Evaluation of National Seismograph Network Detection Capabilities

Final Report

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Simulation of USNSN Capabilities

Abstract

This final report presents detection thresholds, detection probabilities, and location error ellipse projections for the United States National Seismic Network (USNSN) with and without real-time cooperative stations in the eastern United States. Network simulation methods are used with spectral noise levels at stations in the USNSN and other stations to simulate the processes of excitation, propagation, detection, and processing of seismic phases.

The USNSN alone should be capable of detecting 4 or more P waves for shallow crustal earthquakes in nearly all of the eastern and central United States at the magnitude 3.8 level. When real-time cooperative stations are used in conjunction with the USNSN, the network should be capable of detecting 4 or more P waves from events 0.2 to 0.3 magnitude units lower. The planned expansion of the USNSN and cooperative stations should improve detection levels by an additional 0.2 to 0.3 magnitudes units in many areas. Location uncertainties for the USNSN should be significantly improved by addition of real-time cooperative stations. Median error ellipses for magnitude 4.5 earthquakes in the eastern and central US depend strongly upon location, but uncertainties should be less than 100 square km in the central United States and degrade to 200 square km or more off-shore and to the south and north of the international boundaries. Close cooperation with the Canadian National Network should substantially improve detection thresholds and location uncertainties along the Canadian border.

 

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1.0 Project Review

The research objective is to provide analysis that will allow evaluation of the quality and validity of seismic detections, event locations, magnitudes, focal mechanisms, moments, and corner frequencies for events throughout the eastern and central US based on data from the U.S. National Seismograph Network (USNSN). The project uses the Monte Carlo network simulation and analysis systems, XNICE and NetSim, to determine the capabilities of the USNSN to detect, locate, and characterize earthquake sources with or without the use of supplemental local seismic network data.

Results are expected to be useful for defining uncertainties in event locations, focal mechanisms, and other source parameters based on the USNSN and for determining criteria to identify what supplemental data could be used to improve uncertainties. Among the products of this research program are maps covering the entire eastern and central U.S. which show detection thresholds, location uncertainty, and source characterization capability for the USNSN alone and in combination with supplemental seismic stations.

2.0 The USNSN and Cooperating Stations

Plans and specifications for the USNSN can be found in Buland (1993). The network consists of permanent 3-component observatory quality stations with direct real-time telemetry to the USGS NEIC. In addition, the network is augmented with direct real-time telemetry of quality stations provided by cooperating institutions. Operational and planned stations are listed in Tables 2.1-2.3 and their locations are shown in Figure 2.1. Since our 1995 annual report (McLaughlin and Bennett, 1995) there have been several changes to the network of USNSN and cooperative stations. Stations COR, TUL, LKWY, BW06, ISCO, WCI, WVT, DAC, LDS, TPH, and VTV have come on-line. RSNY was closed on 12/20/95 and will be replaced by a station near Newcomb, NY. CBM was closed on 12/07/94 and will be replaced by a station near Holten, ME. GOL was closed on 03/07/96.

Table 2.1
Operating USNSN Stations

Code	Lat.	Lon.	Station Name	Affiliation
AAM	42.300N	83.656W	Ann Arbor, MI	USGS
ALQ	34.943N	106.457W	Albuquerque, NM	USGS
BINY	42.199N	75.986W	Binghamton, NY	USGS
BLA	37.211N	80.421W	Blacksburg, VA	USGS
BMN	40.431N	117.222W	Battle Mtn., NV	USGS
				UNR
BW06	42.778N	109.556W	Boulder Array, WY	USGS
CBKS	38.814N	99.737W	Cedar Bluffs, KS	USGS
				SLU
CEH	35.891N	79.093W	Chapel Hill, NC	USGS
COR	44.59N	123.30W	Corvalis, OR	USGS
DUG	40.195N	112.813W	Dugway, UT	USGS
				ARPA
EYMN	47.946N	91.495W	Ely, MN	USGS
				AFTAC
GOGA	33.411N	83.467W	Godfrey, GA	USGS
GWDE	38.826N	75.617W	Greenwood, DE	USGS
ISCO	39.799N	105.613W	Idaho Springs, CO	USGS
JFWS	42.915N	90.249W	Mineral Point, WS	USGS
				SLU
LBNH	44.240N	71.926W	Lisbon, NH	USGS
LSCT	41.678N	73.224W	Lakeside, CT	USGS
MCWV	39.658N	79.846W	Mtn. Chateau, WV	USGS
MIAR	34.546N	93.573W	Mt. Ida, AR	USGS
MYNC	35.074N	84.128W	Murphy, NC	USGS
NEW	48.263N	117.120W	Newport, WA	USGS
OXF	34.512N	89.409W	Oxford, MS	USGS
				LLNL
				CERI
RSSD	44.120N	104.036W	Black Hills RS Obs., SD	USGS
TPNV	36.929N	116.224W	Topapah, NV	USGS
				UNR
WMOK	34.738N	98.781W	Wichita Mtn., OK	USGS
WVOR	42.434N	118.637W	Wildhorse Valley, OR	USGS
				BR
				UNR
WVT	36.130N	87.830W	Waverly, TN	USGS
				SLU
YSNY	42.476N	78.537W	Yorkshire, NY	USGS
GOL	39.700N	105.371W	Bergan Park, CO	USGS - closed
CBM	46.932N	68.121W	Caribou, ME	USGS - closed
RSNY	44.548N	74.530W	Adirondack RS Obs., NY	USGS - closed

