IMPROVING REGIONAL SEISMIC EVENT LOCATION THROUGH CALIBRATION OF THE INTERNATIONAL MONITORING SYSTEM

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ABSTRACT

At Lawrence Livermore National Laboratory (LLNL), we are working to help calibrate the 170 seismic stations that are part of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) monitoring network, in order to enhance the network's ability to locate small seismic events. These low magnitude events are likely to be recorded by only the closest of seismic stations, ranging from local to near teleseismic distances. At these distance ranges, calibration statistics become highly nonstationary, challenging us to develop more general statistical models for proper calibration.

To meet the goals outlined above, we are developing a general nonstationary framework to accurately calibrate seismic travel-time predictions over the full distance range, from local, to regional, to teleseismic distances. The objective of this framework is to develop valid region-specific corrections for the Middle East, North Africa, and portions of the Soviet Union, to assess our progress towards meeting calibration goals, and to perform cost-benefit analysis for future calibrations. The framework integrates six core components essential to accurate calibration. First, is the compilation and statistical characterization of well located reference events, including aftershock sequences, mining explosions and rockbursts, calibration explosions, and teleseismically constrained events (Harris et al., SSA 1999; Hanley et al., SSA 1999). Second, is the development of generalized velocity models based on these reference events (McNamara et al., SSA 1998; Pasyanos, SSA 1999). Third, is the development of nonstationary spatial corrections (nonstationary Bayesian kriging) that refine the base velocity models (Schultz et al., SSA 1998). The fourth component is the development of a detection model on a station-by-station basis. The fifth component is the cross-validation of calibration results to ensure internal consistency along with the continual benchmarking of our nonstationary model where event locations are accurately known (Myers and Schultz., SSA 1999). Finally, the sixth component is the development of location uncertainty maps, demonstrating how calibration is helping to improve location accuracy across both seismically active and aseismic regions. Together, these components help us to ensure the accurate location of events, and just as important, help to ensure the accurate representation of bias uncertainty and random uncertainty in the predicted error ellipses.

Key Words: assessing progress, location, kriging, discrimination, detection, cross-validation

OBJECTIVES:

Seismic monitoring requires the accurate detection, location and identification of seismic events as they occur regionally, both in seismic and aseismic regions. Enhancement in these areas can come from the application of geophysical corrections to various properties of the seismic waveform such as travel-time, magnitude, amplitude, attenuation and dispersion measurements. Given *a priori* information about the velocity structure, corrections can be developed to improve estimates of travel-time prediction in aseismic regions. In seismically active regions historic sets of events, for which the source location parameters are well constrained, can be used to develop corrections that improve on travel-time predictions.

The goal of the location project at LLNL is to provide an innovative statistical framework for seismic location (both in seismic and aseismic regions) that can be used to propagate uncertainties accurately from model predictions and empirical corrections to our confidence in a specific location. To meet these goals we are developing a general nonstationary framework to accurately calibrate seismic travel-times over the full range, from local, to regional, to teleseismic distances. The objectives of our work are to develop valid region-specific corrections for the Middle East, North Africa, and portions of the Soviet Union, to assess our progress towards meeting monitoring goals, and to perform cost-benefit analysis for future calibrations.

RESEARCH ACCOMPLISHED

The Challenge: Regional Calibration

Regional variation in the propagation of seismic waves is the largest source of uncertainty for seismic monitoring of the CTBT (Figure 1). Unlike the Threshold Test Ban Treaty, which banned nuclear explosions larger than 150 kt, the CTBT bans all nuclear explosions. Thus the emphasis has shifted from estimating yields of large, easily identified nuclear explosions from the data recorded at numerous stations throughout the world to detecting, locating, and identifying nuclear explosions using data recorded at a few stations located at regional distances (less than about 2000 kilometers) from the explosions. The CTBT monitoring challenge is further complicated by the many earthquakes and mining explosions that generate tens of thousands of seismic signals annually, some very similar to the signals generated by nuclear explosions.

