INTEGRATING DIVERSE CALIBRATION PRODUCTS TO IMPROVE SEISMIC LOCATION

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ABSTRACT

The monitoring of nuclear explosions on a global basis requires accurate event locations. As an example, under the Comprehensive Nuclear-Test-Ban Treaty, the size of an on-site inspection search area is 1,000 square kilometers or approximately 17 km accuracy, assuming a circular area. Achieving this level of accuracy is a significant challenge for small events that are recorded using a sparse regional network. In such cases, the travel time of seismic energy is strongly affected by crustal and upper mantle heterogeneity and large biases can result. This can lead to large systematic errors in location and, more importantly, to invalid error bounds associated with location estimates. Corrections can be developed and integrated to correct for these biases. These path corrections take the form of both three-dimensional model corrections along with three-dimensional empirically based travel-time corrections. LLNL is currently working to integrate a diverse set of velocity model and empirically based travel-time products that are provided internally by the DOE laboratories and externally through contracts into one consistent and validated calibration set.

To perform this task, we have developed a hybrid approach that uses three-dimensional model corrections for a region and then empirically uses reference events when available to improve these path corrections. This empirical approach starts with the best *a priori* three-dimensional velocity model that is produced for a local region and uses this as a baseline correction. When multiple competing models are provided from various sources for a local region, uncertainties in the models are compared against each other using our ground truth data and our analysts picks. Based on the results of this comparison an optimal model is selected. We are in the process of combining three-dimensional models on a region-by-region basis and integrating the uncertainties to form a global correction set. Our Bayesian kriging approach then combines the set of optimal models and their statistics with empirical calibrations to give an optimal three-dimensional *a posteriori* calibration estimate. In regions where there is limited or no coverage by reference events, travel-time corrections are based primarily on the model. The integrated *a priori* model is particularly important in these areas. In regions with adequate calibration events, the corrections are based primarily on these events. We demonstrate improvement in event location through the reduction of regional bias. In regions with sparse or no ground truth, the *a priori* model will need to be spot-validated with the use of dedicated calibration experiments or through the use of mining explosions, where available.

Key Words: calibration, product integration, event location, reference events, model corrections, validation

OBJECTIVE

The monitoring of nuclear explosions on a global basis requires accurate event locations. Unfortunately, crustal and upper mantle velocity anomalies often lead to systematic travel-time anomalies that in many cases lead to large systematic errors in location estimates. Typically these velocity anomalies are not accounted for in the location process and the predicted errors misrepresent the true uncertainty of the event location. At Livermore, we are working to implement a unified framework that combines empirical-based and model-based path corrections to remove bias from the location problem. Our framework will incorporate any combination of *a priori* and *a posteriori* one-dimensional, two-dimensional, and three-dimensional models. These models that are derived from a variety of sources including external contracts, are combined with our empirically based travel time corrections. The errors are then propagated into our coverage ellipse estimates. This paper focuses on the Livermore effort to integrate a diverse set of three-dimensional velocity model and empirical based travel-time products into one consistent and validated calibration set.

RESEARCH ACCOMPLISHED

We continue to work closely with Sandia National Laboratories (SNL) to implement a framework that allows us to design, build, integrate, and visualize calibrations that are produced from our own internal DOE research and that provided through research associated with external contracts. This is not an entirely new project. Instead, it is the natural extension of our empirical and modeling calibration efforts over the past five years. A large part of our effort at Livermore has been concerned with generating standardized detection, travel-time, and amplitude correction volumes on a regional basis. The tessellated output of the correction volumes combines a set of sub-regions into one global correction set. The global set of integrated corrections is then fed directly into the appropriate detection, location, and discrimination algorithms and leads to the primary improvement in our ability to locate and discriminate events. In our framework, we address four core issues.

Knowledge Base Product Visualization. We are working to provide improved end-to-end visualization of all calibration events (i.e. ground truth events), their uncertainties, constructed models, empirically kriged surfaces on a region-by-region basis. We can now provide a completely integrated demonstration of the DOE laboratories' geographic regionalization.