Table 2.2
Cooperating Real-Time Stations

Code	Lat.	Lon.	Station Name	Affiliation
CCM	38.056N	91.245W	Cathedral Cave, MO	SLU
CMB	38.035N	120.383W	Columbia College, CA	BDSN
DAC	36.277N	117.594W	Darwin, CA	SANDIA
ELK	40.745N	115.239W	Elko, NV	LLNL
HRV	42.506N	71.558W	Harvard, MA	IRIS
HKT	29.950N	95.833W	Hockley, TX	IRIS
ISA	35.663N	118.474W	Isabella, CA	TS
LDS	37.243N	113.351W	Leeds, UT	SANDIA
LKWY	44.565N	110.400W	Lake, WY	UUSS
LTX	29.334N	103.667W	Lajitas, TX	AFTAC
MNV	38.433N	118.153W	Mina, NV	LLNL
PFO	33.609N	116.460W	Pinyon Flats Obs., CA	UCSD
SAO	36.765N	121.445W	San Andreas Obs., CA	BDSN
SSPA	40.636N	77.888W	Standing Stone, PA	IRIS
SMTC	32.949N	115.720W	Superstition Mtn., CA	TS
TPH	38.075N	117.223W	Tonopah, NV	SANDIA
TUC	32.310N	110.784W	Tucson, AZ	IRIS
TUL	35.91N	95.79W	Leonard, OK	OGS
VTV	34.567N	117.333W	Victorville, CA	TS
WCI	38.210N	86.360W	Wyandotte Cave, IN	SLU
WDC	40.580N	122.540W	Whiskeytown Dam, CA	BDSN

Table 2.3
Planned USNSN and Cooperative Stations

Code	Lat.	Lon.	Station Name	Affiliation
FWY	42.6N	111.0W	Afton, WY	WGS UUSS
HWUT	41.7N	111.20W	Hardware Ranch, UT	UUSS
KNB	37.017N	112.822W	Kanab, UT	LLNL
MRUT	38.5N	112.2W	Marysvale, UT	UUSS
NEL	35.712N	114.843W	Nelson, NV	SANDIA
PWLA	34.98N	88.064W	Pickwick Lake, AL	SLU/CERI
XXIA	41.0N	95.0W	IA	SLU
XXID	43.6N	116.1W	ID	LLNL
XXMT	46.7N	114W	MT	LLNL
XXND	46.6N	100.3W	ND	USGS
XXOH	40.0N	83.0W	OH	USGS
XXNY			Newcomb, NY	USGS
XXME			Holton, ME	USGS

Key to Affiliations and Participating Institutions:

AFTAC: Air Force Technical Applications Center, Patrick Air Force Base, Florida

ARPA: Advanced Research Projects Agency

BDSN: Berkeley Digital Seismograph Network, University of California-Berkeley, Berkeley, California

BR: Bureau of Reclamation

CERI: Center for Earthquake Research and Information, University of Memphis, Memphis, Tennessee

IRIS: Incorporated Research Institutions for Seismology

LLNL: Lawrence Livermore National Laboratory, Livermore, California

OGS: Oklahoma Geological Survey

SLU: Saint Louis University, Saint Louis, Missouri

TS: Terrascope, California Institute of Technology, Pasadena, California

UCSD: University of California-San Diego

UNR: University of Nevada-Reno, Reno, Nevada

USGS: United States Geological Survey, Golden, Colorado

UUSS: University of Utah Seismograph Stations, Salt Lake City, Utah

WGS: Wyoming Geological Survey, Laramie, Wyoming

USNSN and Real-Time Cooperative Stations

Figure 2.1 Map of operational USNSN, cooperating, and planned stations located in the continental US.

3.0 Network Simulation and Capability Assessment

Network simulations are a way in which the capabilities of seismic networks can be predicted. It is common for these programs to be used in the planning and subsequent assessment of networks as they evolve with time. These capabilities include detection thresholds, location thresholds and uncertainties, and event characterization thresholds and uncertainties. The software and statistical basis for these network simulations is quite mature. Initial work was limited to the detection of 1 Hz teleseismic P-waves and limited analysis of location capabilities (Booker, 1964; and Wirth 1971) with the development of the NETWORTH and NETWORK programs. However, it was soon realized that these programs could be used to simulate detection and limited event characterization and identification capability using multiple seismic phases (Basham and Whitham, 1971). Subsequently the SNAP-D program was developed (Ciervo, *et al.*, 1985) which included short-period P- and S-waves as well as teleseismic short-period (1 Hz bandwidth) P- and S-waves, and long-period (20 second) Rayleigh waves. However, these programs could not fully analyze the highly nonlinear processes involved with broadband multi-phase location and event characterization. In order to fully analyze network identification capability it was found that the programs required more sophisticated Monte Carlo methods and multi-frequency simulation of many phase types to simulate regional networks and event characterization. To this end the two programs NICE (Barker, *et al.* 1986, 1994) and NetSim (Serenio, *et al.* 1990) were developed. NetSim built upon the traditional detection statistics of the SNAP-D program and added Monte Carlo event location capability while NICE fully embraced the Monte Carlo approach for both event detection determination as well as event location and identification modeling. Both NetSim and NICE use the same models for source, phase propagation, and detection. They differ in the approach to estimating simple detection thresholds but both use Monte Carlo approaches for analysis of location capability. The NetSim program has not been extended to analyze the event characterization problem which is the primary purpose of the NICE program. Therefore we use the NetSim program for the estimation of simple detection capabilities and the NICE program for analysis of event characterization.

