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# Exploration Seismology

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# Exploration Seismology

SECOND EDITION

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# Preface

Many improvements have occurred in the seismic method since the publication of the first edition in 1982. Concepts that were of academic concern then have since become practical tools and some of the new concepts we have added may become tomorrow's tools.

We want this book to be a reference work as well as a textbook and guide for practicing geophysicists. These three objectives are not always compatible and readers will often skip over portions that do not fit their current needs, hopefully later referring back to skipped portions. For those readers who do skip about, we have cross-referenced sections, equations, and figures. For those who are rusty with their mathematics, we express concepts in words as well as by equations.

Our special interest is in the interpretation of geophysical data, but an interpreter needs to have a thorough understanding of geophysical principles in order to determine the validity of his data and the possibility that features he sees are artifacts of acquisition or processing. To this end, we have tried to emphasize seismic fundamentals.

We give a systematic derivation of relationships from first principles, except for a few cases where the derivations are excessively lengthy or involve higher mathematics, in which instances we refer the reader to other sources. As the preface to our first edition states, "A reader willing to take the mathematics on faith should be able to jump over the equations and still see the implications of the mathematical conclusions, which we have endeavored to explain in words rather than merely letting the equations speak for themselves. We have been encouraged by Sir Harold Jeffreys' preface to *The Earth* (1924):

> If the geologist cannot follow a part of the book, I hope he will omit it and go on. . . . Mathematically trained readers, with few exceptions, will do the same.

Our treatment of seismic theory has been expanded. We have expanded partitioning at interfaces, the heart of most seismic applications, and made it a separate chapter. Anisotropy, AVO, Stoneley waves, and tube waves, merely mentioned in our first edition, are now discussed in more detail. 3-D methods and 3-D interpretation now occupies an entire chapter. Techniques somewhat out of the mainstream, such as VSP, *S*-wave methods, and channel waves are now expanded into a full chapter on specialized techniques, and we have added new topics such as tomography and geostatistics. One chapter is devoted to nonpetroleum applications, including not only coal and engineering seismic work, but also the growing areas of groundwater, environmental, and reservoir geophysics. Our final chapter on mathematical background is again intended to refresh a reader's forgotten mathematical concepts.

Terms defined are indicated by *italics.* Precision of terminology is often one of the clearest indications of a person's degree of understanding and we have made special effort to define and use the specialized vocabulary of seismology precisely.

This book is structured to be as consistent as possible. Mathematical conventions, definitions, and the symbols used throughout the book are listed immediately following this preface. We have tried to conform to accepted practices and nomenclature, but we have had to use some symbols for several purposes.

Each chapter begins with an overview to orient the reader as to the various topics to be discussed and their relationship to each other. All chapters except the first end with problems; these endeavor to elucidate aspects not treated in the text and develop proofs and additional relationships. Each problem has been designed to illustrate a specific point and we have included hints where we anticipate students may have difficulty in knowing how to proceed. Enlarging the book's figures to use with the problems involving them should not prove difficult with the ready availability of enlarging copiers.

We acknowledge the assistance of many people in the preparation of this book and express our thanks to them. In addition to those cited in our first edition (Harry Mayne, Dan Skelton, Bill Laing, O. Leenhardt, Bruce Frizelle, Howard Taylor, Thomas Thompson, and Willis Reed), we particularly thank Barbara Barnes, Leslie Denham, Brian Evans, Tony Lauhoff, Dereck Palmer, and Margaret Sheriff for their help with this edition. We also express appreciation to the University of Houston Geosciences Department and the Curtin University of Technology (where one of us (RES) worked on this book while the Haydn Williams Fellow).

