CES

ARD A., ENDERS A. ROBINSON, and SVEN TREITEL (Eds.): The MIT Analysis Group (GAG) Reports, *Geophysics*, vol. 32, no. 3, 1967.
A.: The Dispersion of Surface Waves on Multilayered Media, *Bull. Am.*, vol. 43, pp. 17–34, 1953.
JON F.: Coarse Grid Calculations of Waves in Inhomogeneous Media ation to Delineation of Complicated Seismic Structure, *Geophysics*, 3, 1970.
JON F.: Numerical Holography, *Acoustic Holography*, vol. 3, Plenum
JON F.: Toward a Unified Theory of Reflector Mapping, *Geophysics*, 3, 1971.
JON F., and A. G. JOHNSON: Extrapolation of Time Dependent Wave- Their Path of Propagation, *Geophys. J. R. Astron. Soc.*, vol. 26, nos. –295, 1971.
, and JON F. CLAERBOUT: Numerical Calculations of Elastic Waves in homogeneous Media, *J. Geophys. Res.*, vol. 77, no. 8, pp. 1476–1482,
JON F., and S. M. DOHERTY: Downward Continuation of Moveout eismograms, *Geophysics*, vol. 37, no. 5, pp. 741–768, 1972.

[9] *IEEE Trans. Audio Electrostat.*, Special Issue on fast Fourier transform, June, 1967.
[10] WOLD, HERMAN: "Stationary Time Series," Almquist and Wiksell, Stockholm, 1938.
[11] ROBINSON, ENDERS A.: "Random Wavelets and Cybernetic Systems," Griffin, London, 1962.
[12] GRENANDER, ULF, and GABOR SZEGO: "Toeplitz Forms and Their Applications," University of California Press, Berkeley and Los Angeles, 1958.
[13] LEVINSON, NORMAN: The Wiener RMS (Root Mean Square) Error Criterion in Filter Design and Prediction, Appendix B *in* NORBERT WIENER: "Extrapolation, Interpolation and Smoothing of Stationary Time Series," Technology Press of the Massachusetts Institute of Technology, Cambridge, 1947.
[14] ATKINSON, F. V.: "Discrete and Continuous Boundary Problems," Academic Press, New York, 1964.
[15] WHITTLE, P.: "Prediction and Regulation," English Universities Press, Ltd., London, 1963.
[16] KOLMOGOROV, A.: Sur l'interpolation et l'extrapolation des suites stationnaires, *C. R. Acad. Sci.* (Paris), vol. 208, pp. 2043–2045, 1939.
[17] GABOR, D.: Theory of Communication, *J. IEEE*, vol. 93, no. 1, pp. 429–441, 1946.
[18] MOSTELLER, F., and R. E. K. ROURKE: "Sturdy Statistics," Addison Wesley Publishing Co., Inc., Reading, Mass., 1973.
[19] CLAERBOUT, J. F.: Spectral Factorization of Multiple Time Series, *Biometrica*, vol. 53, nos. 1 and 2, pp. 264–6, 1966.
[20] SENETA, EUGENE: "Non-Negative Matrices," John Wiley and Sons, Inc., New York, 1973.
[21] GOLUB, G.: Numerical Methods for Solving Linear Least Squares Problems, *Numerische Mathematik*, vol. 7, pp. 206–216, 1965.
[22] SINGLETON, R. S.: Algorithm 347 Sort, *Comm. ACM*, vol. 12, 1969.
[23] HOARE, C. A. R.: Quicksort, *Comput. J.*, vol. 5, pp. 10–15, 1962.
[24] PLACKETT, R. L.: Studies in the History of Probability and Statistics, Chapt. XXIX, *in* The Discovery of the Method of Least Squares: *Biometrica*, vol. 59, no. 2, pp. 239–251, 1972.
[25] CLAERBOUT, JON F., and FRANCIS MUIR: Robust Modeling with Erratic Data, *Geophysics*, vol. 38, no. 5, pp. 826–844, 1973.
[26] CLAERBOUT, JON F., and E. A. ROBINSON: The Error in Least-Squares Inverse Filtering, *Geophysics*, vol. 29, no. 1, pp. 118–120, 1964.
[27] BURG, JOHN PARKER: The Relationship Between Maximum Entropy Spectra and Maximum Likelihood Spectra, *Geophysics*, vol. 37, no. 2, pp. 375–376, 1972.
[28] WIDROW, B., P. E. MANTEY, J. J. GRIFFITHS, and B. B. GOODE: Adaptive Antenna Systems, *Proc. IEEE*, vol. 55, pp. 2143–2159, 1967.
[29] LEVIN, M. J.: Maximum Likelihood Array Processing, MIT Lincoln Laboratory Technical Report, 1964.
[30] GOUPILLAUD, P.: An Approach to Inverse Filtering of Near Surface Layer Effects from Seismic Records, *Geophysics*, vol. 26, no. 6, pp. 754–760, 1961.
[31] KUNETZ, G.: Generalization des opérateurs d'antirésonance a un nombre quelconque de réflecteurs, *Geophys. Prosp.*, vol. 12, pp. 283–289, 1964.
[32] WHITE, J. E.: Use of Reciprocity Theorem for Computation of Low-Frequency Radiation Patterns, *Geophysics*, vol. 25, no. 3, pp. 613–624, 1960.
[33] RICHTMYER, ROBERT D., and K. W. MORTON: "Difference Methods for Initial Value Problems," John Wiley and Sons, Inc., New York, 1967.

