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CTBT Integrated Verification System Evaluation Model Supplement

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CTBT Integrated Verification System Evaluation Model Supplement

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ABSTRACT

Sandia National Laboratories has developed a computer based model called IVSEM (Integrated Verification System Evaluation Model) to estimate the performance of a nuclear detonation monitoring system. The IVSEM project was initiated in June 1994, by Sandia's Monitoring Systems and Technology Center and has been funded by the U.S. Department of Energy's Office of Nonproliferation and National Security (DOE/NN). IVSEM is a simple, "top-level," modeling tool which estimates the performance of a Comprehensive Nuclear Test Ban Treaty (CTBT) monitoring system and can help explore the impact of various sensor system concepts and technology advancements on CTBT monitoring. One of IVSEM's unique features is that it integrates results from the various CTBT sensor technologies (seismic, infrasound, radionuclide, and hydroacoustic) and allows the user to investigate synergy among the technologies. Specifically, IVSEM estimates the detection effectiveness (probability of detection), location accuracy, and identification capability of the integrated system and of each technology subsystem individually. The model attempts to accurately estimate the monitoring system's performance at medium interfaces (air-land, air-water) and for some evasive testing methods such as seismic decoupling. The original IVSEM report, **CTBT Integrated Verification System Evaluation Model**, SAND97-2518, described version 1.2 of IVSEM. This report describes the changes made to IVSEM version 1.2 and the addition of identification capability estimates that have been incorporated into IVSEM version 2.0.

Key Words: synergy, International Monitoring System, Comprehensive Nuclear Test Ban Treaty, CTBT, data fusion, sensor system integration, treaty verification, model

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Acronyms and Definitions

ACDA	Department of State Arms Control and Disarmament Agency
CTBT	Comprehensive Nuclear Test Ban Treaty
DOE	U.S. Department of Energy
FORTRAN	A computer programming language
IDL	Interactive Data Language software
IMS	International Monitoring System (CTBT, 1996)
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratories
NCDC	National Climatic Data Center
NDC	National Data Center
PC	Personal computer
PNNL	Pacific Northwest National Laboratory
SNL	Sandia National Laboratories

Attribution--Associating a nuclear explosion with a specific country or group

Auxiliary stations--Seismic stations in the IMS not used for detection but used to help locate and identify events

Detection effectiveness--Ability of the monitoring system to detect a nuclear explosion, often called probability of detection

Hydroacoustic sensors--Sensors which measure low frequency sound (pressure) waves in the oceans

Identification capability--Monitoring system's ability to distinguish nuclear detonations from other events

Infrasound sensors--Sensors which measure low frequency sound (pressure) waves in the atmosphere

Location accuracy--Area of location uncertainty measured in square kilometers, 90% confidence that true location is within the area

Primary stations--Seismic stations in the IMS used to detect, locate, and identify events

Radionuclide sensors--Sensors which detect gamma rays from the decay of nuclear fission products

Seismic sensors--Sensors which measure earth motion

INTRODUCTION

The Integrated Verification System Evaluation Model (IVSEM) project was initiated in June, 1994 by Tom Sellers, who was then the director of Sandia's Monitoring Systems and Technology Center. The Arms Control Studies Department was asked to investigate the feasibility of developing a simple, "top-level," modeling tool which can help explore the impact of various sensor system concepts on CTBT monitoring and verification to be used by U.S. and international decision makers. The tool's main emphasis was to integrate results from the various sensor technologies and to investigate the synergy among the technologies. Comprehensive modeling, which had already been done for many of the individual technologies, was to be avoided in the interest of making the model fast and easy to use; however, the model was required to have acceptable fidelity to the more comprehensive models and to the true performance of monitoring technologies. The model was developed for application on a personal computer (PC) so that it can be easily transported to other work sites and used by a variety of analysts. It has also been adapted for use on Sun, HP, and Silicon Graphics computer workstations.

Version 1.0, which estimated system detection effectiveness, was completed in November 1995. Version 1.1, which estimated system location accuracy as well as detection effectiveness, was completed in July 1996. Version 1.2 which made significant improvements to Version 1.1 was completed in October 1997. All three versions were provided to DOE labs and selected government contractors for evaluation and comment. Version 2.0 makes several improvements to both computation and the graphical user interface, and it adds an estimate of monitoring system identification capability: 1) updates underground infrasound coupling; 2) adjusts seismic amplitudes for stable and unstable regions and adjusts seismic periods and noise values; 3) increases number of random radionuclide cloud trajectories from one to five and improves radionuclide cloud altitude computation for underground explosions that vent; 4) replaces the location algorithm; 5) allows for an annual average in addition to single month calculations; 6) allows for the user to define a computational region of the globe; 7) allows for the user to define a spatial resolution down to 1° (the previous resolution was 7.5°); 8) increases the IVSEM internal world map resolution from two degrees to one degree; 9) increases wind data resolution from fifteen degrees to five degrees; 10) adds identification capability estimates for each subsystem and for the integrated system; and 11) allows the user to select his own color scheme for graphic output.

The project's objective has changed little since it started:

Objective:

Develop a basic, easy to use, fast running model which estimates the performance of a CTBT monitoring system, runs on a PC, and can aid in evaluating:

Monitoring system concepts and configurations;
Synergy among monitoring technologies; and
Technology improvements.

The model includes the four international monitoring system (CTBT, 1996) technologies:

- Seismic,**
- Infrasound,**
- Radionuclide, and**
- Hydroacoustic.**

It can estimate the performance of each technology subsystem individually and it can estimate the performance of the integrated system with or without (a user option) accounting for synergy among the technologies. When we talk about monitoring system performance, we refer to four elements of performance:

- Detection effectiveness;**
- Location accuracy;**
- Identification effectiveness; and**
- Attribution.**

We define system detection effectiveness to be the measure of "how good" the system is at detecting an event. Due to the probabilistic nature of detection, the calculated value of system detection effectiveness can be characterized as a probability of detection or a weighted probability of detection. The model has been shown to make accurate estimates of system detection effectiveness by validation activities that we have completed to date (Edenburn, 1997) by comparing IVSEM results to other models and to actual system performance where possible. The model estimates monitoring system performance at medium interfaces (air-land, air-water) and for some evasive testing methods such as seismic decoupling.

The model estimates location accuracy in square kilometers. Location accuracy estimates take into account each station's detection probability and the station-to-event bearing angle errors or signal arrival time errors. The estimate uses a probabilistic model implemented through "Monte Carlo" sampling. Location accuracy estimates have been compared to those of more comprehensive models with good agreement.

IVSEM estimates the probability that a nuclear explosion will be identified as an explosion, and it estimates the probability that the nuclear explosion will be identified as a nuclear event. The model graphically shows regions of the globe where the nuclear explosion is identified as an explosion, regions where it is identified as a nuclear event, and regions where it is identified as both or neither.

The Model does not address attribution, which is beyond its scope.

This report builds on our original report (Edenburn, 1997), covers changes to IVSEM's estimation of system detection effectiveness and location accuracy, and describes estimates for identification capability which has been added since the last version.

Throughout this report, we present output products from IVSEM using CTBT-like examples. In every case, our intent is to illustrate IVSEM's capability rather than to estimate the International Monitoring System's performance against a specific nuclear test scenario. For that reason, we do not reference scenario parameter values such as yield, height or depth of burst, or time of year. Many of the network configurations are hypothetical and do not represent actual IMS station locations or performance.

SUMMARY MODEL DESCRIPTION

The model has a FORTRAN core, an IDL graphical user interface, and will run on a PC using Microsoft Windows NT or 95 (or later) or on a Sun, HP, or Silicon Graphics work station. The IDL interface facilitates entering input data, runs the FORTRAN core, and provides output charts in a variety of forms. The model will run a single event application in a few seconds and a world coverage application in a few minutes. Specific run time depends on the selected resolution, the particular application to be run, and on the computer that is used.

Model operation consists of five sequential steps:

Model input--Input consists of model control parameters, event specification, technology parameters, station specification files, a detection effectiveness table, a world map file, and a wind data file.

Individual station detection responses--The model determines the probability of detection (the probability of a positive sensor response) for each individual station within each technology. The probability of a positive response depends on the signal strength reaching the station, the station's noise, the station's threshold setting, and statistical tests specific to the type of sensor technology.

System integration and detection effectiveness--Individual station detection probabilities are combined to find the probability that a specific number of stations within that technology respond. From these probabilities, we determine the probability that a specific combination of stations respond, for example, a specific system response might be that 1 seismic, 2 infrasound, 1 radionuclide, and 0 hydroacoustic stations respond with probability 0.23. The combination of all possible specific system responses with their associated probabilities is what we call the system detection response. Also associated with each specific system response is a detection effectiveness value for that response. If the detection effectiveness value for a response is 1.0, then that response constitutes a detection. If the detection effectiveness value is 0.0, then that response is not sufficient to constitute a detection. Values between 0.0 and 1.0 can be used to indicate levels of detection certainty. Detection effectiveness values are supplied by the user in the form of a detection effectiveness definition table. The detection effectiveness definition table defines how many responding stations from each technology or combination of technologies constitute a detection. System detection probability is calculated by multiplying response probability by response detection effectiveness for each specific response and adding the products over all specific responses. Using a similar process, individual subsystem detection probabilities are also estimated.

System location accuracy estimate--Stations with a detection probability greater than 0.2 are included in a probabilistic analysis using 100 random trials to estimate the system's location accuracy, which is a 90% confidence area, in square kilometers. The probability that a station participates in any specific random location trial is equal to its detection probability. If a station participates in a trial, it is randomly assigned a "measured" signal arrival time or "measured" station-to-event bearing angle, or both,

depending on the type of station and on the station's statistical error distribution. Each station provides a bearing residual or arrival time residual (or both) to the location analysis for the trial. A location estimate is made for each random trial by minimizing the sum of the weighted residuals. The location estimates for the 100 random trials are used in a bivariate Gaussian analysis to find the elliptical area that has a 90% chance of including all location estimates. Location estimates are made for the integrated system and for each individual monitoring technology subsystem.

System identification capability estimate--All four sensor technologies (seismic, infrasound, hydroacoustic, and radionuclide) are capable, under the right conditions, of identifying a nuclear explosion as an explosion. Of these four, only radionuclide stations can identify a nuclear explosion as being nuclear. Seismic and hydroacoustic algorithms estimate the subsystem's ability to discriminate between explosions and earthquakes in the form of a discrimination probability. They do not estimate an ability to discriminate between a nuclear explosion and other types of explosions. For infrasound identification, we assume that identification probability is equivalent to detection probability, since, at present, we believe that signals from nonexplosive events such as lightning, wind, and earthquakes will be easily discriminated. If a radionuclide station detects radionuclides, the source is nuclear but not necessarily a nuclear explosion. If isotope ratios are in the proper range, then a radionuclide station may be able to identify a nuclear explosion as an explosion as well as a nuclear event. Identification probabilities from the four subsystems are integrated to estimate the probability for identification as an explosion and the probability for identification as a nuclear event. IVSEM does not model regional seismic discrimination; thus, identification results will be conservative in that regional seismic discrimination, which will enhance identification capability, is not included.

Model output--System and subsystem detection effectiveness, location accuracy, and identification capability results are written to tables which can be printed or to files which can be read by the graphical user interface and converted to charts showing graphical representations of effectiveness. Examples of global coverage output are shown in Figures 1 and 2. Different levels of detection effectiveness, location accuracy, or identification capability are represented by different colors on the contour plots. Contours are obtained by covering the sphere with simulated explosions on a latitude-longitude grid that has a user-specified resolution. The value of detection probability, location area, or identification probability at each point on the grid is used to determine contour lines and make contour plots like the ones in the next three figures.

Each of these steps is explained in more detail below.

