CONF-9609185--5

SAND96-1624C

SYNERGY AMONG INTERNATIONAL MONITORING SYSTEM TECHNOLOGIES

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ABSTRACT

This paper describes the results of an International Monitoring System synergy study using Sandia National Laboratory's IVSEM (Integrated Verification System Evaluation Model). The study compares individual subsystem performance (seismic, infrasound, radionuclide, and hydroacoustic) with integrated system performance. The integrated system exhibits synergy because different sensor technologies cover different locations; thus, the integrated system covers more locations than can any individual subsystem. Synergy and system performance can be further enhanced by allowing mixed technology detection and location.

Key Words

synergy
International Monitoring System
Comprehensive Nuclear Test Ban Treaty
data fusion
sensor system integration
treaty verification

INTRODUCTION AND BACKGROUND

An International Monitoring System (IMS) will be an integral part of the Comprehensive Nuclear Test-Ban Treaty (CTBT) presently being negotiated at the Conference on Disarmament. The role of the IMS will be to help ensure verification of compliance with the treaty. The IMS will comprise seismic, infrasound, hydroacoustic, and radionuclide sensor subsystems. These subsystems will work both independently and as an integrated system to detect, locate, and identify nuclear detonations. Working together as an integrated system will be particularly important when conditions make detection most difficult. These conditions include testing of low yield devices, testing at medium interfaces (air-land, air-water), and testing evasively.

Sandia National Laboratories has developed a computer based model called IVSEM (Integrated Verification System Evaluation Model) to estimate the performance of an IMS. We have used IVSEM to illustrate the synergy among monitoring subsystems by applying it to a small, shallow-buried/submerged explosion, and this report will present results of that synergy study.

The IVSEM project was initiated in June, 1994, by Sandia's Monitoring Systems and Technology Center and has been funded by DOE/NN-20. IVSEM is a simple, "top-level," modeling tool which estimates the performance of a CTBT monitoring system and can help explore the impact of various sensor system concepts and technology advancements on CTBT monitoring and verification. The tool's main emphasis is to integrate results from and to account for synergy among the various sensor technologies (seismic, infrasound, radionuclide, and hydroacoustic). Specifically, IVSEM estimates the detection effectiveness (probability of detection) and location accuracy 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.

IVSEM consists of a FORTRAN core and an IDL graphics interface, which facilitates input and displays results The model was developed for application on a personal computer so that it can be easily transported to other work sites and used by a variety of analysts. Since July, 1995, the model has been reviewed by personnel from DOE, LANL, LLNL, PNL, AFTAC, ARPA, ACIS, ACDA, and the U.S. CTBT delegation in Geneva. The latest version, 1.1, was released to selected government labs, agencies, and their contractors at a user's workshop in July, 1996. The model can estimate system performance for a single event in a few seconds, and it can produce global contour plots of detection probability and location accuracy (in square kilometers) in 5 to 10 minutes when operated on a personal computer with a Pentium processor.

IVSEM makes three sequential computations: 1) individual station detection probabilities are estimated; 2) detection probabilities from individual stations are integrated to estimate system and subsystem detection probabilities; and 3) system and subsystem location accuracy estimates are made.

Individual station detection probabilities--The model estimates the detection probability for each station within each subsystem. A station's detection probability depends on the event's source strength, the signal's propagation, noise at the sensor, the station's threshold setting, and a statistical test which is specific to the sensor technology used at the station.

System detection probability--Individual station detection probabilities are combined to find the probability that a specific number of stations within a single technology respond. From these probabilities, we find 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 sensors respond, and the probability for this specific response might be 0.23. The combination of all possible specific system responses associated with their 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. 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 constitute a detection. Multiplying response probability by response detection effectiveness for each specific response and adding the products over all specific responses results in the system's detection probability. Using a similar process, individual subsystem detection probabilities are also estimated.

