FORENSIC SEISMOLOGY AND NUCLEAR TEST BANS

With the signing in 1996 of the Comprehensive Nuclear Test Ban Treaty, interest has grown in forensic seismology: the application of seismology to nuclear test ban verification. When governments first enquired of their experts whether nuclear explosions fired underground could be detected and recognized from the seismic waves they generate, seismologists were unable to provide reliable advice. Stimulated by the demands of governments, forensic seismologists have since the 1950s educated themselves, and data collected for forensic seismology and the analysis methods developed have proved valuable for seismological research in general.

This book, based on over 50 years of experience in forensic seismology research, charts the development of methods of seismic data analysis. Topics covered include: the estimation of seismic magnitudes, travel-time tables and epicentres; seismic signal processing; and the use of seismometer arrays.

Illustrated with seismograms from explosions and earthquakes, the book demonstrates methods and problems of visual analysis. Exercises are provided for each chapter to help readers familiarize themselves with practical issues in the field of forensic seismology, and solutions to the exercises are available online. The book is a key reference work for academic researchers and specialists in the area of forensic seismology and Earth structure, and will also be valuable to postgraduates in seismology and solid earth geophysics.

ALAN DOUGLAS worked for over 35 years as a seismologist at the Atomic Weapons Establishment, Aldermaston. From 1982 to 2001 he was the Head of the AWE Seismology Group, and continues to act as a consultant to the AWE. For many years he was a Visiting Professor at The University of Reading and is currently a Visiting Professor at University College London. Professor Douglas is the author of over 100 research papers and reports on seismology applied to the verification of nuclear test ban treaties. In 2005 he received the Award for Service to Geophysics from the Royal Astronomical Society, of which he is also a Fellow.

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For Henry (Hal) Ivison Shipley Thirlaway.

Contents

Preface

Sometime in the early 1970s, Dr Ronald (Ron) Girdler, University of Newcastle, UK, made a plea for someone in the seismology group at the Atomic Weapons Establishment (AWE[1]), UK, to write a book on earthquake seismology based on the AWE's research in forensic seismology,[2] that is, seismology applied to the verification of nuclear test bans. The principal purpose of the research was to provide comprehensive advice on forensic seismology on which the UK government could base its policy for the control of underground nuclear tests. The work at the AWE, however, has applications to seismology in general which was what interested Ron Girdler.

The UK's forensic seismology programme began at the AWE in the late 1950s. Work was carried out at both AWE Aldermaston (principally on the design and manufacture of seismological recording systems) and at the outstation AWE Foulness (on decoupling, seismogram analysis and seismometry). In 1961, much of the forensic seismology work moved to an unclassified site at Blacknest, a country house near AWE Aldermaston. Over the next ten years forensic seismology research at the AWE was increasingly concentrated at Blacknest.

I and my colleagues at AWE Blacknest, Peter Marshall and Frederick (Fred) Key, produced a rough draft of a possible book but it was clear from the draft that: some of the subjects covered, such as the application of seismometer arrays in seismology were then still undeveloped; the analogue recording and processing systems then used were obsolescent; and overall, the range of subjects covered was too limited. The scope of the book was too restricted to be of use to undergraduates, postgraduates and practising seismologists.

With the opening for signature in 1996 of the Comprehensive Nuclear Test Ban Treaty (CTBT) there is a need for a book on forensic seismology. Many seem to assume that by now there must be standard methods of recording and processing seismograms and locating the seismic disturbances detected. If this were true, then it would just be a matter of applying to the observations some identification criteria to distinguish the suspicious disturbances from the definite earthquakes. Some progress towards standardization has

[1] Formerly the Atomic Weapons Research Establishment, AWRE.
[2] Forensic is defined as pertaining to courts of justice. Forensic medicine is the application of medical science to the elucidation of doubtful questions in such a court. The definition of forensic seismology is then obtained by substituting 'seismological' for 'medical'.

been made but more needs to be done and the process of identification seems unlikely ever to be a matter of applying well-defined rules. The process of identification resembles a criminal investigation: there are clues in the seismograms as to the nature of a disturbance and these have to be assessed and a decision made whether to charge the state suspected of carrying out a clandestine test and thus breaking the test ban, or to acquit the suspect.

The main area of expertise of AWE Blacknest is in the recording, interpretation and analysis of seismic signals recorded in the frequency band from around 0.01 to 10 Hz and particularly in the range 0.1–5 Hz. The principal aim is to extract as much information from the seismograms as possible. The seismologists have interpreted many thousands of seismograms and in the process accumulated a library of body-wave seismograms that are in some way noteworthy. Some conform to what is expected given accepted models of the earthquake and explosion source, whereas others appear to be inconsistent with such models and with current views on Earth's structure. Periodically there have been suggestions that a book on the interpretation of these seismograms would be useful. Such a book would, however, require a preamble describing the various methods of processing used to produce the seismograms. A third possible book has also been discussed: one describing the history of the AWE's work in forensic seismology. Such a history could not be written without covering much of the modern developments in seismology.

In this book I attempt to cover the subject matter of all three proposed books: forensic seismology; the history of the AWE's work in the subject; and noteworthy seismograms. The subjects covered are, as in the aborted book with Marshall and Key, those that have been of particular importance in forensic seismology, especially those in which AWE Blacknest, on behalf of the UK, has made significant contributions and which have applications in seismology in general. Now, however, the range of subjects covered is much greater than when Ron Girdler first made his plea over 35 years ago.

