
ELECTRONIC FILTER DESIGN HANDBOOK

**Arthur B. Williams
Fred J. Taylor**

Fourth Edition

McGRAW-HILL

**New York Chicago San Francisco Lisbon London Madrid
Mexico City Milan New Delhi San Juan Seoul
Singapore Sydney Toronto**

The McGraw-Hill Companies

Copyright © 2006 by The McGraw-Hill Companies, Inc. All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.

1 2 3 4 5 6 7 8 9 0 DOC/DOC 0 1 9 8 7 6

ISBN 0-07-147171-5

The sponsoring editor for this book was Wendy Rinaldi, the editing supervisor was Jody McKenzie, and the production supervisor was Jean Bodeaux. It was set in Times Roman by International Typesetting and Composition. The art director for the cover was Handel Low.

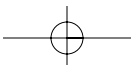
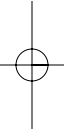
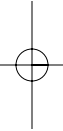
Printed and bound by RR Donnelley.

McGraw-Hill books are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. For more information, please write to the Director of Special Sales, McGraw-Hill Professional, Two Penn Plaza, New York, NY 10121-2298. Or contact your local bookstore.

Information contained in this work has been obtained by The McGraw-Hill Companies, Inc. ("McGraw-Hill") from sources believed to be reliable. However, neither McGraw-Hill nor its authors guarantee the accuracy or completeness of any information published herein, and neither McGraw-Hill nor its authors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that McGraw-Hill and its authors are supplying information but are not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought.

*From Arthur B. Williams
To my Family
Ellen, Howard, Bonnie, Robin, Mitchell
and grandchildren Leviah and Ilona*

*From Dr. Fred J. Taylor
To my grandchildren Schuyler, Bennett,
and Graysen and their
devoted grandmother Lori*



ABOUT THE AUTHORS

Arthur Williams is the Chief Scientist at Telebyte Inc., a developer and manufacturer of broadband test equipment and data communication products. Previously, he was Senior Staff Engineer and Manager of Engineering for Tellabs Inc. Author of five books and holder of eleven patents, Mr. Williams has served as a consultant to the industry and is currently the Chairman of the IEEE Circuits and Systems (CAS) chapter on Long Island.

Fred J. Taylor is co-founder and Chairman of the Board of the Athena Group, a DSP semiconductor silicon intellectual property company and education technology innovator. He is also professor of electrical and computer engineering, and computer and information science engineering at the University of Florida. Author of ten textbooks and holder of three patents, Dr. Taylor serves as a consultant to Fortune 500 companies and government agencies.

- Elliptic-Function Filters / 90
- Duality and Reciprocity / 93
- Designing for Unequal Terminations / 93
- Effects of Dissipation / 97
- Using Predistorted Designs / 99
- 3.2. Active Low-Pass Filters / 103
 - All-Pole Filters / 103
 - VCVS Uniform Capacitor Structure / 113
 - The Low-Sensitivity Second-Order Section / 114
 - Elliptic-Function VCVS Filters / 116
 - State-Variable Low-Pass Filters / 120
 - Generalized Impedance Converters / 128
- Bibliography / 135

Chapter 4. High-Pass Filter Design

137

- 4.1. LC High-Pass Filters / 137
 - The Low-Pass to High-Pass Transformation / 137
 - The T-to-Pi Capacitance Conversion / 142
- 4.2. Active High-Pass Filters / 143
 - The Low-Pass to High-Pass Transformation / 143
 - All-Pole High-Pass Filters / 144
 - Elliptic-Function High-Pass Filters / 145
 - State-Variable High-Pass Filters / 151
 - High-Pass Filters Using the GIC / 159
 - Active Elliptic-Function High-Pass Filters Using the GIC / 161
- Bibliography / 164

Chapter 5. Bandpass Filters

165

- 5.1. LC Bandpass Filters / 165
 - Wideband Filters / 165
 - Narrowband Filters / 167
 - Narrowband Coupled Resonators / 183
 - Predistorted Bandpass Filters / 189
 - Elliptic-Function Bandpass Filters / 192
- 5.2. Active Bandpass Filters / 199
 - Wideband Filters / 199
 - The Bandpass Transformation of Low-Pass Poles and Zeros / 202
 - Sensitivity in Active Bandpass Circuits / 207
 - All-Pole Bandpass Configurations / 207
 - Elliptic-Function Bandpass Filters / 224
 - State-Variable (Biquad) Circuit / 230
- Bibliography / 237