Network simulation methodologies use a model for the excitation and propagation of seismic phases from the source to the receiver and then use signal detection statistics to evaluate the probabilities of detection for a given source-receiver combination as a function of the event magnitude (or moment) and the noise levels at the station. Finally the procedures used in seismic bulletin generation are simulated to evaluate how well the available data will yield locations, magnitudes, and focal mechanisms for event characterization. Critical to this model is the partitioning of the process into four parts: source, path, receiver, and bulletin processing.

$$\text{Log}(A(\text{phase_type}, \text{region}, \text{station}, f, M)) = \text{Log}(S(\text{region}, f, M)) + P(\text{phase_type}, \text{region}, f, \Delta) + E(\text{phase_type}, \text{station}, f) + \epsilon$$

3.1 Source, $S(\text{region}, f, M)$

We need a description of the source strength as a function of frequency and magnitude or moment, $S(\text{region}, f, M)$. For this purpose we scale a reference Brune source spectrum with moment, M . The low-frequency value of the source spectrum, $S(f=0, M) = M$, and the high-frequency asymptote is proportional to f^2 . We have used a nominal stress-drop set to 100 bars. A log-normal variation in source strength is assumed with a zero mean and a standard deviation, $\sigma_S = 0.2$ nominal.

3.2 Path, $P(\text{phase_type}, \text{region}, f, \Delta)$

Seismic logarithmic amplitudes must be specified as a function of phase type, distance, and frequency, $P(\text{phase_type}, \text{region}, f, \Delta)$. These attenuation functions are tabulated for the regional phases P, Pg, Pn, S, Sn, and Lg as well as the teleseismic phases, P, pP, sP, S, PKP, pPKP, sPKP, and LR. The propagation (attenuation) function is then assigned a standard deviation, $\sigma_P = 0.2$ nominal.

3.3 Receiver, $E(\text{phase_type}, \text{station}, f)$, and Noise, $N(\text{station}, f)$

Next we apply corrections for logarithmic station effects, $E(\text{phase_type}, \text{station}, f)$. If the station is an array, then a frequency dependent array gain is applied for each phase type. In the case of the USNSN, we do not have any such corrections, but they are applied to teleseismic signals recorded on arrays such as at the Canadian, YKA array. If a station is found to have systematically smaller or larger amplitudes, then the correction may also be applied. The station corrections may also have standard deviations, $\sigma_E(\text{phase_type}, f)$. Therefore, the predicted amplitude of a given phase is given by $\text{Log}(A(\text{phase_type}, \text{region}, \text{station}, f, M)) = \text{Log}(S(\text{region}, f, M)) + P(\text{phase_type}, \text{region}, f, \Delta) + E(\text{phase_type}, \text{station}, f) + \epsilon$, where ϵ is a random normal deviate with standard deviation,

A statistical model for the signal detection is next applied. The mean logarithmic noise levels as a function of frequency at each station are stored in tables, $N(\text{station}, f)$, along with a standard deviation, $\sigma_N(f)$. The predicted logarithmic signal-to-noise ratio, $\text{SNR}(\text{phase_type}, \text{station}, f, M) = \text{Log}(A) - N$, has standard deviation, . Since secondary regional phases such as S may be masked by coda from preceding arrivals such as Pg, a coda decay function is applied to the preceding P phases. If the predicted coda level is above the ambient noise level then it is used instead of the ambient noise level.

We define the logarithmic signal-to-noise ratio of 0.5 as the 50% probability of detection and assume a cumulative normal for the probability of detection with standard deviation, σ_{SNR} . The total standard deviation is typically on the order of 0.5 to 0.7 depending upon the phase type and the station noise variability. A station reliability factor is applied, $P_R(\text{station})$, which is typically about 0.95 but may be reduced for less reliable stations. Also, we have found that we must discard low probability detections (less than about 0.2 probability) in order to properly model network detections. Finally we write the probability of detection of a given phase at a specific station as a function of frequency and distance, and moment as

$$\text{Pr}(\text{phase_type}, \text{station}, f, M, \Delta) = P_R \Psi((\text{SNR}-0.5)/\sigma_{\text{SNR}}) \text{ if } P_R \Psi((\text{SNR}-0.5)/\sigma_{\text{SNR}}) \geq 0.2$$

and

$$\Pr(\text{phase_type, station, f, M, } \Delta) = 0 \text{ if } P_R \Psi((\text{SNR}-0.5)/\sigma_{\text{SNR}}) < 0.2.$$

where $\Psi(x)$ is the normal cumulative probability function.

It is a straight forward exercise to directly compute the probability of a network of stations detecting a specified phase or combinations of phases using the above formula as a function of event location for a fixed moment or magnitude. The reader is directed to Ciervo, *et al.* (1985) for a discussion of the probability calculus involved. Similarly, it is possible to iterate on the probability calculation to determine at which magnitude (or moment) a specified probability of detection will be exceeded. These two types of calculations (magnitude threshold for fixed probability and probability for fixed magnitude) are the most common since they do not require Monte Carlo methods.

3.4 Bulletin Preparation

Once phases have been detected, the next step is the timing of arrivals, and the location of each event. We assume that all detected phases are associated. Following event location, event characterization analysis such as focal mechanism determination or moment tensor inversion can proceed. The outcomes of these processes are strongly dependent upon the patterns of detections, signal-to-noise, and signal bandwidth. Monte Carlo methods have been developed to simulate these procedures. These Monte Carlo methods are used to simulate the statistics of the nonlinear estimation procedures by direct application of the procedures upon ensembles of synthetic data with detection patterns, random noise and travel time errors that are thought to capture the statistics of the errors in real data.