Direct Calibration Modification. We are working to visualize, access, and potentially alter within any geographic subregion the calibration events, statistics, model, and/or kriged surfaces, if required. Subregions can be rapidly redefined. This may be especially useful when adding calibration information in regions where a subset of calibrations and uncertainties need to be added after the fact and in an efficient fashion.

External Product Integration. This process allows the laboratories to identify geographic subregions that correspond to regions covered by external contractors. Contract research provided to Livermore within a geographic subregion can be seamlessly incorporated into the DOE KB. Product integrators assess uncertainties in contributed calibrations and compare these uncertainties with our internal models and with other contributions from external contractors in the region. The optimal model is selected and assigned to that sub-region.

DOE Coordinated Analysis. This process standardizes DOE calibration efforts into one single format and access tool. Use of this tool ensures the seamless coordination and integration of projects. Sub-regions can be easily merged at boundaries and models can be altered to properly merge analyses made by different laboratories in regions that overlap. This process is fully auditable.

This framework is being developed in multiple phases. The first phase involves standardizing the suite of statistical, kriging, modeling and tessellation tools that have been developed by LLNL and SNL over the past two years.

Framework for Integrating Calibrations

The overall goal of our framework is to provide a flexible, interactive environment in which an analyst can produce, test, and manage calibration information for seismic stations. This framework focuses on providing accurate characterizations of location uncertainty given the highly nonstationary and regionally varying nature of seismic travel time, azimuth, and slowness.

To account for variations in regional structure, our framework is designed to account for 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. Figure 1 gives a general overview of how we accurately account for these errors. We begin by cataloging well constrained - both in location and source characteristics - historic earthquakes and explosions in the DOE KB and use these events to spatially map their amplitude and travel-time changes as a function of geographic coordinate. This acts as the data set that we use to both test our internal DOE models and any external models developed by contractors. These data are also used to assign and validate the uncertainties associated with the models (Hanley and Schultz, 2000). As more events occur over time, the two-dimensional and three-dimensional velocity models are continually refined and our ability to account for crustal effects is improved (Flanagan et al., 1999; Swenson et al., 1999; Flanagan et al., 2000;). 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 and propagate the travel-time or amplitude correction along with its uncertainties (Schultz and Myers, 1998; Myers and Schultz, 1999; Myers and Schultz, 2000).

