Pure appl. geophys. 158 (2001) 1341–1348
0033–4553/01/081341–8 $ 1.50 + 0.20/0

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Pure and Applied Geophysics

Introduction

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This is one of several volumes planned to appear in *Pure and Applied Geophysics* covering a range of topics related to monitoring the Comprehensive Nuclear-Test-Ban Treaty (CTBT). This volume concentrates on the measurement and use of surface waves and the papers fall into two general categories: The development and/or application of methods to summarize information in surface waves (e.g., surface-wave tomography) or the use of these summaries to improve capabilities to monitor and verify the CTBT by advancing the art of surface-wave identification, measurement, and source characterization. Because of the emphasis here on a type of wave rather than on a specific application, the papers in this volume overlap those in the other volumes appreciably. Readers interested in the application of surface waves are encouraged also to investigate the contents of the other volumes, after thoroughly digesting the results in this volume, of course.

Surface waves compose the longest and largest amplitude parts of broadband seismic waveforms generated both by explosions and shallow earthquakes. In addition, they contain most of the low frequency information radiated by seismic sources. Measurements of the properties of surface waves have been important for evaluating source mechanisms, estimating yields, and helping to discriminate nuclear explosions from naturally occurring earthquakes, and have been widely used by national and international organizations charged with monitoring and verifying various nuclear test treaties. Under the CTBT, concentration has shifted from teleseismic monitoring of a threshold yield targeted on a few well-defined locations to identifying and characterizing signals from weak nuclear explosions and earthquakes using potentially very noisy and incomplete regional data following events that may be distributed widely in space. Concentration is no longer on yield estimation, but rather on being able to discriminate explosions from naturally occurring earthquakes and to locate small events using sparse regional networks in complex tectonic environments with the accuracy and precision demanded by the CTBT.

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Within the context of the CTBT, the use and interpretation of information from surface waves has grown in significance. There are two general uses of surface waves under the CTBT. First, the comparison of the amplitudes of surface waves and body waves remains the most reliable regional discriminant, an example of which is the well known $m_b : M_s$ discriminant (e.g., STEVENS and DAY, 1985). Second, broadband surface-wave dispersion provides important information used in estimating 3-D seismic models of the crust and uppermost mantle which are necessary to obtain accurate locations of small events for which only regional data may be available. The success of both applications depends on obtaining reliable surface-wave dispersion measurements and representing these measurements in a useful form, usually as group- or phase-velocity maps.

The measurement of the group velocity of Rayleigh and Love waves is performed on the envelope of the surface-wave packet and can be robustly measured across a broad frequency band, from several seconds to hundreds of seconds period (e.g., DZIEWONSKI *et al.*, 1969; LEVSHIN *et al.*, 1972; CARA, 1973; KODERA *et al.*, 1976; RUSSELL *et al.*, 1988; LEVSHIN *et al.*, 1989, 1992; RITZWOLLER *et al.*, 1995). A recent experiment by a number of research groups in the U.S. revealed general agreement among the various methods and codes used to measure group velocities (WALTER and RITZWOLLER, 1998). Phase-velocity measurements are typically obtained by waveform fitting (e.g., WOODHOUSE and DZIEWONSKI, 1984) or by differencing phase spectra obtained at adjacent stations or from nearby events. There are three key reasons why group velocities have been considered more useful in nuclear monitoring than phase velocities. First, absolute phase-velocity measurements are strongly affected by initial source phase (e.g., KNOPOFF and SCHWAB, 1968; MUYZERT and SNIEDER, 1996), which may be poorly known or completely unknown for small events. Group velocities are much less sensitive to source characteristics (e.g., LEVSHIN *et al.*, 1999). Second, phase velocities are difficult to measure unambiguously below about 30 s period. Finally, although multi-station and multi-event differential phase measurements are largely unaffected by source phase, they are typically too sparsely distributed to be of general use in constructing tomographic maps. With a few notable exceptions surface-wave data processing for use in nuclear monitoring has concentrated on estimating velocities rather than wave amplitudes, polarizations, or scattering. If the emphasis on constructing 3-D models to improve regional location capabilities continues, it is likely that a larger share of future efforts will be devoted to short-period phase-velocity estimation and the use of more complicated wavefield effects to constrain 3-D models, such as polarization anomalies (e.g., LEVSHIN *et al.*, 1994; LASKE, 1995) and scattering (e.g., POLLITZ, 1994).