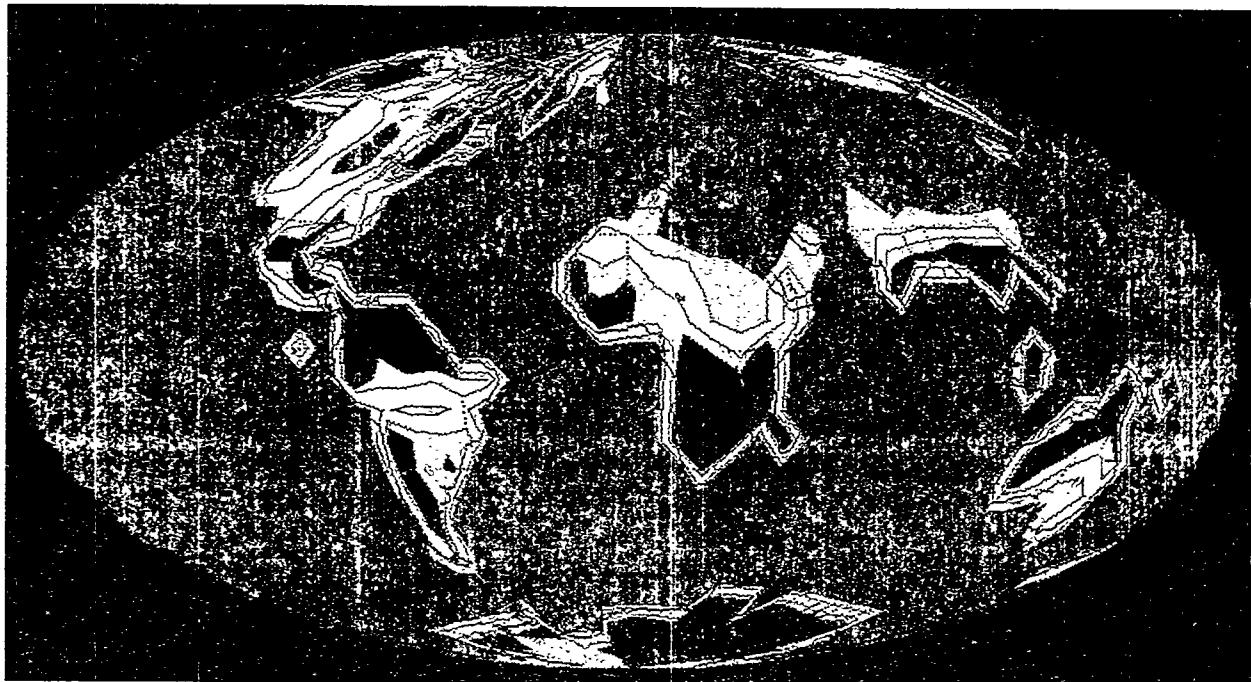


Figure 1. Typical Integrated System Global Detection Effectiveness

○ .9 - 1. ○ .7 - .9 ○ .5 - .7 ○ .3 - .5 ○ .1 - .3 ○ 0..-1 Detection Probability

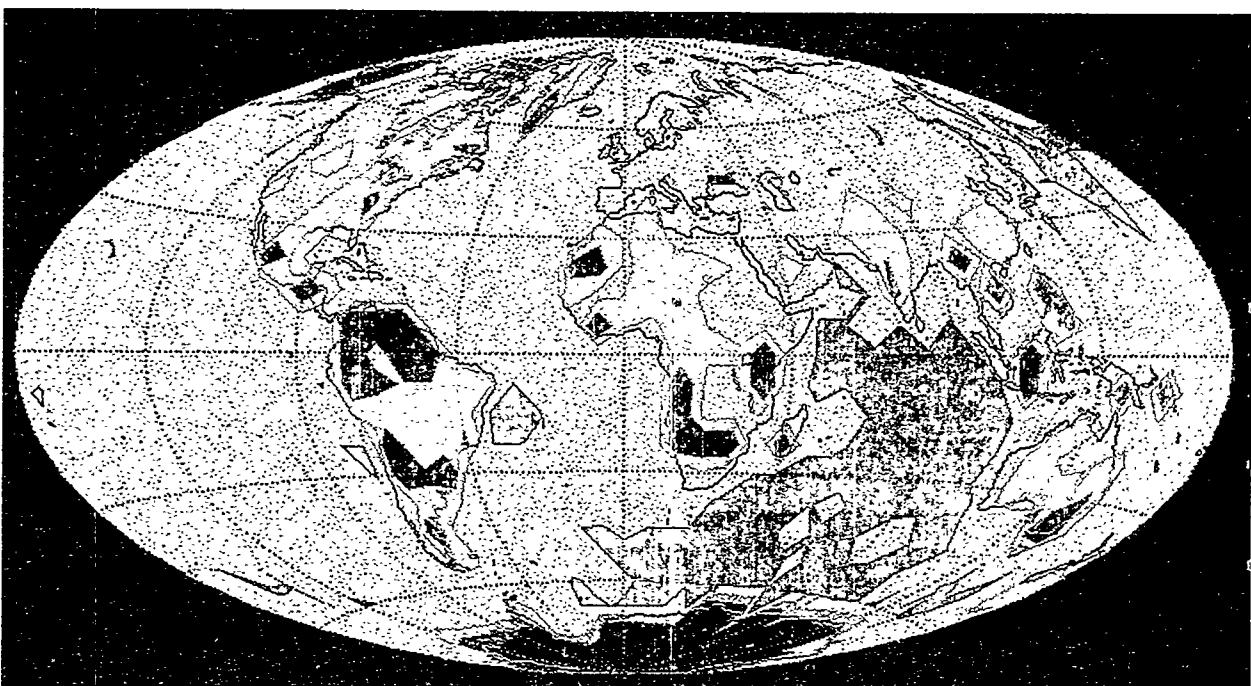


Figure 2. Typical Integrated System Global Location Accuracy

○ 1 - 100 ○ 100 - 1000 ○ 1000 - 10,000 ○ >10,000 km² Location Area

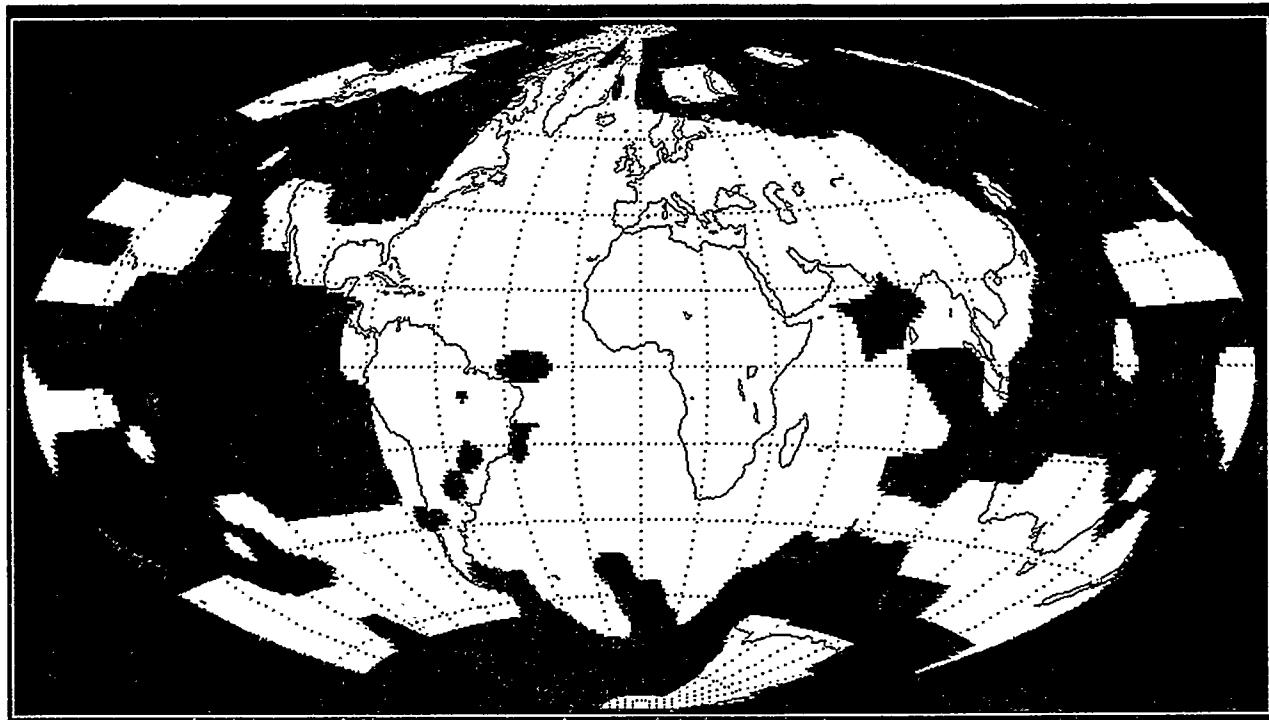


Figure 3. Typical Integrated System Global Identification Capability

- Probability of nuclear ID and explosion ID $> 75\%$
- Probability of nuclear ID and explosion ID $< 75\%$
- ◆ Probability of nuclear ID $< 75\%$, explosion ID $> 75\%$
- Probability of nuclear ID $> 75\%$, explosion ID $< 75\%$

MODEL INPUT

Model input consists of ASCII files which contain data and parameter values used by the model:

- a basic input parameter file,**
- station specification files,**
- a detection effectiveness table,**
- a wind data file, and**
- a world map file.**

One basic input parameter file, one station specification file for each technology, and one detection effectiveness table file are copied from the model's library to the model's input file before the model runs. The resulting combined file can be altered to change any of the default parameter values before it is read into the model. This makes it possible to change parameter values for an application without changing files stored in the library. A basic input parameter file, station specification files, and detection effectiveness table files are stored in the model's library. A current listing of the files is shown in Table 1. The user can create additional library files containing data for special cases he desires to run. The world map file and wind data file cannot be modified by the user. They are read directly into the model.

The basic input parameter file--contains model control (single event vs. global coverage, switches to turn location accuracy and identification capability calculations on or off), event specification (size, time, location, a range of latitude and longitude and resolution for the global coverage option), and specific technology parameter values and descriptive text.

Station specification files--locate each station, specify the station type and number of elements, specify noise or background parameters, and possibly specify station sensitivity.

The detection effectiveness table--allows the user to specify which system responses constitute a system detection.

The model's world map file--LANDSEA1.DAT, divides the Earth's surface into 1.0 degree in latitude by 1.0 degree in longitude sections (IVSEM 1.2 used a 2 degree by 2 degree map). Associated with each section is an integer which describes the surface:

0	seismically stable, unblocked ocean;
1	tectonic, unblocked ocean;
2	seismically stable, blocked (to hydroacoustic signals) ocean;
3	tectonic, blocked ocean;
4	seismically stable land, and
5	tectonic land.

This "map" is used in the following ways: 1) it determines whether an event is in the ocean or on the land for seismic coupling and radionuclide venting calculations; 2) it determines whether the

event and stations are in a seismically stable or tectonic region for seismic propagation calculations; and 3) it is used for signal blocking calculations in the hydroacoustic module.

The wind data file--divides the Earth's surface into 5 degrees in latitude by 5 degrees in longitude sections (IVSEM 1.2 used 15 degree by 15 degree sections). For each section, the wind data file has monthly average wind data at the surface and at 14 altitudes up to about 40 km. Extracted from NCDC (1993), the data consist of average east and north wind vectors and east and north wind vector standard deviations. In the original file, altitudes were given in terms of millibar pressure. We converted altitude from millibars to kilometers using an approximate standard atmosphere algorithm.

Wind data are used in the infrasound module to find average monthly surface wind speeds and, from that, the noise at each station (the infrasound module does not use the wind data file to get 50 km wind velocity; it comes from another source which will be described later); and the radionuclide module uses average monthly wind velocity at the debris cloud's center point altitude to calculate the cloud's speed and path.

The basic input parameter file, station data files, and the detection effectiveness table are described in detail in appendix A.

Table 1. File Library

File Name Description

Basic Input Parameter Files

INP000 1 kt, - 35 m, Kansas, March, full seismic coupling, no rain

Station Files

Seismic: SZM-IMS 168--49 primary + 119 aux--IMS seismic stations, CTBT 9/96

Infrasound: ISN-IMS 59 IMS infrasound stations, CTBT 7/97

Radionuclide: RDN-IMS 79 IMS radionuclide stations, CTBT 9/97

Hydroacoustic: HYD-IMS 11--6 hydrophone, 5 T-phase--IMS hydro stations CTBT 9/97

Detection Effectiveness Tables

EFTAB001 basic effectiveness table #1: 1-RDN, 2-ISN, 3-SZM, HYD, OPT

INDIVIDUAL STATION DETECTION RESPONSES

For each station within each technology subsystem, the model computes the probability that the station will register a response. These computations are done in separate modules for each subsystem. All of the technology subsystem modules follow the same computation sequence.

First, the source signal strength is computed for an event. The type of signal depends on the type of sensor being used.

Second, signal propagation effects and attenuation are estimated and signal strength at the station is computed.

Third, the station's noise characteristics are determined from background noise or wind (depending on the technology) data taken from the station specification file.

Fourth and last, signal and noise characteristics, threshold setting, and sensor sensitivity are combined in a statistical test to determine the station's probability of registering a positive response. The statistical test used depends on the type of technology.

These computations are described in more detail in the following appendices of our original report (Edenburn, 1997) and changes are described in the appendices of this report.

Seismic Detection--Appendix B

Infrasound Detection--Appendix C

Hydroacoustic Detection--Appendix D

Radionuclide Detection--Appendix E

SYSTEM INTEGRATION AND DETECTION EFFECTIVENESS

System Detection Response

The model estimates the probability that, for a specified single event (single event option) or for each individual event on a latitude-longitude grid (global coverage option), each station within each subsystem registers a positive response, and, from these probability values, the model computes a system response. Within each subsystem, we use the individual station response probabilities to compute the probability that exactly N (N is a positive integer) stations register a positive response. We call the probability that exactly N seismic stations respond $P(NS)$. Note that this produces a set of probabilities: $P(0S)$, $P(1S)$, $P(2S)$, $P(3S)$, and etc. The probability that N (this N is not necessarily the same as the N for seismic, hydroacoustic, or radionuclide stations) infrasound stations respond is $P(NI)$; the probability that N radionuclide stations respond is $P(NR)$; and the probability that N hydroacoustic stations respond is $P(NH)$. The system's response is the combination of subsystem responses; for example, 2 seismic plus 1 infrasound plus 1 radionuclide plus 0 hydroacoustic responses is a specific system response. We would designate this specific system detection response as $(2S, 1I, 1R, 0H)$. The general system detection response (NS, NI, NR, NH) represents all possible system responses if we let NS , NI , NR , and NH include all numbers of stations up to the total number in their respective subsystems. The joint probability $P(NS, NI, NR, NH)$ that we get system response (NS, NI, NR, NH) is equal to the product of the individual subsystem response probabilities since the subsystems operate independently. This joint probability is given by the following equation:

$$P(NS, NI, NR, NH) = P(NS) \times P(NI) \times P(NR) \times P(NH) \quad (1)$$

$P(NS, NI, NR, NH)$ is a four dimensional table or matrix which we call the system detection response table. This table is the model's description of a system's detection response to an event.

As an example, suppose the system consists of four seismic sensors and four infrasound sensors but no radionuclide or hydroacoustic sensors. Table 2 is a possible system detection response table where the numbers in the table correspond to the probability that a specific number of seismic and a specific number of infrasound stations responded to an event.

**Table 2. Simplified (Two-Technology) Detection Response Table
(Joint Probabilities)**

Number of Responses		0S	1S	2S	3S	4S
		Seismic	Infrasound			
	0I	.0001	.0015	.0039	.0025	.0000
	1I	.0017	.0215	.0563	.0365	.0000
	2I	.0067	.0821	.2153	.1399	.0000
	3I	.0065	.0799	.2095	.1361	.0000
	4I	.0000	.0000	.0000	.0000	.0000

System Detection Effectiveness

We define system detection effectiveness to be the measure of "how good" the system is at detecting an event. More specifically, it is a weighted probability of detection. The weights come from the detection effectiveness table and, in principle, reflect the "information content" in a detection by a specified number and combination of sensors.

The system detection response is denoted (NS, NI, NR, NH) where NS is the number of seismic stations that respond, NI is the number of infrasound stations that respond, NR is the number of radionuclide stations that respond, and NH is the number of hydroacoustic stations that respond. Associated with each possible system response is the probability of getting that response, $P(NS, NI, NR, NH)$. Also associated with each possible system detection response is a system detection effectiveness $E(NS, NI, NR, NH)$. This value, which we define to be between 0 and 1 inclusively, is a "goodness" of detection or a detection "figure of merit." It is represented by a four dimensional table or matrix and is currently specified in input by the user. It is a qualitative judgement, made by the user, which associates an effectiveness value with each possible system detection response. If the user gives a detection effectiveness value of either 1.00 or 0.00 to each specific system detection response, then he has defined some responses as detections and others as nondetections. In this case, the system detection effectiveness computed by the model will be the probability of detection. If values between 0.00 and 1.00 are used, detection effectiveness is a weighted probability of detection. A simplified, two-technology example detection effectiveness table is shown in Table 3.

**Table 3. Simplified (Two-Technology) Detection Effectiveness Table Example
("Value" or "Information Content in a Specified Combination of Detecting Stations)**

Number of Responses		0S	1S	2S	3S	4S
Infrasound	Seismic	.00	.00	.00	1.00	1.00
	0I	.00	.00	.00	1.00	1.00
	1I	.00	.00	.00	1.00	1.00
	2I	1.00	1.00	1.00	1.00	1.00
	3I	1.00	1.00	1.00	1.00	1.00
	4I	1.00	1.00	1.00	1.00	1.00

The model combines the system detection response table with the system detection effectiveness table to get a system detection effectiveness value. It does this by multiplying the system response probability by the system response effectiveness for each possible system response and adding the results. This is expressed in the following algorithm:

$$\text{System Detection Effectiveness} = \sum [E(NS, NI, NR, NH) \times P(NS, NI, NR, NH)] \quad (2)$$

The summation is done over all values of NS, NI, NR, and NH. The result is an expected value of detection effectiveness.

System detection effectiveness and system detection synergy are discussed more thoroughly in Appendix F of our original report (Edenburn, 1997).

SYSTEM LOCATION ACCURACY ESTIMATE

IVSEM estimates the accuracy with which the overall IMS can locate an event. It also estimates the location accuracy which can be attained by each individual CTBT monitoring technology subsystem. When the operational IMS detects and estimates the location of an event, the estimated location will have an associated error. The size of the error will depend on where the event was located relative to the various types of sensors and which sensors responded. IVSEM estimates location accuracy employing a statistical location error. The statistical model considers two types of stations: bearing stations (infrasound) where each station estimates a station-to-event angular bearing; and signal arrival time stations (infrasound, seismic, and hydroacoustic) where each station records a signal arrival time. Each infrasound station records both bearing angle and signal arrival time. IVSEM does not make a location error estimate for radionuclide sensor detections because associated location accuracies are extremely variable.

Based on geometric considerations, a minimum number of detecting stations is required to obtain a location estimate. The IVSEM location estimate does not include altitude or depth; thus, the estimate is for a surface location. Bearing information from at least two stations or arrival time information from at least three stations is required to make a location estimate.

IVSEM estimates location accuracy using the following process. This process is described in more detail later in Appendix G. Location estimates are made for the integrated system and for each individual subsystem.

In the detection part of its analysis, IVSEM estimates the probability that each station will respond to a specified event. In the real world, stations either detect the event and participate in location or they do not detect and do not participate in location. With statistical modeling however, stations are allowed to have detection probability values between 0 and 1 and may or may not participate in location. This is because a station may detect the signal from an event at one time and fail to detect the signal from an event with the same yield and location at another time due to fluctuations in noise and signal strength or changes in the station's availability. If an event could be repeated a large number of times, a different set of stations might respond each time. We account for this uncertain situation by randomly selecting stations to participate in location in proportion to their detection probabilities. If a station has a detection probability of 0.25, it will participate in roughly one fourth of the location analyses performed. Following the detection analysis, and to account for random station selection, IVSEM uses the following six-step process to implement the statistical location error model.

1. **All stations with detection probability below 0.2 are eliminated.** The practice of the seismic community is to eliminate all stations with detection probability below 0.2. This practice has been extended to all technologies in IVSEM. Auxiliary seismic stations are allowed to participate in the location process if at least three primary stations detect the event. Limits to the number of stations that may participate, imposed in IVSEM version 1.2 to reduce computation time, have been removed in version 2.0.