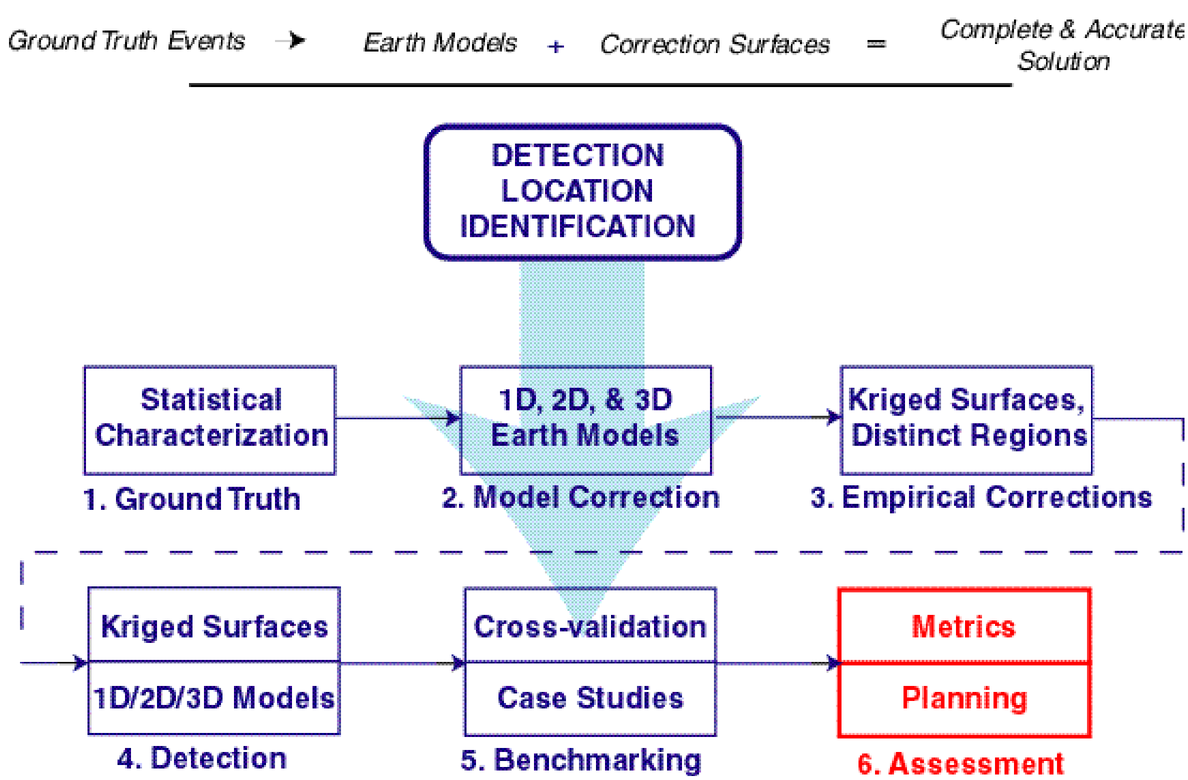

Figure 1: Developing a comprehensive framework for location.

Methodology for Diverse Calibration Integration

Producing calibration information for a region involves the creation of calibration surfaces and/or tessellations for all the stations within the region. This requires the production and refinement of dozens of subregions, both model- and statistical-based. Producing these entities is inherently an interactive process in which the researcher must observe the effect of changes, and use that feedback to decide whether continued modification is required. Figure 2 shows the general structure of a calibration set in our approach.