Who is the book for? The book is aimed principally at practising seismologists who are interested in using analysis techniques developed in forensic seismology. And I hope there is something of interest for seismologists simply curious as to the problems faced by those working in test ban verification. The book should be particularly useful to anyone thinking of specializing in forensic seismology. The International Monitoring System being set up to help verify compliance with the CTBT will always need forensic seismologists.

I also hope that the book will be of use to postgraduates in mathematics, physics, geology and geophysics carrying out research in seismology. In addition I will be disappointed if undergraduate students of geophysics do not learn something useful on observational seismology from the Prologue and Chapters 1–3. The book should provide ancillary material for seismology courses that include a forensic element.

Some of the figures have been produced using the Generic Mapping Tools (GMT) package and a few have been scanned from other publications. Neil Selby kindly supplied the figures showing the surface-wave radiation patterns. The remainder of the figures I have designed and produced using the graphics package of Bradford University Software Systems. Consequently, I have been able to tailor the bulk of the figures to better illustrate the point to be made than is usually possible with figures taken from the published work of others. It is planned to make copies of the figures available for download from the publisher's web site. I hope teachers of seismology will find the figures useful to illustrate their lectures. Several figures are from papers published by AWE Blacknest staff and are MoD Crown Copyright. I am grateful to the MoD for permission to reproduce these figures.

One difficulty with writing a book over a period of 35 years is that many of the books I used to teach myself basic statistics, signal processing and time-series analysis are long out of print. Most people find books early in their careers that become favorites because they are easy to use and clear in their explanations. I have retained these early references but include, on the advice of university staff and recent graduates, references to more modern books that are current favourites in universities.

Three people played a large part in the foundation of forensic seismology at the AWE: H. (Hal) I. S. Thirlaway, E. (Eric) W. Carpenter,[3] and F. (Frank) E. Whiteway. In the ten years from 1956 to 1966, Eric made significant advances in forensic seismology. In particular, he developed methods of computing P seismograms from explosion source and Earth models. Much of Eric's work formed the basis of later advances made at AWE Blacknest. Frank led the team of scientists and engineers, who designed and built the advanced seismological recording stations (arrays) that provided the AWE seismologists with some of the highest-quality seismograms available anywhere in the world.

Above all, the success of AWE Blacknest owes most to Hal who managed the forensic seismology programme for over 20 years until his retirement in 1982. As a manager he had a light touch, research staff were encouraged to follow their hunches, unpromising lines of research could be dropped after at most a brief report and new lines started almost overnight. Hal spent much of his day wandering around the building talking to staff, encouraging, guiding and, for junior staff, filling in a bit of history on the early days of forensic seismology; he also encouraged his staff to form links with universities, as visiting lecturers, supervisors of postgraduate research students and participants in joint research projects with university staff.

Countless others, practising forensic seismologists, students, academics and station operators have contributed to the work of AWE Blacknest. I and the other seismologists could not have carried out our research without the recordings provided by those who run seismological stations, and the support of data processors, seismogram analysts and programmers. I am especially grateful to John Young, one of the longest serving members of the seismology group, who taught me FORTRAN programming: together we built up a software library for the analysis and processing of seismological data that only began to be superseded in the year 2000. John assembled one of the best collections in the world of seismograms of explosions and significant earthquakes. The collection has been invaluable in preparing figures for this book.

Some of the others who have made significant contributions to the work of AWE Blacknest should be evident from the citations. I am grateful to all those who have contributed

[3] It was Kathleen Carpenter, Eric's wife, who first suggested the term 'forensic seismology' for seismology applied to test ban verification.

to what success AWE Blacknest has had, and for what I have learned from talking and working with them. I am also grateful to those who have read and commented on drafts of the book; these include Peter Marshall, David Bowers, David Green, John Douglas, Robert (Bob) Pearce and Ross Heyburn. I am particularly grateful to Peter Marshall and Bob Pearce. Peter not only read sections of the book but also helped to clarify points where my memory was hazy on the development of forensic seismology and the work at AWE Blacknest. Peter also tracked down obscure references. Bob read the whole book in great detail and made many suggestions on style and content. Despite all the good advice and help the book still contains errors: these errors are, unfortunately, all my own.

When I joined AWE Blacknest in 1964 much of the early excitement and optimism over a CTBT had evaporated. From 1958 through the Kennedy years giants of seismology and physics were engaged in negotiations that some assumed would end with the signing of the CTBT. The political upheavals associated with the Cold War meant that many began to see there was little prospect of a CTBT and had to settle for the Partial Test Ban, which prohibits tests everywhere except underground. Some of the early excitement is captured by Trebor Sirrah (aka Robert Harris), a US Naval Officer with a gift for parody and pastiche. Trebor's work was issued (privately I assume) in a pamphlet: 'a fault along the Potomac'. I have used quotes from the pamphlet as epigraphs to some of the chapters. If Trebor is still around I would love to hear from him.