Location simulation proceeds as follows. For a fixed location and magnitude (moment), up to 1000 events are randomly generated at the same location with detections at each station in the network. Arrival time errors are assigned to each detected phase, and a location algorithm is applied using P, Pn, Pg, S, Sn, Lg, and teleseismic P, S, and PKP. We have the option to assume that three component stations and/or arrays can estimate the arrival directions of P, Pn, Pg, teleseismic P and PKP with a specified standard deviation in direction. The location errors for each simulated event in the ensemble are then tabulated and summary statistics are computed. These summary statistics are tabulated on a grid of latitudes and longitudes and are contoured for display. We have restricted our analysis to shallow crustal depths for the eastern U.S.

4.0 Noise Database

In order to conduct simulations we must have a noise model for each station. This noise model consists of the mean noise power as a function of frequency and a statistical variance for the noise level at each frequency. For stations that we do not have noise models, we use surrogate stations in the same general region or a station located about the same distance to the coast. Our current database contains noise models for about 500 historical and operating stations around the world (see Figure 4.1). Some sample noise spectra for USNSN and real-time cooperative stations are shown in Figures 4.2a through 4.2h.

Stations in Noise Database

Figure 4.1 Map of world-wide noise database.

Figure 4.2a Spectral noise model for station ALQ. Crosses show the smooth mean noise level. Dotted lines show the USGS high noise model, the mean GTSN day time noise level, and the USGS low noise model. ALQ is a quieter than average station.

Figure 4.2b Spectral noise model for station BLA. Crosses show the smooth mean noise level. Dotted lines show the USGS high noise model, the mean GTSN day time noise level, and the USGS low noise model. BLA is a slightly noisier than average station.

Figure 4.2c Spectral noise model for station HRV. Crosses show the smooth mean noise level. Dotted lines show the USGS high noise model, the mean GTSN day time noise level, and the USGS low noise model. HRV is a noisier than average station.

Figure 4.2d Spectral noise model for station LBNH. Crosses show the smooth mean noise level. Dotted lines show the USGS high noise model, the mean GTSN day time noise level, and the USGS low noise model. LBNH is a noisier than average station. Error bars show the variation in noise sampled.

Figure 4.2e. Spectral noise model for station LTX. Crosses show the smooth mean noise level. Dotted lines show the USGS high noise model, the mean GTSN day time noise level, and the USGS low noise model. LTX is a quieter than average station.

Figure 4.2f. Spectral noise model for station MIAR. Crosses show the smooth mean noise level. Dotted lines show the USGS high noise model, the mean GTSN day time noise level, and the USGS low noise model. MIAR is a noisier than average station. Error bars show the variation in noise sampled.

Figure 4.2g Spectral noise model for station MYNC. Crosses show the smooth mean noise level. Dotted lines show the USGS high noise model, the mean GTSN day time noise level, and the USGS low noise model. MYNC is a noisier than average station.

Figure 4.2h Spectral noise model for station OXF. Crosses show the smooth mean noise level. Dotted lines show the USGS high noise model, the mean GTSN day time noise level, and the USGS low noise model. OXF is a noisier than average station.

5.0 Maps of Network Detection Capability

Figure 5.1 shows estimated contours of m_bLg for 90% probability of detection of 4 or more P waves by the currently operating USNSN stations. The 4 P-wave detection threshold is useful, since it usually requires 4 or more P waves to define and locate an event with assurance. However, since the USNSN does not operate entirely alone, in order to get a fair view of the detection threshold of the system we must include cooperating stations that are used in conjunction with the USNSN to detect earthquakes in the eastern US. Figure 5.2 shows estimated contours of m_bLg for 90% probability of detection of 4 or more P waves by the currently operating USNSN plus the real-time cooperative stations. Note that when compared to Figure 5.1, the detection levels are significantly improved in the central US, and along the eastern seaboard with the addition of the cooperating stations. Figure 5.3 illustrates how this detection pattern is expected to change with the addition of planned USNSN stations. We should not consider the decline in detection capability to the north as realistic since the Canadian Geological Survey (CGS) operates the extensive Canadian National Seismic Network (CNSN) (see North and Beverly, 1994; North 1994). Although US - Canadian cooperation is still informal, we can illustrate the potential benefits of this cooperation with detection probabilities for the USNSN plus cooperative US stations and the CNSN (Figure 5.4).

It should be noted that detection thresholds are not sharp cut-offs. There is a finite probability that small events will be detected below the 4 P-wave 90% detection threshold. Figure 5.6, 5.7 illustrates this by showing USNSN plus cooperative stations detection probability contours for $m_bLg = 3.25$. Note that detection is 80% assured in much of the eastern US while it drops off virtually to zero toward the east in the Atlantic Ocean and toward the south in the Gulf of Mexico and Mexico. Because of a scarcity of stations in the upper Mid-west, the detection probability drops below 80% in a region of southern Indiana, Illinois, and western Kentucky. Figure 5.8 demonstrates that the planned network of USNSN plus cooperative stations will fill this gap and the detection of $m_bLg = 3.25$ events will be 80% to 90% assured across much of the central and eastern US. The detection threshold will still be slightly higher than $m_bLg = 3.5$ along the Gulf of Mexico and in southwest Texas. Figure 5.8 shows probability of 4 P detection at $m_bLg = 3.25$ for the combined US and Canadian national real-time networks. Probabilities of detection at $m_bLg = 3.0$ to 3.25 should be significantly higher in the northern US and southern Canada with close coordination of the USNSN and CNSN networks.

Figure 5.1. Estimated contours of m_bLg for 90% probability of detection of 4 P-waves at the USNSN stations only.

Figure 5.2. Estimated contours of m_bLg for 90% probability of detection of 4 P-waves at the USNSN and real-time cooperative.