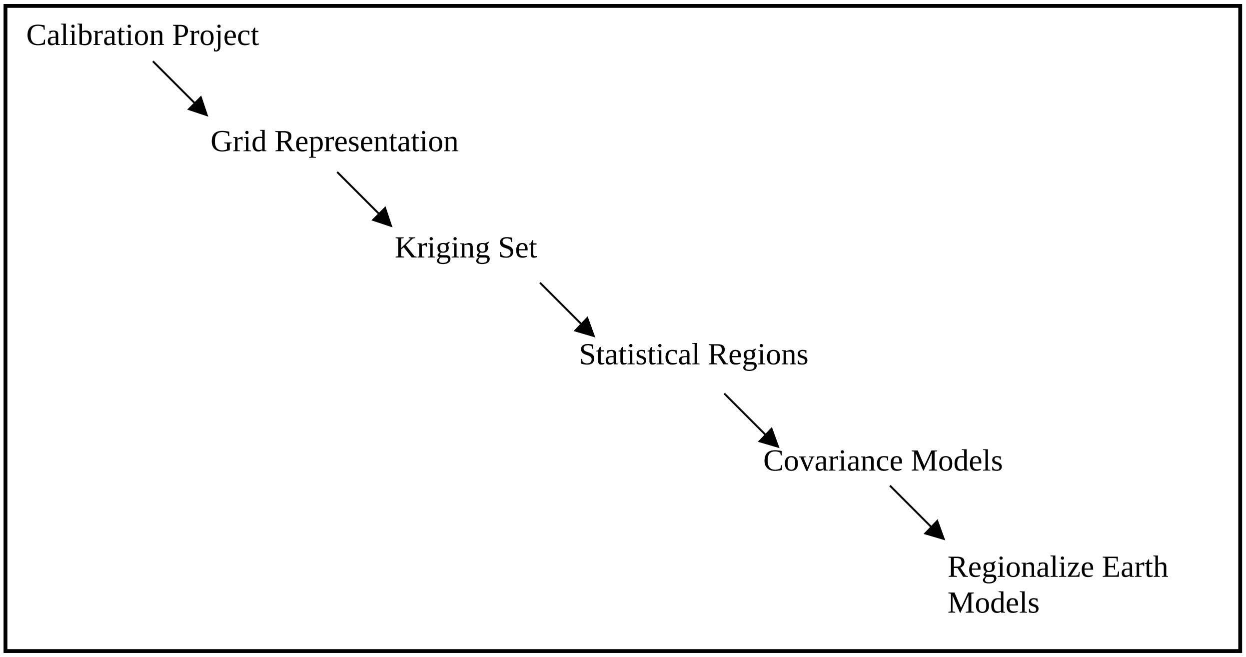

Figure 2: General structure of how calibrations are integrated to form both location and amplitude corrections.

The framework we have designed handles multiple mesh (tessellation) and station-phase-attribute surfaces at once. For each correction surface, a suite of algorithms is incorporated to spatially reduce the dimensionality of the data we integrate while retaining all pertinent calibration information. Distinct calibration data quality groups are spatially associated within geographic subregions. These subregions are created and edited in terms of their boundaries. Various trends and velocity models can be removed within each subregion, as shown in Figure 3. Outlier removal is supported but not encouraged. Statistical tests, graphical methods, and analyst discretion (which may be arbitrary) are supported as methods to identify outliers.

Data with similar spatial statistics are grouped within statistical regions (Figure 4). Statistical regions are completely independent of kriging regions, so statistical regions may overlap any number of kriging regions. However, it may be common for statistical and kriging regions to have identical boundaries. Statistical analysis consists of stationary or non-stationary, isotropic or anisotropic variogram two-dimensional and three-dimensional modeling. In the future, more general statistical modeling will be incorporated. Incorporating non-parametric non-stationary, anisotropy, and/or co-variograms (mixing data sets) are some of the options that work towards increased variogram generality. Variograms are then assigned to a specific kriging region. After assigning variograms to all regions with both DOE calibration data and external contract data integrated, the data set can be kriged.

It may be desirable to krig on any number of optimally spaced (regular, irregular) grids (e.g. tessellation). The grids may be optimized for one kriged surface or a collection of surfaces. If tessellation is chosen, the bounds of the tessellation and the lowest density spacing are specified to ensure accuracy at all times. A collection of surfaces over which the tessellation is optimized must also be specified. The resulting tessellation (node and triangle information) is saved so subsequent surfaces can be kriged on the same mesh.

Using this process we are able to assure that realistic modeling uncertainties are assigned and propagated on a regional basis. Calibration data and models from a diverse set of sources including the laboratories and contracting universities can be integrated into one correction surface suite and the uncertainties are standardized on a global scale. We continue to validate this process with newly acquired ground truth events and refine it as required.

CONCLUSIONS AND RECOMMENDATIONS

In general, we have developed a hybrid approach to location that uses three-dimensional model corrections for a region and then uses reference events when available to improve the path correction. Our approach is to select the best *a priori* three-dimensional velocity model that is produced for a local region and then use this as a baseline correction. When multiple models are produced for a local region, uncertainties in the models will be compared against each other using ground truth data and an optimal model will be chosen. We are working towards implementing a calibration integration process of combining three-dimensional models on a region-by-region basis and integrating the uncertainties to form a global correction set. The Bayesian kriging prediction combines the optimal model combination and its statistics with the empirical calibrations to give an optimal *a posteriori* calibration estimate. The result, as shown in Figure 5, is improved location estimates and robust location uncertainties that show significant improvement in calibrated regions (Schultz and Myers, 1999; Schultz et al., 1999).

To aid this process we have developed a general framework to provide a flexible, interactive environment in which a researcher can produce, test, and manage calibration information for seismic stations. This approach allows a general statistical analysis on a regional basis and results in a self consistent global calibration set.