System location accuracy--Stations which respond to the event are used in a statistical location analysis to estimate the system's location error in square kilometers. Each station has an associated bearing angle or signal arrival time which the model assumes are random variables with Gausian distributions. The statistical location analysis uses 100 random repetitions. Each repetition randomly selects stations to participate in a location set based on each station's detection probability, assigns each station in the set a randomly selected station-to-event bearing angle (infrasound stations) or signal arrival time (infrasound, seismic, and hydroacoustic stations) and, from these, estimates an event location and a location error. From the 100 random repetitions, the 90^{th} percentile error is selected as IVSEM's location error estimate. This location error process is performed for the system and for each individual subsystem.

SYNERGY STUDY OBJECTIVE AND ASSUMPTIONS

The study's objective is to illustrate synergy among the IMS technologies in both detection and location. Our working definition of synergy is--agents or elements working together to accomplish an effect which none can accomplish individually. This definition is our condensation of definitions from **The American Heritage Dictionary, Webster's Third International Dictionary, and Webster's New World Dictionary, College Edition**. The agents or elements in the definition refer to individual sensor subsystems in the IMS: seismic, infrasound, radionuclide, and hydroacoustic. Working together as a system, the subsystems can accomplish more that they can accomplish working individually--the system can detect events which individual subsystems cannot detect and it can locate events more accurately than can any individual subsystem.

Before discussing synergy further, we must define what detection of an event means to IVSEM. IVSEM does not necessarily recognize detection by a single station as being a Detection. To be called a Detection (with a capital D) the system response to an event must meet a specified criterion for Detection . There are many ways we can define the Detection criterion. For example, we may define Detection as requiring detection by three or more stations of any kind; or we may define Detection as requiring detection by three or more seismic, or three or more infrasound, or three or more hydroacoustic, or one or more radionuclide stations; or we may define Detection as detection by three or more seismic, or two or more infrasound and one or more radionuclide, or two or more hydroacoustic and one or more radionuclide stations. If the Detection criterion is not met, the system response from the few stations which individually detected the event is assumed to be a false alarm. When using IVSEM, we must specify those system responses which constitute a Detection. This is done in a user supplied detection effectiveness definition table.

There are two types of synergy we will consider in describing how IMS subsystems interact. The first type of synergy is what we will call "supplementary synergy." Working independently, individual subsystems will detect events in some locations or media (by location we mean latitude, longitude, and altitude or depth) but not in others. Synergy is achieved if some subsystems cover locations and media that others do not. If detection by any of the four individual subsystem's working independently constitutes Detection by the system, then the system will Detect events in more locations than will any individual subsystem. This is what we will call supplementary synergy. We implemented this definition in IVSEM by specifying that Detecting an event requires detection by at least three stations of a single nonradionuclide technology or detection by one radionuclide station. That is, detections by three or more seismic, or three or more infrasound, or three or more hydroacoustic, or one or more radionuclide stations constitutes Detecting an event. We implemented supplementary synergy for location in IVSEM by having IVSEM select the lowest location error estimated for any of the four individual subsystems. For this type of synergy, we do not mix types of stations when forming a detection or making a location error estimate.

The second type of synergy is what we call "complementary synergy." For this type of synergy, results from individual stations can "cross the subsystem boundary" and work together as mixed station results to form detections or location estimates. To implement this type of synergy in IVSEM, we define Detection to be detection by any three or more nonradionuclide stations or any one or more radionuclide stations. That is, Detection consists of detection by three seismic stations, or two seismic plus one infrasound, or one seismic plus one infrasound plus one hydroacoustic, or any other combination that adds up to three or more. For location accuracy, this type of synergy is implemented by allowing stations of all types (except radionuclide) to participate together in the location error estimate.

For this study, we compared results from IVSEM using both types of synergy. We assumed a small, shallow buried or submerged nuclear detonation as the event. The event was selected to challenge the monitoring system in that source strength for seismic, infrasound, hydroacoustic, and radionuclide signals were reduced because of the event's shallow depth. Other assumptions for the study are discussed below.

