## Essentials of Geophysical Data Processing

CLARK R. WILSON University of Texas at Austin



Contents

F	Preface		<i>page</i> ix
1	An Introduction with Geophysical Time Series Examples		
	1.1	Global Mean Sea Level	1
	1.2	Stream Discharge	2
	1.3	Eastern Pacific Sea Level	2 4
	1.4	El Nino Southern Oscillation (ENSO) Index	4
	1.5	Lake Vostok Ice Core Temperature History	6
	1.6	Hector Mines Earthquake Seismograms	7
	1.7	Simulated Seismograms, White Noise, and Computing Environments	9
	1.8	Chapter Summary	9
2	Anal	og Signals and Digital Time Series	11
	2.1	Digital Time Series Notation	11
	2.2	Digitizing Analog Signals	12
	2.3	Undersampling and Aliasing	14
	2.4	Time Series Statistics	15
		2.4.1 Mean or Average Value	15
		2.4.2 Variance and Standard Deviation	16
		2.4.3 Autocorrelation	17
	2.5	Numerical Representation of Samples	19
	2.6	Decibels	20
	2.7	Applications to Digital Audio Recording	21
	2.8	Chapter Summary	22
	Exe	rcises	23
3	Sinus	25	
	3.1	Sinusoids	25
	3.2	Fourier Series	26
	3.3	Partial Fourier Sums	29
	3.4	Complex Numbers	29
	3.5	Complex Sinusoids	31
	3.6	Chapter Summary	33
	Exer	cises	34
4	The D	iscrete Fourier Transform	37
	4.1	Fourier Series in Complex Notation	37
	4.2	From Fourier Series to DFT	38