Chapter 6. Band-Reject Filters

239

- 6.1. LC Band-Reject Filters / 239
 - The Band-Reject Circuit Transformation / 239
 - All-Pole Band-Reject Filters / 240
 - Elliptic-Function Band-Reject Filters / 245
 - Null Networks / 252
- 6.2. Active Band-Reject Filters / 257
 - Wideband Active Band-Reject Filters / 257

CONTENTS

vii

Band-Reject Transformation of Low-Pass Poles /	261
Narrowband Active Band-Reject Filters /	265
Active Null Networks /	271
Bibliography /	277

Chapter 7. Networks for the Time Domain

279

7.1. All-Pass Transfer Functions /	279
First-Order All-Pass Transfer Functions /	279
Second-Order All-Pass Transfer Functions /	281
7.2. Delay Equalizer Sections /	283
LC All-Pass Structures /	283
Active All-Pass Structures /	287
7.3. Design of Delay Lines /	292
The Low-Pass to All-Pass Transformation /	292
LC Delay Lines /	293
Active Delay Lines /	297
7.4. Delay Equalization of Filters /	299
First-Order Equalizers /	300
Second-Order Equalizers /	303
7.5. Wideband 90° Phase-Shift Networks /	307
7.6. Adjustable Delay and Amplitude Equalizers /	313
LC Delay Equalizers /	314
LC Delay and Amplitude Equalizers /	316
Active Delay and Amplitude Equalizers /	319
Bibliography /	323

Chapter 8. Refinements in LC Filter Design and the Use of Resistive Networks

325

8.1. Introduction /	325
8.2. Tapped Inductors /	325
8.3. Circuit Transformations /	327
Norton's Capacitance Transformer /	328
Narrowband Approximations /	330
8.4. Designing with Parasitic Capacitance /	333
8.5. Amplitude Equalization for Inadequate Q /	336
8.6. Coil-Saving Elliptic-Function Bandpass Filters /	340
8.7. Filter Tuning Methods /	343
8.8. Measurement Methods /	345
Insertion Loss and Frequency Response /	345
Input Impedance of Filter Networks /	346
Time-Domain Characteristics /	347
Measuring the Q of inductors /	351
8.9. Designing for Unequal Impedances /	351
Impedance Matching /	351
Exponentially Tapered Impedance Scaling /	351
Minimum Loss Resistive Pad for Impedance Matching /	352
8.10. Symmetrical Attenuators /	355
Bridged T Attenuator /	356
8.11. Power Splitters /	357
Resistive Power Splitters /	357
A Magic-T Splitter /	357
Bibliography /	360

Chapter 9. Design and Selection of Inductors for LC Filters **361**

- 9.1. Basic Principles of Magnetic-Circuit Design / 361
 - Units of Measurement / 361
 - Saturation and DC Polarization / 362
 - Inductor Losses / 363
 - Effect of an Air Gap / 363
 - The Design of Coil Windings / 364
- 9.2. MPP Toroidal Coils / 367
 - Characteristics of Cores / 367
 - Winding Methods for Q Optimization / 371
 - Designing MPP Toroids from Q Curves / 372
- 9.3. Ferrite Pot Cores / 376
 - The Pot Core Structure / 376
 - Electrical Properties of Ferrite Pot Cores / 377
 - Winding of Bobbins / 380
 - RM Cores / 382
- 9.4. High-Frequency Coil Design / 383
 - Powdered-Iron Toroids / 383
 - Winding Methods / 384
 - Air-Core Inductors / 387
 - Surface Mount RF Inductors / 387
- Bibliography / 392

Chapter 10. Component Selection for LC and Active Filters **393**

- 10.1. Capacitor Selection / 393
 - Properties of Dielectrics / 393
 - Capacitor Construction / 394
 - Selecting Capacitors for Filter Applications / 398
- 10.2. Resistors / 403
 - Fixed Resistors / 403
 - Variable Resistors / 408
 - Resistor Johnson (Thermal) Noise / 409
- 10.3. Operational Amplifiers / 410
 - A Review of Basic Operational-Amplifier Theory / 410
 - An Analysis of Non-Ideal Amplifiers / 413
 - Practical Amplifier Considerations / 415
 - Operational Amplifier Selection / 417
 - A Survey of Popular Amplifier Types / 419
- 10.4. General Manufacturing Considerations / 422
- Bibliography / 423