2. **Station parameters are calculated.** Based on event and station latitudes and longitudes, an azimuth angle, α , from the event to each station is calculated with east being angle 0.0. The east, X_+ , and north, Y_+ , distances from the event to each station are calculated ($X_i = D_i \cos(\alpha_i)$; $Y_i = D_i \sin(\alpha_i)$; where D_i is event to station distance). Although the location error model uses Cartesian instead of spherical coordinates, the angular orientation and distance from the event to each station are correct.

A mean arrival time or mean station-to-event bearing angle (or both) is calculated for each station. Mean arrival time is simply distance divided by speed for infrasound and hydroacoustic stations. Infrasound signal speed is assumed to be 0.3 km/s, and hydroacoustic signal speed is assumed to be 1.5 km/sec. Seismic signal arrival time is found using a table which gives signal travel time as a function of angle in one degree increments with linear interpolation between. Mean bearing angles for infrasound stations are assumed to be the true bearing angle.

Bearing angle and arrival time standard deviations are calculated using algorithms built into the model:

$$\text{Seismic: } \sigma = \{0.75^2 + [1.15/(\text{snr}-1)]^2\}^{1/2} \text{ sec}$$

$$\text{Hydroacoustic: } \sigma = \{1^2 + .02^2 D_i\}^{1/2} \text{ sec}$$

$$\text{Hydroacoustic "T-Phase": } \sigma = \{5^2 + .02^2 D_i\}^{1/2} \text{ sec}$$

Infrasound arrival time: $\sigma = 2\%$ of signal travel time

Infrasound bearing: $\sigma = 1.8^\circ$ from 0 to 3000 km;
 increasing to 7° at 4000 km;
 7° from 4000 to 10,000 km;
 increasing to 27.5° at 15,000 km;
 27.5° beyond 15,000 km.

The seismic standard deviation was suggested by John Claassen (SNL, April 1996) for a well calibrated network. It consists of a 0.75 second "arrival time" error and a "model" error which depends on signal-to-noise ratio. Hydroacoustic standard deviations were suggested by Dave Harris (LLNL, May 1996) as very preliminary rough estimates. They include "pick" errors of 1 second for hydroacoustic stations and 5 seconds for island "T-phase" stations and travel time errors for both station types of $0.02(D_i)^{1/2}$. A "pick" error is the error associated with selecting the signal's arrival time from a signal profile. The infrasound arrival time standard deviation was suggested by Rod Whitaker (LANL, April 1996) as having some sketchy, historical basis from the Nevada Test Site. The infrasound bearing standard deviation was suggested by Dean Clauter (NDC, April 1996).

Weights for each station are calculated. For all stations the weight is $1/\sigma_i^2$.

3. **Stations are randomly selected to participate in a location trial.** For each station selected in step #1, a random number is chosen from a uniform distribution with range 0 to 1. If the station's detection probability exceeds the random number, it is included in the location trial.
4. **The area of a 90% location confidence ellipse is computed for the station set.** This is done by finding the event time and location (x,y) which minimize the sum of the weighted, squared residuals as explained in Appendix G. This procedure is different than that used in version 1.2.
5. **Steps 3 and 4 are repeated 100 times to get 100 area values.** 100 trials may not cover all possible station combinations, but they will get the likely ones.
6. **The 90% confidence area's expected value is computed as IVSEM's location error estimate.** The 100 area values are averaged to get the expected value for the area of a 90% confidence ellipse. Since station sets are randomly selected, the number of times a specific set comes up will be in proportion to its probability of occurrence, and the area average is equivalent to the area's expected value. Using the 90% confidence area means that the location estimate will fall within the 90% confidence ellipse 90% of the time.

The location accuracy model is described in more detail in Appendix G

IVSEM location accuracy results have been compared to results from more comprehensive models. The results agree very well. Location accuracy validation is covered in Appendix H of our original report (Edenburn, 1997). While we changed the location model used in IVSEM, location accuracy results have changed very little. The few changes we have found are for cases where a very few, low probability station combinations give large location accuracy errors.

SYSTEM IDENTIFICATION CAPABILITY ESTIMATE

IVSEM version 1.2 estimated detection effectiveness and location accuracy but not identification capability. Identification capability is available in IVSEM version 2.0 allowing it to estimate a monitoring system's ability to identify a nuclear explosion as a nuclear explosion. This section gives a brief overview of IVSEM's identification algorithms. A more detailed discussion of each subsystem's algorithms is found in the appendix for that subsystem.

Infrasound Identification--The infrasound network may be able to identify an event as an explosion but will not identify it as a nuclear explosion. Infrasound explosion identification probability is equated to detection probability since sources other than explosions will probably be easily distinguished.

Hydroacoustic Identification--If the scaled burst depth is greater than 180 m, there will be a bubble pulse, and we assume that the event can be identified as an explosion. If the scaled burst depth is less than 180 m and the 35 to 100 Hz signal exceeds a threshold, we assume that the event can be distinguished from an earthquake and identified as an explosion. If the event is above the water, we assume that it cannot be identified.

Seismic Identification--Seismic identification algorithms model teleseismic discrimination only. They do not model regional discrimination; thus, identification results will be conservative in that regional discrimination, which will enhance identification capability, is not included. For teleseismic identification we estimate the probability that the network would identify the explosion as an explosion using an M_s/m_b test.

Radionuclide Identification--We equate the probability of identifying the event as nuclear to the detection probability. In addition we estimate the probability that the nuclear explosion can be identified as an explosion using the ratio of Xe^{133m} activity to Xe^{133g} activity. Nuclear explosions have a higher ratio than reactor, medical isotope, or fuel processing sources.

Identification Integration--IVSEM estimates the probability that a nuclear explosion is identified as an explosion, and it estimates the probability that the nuclear explosion is identified as a nuclear event. We graphically show regions of the globe where the nuclear explosion is identified as an explosion, regions where it is identified as a nuclear event, and regions where it is identified as both or neither.

Seismic identification capability is calculated as a network identification capability and infrasound identification capability is set equal to the subsystem's detection effectiveness. In contrast, radionuclide and hydroacoustic identification capabilities are estimated for individual stations. To get subsystem identification capability estimates for these two technologies, we combine individual station capabilities as follows:

$$\mathbf{PID}_{\text{subsystem}} = 1 - \Pi (1 - \mathbf{PID}_{\text{station}}) \quad (3)$$

PID is identification probability, and Π represents taking the product over all stations.

We combine subsystem identification probabilities to get the monitoring system's identification probability as follows:

$$\mathbf{PIDX}_{\text{system}} = 1 - (1 - \mathbf{PIDX}_{\text{seismic}})(1 - \mathbf{PIDX}_{\text{infrasound}})(1 - \mathbf{PIDX}_{\text{hydroacoustic}})(1 - \mathbf{PIDX}_{\text{radionuclide}}) \quad (4)$$

$$\mathbf{PIDN}_{\text{system}} = \mathbf{PIDN}_{\text{radionuclide}} \quad (5)$$

\mathbf{PIDX} represents the probability that the nuclear explosion is identified as an explosion, and \mathbf{PIDN} represents the probability that it is identified as nuclear.

MODEL OUTPUT

The model estimates system detection effectiveness (probability of detection or weighted probability of detection), location accuracy in square kilometers, and identification capability for a specified event. The model operates in one of two modes. The first mode is estimating subsystem and system effectiveness for a single event. In this mode, details of system performance are saved in an output file. The second mode is global coverage for which the model estimates system effectiveness values for events over a user specified number of points located on a latitude-longitude grid. Subsystem and system effectiveness values for each event point are saved in an output file that is used for making contour plots. Detailed system performance information for each event point is not saved in the world coverage mode. Output files have been designed to interface with the graphical user interface to produce various types of charts.

Single Event Mode

When the model operates in the single event mode, output table SPLOTEFF is generated. SPLOTEFF is organized into four sections. The first section reflects model input including station data and the detection effectiveness table. The second summarizes output data to be used by the graphical user interface. It starts with location areas in km^2 for the 100 randomly selected station sets for each of the subsystems and the integrated system and is followed by a detection probability table and a summary of detection effectiveness, location accuracy, and identification capability. The third section is a table that gives each station's location in longitude and latitude and its probability of detection. The table's body consists of four columns: longitude in degrees, latitude in degrees, a station type tag such as SZM for seismic, and the station's probability of detection. The table is used to draw station location response maps by the graphical user interface. The fourth section gives more detailed results:

- a summary of input parameters,
- selected performance parameters for each station in each subsystem,
- a list of stations which participate in location and their location parameters,
- location accuracy details for each subsystem and for the integrated system,
- summary of location results,
- summary of identification results,
- summary of detection results, and
- an overall summary of detection, location, and identification results.

This section may be helpful in understanding how the model operates.

World Coverage Mode

When the model operates in the world coverage mode, it generates the output CPLOTEFF. This table also has four parts. The first part reflects model input including station files and the detection effectiveness table. The second part is a table that gives subsystem and system detection effectiveness, location accuracy, and identification capability for each event location on the user selected longitude-latitude grid. The table's body consists of 17 columns. The first

two are event latitude and longitude. The second five columns are detection effectiveness for the seismic, infrasound, radionuclide, and hydroacoustic subsystems in that order. The next five columns give the logarithm (base 10) of location area (in km^2) in the same order. The last five columns show identification capability also in the same order. Identification capability is given as a four digit integer. The first two digits are the probability, in percent, for identification as a nuclear event. The last two digits are the probability, in percent, for identification as an explosion. This table is used to provide data for making subsystem and system effectiveness contour plots by the graphical user interface. The third part is a table that gives each station's location in longitude and latitude. The table's body consists of three columns: longitude in degrees, latitude in degrees, and a station type tag such as SZM for seismic. The file is used to draw station location maps by the graphical user interface. The fourth part is a brief summary of input data.

This table does not provide detailed computations as did SPLOTEFF because providing detailed computations for each of the coverage cases is not practical. If you would like to see detailed computations, pick a specific event location and run the model in the single event mode (see Appendix A).

SUMMARY

IVSEM has a FORTRAN core and an IDL graphical user interface and can be implemented on a PC using Microsoft Windows NT or 95 (or later) or on a Sun, HP, or Silicon Graphics workstation. The IDL interface facilitates entering input data, runs the FORTRAN core, and provides output charts in a variety of forms. The model will run a single event application in a few seconds and a world coverage application in a few minutes.

Model operation consists of five sequential steps:

Model input--Input consists of model control parameters, event specification, technology parameters, station specification files, a detection effectiveness table, a world map file, and a wind data file.

Individual station detection responses--The model determines the probability of detection (the probability of a positive sensor response) for each individual station within each technology.

System integration and detection effectiveness--Individual station detection probabilities are combined to find the probability that a specific number of stations within that technology respond. From these probabilities, IVSEM determines the joint probability that a specific combination of stations respond. Multiplying response joint probability by response detection effectiveness (detection effectiveness values are supplied by the user in the form of a detection effectiveness definition table) for each specific response and adding the products over all specific responses results in the system's weighted detection probability. Using a similar process, individual subsystem detection probabilities are also estimated.

System location accuracy estimate--Individual station detection responses are used in a probabilistic analysis to estimate the system's location error in square kilometers. Location errors are also estimated for each individual subsystem.

System identification capability estimate--IVSEM estimates the probability that a nuclear explosion is identified as an explosion, and it estimates the probability that the nuclear explosion is identified as a nuclear event. We graphically show regions of the globe where the nuclear explosion is identified as an explosion, regions where it is identified as a nuclear event, and regions where it is identified as both or neither.

Model output--System and subsystem detection effectiveness and location accuracy results are written to tables which can be printed or to files which can be read by the graphical user interface and converted to charts showing graphical representations of effectiveness.

The model has been briefed to DOE, ACIS, ACDA, and the U.S. CTBT delegation in Geneva. It has been used extensively to support the U.S. CTBT delegation in Geneva.

REFERENCES

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APPENDIX A. MODEL INPUT

Basic Input Parameter File

Figure A1 shows a basic input file for the model. It contains model control, event specification, and specific technology parameter values and descriptive text. Recommended values for some parameters are given in the descriptive text. The first line gives a description of the case which the file represents. This example is one basic input file contained in the model's library. Default basic input files are typically named INPXXX.DAT where XXX is a specific descriptor like 003 or PDQ.

Model Control Parameters

The first model control parameter determines whether the run will be a single event application, a world coverage application for a single month, or a world coverage application averaged over a year. If a value of 1 is entered, a single nuclear event will be "detonated" at a specific, user defined location and the system response to that event will be estimated. If a value of 2 is entered, a nuclear event will be "detonated" on a user specified latitude-longitude grid for a specific month. If a value of 3 is entered, a nuclear event will be "detonated" on a user specified latitude-longitude grid for each month and results will be averaged over the year. (This annual average option requires significant computation time.) The system's estimated detection effectiveness, location accuracy, and identification capability for each event will be written to an output file.

The second parameter is a location accuracy option switch. If the switch is set to 0, IVSEM will skip the location accuracy computation. If it is set to 1, IVSEM will do the location accuracy computation with full synergy; that is, system location accuracy will integrate stations from all technology subsystems. If it is set to 2, IVSEM will do the location accuracy without synergy; that is, system location accuracy will equal the location accuracy of the best individual subsystem.

The third parameter is an identification option switch. If the switch is set to 0, IVSEM will skip the identification, and if the switch is set to 1, IVSEM will estimate identification capability.

The fourth parameter is a model progress tracking parameter. The default value is 0, but if set to 1, the model will tell which subroutine is executing, and (for a coverage application) the event location for which computations are being made. This option helps locate errors.

Figure A1. Typical Basic Input Parameter File

```
DEFAULT INPUT DATA; SCENARIO #0, 1 kt, -20 m, KANSAS

MODEL CONTROL
 2 1-single event, 2-single month contour plot, 3-annual ave cont plot
 1 location accuracy param (0 no location, 1 with synergy, 2 no synergy)
 1 identification parameter (0 no identification, 1 identification)
 0 progress tracking parameter (0 for no tracking, 1 for tracking)

EVENT SPECIFICATION
1996 year
 3 month
 1 day
 0 hour
 0 minute
 40. latitude for single event
-100. longitude for single event
 -90. minimum latitude for contour plot (must be >= -90)
  90. maximum latitude for contour plot (must be <= 90)
-180. minimum longitude for contour plot (must be >= -180)
 180. maximum longitude for contour plot (must be <= 180)
 7.5 resolution for lat and lon contour plot (default 7.5 deg)
 0. altitude in km
 1. yield in kt

SEISMIC TECHNOLOGY SPECIFICATION
 1 include index (1 for include, 0 for leave out)
 1. cavity decoupling factor (typically 1 to 70)
 1.0 medium decoupling factor for land (1. for rock, 3.2 for alluvium)
 .16 medium decoupling factor for water (recommend .16)
 3. threshold to noise ratio (recommend 3.)
 10 EQs falsely identified as EXs each year with mb-Ms test (1 to 1000)
 1. location accuracy--toa std deviation multiplier (recommend 1.)

INFRASOUND TECHNOLOGY SPECIFICATION
 1 include index (1 for include, 0 for leave out)
 1.5 threshold (number of noise standard deviations)
 1. location accuracy--bearing std deviation multiplier (recommend 1.)
 1. location accuracy--toa std deviation multiplier (recommend 1.)

RADIONUCLIDE TECHNOLOGY SPECIFICATION
 1 include index (1 for include, 0 for leave out)
 336 maximum allowed detection time from the event in hours (>24)
 1. fission fraction
 1. earth vent fraction (use 0.-1. or >1. for built-in computation)
 2.6 threshold (number of background standard deviations)
 0. rain intensity in mm/hr
 0. rain duration in hrs

HYDROACOUSTIC TECHNOLOGY SPECIFICATION
 1 include index (1 for include, 0 for leave out)
 1. location accuracy--toa std deviation multiplier (recommend 1.)
```

toa means signal time-of-arrival

Event Specification Parameters

These parameters give the event's time, its location, its altitude, and its yield. The only critical time parameter is the month number. The month determines which wind data are used to determine infrasound attenuation, infrasound noise, and radionuclide cloud movement. We have determined that, averaged over the earth, March is the worst month for a synergistic combination of infrasound and radionuclide detection. Wind conditions do not affect seismic or hydroacoustic computations. We use March (month 3) as the default month.

