Time-Frequency Signal Analysis and Processing
List of Contributors

K. Abed-Meraim
Université d'Orléans, Orléans, France

J. Ahmad
Abasyn University, Islamabad, Pakistan

A. Aïssa-El-Bey
Institut Mines-Télécom, Télécom Bretagne, Brest Cedex 3, France

A. Akan
Istanbul University, Avcilar, Istanbul, Turkey

O. Akay
Dokuz Eylül University, Buca/Izmir, Turkey

S. Ali
Qatar University, Doha, Qatar

T. Alieva
Universidad Complutense de Madrid, Madrid, Spain

M.G. Amin
Villanova University, Villanova, PA, USA

S. Assous
Geoscience Development, Weatherford Laboratories Ltd, Gotham Road, East Leake LE12 6JX, UK

F. Auger
L'Université Nantes Angers Le Mans (LUNAM), Saint Nazaire Cedex, France

S. Aviyente
Michigan State University, East Lansing, MI, USA

M.A. Awal
University of Queensland Centre for Clinical Research, Brisbane, QLD, Australia

G. Azemi
Razi University, Kermanshah, Iran (formerly University of Queensland Centre for Clinical Research, Brisbane, QLD, Australia)

M.J. Bastiaans
Eindhoven University of Technology, Eindhoven, The Netherlands

R.G. Baraniuk
Rice University, Houston, TX, USA

S. Barbarossa
Sapienza University of Rome, Rome, Italy

B. Barkat
Petroleum Institute, Abu Dhabi, United Arab Emirates
V. Barroso  
Instituto Superior Técnico, Lisboa, Portugal

A. Beghdadi  
Université Paris 13, Villetaneuse, France

A. Belouchrani  
Ecole Nationale Polytechnique, Algiers, Algeria

B. Boashash  
Qatar University, Doha, Qatar; University of Queensland Centre for Clinical Research, Brisbane, QLD, Australia

J.F. Böhme  
Ruhr-Universität Bochum, Bochum, Germany

A.-O. Boudraa  
Institut de Recherche de l’École Navale, Almada, France

G.F. Boudreaux-Bartels  
University of Rhode Island, Kingston, RI, USA

S. Carstens- Behrens  
University of Applied Sciences Koblenz, Remagen, Germany

V. Chandran  
Queensland University of Technology, Brisbane, QLD, Australia

E. Chassande -Mottin  
Université Paris Diderot, Paris Cedex 13, France

P. Colditz  
University of Queensland Centre for Clinical Research, Brisbane, Australia

A. Djebbari  
Université Abou Bekr Belkaid, Tlemcen, Algeria

S. Djukanović  
University of Montenegro, Podgorica, Montenegro

I. Djurović  
University of Montenegro, Podgorica, Montenegro

S. Dong  
University of Queensland Centre for Clinical Research, Brisbane, QLD, Australia

A. El-Jaroudi  
University of Pittsburgh, Pittsburgh, PA, USA

M.K. Emresoy  
University of Pittsburgh, Pittsburgh, PA, USA

B.G. Fergusson  
Defence Science and Technology Organisation, Pyrmont, NSW, Australia

P. Flandrin  
Ecole Normale Supérieure de Lyon, Lyon Cedex 07, France
G.J. Frazer  
Defence Science and Technology Organisation, Edinburgh, SA, Australia