Chapter 11. Normalized Filter Design Tables **425**

Chapter 12. Introduction to Digital Filters **497**

- 12.1. Introduction to Signal Processing / 497
- 12.2. Introduction to Digital Signal Processing (DSP) / 497
- 12.3. The Relation to Analog Filters / 498
 - Digital Advantages / 498
 - Analog Advantages / 499
- 12.4. Signal Representation / 500

CONTENTS

ix

12.5. Digital Data Representation /	500
12.6. Sampling Theorem /	505
12.7. Signal Reconstruction /	506
12.8. Practical Interpolators /	506
12.9. Sampling Modalities /	507
12.10. Aliasing /	507
12.11. Data Conversion /	509
12.12. Finite Wordlength Effects /	510
12.13. Mathematical Signal and System Representation /	512
12.14. Spectral Representation /	514
Bibliography /	515

Chapter 13. Finite Impulse-Response Filters

517

13.1. Digital Filters /	517
13.2. FIR Digital Filters /	517
13.3. Stability /	519
13.4. Linear-Phase Behavior /	520
13.5. Non-Linear-Phase Behavior /	522
13.6. Minimum Phase Behavior /	523
13.7. Fir Design Methods /	524
13.8. Window Design Method /	524
13.9. Non-Rectangular Window Design Method /	526
13.10. Least Squares FIR Design /	530
13.11. Equiripple FIR Design /	532
13.12. Equiripple Hilbert FIR Design /	538
13.13. Equiripple Differentiator FIR Design /	538
13.14. Special Case FIR Digital Filters /	539
13.15. Multiplier-Free FIR Filters /	541
13.16. L-Band FIR Filters /	542
13.17. Mirror and Complement FIR Filters /	544
13.18. Frequency Sampling FIR Filters /	547
13.19. Savitzky-Golay FIR Filters /	550
13.20. Raised FIR Filters /	551
13.21. Matlab FIR Support /	553
13.22. Fir Architectures /	553
13.23. Direct Form FIR /	553
13.24. Transpose Form FIR /	557
13.25. Symmetric Form FIR /	558
13.26. Lattice Form FIR /	558
13.27. Distributed Arithmetic /	561
13.28. Canonic Signed Digit (CSD) /	564
13.29. Finite Wordlength Effect /	566
13.30. Coefficient Rounding /	567
13.31. Arithmetic Error /	568
13.32. Scaling /	569
13.33. Multiple Mac Architecture /	569
Bibliography /	571

Chapter 14. Infinite Impulse-Response Filters

573

14.1. Introduction /	573
14.2. Classic Analog Filters /	576
14.3. Matlab Analog Filter Production /	579
14.4. Impulse Invariant IIR /	580

x

CONTENTS

14.5. Bilinear z -Transform IIR /	583
14.6. Matlab Classic IIR Support /	588
14.7. Other IIR Models /	590
14.8. Comparison of FIR and IIR Filters /	592
14.9. State Variable Filter Model /	593
14.10. Architecture /	595
14.11. Direct II Architecture /	596
14.12. Matlab Direct II Architecture /	598
14.13. Cascade Architecture /	600
14.14. The Matlab Cascade Architecture /	602
14.15. Parallel Architecture /	604
14.16. Lattice/Ladder Architecture /	605
14.17. Matlab Ladder/Lattice Support /	608
14.18. Normal Architecture /	609
14.19. Stability /	611
14.20. Finite Wordlength Effects /	612
14.21. Overflow Arithmetic /	613
14.22. Register Overflow /	614
14.23. Arithmetic Errors /	617
14.24. Coefficient Rounding Errors /	622
14.25. Scaling /	623
14.26. Zero Input Limit Cycling /	624
Bibliography /	626

Chapter 15. Multirate Digital Filters

627

15.1. Introduction to Multi-Rate Signal Processing /	627
15.2. Decimation /	628
15.3. Interpolation /	633
15.4. Sample Rate Conversion /	636
15.5. Polyphase Representation /	637
15.6. Filter Banks /	642
15.7. DFT Filter Banks /	647
15.8. Cascade Integrator Comb (CIC) Filter /	649
15.9. Frequency Masking Filters /	651
15.10. Matlab Multirate Support /	656
Bibliography /	658