Event location is specified by latitude and longitude, both in degrees. For the single event option, the user specifies event latitude and longitude. For the world coverage options, the user specifies a range for latitude and longitude and a resolution in degrees. For full earth coverage the user must select a latitude range from -90 to 90 and a longitude range from -180 to 180. If a resolution of 7.5 degrees is selected, the latitude and longitude will be covered in 7.5 degree increments. Using resolution values greater than 7.5 degrees for full world coverage will increase computation time.

The event's altitude is specified in kilometers. Positive values imply an atmospheric detonation, and negative values imply a subsurface detonation. The model's map does not contain topographical information; thus, the world's surface is assumed to have a uniform, sea level altitude.

Yield is specified in kilotons.

Specific Technology Parameters

Seismic sensor technology parameters--consist of the "include index," decoupling parameters, a threshold parameter, and a location accuracy parameter.

The first parameter is the "include index." If set to 0, the seismic technology is turned off and excluded from the application. A value of 1 activates the technology.

The second parameter is a cavity decoupling factor. The seismic signal's amplitude can be reduced by this factor if the detonation is in a cavity. A default value of 1 should be used for full coupling. Seismologists believe that the maximum possible decoupling value is around 70 (1.85 in magnitude units) for a cavern which has been designed especially for that purpose.

The third parameter is a medium decoupling factor for a detonation in earth or rock. A value of 1, the default, should be used if the device is detonated in solid rock. A value of 3.2 should be used as an average value for alluvium. This parameter may vary by a factor of 2 for various types of alluvium.

The fourth parameter is the decoupling factor for an underwater detonation. MRC (1994) specified that the magnitude for a detonation in water is 0.8 magnitude units higher than for one in granite. This results in a decoupling factor of 0.16 for a water detonation. This decoupling factor is less than 1 which says that the signal for a water detonation is greater than that for a detonation in solid rock by a factor of 6.3 (0.8 in magnitude units).

The fifth parameter is the threshold-to-noise ratio which the signal-to-noise ratio must exceed to get a station detection. Seismologists currently use a value of 3 which we have adopted as our default value. If the signal-to-noise ratio is equal to this threshold, the response probability is 0.5.

The sixth parameter specifies the number of earthquakes which are allowed to be falsely identified as explosions each year. This parameter sets the threshold value for discriminating between earthquakes and explosions. If the value is set lower, there will be fewer earthquakes mistakenly identified as explosions, but the probability of "missing an explosion--falsely identifying a nuclear explosion as an earthquake--becomes greater.

The seventh parameter is a location accuracy parameter. The signal arrival time error built into the model is multiplied by this parameter. If the input parameter is given a value of 1.0, the built-in error will be used; if it is given a value of 1.7, the built-in error will be multiplied by 1.7. The built-in error is an rms arrival time error and is the square root of the sum of two squared errors. The first error is a constant error of 0.75 seconds. The second error is 0.15 seconds divided by signal-to-noise ratio minus 1. The default value for the location accuracy parameter is 1.0 which does not alter the built-in error.

The model does not use the cavity decoupling factor if the detonation is in air or water; and it determines whether the detonation is in air, land, or water using the altitude parameter and a world map of land and sea locations. For a world coverage application, the medium decoupling factor for land is constant for all land detonations. The model's map does not distinguish between solid rock and alluvium locations.

Infrasound technology parameters--consist of the "include index," a threshold value, and two location accuracy parameters.

The first parameter is the "include index." If set to 0, the infrasound technology is turned off and excluded from the application. A value of 1 activates the technology.

The second parameter is the threshold value which the signal-to-noise ratio must exceed to get a station detection. If the signal-to-noise ratio is equal to the threshold value, the probability of a station response to the event is 0.5. The threshold's default value is 1.5.

The third parameter is a location accuracy parameter for bearing errors. The bearing error built into the model is multiplied by this parameter. The built-in error is an rms bearing error, and it is equal to 1.8 degrees for station-to-event distances between 0 and 3000 km; it increases linearly to 7.0 degrees for distances between 3000 and 10,000 km; it increases

linearly to 20 degrees for distances between 10,000 and 15,000 km; and it is 20 degrees beyond 15,000 km. The default value of the input parameter is 1.0 which does not alter the built-in error.

The fourth parameter is a location accuracy parameter for arrival time errors. The arrival time error built into the model is multiplied by this parameter. The built-in error is an rms arrival time error which is assumed to be 2% of signal travel time. The default value of the input parameter is 1.0 which does not alter the built in error.

Radionuclide technology parameters--consist of the "include index," the maximum allowed detection time, a fission fraction, a vent fraction, a threshold, and two rain parameters.

The first parameter is the "include index." If set to 0, the radionuclide technology is turned off and excluded from the application. A value of 1 activates the technology.

The second parameter is the maximum allowed detection time which is the length of time (in hours) after an event in which the radionuclide subsystem is allowed to get a detection. The default is 240 hours (10 days). For this default value, a detection occurs if radiation from any 24 hour sample within the 10 day period exceeds the specified threshold value. Smaller or larger values can be used, and execution time is directly dependent on maximum allowed detection time.

The third parameter is the fission fraction which specifies the fraction of fissions generated from fission neutrons in contrast to the fraction generated from fusion neutrons. This parameter has a small effect on the source term. We use a default value of 1.0 to indicate a fission weapon.

The fourth parameter is the vent fraction which is the fraction of fission product material assumed to vent immediately from an underground or underwater detonation. If a value greater than 1 (2 is the default) is specified, the model computes a value which depends on scaled depth of burst. If a value between 0 and 1 is specified, the model uses that value as the vent fraction. Radionuclides which are assumed to vent immediately become a part of the elevated debris cloud which may ultimately trigger sensors. Radionuclides which vent slowly are assumed to become part of a diffuse, low concentration, ground cloud which does not trigger sensors because ground winds have low speed and the cloud will probably not reach a sensor before the radionuclides decay.

The fifth parameter is a threshold which the sample activity must exceed to get a station detection. Every station site is given an average and a standard deviation of preexisting background radiation for each radionuclide. The default threshold of 2.6 specifies that the signal (which includes background radiation) must be 2.6 standard deviations above the average background radiation to get a sensor response probability of 0.5. The default value of 2.6 gives roughly 1.7 false alarms per year (for a 24 hour sample period).

The sixth parameter is rain intensity in mm/hr. Our default value is 0. A heavy rain might be 40 mm/hr. Rain removes aerosols from the atmosphere. A long, light rain will remove aerosols more effectively than a short, heavy rain if the total rainfall is the same for both.

The seventh parameter is rainfall duration in hours. Our default value is 0.

Hydroacoustic technology parameters-- consist of the "include index," a threshold, and a location accuracy parameter.

The first parameter is the "include index." If set to 0, the hydroacoustic technology is turned off and excluded from the application. A value of 1 activates the technology.

The second parameter is a location accuracy parameter. The built-in rms signal arrival time error is multiplied by this parameter. The built-in rms arrival time error is the square root of the sum of two squared errors. The first error is a constant pick-time error of 1 sec. for hydroacoustic stations and 5 sec. for island T-phase stations. Pick-time error is the error associated with selecting an arrival time from a signal profile. The second error is a travel time error and is assumed to be 0.02 times the square root of station-to-event distance. The input parameter's default value is 1.0 which does not alter the built in error.

Station Specification Files

All station specification files consist of a header line which describes the file and station data lines which specify station parameters. The first 15 characters of the header line is a short description of the file and is used in the model's output. The remaining characters in the header line give a more complete description of the file. Following the header line there is one station specification line for each station. The model counts the number of station lines to determine the number of stations. At present, the model restricts the maximum number of stations for a single technology to 200 for seismic stations, 100 for infrasound stations, 150 for radionuclide stations, and 50 for hydroacoustic stations; thus, the number of stations listed in a single file must not exceed these numbers.

A typical (but truncated) seismic station data file is shown in Figure A2. All seismic library files are named SZM-XXXX.DAT where XXXX is a unique descriptor of the file.

The first parameter in each station specification line is a station on-off parameter. If set to 1, the station is on in the IVSEM analysis. If set to 0, the station is off.

The second and third parameters in each station specification line are station latitude and longitude in degrees.

The fourth parameter specifies whether the station is primary or auxiliary. A value of 1 means the station is primary. A value of 0 means it is auxiliary. Only primary stations are used for event detection. Both primary and auxiliary stations are used for location accuracy estimation if the verification system detects the event.

The fifth parameter is the number of elements used at the station. If the number of elements exceeds one, the station is called an array.

The sixth parameter is the noise value in nanometers for teleseismic distances. Different stations will have different noise values; however, in the absence of specific station data, we use uniform noise values.

The seventh and eighth parameters are noise values for intermediate distances (1111 to 2500 km for stable regions, 500 to 2000 km for tectonic regions) and regional distances (less than 1111 km for stable regions, less than 500 km for tectonic regions) respectively.

The ninth parameter is the noise value, in nanometers, for surface waves used in the identification analysis.

The last parameter is a station description which is not used by the model.

Figure A2. A Typical, but Truncated, Seismic Station File

SZM-IMS-168	49	primary	+	119	Auxilliary	IMS	Seismic	Stations	CTBT	9/24/96
1	-40.7	-70.6	1	1	.79	.179	.114	29.30	Argentina	Paso Flores
1	-19.9	134.3	1	20	.50	.064	.044	29.30	Australia	Warramunga
1	-23.7	133.9	1	19	.49	.048	.034	29.30	Australia	Alice Spring
1	-31.9	141.6	1	1	.79	.425	.241	29.30	Australia	Stephens Creek
1	-67.6	62.9	1	1	1.25	.323	.267	29.30	Australia	Mawson Antarctica
1	-16.3	-68.1	1	1	.33	.213	.117	19.48	Bolivia	La Paz
1	-15.6	-48.0	1	1	.84	.252	.160	32.97	Brazil	Brazilia
1	50.2	-95.9	1	1	.73	.498	.315	29.30	Canada	Lac du Bonett
1	62.5	-114.6	1	20	1.52	.245	.055	29.30	Canada	Yellowknife
1	54.8	-66.8	1	1	1.19	.102	.049	29.30	Canada	Schefferville
1	5.2	18.4	1	1	.25	.136	.116	244.60	CAR	Bangui
1	49.3	119.7	1	9	.35	.452	.371	15.00	China	Hailar
1	36.1	103.8	1	9	2.01	2.244	1.290	14.54	China	Lanzhou
1	4.9	-74.3	1	1	1.13	.622	.379	29.30	Colombia	El Rosal
1	6.7	-4.9	1	1	.36	.197	.120	29.30	Coast Ivory	Dimbroko
1	26.0	33.0	1	10	.36	.197	.120	29.30	Egypt	Luxor

A typical, but truncated, infrasound station data file is shown in Figure A3. All infrasound station files are named ISN-XXXX.DAT where XXXX is a unique file descriptor.

The first parameter is each station specification line is a station on-off parameter. If set to 1, the station is on in the IVSEM analysis. If set to 0, the station is off.

The second and third parameters in each station data line are station latitude and longitude in degrees.

The fourth parameter is the number of elements used at the station. A greater number of elements will result in a larger signal. We use four elements as a default.

The fifth parameter is a noise reduction factor for the station. Noise reduction may be accomplished by a "spider" or hoses. The default noise reduction is 4.0.

The sixth parameter is the average wind speed at the site in m/s. The average wind speed is used to calculate the station's noise. If the wind speed is set to 99.0, the infrasound module computes average monthly wind speed from surface wind data in the wind data file based on the station's regional location. The average monthly surface wind speed computed from the wind data file may or may not be the best average wind speed to use because careful location may result in an average local wind speed which is significantly lower than the average regional wind speed.

The last parameter is a description of the station and is not used by the model.

Figure A3. A Typical but Truncated Infrasound Station File

ISN-IMS-59	59	IMS	infrasound	stations	CTBT	7/97	
1	-40.7	-70.6	4	4.0	3.8	Argentina	PASO FLORES
1	-55.0	-68.0	4	4.0	6.6	Argentina	USHUAIA
1	-68.4	77.6	4	4.0	11.3	Australia	DAVIS BASE, ANTARCTICA
1	-32.9	117.2	4	4.0	3.3	Australia	NARROGIN
1	-42.1	147.2	4	4.0	3.5	Australia	HOBART
1	-12.3	97.0	4	4.0	7.4	Australia	COCOS IS
1	-19.9	134.3	4	4.0	2.6	Australia	WARRAMUNGA
1	-16.3	-68.1	4	4.0	2.4	Bolivia	LA PAZ
1	-15.6	-48.0	4	4.0	2.3	Brasil	BRASILIA
1	50.3	-95.9	4	4.0	4.7	Canada	LAC DU BONNET
1	16.0	-24.0	4	4.0	7.0	Cape Verde Is	CAPE VERDE
1	5.2	18.4	4	4.0	1.6	CAR	BANGUI
1	-27.0	-109.2	4	4.0	4.4	Chile	EASTER ISLAND
1	-33.8	-80.7	4	4.0	3.5	Chile	JUAN FERNANDEZ
1	40.0	116.0	4	4.0	2.5	China	BEIJING
1	25.0	102.8	4	4.0	2.5	China	KUNMING
1	6.7	-4.9	4	4.0	2.4	Cote d'Ivoire	DIMBROKO
1	76.5	-68.7	4	4.0	2.8	Denmark	DUNDAS, GREENLAND
1	11.3	43.5	4	4.0	3.3	Djibouti	DJIBOUTI
1	.0	-91.7	4	4.0	4.6	Ecuador	GALAPAGOS IS
1	-10.0	-140.0	4	4.0	9.4	France	MARQUESAS
1	-22.1	166.3	4	4.0	4.0	France	PORT LAGUERRE
1	-49.2	69.1	4	4.0	11.8	France	KERGUELEN IS

A typical (but truncated) radionuclide station data file is shown in Figure A4. Radionuclide station data files are named RDN-XXXX.DAT where XXXX is a unique file descriptor.

The first parameter in each station specification line is a station on-off parameter. If set to 1, the station is on in the IVSEM analysis. If set to 0, the station is off. For the radionuclide subsystem this parameter also switches the xenon and barium sensors on or off independently:

- 0 -- both sensors are off (the station is off);
- 1 -- both sensors are on;
- 2 -- the barium sensor is on and the xenon sensor is off; and
- 3 -- the barium sensor is off and the xenon sensor is on.

The second and third parameters in each station data line are station latitude and longitude in degrees.

The fourth, fifth, and sixth parameters are the average and standard deviation of local background radiation levels and the minimum detectable activity, respectively, for each station in Bq/m^3 for Xe-133g. Notice that the background values are higher in the northern hemisphere than in the southern hemisphere, a result of nuclear power generation and fuel processing site locations.

The seventh, eighth, and ninth parameters are the average and standard deviation of local background radiation levels and the minimum detectable activity, respectively, for each station in Bq/m^3 for Ba-140. (To date, we have used Ba-140 background levels of 0.0 for all stations.)

The tenth, eleventh, and twelfth parameters are the average and standard deviation of local background and minimum detectable activity in Bq/m^3 for Xe-133m.

The last parameter describes the station and is not used by the model.

Figure A4. A Typical but Truncated Radionuclide Station File

RDN-IMS-79 79 IMS Radionuclide Stations CTBT 9/97												
1	-34.0	-58.0	2.5E-6	1.2E-6	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Argen
1	-24.0	-65.0	5.0E-6	2.5E-6	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Argen
1	-41.0	-71.3	2.5E-6	1.2E-6	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Argen
1	-37.5	144.6	2.5E-6	1.2E-6	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Austr
1	-67.6	62.5	5.0E-7	2.5E-7	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Austr
1	-19.2	146.8	5.0E-6	2.5E-6	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Austr
1	-54.0	159.0	2.5E-6	1.2E-6	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Austr
1	-12.0	97.0	5.0E-6	2.5E-6	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Austr
1	-12.4	130.7	5.0E-6	2.5E-6	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Austr
1	-31.9	116.0	2.5E-6	1.2E-6	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Austr
1	-22.5	-43.1	5.0E-6	2.5E-6	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Brazil
1	-8.0	-35.0	5.0E-6	2.5E-6	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Brazil
1	4.2	9.9	1.0E-5	5.0E-6	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Camero
1	49.3	-123.2	2.0E-3	1.0E-3	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Canada
1	74.7	-94.9	2.5E-5	1.2E-5	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Canada
1	62.5	-114.5	2.5E-5	1.2E-5	1.0E-3	0.0E+0	0.0E+0	5.7E-4	0.0E+0	0.0E+0	3.0E-5	Canada

A typical hydroacoustic station data file is shown in Figure A5. Hydroacoustic station data files are named HYD-XXXX.DAT where XXXX is a unique file descriptor.

