

Contents

1	Introduction	1
1.1	Background	1
1.2	Motivation	3
1.2.1	Signal-Noise Separation Problem	3
1.2.2	Signal-Signal Separation Problem	4
1.3	Application of Statistics in Signal Separation	5
1.4	Aims and Objectives of the Present Study	7
1.5	Outline of the Thesis	10
2	GRACE Observations of Mass Changes	12
2.1	From Geopotential Coefficients to Total Water Storage (TWS) Changes	13
2.1.1	Low Degree Coefficients	14
2.1.2	Smoothing	15
2.1.3	Area Averaging	16
2.1.4	Leakage Problem	16
2.1.5	Glacial Isostatic Adjustment	17
2.1.6	Error Estimation	17
2.2	High-frequency Atmospheric and Oceanic Mass Redistribution	18
2.3	Computational Steps for Estimating TWS Changes	21
3	Second Order Statistical Signal Decomposition	22
3.1	Principal Component Analysis/Empirical Orthogonal Function (PCA/EOF)	22
3.1.1	Central Idea of PCA	23
3.1.2	PCA from Eigenvalue Decomposition	23
3.1.3	PCA as a Data Whitening Method	27
3.2	Rotated EOF	28
3.3	Extended EOF/Multi-Channel Singular Spectrum Analysis	30
3.4	Complex EOF	32
3.5	Statistical Tests for the Significance of Modes	36
3.5.1	Dominant-variance Rules	37
3.5.1.1	Simple Rules	38
3.5.1.2	Considering Sampling Errors	39
3.5.2	Time-history Tests	41
3.6	Error Estimation of Reconstruction	43

4	Higher Order Statistical Signal Decomposition	45
4.1	Blind Source Separation	46
4.2	Statistical Independence	48
4.3	Independent Component Analysis (ICA)	49
4.4	A Remark on the Application of ICA for Noise Reduction in GRACE Products .	51
4.5	On Independence Criteria	53
4.5.1	ICA by Joint Diagonalization of the Fourth-Order Cumulant Tensor . . .	54
4.5.1.1	Joint Diagonalization (JD)	56
4.5.1.2	Spatial and Temporal ICA Algorithms	57
4.5.2	Alternative ICA Criteria Based on Joint Diagonalization of Cumulants . .	58
4.5.3	Complex ICA by Joint Diagonalization of the Fourth-Order Cumulant Tensor	59
4.5.3.1	Spatial and Temporal Complex ICA Algorithms	60
4.5.4	ICA Based on Entropy	61
4.6	Separation of Deterministic Signals	62
4.6.1	Setup of the Proof	62
4.6.2	Separation of Sinusoidal Signals and a Linear Trend	63
4.6.3	Numerical Illustration	65
4.7	Summary of the Introduced Statistical Decomposition Techniques	67
4.8	Uncertainty Computation of the ICA Decomposition	68
5	Applications of Statistical Signal Separation Techniques for Analyzing GRACE-TWS	69
5.1	Decomposition of GRACE-like Simulated Total Water Storage Changes	69
5.1.1	Performance Analysis of the PCA, REOF and ICA	69
5.1.2	Performance Analysis of PCA and ICA for a Regional Case	73
5.1.3	Performance Analysis for a Case with Propagating Signals	74
5.2	Independent Patterns of Global Total Water Storage Changes	78
5.2.1	Temporally Independent Patterns from Global GRACE-TWS Changes . .	78
5.2.2	Extracting the El Niño Pattern from Global GRACE-TWS Changes . . .	81
5.2.3	Summary and Discussion of the Global Results	82
5.3	Independent Patterns of Total Water Storage Changes over Australia	83
5.3.1	Numerical Results over Australia	84

5.3.2	Summary and Discussion of the Results over Australia	90
5.4	Statistical Partitioning of Total Water Storage Changes	91
5.4.1	Methodology of Statistical TWS Partitioning	92
5.4.2	Numerical Results over the Middle East Region	94
5.4.3	Summary and Discussion of the Statistical Partitioning Results	95
5.5	Multivariate Forecasting of Total Water Storage Changes	96
5.5.1	Required Data for Forecasting TWS	96
5.5.2	Methodology of Statistical Forecasting	96
5.5.3	Numerical Results over West Africa	98
5.5.4	Summary and Discussion of the Forecast Results	103
6	Conclusion and Outlook	104
6.1	Conclusion	104
6.2	Outlook	107
	Acronyms	111
	Lists	113
	List of Figures	113
	List of Tables	118
	References	119