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# Mathematical conventions and symbols

## General rules and definitions

*General functions*

| | |
|---|---|
| $g_t$ | Function of the discrete variable $t = n\Delta$, $n = 0, \pm 1, \pm 2, \ldots$ |
| $g(t)$ | Function of a continuous variable $t$ |
| $g(t) * h(t)$ | Convolution of $g(t)$ with $h(t)$ |
| $\hat{g}(\zeta)$, $\hat{G}(\omega)$ | Functions involving the cepstrum transform: $\log G(\omega) = \hat{G}(\omega) \leftrightarrow \hat{g}(\zeta)$ |
| $G(\nu)$ | Transform of $g(t)$ to a function of frequency $\nu$; the arguments $\nu$ or $\omega$ indicate Fourier transform, $s$ Laplace transform, $z$ $z$-transform |
| $\phi_{gh}(\tau)$ | Correlation of $g(t)$ with $h(t)$ as function of the time shift $\tau$; a cross-correlation if $g \neq h$, $\phi_{gg}(\tau)$ = autocorrelation |

*Special functions*

| | |
|---|---|
| $\text{box}_a[t]$ | Boxcar of unit height and width $a$, centered at $t = 0$ |
| comb$[t]$ | Series of equally spaced unit impulses |
| sgn$[t]$ | Sign of $t = -1$ for $t < 0$, $+1$ for $t > 0$ |
| sinc$[t]$ | $(1/t) \sin t$ |
| step$[t]$ | Unit step function, step$(t) = 0$ for $t < 0$, $+1$ for $t > 0$ |
| $\delta[t]$, $\delta_t$ | Unit impulse at $t = 0$ |

*Mathematical conventions*

| | |
|---|---|
| $\approx$ | Approximately equal to |
| $\leftrightarrow$ | Denotes corresponding functions in different domains, the arguments $\nu$, $\omega$, $s$, $z$ indicating the type of transform; thus, $g(t) \leftrightarrow G(\nu)$ and $g(t) \leftrightarrow G(\omega)$ indicate Fourier transforms, $g(t) \leftrightarrow G(s)$ a Laplace transform, $g_t \leftrightarrow G(z)$ a $z$-transform; $g(x, y) \leftrightarrow G(\ell, \theta)$ a Radon transform; lowercase letters indicate the time domain, uppercase the frequency domain. |
| $[a, \overset{\downarrow}{b}, c, d]$ | Denotes a time sequence consisting of the elements $a, b, c, d$, with the superscribed arrow indicating the value associated with $t = 0$ ($b$ in this instance); values not otherwise specified are zero. |
| $\mathbf{A}$ | Vector quantity, magnitude is $\lvert\mathbf{A}\rvert$ |
| $\mathbf{A} \cdot \mathbf{B}$, $\mathbf{A} \times \mathbf{B}$ | Scalar and vector products of $\mathbf{A}$ and $\mathbf{B}$ |
| $\mathscr{A}$ | Matrix with elements $a_{ij}$ |
| $\mathscr{A}^{\mathrm{T}}$ | Transpose of matrix $\mathscr{A}$ |
| $\arg(\omega)$ | Argument of $\omega$ |
| $\mathfrak{B}$ | Principal value of |
| $\nabla$ | Del, the vector operator, $\mathbf{i}(\partial/\partial x) + \mathbf{j}(\partial/\partial y) + \mathbf{k}(\partial/\partial z)$ |
| $\nabla^2$ | Laplacian operator, $\partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$ |
| $\nabla\phi$ | Gradient of $\phi$ (grad $\phi$) |
| $\nabla \cdot \mathbf{A}$ | Divergence of $\mathbf{A}$ (div $\mathbf{A}$) |
| $\nabla \times \mathbf{A}$ | Curl of $\mathbf{A}$ (curl $\mathbf{A}$) |
| $\det(a)$ | Determinant with elements $a_{ij}$ |
| $\blacktriangle\{\quad\}$ | Difference operator |
| $D\{\quad\}$ | Derivative operator |
| $D^{-1}\{\quad\}$ | Integration operator |
| $E\{\quad\}$ | Delay operator |
| $\exp(x)$ | $e^x$ |
| $g(0+)$, $g(0-)$ | Value of $g$ when approaching 0 from right, left |
| $\overline{G(z)}$, $G(z^{-1})$ | Complex conjugate of $G(z)$ |
| $P(e_j)$ | Probability of $e_j$ |
| $\mathrm{Re}\{g(t)\}$, $\mathrm{Im}\{g(t)\}$ | Real, imaginary parts of $g(t)$ |
| $\lvert w\rvert$, $\lvert\mathbf{W}\rvert$ | Absolute value or modulus of $w$, $\mathbf{W}$ |
| $\dot{x}, \dot{y}, \dot{z}$ | Time derivatives of $x, y, z$ |
| $\prod_{i=0}^{n} a_i$ | Product $a_0 a_1 a_2 a_3 \cdots a_n$ |
| $\sum_{i=0}^{n} g_i$ | Sum $g_0 + g_1 + \cdots + g_n$ |
| $\sum_k g_k$ | Sum of $g_k$ over appropriate values of $k$ |