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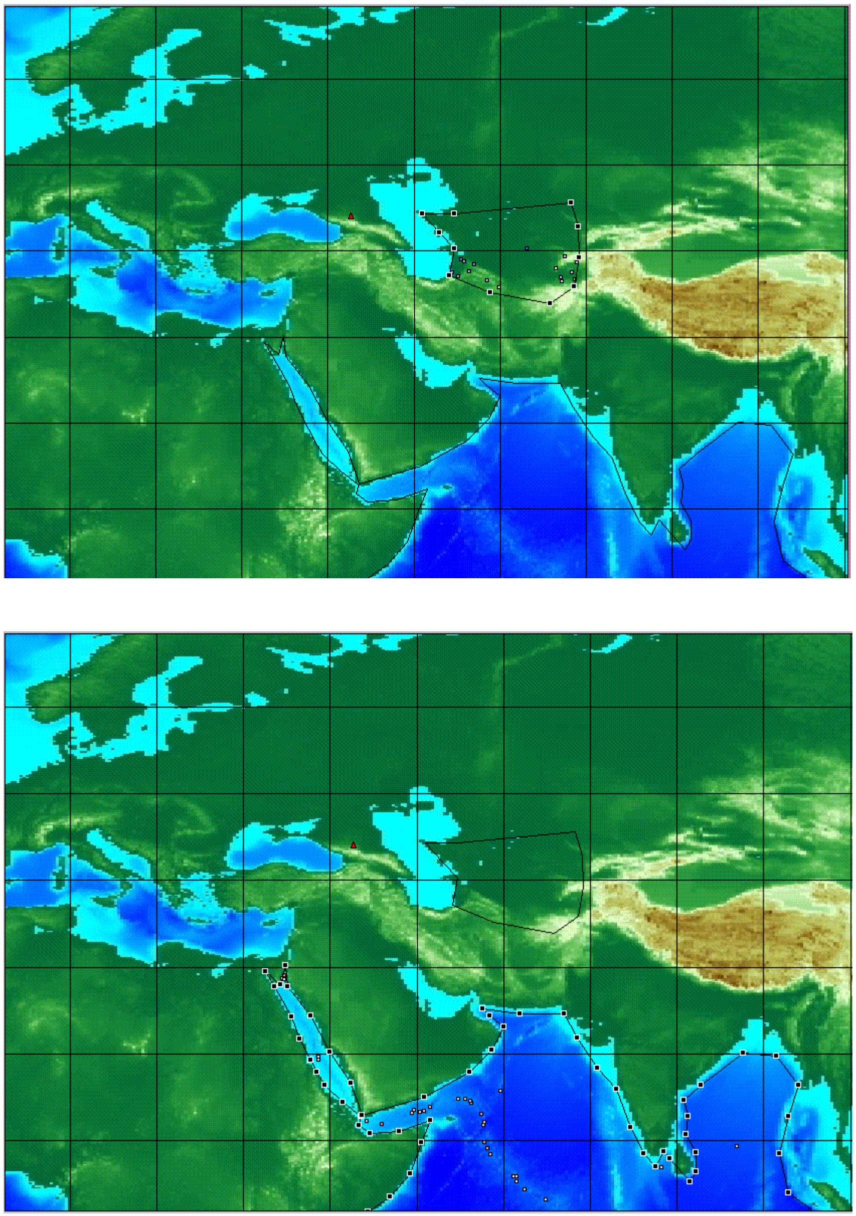

Figure 3: Two examples of integrated model subregions, the first (highlighted with squares) is a fast velocity zone east of the Caspian, while the second is an oceanic subregion that is represented by an oceanic model.

