THE CONFIDENCE-BUILDING MEASURE ROLE OF SEISMIC CALIBRATION

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ABSTRACT

Confidence-Building Measures (CBMs) under the Comprehensive Nuclear-Test-Ban Treaty (CTBT) address the political goal of alleviating compliance concerns raised by chemical explosions and the technical goal of calibrating the International Monitoring System (IMS; ref. Article IV, E, and Part III of the Protocol to the Treaty). The term "calibration" appears in the Treaty associated only with CBMs and On-Site Inspections (OSIs) and has different meanings in each case. For OSI, calibration refers to calibration of the on-site monitoring instruments, whereas, for CBMs, it refers to seismic travel-time corrections for specific paths to improve event location. Calibration of a path is either carried out empirically using known sources or compensated for through earth models. Known sources are called "calibration" or "reference" events and are characterized by information known as ground truth. In practice, the accuracy of the ground truth varies for different types of reference events. Mining explosions or explosions carried out for the express purpose of calibration have the highest degree of accuracy since the location and origin time are known from direct measurement. An example of a calibration event with less accurate ground truth is an earthquake that occurs within a local network with large enough magnitude to be observed regionally. Such events have location accuracy typically less than 5 km. Outside of mining regions and seismically active regions where reference events are plentiful, path calibration will need to be estimated with earth models developed from studies such as seismic refraction experiments. These models will be the result of the integration of all available information and need to be tested—most likely with dedicated calibration experiments—over the region for which they are considered to be valid. Clearly, developing path calibrations is a large effort that requires the cooperation of scientists all over the world.

This paper describes preferred methods of seismic calibration and recommends near-term high-priority courses of action to achieve it.

Key Words: calibration, confidence-building measures, mining explosions

Introduction

Nuclear explosion monitoring capability is fundamentally dependent on the installation of monitoring stations. Currently, the Preparatory Commission (PrepCom) for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) is installing stations in anticipation of entry-into-force of the Treaty. These stations, especially the seismic ones, will provide the essential detection capability. However, once installed, their potential location capability will not be realized until they are fully calibrated. The Treaty does not require the CTBTO to calibrate the stations. Instead, station calibration is a voluntary activity allowed under the Confidence-Building Measures provision in the Treaty. In a sense, the Treaty can be viewed as a global "neighborhood watch" system, where the CTBTO functions as the eyes and the stations as the ears.

There are many aspects of seismic calibration as evidenced by the several terms needed to describe a seismogram. A seismogram is a recording made by a seismometer of the ground motion from a source propagated through the earth and corrupted by background noise. The waveform model used to describe the observed signal at a given station is a convolution of source, path, and instrument response terms superimposed on additive background noise (from both earth and instrument sources):

$$\text{Seismogram}(t, R, \ldots) = \text{source}(t,\ldots)*\text{path}(t,R,\ldots)*\text{instrument}(t,\ldots) + \text{noise}(\ldots)$$

Many variables contribute to each term; however, with seismic calibration, the primary variables of interest are time (t) and distance (R). The path term represents the impulse response of the earth structure between the location of an equivalent point source and the location of a receiving station. Similarly, the instrument term defines the impulse response of the recording instrument. Finally, the noise term defines the earth noise present at any given site. The path is the only term dependent on the distance between source and receiver, R, and it is the primary source of error in the event location process. Fortunately, much of this error can be reduced through travel-time corrections, which are the primary focus of calibration.

The purpose of this paper's focus on seismic calibration is to highlight the significant role that can be played by the global research community, in particular, on work based on historical and surrogate station data that will allow partial calibration of a station or network in advance of installation. The research role is larger for the seismic community than for the other technical communities supporting ground-based monitoring technologies because of the inhomogeneity of the transmission medium for the seismic signal. In contrast, the hydroacoustic transmission medium, water, is relatively homogeneous. The inhomogeneity of the earth greatly complicates the path term in the above equation. However, unlike radionuclide and infrasound technologies, whose signals depend in part on ever-changing atmospheric wind conditions, the seismic transmission medium is static and, once characterized, is essentially constant, allowing progressive reduction of uncertainty. This progressive nature of seismic calibration makes the long and labor-intensive effort worthwhile.

Seismic Calibration Approaches

Travel-time corrections can be empirical or model based. Empirical calibrations provide more confidence than model-based approaches; however, model-based calibrations are useful when sufficient empirical data are not available to provide corrections across large geographic areas, for example large aseismic regions. Furthermore, the advantages of emperical and model-based approaches can be combined using Bayesian techniques (Schultz et al., 1998).

In the modeling approach, travel times are calculated by tracing rays through two- or three-dimensional earth models of P and S velocities that represent the region being calibrated (Firbas et al., 1998). The P and S velocity models may be derived in a variety of ways, depending on the kind of information available. A hierarchy of techniques has been devised to obtain velocity structure models:

1) Refraction lines provide the most direct estimate;
2) Pn, Sn, teleseismic P and S, and surface wave tomography provide partial constraints over wide regions;
3) Receiver functions provide partial constraints at a single geographic location;
4) Analogy to geophysically similar regions provides a highly uncertain estimate but one that can be applied in the complete absence of data.