Abbreviations and mathematical symbols

Abbreviations

AWE	Atomic Weapons Establishment, Aldermaston.
AWRE	Atomic Weapons Research Establishment, Aldermaston.
CANSAM	Canadian Seismic Array Monitor.
CCD	Conference of the Committee on Disarmament.
CGS	Coast and Geodetic Survey.
CMT	Centroid-moment-tensor.
col	Column vector.
CTBT	Comprehensive Nuclear Test Ban Treaty.
CTBTO	Comprehensive Nuclear Test Ban Treaty Organization.
DAMTP	Department of Applied Mathematics and Theoretical Physics, Cambridge.
DPRK	The Democratic People's Republic of Korea.
DS	Delay-and-sum array processing.
DSS	Designated Seismic Station.
E–W	East–West.
EMF	Electromotive force.
EUS	Eastern USA.
FFT	Fast Fourier transform.
FM	Frequency modulation.
GCI	Global communications infrastructure.
GSE	Ad Hoc Group of Scientific Experts.
GSETT 1, 2 and 3	Group of Scientific Experts Technical Tests 1, 2 and 3.
GT*n*	Ground truth event – epicentre known to within *n* km.
HF	High frequencies.
HSM	Homogeneous station method.
IAEA	International Atom Energy Agency.
IASPEI	International Association for Seismology and the Physics of Earth's Interior.
*iasp*91	The IASPEI travel time tables.

IMS	International Monitoring System.
IDC	International Data Centre.
IRIS	Incorporated Research Institutes for Seismology.
ISC	International Seismological Centre.
ISS	International Seismological Summary.
J–B Tables	Jeffreys–Bullen travel-time tables.
JED	Joint epicentre determination.
JHD	Joint hypocentre determination.
JVEs	Joint Verification Experiments.
LASA	Large Aperture Seismic Array.
Lg	Short-period surface wave.
LHS	Left-hand side of an equation.
LP	Long period.
LRSM	Long-range seismic measurements.
LSMF	Least squares matrix factorization.
LVZ	Low velocity zone.
MoD	UK Ministry of Defence.
MIT	Massachusetts Institute of Technology.
MP	Minimum power.
MSE	Minimum signal error.
NEA	Noise-equivalent acceleration.
NEIC	National Earthquake Information Center.
NGO	Non-government organization.
NLNM	New Low Noise Model.
NTS	Nevada Test Site.
N–S	North–south.
NZ	Novaya Zemlya.
OSI	On-site inspection.
P_1–P_4	Concrete piers on which seismometers operate in the WOL vault.
PDE	Preliminary determination of epicentre.
pIDC	Provisional International Data Center.
PNE	Peaceful nuclear explosion.
PNET	Peaceful Nuclear Explosion Treaty.
PREM	Preliminary Reference Earth Model.
PTBT	Partial Test Ban Treaty.
RDP	Reduced displacement potential.
REB	Reviewed Event Bulletin.
Rg	Short-period Rayleigh wave.
RHS	Right-hand side of an equation.
rms	Root-mean-square.
RVP	Reduced velocity potential.
SADA	Seismometer Array Data Analyser.

SASP	Seismometer array station processor.
SDCS	Special Data Collection System.
SIPRI	International Institute for Peace and Conflict Research.
SNI	Signal-to-noise improvement.
SNR	Signal-to-noise ratio.
SP	Short period.
SRAS	Seismic record analysis sheet.
SSSC	Source-specific station-correction.
STS	Shagan River Test Site.
TTBT	Threshold Test Ban Treaty.
TWG II	Technical Working Group II.
UGT	Underground nuclear test.
UK	United Kingdom of Great Britain and Northern Ireland.
UN	United Nations.
UNIDIR	United Nations Information Directorate.
USA	United States of America.
USSR	Union of Soviet Socialist Republics.
VBB	Velocity broad band.
WUS	Western USA.
WWSSN	World Wide Standardized Seismograph Network.

Seismological stations

AD-IS	Adak Island, Aleutian Islands, Alaska, USA (51.88° N 176.68° W).
AAK	Ala-Archa, Kyrgyzstan (42.63° N 74.49° E).
ANMO	Albuquerque, New Mexico, USA (34.95° N 106.46° W).
ALPA	Alaska Long Period Array (ALAR) USA (65.07° N 147.56° W).
AR-WS	Aurora, Wisconsin, USA (45.70° N 88.14° W).
ARE	Arequipa, Peru (16.46° S 71.49° W).
ARCES	ARCESS, Array, Norway (69.53° N 25.51° E).
ARU	Arti, Sverdlovskaya Oblast, Russia (56.43° N 58.56° E).
ASAR	Alice Springs Array, Australia (23.67° S 133.90° E).
AX-AL	Alexander City, Alabama, USA (32.84° N 86.18° W).
BCAO	Bangui, Central African Republic. (4.43° N 18.54° E).
BE-FL	Belleview, Florida, USA (28.91° N 82.06° W).
BL-WV	Beckley, W. Virginia, USA (37.80° N 81.31° W).
BNA	Blacknest Array, UK (51.36° N 1.19° W).
BKN	Blacknest, UK (51.36° N 1.19° W).
BOSA	Boshof, South Africa (28.61° N 25.26° N),
BR-PA	Berlin, Pennsylvania, USA (39.92° N 78.84° W).
BRVK	Borovoye, Kazakhstan (53.06° N 70.28° E).
BUW	Buckleberry West, UK (51.41° N 1.22° W).

