## Statistical Signal Processing of Complex-Valued Data

The Theory of Improper and Noncircular Signals

PETER J. SCHREIER University of Newcastle, New South Wales, Australia

LOUIS L. SCHARF Colorado State University, Colorado, USA



## **Contents**

	Prefe Nota		<i>age</i> xiii xvii
Part I	Introduc	tion	1
1	The	origins and uses of complex signals	3
	1.1 1.2 1.3 1.4	<ul> <li>Cartesian, polar, and complex representations of two-dimensional signals</li> <li>Simple harmonic oscillator and phasors</li> <li>Lissajous figures, ellipses, and electromagnetic polarization</li> <li>Complex modulation, the Hilbert transform, and complex analytic signals</li> <li>1.4.1 Complex modulation using the complex envelope</li> <li>1.4.2 The Hilbert transform, phase splitter, and analytic signal</li> <li>1.4.3 Complex demodulation</li> <li>1.4.4 Bedrosian's theorem: the Hilbert transform of a product</li> <li>1.4.5 Instantaneous amplitude fragments and phase</li> </ul>	4 5 6 8 9 11 13 14
	1.5	<ul> <li>1.4.5 Instantaneous amplitude, frequency, and phase</li> <li>1.4.6 Hilbert transform and SSB modulation</li> <li>1.4.7 Passband filtering at baseband</li> <li>Complex signals for the efficient use of the FFT</li> <li>1.5.1 Complex DFT</li> <li>1.5.2 Twofer: two real DFTs from one complex DFT</li> <li>1.5.3 Twofer: one real 2<i>N</i>-DFT from one complex <i>N</i>-DFT</li> </ul>	14 15 15 17 18 18 18
	1.6 1.7 1.8 1.9	<ul> <li>The bivariate Gaussian distribution and its complex representation</li> <li>1.6.1 Bivariate Gaussian distribution</li> <li>1.6.2 Complex representation of the bivariate Gaussian distribution</li> <li>1.6.3 Polar coordinates and marginal pdfs</li> <li>Second-order analysis of the polarization ellipse</li> <li>Mathematical framework</li> <li>A brief survey of applications</li> </ul>	19 20 21 23 23 25 27
2	Intro	duction to complex random vectors and processes	30
	2.1	<ul><li>Connection between real and complex descriptions</li><li>2.1.1 Widely linear transformations</li><li>2.1.2 Inner products and quadratic forms</li></ul>	31 31 33