D. Frunzaverde  
Eftimie Murgu University of Resita, Resita, Romania

L. Galleani  
Politecnico di Torino, Torino, Italy

A. Gholami  
Institute of Geophysics, University of Tehran, Iran

H. Hassanpour  
Shahrood University of Technology, Shahrood, Iran

F. Hlawatsch  
Vienna University of Technology, Vienna, Austria

Z.M. Hussain  
University of Kufa and, Edith Cowan University, Australia

B.-G. Iem  
Gangneung-Wonju National University, Gangwon-do, Republic of Korea

R. Iordache  
GE Healthcare, 78530 Buc, France

B.K. Jawad  
Qatar University, Doha, Qatar

G. Jones  
Accipiter Radar Technologies Inc., Fenwick, ON, Canada

D.L. Jones  
University of Illinois at Urbana-Champaign, Urbana, IL, USA

V. Katkovnik  
Tampere University of Technology, Hervanta, Tampere, Finland

N.A. Khan  
Qatar University, Doha, Qatar

J. Lerga  
University of Rijeka, Rijeka, Croatia

A.R. Leyman  
National University of Singapore, Singapore

N. Linh-Trung  
Vietnam National University, Hanoi, Vietnam

A.R. Lindsey  
Austral Engineering and Software, Inc., Athens, OH, USA

K.W. Lo  
Defence Science and Technology Organisation, Pyrmont, NSW, Australia
W. Mack Grady
Baylor University, Waco, TX, USA

S.L. Marple Jr.
Georgia Tech Research Institute, Atlanta, GA, USA

G. Matz
Vienna University of Technology, Vienna, Austria

A. Mert
Piri Reis University, Tuzla, Istanbul, Turkey

A. Napolitano
University of Napoli “Parthenope”, Napoli, Italy

P.M. Oliveira
Escola Naval, Almada, Portugal

A. Omidvarnia
The University of Melbourne, Melbourne, Australia

D.M. Onchis
Eftimie Murgu University of Resita, Resita, and West University of Timisoara, Timisoara, Romania

P.J. O’Shea
Qatar University, Doha, Qatar; University of Queensland, Brisbane, QLD, Australia

S. Ouelha
Qatar University, Doha, Qatar

J.M. O’Toole
University College Cork, Corcaigh, Ireland

A. Papandreou-Suppappola
Arizona State University, Tempe, AZ, USA

E.J. Powers
The University of Texas at Austin, Austin, TX, USA

G.R. Putland
Lund Values Research Group, Prosper Australia, Melbourne, VIC, Australia

L.J. Rankine
Business Engineers Australia, QLD (formerly University of Queensland, Brisbane, QLD, Australia)

B. Ristic
RMIT University, Swanston Street, Melbourne, VIC 3000 Australia

F. Salzenstein
University of Strasbourg, Strasbourg, France

N. Saulig
University of Rijeka, Rijeka, Croatia
A.M. Sayeed  
University of Wisconsin–Madison, Madison, WI, USA

E. Sejadić  
University of Pittsburgh, Pittsburgh, PA, USA

A.Z. Sha'ameri  
Universiti Teknologi Malaysia, Johor, Malaysia

I. Shafi  
Abasyn University, Islamabad, Pakistan

S.I. Shah  
Abasyn University, Islamabad, Pakistan

Y.-J. Shin  
Yonsei University, Seoul, Korea

M. Simeunović  
University of Montenegro, Podgorica, Montenegro

S. Stanković  
University of Montenegro, Podgorica, Montenegro

LJ. Stanković  
University of Montenegro, Podgorica, Montenegro

N.J. Stevenson  
Helsinki University Central Hospital, P.O.Box 280, 00029 HUS, Finland

V. Sucic  
University of Rijeka, Rijeka, Croatia

S.B. Suppappola  
Cirrus Logic Inc., Mesa, AZ, USA

G. Tauböck  
Acoustics Research Institute, The Austrian Academy of Sciences, Vienna, Austria

S. Touati  
King Saud University, Riyadh, Kingdom of Saudi Arabia

M. Tsitsvero  
Sapienza University of Rome, Rome, Italy

A.J. van Leest  
ASML, Veldhoven, The Netherlands

S. Ventosa  
Institut de Physique du Globe de Paris, Paris, France

W.J. Williams  
The University of Michigan, Ann Arbor, MI, USA
X.-G. Xia  
University of Delaware, Newark, DE, USA

P. Zarjam  
Kermanshah Azad University, Iran, and University of New South Wales, Sydney, Australia

Y.D. Zhang  
Villanova University, Villanova, PA, USA
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Time-Frequency Signal Analysis and Processing
A Comprehensive Reference

Edited by
Boualem Boashash
Preface to the First Edition

Time-Frequency Signal Analysis and Processing (TFSAP) is a collection of theory and algorithms used for analysis and processing of nonstationary signals, as found in a wide range of applications including telecommunications, radar, and biomedical engineering. This book brings together the main knowledge of TFSAP, from theory to applications, in a user-friendly reference suitable for both expert and nonexpert readers.