CCM	Cathedral Cave, Missouri, USA (38.06° N 91.24° W).
CMAR	Chang Mai Array, Thailand (18.46° N 98.94° E).
COL	College Outpost, Alaska, USA. (64.90° N 147.79° W).
COR	Corvallis, Oregon, USA (44.59° N 123.30° W).
CP-CL	Campo, California, USA (32.73° N 116.37° W).
DH-NY	Delhi, New York, USA (42.24° N 74.89° W).
DR-CO	Durango, Colorado, USA (37.46° N 107.78° W).
EKA	Eskdalemuir Seismometer Array, UK (55.33° N 3.16° W).
FCC	Fort Churchill, Canada (58.76° N 94.09° W).
FINES	FINESS Array, Finland (61.44° N 26.08° E).
FK-CO	Franktown, Colorado, USA (39.58° N, 104.46° W).
FM-UT	Fillmore, Utah, USA (39.22° N 112.21° W).
GBA	Gauribidanur Seismometer Array, India (13.60° N 77.44° E).
GRF	Graefenberg Seismological Observatory, Germany (49.69° N 11.22° E).
GV-TX	Grapevine, Texas, USA (32.89° N 97.00° W).
HEA	Headley, UK (51.36° N 1.26° W).
HIA	Hailar, Nei Monggol Zizhiqu, China (49.27° N 119.74° E).
HL-ID	Hailey, Idaho, USA (43.65° N 114.25° W).
HN-ME	Houlton, Maine, USA (46.16° N 67.99° W).
HY-MA	Hysham, Montana, USA (45.97° N 107.08° W).
JE-LA	Jena, Louisiana, USA (31.78° N 92.02° W).
JP-AT	Jasper, Alberta, Canada (52.90° N 118.09° W).
JR-AZ	Jerome, Arizona, USA (34.83° N 111.99° W).
KEV	Kevo, Finland (69.76° N 27.01° E).
KC-MO	Kansas City, Missouri, USA (39.36° N 94.67° W).
KMI	Kunming, Yunnan, China (25.12° N 102.74° E).
KN-UT	Kanab, Utah, USA (37.02° N 112.83° W).
KON	Kongsberg Seismological Observatory, Norway (59.65° N 9.60° E).
LASA	Large Aperture Seismic Array, Montana, USA (46.69° N 106.22° W).
LC-NM	Las Cruces, New Mexico, USA (32.40° N 106.60° W).
LV-LA	Liddieville, Louisiana, USA (32.14° N 91.88° W).
MAJO	Matsushiro, Nagano, Japan (36.54° N 138.21° E).
MAT	Matsushiro, Nagano, Japan (36.54° N 138.21° E).
MDJ	Mudanjiang, Jilin, China (44.62° N 129.59° E).
MIAR	Mount Ida, Arkansas, USA (34.55° N 93.57° W).
MN-NV	Mina, Nevada, USA (38.44° N 118.15° W).
MO-ID	Mountain Home, Idaho, USA (43.07° N 116.27° W).
MV-CL	Marysville, California, USA (39.21° N 121.29° W).
MBC	Mould Bay, Canada (76.24° N 119.36° W).
NIL	Nilore, Pakistan (33.65° N 73.25° E).
NAO	Norwegian Seismic Array (NORSAR), Norway (60.82° N 10.83° E).
NEW	Newport, Washington, USA (48.26° N 117.12° W).

NG-WS	Niagara, Wisconsin, USA (45.76° N 88.15° W).
NHA	Nha-Trang, Vietnam, (12.21° N 109.21° E).
NORES	NORESS Array, Norway (60.74° N 11.54° E).
NP-NT	Mould Bay, NW Territory, Canada (76.25° N 119.37° W).
NVS	Novosibirsk, Novosibirskaya Oblast, Russia Federation (54.84° N 83.23° E).
OBN	Obninsk Seismological Observatory, Russian Federation (55.11° N 36.57° E).
PG-BC	Prince George, British Columbia, Canada (54.00° N 122.52° W).
PM-WY	Pole Mountain, Wyoming, USA (41.21° N 105.36° W).
PMW	Pole Mountain, Wyoming, USA (41.21° N 105.34° W).
QIZ	Qiongzhong, Hainan Dao, China (19.03° N 109.84° E).
QUE	Quetta, Pakistan (30.19° N 66.95° E).
RK-ON	Red Lake Ontario, Canada (50.84° N 93.67° W).
RSSD	Black Hills, S. Dakota, USA (44.12° N 104.04° W).
SI-BC	Smithers, British Columbia, Canada (54.79° N 127.07° W).
SJ-TX	San Jose, Texas, USA (27.61° N 98.31° W).
SSE	Sheshan, Jiangsu, China (31.10° N 121.19° E).
SV3QB	Schefferville, Quebec, Canada (54.81° N 66.75° W).
SW-MA	Sweetgrass, Montana, USA (48.97° N 111.96° W).
TF-CL	Taft, California, USA (35.16° N 119.97° W).
TFO	Tonto Forest Observatory, USA (34.27° N 111.27° W).
TUL	Tulsa, Oklahoma, USA (35.91° N 95.79° W).
UKNET	UK network of broad-band stations.
UPP	Uppsala, Sweden (59.86° N 17.63° E).
WDC	Whiskeytown Dam, California, USA (40.58° N 122.54° W).
WH-YK	Whitehorse, Yukon Territory, Canada (60.73° N 135.15° W).
WI-NV	Winnemucca, Nevada, USA (41.35° N 117.46° W).
WMQ	Urumqi, Xinjiang Uygur Zizhiqu, China (43.82° N 87.70° E).
WMSO	Wichita Mountains Seismic Observatory, USA (34.72° N 98.59° W).
WOL	Wolverton, UK (51.31° N 1.22° W).
WRA	Warramunga Seismometer Array, Australia (19.95° S 134.35° E).
YKA	Yellowknife Seismometer Array, Canada (62.49° N 114.61° W).
YSNY	Yorkshire, New York, USA (42.48° N 78.54° W).