Seismic--The subsystem is comprised of the 50 primary and 120 auxiliary stations specified by Conference on Disarmament document # CD/NTB/WP.330. In IVSEM, only the primary stations are used for detection. The auxiliary stations are used in the location accuracy estimate if the system detects an event. Explosions are assumed to be fully coupled in rock except where stated otherwise. Explosions in the oceans are assumed to be super-coupled which results in an effective magnitude increase of 0.8. The system is assumed to be a mature, well calibrated network in all areas. Arrival time errors, used in the location accuracy estimate have two components: a 0.75 sec. arrival time error and a 0.15/(SNR-1) "model" error. (SNR is signal-to-noise ratio.) These arrival time errors were suggested by John Claassen (Sandia National Laboratories).

Infrasound--The subsystem is comprised of the 60 stations specified by Conference on Disarmament document # CD/NTB/WP.330. We ran the model with 50 km altitude winds typical of October. October is one of the worst months for infrasound detection. Signal arrival time errors used in the location accuracy estimate are assumed to be 2% of travel time. This error was suggested by Rod Whitaker (Los Alamos National Laboratory) as having some, although sketchy, historical NTS test basis. Station-to-event bearing errors are assumed to depend on station-to-event distance as follows: 1.8° between 0 and 3000 km; increasing to 7.0° between 3000 and 10,000 km; increasing to 20.0° between 10,000 and 15,000 km; and, 20.0° for 15,000 km and up. These bearing errors were suggested by Dean Clauter (Air Force Technical Application Center).

Hydroacoustic--The subsystem is comprised of the 6 hydroacoustic and 5 island "T-phase" stations specified by Conference on Disarmament document # CD/NTB/WP.330. Arrival time errors used in the location accuracy estimate are assumed to have two components: a 1 sec. "pick" error (5 sec. for "T-phase" stations) and a travel time error equal to 0.02 multiplied by the square root of station-to-event distance. "Pick" error refers to the accuracy with which arrival time can be picked from a signal profile. These signal arrival time errors were suggested by Dave Harris (Lawrence Livermore National Laboratory) and are very preliminary.

Radionuclide--The subsystem is comprised of the 80 stations specified by Conference on Disarmament document # CD/NTB/WP.330. We ran the model with typical October winds and allowed up to 10 days for detection. October is one of the worst months for radionuclide detection. We assume that all stations are capable of detecting both xenon and barium. Xenon sensitivity is 1 mBq/m^3, and barium sensitivity is 30 uBq/m^3. We allowed the model's built-in algorithms to compute vent fractions: no venting for the -200 m case; 100% free xenon venting for the -35 m cases; 12% barium and other aerosol venting for the -35 m case on land; and 65% barium and other aerosol venting for the -35m case in the ocean. We also assumed that there was no rain.

RESULTS AND CONCLUSIONS

Figure 1 shows detection probability for each of the individual labeled subsystems. Detection requires detection from 3 stations within the subsystem. Each subsystem has significant holes in its coverage. Figure 2 shows system detection for both complementary and supplementary synergy. The Detection requirement for supplementary synergy is that three or more stations of the same type, or one or more radionuclide stations, must detect the event. The Detection requirement for complementary synergy is that any three or more stations, of any type except radionuclide, or one or more radionuclide stations detect the event. Both system figures give significantly better results that any subsystem acting alone. Complementary synergy operation gives better detection results than supplementary synergy because it integrates the subsystems by allowing information from stations of different technology types to cross the subsystem boundary and work together to form a Detection. Figure 3 further illustrates supplementary synergy by showing the effects of removing individual subsystems under supplementary synergy. Removing a subsystem decreases system performance except in the hydroacoustic case. The hydroacoustic subsystem does not contribute to detection because the seismic subsystem completely covers detection in the ocean areas due to signal supercoupling for submerged events.

Figure 4 shows estimated location errors for each of the individual labeled subsystems. Radionuclide results are not shown. Figure 5 shows location errors for the system. The supplementary synergy figure shows results when the smallest location error among subsystems is used, but mixed stations are not allowed to form a location. The complementary synergy figure shows results when stations of different technology type can be combined to form a location. Notice that complementary synergy gives significantly lower errors than supplementary synergy in many areas, particularly in the oceans. This is a result of allowing hydroacoustic stations to participate in location. Figure 6 further illustrates supplementary synergy by showing what happens to location accuracy when individual subsystems are removed under supplementary synergy. Removing the seismic subsystem causes a significant increase in location error, illustrating the importance of the seismic subsystem to location. Removing the radionuclide subsystem does not change supplementary synergy location accuracy. This is because the radionuclide subsystem does not contribute to system location accuracy in IVSEM.