The contents of the book include:

1. a comprehensive tutorial introduction to TFSAP, accessible to anyone who has taken a first course in signals and systems;
2. more specialized theory and algorithms, concisely presented by some of the leading authorities on the respective topics; and
3. studies of key applications, written by leading researchers, showing how to use TFSAP methods to solve practical problems.

The motivation for producing this book was twofold:

• My original and widely used decade-old tutorial on TFSAP [1] needed updating in two respects. First, some of the advances of the last decade are sufficiently fundamental to warrant inclusion in an introductory treatment, while others are sufficiently important to demand coverage in any comprehensive review of TFSAP. Second, new applications have widened the range of disciplines interested in TFSAP, and thus reduced the common background knowledge that may be expected of readers. Part I of this book addresses these needs.
• The need for a standard language of discourse became apparent in 1990 while I was editing the 23 contributions to the first comprehensive book in the field [2]. These seminal contributions to TFSAP led to further developments throughout the 1990s, including some significant advances in practical methods suitable for nonstationary signals including instantaneous frequency estimation [3]. These efforts continued apace as this book was being written. Such rapid progress produced a variety of new terminologies and notations that were in need of standardization and inclusion in an updated reference book.

The organization of this book uses five parts, each part including several chapters, and each chapter comprising several articles. Part I introduces the basic concepts while Parts II–V cover more advanced or specialized areas.

Part I defines and explains the basic concepts of TFSAP, intuitively derives a variety of well-known time-frequency distributions (TFDs), and then reduces them to a common form. This leads to the general treatment of quadratic TFDs in Chapter 3, which should be regarded as the core of the book and as a prerequisite for the later chapters.

Part II gives more details on some fundamental topics of TFSAP, such as TFD design and signal analysis in the \((t,f)\) plane.

Part III describes specialized techniques used in implementation, measurement, and enhancement of TFDs.

Part IV presents the key statistical techniques for TFSAP of noisy signals, including a full treatment of detection and classification methods.
Part V describes a representative selection of TFSAP applications, encompassing telecommunications, radar, sonar, power generation, image quality, automotive applications, machine condition monitoring, and biomedical engineering.

Usability is enhanced by an updated consolidated bibliography (alphabetical by author) and a two-level index (which also serves as a dictionary of abbreviations).

Under the standard review procedure used for this book, each article had two (usually external) reviewers concentrating on scientific rigor and accuracy, plus two anonymous internal reviewers concentrating on clarity and consistency.

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Acknowledgments are due to a number of people who made possible the completion of this book. Foremost among them are my two sons, who aided me to continue this work during and after my wife’s final illness, thus contributing to my sense of balance and purpose during this difficult period. I thank all authors and reviewers, and the organizers of the Special Sessions on TFSAP at ISSPA conferences, for their expertise, timely effort, and professionalism, and for facilitating the exchange of ideas between contributors to this book. I thank my research students and the SPRC staff for valuable assistance. In particular, Gavin Putland assisted with the technical editing of portions of Part I and was responsible for the final mix-down of the authors’ L\LaTeX\textsuperscript{TM} and PostScript\textsuperscript{TM} files.