Mathematical symbols

Some symbols have several definitions.

$\widehat{}$	An estimate.
α	P-wave speed. Significance level. Scalar multiplier. A ratio of electrical resistance to inductance.

α_{n}	Speed of the $\mathrm{P_n}$ wave.
α_0	P-wave speed in the surface layer or half-space at the receiver.
α_1	P-wave speed in the source layer or half-space at the source.
β	S-wave speed.
β_0	The S-wave speed in the surface layer.
$\boldsymbol{\beta}$	Vector of unknowns.
$\Gamma(\boldsymbol{\kappa})$	Array response.
γ	The logarithmic decrement: $\ln(A_r/A_{r+1})$ or $\lambda_{\mathrm{s}}\pi/(1-\lambda_{\mathrm{s}}^2)^{1/2}$. The coefficient of anelastic attenuation for Lg. Standard deviation of the detection threshold.
$\gamma_{12}(\omega)$	Coherence.
Δ	Epicentral distance.
Δf	Digital frequency interval.
Δt	Digital sampling interval.
δm	A small mass used in seismometer calibration.
$\delta(t)$	Delta function.
ΔW	Loss of energy in one cycle of an elastic wave.
ϵ_j	Error in arrival time at a seismometer of an array.
$\epsilon(l+1)$	The prediction error.
ε	An estimate of the standard deviation of observations.
ζ	Angle between the seismometer spring and the vertical. A $\pi/4$ phase shift.
θ	Angle between the X_2 axis and a ray. Angle of incidence of S.
θ_0	Angle of incidence below a dipping boundary.
θ_1	Angle of incidence at the free surface.
θ_{I}	Angle of incidence.
θ_{P}	Take-off angle of P.
θ_{S}	Take-off angle of S.
ϑ	Colatitude of a point of observation relative to the epicentre as pole. Azimuth of a station from an epicentre measured clockwise from north. Angular deflection of a galvanometer mirror. Deflection of a seismometer boom from the horizontal.
ϑ_j	Azimuth of a station j from an epicentre measured clockwise from north.
ϑ_{ij}	Azimuth of a station j from an epicentre i measured clockwise from north.
κ	Angular-horizontal wave number.
$\boldsymbol{\kappa}$	Vector wave number $\omega/\mathbf{c}$.
κ_{x}	Component of the horizontal wave number in the x direction.
Λ	Boltzmann's constant.
λ	Horizontal wavelength. A Lagrangian multiplier.

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More information

$\lambda(k)$	kth element of a vector of Lagrangian multipliers.
λ_s	Seismometer damping.
λ_G	Galvanometer damping.
μ	A variable.
	The modulus of rigidity.
	The 50% detection threshold.
	Jeffreys' parameter.
ν	Measure of proportion of non-gaussian errors.
ϖ	Jeffreys' weighting function.
ρ	Density.
	Correlation coefficient.
ρ_0	Density in the surface layer or half-space at the receiver.
ρ_1	Density in the source layer or half-space.
ρ_{ij}	Correlation coefficient between channels i and j.
σ^2	Variance. σ is the root-mean-square (rms).
σ_s^2	Variance of the station-magnitude estimates about the true value.
σ_1^2 and σ_2^2	Noise power on channels 1 and 2.
σ_ϖ^2	A variance.
σ_{AV}^2	Average noise power over all channels of an array.
σ_B^2	Noise power on the beam of an array.
σ_{DS}^2	Noise power on the DS output of an array.
σ_{MP}^2	Noise power on the MP output of an array.
$\sigma_s\sigma_G$	Coupling between seismometer and galvanometer.
τ	A time interval, sampling interval, lag or rise time.
$\Phi'_{12}(l)$	Cross-correlation function.
$\Phi_{12}(l)$	Cross-covariance function.
$\phi(\omega)$	Phase at frequency ω.
$\Phi(u)$	The standard cumulative normal distribution.
Φ_{DS}	$(\sigma_{AV}^2/\sigma_{DS}^2)^{1/2}$.
Φ_{MP}	$(\sigma_{AV}^2/\sigma_{MP}^2)^{1/2}$.
Φ_A	Φ_{MP}/Φ_{DS}.
ϕ	Back azimuth from a station to an epicentre measured clockwise from north.
	Angle between the X_3 plane and the plane containing the ray and the X_2 axis.
	Angle of reflection of P.
ϕ^a	Phase shift of seismometer for ground acceleration.
ϕ^d	Phase shift of seismometer for ground displacement.
ϕ^v	Phase shift of seismometer for ground velocity.
φ	Dip of a boundary.
$\psi(t)$	Reduced displacement potential.
ω	Angular frequency.

ω_0	An angular frequency.
ω_{H}	A high-frequency limit.
ω_{L}	A low-frequency limit.
ω_{c}	Corner frequency.
ω_{N}	Nyquist frequency.
ω_{G}	Galvanometer natural frequency.
ω_{s}	Seismometer natural frequency.