## Latin symbols

| | |
|---|---|
| $a$ | Element spacing, rate of increase of velocity with depth, area, width of a boxcar |
| $a, b, c$ | Constants |
| $a_i$, $b_i$ | Angles of incidence |
| $a_n$, $b_n$, $c_n$ | Fourier-series coefficients |
| $A, B$ | Constants |
| $A, B, C$ | Amplitudes of waves or of displacements |
| $A(t)$ | Amplitude of envelope, amplitude attributed to reflectivity |
| $A(\nu)$, $B(\nu)$ | Amplitude spectrum |
| $\mathscr{A}$, $\mathscr{B}$ | Amplitudes of displacement potential functions, matrices |
| $c_{\mathscr{V}}$, $c_{\mathscr{P}}$ | Specific heat at constant volume, pressure |
| $C$ | Incompressibility $= 1/k$, volume fraction of clay |
| $D$ | Displacement potential function for diffraction, distance |

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| | |
|---|---|
| $D_S$, $D_W$ | Depth of source, weathering |
| $e_i$ | Error in $i$th output |
| $e_t$ | Impulse response of sequence of reflectors |
| $E$ | Sum of errors squared, Young's modulus, energy, energy density, energy ratio |
| $E_s$, $E_d$ | Elevation of surface, datum |
| $E_R$, $E_T$ | Fraction of energy reflected, transmitted |
| $f(t)$, $f_t$ | Filter in time domain, function of $t$ |
| $f_H(t)$, $f_t^H$ | High-pass filter |
| $f_L(t)$, $f_t^L$ | Low-pass filter |
| $f_u(t)$ | Response of filter to unit step in time domain |
| $F$ | Array response, constant, magnitude of force, depth-conversion factor |
| $F(\nu)$, $F(\omega)$, $F(z)$ | Filter in frequency domain |
| $F_u(s)$ | Transform of response to unit step |
| $\mathbf{F}$ | Force, force per unit mass, vector wave function |
| $g$ | Acceleration of gravity |
| $g(t)$, $g_t$ | Seismic trace in time domain, input trace, function of $t$ |
| $g_\perp(t)$ | Quadrature trace |
| $\hat{g}(\zeta)$ | Cepstrum of $\hat{G}(\omega)$ or $\hat{G}(z)$ |
| $G(\nu)$, $G(\omega)$, $G(z)$ | Seismic trace in frequency domain |
| $h$ | Damping factor, distance to reflector or refractor, depth, thickness |
| $h(t)$, $h_t$ | Output in time domain |
| $\mathscr{h}(t)$, $\mathscr{h}_t$ | Desired output, complex trace |
| $H$ | Magnetic field strength, depth |
| $H(\nu)$, $H(\omega)$, $H(z)$ | Output in frequency domain |
| $\mathscr{H}(\nu)$, $\mathscr{H}(\omega)$, $\mathscr{H}(z)$ | Desired output in frequency domain |
| $i$ | Current, index |
| $i_0$ | Angle of raypath at source point |
| $i_t$ | Inverse filter in time domain |
| $\mathbf{i}$, $\mathbf{j}$, $\mathbf{k}$ | Unit vectors in $x$-, $y$-, $z$-directions |
| $I$ | Intensity |
| $I(\nu)$ | Transform of inverse filter |
| $\mathrm{j}$ | $(-1)^{1/2}$ |
| $j$ | Index |
| $k$ | Constant, bulk modulus, index |
| $K$ | Force on geophone coil per unit current, effective elastic modulus |
| $\ell$ | Distance in Radon transform |
| $\ell$, $m$, $n$ | Direction cosines relative to $x$-, $y$-, $z$-axes |
| $\ell_1$, $\ell_2$, $\ell_4$ | Criteria in optimum filtering |
| $L$ | Kinetic energy per unit volume, length, prediction lag, self inductance |