Boualem Boashash, Editor

REFERENCES

Preface to the Second Edition

In the decade after the publication of the first edition of this book, advances in the field of time-frequency signal analysis and processing accumulated to an extent that called for an expanded and updated edition. This second edition contains:

1. over 30 new sections by leading experts in their respective fields; covering new time-frequency \((t,f)\) methods, techniques, algorithms, and applications;
2. new tutorial sections on AM/FM decomposition of signals (Section 1.4), time-scale and wavelet transforms (Section 2.7.6), time-frequency distributions (TFDs) vs. time-scale methods (Section 2.7.7), high-resolution TFDs (Section 3.3.4), positivity of \((t,f)\) distributions (Section 3.4), Ambiguity function and Radar (Section 3.5); thus making Chapter 3 the most important;
3. a new chapter on “Getting Started” in \((t,f)\) computation using the original \((t,f)\) toolbox updated for this second Edition (Chapter 17);
4. a new introductory chapter (numbered I to minimize numbering changes), written at a more intuitive level, making the book accessible to a wider readership reflecting the widening use of the \((t,f)\) approach; and
5. a new chapter on \((t,f)\) methods in neuroscience. This emerging field of \((t,f)\) application is the subject of the new Chapter 16, containing six new sections; these concern the assessment of brain EEG and ECG abnormalities (Section 16.1), \((t,f)\) modeling of EEG signals (Section 16.2), EEG \((t,f)\) features for classification (Section 16.3), brain networks analysis (Section 16.4), EEG \((t,f)\) analysis using empirical mode decomposition (Section 16.5), and perspectives for further advances (Section 16.6).

Among the new sections, four relate \((t,f)\) methods to time-scale methods (Section 4.1), systems (Section 4.9), energy (Section 4.10) and the EMD with the Hilbert spectrum (Section 4.12); four concern directional kernels (Section 5.9), adaptive directional kernels (Section 5.10), the modified \(S\)-transform (Section 5.11) and TFDs positivity (Section 5.12). Other new topics include memory-efficient computation of TFDs (Section 6.6), compressive sensing (Section 7.6), signal complexity (Section 7.7), neural networks for \((t,f)\) localization (Section 7.8), the improvement of \((t,f)\) representations using \((t,f)\) post-processing (Section 7.5), introducing multichannel/multisensor \((t,f)\) processing (Section 8.1), audio source separation (Section 8.6), cyclostationary signals (Section 9.6), extraction of signal components (Section 10.6), polynomial-phase parameter estimation (Section 10.7), IF sequential Bayesian estimation (Section 10.8), subspace noise filtering (Section 11.5), speech enhancement (Section 11.6), generalizing one-dimensional concepts in matched filtering (Section 12.5), \((t,f)\) feature definition (Section 12.6), modulation parameter estimation (Section 13.5), sparse TFDs in geophysics (Section 14.6), audio signals’ \((t,f)\) characteristics (Section 14.7), using \((t,f)\) features to improve medical diagnosis (Section 15.5), and structural condition monitoring (Section 15.7).

More information on the scope of new and existing chapter/sections appears in the table of contents and chapter overviews.

The \((t,f)\) toolbox package (available at the Elsevier website) complements the other chapters of this book. It describes in a simple way the most important algorithms presented in the book and makes them ready for use via an easy practical graphical user interface (GUI). With the aid of Chapter 17, new users can start using the algorithms on simulated and real examples, compare with the results presented in the
book, and insert the algorithms in their own applications. Source code will be made available. Readers can use the package as an introduction to the field (in combination with the tutorial in Chapter 17), or as a set of MATLAB™-compatible commands that can be accessed from the command line or called from other programs, or as source code that can be adapted for particular applications.

The \((t,f)\) toolbox TFSAP is a recent upgrade to the package formerly known as TFSA, the first package in its field, which was released publicly in 1987 at the inaugural ISSPA conference in Brisbane, Australia, and frequently upgraded thereafter. It was originally purchased by several hundred universities and research institutions throughout the world, and also made available free of charge as part of evaluation agreements.