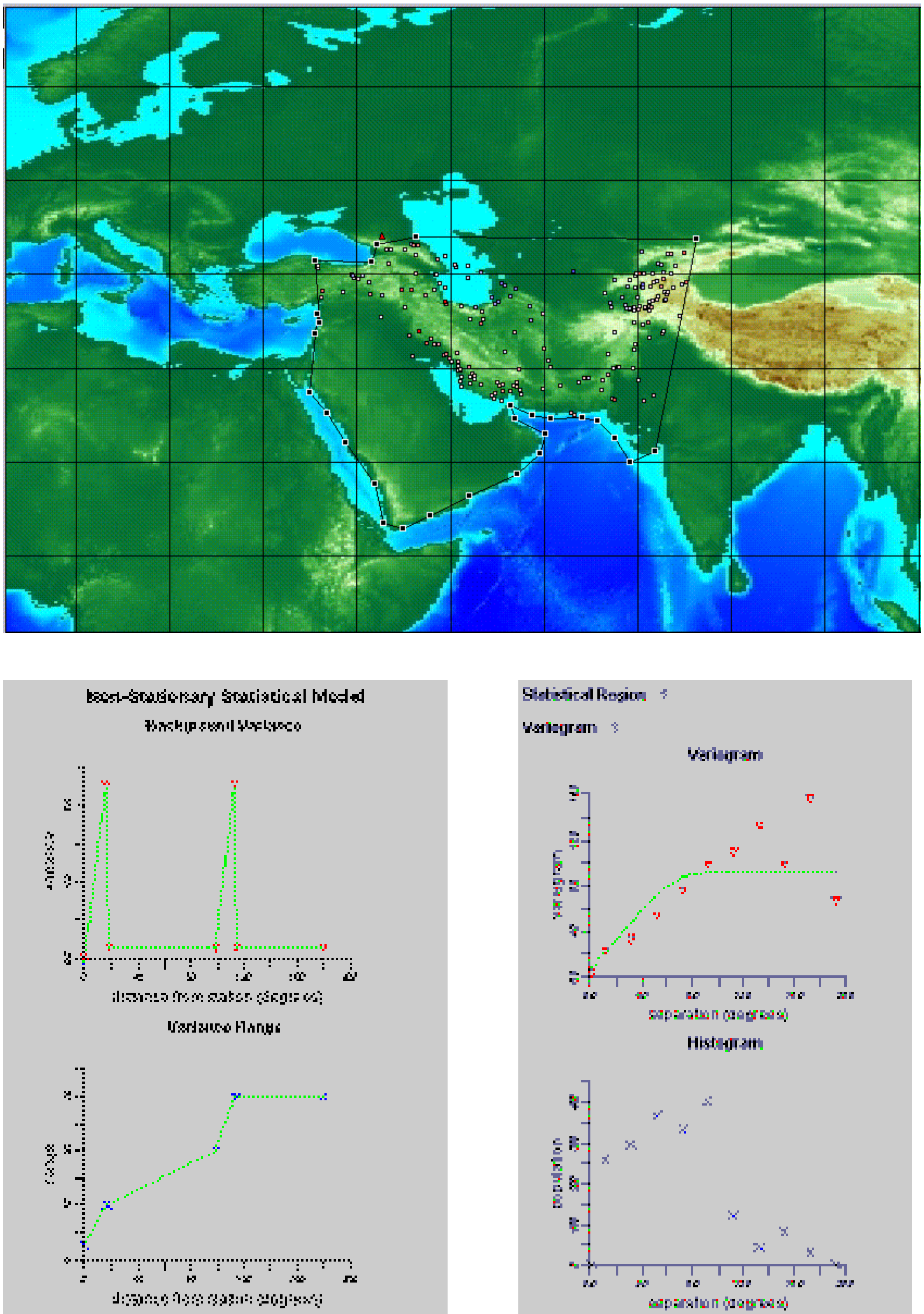

Figure 4: Statistical subregions where the statistics of data and model products provided by external contracts are integrated into one statistical model and a self-consistent set of statistics is applied. This assures accurate uncertainty estimates as an end product.