To conclude, the integrated system exhibits synergy because different sensor technologies cover different locations; thus, the integrated system covers more locations than can any individual subsystem. Synergy and system performance can be further enhanced by allowing mixed technology detection and location.

Figure 1. Detection Probability for a Small, Shallow Buried or Submerged Event

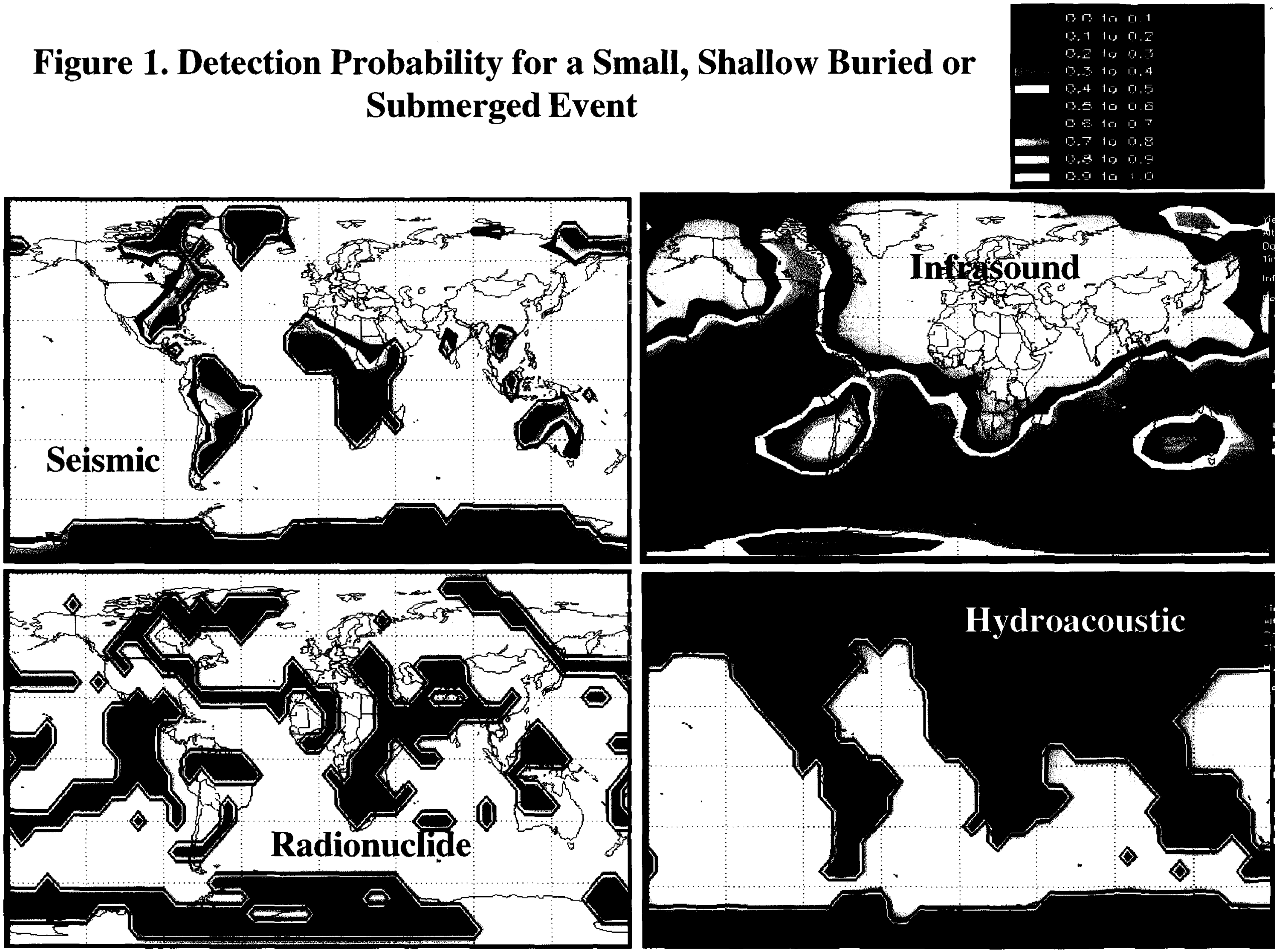

Figure 2. System Detection Probability for a Small, Shallow Buried or Submerged Event

