ocean bound islands. There is some concern that in these areas the location accuracy may not always be sufficient to call for the proper auxiliary station data at the low thresholds underlying these results (Figure 5).

Figure 7. This plot illustrates the location accuracy when stations in both the primary and auxiliary networks are used to determine the locations of events having the magnitudes shown in Figure 5. The location accuracies are based on P arrivals only and are stated in square kilometers at a confidence level of 90%. Only contained shallow events were assumed to occur. This result shows that the combined networks can locate events with accuracies somewhat better than 500 square kilometers (lightest areas) in a large portion of northern hemisphere and in small portions of the southern hemisphere. The accuracies elsewhere are poorer than this value. Events in the darkest portions of the contour plot are locatable within epicentral areas greater than 4500 square kilometers. The poor accuracies across Australia are attributable to the low event magnitudes there and the higher noise associated with the auxiliary stations. The higher accuracies to the east of Australia are thought to result from the combined contribution of the Australian stations and three stations to the east of Australia. The use of the primary and auxiliary stations improves the location accuracy in comparison to using the primary stations alone (See Figure 6).

Figure 8. Global estimates are shown of the detection threshold at which 3 or more P arrivals are detected 90% of the time by the primary network. The PKP waves were included among the P arrivals so as to enhance detection at distances larger than 140 degrees. This result shows that the primary network under this detection criterion can detect events having magnitudes somewhat beneath 3.25 in small regions of Eurasia and central North America and under 3.5 in large portions of Eurasia, Africa, and North America. The detection thresholds for most of the remaining landmasses are beneath 3.75 magnitude units except for Central America, southern South America, a portion of southern Africa, and much of Antarctica where the thresholds are larger. This network detection criterion is considered to be a robust criterion since three or more P detections usually results in well associated arrivals. Note that this more stringent criterion results in thresholds generally higher by 0.125 to 0.25 magnitude units than that produced by the 2 P criterion.

Figure 9. This plot estimates the location accuracy of the primary network at the detection threshold shown in Figure 8. The accuracies are based on P arrivals only and are stated in square kilometers at a confidence level of 90%. Only contained shallow events were assumed to occur. This result shows that the primary network alone can locate events with accuracies better than 300 square kilometers in a large region of central Eurasia and a very small portion of northern Africa. The good accuracy there is thought to be attributable to the density of array stations designated for this region. The accuracies on most continental landmasses except for their margins, Antarctica, and Greenland are better than 800 square kilometers. Events in the darkest portions of the contour plot are locatable within epicentral areas greater than 4300 square kilometers. These areas include Greenland, margins of Australia, "western" Antarctica, Central America, Indonesia, New Zealand, and most of the ocean bound islands. Except for these regions, the accuracies are thought to be high enough to call for the appropriate auxiliary station data to assist in improving the event location.

Figure 10. This plot illustrates the location accuracy when stations in both the primary and auxiliary networks are used to determine the location of an event having the magnitude shown in Figure 8. The accuracies are based on P arrivals only and are stated in square kilometers at a confidence level of 90%. Only contained shallow events were assumed. At these detection thresholds the combined networks can locate events with accuracies better than 300 square kilometers in a very large portion of the northern hemisphere. The accuracies on the major landmasses are typically better than 800 square kilometers except at the coastal margins and in "central" Antarctica. Events in the darkest portions of the contour plot are locatable within epicentral areas greater than 4300 square kilometers. The accuracies found here are better than those associated with the 2P detection criteria since the station SNRs for this more stringent criterion are higher. Again the use of primary and auxiliary stations improves the location accuracy in comparison to primary stations alone (See Figure 9).