The first parameter in each station specification line is a station on-off parameter. If set to 1, the station is on in the IVSEM analysis. If set to 0, the station is off.

The second and third parameters in each station data line are station latitude and longitude in degrees.

The fourth parameter specifies whether the station is a hydroacoustic station or an island “T-phase” station. A value of 0 denotes a hydroacoustic station, and 1 denotes a “T-phase” station. Island “T-phase” stations are seismic stations which measure seismic P waves induced by hydroacoustic waves at the ocean-island interface. Both types of stations participate in both detection and location.

The fifth parameter is a local noise parameter: a value of 1 implies high noise; 2 implies medium noise; and 3 implies low noise. This parameter should depend on the station's distance from shipping lanes and other sources of low frequency (roughly 1 to 100 Hz) noise.

The final parameter is a station description which is not used by the model.

Figure A5. A Typical Hydroacoustic Station File

```
HYD-IMS-11      6 hydrophone, 5 T-phase IMS Hydroacoustic Stations  CTBT 9/97
1  -34.9  114.6  0  2  Australia  Cape Leeuwin
1  53.3  -132.5  1  1  Canada    Queen Charlotte Is
1  -33.7  -78.8  0  2  Chile     Fernandez
1  -46.5  52.2   0  3  France    Crozet
1  16.3   -61.1  1  1  France    Guadeloupe
1  18.2   -114.6  1  2  Mexico    Clarion Is.
1  39.3   -31.3  1  1  Portugal  Flores Is.
1  -7.3   72.4   0  1  UK        BIOT/Chagos
1  -37.2  -12.5  1  3  UK        Tristan da Cunha
1  -8.0   -14.4  0  1  USA       Ascension
1  19.3   166.6  0  2  USA       Wake
```

Detection Effectiveness Table

A typical detection effectiveness table is shown in Figure A6. Detection effectiveness table files are named EFTABXXX.DAT in the library where XXX is a unique file descriptor. The table has four dimensions, one for each technology. The values in the table represent the user's judgement as to which system responses (i.e., combination of sensors for each technology responding to an event) should constitute a detection. In this table, 1 denotes that the combination of station responses constitutes a system detection and 0 denotes that it does not. The user can fill out the table to meet his needs. See Appendix A in Edenburn 1997 for more detail.

Figure A6. A Typical Detection Effectiveness Table

```

EFT #1: 3 Seismic, 3 Hydroacoustic, 2 Infrasound, or 1 Radionuclide required
*
*          Infrasound(col)/Seismic(row)
*  0 hydroacoustic      0 hydroacoustic      0 hydroacoustic
*  0 radionuclide       1 radionuclide       2 radionuclide
*  0 1 2 3 4           0 1 2 3 4           0 1 2 3 4
*  0 .00 .00 .00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  1 .00 .00 .00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  2 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  3 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  4 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*
*  1 hydroacoustic      1 hydroacoustic      1 hydroacoustic
*  0 radionuclide       1 radionuclide       2 radionuclide
*  0 .00 .00 .00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  1 .00 .00 .00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  2 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  3 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  4 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*
*  2 hydroacoustic      2 hydroacoustic      2 hydroacoustic
*  0 radionuclide       1 radionuclide       2 radionuclide
*  0 .00 .00 .00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  1 .00 .00 .00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  2 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  3 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  4 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*
*  3 hydroacoustic      3 hydroacoustic      3 hydroacoustic
*  0 radionuclide       1 radionuclide       2 radionuclide
*  0 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  1 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  2 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  3 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  4 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*
*  4 hydroacoustic      4 hydroacoustic      4 hydroacoustic
*  0 radionuclide       1 radionuclide       2 radionuclide
*  0 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  1 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  2 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  3 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*  4 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00

```

References

MRC, 1994: Assessment of Techniques for Nuclear Testing that Evade Detection, MRC/WDC-R-340, November 1994.

APPENDIX B. SEISMIC DETECTION AND IDENTIFICATION

Introduction

The purpose of the seismic module in IVSEM 2.0 is to provide a simple, fast-running model that can be used to generate a first-order analysis of seismic network detection, location, and identification performance. The detection and location processes are basically the same as used in Version 1.2 of IVSEM, so only a brief summary description will be given here.

Seismic monitoring of nuclear explosions is based on the fact that underground explosions generate various types of seismic waves. These waves can travel for long distances (thousands of kilometers) from the explosion. These waves can be detected at monitoring stations as very small movements of the Earth, on the order of nanometers. Seismic monitoring is based upon the detection of those waves produced in the Earth by explosive event. Explosions primarily generate waves with relatively short periods of 1 second or less. These waves, called P waves, are compression waves. In the IVSEM model, seismic detection is based upon the P wave envelope amplitude

Detection

The approach used in the model is based upon empirical equations. A seismic magnitude is generated, based upon the device yield, the depth of burial, the medium of burial, and the effects of any evasion attempts. The seismic magnitude is a dimensionless number that is a measure of the energy that has been coupled into the earth to produce seismic waves. The magnitude used in this model is the mB, or body wave magnitude. This is the measure of the energy that goes into the production of P waves. The equation currently used for estimating the magnitude is shown here:

$$mB = 4.0 + .9 \log(Y)$$

mB is the seismic body wave magnitude, and Y is the explosive yield in kilotons. This equation was derived using data from events in seismically unstable regions. If the explosion is in a seismically stable region, 0.3 is added to mB. For explosions in cavities (evasive explosions) and in materials other than hard rock, mB can be modified by user inputs to account for differences in coupling the explosion's energy into the surrounding medium. Modifications to the seismic magnitude, due to the explosion's depth or height of burst, are produced internally in the IVSEM code based upon hydrocode results.

P waves are used for detection in this model because they travel the fastest and are the first arrivals at a monitoring station. This magnitude and the great circle distance from the event epicenter to the receiving station are entered into a series of equations in order to find the signal

amplitude at the receiving station. If the receiving station is in a seismically active region, P wave amplitude is decreased by 0.3 magnitude units. IVSEM models P waves at frequencies of from .8 to 5 Hz. The detection process is based upon the amplitude envelope at the optimum frequency for detection, which varies according to whether the stations are at regional (less than 2000 km from the event), or teleseismic distances (greater than 2000 km).

A statistical process is used to model detection. Figure B1 shows the basic nature of the process.

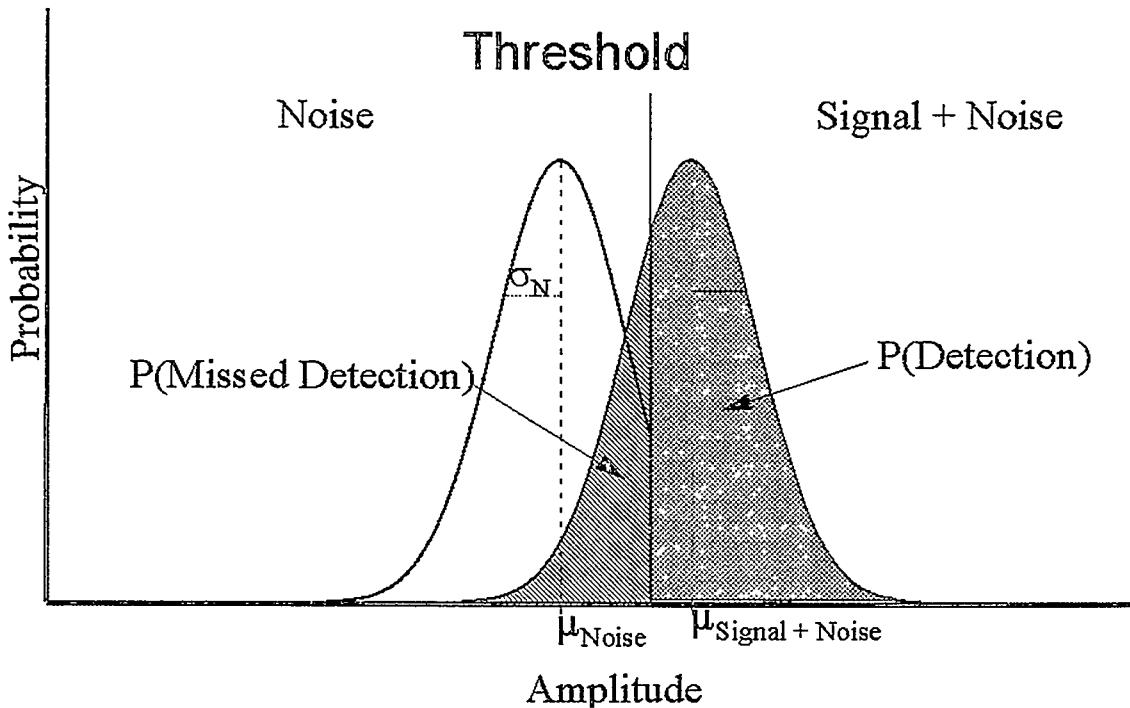


Figure B1. The Detection Process

Based upon the signal received at the station and the local noise, which is contained in the station data file, a signal-to-noise ratio is generated. Array gain, which is assumed to be equal to the square root of the number of station array elements, is used to increase the signal-to-noise ratio. The signal + noise is assumed to be log-normally distributed with the mean equal to the signal amplitude calculated by the propagation equations. The probability of detection is found by integrating the signal-to-noise probability density function from a lower bound, which is the threshold signal-to-noise ratio, to an upper bound representing the maximum possible signal + noise value. The threshold is an input value. The final step in the process is to multiply the probability of detection by a station reliability value.

A detection by a single seismic station is usually considered insufficient to declare an event, due to the high false alarm rate experienced by seismic stations. Usually detections by three or more stations are needed. This is because a location estimate is considered necessary to form an event.

IVSEM takes the individual station detection probabilities and generates the probability of each specific number of stations detecting the event. These probabilities are used with a detection effectiveness table to give the probability of the network declaring a detection as a function of the

number of stations that detect an event. The final output is a network effectiveness figure, which can be considered as the probability that at least N stations detect the event, the value N being in the input tables.

Location

Location accuracy is estimated by minimizing the sum, over all detecting stations, of the weighted, squared signal arrival time residuals as described in Appendix G. Seismic signal travel time curves are used as the signal travel time model, and accuracy is driven by estimated model errors and "pick-time" errors. The result is the expected value for the area of a 90% confidence ellipse.

Identification

Discriminating between explosions and earthquakes is a key part of the seismic monitoring process because of the large number of earthquakes that generate seismic signals. Without reliable methods for discriminating between explosions and earthquakes, a seismic monitoring system would be virtually useless for monitoring nuclear explosions. At the present time, there are no known means for discriminating between a nuclear explosion and an explosion involving large amounts of conventional high explosive. Proof that an explosion source is nuclear will depend upon other phenomena, such as radionuclide release.

Seismic signals can be grouped into two basic types. One group contains signals that propagate for a relatively short distance, up to about 2000 km. These signals travel through and just below the crust and are called regional phases. Regional phases include both compressive and shear waves. The other group consists of phases that travel for long distances, from about 2000 km up to global range. They travel through the mantle and core or over the surface of the earth. This group is called teleseismic waves. The Ms/mB test is commonly used for discrimination when stations detect teleseismic waves, and it is the test modeled in IVSEM. A number of tests involving several regional phases have been proposed, but none of them are very well developed for all parts of the globe, and we elected not to model them in IVSEM.

IVSEM estimates the probability that a seismic network can correctly identify a nuclear explosion as an explosion by discriminating between explosions and earthquakes. Its identification capability is approximate. IVSEM does not generate event phase profiles and perform a variety of tests to determine their type. Instead it estimates the performance of the system as a whole.

Teleseismic Identification

Teleseismic identification has been studied for years, and several tests are available. The Ms/mB test is considered a standard test to be used for teleseismic events. It is relatively simple to convert to an automated process and is considered reliable down to events of magnitude 4. There

is also sufficient data available to support the statistical approach. The Ms/mB test is based upon the fact that explosions and earthquakes generate seismic phases by different mechanisms. Earthquakes generate both compressive body waves and surface waves. Explosions, on the other hand generate almost pure compressive waves. As a result, an earthquake of a particular body wave magnitude, mB, will have a larger surface wave magnitude, Ms, than will an explosion of the same mB. Given statistical Ms and mB data for both earthquakes and explosions, the probability of correctly identifying an explosion as an explosion can be calculated.

IVSEM uses the Ms/mB test as illustrated by Figures B2 and B3 and described below.

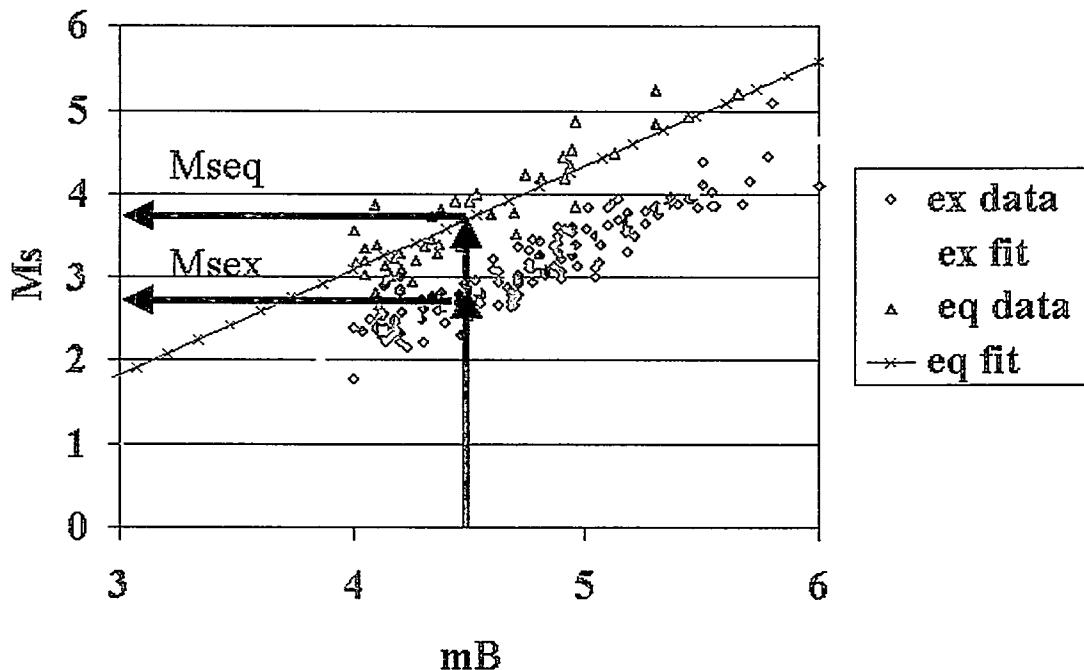


Figure B2. Determination of Ms from event mB.

The event body wave magnitude, mB, is a specific, fixed value calculated in the detection subroutine. For this given mB, the average value and the standard deviation of Ms for an explosion is found using an algorithm generated from seismic data. Numerous sets of Ms and mB data have been published over the years. The data used to generate this algorithm comes from the 1972 Mashall and Basham paper "Discrimination between Earthquakes and Underground Explosions employing an Improved Ms Scale". In addition to the average Ms value and standard deviation, a threshold Ms value is selected from lookup tables that were generated offline from earthquake data. The threshold value is selected to give a user-specified maximum tolerable annual number of false identifications (earthquakes identified as explosions) in a one unit mB band centered on the specified mB value. This number of false identifications depends on the average earthquake Ms and its standard deviation (assuming that the earthquake Ms value has a normal distribution) and on the annual number of earthquakes from NEIC data in the one unit mB band. If an Ms value is below the threshold value, the event is called an

explosion, and if it is above the threshold, the event is called an earthquake. The process is illustrated in Figure B3.