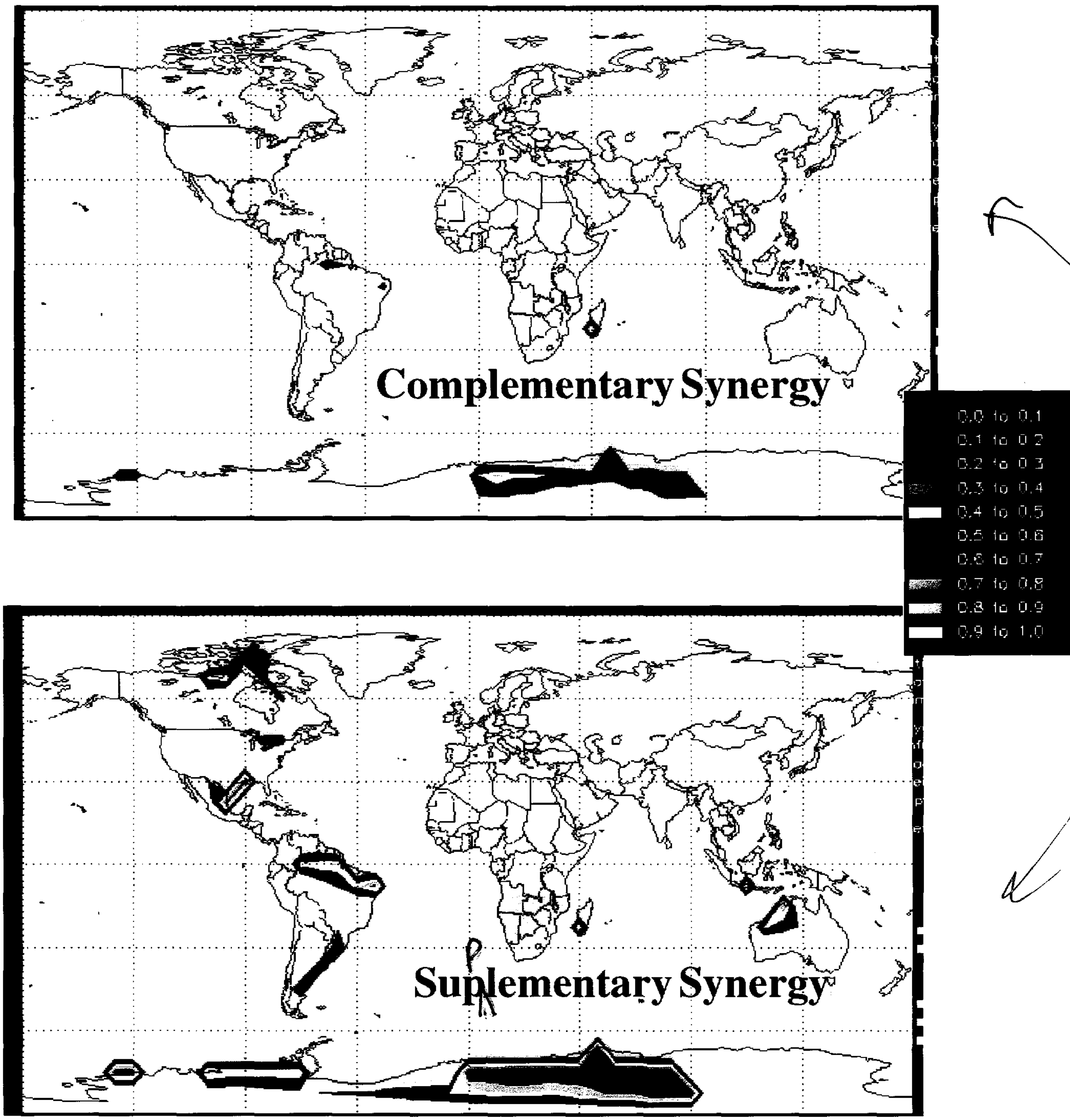

Figure 3. Dedtction Probability for a Small, Shallow Buried or Submerged Event

