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NET-VISA: Network Processing Vertically Integrated Seismic Analysis

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Abstract The automated processing of multiple seismic signals to detect and localize seismic events is a central tool in both geophysics and nuclear treaty verification. This paper reports on a project begun in 2009 to reformulate this problem in a Bayesian framework. A Bayesian seismic monitoring system, NET-VISA, has been built comprising a spatial event prior and generative models of event transmission and detection, as well as an inference algorithm. The probabilistic model allows for seamless integration of various disparate sources of information. Applied in the context of the International Monitoring System (IMS), a global sensor network developed for the Comprehensive Nuclear Test Ban Treaty (CTBT), NET-VISA achieves a reduction of around 60% in the number of missed events compared with the currently deployed system. It also finds events that are missed by the human analysts who postprocess the IMS output.

Introduction

The Comprehensive Nuclear Test Ban Treaty (CTBT), which bans all nuclear explosions on Earth, is gaining renewed attention in light of growing worldwide interest in mitigating the risks of nuclear weapons proliferation and testing. To monitor compliance with the treaty, the Preparatory Commission for the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) has installed a suite of sensors known as the International Monitoring System (IMS). The IMS includes waveform sensor stations (seismic, hydroacoustic, and infrasound) connected by a worldwide communications network to a centralized processing system in the International Data Center (IDC) in Vienna. The IDC operates continuously and in real time, performing station processing (analysis and reduction of raw seismic sensor data to detect and classify signal arrivals at each station) and network processing (association of signals from different stations that have presumably come from the same event). Perfect performance remains well beyond the reach of current technology: the IDC's automated system, a highly complex and well-tuned piece of software, misses nearly one-third of all seismic events in the magnitude range of interest, and about half of the reported events are spurious. A large team of expert analysts postprocesses the automatic bulletins to improve their accuracy to acceptable levels.

The IDC results indicate that the network processing problem is far from trivial. There are three primary sources of difficulty: (1) the travel time between any two points on Earth and the attenuation of various frequencies and wave types are not known accurately; (2) each detector is subject to local noise that may mask true signals and cause false detections (as much as 90% of all detections are false); and (3) many thousands of detections are recorded per day, so the problem of proposing and comparing possible events (subsets of detections) is daunting. These considerations suggest that an approach based on probabilistic inference and combination of evidence might be effective, and this paper demonstrates that this is in fact the case. For example, such an approach automatically takes into account nondetections as negative evidence for a hypothesized event, something that classical methods typically do not do.

The existing network processing algorithm in use at the IDC, known as global association (GA) (Le Bras *et al.*, 1994), uses various heuristics to cluster arrivals, and then determines the location of the event in each cluster. The event location algorithm is based on the original iterative linear least squares method of Geiger (1910, 1912). Of course, the algorithm has been enhanced considerably over the years, for example, by the use of singular value decomposition to solve the resulting matrix equations (Menke, 1989; Lay and Wallace, 1995) and by the use of azimuth and slowness to constrain the solution (Magotra *et al.*, 1987; Roberts *et al.*, 1989). However, in the words of Myers *et al.* (2007) (p. 1049), "Seismic event location is—at its core—a minimization of the difference between observed and predicted arrival times." Further, all of these classical methods rely only on the associated arrivals to locate an event. Even the multiple-event location algorithms, such as those due to Waldhauser and Ellsworth (2000) and Myers *et al.* (2007), ignore data from stations that fail to detect an event.

In this paper, we present a probabilistic model of seismic event occurrence, P_θ (see Table 1 for a list of all mathematical notations), and another probabilistic model of seismic detections triggered by events (or noise), P_ϕ. We also describe how the model parameters θ and ϕ are estimated from

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