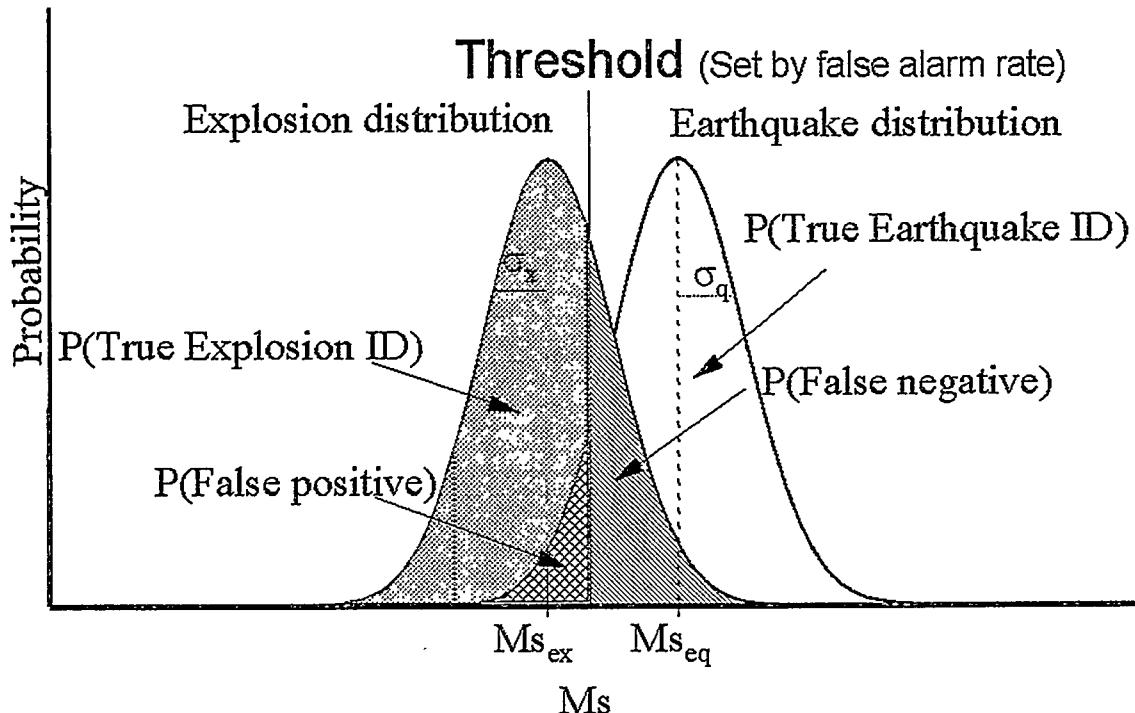


Figure B3. Probability of True Identification

The actual explosion Ms is regarded as being normally distributed about the average Ms calculated from the fit to the data. The probability of a true identification is the integral of the normal probability curve representing the explosion with the mean Ms_{ex} and a standard deviation sigma from a threshold down in the direction of smaller Ms .

In conjunction with the Ms/mB test, another test, referred to as a station configuration test, is performed. The probability is calculated that, for a hypothetical earthquake with magnitude mB , the surface wave (Rayleigh) from that earthquake would have been detected by at least one station in the network which is more than 1500 km from the event. This is done by taking sample earthquake Ms values from the Ms distribution that is based on the mean Ms value and standard deviation for the specified mB . For each earthquake Ms value the surface wave amplitude at each station is estimated and that station's detection probability for the surface wave is found. From this is calculated the probability that at least one station would have detected the surface wave from the hypothetical earthquake. If no stations would have detected an earthquake surface wave, then one could argue that the event could have been an earthquake, not an explosion, but that stations were too far away to detect its surface wave and thus the Ms/mB test is invalid. Because of this argument, the probability that the nuclear explosion passes the Ms/mB test is multiplied by the probability that at least one station would have detected the surface wave from a hypothetical earthquake to get the overall teleseismic identification probability.

Regional Identification

Teleseismic identification procedures work well for events down to about magnitude 4. Below this magnitude, the test can be unreliable primarily because a surface phase is typically not detected for earthquakes. In addition, phases used for some depth tests may not be detectable, and finally, there may be insufficient detecting stations to produce a good location estimate. For these reasons, regional discriminations have to be developed for dealing with small magnitude events. Also, additional discriminants can add confidence to identification even for large events.

The state of regional discrimination is not so far advanced as that of teleseismic discrimination. Numerous discriminants have been proposed for regional identification. These discriminants include Ms/mB ratios, Moment/ mB ratios, ml/mB ratios, $mlcoda/mB$ ratios, various spectral ratios and P/S ratios. After consideration of all the discriminants and consulting with seismic specialists at Los Alamos National Laboratory and Lawrence Livermore National Laboratory, we decided not to include regional seismic discrimination in IVSEM because we do not know how well currently used tests can be extended to untried regions of the globe and because data for regional discrimination is not well developed. Not including regional discrimination will make our identification capability estimates conservative since using regional discrimination will enhance the network's ability to discriminate between explosions and earthquakes.

Overall Identification Probability

The identification test is contingent on having a detection and is a conditional probability. That is, it represents the probability of identifying an event given that the event is detected. Thus, to find the overall probability of identification, the test result must be multiplied by the system detection probability. The Ms/mB test is independent of system detection; however, there may be some statistical dependence between system detection and the station detection requirements used in conjunction with the Ms/mb test. This dependence may introduce some small error into the identification probability estimate.

Sample Results

Some typical results for stable (Iran) and active (Utah) regions are shown in the following table.

Table B1. Seismic Identification Probabilities

Yield (kt)	Unstable Geology		Stable Geology	
	mB	P(Ms/mB)	mB	P(Ms/mB)
5.	4.6	.95	4.9	1.0
2.	4.3	.84	4.6	1.0
1.	4.0	.71	4.3	.99
.5	3.7	.52	4.0	.95
.2	3.4	.26	3.7	.69
.1	3.1	.06	3.4	.45

$P(Ms/mB)$ is the probability that the explosion passes the Ms/mB test

Validation

In order to evaluate IVSEM's identification process validity, IVSEM results were compared with data from the PIDC for the South Asian nuclear tests of May 1998. Regional phase data is available for the Indian test, while only teleseismic data was recorded for the Pakistani test. mB and Ms data for the tests is shown in Figure B4, along with the data and curve fit used for the IVSEM Ms-mB test. (The two symbols for the Pakistan test represent two different estimates of Ms, and average for three stations detecting surface waves and a network maximum likelihood estimate.)

It can be seen that the south Asian tests fit in the vicinity of the other explosion data in Figure B4. This would indicate that the Ms/mB test would indicate a high probability of true identification. IVSEM test runs using yields and coupling conditions that would produce mBs of 5 and 4.9, the PIDC estimates for the Indian and Pakistan tests, respectively, resulted in probabilities of correct identification using the Ms/mB test of 98 and 97 percent. Given that there is universal acceptance among the seismic community that the events were in fact the claimed nuclear tests, this indicates that IVSEM's results are consistent with reality for these events.

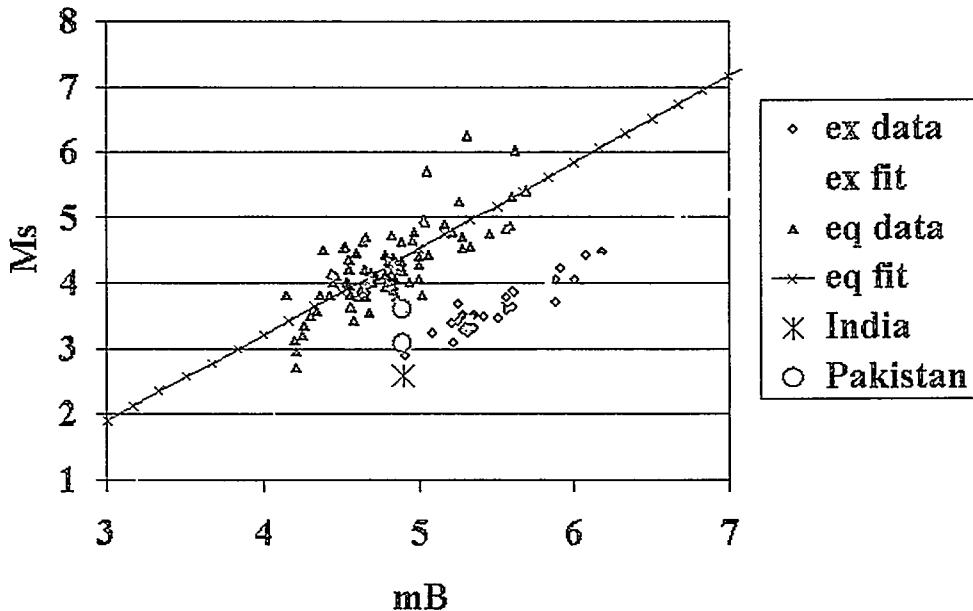


Figure B4. Ms-mB data for the South Asian Tests

IVSEM will perform a good, first-level estimate of seismic detection, location, and identification capabilities sufficient to perform tradeoff studies and preliminary network evaluations. Validation of IVSEM's detection estimates against those of the more detailed NETSIM simulation has been performed, and good agreement has been obtained; however, IVSEM's ability to estimate regional identification capability is very limited. There are numerous identification tests that have been proposed and used by the seismic community. IVSEM is not intended to model the entire process used by human seismologists. Rather it uses generic tests to estimate the capability that might be obtained by an automated identification screening process. IVSEM's identification probability estimates are not absolute predictions. Finally, IVSEM requires a knowledgeable user to avoid misleading results.

References

Marshall, P, and Basham, P, "Discrimination Between Earthquakes and Underground Explosions employing an Improved Ms Scale", Geophysical Journal of the Royal Astronomical Society, vol 28, pp 431-458, 1972.

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Personal communication from Hans Hartse of LANL, spring 1999.

APPENDIX C. INFRASOUND DETECTION AND IDENTIFICATION

Introduction

The purpose of the infrasound module in IVSEM is to provide a simple, fast-running detection, location, and identification model of an infrasound network that can be used to perform first order analysis of network effectiveness.

Infrasound monitoring is based upon the detection of low frequency sound waves from nuclear events. These waves, which have frequencies of 10 Hz and below, are the extremely attenuated remnants of the shock waves produced by events. These waves travel by refraction of the upper atmosphere, and are detected by low frequency microphones or microbarographs. Infrasound signals are a good means of detection for atmospheric nuclear events, because the waves can travel thousands of kilometers through the atmosphere and be detected. Bearing and signal arrival time analysis can be used with a network of stations to produce an estimate of event location as well.

Directly propagated infrasonic waves attenuate too rapidly to be detected beyond a few hundred km. Long distance propagation of infrasonic waves in this model is based upon their refraction from high altitudes. High altitude winds produce a turnaround at altitudes of 50 km. The waves traveling upward are turned around and travel back to the ground. The refracted waves descend and reflect from the earth to return to high altitude and are refracted again. This process can be repeated several times over distances of thousands of km. In addition, the temperature profile of the atmosphere produces a refraction effect that results in a total turnaround of upwardly directed infrasonic waves at an altitude of 90-110 km. The infrasonic waves can be detected by very sensitive microphones or microbarographs. Figure C1 shows different propagation modes that infrasound signals can use. Data from LANL indicates that the 50 km signal is stronger for explosion-produced waves than the 100 km signal, and this signal type is used in IVSEM.

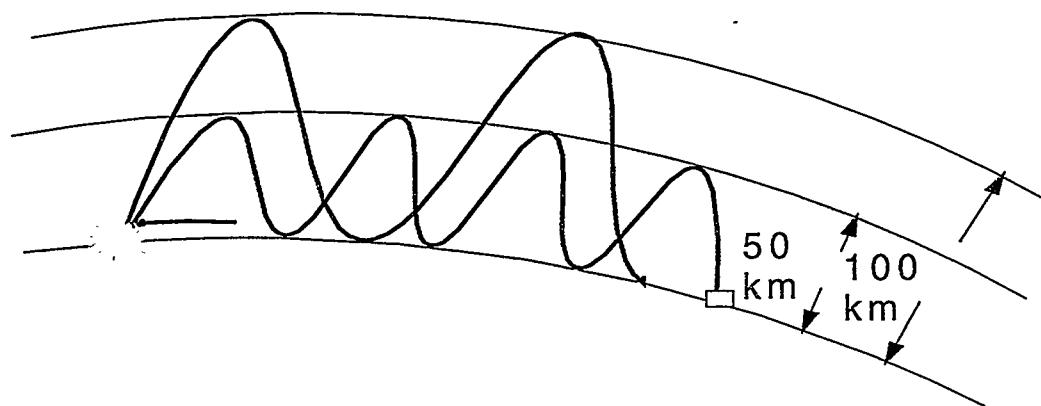


Figure C1. Infrasound Signal Propagation Modes

The basic approach taken in the model is empirical. Data obtained from observations of nuclear and large high explosive events have been scaled to find the signal amplitude as a function of distance from a standard one kt atmospheric burst. The signal pressure is then multiplied by the square root of the effective yield of the event, a standard method of pressure scaling for blast waves.

Detection

The effective yield is the true yield as input, modified by height of burst effects. The shock wave from an atmospheric event will be reflected from the ground. The reflected shock wave can combine with the upward traveling shock wave to form a single stronger shock. This reflection effect can be modeled as an increased effective yield.

Figure C2 shows the data that was used to generate the basic empirical relationship used to calculate the signal strength as a function of effective yield and distance. This is a combination of data taken from numerous reports.

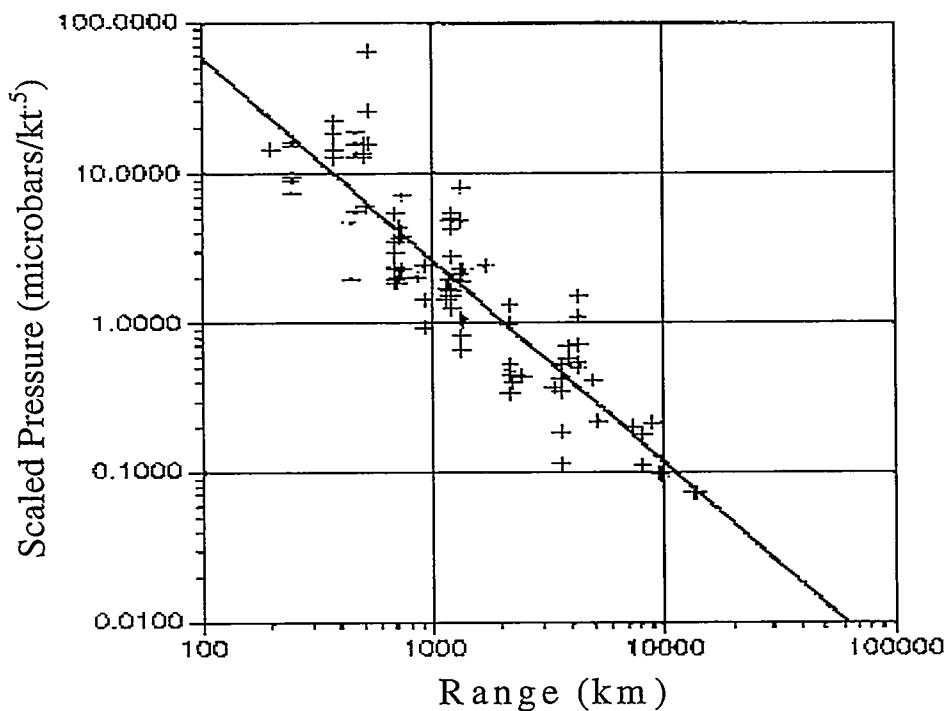


Figure C2. Signal Amplitude Versus Range

An equation was fit to the data in Figure C2. It is shown here:

$$P = (29374)(Y^5)(R^{-1.349}) \quad (C1)$$

P = pressure in microbars

Y = effective event yield in kilotons

R = distance from the source in kilometers

The data was collected from early nuclear atmospheric tests and later high explosive tests. The equation was fit to the data at a model review meeting in October 1995. This equation is believed to represent the return from the 50 km region, which predominates.