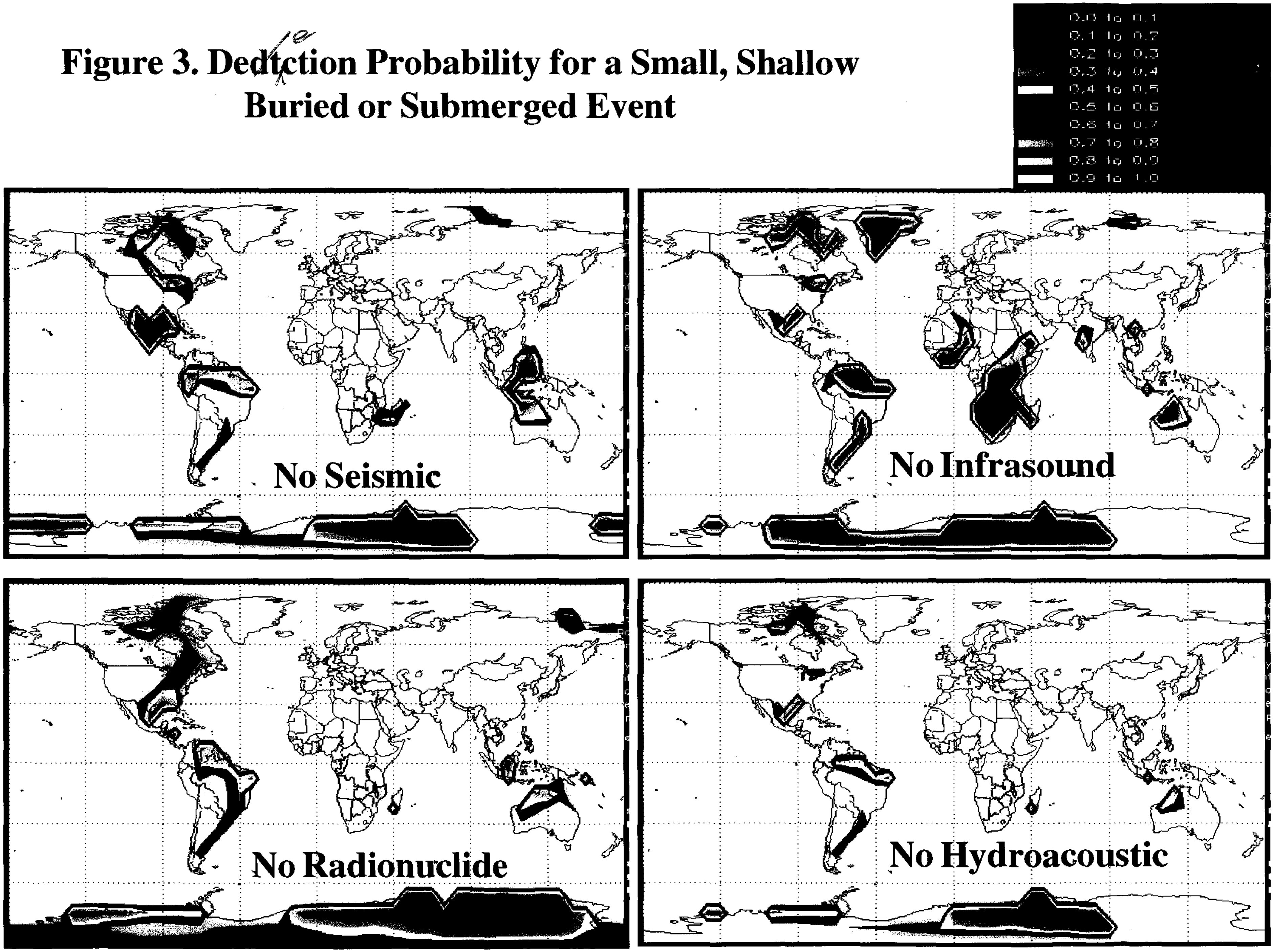

Figure 4. Location Error is Square Kilometers for a Small, Shallow Buried Event