5.0 Maps of Network Detection Capability

Figure 5.3 Estimated contours of m_bLg for 90% probability of detection of 4 P-waves at planned USNSN and real-time stations.

Figure 5.4 Estimated contours of m_bLg for 90% probability of detection of 4 P-waves at combined USNSN, cooperative stations, and Canadian National Network for 90% detection of 4 P-waves.

Figure 5.5 Probability of detection of 4 P-waves at USNSN stations for $m_b L_g = 3.25$.

Figure 5.6 Probability of detection of 4 P-waves at USNSN and real-time cooperative stations for $m_b L_g = 3.25$.

6.0 Maps of Network Location Capability

Figure 5.7 Probability of detection of 4 P-waves at planned USNSN and real-time cooperative stations for $m_b L_g = 3.25$.

Figure 5.8 Probability of detection of 4 P-waves for USNSN, cooperative stations, and Canadian National Network for 4 P-waves at $m_b L_g = 3.25$.

6.0 Maps of Network Location Capability

Once seismic phases are detected and associated to form an event with a preliminary location, the event must be located as precisely as possible. The precision with which an earthquake is located is often stipulated by a 90% probability error ellipsoid. Ninety percent of all true locations should lie inside such ellipsoids provided all arrival errors are purely random, independent, and without systematic errors. The ellipsoid is typically specified by its semi-major axis, semi-minor axis and the azimuth (strike) of the semi-major axis.

In order to simulate the estimation of error ellipsoids, we use Monte Carlo approaches. At a given location we generate an ensemble of synthetic events with a specified magnitude (or moment). For each synthetic event we generate a set of phase arrivals at each station in the network. The amplitude of the phase and its arrival time are given by deterministic models plus random terms. The synthetic noise level at the station is then predicted from the noise model plus a random term. The probability of detection at the station is then evaluated and a random number is selected from a uniform distribution from zero to unity. If the probability is greater than the random number the phase amplitude and arrival time are added to the synthetic event bulletin, otherwise the phase is discarded. Each event in the synthetic bulletin is then located using a standard location algorithm and the location and the estimated location precision is tabulated in the synthetic bulletin. Statistics are computed from the Monte Carlo synthetic bulletin to determine the 50th and 90th percentile for the 90% error ellipsoids in the synthetic bulletin. This procedure is then repeated for another location (latitude and longitude). Finally, the statistics can be contoured on a map to illustrate the location capability of the network for the fixed event size (magnitude or moment) as a function of location.

6.1 Location Error Assuming Uncorrelated Travel Time Errors

Figure 6.1a illustrates location capability of the USNSN alone at a magnitude of $m_b L_g = 3.5$. Contours of the area (in square km) of the median (50th percentile) ellipsoid are shown for a shallow magnitude $m_b L_g = 3.5$ earthquake. We would expect that 50% of the 90% error ellipsoids for events would be smaller than the contours and 50% larger than the contours at each location on the map. In other words, we expect that 50% of all shallow $m_b L_g = 3.5$ earthquakes would have estimated locations better than the contours shown. Similarly, Figure 6.1b shows the contours of the 90th percentile ellipsoid area. Ninety percent of all $m_b L_g = 3.5$ earthquakes should have estimated location errors better than contours shown. Contours in Figures 6.1a and 6.1b are in units of area (square km) which equals $\pi * A_{\text{minor}} * A_{\text{major}}$ where A_{minor} and A_{major} are lengths of the semi-minor and semi-major axes of the ellipse. Figure 6.1c shows contours of the 50th percentile semi-major axis, A_{major} , for $m_b L_g = 3.5$ detected by the USNSN. While the area of an error ellipsoid may be a good measure of the size of the ellipsoid, in practice, the semi-major axis is often the statistic of interest. While the area of the location ellipsoid provides a good indication as to how well the event is located, it is often the case because of network geometry, the ellipsoid becomes elongated and the location uncertainty is better described by the semi-major axis.

As with the detection thresholds, it is unfair to consider the USNSN location capability without including the real-time cooperative stations. Figure 6.2a shows contours of the simulated median ellipsoid area for $m_b L_g = 3.5$ while Figure 6.2b shows the 90th percentile con-

tours, and Figure 6.2c shows contours of the 90th percentile semi-major axis. Note that location capability is much improved by the use of the cooperative stations. Figures 6.3a-c illustrate the improvements expected by additional planned USNSN stations. Figures 6.4a-c illustrate the significant improvements that are expected near the Canadian border when the USNSN and CNSN are used in concert for locations.

Obviously, earthquake locations are expected to improve for larger events as illustrated by the simulated 50th and 90th percentile ellipsoid areas shown in Figures 6.5a-c and 6.6a-c for $m_b L_g = 4.5$ located by the USNSN and USNSN plus cooperative stations.

6.2 Monte Carlo Versus Formal Location Uncertainties

Network simulations use two methods for estimating network location capability. The first method tabulates estimated location covariance's from a Monte Carlo ensemble of event realizations. The second method tabulates formal location errors from a Monte Carlo ensemble of event realizations. In this section, we compare these two methods.

Earthquake epicenter location is normally treated as a non-linear least squares (NLLSQ) estimation procedure. The location is estimated by a step-wise minimization of a linearized least-squares estimator. At each step the location is perturbed to minimize the objective function composed of a weighted sum of the squares of the travel time residuals. The weighted sum of the square residuals (the objective function) is a non-linear function of the location. In the linearized formulation, the objective function is replaced by a Taylor series expansion at each iteration. The new source location is chosen to minimize the truncated series. The procedure iterates until a minimum in the objective function is found (least squares).