Figure 11. Global estimates are shown of the magnitude threshold at which 4 or more P arrivals are detected 90% of the time. This result shows that the primary network under the stated detection criterion can detect events having magnitudes just under 3.5 in a central region of Eurasia and under 3.75 in much of the northern hemisphere and the central core of South America. The detection threshold is over 3.75 on the remaining landmasses. This result also indicates that the primary network only achieves a threshold at or beneath 3.5 in a small portion of the globe. Since mining events in many of the regions of world are to be detected and located down to magnitude 3.5, these events will not be regularly observed. Those auxiliary stations assigned to locating these mining events should, as a consequence, be part of the primary network to reduce the detection threshold in those regions. This network detection criterion has been historically used as the basis for judging global detection performance. What is not often discussed is that 10% of the time four or more P arrivals will not be observed at these magnitudes. However, it is shown in Figure 21 that at approximately these same thresholds, only 1% of the events are missed if the number of P arrivals is relaxed to 3 or more and the network detection probability increased to 99%..

Figure 12. This plot illustrates the estimated location accuracy of the primary network at the detection thresholds shown in Figure 11. The accuracies are based on P arrivals only and are stated in square kilometers at a confidence level of 90%. Contained shallow events were assumed to occur everywhere. This result shows that the primary network can locate events with accuracies just under 250 square kilometers in a large portion of the Eurasia and a small central region of North America. These good accuracies are thought to be attributable to the larger density of array stations designated for these regions. Throughout much of the northern hemisphere the estimated accuracy is better than 500 square kilometers except at the continental margins. The location capability in the southern hemisphere is considerably poorer than those in the northern hemisphere.

Figure 13. This plot illustrates the estimated location accuracy of the primary and auxiliary networks at the detection thresholds shown in Figure 11. The accuracies are based on P arrivals only and are stated in square kilometers at a confidence level of 90%. Contained shallow events were assumed to occur everywhere. This result shows that the combined networks can locate events with accuracies just under 250 square kilometers in a major portion of the northern hemisphere and the central core of Australia. These good accuracies are thought to be attributable to the density of array stations designated for these regions. Except for the continental margins and Antarctica, accuracies better than 500 square kilometers are achievable on most landmasses. The location accuracies are poorer than 1000 square kilometers on the remaining portions of the world. These poorer accuracies may be found on the continental margins, in "western" and "central" Antarctica, on the southern tip of South America, within Indonesia, and on the oceanic islands.

Figure 14. Global estimates are shown for the detection threshold at which 4 or more arrivals are detected 90% of the time for the primary network. Both P and S waves contributed to the detections. Of the 4 arrivals two were required to be P arrivals to assure that the observations are well associated. Actual station noise statistics were used when available and GTSN like noise statistics were used for those stations whose noise characteristics were not available. This result shows that the primary network under this network criterion can detect events having magnitudes under 3.5 but larger than 2.75 on most continental landmasses. Higher detection thresholds were estimated on portions of Central America, margins of South America, margins of Africa, margins of Australia, Indonesia, Antarctica, and the oceanic islands. A comparison of these thresholds to those associated with the 2 or more P arrival detection criterion (Figure 5) indicates that the detection levels are almost identical. This implies that the secondary (S) arrivals as modeled made consistent contributions to the detections when the P arrivals did. These estimates must be regarded as optimistic in some parts of the world since the S waves do not always propagate. The thresholds in the ocean may be optimistic since the teleseismic S is thought to be modeled incorrectly.

Figure 15. This plot estimates the location accuracies of the primary network at the detection thresholds shown in Figure 14. Both P and S waves contributed to the accuracy estimates. The accuracies are stated in square kilometers at a confidence level of 90% and are based on contained shallow events. This result shows that the primary network can locate events with accuracies somewhat better than 250 square kilometers over most of the northern hemisphere, a small region of South America, and much of Africa. It is clear that the secondary arrivals make a significant contribution to locating events. Location accuracies are poorest in the "western" portion of Antarctic and on the islands of the southern Pacific. Since the secondary (S) arrivals are not propagated in all regions of the world, these estimates are to be regarded as optimistic. In these regions more realistic estimates would lie somewhere between those of Figure 6, where only P arrivals were modeled, and the ones stated here. The location accuracies in the ocean may be optimistic since the teleseismic shear wave is thought to be inadequately modeled.