The resulting travel times will be more appropriate for the modeled region than those based on a one-dimensional global model. However, both are indirect calibrations and have high uncertainty. For this reason, empirical corrections are preferred where high-quality ground truth about events exists because they are based on actual measurements, and their certainty can be determined.

Ground-Truth Data Drives the Calibration Effort

Empirical travel-time corrections are based on ground truth. Ground-truth events are seismic events for which the type of source and its location in space and time are well known, as are the uncertainties in these parameters. Ground-truth events include well-located earthquakes from global, regional, local, and temporary networks. They also include man-made seismic sources such as mining and other industrial or military explosions, as well as dedicated calibration shots. The most basic ground-truth information includes source type and accurate location and origin time along with error estimates on these quantities. Great care must be taken to obtain accurate error estimates so that appropriate weights can be applied when combining ground-truth information from many sources. In general, ground-truth accuracy trades off with coverage. For example, ground truth from global and regional earthquake catalogs provides the highest levels of coverage but has the largest errors, since earthquake locations are not precisely known. At the other extreme, for example, high ground-truth accuracy but low level of coverage, are dedicated calibration explosions. For such experiments, it is good practice to deploy instruments locally to accurately verify origin time and location. A highly recommended dedicated calibration shot, known as the reciprocal or inverse calibration shot (Shelton Alexander, private communication, 1999), provides data on many paths simultaneously. In this type of experiment, a large explosion is detonated near an IMS station and recorded at high-priority locations by portable, temporary seismic stations.

As a first step, we suggest beginning the empirical calibration of a given region with ground-truth data from global catalogs. This generally provides reasonable coverage and improvement in accuracy in a cost-effective manner. Higher quality ground-truth information can be added to improve calibration in certain areas or to test the effectiveness of the more common, lower quality information. High-quality ground truth is also critical to evaluate the regional models discussed above.

For global catalog data, studies comparing locations to known ground truth show that an accuracy of ±15 km can be obtained by requiring a certain number of reporting stations within an allowable threshold gap (Sweeney, 1998). These data are referred to as GT15 data, shorthand for ground-truth accuracy of 15 km. This is a significant level of accuracy because it is slightly less than the radius of a 1000-km^2 circle, the 1000 km^2 being the maximum area of an on-site inspection under the CTBT. Regional network locations provide GT5-10 locations, while local networks, for example those deployed during aftershock studies, provide GT5 or better. Additional accuracy can be obtained using locations based on surface rupture from geological or satellite observations to obtain accuracy of GT5 or less. Higher accuracy can be obtained from industrial blasts. These can be described as GT2. Finally, dedicated explosions of tens of meters and millisecond level accuracy have essentially no error and are designated GT0 (Leith and Kluchko, 1998). The Comprehensive Nuclear-Test-Ban Treaty Preparatory Commission recommends that calibration explosions be known to within 100-m location and 0.1-s timing accuracy (PrepCom, 1999).

As the final step, the correction surfaces generated by interpolating ground-truth data must be validated. Dramatic improvements in location quality have been shown in comparisons of locations of the Racha, Georgia, aftershock sequence using a regional array, before and after calibration, based on GT15 data (Figure 3, Myers and Schultz, 2000).

Summary and Recommendations

Calibration of seismic monitoring stations improves confidence in the treaty. Although the Confidence-Building Measures part of the treaty only calls out a subset of calibration activities (i.e., chemical calibration explosions), a wide range of calibration activities has confidence-building value. The Confidence-Building Measures part of the treaty opens the door to contribute to calibration. Indeed, calibration is just beginning to show its value as more stations come online, effectively putting into place a global neighborhood watch system. For seismic methods to operate at their maximum accuracy, regional path travel-time corrections need to be made and applied. These corrections can be calculated from regional geophysical models or, preferably, from empirical calibration event data sets. Empirical calibrations are preferred since they are actual measurements and their uncertainty can be directly evaluated. The following activities have significant confidence-building value and are recommended to aid seismic calibration:

1) **High-quality ground truth for explosions**. The Treaty already urges States to provide the PTS with such information and data on explosions of 300 tonnes or greater.
2) **Dedicated calibration experiments**. These experiments are needed to validate models and to fill in reference event information. Reciprocal experiments as discussed above are particularly useful.
3) **Local and regional seismic data**. Data from local and regional networks that can locate events within 10 km or better should be made widely available through web sites (for example, the USGS web page entitled Routine United States Mining Seismicity (http://neic.usgs.gov/neis/mineblast/index/html). Such data have confidence-building value by defining the background seismicity for a region.

Guidance is available for use by all researchers. Documents include

1) Guidelines and Reporting Formats for the Implementation of Confidence-Building Measures (PrepCom 9, 1999),
2) Knowledge Base Contributor's Guide (Carr, et al., 2000),
3) The Integration Process Design for Incorporating *Information Products* into the Department of Energy *Knowledge Base* (Moore et al., 2000).

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