In addition to new material, this second edition also updates the text and references of existing sections, ensures more consistent use of common terminology and notations, and enriches the cross-referencing between the various parts of the book. The result is a comprehensive and connected presentation of standard and novel topics in \((t,f)\) signal analysis and processing. My hope is that it achieves the best possible outcome, within the constraints of a single volume, in equipping modern researchers and engineers with the information and tools necessary to undertake any study, research, or development project in this important scientific field.

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I thank several colleagues, postdocs, and research assistants who provided much needed help to complete this project. First, Dr Gavin Putland and Ms Ayat Salim assisted with \LaTeX\ editing of the sections in the book and all related tasks. In addition, several other colleagues contributed to the technical reviews of individual chapters or sections; they include: S. Ouelha, N. A. Khan, E. Sejdic, S. Touati, S. Ali, A. Aïssa-El-Bey, G. Azemi, J. O’Toole, S. Aviyente, B. Jawad, N. Stevenson, H. Hassanpour, A. Saleem, S. Dong, A. Zuri-Sha’ameri, M. A. Awal, A. Ouahabi and M. Alsad. In addition, all individual sections of this book were technically reviewed by at least two experts in the field, as shown in the first page of each section.

Publication of this second edition was facilitated by several grants from Qatar Foundation. In particular, the work in the contributions in Sections 4.1, 11.6, 13.5, 14.7, and 15.6 and the updates to Sections 7.1, 7.9, 14.4, and 14.5, was funded by Qatar National Research Fund, grant number NPRP 6-680-2-282. The work in Sections 5.11, 6.6, 7.7, 10.6, 11.5, 12.5, 15.5, 16.2, 16.3, 16.4, and 16.6, and the updates to Chapters 1 and 2 and Sections 4.6, 4.12, 5.4, 5.5, 5.7, 5.12, 6.1, 6.5, 7.4, 8.1, 10.3, 10.4, 10.5, 11.2, 11.4, 15.4 and 16.1 was funded by Qatar National Research Fund, grant number NPRP 6-885-2-364. The work in Chapter 17, Sections 5.9, 5.10, 7.5, and 12.6, and the updates to Chapter 3, was funded by Qatar National Research Fund, grant number NPRP 4-1303-2-517. The work reported in Section 16.6 was funded by the Australian Research Council and the National Health & Medical Research Council, Australia.

Boualem Boashash, Editor
Symbols frequently used in this book are listed below in alphabetical order, with Latin (English) letters before Greek letters. The meaning in the list below should be assumed unless the symbol is otherwise defined in context.

**Latin**

- \( A(f) \): amplitude spectrum
- \( a(t) \): instantaneous amplitude (real envelope), e.g., of \( s(t) = a(t) \cos \phi(t) \) or \( z(t) = a(t) e^{j\phi(t)} \)
- \( A_z(v, \tau) \): symmetrical ambiguity function (SAF) of \( z(t) \)
  \[ A_z(v, \tau) = \int_{-\infty}^{\infty} z(t + \frac{\tau}{2}) z^*(t - \frac{\tau}{2}) e^{-j2\pi \nu t} \, dt \]
- \( A_z(v, \tau) \): filtered ambiguity function of \( z(t) \)
  \[ A_z(v, \tau) = g(v, \tau) A_z(v, \tau) \]
- \( B \): bandwidth of signal
- \( \text{DFT}_{n \rightarrow k}\{x[n]\} \): discrete Fourier transform of \( x[n] \), (from \( n \) to \( k \) domain)
- \( \text{DTFT}_{n \rightarrow f}\{x[n]\} \): discrete-time Fourier transform of \( x[n] \), to \( f \) domain
- \( f \): frequency
- \( f_i(t) \): instantaneous frequency
- \( \mathcal{F}_{t \rightarrow f}\{x(t)\} \): Fourier transform (FT) of \( x(t) \), to \( f \) domain
- \( \mathcal{F}_{f \rightarrow t}^{-1}\{X(f)\} \): inverse Fourier transform (IFT) of \( X(f) \), back to \( t \) domain
- \( \mathcal{F}_z(t, f) \): short-time Fourier transform (STFT) of \( z(t) \) with window \( w(t) \)
- \( g^a \): fractional FT with parameter \( a \)
- \( \mathcal{F}_v \): frequency-shift operator: \( \mathcal{F}_v s(t) = e^{j2\pi v t} s(t) \)
- \( G[l, k] \): discrete Doppler-frequency kernel
- \( g[l, m] \): discrete Doppler-lag kernel
- \( G[n, m] \): discrete time-lag kernel
- \( G(t, \tau) \): time-lag kernel
  \[ G(t, \tau) = \int_{-\infty}^{\infty} g(v, \tau) e^{j2\pi vt} \, dv \]
- \( G(v, f) \): Doppler-frequency kernel
  \[ G(v, f) = \int_{-\infty}^{\infty} g(v, \tau) e^{-j2\pi ft} \, d\tau \]
- \( g(v, \tau) \): Doppler-lag kernel
- \( g_\theta(v, \tau) \): multi-directional Doppler-lag kernel with set of signal direction angles \( \theta \)
- \( H \): operator of system or channel
- \( \mathcal{H}\{s(t)\} \): Hilbert transform of real signal \( s(t) \)
- \( \text{Im}\{\cdot\} \) or \( \Im\{\cdot\} \): imaginary part of \( \cdot \)
\[ k \]