Figure 16. This plot illustrates the estimated location accuracies of the primary and auxiliary networks at the detection thresholds shown in Figure 14. Both P and S waves contributed to the accuracy estimates. The accuracies are stated in square kilometers at a confidence level of 90% and are based on contained shallow events. This result shows that the combined networks can locate events with accuracies somewhat better than 250 square kilometers over most of the continental landmasses. It is clear that the secondary arrivals and observations by the auxiliary stations make a significant contributions to locating events. Location accuracies are poorest on the islands of the southern Pacific. Since the secondary (S) arrivals are not propagated in all regions of the world, these estimates may again be regarded as optimistic. In these regions more realistic estimates would lie somewhere between those of Figure 6, where only P arrivals were modeled, and those shown here. The location accuracies in the ocean may be optimistic since the teleseismic S is thought to be modeled too efficiently.

Figure 17. This plot documents the increase in the detection threshold when the network detection criterion requires 4 or more P arrivals at 90% probability as opposed to 2 or more P arrivals. The threshold is increased by more than 0.25 magnitude units on most landmasses with some significantly larger increases in those regions having an inadequate density of stations to achieve the 4 or more P criterion at levels near the 2 P threshold. Recognize that the regions in which the detection thresholds change significantly are also regions where the detection sensitivity is the greatest under the 2 P criterion. The station density is simply insufficient to achieve the 4 P criterion at levels near the 2P threshold.

Figure 18. This plot documents the increase in the detection threshold when the network detection criterion requires 4 or more P arrivals at 90% probability as opposed to 3 or more P arrivals at the same probability. The threshold is primarily increased by more than 0.125 magnitude units on most landmasses with some significantly larger increases in those regions having an inadequate density of stations to achieve the 4 or more P criterion at levels near the 3 P threshold. Recognize that the regions in which the detection thresholds change significantly are also regions where the detection sensitivity is the greatest under the 2 P criterion. These larger changes appear to be associated with regions having a goodly number of array stations on the interior of the continent.

Figure 19. This plot documents the improvement (decrease) in detection threshold when the $(P+Pg)/4 + ((P+Pg)/3 \cdot (S+Lg))/1 + ((P+Pg)/2 \cdot (S+Lg))/2$ criterion is used as a network detection criterion as opposed to the $(P+Pg)/4$ criterion. The threshold decreases by more than 0.25 magnitude units on most landmasses with some significantly better enhancements in those regions where the station density is inadequate to achieve 4 P detection criterion at levels comparable to the low levels achieved by the 4 or more arrival criterion. A comparison of these results with those Figure 17 indicates that the $(P+Pg)/4 + ((P+Pg)/3 \cdot (S+Lg))/1 + ((P+Pg)/2 \cdot (S+Lg))/2$ criterion and the $(P+Pg)/2$ achieve approximately the same detection levels.

Figure 20. This contour map illustrates the increase in the detection threshold that occurs for the 3 P or more criterion when 99% rather than 90% probability of detection is required. The threshold primarily rises by 0.125 magnitude units except in some isolated areas where 0.25 to 0.5 additional magnitude units are required. The significant changes in threshold as illustrated here and in Figures 17, 18, and 19 appear to flag areas where the low thresholds can not be maintained at the more stringent detection criteria. As a results, one can expect the detection threshold to vary significantly depending on the number of P arrivals that are observed regardless of the number of secondary arrivals. These regions appear to emphasize station coverage on the interior of the continents.

Figure 21. This plot illustrates the detection threshold when the primary network uses a 3 P detection criterion with 99% probability. This result indicates that the primary network achieves a threshold at or beneath 3.5 in a large central region of Eurasia. Thresholds elsewhere are higher, particularly on the islands of the southern oceans. Since mining events in many of the regions of world are to be detected and located down to magnitude 3.5, such events will not be regularly observed nor located by a network when its threshold is somewhat higher than magnitude 3.5. As a consequence, any auxiliary stations assigned to locating these mining events should become part of the primary network to help reduce the detection threshold in those regions.