The estimation of dispersion maps by tomography (e.g., DITMAR and YANOVSKAYA, 1987; YANOVSKAYA and DITMAR, 1990) is now commonplace and new methods such as kriging (e.g., SCHULTZ *et al.*, 1998) have emerged. Dispersion maps on a variety of scales have appeared in the last several years. For example, there are global phase-velocity maps (e.g., LASKE and MASTERS, 1996; TRAMPERT and WOOD-

HOUSE, 1996; ZHANG and LAY, 1996; EKSTRÖM *et al.*, 1997; VAN DER HEIJST and WOODHOUSE, 1999) as well as regional studies across Eurasia (e.g., WU *et al.*, 1997; CURTIS *et al.*, 1998; GRIOT *et al.*, 1998; RITZWOLLER and LEVSHIN, 1998; RITZWOLLER *et al.*, 1998; YANOVSKAYA and ANTONOVA, 2000) and elsewhere (e.g., Antarctica: VDOVIN, 1999; South America: VDOVIN *et al.*, 1999; Arctic: LEVSHIN *et al.*, 2001). Two papers in this volume describe the application of surface-wave tomography to regions of interest for monitoring the CTBT. *Pasyanos, Walter, and Hazler* present a study of the Middle East, North Africa, southern Eurasia and the Mediterranean using Rayleigh and Love waves at periods ranging from 10 s to 60 s. *Mokhtar, Ammon, Herrmann, and Ghalib* present a tomographic inversion of Rayleigh and Love group velocities across the Arabian peninsula in the period range of 5–60 s. These and other observational efforts exemplify the advances that are emerging as data sets accumulate and, in particular, as the frequency band of observation lowers.

Advances in surface wave methodology continue to emerge both on regional (e.g., STEVENS and MCLAUGHLIN, 1997) and global scales (e.g., WANG and DAHLEN, 1995; WANG *et al.*, 1998). In this volume, *Barmin, Ritzwoller, and Levshin* discuss a tomographic method for constructing both isotropic and azimuthally anisotropic surface-wave maps. Although their algorithm is based on a regular grid, it extends naturally to irregular grids, and recent advances in the construction and use of irregular grids in tomography (e.g., SAMBRIDGE *et al.*, 1995; SPAKMAN and BIJWAARD, 1998) are now being exploited in surface-wave tomography, as described here by *Spakman and Bijwaard.* Irregular grids are most useful when the spatial distribution of data is inhomogenous, as is common in regional surface-wave tomography. Also in this volume, *Larson and Ekström* show that at periods above about 50 s group velocity maps constructed directly with regional tomography agree well with those computed from phase-velocity maps which were themselves constructed globally. Thus, information from disparate data types appears to provide consistent constraints on the 3-D structure of the earth. Other researchers have demonstrated that broadband group- and phase-velocity maps can be simultaneously inverted for 3-D structure on both regional (e.g., VILLASEÑOR *et al.*, 2001) and global scales (e.g., *Stevens and McLaughlin* in this volume). In addition, VILLASEÑOR *et al.* (2001) established that the resulting model of the mantle agrees well with a recent model constructed with teleseismic body wave travel times (e.g., SPAKMAN and BIJWAARD, 1998).

Tomographic maps have four principal applications: to detect and extract surface waves from noisy records, to help discriminate nuclear explosions from other sources of seismic energy, to characterize sources, and to be used as data in inversion for the shear-velocity structure of the crust and uppermost mantle.

First, the focus of the CTBT on small events makes the detection of seismic signals and the extraction of useful information a crucial task. The detection and extraction of surface waves is facilitated by using phase-matched filters (e.g., HERRIN and GOFORTH, 1977; HERRMANN and RUSSELL, 1990), which are designed to compensate for the dispersion of the surface wave-train. In this volume, *Levshin and*

Ritzwoller argue that to perform optimally these filters need to be tuned regionally with group velocity delays which may be efficiently summarized as group travel-time correction surfaces for each monitoring station. They and *Barmin*, *Ritzwoller*, *and Levshin* present examples in this volume of group velocity correction surfaces for a few stations in Central Asia. *Levshin and Ritzwoller* also demonstrate how these correction surfaces can be used to detect weak surface-wave signals buried in noise.