A phenomenon that has been observed in connection with infrasound observations of nuclear and large high explosive events is that the signal strength is dependent upon the event-to-station geometry, and this dependence varies with the season. The source of this effect is the strength and direction of the winds in the 50 km refraction zone. The predominant winds in the 50 km altitude band are the east-west winds, called the zonal winds. The north-south winds, called the meridional winds, are of much smaller magnitude, averaging 10% or less the strength of the zonal winds. These winds vary according to season and latitude.

The original data used in the model were obtained from data published by the Committee on Space Research of the International Astronautical Federation (COSPAR, 1972), and W. L. Webb (Webb, 1967). In Version 2.0, this data has been replaced by the outputs of the upper altitude model HWM, which was obtained from the Naval Research Laboratory. This model provides more complete global wind coverage than the earlier COSPAR data.

An average wind velocity is found along the path between the event and the receiving station. The projection of this average velocity vector along the signal propagation path furnishes a value that is input into the following equation:

$$W = 10^{(0.173V)} \quad (C2)$$

V = wind velocity along the path from the event to the station in meters /sec

W = dimensionless signal amplitude correction factor

For the IVSEM model, it is currently assumed that the signal and noise for infrasonic detection are normally distributed. The signal mean value is calculated using equations C1 and C2, and we assume it has a standard deviation of 60% of its mean value.

The noise is a function of the local wind velocity. Wind blowing over a microphone or a microbarograph will apply a pressure to the instrument. Because of turbulence and wind fluctuations, the pressure is constantly changing, but the pressure and its fluctuations can be related to average wind speed. The instrument nulls out the average pressure and only measures fluctuations in pressure; thus, the mean value of the noise is 0. The values for noise standard deviation currently used in IVSEM are calculated from the local wind velocity.

An infrasound station may use a system of windbreaks or porous hoses or pipes to decrease the local noise. This results in a reduction of the noise by a factor that may be four or higher. The exact value is a function of the type of system used. The noise reduction factor is a user-defined input.

A standard signal processing approach is used to model the detection process. Figure C3 shows this process. Gaussian signal and noise statistics are assumed. A gaussian signal plus noise curve is computed, and the area under the curve is integrated to determine the probability of detection. The threshold is set to a multiple of the noise sigma. The exact multiple is a user input.

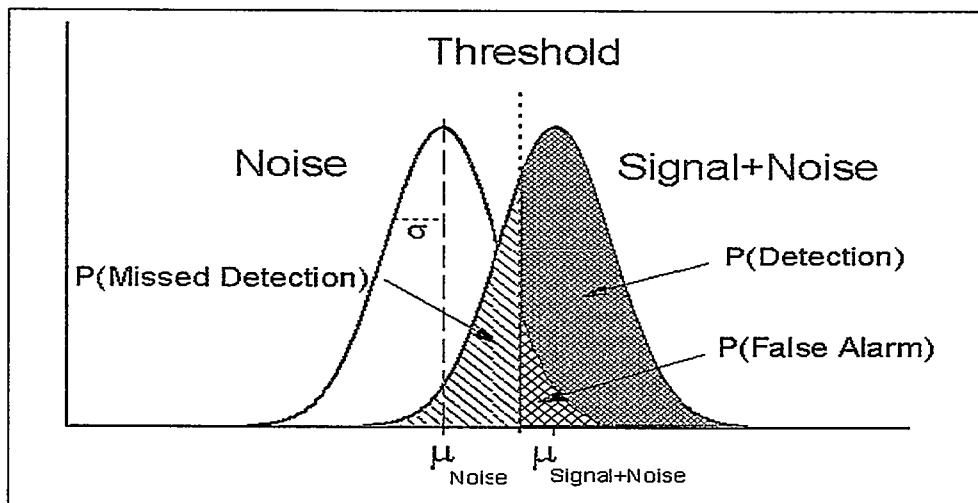


Figure C3. Signal Detection Process

A detection by a single station is usually considered insufficient to declare an event. Usually, detections by several stations are needed to factor out single station anomalies and because a location estimate is considered necessary to form an event. The time-of-arrival analysis used to estimate event location needs at least three stations to form an event. Infrasound stations can produce bearing estimates as well as time-of-arrival estimates. Two or more bearing estimates can be used for triangulation to estimate event location and form an event.

IVSEM takes the individual station detection probabilities and generates the probability of set numbers of stations detecting the event. These probabilities are then modified by the use of detection effectiveness tables, which give the probability of the network declaring a detection as a function of the number of stations which detect an event. The final output is a network effectiveness figure, which can be considered as the probability that at least N stations detect the event.

Location

Location estimation is based upon both time-of-arrival analysis and triangulation from bearing estimates. In IVSEM, each infrasound station is treated as two stations for location accuracy determination purposes. One station participates in time-of-arrival analysis and the other participates in triangulation. A series of Monte Carlo trials is performed where an estimated event location is found which minimizes the sum of arrival time and bearing residuals. This estimate is compared to the true event location. The area in which 90% of the estimated locations fall is the figure of merit for location accuracy analysis.

Identification

The art of identifying infrasound events is very much in its infancy. Some qualitative features are available to indicate some information about the event. For example, the frequency of the main arrival is roughly proportional to the energy release. The duration of the signal also is an indication of the event nature. Some natural signals, for example, earthquake-produced infrasound, are longer in duration than explosive signals. To date, however, statistical analyses have not been performed which would indicate what the identification capability for an operational network. As a result, a rigorous analysis of identification performance is not currently performed in IVSEM.

Due to the dispersive nature of the sound medium, it may never be possible to distinguish a nuclear explosion from other explosive sources on the basis of the infrasound signal alone.

Available data does indicate that natural sources of infrasound with energy releases close to the range of nuclear explosions are relatively rare, in the neighborhood of a few a year. These sources—mostly volcanic eruptions and bolides—generally have distinctive signatures apart from infrasound that would enable relatively quick discrimination.

Until enough data is available to permit a statistical approach, in the IVSEM infrasound module identification probability will be set equal to the network detection probability. This is done on the assumption that large natural sources of infrasound will be identified by their other signatures so that whatever thresholds may be set in terms of signal period and duration will always be exceeded by any nuclear explosion.

APPENDIX D. HYDROACOUSTIC DETECTION AND IDENTIFICATION

Introduction

The hydroacoustic monitoring section of the Integrated Verification System Evaluation Model (IVSEM) was described in our original report (Edenburn 1997). This model simulates acoustic signal generation, the coupling and the transmission losses, the background noise environment, and the detection processes associated with explosions in the ocean or low air burst above the ocean. This effort was undertaken by Sandia National Laboratories' Nuclear Weapons Program Integration and Studies Center.

To predict the capability of proposed hydroacoustic networks to detect underwater explosions or air bursts in proximity to the ocean surface, a model was developed and incorporated into IVSEM. IVSEM detection and location estimates have been compared to those of HydroCAM, a much more comprehensive hydroacoustic model developed through efforts at LLNL, NRL, and BBN. Results compare favorably.

The methods used in IVSEM's hydroacoustic model rely heavily on the use of text books and journal articles for both analytical estimates and test results of hydroacoustic effects. When necessary, the relevant information was extrapolated to approximate the conditions of a nuclear event. Because of the nature of the IVSEM model, two constraints were placed upon the hydroacoustic model. First, the model must be simple and second, the model must be fast running on a PC. Clearly, this model will not supply exact answers in terms of the absolute precision. Rather it is intended to show relative trends as the parameters are varied.

It is well known that the ocean is a very easy medium through which to propagate sound. Explosions on the order of 1 kiloton will propagate to extreme distances assuming there is not some form of blockage present. As is shown in the original report, the model successfully handles the propagation, attenuation, blocking, and detection functions associated with this yield burst, however, the model does not consider the larger question of what to do about naturally occurring and man-made false alarms.

The transmission of acoustic energy to very long ranges in the ocean is made possible by the presence of the Deep Sound Channel (DSC) or as it is sometimes called the SOFAR duct, for SOund Fixing And Ranging. Low-frequency sound is preferentially favored for long distance propagation via the DSC. For example, in 1960 a 150 kg charge of TNT was detonated in the sound channel off Perth, Australia and was clearly recorded on hydrophones located in the DSC off Bermuda, a distance of nearly 20000 km. The DSC is a consequence of the deep ocean sound velocity profile. This profile has a minimum at a depth which varies from about 0.75 km to 1.25 km in the midlatitudes to near the surface in the polar regions. This minimum sound speed depth is called the axis of the deep sound channel. This velocity minimum causes the ocean to act like a lens continually bending the sound rays toward the depth of minimum velocity. Thus, for a

source in the DSC, a portion of the acoustic energy remains within the channel and is assumed to encounter minimal losses aside from geometric spreading and attenuation. This is an idealization which greatly simplifies the calculation of the sound attenuation as it propagates across the oceans. Neglected are the interaction with the bottom, including attenuation due to a variety of bottom materials, surface interactions, and propagation losses through shallow water regions.

Detection

The hydroacoustic problem has been partitioned into several broad functional areas which can be investigated separately in developing a model for evaluating the detection probability of a particular sensor given a sensor-event separation distance, an event yield, and an event burst depth. These areas may be classified as: source, coupling, axis-loss, blocking, long-range transmission, and noise. The relationships which will be developed for each of these different areas will then be combined to provide an estimate of the probability the event will be detected by a given sensor.

The first area, denoted as the source parameter, relates to defining the acoustic strength of a particular explosion. To obtain a source term, one must have a means of associating a point-source acoustic signal intensity with an input explosion yield. This signal intensity will also be a function of the position of the burst with respect to the ocean surface as well as frequency. As is common in underwater acoustic systems analysis, the source term, as well as all of the other parameter values, will be expressed in terms of decibel levels.

The next functional area, denoted as the coupling parameter, represents that fraction of the acoustic intensity which couples into the water. This is to account for bursts occurring near to or above the ocean surface where significant amounts of source energy may not participate in the generation of an acoustic signal. This parameter is a function of the burst yield and its position with respect to the ocean surface.

Axis-loss accounts for the reduction in signal intensity caused by a burst not being located on the DSC axis. Variables which affect this parameter include the distance the burst is off the DSC axis and the local ocean sound velocity profile.

Blocking calculations account for land masses or sea mounts that block hydroacoustic signals if the land mass or sea mount falls on the great circle path between the explosion and the sensor.

A critical parameter when considering sensor-event distances of many thousands of kilometers is the loss of signal intensity due to such transmission loss factors as geometric spreading, attenuation, or signal blockage. The transmission parameter will be a function of the range and of several variables dependent upon the specific sensor-event path.

The final input parameter which is necessary in evaluating the likelihood of detection is that of the ambient ocean noise. It is this noise background that complicates the task of being able to detect the presence of the desired source signal. Because the ambient ocean noise is due to a variety of different sources such as surface perturbations, turbulence, distant shipping and storms, molecular motion, and seismic disturbances, it is observed to have different characteristics at different frequencies.

All of the above parameters define relationships which are combined in the model with the specifics of the burst location and yield to determine the probability of the explosion being detected by a given sensor or set of sensors. This probability that if a burst signal is actually present, the correct decision, "burst present," is made is called the detection probability $P(D)$. The probability that if no detonation has actually taken place, the incorrect decision, namely "burst present" is made is called the false-alarm probability $P(FA)$. Once all of the above parameter values are calculated, an overall signal-to-noise ratio can be derived. This signal-to-noise ratio will be used, in conjunction with the signal duration, signal bandwidth, and assumed knowledge of signal shape, to determine $P(D)$ at some preassigned level of false-alarm probability.

The details of this detection model are given in our original report. The detection portion of the model has not changed since that report was published; however, we have added an estimate of the hydroacoustic network's ability to identify an explosion; that is, its ability to distinguish an explosion from an earthquake.

Identification

Identification in the context of IVSEM hydroacoustic detection is defined as the determination of an event as either an explosion or an earthquake. A simple schema has been devised and incorporated into the IVSEM computer code for the identification of a hydroacoustic event. The background of why this algorithm was selected and the specifics of its implementation into IVSEM follow.

The basic phenomenology (Urick 1983) of one portion of the identification algorithm is based upon the presence of and the detection of a bubble pulse accompanying an underwater explosion. The shock wave from an underwater detonation is normally followed by a series of pressure pulses called bubble pulses. These bubble pulses are caused by successive oscillation of the globular mass of gaseous materials that remains after the detonation is complete. For a nuclear explosion, the heat and pressure of the initial explosion create underwater bubbles primarily consisting of steam. At the instant of minimum volume of the oscillating bubble, a positive pressure pulse is generated with successive pulsations generating additional pulses each successively weaker than the preceding one. The bubble pulse period, the time between the burst and the first minimum, is a function of the depth of burst and the explosive yield. No bubble pulses occur at depths so shallow that the bubble breaks the sea surface. The pressure signature of an explosion consists of the initial shock wave followed by a small number of bubble pulse indications. At long ranges, these signatures are complicated by refractions,

multipath propagations, reflections, and distortions. However, the bubble period tends to persist in the signature even at long ranges. The bubble pulse signal will appear as a delayed and superimposed signal, which can be identified by standard techniques for detecting delayed signals- either autocorrelation or cepstral techniques (Friend 1995).

DNA 1996 categorizes bursts that satisfy the following as being “deep”:

$$240 \text{ W}^{25} < d_b < 600 \text{ W}^{25}$$

where W is the explosion yield in kilotons and d_b is the burst depth in feet.

Someplace in the above range, the depth of burst is equal to or greater than the radius of the fully expanded bubble, permitting at least one bubble pulse. Being conservative, the minimum depth at which a bubble pulse is assumed to always exist was set in IVSEM to be equal to 600 W²⁵ feet. Thus, if a burst is detonated at or below 600 W²⁵ feet, then the probability of identification is set at 1.0 degraded only by the assumed reliability of the sensor network. This correct identification of an event at which a bubble pulse is present is assumed to hold regardless of whether the sensing equipment is located at an in-ocean station or at an island T-phase station.

If the burst occurs in the water but above the depth assumed to guarantee sufficient bubble pulse cycles to propagate a signal, i.e. at depths less than 600 W²⁵ feet, then a classification algorithm based upon signal spectral content is employed. That is, the amount of high frequency content in the received signal is measured to determine whether an explosion or an earthquake occurred. An earthquake is expected to be devoid of high frequency content above some cutoff value. Depending upon the reference, this upper frequency cutoff of earthquakes can be from 25 Hz (Friend 1995) up to perhaps 40-60 Hz (Johnson 1967). A midrange value of 35 Hz (Friend 1995) was chosen as the default upper frequency cutoff for earthquake identification in IVSEM. Thus, the probability that an explosion can be identified without the presence of a bubble pulse is therefore the probability that a station can detect the high-frequency portion of the signal, i.e. that from 35 Hz to 100 Hz. This probability is of course dependent upon the explosion yield, depth-of-burst, and the range from the burst to the station. Within IVSEM, the probability of detection of the portion of the signal in the 35-100 Hz band is also dependent upon the assumed probability of false alarm. While a default value of 10⁻⁶ is nominally used as the probability of false alarm in the standard “detection” calculation, a more optimistic value of 10⁻⁴ is set as the default false alarm probability in calculating the identification probability. In addition, the probability of identification for non-bubble pulse in-water events will include the same sensor reliability degradation as used in the detection calculation.

Hydroacoustic signals convert to a seismic phase when they hit an island. It is this seismic signal, after a very short seismic propagation path, which is then detected by seismometers at an island T-phase station. However, higher frequencies, those greater than 25 Hz (Friend 1995), are attenuated by this hydroacoustic-to-seismic conversion.

Because of this, T-phase stations are assumed to have no capability to identify an explosion based solely on the signal frequency content, i.e. if no bubble pulse is present.

Likewise for an airburst event, the IVSEM Hydroacoustic detection code does not sufficiently characterize the spectrum of the resultant in-water acoustic wave from an airburst to be able to realistically employ a high-frequency cutoff classifier as was done for in-water bursts. Hence, airbursts are assumed not to be identifiable as either explosions or earthquakes by the present IVSEM code.