The first derivatives are zero at the minimum of the objective function, and it is assumed that the function is well represented by a quadratic form. Under these assumptions, error estimates for the epicenter location are derived that depend upon the curvature (second derivatives) of the objective function and the data variance's. This formulation reduces to an equation for the location covariance matrix, $S = (A^T A)^{-1} s^2$, where A is a matrix of derivatives of the individual station-phase travel times w.r.t. distance and s^2 is a normalized data variance. We refer to location error estimates derived from this formal linearization procedure as "formal errors". The formal covariance estimates, S , depend only upon the "curvature matrix", $(A^T A)^{-1}$.

Since the objective function is nonlinear, the shape of the function near the minimum may depart from a simple quadratic form. Under these conditions the estimated location covariance matrix may be an underestimate of the true location covariance. This assumption may be tested by comparing the ensemble of Monte Carlo locations with the predicted location errors.

Figure 6.7a,b,c shows a Monte Carlo ensemble of $m_b L_g = 3.5 \pm 0.1$ events generated for three locations in the Midwest. The 90% confidence error ellipse derived from the population of Monte Carlo errors is shown on each plot. Each Monte Carlo realization was generated by adding Gaussian random numbers to the predicted travel times and then locating the event. A full Monte Carlo procedure was used;

Figure 6.1a Contours of 50th percentile location ellipsoid area (square km) for $m_b L_g = 3.5$ detected by the USNSN. Note that location capability of the USNSN quickly degrades around the periphery of the network and is best (about 200-250 square km) in the center of the network.

Figure 6.1b. Contours of 90th percentile location ellipsoid area (square km) for $m_b L_g = 3.5$ detected by the USNSN. Note that location capability of the USNSN quickly degrades around the periphery of the network and is best (about 250-300 square km) in the center of the network.

6.0 Maps of Network Location Capability

Figure 6.1c. Contours of 50th percentile semi-major axis (km) for $m_bLg=3.5$ detected by the USNSN.

Figure 6.2a. Contours of 50th percentile location ellipsoid area (square km) for $m_bLg=3.5$ detected by the USNSN and real-time cooperative stations.

Figure 6.2b. Contours of 90th percentile location ellipsoid area (square km) for $m_bLg=3.5$ detected by the USNSN and real-time cooperative stations.

Figure 6.2c. Contours of 90th percentile semi-major axis (km) for $m_bLg=3.5$ detected by the USNSN and real-time cooperative stations.

6.0 Maps of Network Location Capability

Figure 6.3a. Contours of 50th percentile location ellipsoid area (square km) for $m_b L_g = 3.5$ detected by the planned USNSN and real-time cooperative stations.

Figure 6.3b. Contours of 90th percentile location ellipsoid area (square km) for $m_b L_g = 3.5$ detected by the planned USNSN and real-time cooperative stations.

Figure 6.3c. Contours of 90th percentile semi-major axis (km) for $m_bLg=3.5$ detected by the planned USNSN and real-time cooperative stations.

Figure 6.4a. Contours of 50th percentile location ellipsoid area (square km) for $m_bLg=3.5$ detected by the USNSN, CNSN, and real-time cooperative stations.

6.0 Maps of Network Location Capability

Figure 6.4b. Contours of 90th percentile location ellipsoid area (square km) for $m_b L_g = 3.5$ detected by the USNSN, CNSN, and real-time cooperative stations.

Figure 6.4c. Contours of 90th percentile semi-major axis (km) for $m_b L_g = 3.5$ detected by the USNSN, CNSN, and real-time cooperative stations.

Figure 6.5a. Contours of 50th percentile location ellipsoid area (square km) for $m_b Lg=4.5$ detected by the USNSN and real-time cooperative stations.

Figure 6.5b. Contours of 90th percentile location ellipsoid (square km) for $m_b Lg = 4.5$ detected by the USNSN and real-time cooperative stations.

6.0 Maps of Network Location Capability

Figure 6.5c. Contours of 90th percentile semi-major axis (km) for $m_b Lg = 4.5$ detected by the USNSN and real-time cooperative stations.

Figure 6.6a. Contours of 50th percentile location ellipsoid area (square km) for $m_b Lg = 3.5$ detected by the planned USNSN and real-time cooperative stations.

Figure 6.6b. Contours of 90th percentile location ellipsoid area (square km) for $m_b Lg=3.5$ detected by the planned USNSN and real-time cooperative stations.

Figure 6.6c. Contours of 90th percentile semi-major axis (km) for $m_b Lg = 4.5$ detected by the planned USNSN and real-time cooperative stations.

6.0 Maps of Network Location Capability

Figure 6.7a,b,c. Monte Carlo locations for 35N (bottom), 40N (middle), and 45N (top) at 85W for $m_b L_g = 3.5 \pm 0.1$. The 90% confidence ellipse is drawn for each ensemble of realizations. There are approximately 200 to 300 events on each plot.

- 1) synthetic events with uniformly distributed moment from 10^{10} to 10^{15} Nt-m, and a log-normal distributed stress drop of 100 bars and a 50% standard deviation were generated on a grid of locations,
- 2) spectral amplitudes of P, Pn, Pg, Sn, and Lg phase arrivals were computed at all stations for each event,
- 3) probability of detection of each phase arrival was calculated using a statistical noise model at each station, 95% station reliability, and log-normal phase amplitude variability of 50% standard deviation,
- 4) realizations of phase detection were selected for each event based on the predicted probabilities,
- 5) travel times for each detected phase of each event realization were computed and a Gaussian random variable was added with standard deviations of 1.5, 2.5, 3.5, and 5.5 sec for P, Pg, Sn, and Lg respectively,
- 6) location and location error was estimated for each event using Pn, Pg, Sn, and Lg travel times,
- 7) network m_b Lg was computed for each event from the detected Lg phase amplitudes,
- 8) and finally each detected event was added to the synthetic location bulletin.