The second important application of surface-wave observations is in the discrimination of nuclear explosions from numerous other natural and human-made seismic phenomena. The surface-wave magnitude in combination with the body-wave magnitude obtained for each event is then used as part of the well known $m_b : M_s$ discriminant. After the surface wave has been extracted from the observed waveform, the amplitude is typically measured in a window centered around 20 s period from which the surface-wave magnitude M_s is inferred. The exact procedure varies depending on the monitoring agency. There has been considerable debate concerning the appropriate distance correction to use in computing M_s (e.g., MARSHALL and BASHAM, 1972; VON SEGGERN, 1975; HERAK and HERAK, 1993), and for paths less than ~20° it is common practice not to use surface-wave amplitude measurements. The effect has been to constrain M_s to relatively large events for which surface waves are well observed beyond epicentral distances of 20°. The prototype International Data Centre (PIDC) recently adopted a new M_s-distance relation of REZAPOUR and PEARCE (1998) which appears to justify the use of surface-wave amplitudes at all distances below 100 degrees and hence extends M_s to smaller events. The procedure for estimating M_s at the PIDC is thoroughly described in this volume by *Stevens and McLaughlin* who show that the automated methods that they developed and that are now in place at the PIDC demonstrate a detection threshold approximately one magnitude unit lower than those of other global networks that use visual detection of surface waves. They also argue that continuing improvements in 3-D earth models will advance surface-wave identification and reduce the magnitude threshold further. Observational efforts aimed at producing group velocity maps at periods well below 20 s, such as those of *Pasyanos*, *Walter*, *and Hazler* and *Mokhtar*, *Ammon*, *Herrmann*, *and Ghalib* in this volume, hold out the hope to reduce the period at which M_s is measured below 20 s. The effect envisioned will be to reduce the size of events further for which reliable M_s measurements can be obtained. *Levshin and Ritzwoller* sound a cautionary note by demonstrating how spectral amplitudes below 20 s period vary strongly on the relatively small scales across the Kirghiz Seismic Network (KNET). Also in this volume *Herak*, *Panza*, *and Costa* demonstrate how estimates of M_s depend on source depth because the maximum observed amplitude near 20 s period is a function of the excitation of overtones. They postulate a correction to M_s depending on earthquake depth, which they argue is important for calibrating the M_s scale but is of little practical significance for the $m_b : M_s$ discriminant because the correction is zero for events shallower than 20 km.

The third application of surface-wave observations relevant to monitoring the CTBT concerns source characterization, because source depth and the source mechanism may together form a useful discriminant. For example, events that are deeper than 2–3 km below the earth's surface are most probably natural phenomena. The difficulty is in discriminating very shallow natural events from explosions. In this volume, *Bukchin*, *Mostinsky*, *Egorkin*, *Levshin*, *and Ritzwoller* argue that source depth and both the isotropic and nonisotropic components of the moment tensor can be estimated if body-wave polarization data and surface-wave amplitudes are considered simultaneously. (A good introduction to moment tensor estimation is presented by DZIEWONSKI *et al.*, 1981). They test the hypothesis that events missing the isotropic component are earthquakes and near-surface events which have a significant isotropic component are explosions, by analyzing data following events on and near the Lop Nor test site in China. They argue that tests of this potential discriminant are encouraging, but a much larger data set of earthquakes must be considered to determine the false alarm rate (i.e., the percentage of earthquakes with surface-wave amplitudes consistent with a substantial isotropic component of the moment tensor).

The fourth and final application of surface-wave dispersion data regards improving and focusing regional models. The inversion of broadband regional surface-wave maps can provide a more detailed picture of the earth's lithosphere than can emerge from globally propagating surface waves or observations of teleseismic body waves alone. By raytracing through such models, it is possible to construct body wave travel-time correction surfaces for a set of monitoring stations for use in improving location estimates of weak seismic events (e.g., VILLASEÑOR *et al.*, 2000). This is especially important in regions of complex structure, where locations based on global models or coarse regional models are invariably biased in the absence of good azimuthal coverage. In this volume, *Hazler*, *Sheehan*, *McNamara*, *and Walter* present one-dimensional shear-velocity models for several tectonic regions of North Africa by inverting average Rayleigh wave group velocity dispersion curves from 10 s to 160 s period. This set of 1-D models is posited as a replacement for a 3-D model which, the authors argue, cannot be reliably estimated given the poor data distribution traversing most of North Africa. On a vastly larger scale, *Stevens and McLaughlin* present the results of inverting group and phase velocities on a 5° × 5° grid worldwide.

The papers presented in this volume cut across essentially all of the major applications of surface waves to monitoring the CTBT. We believe that for this reason the volume will provide a reasonable introduction to the state of research in this area and act as a guide for further exploration.

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