Detection, location, and identification of small seismic events all require a region-specific understanding of the effects of the path between the sources and the recording stations, because the heterogeneity of the earth's crust and upper mantle have significant effects on the properties of their seismic signals. Thus, we are developing a DOE Knowledge Base (KB) of regional seismic properties to help meet monitoring goals. This KB characterizes regional variations in the travel-times, amplitudes, and frequency content of the seismic waves generated by small, shallow sources. In addition, we are developing new methods that use this information to discriminate between nuclear and non-nuclear sources.

Location Research

To account for variations in regional structure, we have developed and continue to refine our comprehensive statistical framework that accounts for the dramatic variations in travel-times and amplitudes that occur over relatively short distances in the crust - variations that can lead to significant errors in event location and identification. Figure 2 gives a general overview of how we accurately account for these errors. We have catalogued the majority of well constrained - both in terms of location and source characteristics - historic earthquakes and explosions into the DOE KB and we use these events to spatially map their amplitude and travel-time changes as a function of geographic coordinate. We are continuing to use this information to refine our models of the earth's velocity structure. These refined models can be used to account for the travel-time and amplitude fluctuations when a potential clandestine nuclear test occurs. As more events occur over time, the velocity models are continually refined and our ability to account for crustal effects is improved. However, one quickly realizes that model prediction will never be perfect. By its very nature, a model of the earth is underdetermined by the observational data and, thus, gives only an average estimate of the true earth structure. More precisely, if one tried to predict the travel-time or amplitude of an event that was used to develop the model, one could not recover its exact characteristics. To provide an accurate characterization, we have developed a set of innovative statistical techniques and algorithms that work together with the model to empirically predict the travel-time or amplitude correction.

At the heart of our approach is the nonstationary Bayesian kriging (NBK) technique. This technique accounts for the nonstationarities in the correction surface that exist between geophysically distinct regions and allows for the introduction of the tomography models through *a priori* distribution. In addition, this technique allows for interpolation and extrapolation and provides robust error estimates in the predictions. Using this technique, we have demonstrated that we can provide the full correction when a new event is co-located with an historic event in the region. In the case that the new event is not co-located, but instead is located near a set of historic events, we can provide a robust estimate of the event correction based on the spatial correlation of seismic attributes for nearby events. We have continued to evaluate and improve upon this technique during the last year, and all comparison studies at Livermore and Los Alamos National Laboratories have shown that combining optimal velocity models with NBK approach outperforms other approaches.

During this last year, we have demonstrated the benefit of this calibration framework using accurately located aftershock sequences and well constrained explosions at former nuclear test sites, as shown in Figure 3 (Myers and Schultz, 1999). Using what we have learned from these focused studies, we have been applying this method to broad areas of North Africa, the Middle East and the former Soviet Union. More specifically, we have developed and refined a procedure which involves a number of specific steps, including: 1) collecting all available seismic data; 2) defining geophysical boundaries where propagation characteristics change abruptly; 3) using collected seismic data to develop refined 3D tomographic models of the earth's crustal and upper mantle structure; 4) calibrating the magnitude scale; 5) applying magnitude and distance relations; 6) determining detection capability for each seismic phase; 7) evaluating and optimizing seismic location measures, and 8) establishing independent source information to avoid circularity in testing location and identification performance. Although each step in this calibration procedure requires much effort, once calibrated, we have been able to integrate all the information into a station correction surface using NBK to interpolate and extrapolate corrections to a new event of interest.

CONCLUSIONS AND RECOMMENDATIONS

The Department of Energy effort is entering a new phase where field calibration projects are increasingly becoming more critical to its CTBT mission. As discussed above, we have collected the majority of readily available historic data in the Middle East, North Africa and the former Soviet Union and are incorporating much of these into our current calibrations. As this work is completed the primary improvements to monitoring will come from the installation of stations and the realization of dedicated calibration experiments. Station installations may include new IMS stations coming on line and other supporting stations that may further enhance the IMS network. Calibration experiments include controlled explosions where the location, origin time, and source characteristics are well known. Experiments can also include the careful monitoring of known mining areas, local deployments to obtain accurate locations for aftershocks and the deployment of stations to better constrain the crustal structure in a region. Given such a broad variety of calibration opportunities and a limited level of funding, it is essential that we provide an objective tool to plan and, thus, prioritize future station installation and calibration experiments based on their combined benefit and cost.