$\mathcal{A}$	Time-domain amplitude for magnitude estimation.
$\mathcal{A}_0$	An amplitude measured on a seismogram.
A	Amplitude.
	Constant of integration.
A_0	An amplitude.
$A(t)$	A time series.
$A(\omega)$	Amplitude at frequency ω
A_r	Amplitude of peak r.
A_{a}	Constant acceleration response.
A_{d}	Constant displacement response.
A_{v}	Constant velocity response.
$A(\Delta, h, H)$	Arrival time at distance Δ, from depth h, origin time H.
$\mathcal{A}_{20}$	The maximum horizontal ground movement for surface waves of 20 s period.
A_{ij}	Arrival time at station j from source i.
$\mathcal{A}_{\max}$	The maximum amplitude of a surface wave signal.
a	Yield exponent.
	Activity constant.
	Fall-off of gaussian filter.
	Dispersion exponent.
	Array scaling constant.
$a_1(\omega)$	Response of a short-period recording system as a function of ω.
$a_2(\omega)$	Response of a broad-band recording system as a function of ω.
$a_j(\omega)$	A weight for channel j at frequency ω.
a_1 and a_2	Exponents in complimentary function of a seismometer.
a'	Activity constant.
a_{ijk}	$\log_{10}(\mathcal{A}/\mathcal{T})$, for the ith source at station j in the kth distance range.
B	Dimensionless quantity in the reduced-displacement potential.
	Constant of integration.
B or $B(\kappa)$	Wave-number response of an array.
$B_{\mathrm{b}}(\Delta)$	The calibration function for estimating m_{b} at distance Δ.
$B^s_{20}(\Delta)$	The calibration function for estimating M_{s} at distance Δ from 20 s period surface waves.

$\mathrm{B}(\Delta, h)$	Calibration curve for computing magnitude for distance Δ and focal depth h.
$b(\omega)$	The response with frequency ω of an attenuation operator.
b	Yield exponent. b value.
	Effect of source size.
b'	b-value.
b_i	Effect of source size.
b_1	$\mathrm{d}k/\mathrm{d}\omega$.
b_2	$\mathrm{d}^2k/\mathrm{d}\omega^2$.
C	Station magnitude correction.
C_s	The spring constant: restoring force per unit extension.
C_G	Restoring force per unit deflection of a suspended galvanometer mirror.
c	Speed.
	Apparent – surface speed.
	Phase speed.
	Magnitude baseline effect.
$\mathbf{c}$	Wave velocity.
	Apparent-surface velocity.
	Phase velocity.
c_R	Rayleigh wave speed.
D	Correction for variation in pP−P time for explosions.
	Determinant of a matrix.
	Twice the side length of a four-element square array.
D_s	Seismometer damping.
D_G	Galvanometer damping.
D_k	Trial distance effect for the kth distance interval. Interval over which slowness is $\mathrm{d}T/\mathrm{d}\Delta_k$.
d	Distance between seismometers.
	Initial extension of a spring.
	Ground displacement.
	Deflection of the central plate of a differential seismometer.
d_KS	Kolmogorov–Smirnoff distance.
$\mathrm{d}T/\mathrm{d}\Delta$	Gradient of a travel time curve in seconds per degree.
E	EMF.
$E(t)$ and $-E(t)$	Voltages on the upper and lower plates of a differential capacitor used in feedback seismometers.
E_0	Output from a differential capacitor for a deflection of the central plate of d.
$\mathrm{E}(e)$	Expectation of e.
ER	Energy ratio.
E_i	Effect for explosion i.

$e(t)$	Envelope of spectrogram.
	Deviation in a signal from the average.
F	Constant of integration.
$F^{\mathrm{P}}(t, t^*)$	The attenuation operator for P waves.
$F(t)$	Applied force due to Brownian motion.
$\mathrm{F}_{95,p,n}$	The 95% F statistic for p and n degrees of freedom.
$f(t)$	A time series.
$f_{\mathrm{H}}(t)$	The Hilbert transform of $f(t)$.
$f_{\mathrm{A}}(t)$	Analytic function of $f(t)$.
f	Frequency.
f_{c}	Corner frequency.
f_{N}	Nyquist frequency.
G	Threshold.
$G^{\mathrm{P}}(\Delta)$	The effect of geometrical spreading of P waves.
g	Acceleration due to gravity.
$g(t)$	A time series.
H	Origin time.
	Flux density in the seismometer air gap.
H_i	The trial origin time of source i.
$\mathbf{H}$	A matrix of equations of condition.
h	Focal depth.
$h(t)$	The impulse response of a filter.
	A time series.
$h_{\mathrm{H}}(t)$	The Hilbert transform of $h(t)$.
$h_1(t)$, $h_2(t)$ etc	Digital time series.
I	Electric current.
I_{A} and I_{B}	Currents flowing in a T-attenuator network linking seismometer and galvanometer.
$I(t)$	Impulse response of a seismograph.
$J_0(x)$	The zero-order Bessel function of the first kind.
K	A factor independent of distance.
	Moment of inertia of the suspended mass of a galvanometer.
K_{s}	Electrodynamic constant of a seismometer.
K_{G}	Electrodynamic constant of a galvanometer.
K_{c}	Electrodynamic constant of a seismometer calibration coil.
k	Time constant in the Haskell source.
$\mathcal{K}$	$\kappa/2\pi$.
ℓ_j, θ_j	Polar coordinates of seismometer j in an array.
l	A length.
	Length of a pendulum.
	Half the separation of the upper and lower capacitor plates in a feedback seismometer.