Figure 6.7a,b,c shows 90% confidence error ellipses based upon analysis of the Monte Carlo errors defined as "synthetic location" - "true location". This analysis assumes errors are Chi-squared distributed with two degrees of freedom, or equivalently as two independent Gaussian random deviates along the semi-major and semi-minor axes of the error ellipse. Under these assumptions, the $X \times 100\%$ confidence error ellipse should contain $N \times X \pm S$ of the N events in the Monte Carlo ensemble, where the standard deviation $S^2 = N \times (X \times (1-X))$. In contrast to confidence ellipses estimated in this manner we can examine location ellipses estimated from each realization.

Figure 6.8a,b,c shows examples of 90% formal error ellipses from synthetic locations. There are far too many of them to examine them in detail, but we can see that the ellipses tend to be elongated along the same general direction as the scatter in estimated locations. We expect 90% of the 90% confidence ellipses to contain the true location. In fact we find only 80% to 85% of the ellipses contain the true location. This discrepancy is common for selected locations around the network. Formal 90% confidence ellipses are underestimated at selected locations within the USNSN network. Simple tests of significance verify that these are not due to sample variability. The Monte Carlo populations are large enough to distinguish when formal 90% confidence ellipses differ significantly from the Monte Carlo derived 90% confidence ellipses. No places in the network were found where the converse was true. While in most locations, the formal errors appear to be consistent with the Monte Carlo errors, there are no places where the formal errors bounds are larger than the Monte Carlo error bounds.

This tendency for formal error ellipses to underestimate the 90% confidence region is illustrated in Figure 6.9. Contours are shown for the percentage of so-called 90% confidence

6.0 Maps of Network Location Capability

Figure 6.8a,b,c. Monte Carlo locations for 35N (bottom), 40N (middle), and 45N (top) at 85W for $m_b L_g = 3.5 \pm 0.1$. The formal 90% confidence ellipse is drawn for each realization. There are approximately 200 to 300 events on each plot. Between 75% and 85% of the error ellipses contain the true location.

Figure 6.9. Map showing contours of the percentage of true locations contained within the formal errors of a Monte Carlo simulation of synthetic events with $3.0 < m_b Lg < 4.2$. Sampling uncertainty is better than $\pm 1\%$ across most of the map.

Figure 6.10. Comparison of the normalized cumulative errors compared to that predicted by a best fitting Chi-squared distribution. The non-linear Monte Carlo distribution did not generate excessive errors in the tails or a skewed distribution of error. While the formal methods underestimate the bounds, they appear to assume the correct shape of the error distribution.

ellipses that contain the true location for events between $m_b Lg$ 3 and 4. The sample uncertainty is about $\pm 1\%$.

If the distribution of errors was different from the assumed Chi-Squared distribution, then we might have tails of the distribution contaminated by a few "bad" locations and hence under estimates of the 90% confidence bounds. However, when we examine the Monte Carlo produced errors and compare them to the best fitting Chi-squared distribution in Figure 6.10, we find that the cumulative distribution of errors produced by the fully non-linear network simulation are indistinguishable from Chi-squared. Therefore, while the formal procedure assumes the right shape of the error distribution, the formal method underestimates the scaling represented by the "curvature matrix".

This simple result has interesting consequences. Nearly all location programs cite formal confidence ellipses based derived from linearization of the nonlinear estimation problem. It appears the curvature of the objective function is sometimes over estimated. The objective function is often flatter than estimated near the minimum, and therefore formal confidence bounds are often too small.

7.0 CMT Source Characterization Capabilities

We have reviewed methods currently being used or developed by several researchers (Caltech, Berkeley, Harvard, and SLU) for routine regional centroid moment tensor (CMT) inversion. We make estimates of CMT capability based on a minimum criteria of simultaneous P, S, and fundamental surface waves all with signal-to-noise ratios (SNR) greater than 5 on the vertical components at three or more stations in a period band between 40 and 10 seconds. In order to model the low-frequency waveforms both adequate bandwidth and SNR are required somewhat larger than for simple detection and location. A SNR > 5 across the bandwidth should provide adequate waveforms for modeling. While single station CMT inversions are possible, such inversions generally require adequate SNR transverse (SH) signals on horizontal components as well as vertical components and the station must be at a favorable azimuth to constrain the mechanism. Since low-frequency noise levels for most USNSN stations are generally a factor of ten higher on the horizontal components compared to the vertical components for nearly all USNSN stations, the thresholds will be determined by multiple station CMT inversion capabilities.

To this end we have made estimates of a 3-station CMT determination threshold for the operational plus planned USNSN plus real-time cooperating stations. At this time, the method has several simplifications. First, our long-period noise levels at many USNSN stations are still poorly estimated. Second, we have used a simplified excitation and propagation model for the surface waves. Third, the estimated bandwidth is somewhat crude since researchers often adjust their bandpass filters to maximize SNR. Fourth, we have ignored the criteria of azimuthal coverage required to constrain the mechanism. These limitations can be improved upon later, however, we find that the capability projections are reasonable within these limitations.

