

**IMPROVED HYPER-TEMPORAL FEATURE EXTRACTION METHODS FOR LAND
COVER CHANGE DETECTION IN SATELLITE TIME SERIES**

By

Brian Paxton Salmon

Submitted in partial fulfilment of the requirements for the degree

Philosophiae Doctor (Electronic)

in the

Faculty of Engineering, Built Environment and Information Technology

Department of Electrical, Electronic and Computer Engineering

UNIVERSITY OF PRETORIA

August 2012

SUMMARY

IMPROVED HYPER-TEMPORAL FEATURE EXTRACTION METHODS FOR LAND COVER CHANGE DETECTION IN SATELLITE TIME SERIES

by

Brian Paxton Salmon

Promoter: Prof J.C. Olivier
Department: Electrical, Electronic and Computer Engineering
University: University of Pretoria
Degree: Philosophiae Doctor (Electronic)
Keywords: classification, clustering, change detection, extended Kalman filter,
Fourier transform, satellite, time series

The growth in global population inevitably increases the consumption of natural resources. The need to provide basic services to these growing communities leads to an increase in anthropogenic changes to the natural environment. The resulting transformation of vegetation cover (e.g. deforestation, agricultural expansion, urbanisation) has significant impacts on hydrology, biodiversity, ecosystems and climate. Human settlement expansion is the most common driver of land cover change in South Africa, and is currently mapped on an irregular, ad hoc basis using visual interpretation of aerial photographs or satellite images. This thesis proposes several methods of detecting newly formed human settlements using hyper-temporal, multi-spectral, medium spatial resolution MODIS land surface reflectance satellite imagery. The hyper-temporal images are used to extract time series, which are analysed in an automated fashion using machine learning methods. A post-classification change detection framework was developed to analyse the time series using several feature extraction methods and classifiers. Two novel hyper-temporal feature extraction methods are proposed to characterise the seasonal pattern in the time series. The first feature extraction method extracts Seasonal Fourier features that exploits the difference in temporal spectra inherent to land cover classes. The second feature extraction method extracts state-space vectors derived using an extended Kalman filter. The extended Kalman filter is optimised using a novel criterion which exploits the information inherent

in the spatio-temporal domain. The post-classification change detection framework was evaluated on different classifiers; both supervised and unsupervised methods were explored. A change detection accuracy of above 85% with false alarm rate below 10% was attained. The best performing methods were then applied at a provincial scale in the Gauteng and Limpopo provinces to produce regional change maps, indicating settlement expansion.

OPSOMMING

VERBETERDE HOË TYD-RESOLUSIE KENMERKONTREKKINGSMETODES VIR DIE DETEKSIE VAN VERANDERING IN LANDBEDEKKING MET BEHULP VAN 'N SATELLIETTYDREEKS.

deur

Brian Paxton Salmon

Promotor: Prof J.C. Olivier
Departement: Elektriese, Elektroniese en Rekenaar Ingenieurswese
Universiteit: Universiteit van Pretoria
Graad: Philosophiae Doctor (Elektronies)
Sleutelwoorde: klassifikasie, groepering, veranderingopsporing, uitgebreide Kalman-filter,
Fourier-transform, satelliet, tydsreekse

Die groei in die globale bevolking veroorsaak verhoogde verbruik van natuurlike hulpbronne. Die behoefte om basiese dienste te lewer aan hierdie groeiende gemeenskappe lei tot 'n toename in antropogeniese veranderinge aan die natuurlike omgewing. Die gevolglike transformasie van plantbedekking (bv. ontbossing, landbou-uitbreiding, verstedeliking) het 'n beduidende impak op hidrologie, ekosisteme en die klimaat. Nedersettingsuitbreiding is die mees algemene oorsaak van landbedekkingsverandering in Suid-Afrika en informasie oor waar en wanneer nuwe nedersettings, voorkom word tans op 'n onreëlmatige basis bekom deur die visuele interpretasie van lugfotos of satellietbeelde. Hierdie tesis stel verskeie metodes voor vir die opsporing van nuutgestigte nedersettings met behulp van hiper-temporale, multi-spektrale, medium ruimtelike resoluksie MODIS-grondoppervlakte reflektansie satellietbeelde. Die hiper-temporale beelde word gebruik om tydsreekse te onttrek, wat dan outomaties ontleed word met behulp van masjienleer metodes. 'n *Post*-klassifikasie veranderingopsporingsraamwerk is ontwikkel om tydsreekse te analiseer deur gebruik te maak van verskeie kenmerkonttrekkingsmetodes en klassifiseerders. Twee nuwe hiper-temporale kenmerkonttrekkingsmetodes word voorgestel om die seisoenale patroon in die reeks te karakteriseer. Die eerste kenmerkonttrekkingsmetode onttrek Seisoen Fourier-eienskappe

uit die tydsreeks, wat die temporale spektrum eienskappe van verskillende landbedekkingsklasse beklemtoon. Die tweede kenmerkonttrekkingsmetode onttrek toestand-ruimte vektore uit die tydsreeks, wat verkry word met behulp van 'n uitgebreide Kalman-filter. Die uitgebreide Kalman-filter is geoptimeer deur gebruik te maak van 'n nuwe maatstaf wat gebaseer is op die inligting in die ruimtelike-temporale domein. Die *post*-klassifikasie veranderingopsporingsraamwerk is geëvalueer met verskillende klassifiseerders; beide toesig en sonder-toesig metodes is ondersoek. 'n Veranderingopsporingsakkuraatheid bo 85% met 'n valsalarmskoers onder 10% is behaal. Die beste metodes is toegepas op 'n provinsiale skaal in die Gauteng- en Limpopo-provinsies om plaaslike veranderings kaarte te produseer.