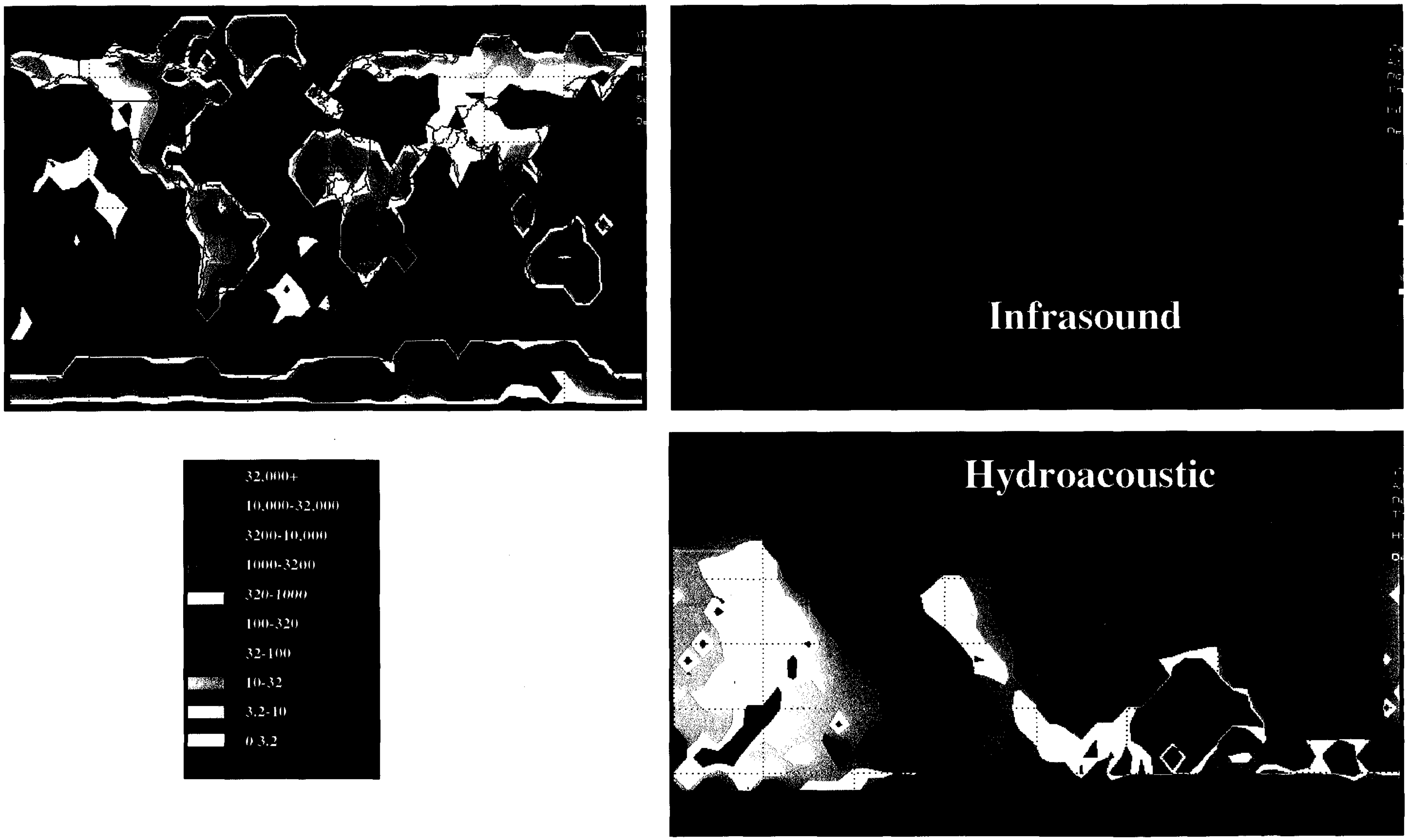

Figure 5. System Location Error in Square Kilometers for a Small, Shallow Buried or Submerged Event