	2.2	Second-order statistical properties	34
		2.2.1 Extending definitions from the real to the complex domain	35
		2.2.2 Characterization of augmented covariance matrices	36
		2.2.3 Power and entropy	37
	2.3	Probability distributions and densities	38
		2.3.1 Complex Gaussian distribution	39
		2.3.2 Conditional complex Gaussian distribution	41
		2.3.3 Scalar complex Gaussian distribution	42
		2.3.4 Complex elliptical distribution	44
	2.4	Sufficient statistics and ML estimators for covariances:	
		complex Wishart distribution	47
	2.5	Characteristic function and higher-order statistical description	49
		2.5.1 Characteristic functions of Gaussian and elliptical distributions	50
		2.5.2 Higher-order moments	50
		2.5.3 Cumulant-generating function	52
		2.5.4 Circularity	53
	2.6	Complex random processes	54
		2.6.1 Wide-sense stationary processes	55
		2.6.2 Widely linear shift-invariant filtering	57
	Note	28	57
Dort II. Co	mnlo	r randam vaatara	59
	mpie	k random vectors	39
3	-	and-order description of complex random vectors	61
	Seco	nd-order description of complex random vectors	61
	-	nd-order description of complex random vectors Eigenvalue decomposition	61 62
	Seco	end-order description of complex random vectors Eigenvalue decomposition 3.1.1 Principal components	61 62 63
	<b>Seco</b> 3.1	<ul> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> </ul>	61 62 63 64
	Seco	<ul> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> </ul>	61 62 63 64 65
	<b>Seco</b> 3.1	<ul> <li>and-order description of complex random vectors</li> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> <li>3.2.1 Entropy</li> </ul>	61 62 63 64
	<b>Seco</b> 3.1	<ul> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> <li>3.2.1 Entropy</li> <li>3.2.2 Strong uncorrelating transform (SUT)</li> </ul>	61 62 63 64 65 67
	<b>Seco</b> 3.1	<ul> <li>and-order description of complex random vectors</li> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> <li>3.2.1 Entropy</li> <li>3.2.2 Strong uncorrelating transform (SUT)</li> <li>3.2.3 Characterization of complementary covariance matrices</li> </ul>	61 62 63 64 65 67 67
	<b>Secc</b> 3.1 3.2	<ul> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> <li>3.2.1 Entropy</li> <li>3.2.2 Strong uncorrelating transform (SUT)</li> </ul>	61 62 63 64 65 67 67 69
	<b>Secc</b> 3.1 3.2	<ul> <li>and-order description of complex random vectors</li> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> <li>3.2.1 Entropy</li> <li>3.2.2 Strong uncorrelating transform (SUT)</li> <li>3.2.3 Characterization of complementary covariance matrices</li> <li>Degree of impropriety</li> </ul>	61 62 63 64 65 67 67 69 70
	<b>Secc</b> 3.1 3.2	<ul> <li>and-order description of complex random vectors</li> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> <li>3.2.1 Entropy</li> <li>3.2.2 Strong uncorrelating transform (SUT)</li> <li>3.2.3 Characterization of complementary covariance matrices</li> <li>Degree of impropriety</li> <li>3.3.1 Upper and lower bounds</li> </ul>	61 62 63 64 65 67 67 67 69 70 72
	<b>Secc</b> 3.1 3.2	<ul> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> <li>3.2.1 Entropy</li> <li>3.2.2 Strong uncorrelating transform (SUT)</li> <li>3.2.3 Characterization of complementary covariance matrices</li> <li>Degree of impropriety</li> <li>3.3.1 Upper and lower bounds</li> <li>3.3.2 Eigenvalue spread of the augmented covariance matrix</li> </ul>	61 62 63 64 65 67 67 67 69 70 72 76
	<b>Seco</b> 3.1 3.2 3.3	<ul> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> <li>3.2.1 Entropy</li> <li>3.2.2 Strong uncorrelating transform (SUT)</li> <li>3.2.3 Characterization of complementary covariance matrices</li> <li>Degree of impropriety</li> <li>3.3.1 Upper and lower bounds</li> <li>3.3.2 Eigenvalue spread of the augmented covariance matrix</li> <li>3.3.3 Maximally improper vectors</li> </ul>	61 62 63 64 65 67 67 69 70 72 76 76
	<b>Secc</b> 3.1 3.2 3.3 3.4	<ul> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> <li>3.2.1 Entropy</li> <li>3.2.2 Strong uncorrelating transform (SUT)</li> <li>3.2.3 Characterization of complementary covariance matrices</li> <li>Degree of impropriety</li> <li>3.3.1 Upper and lower bounds</li> <li>3.3.2 Eigenvalue spread of the augmented covariance matrix</li> <li>3.3.3 Maximally improper vectors</li> <li>Testing for impropriety</li> <li>Independent component analysis</li> </ul>	61 62 63 64 65 67 67 67 69 70 72 76 76 77
	Secc 3.1 3.2 3.3 3.4 3.5 Note	<ul> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> <li>3.2.1 Entropy</li> <li>3.2.2 Strong uncorrelating transform (SUT)</li> <li>3.2.3 Characterization of complementary covariance matrices</li> <li>Degree of impropriety</li> <li>3.3.1 Upper and lower bounds</li> <li>3.3.2 Eigenvalue spread of the augmented covariance matrix</li> <li>3.3.3 Maximally improper vectors</li> <li>Testing for impropriety</li> <li>Independent component analysis</li> </ul>	61 62 63 64 65 67 67 69 70 72 76 76 76 77 81
3	Secc 3.1 3.2 3.3 3.4 3.5 Note	<ul> <li>Eigenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> <li>3.2.1 Entropy</li> <li>3.2.2 Strong uncorrelating transform (SUT)</li> <li>3.2.3 Characterization of complementary covariance matrices</li> <li>Degree of impropriety</li> <li>3.3.1 Upper and lower bounds</li> <li>3.3.2 Eigenvalue spread of the augmented covariance matrix</li> <li>3.3.3 Maximally improper vectors</li> <li>Testing for impropriety</li> </ul>	<ul> <li>61</li> <li>62</li> <li>63</li> <li>64</li> <li>65</li> <li>67</li> <li>67</li> <li>69</li> <li>70</li> <li>72</li> <li>76</li> <li>76</li> <li>76</li> <li>77</li> <li>81</li> <li>84</li> </ul>
3	Secc 3.1 3.2 3.3 3.4 3.5 Note Corr	<ul> <li>Figenvalue decomposition</li> <li>3.1.1 Principal components</li> <li>3.1.2 Rank reduction and transform coding</li> <li>Circularity coefficients</li> <li>3.2.1 Entropy</li> <li>3.2.2 Strong uncorrelating transform (SUT)</li> <li>3.2.3 Characterization of complementary covariance matrices</li> <li>Degree of impropriety</li> <li>3.3.1 Upper and lower bounds</li> <li>3.3.2 Eigenvalue spread of the augmented covariance matrix</li> <li>3.3.3 Maximally improper vectors</li> <li>Testing for impropriety</li> <li>Independent component analysis</li> </ul>	<ul> <li>61</li> <li>62</li> <li>63</li> <li>64</li> <li>65</li> <li>67</li> <li>67</li> <li>69</li> <li>70</li> <li>72</li> <li>76</li> <li>76</li> <li>76</li> <li>77</li> <li>81</li> <li>84</li> </ul>