- discrete frequency (in bins)

\[ K_z(t, \tau) \]

- instantaneous auto-correlation function (IAF) of \( z(t) \)
\[ = z(t + \frac{\tau}{2})z^*(t - \frac{\tau}{2}) \]

\[ k_z(v,f) \]

- spectral correlation function (SCF) of \( z(t) \)
\[ = Z(f + \frac{v}{2})Z^*(f - \frac{v}{2}) , \text{ where } Z(f) = \mathcal{F}_{t \rightarrow f}\{z(t)\} \]

\[ K_{zz}(t,f) \]

- spatial instantaneous autocorrelation function (SIAF)

\[ s \]

- discrete Doppler (frequency shift)

\[ m \]

- discrete lag (delay, time shift)

\[ n \]

- discrete time (in samples)

\[ \text{Re}\{\cdot\} \text{ or } \Re\{\cdot\} \]

- real part of \( \cdot \)

\[ \text{rect}(x) \]

- function equal to 1 for \(-\frac{1}{2} \leq x \leq \frac{1}{2}\), and 0 elsewhere

\[ R_z(t, \tau) \]

- smoothed instantaneous autocorrelation function (IAF) of \( z(t) \)
\[ = G(t, \tau) * K_z(t, \tau) \]

\[ R_z(t, \tau) \]

- time-varying autocorrelation of random process \( z(t) \)

\[ R_z(\tau) \]

- autocorrelation of wide-sense stationary random process \( z(t) \)

\[ \text{sinc}(x) \]

- \( \frac{1}{\pi x} \sin(\pi x) \)

\[ S_z(t,f) \]

- evolutive (Wigner-Ville) spectrum of random process \( z(t) \)
\[ = \mathcal{F}_{t \rightarrow f}\{R_z(t, \tau)\} \]

\[ S_z(f) \]

- power spectral density of wide-sense stationary process \( z(t) \)
\[ = \mathcal{F}_{t \rightarrow f}\{R_z(\tau)\} \]

\[ S_z^{(H)}(t,f) \]

- sonograph (sonogram) of \( z(t) \) with filter \( H(f) \)

\[ S_z^w(t,f) \]

- spectrogram (squared STFT) of \( z(t) \) with window \( w(t) \)

\[ T \]

- duration of signal

\[ t \]

- time

\[ T_t \]

- time-shift operator: \( (T_t s)(t) = s(t - \tau) \)

\[ w(t) \]

- window function, or white noise

\[ W_z(t,f) \]

- Wigner-Ville distribution (WVD) of \( z(t) \)
\[ = \int_{-\infty}^{\infty} z(t + \frac{\tau}{2})z^*(t - \frac{\tau}{2})e^{-j2\pi f \tau} \, d\tau \]

\[ \text{WT}_x(t,a) \]