$\mathcal{L}_0$	Physical length of a 'zero-length' spring.
L	Likelihood.
	An integer.
	Inductance.
	Number of seconds per degree.
$L/2$	The separation between seismometers.
$L_S(t)$	Response of the source layers.
$L_R(t)$	Response of the receiver layers.
$\mathcal{M}$	Magnitude.
m	An integer.
	Number of seismometers in an array.
m_b	Body-wave magnitude.
m_b^T	m_b threshold.
m_b^{ML}	Maximum-likelihood m_b.
m_b^{ISC}	ISC m_b.
M	Mass.
M_s	Surface-wave magnitude.
$m_b(Lg)$	Body-wave magnitude computed from Lg.
m_Q	Body-wave magnitude of explosions corrected for depth and attenuation.
N	An integer.
$\mathcal{N}_c(\mathcal{M})$	Number of earthquakes per unit time with magnitude greater than $\mathcal{M}$.
$N_{\mathcal{I}}(\mathcal{M})$	Number of earthquakes per magnitude per unit time with magnitude $\mathcal{M}$.
N	Number of earthquakes per unit time at each magnitude (or $\log_{10} \mathcal{A}/\mathcal{T}$) in intervals of 0.1 magnitude units.
$\mathcal{N}_c^o(\mathcal{M})$	Observed number of earthquakes with magnitude greater than $\mathcal{M}$.
$\mathcal{M}^T$	A detection threshold.
$\mathcal{M}_{90}^c$	The 90% cumulative detection threshold.
$\mathcal{M}_{90}^{\mathcal{I}}$	The 90% incremental detection threshold.
n	An integer, for example, number of seismometers in an array; number of degrees of freedom.
	Number of turns in the air gap.
$\mathbf{o}$	Column vector of zeros.
$\mathcal{P}$	Stress drop.
$P\mathrm{e}^{i\omega t}$	A sinusoidal force.
$P(\mathcal{T})$	Path correction for surface waves of period $\mathcal{T}$.
$\mathrm{P_n}(\cos\theta)$	Legendre polynomial of the first kind.
$P(m'\|m, \sigma)$	Probability of choosing a value m' from a population of mean m and variance σ.
P_A	The probability that an earthquake of magnitude m is detected at station A.

$\check{P}_{\mathrm{A}}$	The probability that an earthquake of magnitude m is not detected at station A.
p	An integer.
$\mathrm{Q_n}(\cos\theta)$	Legendre polynomial of the second kind.
Q	Quality factor.
Q_{AV}	Average quality factor for P waves.
Q_α	Quality factor for P waves.
Q_β	Quality factor for S waves.
Q_γ	Quality factor for Rayleigh waves.
Q_0	A sum of squares.
R	Radius of Earth.
$\mathcal{R}$	Decay of Rayleigh waves with distance.
$\mathbf{R}$	Noise correlation matrix.
R_{A}	$R_1 + R_{\mathrm{s}}$.
R_{B}	$R_2 + R_{\mathrm{G}}$.
R_{G}	Internal resistance of a galvanometer.
R_{s}	Internal resistance of a seismometer.
R_{L}	Resistive load.
R_0, R_1 & R_2	Resistances in a T-attenuator network linking seismometer and galvanometer.
R_{Q}	$\sqrt{(R_{\mathrm{A}} + R_0)(R_{\mathrm{B}} + R_0) - R_0^2}$.
R_{ij}	P radiation coefficient for source i for given take-off angle and azimuth to array j.
R_{p}	Reflection coefficient for P incident at the free surface.
r and r_k	Distance magnitude effect.
r	An integer count.
	Radius of the seismometer coils.
$r(j)$	jth element of an autocorrelation function.
$\bar{r}(\omega)$	Power at frequency ω for noise model.
$\bar{r}_{\mathrm{DS}}(\omega)$	Power at frequency ω for noise model on the DS output.
$\bar{r}_{\mathrm{MP}}(\omega)$	Power at frequency ω for noise model on the MP output.
$\mathbf{S}$	Coefficient matrix of normal equations.
s_{jj}	The jth diagonal element of $\mathbf{S}^{-1}$.
$\mathcal{S}$	Semblance.
S	Area of the fault plane.
S_j	Station effect at station j, or seismometer j in an array.
$S(t)$	Source radiation.
$\mathbf{s}$	Vector slowness.
s	Distance of the edge of a fault plane from the centre along a radius through a point.
	The radius of the fault plane.
	Station magnitude effect.