Chapter 16. Digital Filter Technology

661

16.1. Introduction to Signal Processing /	661
16.2. Processor Forms /	662
16.3. General-Purpose Microprocessors (μ PS) /	664
16.4. DSP Processor /	665
16.5. DSP Addressing Modes /	667
16.6. Circular Buffering /	668
16.7. DSP Processor Features /	669
16.8. DSP Processor Parallelism /	669
16.9. Fixed-Point vs. Floating-Point /	670
16.10. DSP Benchmarks /	670
16.11. ADC/DAC Operation /	672
Delta-Sigma ADC /	672
Flash ADC /	672
Successive Approximation ADC /	673
Subrange ADC /	673

CONTENTS

xi

- Pipelined ADC / 674
- Folded ADC / 674
- 16.12. ADC Metrics / 678
- 16.13. ADC Technology Issues / 680
- 16.14. ADC Applications / 681
- 16.15. ADC Enhancements / 683
- 16.16. DAC Technology / 684
- 16.17. DSP Software / 684
 - Assembly Language / 685
 - C Language / 685
 - Prototyping Languages / 691
 - Libraries / 692
 - Reference Designs / 692
 - Profiler / 693
- 16.18. Digital Filter Implementation / 693
- Bibliography / 700

Chapter 17. Switched-Capacitor Filters

701

- 17.1. Introduction / 701
- 17.2. The Theory of Switched-Capacitor Filters / 701
 - The Switched Resistor / 701
 - The Basic Integrator as a Building Block / 702
 - The Limitations of Switched-Capacitor Filters / 703
- 17.3. Universal Switched-Capacitor Second-Order Filters / 704
 - Modes of Operation / 705
 - Operating Mode Features / 705
 - Using the MF10 and LMF100 Dual Universal Second-Order Filter / 709
- 17.4. Types of Switched-Capacitor Filters / 712
 - Universal / 712
 - Microprocessor Programmable Universal Switched Capacitor Filters / 714
 - Pin Programmable Universal Switched Capacitor Filters / 714
 - Dedicated Switched Capacitor Filters / 714
- 17.5. FilterCAD 3.0 Software / 717
- 17.6. The Switched Capacitor Filter Selection Guide / 717
- Bibliography / 717

Chapter 18. Introduction to Microwave Filters

719

- 18.1. Implementation of Filters / 719
- 18.2. Microstrip and Stripline Transmission Lines / 719
- 18.3. Richards' Transformation / 720
 - Line with Short Circuit at Output / 722
 - Line with Open Circuit at Output / 722
- 18.4. Kuroda's Identities / 724
 - Series to Shunt Stub / 724
 - Shunt to Series Stub / 725
 - Combining Richards' Transformation and Kuroda's Identities to Design a Low-Pass Filter / 725
- 18.5. Bandpass Filters / 728
 - Bandpass Filters Using Shorted Parallel Stubs / 728
 - Bandpass Filters Using Edge-Coupled Half-Wavelength Lines / 729
- 18.6. Additional Design Methods Using PC Board Traces / 730
 - Using PC Board Traces to Replace Inductors and Capacitors / 730
- Bibliography / 731

Appendix A. Discrete Systems Mathematics **733**

- A.1. Digital Filter Mathematics (The z -Transform) / 733
- A.2. Inverse z -Transform / 741
- A.3. Matlab Inversion / 753
- A.4. Discrete Fourier Transform (DFT) / 758
- A.5. DFT Error Sources / 762
- Bibliography / 765

Appendix B. Software Summary **767**

- B.1. The Fltrform.xls Spreadsheet of Formulas / 767
- B.2. Filter Solutions (Book Version) Software for the Design of Elliptic-Function Low-Pass Filters / 767
- B.3. ELI 1.0 for the Design of Odd-Order Elliptic-Function Low-Pass Filters up to the 31st Order / 768
- B.4. FilterCAD 3.0 for the Design of Switched Capacitor Filters / 768
- B.5. TX Line for the Design of Microstrip, Stripline, and Other Structures for Microwave Filters / 768

Index 769

PREFACE

This is the fourth edition of the *Electronic Filter Design Handbook*, which was first published in 1981. It was expanded in 1988 to include five additional chapters on digital filters and then updated in 1995. This revised edition contains new material on both analog and digital filters. A CD-ROM has been included containing a number of programs which allow the rapid design of analog filters for input requirements without the tedious mathematical computations normally encountered. The digital filter chapters are all integrated with a profusion of MATLAB examples.