In response to this need, we have utilized our framework above to develop a planning tool. This planning tool draws on the entire CTBT R&D KB and can accurately reflect our current state of the art techniques, algorithms, and calibrations. In the location case, we assess our progress by generating the travel-times for seismic events spanning a given region. This is accomplished by estimating optimal picking and model error processes and their distributions. We then relocate these events and estimate the location uncertainty across the entire region as shown in Figure 4. As an added benefit this tool allows us to objectively measure and report progress as we proceed. With these tools in hand and with our effort in the continued development of new innovative techniques in location and identification, we feel that we are well poised to meet our mission goals in the year 2000 and beyond.

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Figure 1: (a) Seismic signals from nuclear tests prior to the Comprehensive Test Ban Treaty (CTBT) would usually propagate through the simpler structure of the deep mantle and were recorded by a global network of seismic stations. Seismograms associated with these events were relatively simple. (b) Under the Comprehensive Test Ban Treaty, a country may detonate a smaller nuclear test to evade the treaty. In such cases, the explosion may only be recorded seismically at a sparse set of nearby stations. The paths for these events are quite complex as they travel predominantly through the structures of the crust and upper mantle. As part of the DOE CTBT R&D effort, Livermore is working to calibrate the CTBT seismic monitoring network for these complexities.

Input Representation Goal

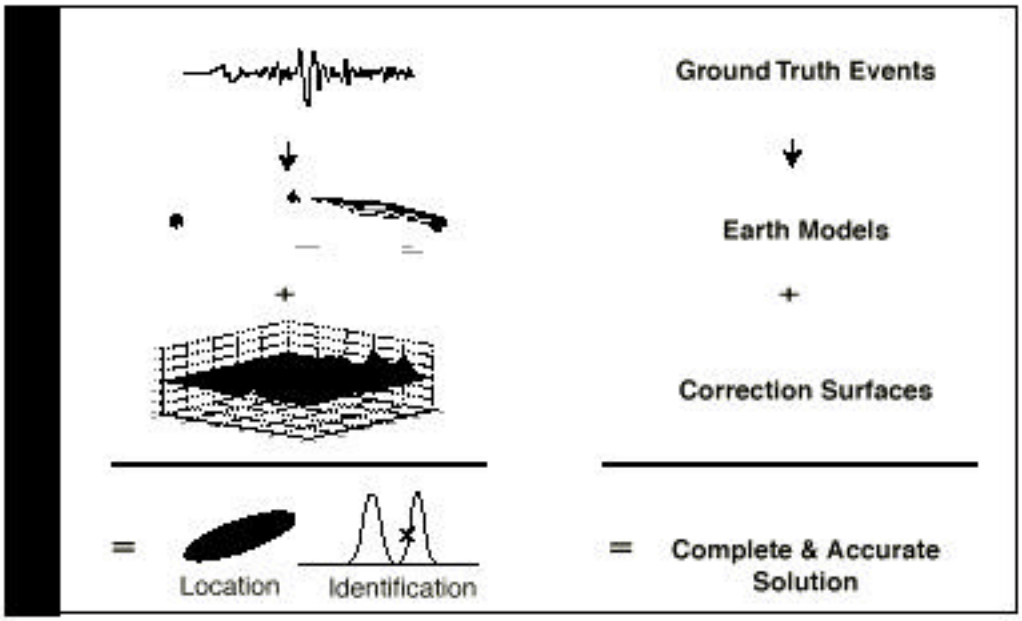

Figure 2: Our goal is to accurately identify and locate clandestine nuclear explosions. This requires us to separate explosion and natural event populations based, in part, on the explosions seismic signature. However, bias uncertainties can cause locations to be in error. To correct for these travel-time biases, we utilize the above statistical framework. Ground truth events are cataloged in our database and then used to refine earth models that can be used to predict travel-time and amplitude anomalies for seismic phases. However, models by their very nature average the data, leaving errors in predictions. We account for these errors by adding correction surfaces to the models through nonstationary Bayesian kriging technique - a technique developed this last year at Livermore. This maximum likelihood technique robustly interpolates and extrapolates corrections spatially and can provide an accurate representation of the error in its prediction.