| $L_k$, $M_k$ | Delay at location $k$ due to structure, normal-moveout error |
| $m$ | Mass |
| $m$, $n$ | Constants, exponential decay parameters, integers |
| $M$ | Effective elastic modulus, width of fringe zone |
| $n$ | Integer, number of layers |
| $n_t$ | Impulse response of near-surface zone |
| $N$ | Noise |
| $p$, $p'$ | Raypath parameter |
| $P$ | Power |
| $p_t$ | Impulse response of waveshape-modifying factors in the earth |
| $\mathscr{P}$ | Pressure |
| $Q$ | Quality factor, probability |
| $r$ | Distance, integer, radius, radial coordinate |
| $r$, $s$ | Receiver, source coordinates |
| $r$, $R$ | Radius, resistance |
| $r_t$ | Additive noise |
| $R$, $R_i$ | Reflection coefficient of $i$th interface, displacement potential function for reflection |
| $R'$ | Resistivity |
| $R_k$, $S_k$ | Delay due to geophone, source at location $k$ |
| $R(\nu)$, $R(\omega)$ | Real part of Fourier transform = cosine transform |
| $s$ | Distance, Laplace transform parameter = $\sigma + \mathrm{j}\omega$ |
| $s_t$ | Impulse response of source |
| $S$ | Entropy density, semblance, signal, spring constant |
| $S_w$ | Water saturation |
| $\mathscr{S}$ | Area, surface |
| $t$ | Time, traveltime |
| $t_0$ | Traveltime for geophone at the source |
| $t_i$, $t_{iu}$, $t_{id}$ | Refraction intercepts |
| $t_{ij}$ | Time shift between traces $i$ and $j$ |
| $t_{uh}$ | Uphole time |
| $\Delta t$ | Time interval |
| $\Delta t_0$, $\Delta t_s$, $\Delta t_g$ | Near-surface corrections |
| $\Delta t_c$ | Differential weathering correction |
| $\Delta t_d/\Delta x$ | Dip moveout |
| $\Delta t_{NMO}$ | Normal moveout (NMO) |
| $T$ | Period, transmission coefficient |
| $\Delta T$ | Specific transit time = $1/V$ |
| $u$, $v$, $w$ | Displacements in $x$-, $y$-, $z$-directions |
| $\dot{u}$, $\ddot{u}$ | Time derivatives of $u$, $\partial u/\partial t$, $\partial^2 u/\partial t^2$ |
| $U$ | Group velocity |
| $v$ | Amplitude of geophone velocity |
| $v_t$ | Vibroseis™ input to ground |
| $V$ | Interval velocity, phase velocity, velocity of a wave |
| $\overline{V}$ | Equivalent average velocity |
| $V_a$ | Apparent velocity |
| $V_{\mathrm{rms}}$ | rms velocity |
| $V_s$ | Stacking velocity |
| $V_u$, $V_d$ | Apparent velocity in updip, downdip directions |
| $V_H$, $V_W$ | Velocity below, in the low-velocity layer (LVL) |
| $V_L$, $V_R$, $V_S$, $V_t$ | Velocity of Love, Rayleigh, Stoneley, tube waves |
| $\mathscr{V}$ | Volume |
| $w$ | Weighting factors |
| $w_t$ | Embedded (equivalent) wavelet, impulse |

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| | |
|---|---|
| | response of water layer, downgoing waveform |
| $W$ | $S$-wave acoustic impedance |
| $x$ | Displacement, distance, offset |
| $x'$, $x_c$ | Critical distance, crossover distance for a refraction |
| $X(\nu)$, $X(\omega)$ | Imaginary part of Fourier transform = −(sine transform) |
| $z$ | Depth, $z$-transform parameter |
| $Z$ | $P$-wave acoustic impedance |