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APPENDIX E. RADIONUCLIDE DETECTION AND IDENTIFICATION

Introduction

The radionuclide model has changed very little between Version 1.2 and Version 2.0. Some small changes have been made, and they will be described in this appendix. Figure E1 shows the various steps in the process that we model, and each of the steps is summarized below. The model estimates the probability that each radionuclide sensor in a sensor network will detect Xe-133g, Xe-133m, and Ba-140. For details, see our original report on Version 1.2, Edenburn 1997.

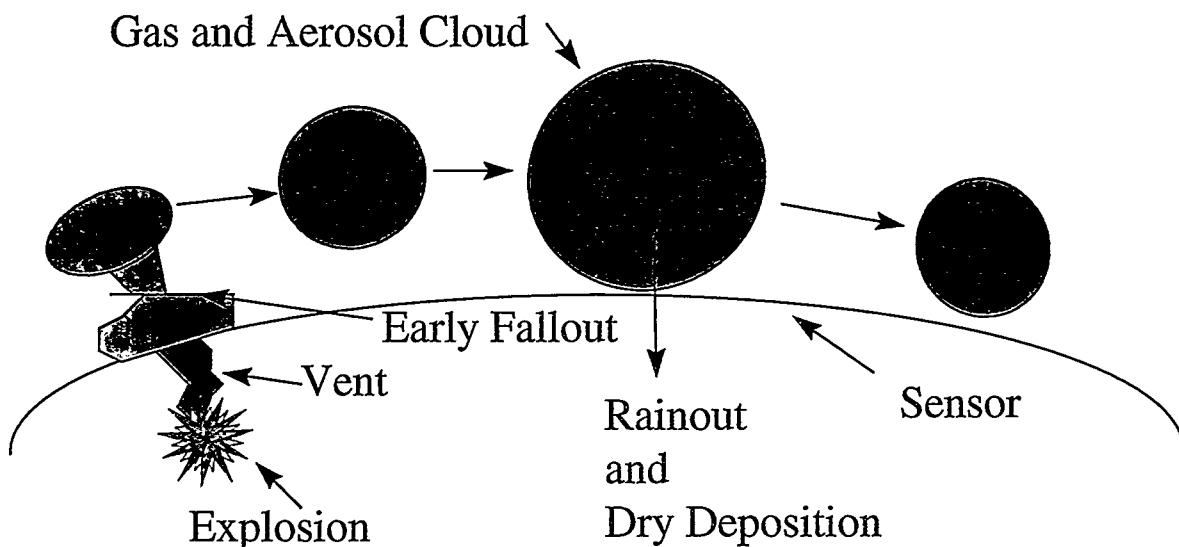


Figure E1. Overall Process

- 1. Initial production of nuclides**--Based on the explosion's yield and fraction of the yield from fission, we calculate the number of atoms of I-133g, Xe-133g, Xe-133m, and Ba-140 which are initially generated by the explosion. The iodine and barium are products of decay chains, but because the parents have very short half-lives, we immediately decay them to I-133g and Ba-140. If the explosion is near the ground, we estimate the fraction of nuclides that will be removed from the cloud by immediate deposition and subtract them from the initial number. If the explosion is below the surface, we estimate the fraction of the initial nuclides that will vent into the atmosphere.

2. Cloud height--We estimate the altitude to which the cloud rises based on the cloud's energy. If the explosion is underground or underwater, the cloud's energy and consequent altitude is reduced. IVSEM1.2 based the cloud's energy on the explosion's depth of burst and not on vent fraction (i.e., vent fraction was calculated from explosion depth based on standard models). The cloud's energy and its consequent altitude were independent of the user specified vent fraction. This was unrealistic, because a high vent fraction cloud will retain more energy than a low vent fraction cloud, and we changed it in Version 2.0. If the user specifies a vent fraction that exceeds the default vent fraction, cloud energy is adjusted (i.e., the user specified vent fraction is now a parameter that affects the amount of energy released in addition to the DOB and medium type). In Version 2.0, clouds with greater than default vent fractions reach higher altitudes than in Version 1.2. Cloud altitude determines the wind field that moves the cloud since wind velocity depends on altitude. In Version 1.2, wind velocities were assumed to be constant over a 15 degree in latitude by 15 degree in longitude "rectangle." Version 2.0 uses a 5 degree by 5 degree resolution instead of 15 by 15.

3. Cloud trajectory--Random wind velocities are generated using the mean and standard deviations of wind components in each 5 degree in latitude by 5 degree in longitude "rectangle." The cloud's center moves with this randomly generated wind field and follows a trajectory. In Version 1.2, we generated a single random cloud trajectory. In Version 2.0 we randomly generate 5 trajectories and average detection probability results for each station over the 5 trajectories.

4. Cloud diffusion and radioactive decay--The cloud diffuses over time due to atmospheric turbulence. At the same time, I-133g decays into Xe-133g and Xe-133m, Xe-133m decays into Xe-133g, and Xe-133g and Ba-140 decay into their daughters.

5. Rain-out and dry deposition--A portion of the aerosols, I-133g and Ba-140, are washed out by rain, if there is any, and they precipitate out by dry deposition over time.

6. Sampling and detection--As the cloud passes over a station, the station collects samples of the nuclear debris over a period of time, allows the sample to sit for a period of time, and then counts the sample activity of Xe-133g, Xe-133m, and Ba-140 over a period of time accounting for the decay of I-133g. Detection probability is determined by statistically comparing the sample's activity to background activity.

Identification

If the radionuclide sensor network detects radionuclides, the event will be identified as a nuclear event. Because of this, we set the probability of identifying the nuclear explosion as a nuclear event equal to the network's detection probability. In addition, one way the radionuclide network can identify an event as an explosion if the ratio of Xe-133m to Xe-133g activity exceeds a specified value. Nuclear weapons release a higher fraction of Xe-133 in the form of Xe-133m than do reactors and fuel processing operations. For reactors and fuel processing plants, the maximum likely ratio of Xe-133m to Xe-133g activity is 0.037. If at least one sensor is able to

measure both Xe-133m and Xe-133g in a sample, and if it measures the Xe-133m to Xe-133g activity ratio in the sample to be greater than 0.037 (this ratio was given to us by Ray Warner at PNNL), then the nuclear explosion is identified as an explosion as well as a nuclear event. Since Xe-133m decays much faster than Xe-133g, a sensor must be able to sample the radioactive cloud and count the sample within 3 to 4 days after the explosion to confirm that the nuclear explosion was an explosion. Otherwise, for this case, the sensor cannot discriminate between a nuclear explosion and a nuclear release from a reactor or fuel processing operation.

Using only the Xe-133m to Xe-133g ratio results in a conservative estimation of the region in which one can distinguish nuclear explosions from other nuclear events. The degree of conservatism depends on the scenario. For example, in deep underground or underwater explosions very few aerosols will be released, only ratios of the various xenon isotopes will be available to distinguish events. The ratio used here is the most significant; the others are too weak to make much contribution. As the amount of aerosols increases, other ratios will become significant. There will be many other nuclides and the full gamma-spectrum would allow many other options for looking at relative yields of various materials. This could expand the region in which identification is possible. None of these other ratios are included in the model at this time.

To do the Xe-133m to Xe-133g ratio statistics properly in the ratio test, we need a standard deviation value for the ratio. This standard deviation is approximated by Equation E-1.

$$\sigma^2 = (A_m \sigma_g / A_g)^2 + (\sigma_m / A_g)^2 \quad (E-1)$$

A_m is the mean activity of Xe-133m, A_g is the mean activity of Xe-133g, σ_g is the standard deviation for the activity of Xe-133g, and σ_m is the standard deviation for the activity of Xe-133m. These values take background activity into account. To perform the ratio test, we assume that the ratio has a Gaussian distribution, and we integrate its density function above the threshold value, which is 0.037, to get the probability that the ratio is greater than 0.037. This is the probability that the nuclear explosion can be identified as an explosion.

APPENDIX F.

SYSTEM DETECTION EFFECTIVENESS AND SYNERGY

System detection effectiveness has not been changed from version 1.2 to 2.0. See the discussion in Appendix F of Edenburn 1997.

APPENDIX G. LOCATION ACCURACY ESTIMATION

Location Accuracy Introduction and Background

IVSEM estimates the accuracy with which the overall IMS can locate an event. It also estimates the location accuracy that can be attained by each individual IMS subsystem. When the IMS detects and estimates the location of an event, the estimated location will have an associated error. The size of the error will depend on where the event was located relative to the various types of sensors and which sensors responded.

The main body of the report outlines the process used to estimate location accuracy and the outline is summarized here:

- 1. All stations with detection probability below 0.2 are eliminated.**
- 2. Station parameters are calculated.**
- 3. Stations are randomly selected to participate in a location trial.** For each station selected in step #1, a random number is chosen from a uniform distribution. If the station's detection probability exceeds the random number, it is included in the location trial.
- 4. The area of a 90% location confidence ellipse is computed for the station set.** This is done by finding the event time and location (x,y) which minimize the sum of the weighted, squared residuals. This procedure is different than that used in version 1.2.
- 5. Steps 3 and 4 are repeated 100 times to get 100 90% confidence area values.** 100 trials may not cover all possible station combinations, but they will get the likely ones.
- 6. The 90% confidence area's expected value is computed as IVSEM's location error estimate.** The 100 area values are averaged to get the expected value for the area of a 90% confidence ellipse. Since station sets are randomly selected, the number of times a specific set comes up will be in proportion to its probability of occurrence, and the area average is equivalent to the area's expected value. Using the 90% confidence area means that the location estimate will fall within the 90% confidence ellipse 90% of the time.

The rest of this appendix will describe step 4. Location estimates are made by minimizing the sum of the weighted, squared residuals for each station. These residuals are described in Appendix G of our original report (Edenburn, 1997). Like version 1.2, version 2.0 minimizes the sum of the weighted, squared residuals, but it uses a slightly different approach to find the 90% confidence area.

Minimization Method

To estimate location accuracy, IVSEM minimizes the sum of the weighted, squared signal arrival time or bearing angle residuals from each detecting station. The general form of a residual equation is given by Equation G1. In this equation r_i is the residual for station “i.” The equation is specifically for stations that measure arrival time but can be generalized to stations that measure bearing angle as well.

$$r_i = T_{i,\text{measured}} - T_{i,\text{modeled}} \quad (\text{G1})$$

$$T_{i,\text{measured}} = T + f(D_i) + \delta_i \quad (\text{G2})$$

$$T_{i,\text{modeled}} = t + f(d_i) \quad (\text{G3})$$

$$r_i = T + f(D_i) + \delta_i - t - f(d_i) \quad (\text{G4})$$

T is the true event time, D_i is the distance from the true event location to station i . δ_i is the signal arrival time error which is a combination of model error and measurement error. d_i is the distance from the estimated location to station i and is a function of x, y , since x, y is the estimated event location. The point (x, y, t) is an event location and time estimate. The travel-time function denoted f relates a signal travel distance to a signal travel time. For infrasound and hydroacoustic stations, IVSEM assumes that f is distance divided by a fixed signal speed. For seismic stations we use the relation between distance and travel time evaluated in our original report (Edenburn, 1997). Our objective is to find the (x, y, t) that minimizes the sum (over all stations) of the weighted, squared residuals. This (x, y, t) value will be the model’s best estimate for event time and location. If we denote the event’s true time and location as $T = 0, X = 0$, and $Y = 0$, then we see that the value of the residual is δ_i if we evaluate it at $t = 0, x = 0$, and $y = 0$. If we call the sum of the weighted, squared residuals R , we can express R as in Equation G5.

$$R = \sum W_i r_i^2 \quad (\text{G5})$$

To accomplish the objective of minimizing R , IVSEM finds the value of (x, y, t) which sets the gradient of R to zero, that is, sets the partials of R with respect to x, y , and t equal to zero. If we denote the partial of R with respect to x as R_x with similar notations for other partials, then the equations to be solved can be written as in Equations G6.

$$\begin{aligned} R_x &= \sum 2 W_i r_i r_{ix} = 0 \\ R_y &= \sum 2 W_i r_i r_{iy} = 0 \\ R_t &= \sum 2 W_i r_i r_{it} = 0 \end{aligned} \quad (\text{G6})$$

We can linearize these equations by expanding r_i in a three dimensional, first order Taylor series around the true event origin ($x = 0, y = 0, t = 0$) which we will denote as p_0 which is a vector.

We will denote the point (x, y, t) by p . Recall that r_i evaluated at p_0 is equal to δ_i .

$$r_i(p) \approx r_i(p_0) + r_{ix}(p_0)(x) + r_{iy}(p_0)(y) + r_{it}(p_0)(t) \quad (G7)$$

$$r_i(p) \approx \delta_i + r_{ix}(p_0)(x) + r_{iy}(p_0)(y) + r_{it}(p_0)(t) \quad (G8)$$

Notice that we expanded the residual around the true event origin instead of from the last location estimate as we did in our original report (Edenburn, 1997). (Derivatives are evaluated at the true event origin instead of at the last location estimate.) This method will be slightly less accurate than the previous method, but its accuracy is very good if errors are unbiased with a Gaussian distribution (which we assume) and are small. The new method will allow us to evaluate a 90% confidence area without using a large number of random trials.

The partials of r_i are found using the specific functional relation between r_i and x, y , and t . This approximation to r_i is linear in x, y , and t and can be substituted into Equations G6. The result of this substitution is given in equations G9.

$$\begin{aligned} \sum W_i r_{ix}(p_0) \delta_i + x \sum W_i r_{ix}(p_0) r_{ix}(p_0) + y \sum W_i r_{ix}(p_0) r_{iy}(p_0) + t \sum W_i r_{ix}(p_0) r_{it}(p_0) &= 0 \\ \sum W_i r_{iy}(p_0) \delta_i + x \sum W_i r_{iy}(p_0) r_{ix}(p_0) + y \sum W_i r_{iy}(p_0) r_{iy}(p_0) + t \sum W_i r_{iy}(p_0) r_{it}(p_0) &= 0 \\ \sum W_i r_{it}(p_0) \delta_i + x \sum W_i r_{it}(p_0) r_{ix}(p_0) + y \sum W_i r_{it}(p_0) r_{iy}(p_0) + t \sum W_i r_{it}(p_0) r_{it}(p_0) &= 0 \end{aligned} \quad (G9)$$

IVSEM solves Equations G9 for x, y , and t using Gaussian elimination. x and y are linear functions of δ_i .

$$\begin{aligned} x &= \sum P_{xi} \delta_i \\ y &= \sum P_{yi} \delta_i \end{aligned} \quad (G10)$$

Since δ_i has a Gaussian distribution then x and y have a bivariate Gaussian distribution, and we can evaluate the variances and covariance as in Equation G11.

$$\begin{aligned}
 \sigma_{xx}^2 &= \sum P_{xi}^2 \sigma_i^2 \\
 \sigma_{yy}^2 &= \sum P_{yi}^2 \sigma_i^2 \\
 \sigma_{xy}^2 &= \sum P_{xi} P_{yi} \sigma_i^2
 \end{aligned} \tag{G11}$$

σ_i^2 is the variance of δ_i . The variance and covariance values are used to find eigenvalues for the inverse of the covariance matrix (Anderson, 1996).

$$\lambda = \frac{\sigma_{xx}^2 + \sigma_{yy}^2 \pm [(\sigma_{xx}^2 + \sigma_{yy}^2)^2 - 4(\sigma_{xx}^2 \sigma_{yy}^2 - \sigma_{xy}^4)]^{1/2}}{2(\sigma_{xx}^2 \sigma_{yy}^2 - \sigma_{xy}^4)} \tag{G12}$$

Two eigenvalues are found by using the different signs on the square-root term. The 90% confidence ellipse area is given by Equation G13.

$$90\% \text{ confidence ellipse area} = \frac{4.605 \pi}{(\lambda_1 \lambda_2)} \tag{G13}$$

This is the 90% confidence area used by IVSEM for a single station set. Area values are found for each randomly generated station set and the expected value is calculated.

References:

Anderson 1996: Kevin Anderson, "A Note on Estimating Location Accuracy in IVSEM," PNNL-11276, August 7, 1996.

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