- Wavelet transform of signal \( x(t) \)
\[ = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(u)h^*(\frac{u-t}{a}) \, du \]
Greek

\( y[n, k] \) discrete time-frequency kernel
\( \gamma(t, f) \) time-frequency kernel \( = \int_{-\infty}^{\infty} G(t, \tau) e^{-j2\pi f \tau} \, d\tau \)
\( \epsilon(t) \) additive noise with mean \( \mu_\epsilon \) and variance \( \sigma_\epsilon^2 \)
\( \theta(f) \) phase spectrum

\( \nu \) Doppler (frequency shift)
\( \Pi_T(t) \) rectangular or box function, also written as \( \text{rect}(t/T) \) defined as:
\[
\text{rect}\left( \frac{t}{T} \right) = \begin{cases} 
1 & \text{if } |t| \leq T/2 \\
0 & \text{if } |t| > T/2 
\end{cases}
\]
\( \rho_c(t, f) \) quadratic time-frequency distribution (TFD) of signal \( z(t) \)
\[
\rho_c(t, f) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{2\pi i \nu (t-u)} g(\nu, \tau) z(u + \frac{\tau}{2}) z^*(u - \frac{\tau}{2}) e^{-j2\pi f \tau} \, d\nu \, du \, d\tau
\]
where \( g(\nu, \tau) \) is the Doppler-lag kernel
\( \rho_{zz}(t, f) \) spatial time-frequency distributions
\( \tau \) lag (delay, time shift)
\( \tau_d(f) \) spectral delay (time delay)
\( \tau_g(f) \) group delay
\( \phi(t) \) instantaneous phase
\( \psi_d,c(u) \) discrete wavelet
\( \nabla \) partial differential vector operator

Math symbols

* convolution in time
\( * \) 2D convolution in both time and frequency
\( \equiv, \triangleq \) or := equal by definition, or defined as
\( \propto \) proportional to
\( \int_{\mathbb{R}} \equiv \int_{-\infty}^{\infty} \)
\( \int_{\mathbb{R}^2} \equiv \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \)
\( \exists \) there exists
Abbreviations

The index of this book also serves as the main dictionary of abbreviations; the index entry for each abbreviation is a cross-reference to the corresponding unabbreviated entry. The most common abbreviations are listed below.