	4.1.2	Principle of multivariate correlation analysis	91
	4.1.3	Rotational, reflectional, and total correlations for complex vectors	94
	4.1.4	Transformations into latent variables	95
4.2	Invaria	ance properties	97
	4.2.1	Canonical correlations	97
	4.2.2	Multivariate linear regression (half-canonical correlations)	100
	4.2.3	Partial least squares	101
4.3	Correl	ation coefficients for complex vectors	102
	4.3.1	Canonical correlations	103
	4.3.2	Multivariate linear regression (half-canonical correlations)	106
	4.3.3	Partial least squares	108
4.4	Correl	ation spread	108
4.5	Testing	g for correlation structure	110
	4.5.1	Sphericity	112
	4.5.2	Independence within one data set	112
	4.5.3	Independence between two data sets	113
Note	es		114
Estir	nation		116
5.1	Hilber	t-space geometry of second-order random variables	117
5.2		num mean-squared error estimation	119
5.3		MMSE estimation	121
	5.3.1	The signal-plus-noise channel model	122
	5.3.2	The measurement-plus-error channel model	123
	5.3.3	Filtering models	125
	5.3.4	Nonzero means	127
	5.3.5	Concentration ellipsoids	127
	5.3.6	Special cases	128
5.4	Widel	y linear MMSE estimation	129
	5.4.1	Special cases	130
	5.4.2	Performance comparison between LMMSE and	
		WLMMSE estimation	131
5.5	Reduc	ed-rank widely linear estimation	132
	5.5.1	Minimize mean-squared error (min-trace problem)	133
	5.5.2	Maximize mutual information (min-det problem)	135
5.6	Linear	and widely linear minimum-variance distortionless	
	respon	ise estimators	137
	5.6.1	Rank-one LMVDR receiver	138
	5.6.2	Generalized sidelobe canceler	139
	5.6.3	Multi-rank LMVDR receiver	141
	5.6.4	Subspace identification for beamforming and spectrum analysis	142
	5.6.5	Extension to WLMVDR receiver	143
5.7	Widel	y linear-quadratic estimation	144

	5.7.1	Connection between real and complex quadratic forms	14
	5.7.2	WLQMMSE estimation	14
Note	s		1
Perfo	ormance	e bounds for parameter estimation	1
6.1	Freque	entists and Bayesians	1
	6.1.1	Bias, error covariance, and mean-squared error	1
	6.1.2	Connection between frequentist and Bayesian approaches	1
	6.1.3	Extension to augmented errors	1
6.2	Quadratic frequentist bounds		
	6.2.1	The virtual two-channel experiment and the quadratic	
		frequentist bound	1
	6.2.2	Projection-operator and integral-operator representations	
		of quadratic frequentist bounds	1
	6.2.3	Extension of the quadratic frequentist bound to improper	
		errors and scores	1
6.3	Fisher	score and the Cramér–Rao bound	1
	6.3.1	Nuisance parameters	1
	6.3.2	The Cramér-Rao bound in the proper multivariate	
		Gaussian model	]
	6.3.3	The separable linear statistical model and the geometry of the	
		Cramér–Rao bound	1
	6.3.4	Extension of Fisher score and the Cramér-Rao bound to	
		improper errors and scores	1
	6.3.5	The Cramér-Rao bound in the improper multivariate	
		Gaussian model	1
	6.3.6	Fisher score and Cramér-Rao bounds for functions	
		of parameters	1
6.4	Quadr	ratic Bayesian bounds	1
6.5	Fisher	-Bayes score and Fisher-Bayes bound	]
	6.5.1	Fisher–Bayes score and information	
	6.5.2	Fisher–Bayes bound	
6.6	Conne	ections and orderings among bounds	
Note	es		1
Dete	ction		1
7.1	Binar	y hypothesis testing	1
	7.1.1	The Neyman–Pearson lemma	
	7.1.2	Bayes detectors	
	7.1.3	Adaptive Neyman–Pearson and empirical Bayes detectors	
7.2	Suffic	iency and invariance	]
7.3	Receiv	ver operating characteristic	1
7.4	Simpl	e hypothesis testing in the improper Gaussian model	1