	4.3	Frequency and Time Ordering	39
	4.4	DFT Normalization Conventions	40
	4.5	Sinusoidal Coefficients of a Climate Time Series	40
	4.6	FFT Algorithms	42
	4.7	Zero-Padding and Interpolation	43
	4.8	DFT Interpolation Example	44
	4.9	Analytic Signal Computation and Application to Measuring	
		Surface Wave Dispersion	44
	4.10	Chapter Summary	47
	Exer	cises	48
5	Linea	Systems and Digital Filters	50
	5.1	Linear Filter Equations	50
	5.2	Discrete Convolution	51
	5.3	Correlation	53
	5.4	Convolution Matrices	53
	5.5	Transfer Functions	54
	5.6	Impulse Response	56
	5.7	Filter Cascades and Inverses	57
	5.8	Chapter Summary	58
	Exer	cises	59
6	Convo	lution and Related Theorems	61
6	<b>Convo</b> 6.1	lution and Related Theorems Convolution Theorem for the Z Transform	61 61
6	<b>Convo</b> 6.1 6.2	<b>lution and Related Theorems</b> Convolution Theorem for the <i>Z</i> Transform DFT Circular Convolution Theorem	61 61 62
6	<b>Convo</b> 6.1 6.2 6.3	<b>lution and Related Theorems</b> Convolution Theorem for the Z Transform DFT Circular Convolution Theorem Autocorrelation Theorem	61 61 62 63
6	<b>Convo</b> 6.1 6.2 6.3 6.4	<b>lution and Related Theorems</b> Convolution Theorem for the Z Transform DFT Circular Convolution Theorem Autocorrelation Theorem Window Functions	61 61 62 63 64
6	<b>Convo</b> 6.1 6.2 6.3 6.4 6.5	<b>lution and Related Theorems</b> Convolution Theorem for the Z Transform DFT Circular Convolution Theorem Autocorrelation Theorem Window Functions Linear Filtering with the DFT	61 61 62 63 64 68
6	Convo 6.1 6.2 6.3 6.4 6.5 6.6	Iution and Related TheoremsConvolution Theorem for the Z TransformDFT Circular Convolution TheoremAutocorrelation TheoremWindow FunctionsLinear Filtering with the DFTChapter Summary	61 61 62 63 64 68 70
6	Convo 6.1 6.2 6.3 6.4 6.5 6.6 Exer	Iution and Related Theorems Convolution Theorem for the Z Transform DFT Circular Convolution Theorem Autocorrelation Theorem Window Functions Linear Filtering with the DFT Chapter Summary cises	61 61 62 63 64 68 70 71
6	Convo 6.1 6.2 6.3 6.4 6.5 6.6 Exer Least	Iution and Related Theorems   Convolution Theorem for the Z Transform   DFT Circular Convolution Theorem   Autocorrelation Theorem   Window Functions   Linear Filtering with the DFT   Chapter Summary   cises   Squares	61 61 62 63 64 68 70 71 73
6	Convo 6.1 6.2 6.3 6.4 6.5 6.6 Exer Least 7.1	Iution and Related Theorems   Convolution Theorem for the Z Transform   DFT Circular Convolution Theorem   Autocorrelation Theorem   Window Functions   Linear Filtering with the DFT   Chapter Summary   cises   Squares   Motivations for Least Squares	61 61 62 63 64 68 70 71 73 73 73
6	Convo 6.1 6.2 6.3 6.4 6.5 6.6 Exer 7.1 7.2	Iution and Related Theorems   Convolution Theorem for the Z Transform   DFT Circular Convolution Theorem   Autocorrelation Theorem   Window Functions   Linear Filtering with the DFT   Chapter Summary   cises   Squares   Motivations for Least Squares   Least Squares via Maximum Likelihood	61 61 62 63 64 68 70 71 73 73 73 74
6	Convo 6.1 6.2 6.3 6.4 6.5 6.6 Exer 7.1 7.2 7.3	Iution and Related Theorems   Convolution Theorem for the Z Transform   DFT Circular Convolution Theorem   Autocorrelation Theorem   Window Functions   Linear Filtering with the DFT   Chapter Summary   cises   Squares   Motivations for Least Squares   Least Squares via Maximum Likelihood   Least Squares via Linear Algebra	61 61 62 63 64 68 70 71 73 73 73 74 77
6	Convo 6.1 6.2 6.3 6.4 6.5 6.6 Exer 7.1 7.2 7.3 7.4	Iution and Related Theorems   Convolution Theorem for the Z Transform   DFT Circular Convolution Theorem   Autocorrelation Theorem   Window Functions   Linear Filtering with the DFT   Chapter Summary   cises   Squares   Motivations for Least Squares   Least Squares via Maximum Likelihood   Least Squares via Linear Algebra   Weighted Least Squares	61 61 62 63 64 68 70 71 73 73 73 73 74 77 81
6	Convo 6.1 6.2 6.3 6.4 6.5 6.6 Exer <b>Least</b> 7.1 7.2 7.3 7.4 7.5	Iution and Related Theorems   Convolution Theorem for the Z Transform   DFT Circular Convolution Theorem   Autocorrelation Theorem   Window Functions   Linear Filtering with the DFT   Chapter Summary   cises   Squares   Motivations for Least Squares   Least Squares via Maximum Likelihood   Least Squares via Linear Algebra   Weighted Least Squares   Parameter Error Covariance Matrix	61 61 62 63 64 68 70 71 71 73 73 73 74 77 81 82
6 7	Convo 6.1 6.2 6.3 6.4 6.5 6.6 Exer <b>Least</b> 7.1 7.2 7.3 7.4 7.5 7.6	Iution and Related Theorems   Convolution Theorem for the Z Transform   DFT Circular Convolution Theorem   Autocorrelation Theorem   Window Functions   Linear Filtering with the DFT   Chapter Summary   cises   Squares   Motivations for Least Squares   Least Squares via Maximum Likelihood   Least Squares via Linear Algebra   Weighted Least Squares   Parameter Error Covariance Matrix   Fitting Data to Sinusoids	61 61 62 63 64 68 70 71 73 73 73 73 74 77 81 82 83
6	Convo 6.1 6.2 6.3 6.4 6.5 6.6 Exer 7.1 7.2 7.3 7.4 7.5 7.6 7.7	Iution and Related Theorems   Convolution Theorem for the Z Transform   DFT Circular Convolution Theorem   Autocorrelation Theorem   Window Functions   Linear Filtering with the DFT   Chapter Summary   cises   Squares   Motivations for Least Squares   Least Squares via Maximum Likelihood   Least Squares via Linear Algebra   Weighted Least Squares   Parameter Error Covariance Matrix   Fitting Data to Sinusoids   Ocean Tide Prediction	61 61 62 63 64 68 70 71 73 73 73 73 74 77 81 82 83 84
6	Convo 6.1 6.2 6.3 6.4 6.5 6.6 Exer <b>Least</b> 7.1 7.2 7.3 7.4 7.5 7.6 7.7 7.8	Initial Addition and Related Theorems   Convolution Theorem for the Z Transform   DFT Circular Convolution Theorem   Autocorrelation Theorem   Window Functions   Linear Filtering with the DFT   Chapter Summary   cises   Squares   Motivations for Least Squares   Least Squares via Maximum Likelihood   Least Squares via Linear Algebra   Weighted Least Squares   Parameter Error Covariance Matrix   Fitting Data to Sinusoids   Ocean Tide Prediction   Seismic Tomography	61 61 62 63 64 68 70 71 73 73 73 73 74 77 81 82 83 84 86
6	Convo 6.1 6.2 6.3 6.4 6.5 6.6 Exer Least 7.1 7.2 7.3 7.4 7.5 7.6 7.7 7.8 7.9	Initial Addition and Related Theorems   Convolution Theorem for the Z Transform   DFT Circular Convolution Theorem   Autocorrelation Theorem   Autocorrelation Theorem   Window Functions   Linear Filtering with the DFT   Chapter Summary   cises   Squares   Motivations for Least Squares   Least Squares via Maximum Likelihood   Least Squares via Linear Algebra   Weighted Least Squares   Parameter Error Covariance Matrix   Fitting Data to Sinusoids   Ocean Tide Prediction   Seismic Tomography   A Model for Global Sea Level Change	61 61 62 63 64 68 70 71 73 73 73 74 77 81 82 83 84 86 88
6	Convo 6.1 6.2 6.3 6.4 6.5 6.6 Exer Least 7.1 7.2 7.3 7.4 7.5 7.6 7.7 7.8 7.9 7.10	Initial Addition and Related Theorems   Convolution Theorem for the Z Transform   DFT Circular Convolution Theorem   Autocorrelation Theorem   Window Functions   Linear Filtering with the DFT   Chapter Summary   cises   Squares   Motivations for Least Squares   Least Squares via Maximum Likelihood   Least Squares via Linear Algebra   Weighted Least Squares   Parameter Error Covariance Matrix   Fitting Data to Sinusoids   Ocean Tide Prediction   Seismic Tomography   A Model for Global Sea Level Change   Chapter Summary	61 61 62 63 64 68 70 71 73 73 73 73 74 77 81 82 83 84 88 84 86 88