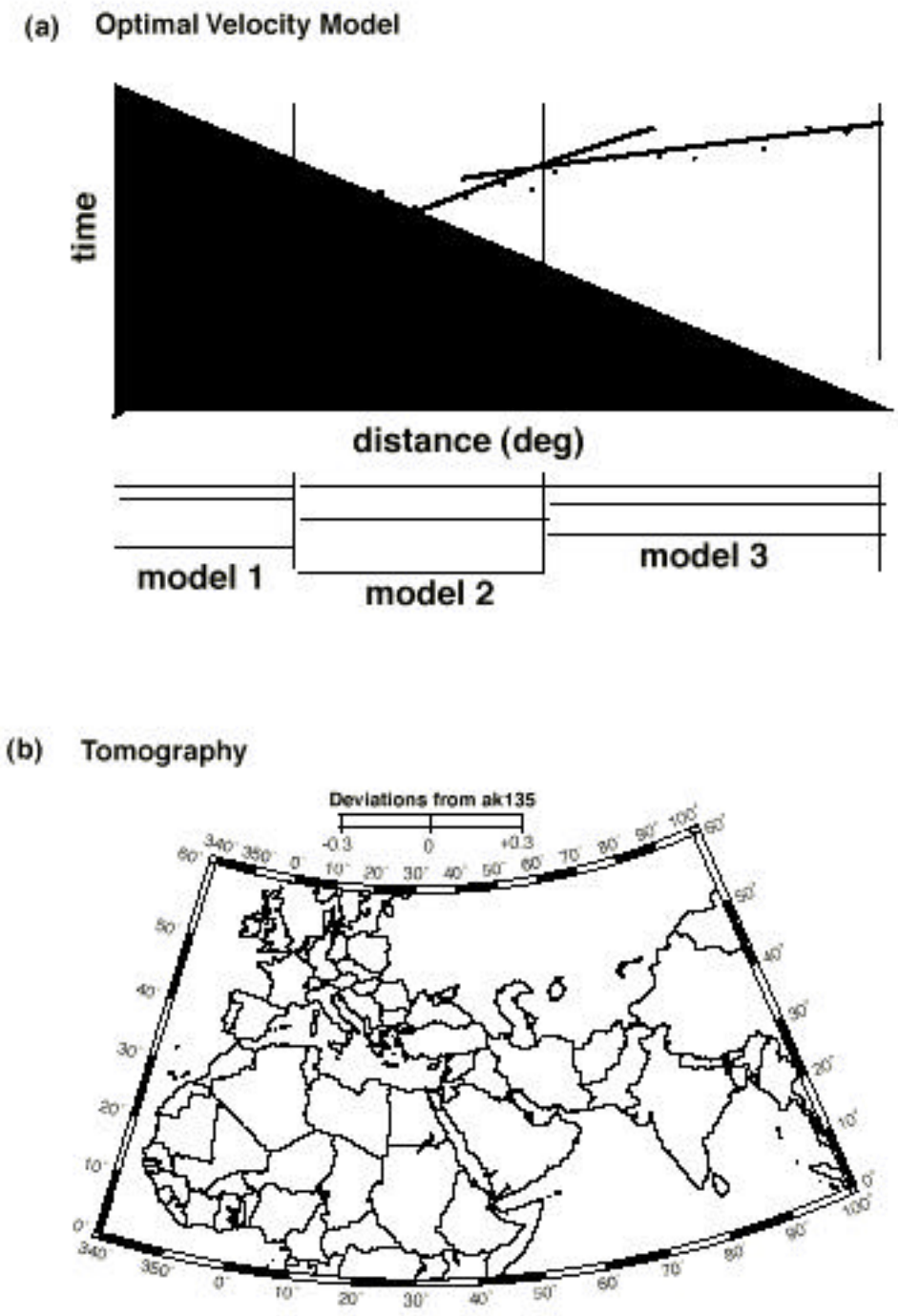

Figure 3: We have developed a comprehensive framework to improve the location of clandestine nuclear tests using the IMS. (a) We are developing optimal two dimensional velocity models for all stations. (b) Where ray path coverage is dense enough we are utilizing 2D and 3D tomography of the crust and upper mantle to further refine our models.