**Greek symbols**

| | |
|---|---|
| $\alpha$ | $P$-wave velocity, angle, angle of approach |
| $\alpha_n$ | Fourier-series coefficients |
| $\beta$ | $S$-wave velocity, angle |
| $\gamma$ | Phase or phase difference, specific heat ratio, potential function, source density |
| $\gamma_n$ | Phase shift |
| $\gamma(t)$ | Instantaneous phase |
| $\gamma(\nu)$, $\gamma(\omega)$ | Phase spectrum |
| $\Gamma$ | Geophone transduction constant, measure of simplicity |
| $\delta$ | Angle of $S$-wave, delay time, logarithmic decrement |
| $\delta_s$, $\delta_g$ | Delay time associated with shotpoint, geophone |
| $\delta(t)$ | Unit impulse at $t = 0$ |
| $\Delta$ | Dilatation, increment, sampling interval |
| $\varepsilon$ | Eccentricity, phase shift upon reflection, strain |
| $\varepsilon_{xx}$, $\varepsilon_{xy}$ | Normal, shearing strains |
| $\boldsymbol{\varepsilon}$ | Error matrix |
| $\zeta$ | Argument of wave function, quefrency |
| $\boldsymbol{\zeta}$ | Vector displacement = $u\mathbf{i} + v\mathbf{j} + w\mathbf{k}$ |
| $\eta$ | Absorption coefficient |
| $\boldsymbol{\eta}$ | Outward-drawn unit normal |
| $\theta$ | Angle, angle of $P$-wave, argument of complex quantity, polar coordinate, spherical coordinate (colatitude) |
| $\theta_c$ | Critical angle |
| $\theta_x$ | Angle of rotation about $x$-axis |
| $\boldsymbol{\Theta}$ | Vector rotation = $\theta_x\mathbf{i} + \theta_y\mathbf{j} + \theta_z\mathbf{k}$ |
| $\kappa$ | Angular wavenumber = $2\pi$(wavenumber) = $2\pi/\lambda$ |
| $\kappa_a$ | $2\pi$(apparent wavenumber) |
| $\kappa_N$ | $2\pi$(Nyquist wavenumber) |
| $\lambda$ | Lamé constant, length ratio, constant, wavelength, weighting factor |
| $\lambda_a$ | Apparent wavelength |
| $\lambda_N$ | Nyquist wavelength |
| $\lambda_{\parallel}$, $\lambda_{\perp}$ | Lamé constants for transversely isotropic medium |
| $\mu$ | Mass ratio, mass/unit length, rigidity (shear) modulus (a Lamé constant) |
| $\mu_{\parallel}$, $\mu_{\perp}$, $\mu^*$ | Rigidity moduli for transversely isotropic medium |
| $\nu$ | Frequency = $\omega/2\pi = 1/T$ |
| $\nu_0$ | Natural frequency, fundamental frequency |
| $\nu_i(t)$ | Instantaneous frequency |
| $\nu_N$ | Nyquist frequency |
| $\boldsymbol{\nu}$ | Vector potential |
| $\xi$ | Dip, distance from origin to moving point on a curve |
| $\Xi$ | Strike |
| $\rho$ | Density, radius (of curvature) |
| $\sigma$ | Convergence factor, Poisson's ratio, standard deviation, strength per unit length |
| $\sigma_{xy}$ | Stress in $x$-direction on surface perpendicular to $y$-axis |
| $\tau$ | Damping factor, tension |
| $\Upsilon$ | Scalar wave function, source density |
| $\phi$ | Angle, loss angle, magnetic flux, porosity, $P$-wave displacement potential function, spherical coordinate (longitude) |
| $\phi_{gh}(\tau)$ | Correlation of $g(t)$ with $h(t)$ as function of time shift $\tau$ |
| $\Phi$ | Transform of $\Phi$, transform of $P$-wave displacement potential function |
| $\Phi_{gh}(\omega)$ | Cross-energy spectrum (transform of $\phi_{gh}(\tau)$) |
| $\chi$, $\boldsymbol{\chi}$ | $S$-wave displacement potential function |
| $\psi$ | Wavefunction, disturbance |
| $\psi(x, z, t)$ | Wavefunction in $x$, $z$, and $t$ dimensions |
| $\psi^*(x, z, t^*)$ | Wavefunction in moving coordinate system |
| $\Psi(\kappa_x, \kappa_z, \omega)$ | transform of wavefunction |
| $\Psi^*_{xz}(\kappa_x, \kappa_z, t)$ | Transform of wavefunction with respect to $x$, $z$ |
| $\omega$ | Angular frequency = $2\pi\nu$ |
| $\omega_0$ | Natural frequency |
| $\omega_N$ | Nyquist frequency |
| $\boldsymbol{\Omega}$ | Vector potential function for rotation |

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