Prior to the introduction of this book in 1981, the design of *LC* and active filters had been reserved for specialists. The *Electronic Filter Design Handbook* treated the design of these filters in a practical manner and provided extensive tabulated data so that the average engineer who had no previous experience could design passive or active filters. This philosophy was expanded to include digital filters in the second edition in 1988, where, for the first time in any book, the design of all three classes of filters was covered in a practical easy-to-follow style. The book was then further updated in its third edition in 1995 to include a number of new technologies and design methods. In this fourth edition, the book now contains additional material and chapters on analog filters, and has been updated on available components to include surface mount technology. A number of powerful design programs have been included on the CD-ROM. Some of the previously included tables on normalized elliptic-function low-pass filters have been replaced by a powerful program, *Filter Solutions* (from Nuhertz Technologies®), which can directly design these filters and create a schematic without tedious calculations. An EXCEL spreadsheet contains formulas from the individual chapters keyed to the text so that the tedious calculations required in the past are no longer necessary.

The digital filter chapters have been completely revised and the vast majority of the material is new. This new edition contains all the topics and studies found in the previous version of the *Electronic Filter Design Handbook*, plus many more that cover the full range of modern fixed-coefficients digital filter design. The coverage provides the reader with both a conceptual understanding of digital filters and the ability to design digital filters for use in a number of application domains. The presentation keeps in mind that traditional digital filters, used a decade ago, remain in popular use today. It's also recognized that non-traditional and multirate filters are of growing importance. Thus, basic digital filter design methods are presented, along with an enriched treatment on multirate solutions. Strong emphasis is placed on achieving filter-technology synergy, which considers issues related to the physical implementation of a digital filter in either hardware or software. This fourth edition also presumes that contemporary engineers will increasingly turn to the computer software to support filter design and analysis activities. These activities are motivated and supported with a profusion of computer-generated examples using the ubiquitous MATLAB software package.

Chapter 1 introduces the concept of modern network theory and discusses the trade-off between active and passive filter implementations.

The mathematical properties of standard filter response types are covered in Chapter 2, including Butterworth, Chebyshev, Bessel, linear phase with equiripple error, transitional,

synchronously tuned, and constant delay with Chebyshev stopband. Extensive normalized curves for both frequency and time-domain parameters of these standard polynomial transfer functions are provided. The highly efficient elliptic-function filter response is also discussed in this chapter and emphasized throughout the handbook. Two programs contained on the CD-ROM, *Filter Solutions (book version)* and *ELI 1.0* (for the design of elliptic-function filters), are introduced.

In Chapter 3 the design of both passive and active low-pass filters is covered using normalized tables. Specialized passive low-pass filter design techniques are illustrated, such as designing for unequal terminations and compensating for the effects of component dissipation (low Q). Various active low-pass filter structures are covered for both all-pole and elliptic-function types.

High-pass filters for both passive and active implementations are discussed in Chapter 4.

Chapter 5 covers bandpass filters. Various passive filter transformations, approximations, and identities are illustrated to ensure practical element values even for extreme conditions of center frequency, bandwidth, or impedance level. Some active bandpass implementations are offered that exhibit low sensitivity at frequencies previously considered too high for active filters.

Techniques for band-reject filter design are presented in Chapter 6, where passive and active types are covered.

Chapter 7 covers the design of networks having properties best described in the time domain. All-pass delay and amplitude equalizers are discussed in detail. Methods are shown for the design of LC , as well as active delay lines and wideband 90° phase shift networks.

Refinements in LC filter design are covered in Chapter 8. Special techniques are presented to manipulate element values so that practical values can always be obtained. Here, measurement techniques are shown, and the design of various forms of resistive attenuators for attenuation and impedance matching is covered. The theory and design of power splitting networks is also explained.

The successful operation of LC filter design is highly dependent upon the proper selection and manufacture of inductors. The design of magnetic components is presented in Chapter 9. The entire process—ranging from the selection of various magnetic material types and shapes to coil-winding methods to achieve the optimum characteristics over the operating frequency range—is explained in detail. New magnetic materials and shapes are covered. Q curves are also provided, as well as those for MPP torroidal cores, ferrite RM and potcores, and surface mount RF inductors.