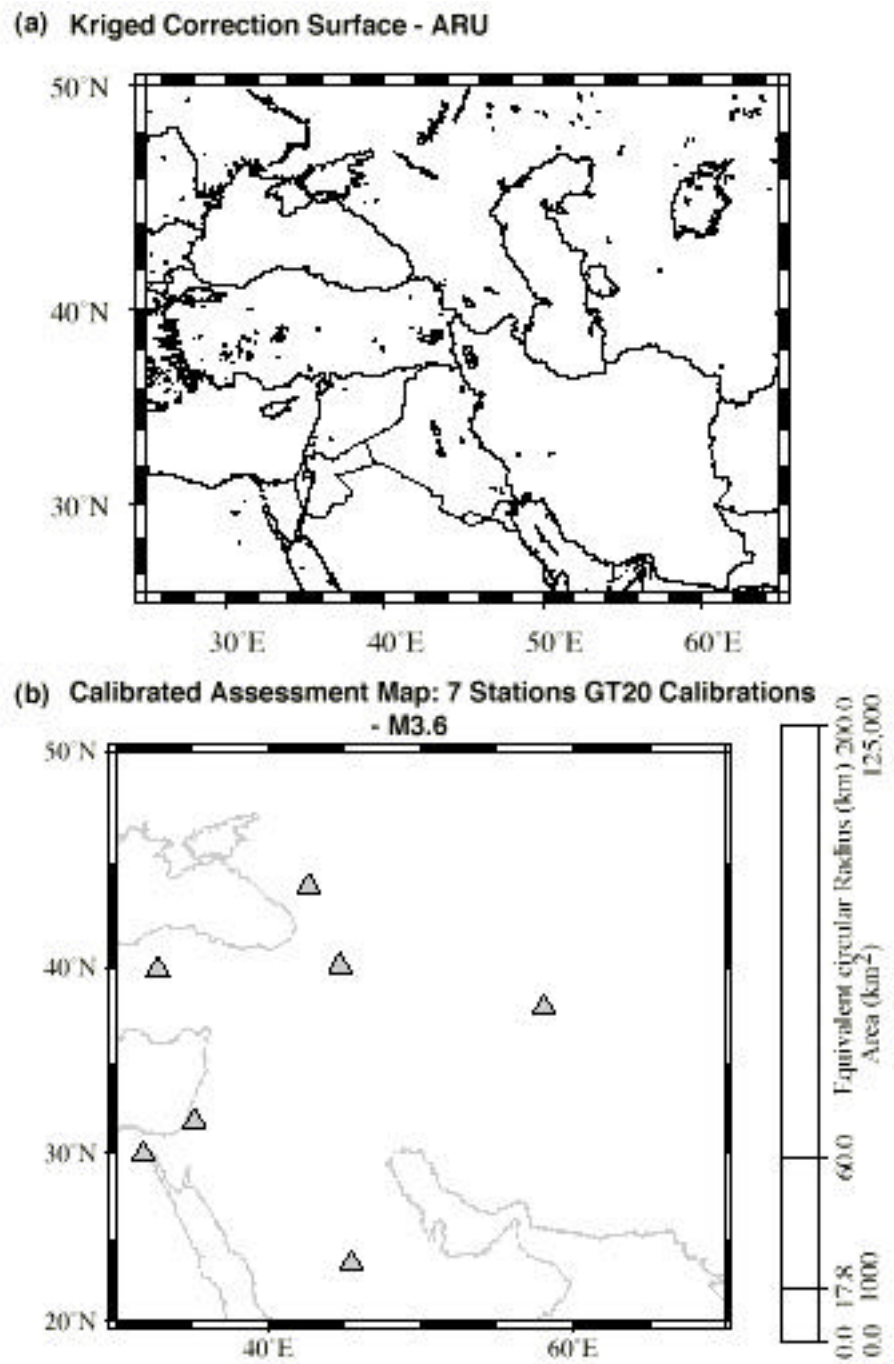

Figure 4: We have developed a planning tool to aid future calibration efforts in location. (a) A kriged correction surface is generated for each station and then used to account for the inaccuracies in our model. (b) Utilizing kriging, we propagate uncertainties in our seismic location. This framework allows us to estimate the actual location performance across a given region. In addition to planning, this performance tool allows us to measure the impact of our calibration effort over time and communicate it to our sponsor.