.: "Computational Methods in Partial Differential Equations," Sons, Inc., New York, 1969.
: "Introduction to Fourier Optics," McGraw-Hill Book Company, 3.
. L. SHANKS, and C. W. FRASIER: Some Aspects of Fan Filtering, 32, no. 5, pp. 789–800, 1967.
HEN M.: "Structure Independent Seismic Velocity Estimation," tation, Geophysics Department, Stanford University, Stanford,
.
NTON: "Wave Equation Synthesis and Inversion of Diffracted ic Reflections," doctoral dissertation, Geophysics Department, rsity, Stanford, California, 1975.

ENCES

Seismic Exploration: Technique and Processing, Birkhouser Verlag,

RICHARDS: *Quantitative Seismology,* Volume I and II, W. H. Freeman York, 1980.
l.): *Seismic Expression of Structural Styles: A Picture and Work Atlas.* n Geology #15, Volumes 1–3, 1983.
A. MOLOTKOV, and I. PSENCIK: *Ray Method in Seismology,* Univerzita e, 1977.
lied Geophysics: Introduction to Geophysical Prospecting, Geology ol. 1, Halsted Press, New York, 1981.
I., CHARLES F. VAN LOAN: *Matrix Computations,* Johns Hopkins Uni- altimore, Maryland, 1983.
N.: *Seismic Wave Propagation in Stratified Media,* Cambridge Univer- York, 1983.
Optimal Seismic Deconvolution, Academic Press, Inc., New York,

V., and R. W. SCHAFER: *Digital Signal Processing,* Prentice-Hall, Inc.

and M. T. SILVIA: *Digital Foundations of Time Series Analysis,* Holden
.
and SVEN TREITEL: *Geophysical Signal Analysis,* Prentice-Hall, Inc.,

Reflection Seismology, A Tool for Energy Resource Exploration, ence, New York, 1981.
Underground Sound: Application of Seismic Waves, Elsevier Science , Inc., New York, 1983.
d DENNIS CUMRO: *Worldwide Assortment of Seismic Field Records* (an 40 field profiles for academic use, includes a data tape) released by the hysical Company, P.O. Box 2469, Houston, Texas, 1983.
NTON: *Deconvolution,* International Human Resource Development Boston, 1984.

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