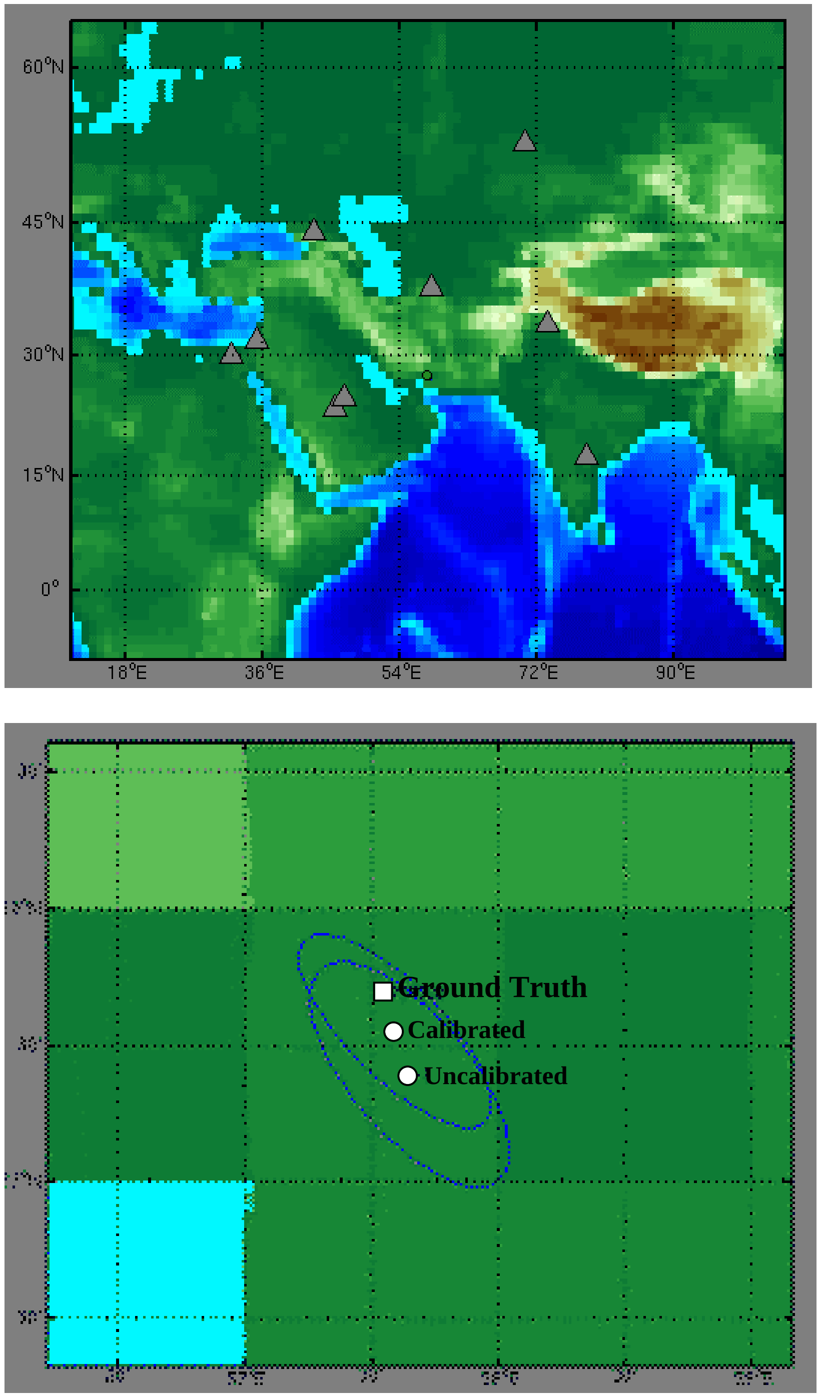

Figure 5: Given the regional station configuration (above) the location and ellipse for a seismic location is shown in the Middle East (below). There is a clear migration of the location towards the known ground truth point and the size of the ellipse is reduced by calibration.