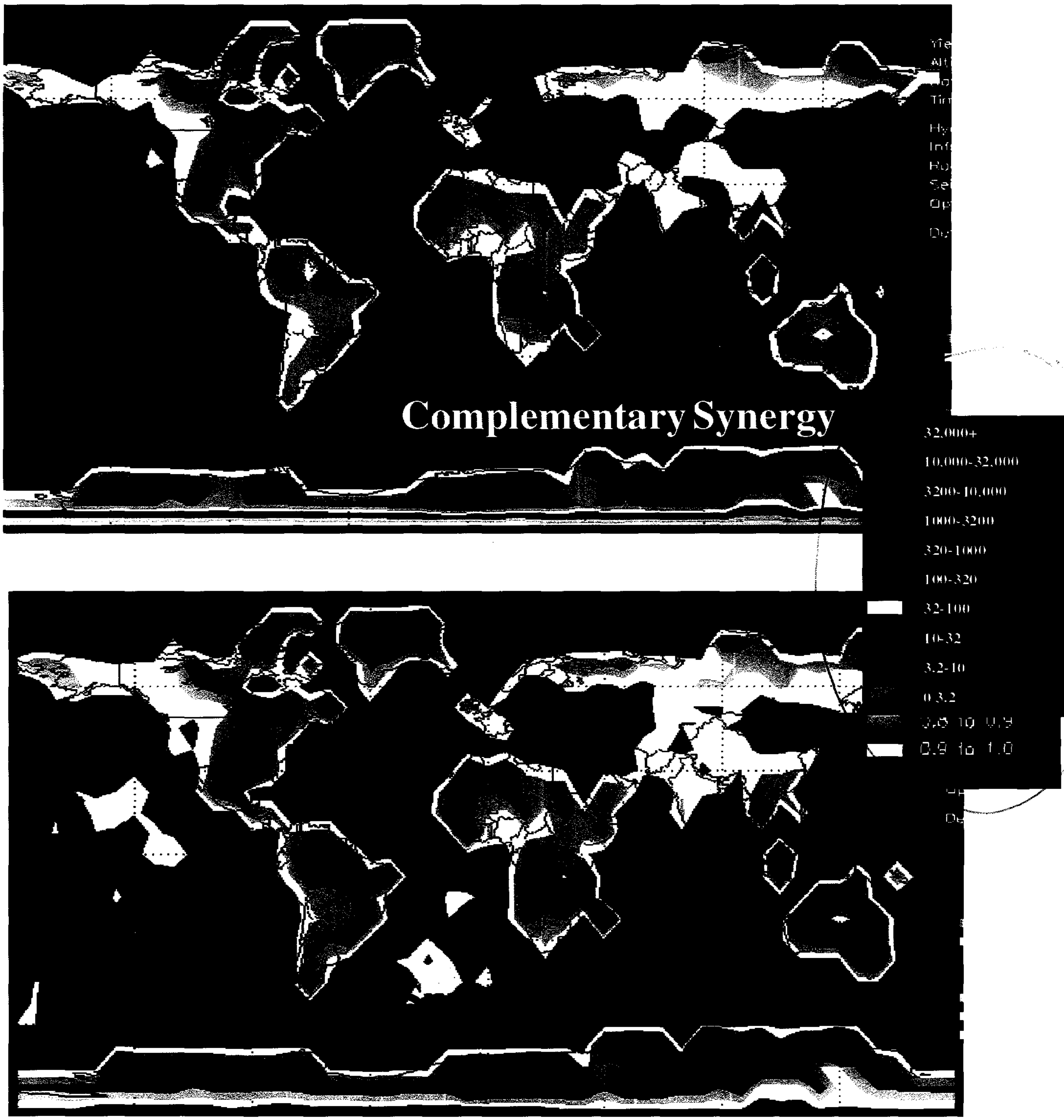

Figure 6. Location Error in Square Kilometers for a Small, Shallow Buried Event