		7.4.1 Uncommon means and common covariance	183
		7.4.2 Common mean and uncommon covariances	185
		7.4.3 Comparison between linear and widely linear detection	186
	7.5	Composite hypothesis testing and the Karlin-Rubin theorem	188
	7.6	Invariance in hypothesis testing	189
		7.6.1 Matched subspace detector	190
		7.6.2 CFAR matched subspace detector	193
	Note	es	194
Part III C	omple	ex random processes	195
8	Wide	e-sense stationary processes	197
	8.1	Spectral representation and power spectral density	197
	8.2	Filtering	200
		8.2.1 Analytic and complex baseband signals	201
		8.2.2 Noncausal Wiener filter	202
	8.3	Causal Wiener filter	203
		8.3.1 Spectral factorization	203
	0.4	8.3.2 Causal synthesis, analysis, and Wiener filters	205
	8.4	Rotary-component and polarization analysis	205
		8.4.1 Rotary components	206
		8.4.2 Rotary components of random signals	208
		<ul><li>8.4.3 Polarization and coherence</li><li>8.4.4 Stokes and Jones vectors</li></ul>	211 213
			213
	8.5	8.4.5 Joint analysis of two signals Higher-order spectra	213
	0.5		210
		<ul><li>8.5.1 Moment spectra and principal domains</li><li>8.5.2 Analytic signals</li></ul>	217
	Note		218
	INOU		221
9	Non	stationary processes	223
	9.1	Karhunen–Loève expansion	224
		9.1.1 Estimation	227
		9.1.2 Detection	230
	9.2	Cramér–Loève spectral representation	230
		9.2.1 Four-corners diagram	231
		9.2.2 Energy and power spectral densities	233
		9.2.3 Analytic signals	235
		9.2.4 Discrete-time signals	236
	9.3	Rihaczek time-frequency representation	237
		9.3.1 Interpretation	238
		9.3.2 Kernel estimators	240
	9.4	Rotary-component and polarization analysis	242

Ç	9.4.1	Ellipse properties	244
ç	9.4.2	Analytic signals	245
9.5 H	Higher	r-order statistics	247
Notes			248
Cyclos	tation	ary processes	250
		cterization and spectral properties	251
		Cyclic power spectral density	251
		Cyclic spectral coherence	253
		Estimating the cyclic power-spectral density	254
		ly modulated digital communication signals	255
		Symbol-rate-related cyclostationarity	255
		Carrier-frequency-related cyclostationarity	258
		Cyclostationarity as frequency diversity	259
	•	Wiener filter	260
		filter-bank implementation of the cyclic Wiener filter	262
1	0.4.1	Connection between scalar CS and vector	
		WSS processes	262
		Sliding-window filter bank	264
		Equivalence to FRESH filtering	265
	0.4.4	Causal approximation	267
Notes			268
Appen	dix 1	Rudiments of matrix analysis	270
A1.1 M	Matrix	factorizations	270
A	41.1.1	Partitioned matrices	270
ŀ	41.1.2	Eigenvalue decomposition	270
I	41.1.3	Singular value decomposition	271
		ve definite matrices	272
I	41.2.1	Matrix square root and Cholesky decomposition	272
		2 Updating the Cholesky factors of a Grammian matrix	272
		Partial ordering	273
		Inequalities	274
		inverses	274
		Partitioned matrices	274
		2 Moore–Penrose pseudo-inverse	275
1	41.3.3	9 Projections	276
Appen	dix 2	Complex differential calculus (Wirtinger calculus)	277
	-	lex gradients	278
		Holomorphic functions	279
		Complex gradients and Jacobians	280
I	42.1.3	Properties of Wirtinger derivatives	281

A2.2 Special cases	282
A2.3 Complex Hessians	283
A2.3.1 Properties	285
A2.3.2 Extension to complex-valued functions	285
Appendix 3 Introduction to majorization	287
A3.1 Basic definitions	288
A3.1.1 Majorization	288
A3.1.2 Schur-convex functions	289
A3.2 Tests for Schur-convexity	290
A3.2.1 Specialized tests	291
A3.2.2 Functions defined on $\mathcal{D}$	292
A3.3 Eigenvalues and singular values	293
A3.3.1 Diagonal elements and eigenvalues	293
A3.3.2 Diagonal elements and singular values	294
A3.3.3 Partitioned matrices	295
References	296
Index	305