The component selection for LC and active filters is discussed in Chapter 10. Coverage includes capacitor characteristics and the selection of fixed and variable resistor types. Johnson (Thermal) noise is also discussed. Operational amplifier theory is reviewed both from a theoretical and a practical standpoint, and expanded and updated device selection charts are provided to enable the rapid choice of the appropriate operational amplifier for a given filter configuration and required operating frequency range. Surface-mount (SMD) components are also emphasized, as well as the manufacturing considerations using this technology.

Chapter 11 contains normalized tables for the rapid design of both passive and active filters. In addition to the standard polynomial types, tables are provided for the unique constant-delay low-pass filters with Chebyshev stopband characteristics.

Chapter 12 introduces digital filters. The presentation begins with a differentiation of analog and digital systems, representations, and design strategies. The sampling theory is established as being a core element in the understanding and realization of digital filters, and issues such as quantifying sampling modalities and aliasing are discussed. Data conversion principles and mechanics (to and from the analog domain) are developed, and the chapter closes with a discussion of computer arithmetic and spectral analysis.

Finite impulse-response filters (FIR) are discussed in Chapter 13. The chapter begins with a general characterization of FIR filters, including stability. Both linear and non-linear

phase FIR are studied in detail, and FIR design procedures based on the window, least-squares, and equiripple methods are presented, as well as the extension of their use as Hilbert and differentiating FIRs. FIR special cases, such as comb, moving average, L-band, mirror, complement, and frequency sampling forms are also described and illustrated. The FIR design strategies are reinforced using MATLAB FIR architectures, including direct, transpose, symmetric, lattice, distribute, and canonic digit form are developed in detail. The chapter concludes with a study of finite word length effects.

Chapter 14 covers the infinite impulse-response (IIR) filters. The presentation begins with a general characterization of FIR filters, including stability. A review of classic analog filters, Butterworth, Chebyshev I and II, and elliptic (Cauer) are presented and used to define classic digital IIR filters. The conversion of analog filters to digital IIR filters are examined in terms of impulse invariant and bilinear z -transforms. The design of an IIR, based upon measured input-output responses, is also presented in terms of auto-regressive models. The IIR filter design process is illustrated using MATLAB IIR filters are described using a natural state variable analysis framework, which is interpreted in terms of a Direct I and II, Cascade, Parallel, Normal, and Lattice architectures. The state variable models are next reinforced using MATLAB. The chapter concludes with an exposition of the analysis procedures required to insure a successful fixed-point IIR implementation and how to minimize run-time finite wordlength (fixed-point) errors.

Multirate filters are discussed in Chapter 15. The presentation begins with a general characterization of multirate systems and their use. Following this, the process of decimation and interpolation are developed, along with sample rate conversion. Multirate systems are then presented using a polyphase framework that is extended to the design filter banks and DFT filter banks. The chapter concludes with the development of high decimation rate filters and frequency masked filters.

Chapter 16 covers the field of digital filter technology. The presentation begins with an overview of technology types including general purpose μ ps, DSP μ ps, application-specific integrated circuits (ASIC), and field programmable gate arrays (FPGA). Various processor organizations are examined. Processor architectural variations and their impact on design choices are developed and compared. A discussion of analog to digital (ADC) architectures is presented and used to define and compare various types of converter architectures. Next, software issues and opportunities are developed and analyzed. The chapter concludes with a filter implementation case study based on Texas Instruments DSP μ p processor architecture.

Chapter 17 covers switched-capacitor filters. The underlying theory behind this technology is presented, and some design examples are shown using standard building-block ICs. A survey and a convenient selection guide (updated) is included, as well as a program called FilterCAD on the CD-ROM. The latter program (from Linear Technology) can help to quickly design a switched-capacitor filter from a set of input parameters. It then provides a schematic of the filter along with both the predicted frequency response and time response.

Chapter 18 is an introduction to microwave filters. It discusses Kuroda's Identities and Richards' Transformation and illustrates some design examples of microstrip filters.

Appendix A provides a review of DSP mathematics. The presentation begins with a comprehensive study of the z -transform and inverse z -transform. Transforms are then investigated using MATLAB. The chapter concludes with a discussion of the discrete Fourier transform (DFT).

The authors would like to thank Leo Moodenbaugh of Telebyte Inc., and Michael Christensen of the University of Florida for their assistance.

ARTHUR B. WILLIAMS
FRED J. TAYLOR