8 Line	ear Filter Design	94
8.1	Introducing the Z Plane	94
8.2	Z Plane Geometry – Stability and Invertibility	96
8.3	Notch Filter Design Using Z Plane Geometry	98
8.4	Differential Equation to Digital Filter Equation	100
8.5	Derivative and Integration Filters	103
8.6	Echo and Reverberation Filters	104
8.7	Sampled Impulse Response Filter Coefficients	108
8.8	Gravity Anomaly Calculations	109
8.9	Ground Motion Amplification in an Earthquake	112
8.1	0 Chapter Summary	114
Exe	ercises	114
9 Leas	st Squares and Correlation Filters	116
9.1	Least Squares Inverse Filters	116
9.2	Yule–Walker Equations	117
9.3	Interpolation Filters	120
9.4	Prediction Error Filters	122
9.5	Deconvolution Filters in Reflection Seismology	123
9.6	Power Spectrum Estimate from the PEF	124
9.7	Vibroseis and Matched (Correlation) Filtering	124
9.8	Correlation Filtering in the Global Positioning System	127
9.9	De-Blurring Filter Design	129
9.1	0 Chapter Summary	133
Exe	ercises	133
10 Pow	er and Coherence Spectra	136
10.	1 The DFT Periodogram	136
10.2	2 Periodogram of White Noise	137
10.3	3 Comparing Power Spectrum Estimation Methods	141
10.4	4 Correlation and Coherence	145
10.5	5 Coherence of Sea Level Variations	146
10.0	5 Searching for Milankovitch Periods	147
10.7	7 Chapter Summary	150
Exe	rcises	150
Appendi	x A Matrices and Vectors	152
Appendi	x B Fourier fransforms of Continuous Functions	155
Appendi	x C Random Variable Concepts and Applications	169
Appendi	x D Further Reading	188
Index		189