s_j	Magnitude effect for station j.
$s(t)$	A signal.
T	Travel time. Baseline shift in travel time tables. Tension in a spring. Substitute variable for integration.
$T(\Delta, h)$	Travel time from depth h to distance Δ
T_s	True period of a seismometer.
T_{ij}	The travel time from the trial hypocentre of source i to station j.
T_0	Tension required to extend a 'zero-length' spring to its physical length.
$\mathcal{T}$	Period (s).
$\mathcal{T}_s'$	Apparent natural period of a damped seismometer.
$\mathcal{T}_s$	Natural period of an undamped seismometer: $2\pi/\omega_s$.
t_0	Arrival time at the origin of an array.
t_r	Time of rth peak.
t_j	Arrival time at seismometer j.
t^*	Ratio of travel time to Q_{AV}.
t	Time, both continuous and sampled.
t_u	Group travel time.
$t_{95,n}$	Student's t at the 95% level and n degrees of freedom.
U	Group speed.
u^N	North–south ground motion.
u^E	East–west ground motion.
u^R	Radial ground motion.
u^T	Transverse ground motion.
$\overline{u}$	The average slip on the fault plane.
$\mathbf{u}$	Vector of coefficients of a multichannel filter.
$\mathbf{u}_i$	Vector of filter coefficients for channel i.
$u_i(k)$	kth filter coefficient for channel i.
$u(t)$	A function of time.
$\bar{u}_z(\omega, \Delta)$	The vertical component of the fundamental-mode Rayleigh wave.
u_r	The radial displacement at distance r.
V_D^a	Dynamic magnification of a seismometer for ground acceleration.
V_D^v	Dynamic magnification of a seismometer for ground velocity.
V_D^d	Dynamic magnification of a seismometer for ground displacement.
V_s	Static magnification of a seismometer.
v	Voltage. Speed of fracture propagation.
W	Energy in one cycle of an elastic wave.
$w(t)$	Impulse response of a filter.
X	Load resistance on a seismometer.
$\mathbf{X}$	A coefficient matrix.
$X(t)$	A complex time series.
$\bar{X}(\omega)$	Fourier transform of $X(t)$.

x	Relative displacement $(z - y)$ of mass and frame of a seismometer. Distance.
$x_1(t)$, $x_2(t)$ etc.	Digital time series.
$\mathbf{Y}$	A matrix.
$\mathbf{y}$	A vector of observations.
y	Position of seismometer mass above equilibrium position.
$y(t)$	Digital time series.
Y	Load resistance on a galvanometer. Explosion yield (kt).
z^{a}	Ground acceleration.
z^d	Ground displacement.
z^v	Ground velocity.

Prologue

Politics and science, Politics and science,
They make a real ideal alliance,
Pick out a threshold to fit your plan,
Anything goes boy! Get that test ban!
Trebor Sirrah (aka Robert Harris)
a fault along the Potomac

In September 1996 the United Nations Information Directorate (UNIDIR) held a press conference in Geneva to announce the successful negotiation of a treaty, the Comprehensive Nuclear Test Ban Treaty (CTBT), that when it enters into force will ban all nuclear explosions. At the request of the UNIDIR, Peter Marshall of the Blacknest Seismology Group of the Atomic Weapons Establishment (AWE) joined the panel to answer technical questions from the press (Figure 1). Why was Peter amongst all the experts who had attended the negotiations chosen to join the panel? Because all the delegates recognized that through his personal qualities and his expertise Peter contributed more than anyone else to the success of the technical negotiations. Professor Dr Peter Wille (German Delegation) expressed what many delegates felt:

> There is no doubt in my mind that this common work would not exist without the unique leadership and guidance of Peter Marshall . . . I consider him the embodiment of credibility, of impartial confidence and judgement and of the deep understanding of the opinions and needs of the various parties and individuals. He has also an excellent . . . disarming sense of humour.

Peter was able to make such a significant technical contribution to the negotiations because he had worked on the application of seismology to the verification of arms-control treaties, that is, forensic seismology, from its beginnings. He was one of a small group of AWE scientists and engineers, who made some of the important advances in forensic seismology; he knew the whole history of the subject: the blind alleys and false dawns; and the strengths and weakness of the verification methods. It was the expertise built up by the group over nearly 40 years that allowed Peter on behalf of the UK (and UN) to play such a prominent role in the negotiations.

Figure 1 UN press conference held in Geneva on 26 September 1996, to announce the successful negotiation of the CTBT. Front row (from the left): Peter Marshall, CMG, OBE (AWE); V. Petrovsky, UN Under-Secretary General; Ms T. Gastaut, Director of the UN Information Directorate (UNIDIR); Ambassador J. Ramakar (Netherlands), Chairman of the CTBT Committee; S. Lodgaard, UNIDIR. (Copyright: Patrick Bertschmann, Studio Bianco)

Almost from the time that it was first realized that it would be possible to build nuclear weapons, there were pressures to curb their development and spread. The coming of the H-bomb in the early 1950s brought a new urgency to the search for ways of limiting such weapons. This led to the establishment of: the International Atomic Energy Agency (IAEA); Pugwash, the non-governmental organization (NGO) of concerned scientists; and in 1958, the first technical discussions – the Conference of Experts, held in Geneva – on how, if a CTBT was negotiated, compliance with such a treaty could be verified. The main conclusion of the Conference was that a suitable monitoring system could be set up to detect and identify explosions in space, in the atmosphere and underwater but not those fired underground.

The Experts meeting was followed by the Conference on the Discontinuance of Nuclear Weapon Tests at which Sir W. G. Penney (Director, AWE), Dr I. Maddock (also AWE) and Dr R. Press (UK Ministry of Defence (MoD)) were the main UK technical delegates. The main obstacle to progress at these negotiations was the difficulty of detecting and identifying explosions fired underground.

The only way of detecting underground explosions the Experts decided is by the seismic waves generated, in particular the first arriving P (primary, sound) wave; but then the