Figure 22. This graph illustrates the location accuracy results of Figure 9 at a different scale. It shows that events cannot be located at all in many ocean areas at the 3 P threshold 10% of the time and when it is possible the accuracy is extremely poor. This largely results from an inadequate distribution of primary stations in the southern hemisphere. Fortunately, when the secondaries are permitted to contribute to the location, the location However, since the secondary arrivals are not always observed or their arrival time is not well defined, the inability to locate in these island regions based on P waves alone could be a serious matter on some occasions. The importance of other types of observations, such hydro-acoustic and infra-sound observations, when integrated with the seismic observations would be helpful in improving the location accuracy of events on landmasses in the southern hemisphere.

Figure 23. This graph illustrates the achievable location accuracy with the primary stations alone. The location accuracy is specified in square kilometers at the 90% percentile level and at the detection threshold of the primary network when at least 3 P arrivals are to be detected with 99% probability (see Figure 21). Here it was assumed that the network is not mature and is initially able to specify the travel-time models to within a one sigma error of 1.5 seconds for the P arrivals. The location accuracies range from under 750 square kilometers to well over 6750 square kilometers in some oceanic areas and parts of the Antarctica. This demonstrates that without calibrated regional location models, the primary network alone cannot achieve the GSE location accuracy requirement of 1000 square kilometers. Some improvement should be possible when the S arrivals are included in the location process.

Figure 24. This graph illustrates the location accuracy achievable by the primary stations alone. The location accuracy is specified in square kilometers at the 90% percentile level and at the detection threshold of the primary network when at least 3 P arrivals are to be detected with 99% probability (see Figure 21). The underlying modeling errors assumed a one sigma error of 0.75 seconds for the P arrivals, a value more representative of a network having well calibrated travel-time models. The location accuracies range from under 300 square kilometers to well over 2700 square kilometers in some oceanic areas and parts of the Antarctica. This result demonstrates that with calibrated regional location models, the primary network can largely achieve the GSE requirement within the major landmasses but not everywhere. Some additional location improvement can be realized through the proper use of the S arrivals in the location process.

Figure 25. This graph illustrates the achievable location accuracy in square kilometers when the primary station observations are augmented with those of the auxiliary stations. The location accuracy is specified at the 90% percentile level and at the detection threshold of the primary network when at least 3 P arrivals are to be detected with 99% probability (see Figure 21). The underlying travel-time errors assumed a one sigma error of 1.5 seconds for the P arrivals, a value more representative of a network not having well calibrated location models. The accuracy ranges from beneath 300 square kilometers to above 4500 square kilometers, primarily on islands in the ocean basins. This results demonstrate that with the help of the auxiliary stations, the GSE location requirement can be achieved in the northern hemisphere in comparison to the use of the primary network alone under the uncalibrated condition. The use of the S arrivals should improve these location accuracy estimates.

Figure 26. This graph illustrates the location accuracy when the primary station observations are augmented with those of the auxiliary stations. The location accuracy is specified in square kilometers at the 90% percentile level and at the detection threshold of the primary network when at least 3 P arrivals are to detected with 99% probability (see Figure 21). In producing these results, it was assumed that the network is mature and is able to specify the travel-time models to within a one sigma error of 0.75 seconds for the P arrivals. The introduction of 67 auxiliary stations into the calibrated network primarily broadens the regions already having good location accuracies. Since these accuracies were based on P arrivals alone, one should expect some improvement in the accuracies when S arrivals are observed and properly included within the location estimates.

Figure 27. The location improvements in square kilometers as provided by the auxiliary stations are illustrated here for the mature network modeling case. The improvements range in 50 square kilometers increments from none (the lightest areas) up to 400 square kilometers (darkest areas).

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