FSK          frequency-shift keying
AOK          adaptive optimal kernel
AUC          area-under-the-curve
AWVD         adaptive Wigner-Ville distribution
B-S          burst-suppression
BD           B-distribution
BJD          Born-Jordan distribution
BSS          blind source separation
BT product   bandwidth-duration product
CDMA         code-division multiple-access
CFD          central finite-difference
CKD          compact-support-Kernel distribution
CRLB         Cramer-Rao lower bound
CSK          compact-support-kernel
CWD          Choi-Williams distribution
DCT          discrete cosine transform
DGF          directional Gaussian filter
DGT          discrete Gabor transform
DI           Doppler-independent
DOA          direction-of-arrival
DWT          discrete wavelet transform
DWVD         discrete WVD
EEG          electroencephalogram
EMBD         extended modified B-distribution
EMD          empirical mode decomposition
FFT          fast Fourier transform
FM           frequency modulation
FrFT         fractional Fourier transform
FT           Fourier transform
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>GAF</td>
<td>generalized ambiguity function</td>
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<tr>
<td>GLRT</td>
<td>generalized likelihood ratio test</td>
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<tr>
<td>GPS</td>
<td>global positioning system</td>
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<tr>
<td>GWD</td>
<td>generalized Wigner distribution</td>
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<tr>
<td>HAF</td>
<td>higher-order ambiguity function</td>
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<tr>
<td>HHT</td>
<td>Hilbert-Huang transform</td>
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<tr>
<td>HVS</td>
<td>human visual system</td>
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<tr>
<td>IA</td>
<td>instantaneous amplitude</td>
</tr>
<tr>
<td>IAF</td>
<td>instantaneous autocorrelation function</td>
</tr>
<tr>
<td>IDGT</td>
<td>discrete Gabor transform (inverse)</td>
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<tr>
<td>IF</td>
<td>instantaneous frequency</td>
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<tr>
<td>IFT</td>
<td>inverse Fourier transform</td>
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<tr>
<td>IMF</td>
<td>intrinsic mode function</td>
</tr>
<tr>
<td>IP</td>
<td>instantaneous phase</td>
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<tr>
<td>ISAR</td>
<td>inverse synthetic aperture radar</td>
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<tr>
<td>KLT</td>
<td>Karhunen-Loève transform</td>
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<tr>
<td>LD</td>
<td>Levin distribution</td>
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<tr>
<td>LFM</td>
<td>linear FM</td>
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<td>LI</td>
<td>lag-independent</td>
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<td>LTV</td>
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<tr>
<td>MBD</td>
<td>modified B-distribution</td>
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<tr>
<td>MDD</td>
<td>Multi-directional distribution</td>
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<tr>
<td>MDK</td>
<td>Multi-directional kernel</td>
</tr>
<tr>
<td>MIMO</td>
<td>multiple-input multiple-output</td>
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<tr>
<td>ML</td>
<td>maximum likelihood</td>
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<tr>
<td>MSE</td>
<td>mean squared error</td>
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<td>MST</td>
<td>modified S-transform</td>
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<tr>
<td>NMF</td>
<td>nonnegative matrix factorization</td>
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<tr>
<td>PCA</td>
<td>principal component analysis</td>
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<td>PD</td>
<td>phase differentiation</td>
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<td>PLV</td>
<td>phase locking value</td>
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<td>PPS</td>
<td>polynomial-phase signal</td>
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<tr>
<td>PSD</td>
<td>power spectral density</td>
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<td>PSK</td>
<td>phase-shift keying</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>PWVDs</td>
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<td>QMF</td>
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<td>QTFRs</td>
<td>quadratic time-frequency representations</td>
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<td>RD</td>
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<td>RID</td>
<td>reduced-interference distribution</td>
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<td>ROC</td>
<td>receiver operating characteristic</td>
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<td>RWT</td>
<td>Radon-Wigner transform</td>
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<td>SAR</td>
<td>synthetic aperture radar</td>
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<td>SDS</td>
<td>spectral delay shift</td>
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<td>SIMO</td>
<td>single-input multiple-output</td>
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<tr>
<td>SISO</td>
<td>single-input single-output</td>
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<td>SM</td>
<td>S-method</td>
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<td>SNR</td>
<td>signal-to-noise ratio</td>
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<td>SS</td>
<td>spread-spectrum</td>
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<td>s.t.</td>
<td>such that</td>
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<td>ST</td>
<td>S-transform</td>
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<td>STFT</td>
<td>short-time Fourier transform</td>
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<td>SVD</td>
<td>singular-value decomposition</td>
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<td>time-frequency energy concentration</td>
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<td>TFRE</td>
<td>time-frequency Rényi entropy</td>
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<td>TFR</td>
<td>time-frequency representation</td>
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<td>TFSP</td>
<td>time-frequency signal processing</td>
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<td>Teager-Kaiser</td>
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<td>TVIR</td>
<td>time-varying impulse response</td>
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<td>TV-HOS</td>
<td>time-varying higher-order spectra</td>
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<td>time-varying transfer function</td>
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<td>wavelet packet transform</td>
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<td>WSS</td>
<td>wide-sense stationary</td>
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<tr>
<td>WT</td>
<td>wavelet transform</td>
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<tr>
<td>XWVVD</td>
<td>cross-Wigner-Ville distribution</td>
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</tbody>
</table>
To my sons
Jamil Mehdi and Issam Alam,
my wife Nadia,
my late spouse Theresa,
and my whole family.