We have reliable long-period noise levels for stations, ALQ, CCM, CMB, HRV, ISA, PFO, BLA, and TUC. Although we have reliable noise levels at short-periods for most of the USNSN, the long-period noise levels have not been as thoroughly documented. We have used a default noise model based on station HRV for near coastal stations, and a default noise model from station ALQ for continental interior stations. Additionally, we have increased the low-frequency noise estimate by a factor of two for stations located on pads rather than sited on piers in vaults, or installed down boreholes. Low-frequency noise estimates were increased by another factor of two for those stations on pads that are not cemented directly to hard bedrock. These are conservative estimates consistent with our experience of long-period noise at stations with diverse installation characteristics. To compensate for the simple surface wave excitation model, we have increased the statistical variability of the surface waves to 0.6 log-units to account for variability from focal mechanism and depth. Long-period P and S excitation and attenuation are based on computed Green's functions for a layered crustal Earth model from 100 to 1000 km.

Threshold estimates are shown in Figures 7.1 - 7.4 for periods of 10, 20, 30, and 40 seconds respectively. In each case we have contoured the surface wave magnitude, M_s , for which we expect to perform a CMT inversion from waveform data at three stations in the

7.0 CMT Source Characterization Capabilities

Figure 7.1. M_s thresholds for 90% probability of $SNR \geq 5$ for 3 stations with P, S, and LR phases at a period of 10 seconds.

Figure 7.2. M_s thresholds for 90% probability of $SNR \geq 5$ for 3 stations with P, S, and LR phases at a period of 20 seconds.

Figure 7.3. M_s thresholds for 90% probability of $SNR \geq 5$ for 3 stations with P, S, and LR phases at a period of 30 seconds.

Figure 7.4. M_s thresholds for 90% probability of $SNR \geq 5$ for 3 stations with P, S, and LR phases at a period of 40 seconds.

Figure 7.5. M_s thresholds for 90% probability of $SNR \geq 5$ for 3 stations with P, S, and LR phases at periods of 10, 20, 30, and 40 seconds.

network at a particular frequency with an $SNR > 5$. If we assume that we must have adequate SNR at all frequencies to proceed with an inversion then the 40 second period threshold dominates the over-all threshold determination. The 40 second period threshold surface is generally flat with a minimum of about $M_s = 3.7$ in the central US and a value of about $M_s \leq 4.2$ covering most of the EUS. The general pattern is similar at each period. Figure 7.5 combines the maximum threshold at each location for the 10 to 40 second band. In the 10 to 40 second period bandwidth the minimum threshold is around $M_s = 4.5$ with most of the eastern US covered within a capability contour of $M_s = 4.8$. Examination of the plots will show that SNR should be optimized in the 30 to 10 second bandwidth consistent with experience.

8.0 Summary

Estimated 4 P-wave detection threshold maps for the USNSN alone, the USNSN plus real-time cooperative stations, the planned USNSN plus real-time cooperative stations, and the USNSN plus Canadian National Seismic Network are presented. Estimated detection capability of the USNSN network is greatly enhanced by addition of real-time cooperative stations. Thresholds are estimated to lie between 3.2 and 3.8 over the eastern US without the real-time cooperative stations. With the real-time cooperative stations useful detection levels lie between 2.8 and 3.4. Additional planned USNSN stations should improve detection thresholds in the upper mid west by 0.2 m_bLg units. Additional significant improvements are to be had by active use of Canadian National Seismic Network stations to improve detection coverage in the upper mid west and New England.

Estimated location uncertainty maps at $m_bLg = 3.5$ and $m_bLg = 4.5$ for the USNSN alone, the USNSN plus real-time cooperative stations, the planned USNSN plus real-time cooperative stations, and the USNSN plus Canadian National Seismic Network are presented. These location uncertainty estimates dramatically demonstrate the need for close cooperation between networks. Location uncertainty based on USNSN stations is limited to between 10 and 30 km over most of the eastern US and capability rapidly degrades on the periphery of the network. Addition of real-time cooperative stations and Canadian National Seismic Network stations should improve this coverage to 8 to 10 km over most of the eastern US. Obviously, in practice, the USGS uses data from many cooperating local networks and locations are often much better than the contours shown. However, much of the eastern US is not covered by dense local networks and the detection and location of infrequent, isolated events depends upon the sparse combined USNSN plus real-time cooperative station network.

We have reviewed methods currently being used or developed by several researchers (Caltech, Berkeley, Harvard, and SLU) for routine regional centroid moment tensor (CMT) inversion. We present estimates of CMT detection threshold based on a minimum criteria of at three or more stations in a period band between 40 and 10 seconds using simplified Green's functions and generic long-period noise levels at all stations. In the 10 to 40 second period bandwidth the minimum threshold should range between $M_s = 4.5 - 4.8$ within most of the eastern US.

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10. SUPPLEMENTARY NOTES

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11. ABSTRACT (200 words or less)

This final report presents detection thresholds, detection probabilities, and location error ellipse projections for the United States National Seismic Network (USNSN) with and without real-time cooperative stations in the eastern United States. Network simulation methods are used with spectral noise levels to simulate the processes of excitation, propagation, detection, and processing of seismic phases.

The USNSN alone should be capable of detecting 4 or more P waves for shallow crustal earthquakes in nearly all of the eastern and central United States at the magnitude 3.8 level. When real-time cooperative stations are included, the network should be capable of detecting 4 or more P waves from events 0.2 to 0.3 magnitude units lower. The planned expansion of the USNSN and cooperative stations should improve detection levels by an additional 0.2 to 0.3 magnitudes units in many areas. Location uncertainties for the USNSN should be significantly improved by addition of real-time cooperative stations. Median error ellipses for magnitude 4.5 earthquakes in the eastern and central U.S. depend strongly upon location but should be less than 100 square km in the central U.S. and degrade to 200 square km or more off-shore and south and north of the international boundaries. Close cooperation with the Canadian National Network should substantially improve detection and location along the Canadian border.

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