This thesis is dedicated to:

God Almighty, for all the countless opportunities that He has given me;

My loving family and friends, thank you for all your love, support, and sacrifice throughout my life.

We all grow up with the weight of history on us. Our ancestors dwell in the attics of our brains as they do in the spiraling chains of knowledge hidden in every cell of our bodies. - Shirley Abbott

ACKNOWLEDGEMENT

The author would like to thank the following people and institutions, without whose help this thesis would not have been possible:

- The Council for Scientific and Industrial Research for supporting me on their PhD studentship programme.
- My study leader, Prof J.C. Olivier, for all the advice and guidance he has given me throughout the course of my studies.
- My co-promoters, Dr. Frans van den Bergh and Dr. Konrad Wessels, for all their insight, advice and help.
- My fellow student, Waldo Kleynhans, for all his useful suggestions and advice.
- The University of Pretoria's computer clusters maintained by Hans Grobler, which greatly aided in my simulations.
- Karen Steenkamp for providing me with the necessary data used for training and validation purposes.
- Willem Marais for providing me with custom developed image processing software.
- The financial assistance of the National Research Foundation (NRF) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to the NRF.

LIST OF ABBREVIATIONS

Autocorrelation Function	ACF
Aikaike Information Criterion	AIC
Atmospheric Infrared Sounder	AIRS
Autocovariance Least Squares	ALS
Ante Meridiem	AM
Advanced Microwave Scanning Radiometer	AMSR
Advanced Microwave Sounding Unit	AMSU-A
Artificial Neural Network	ANN
Advanced Spaceborne Thermal Emission and Reflection radiometer	ASTER
Algorithm Theoretical Basis Document	ATBD
Advanced Very High Resolution Radiometer	AVHRR
Break For Additive Seasonal and Trend	BFAST
Broyden-Fletcher-Goldfarb-Shanno	BFGS
Best Matching Unit	BMU
Bidirectional Reflectance Distribution Function	BRDF
Bias-Variance Equilibrium Point	BVEP
Bias-Variance Score	BVS
Bias-Variance Search Algorithm	BVSA
Clouds and the Earth's Radiant Energy System	CERES
Change Vector Analysis	CVA
Chandra X-ray Center	CXC
Coastal Zone Color Scanner	CZCS
Discrete Fourier Transform	DFT
Extended Kalman Filter	EKF

Expectation Maximization	EM
Earth Observation System	EOS
Earth Resource Technology Satellite	ERTS
Enhanced Thematic Mapper Plus	ETM+
Enhanced Vegetation Index	EVI
Foreign Agricultural Services	FAS
Fast Fourier Transform	FFT
Farm Service Agency	FSA
Gigabit	Gb
Gross Domestic Product	GDP
Group on Earth Observations	GEO
Global Earth Observation System of Systems	GEOSS
Geographical Information System	GIS
Global Positioning System	GPS
Hierarchical Data Format	HDF
High Resolution Infrared Spectrometer	HIRS
Humidity Sounder for Brazil	HSB
Inverse Discrete Fourier Transform	IDFT
Inverse Fast Fourier Transform	IFFT
Instantaneous Field of View	IFOV
Least Squares	LS
Line Spread Function	LSF
Linear Spectral Mixture Analysis	LSMA
Land Use Land Change	LULC
Multi-angle Imaging SpectroRadiometer	MISR
Multilayer Perceptron	MLP
MODerate-resolution Imaging Spectroradiometer	MODIS

Measurements of Pollution in the Troposphere	MOPITT
Multi-Spectral Scanner	MSS
National Aeronautics and Space Administration	NASA
National Argicultural Statistics Services	NASS
Normalized Difference Vegetation Index	NDVI
Near InfraRed	NIR
National Land Cover	NLC
Ordinary Least Squares	OLS
Principal Component Analysis	PCA
Post Meridiem	PM
Point Spread Function	PSF
Radial Basis Function	RBF
Red Green Blue	RGB
Resilient backpropagation	RPROP
Smithsonian Astrophysical Obervatory	SAO
Seasonal Fourier Features	SFF
Signal-to-Noise Ratio	SNR
Self Organizing Map	SOM
Satellite Pour l'Observation de la Terre	SPOT
Signal-to-Quantization Noise Ratio	SQNR
Sum of Squares Error	SSE
Support Vector Machine	SVM
Thematic Mapper	TM
United Nations	UN
United States Department of Argiculture	USDA
Vegetative Cover Conversion	VCC
Vegetation Index	VI

CONTENTS

CHAPTER 1 - INTRODUCTION	1
1.1 Problem statement	1
1.2 Objective of this thesis and proposed solution	3
1.3 Outline of Thesis	5
CHAPTER 2 - REMOTE SENSING USED FOR LAND COVER CHANGE DETECTION	7
2.1 Overview	7
2.2 Spontaneous Settlements	7
2.2.1 Limpopo province	8
2.2.2 Gauteng province	9
2.3 Overview of Remote Sensing	10
2.4 Electromagnetic radiation	11
2.5 Earth's Energy Budget	12
2.5.1 Interaction with the atmosphere	13
2.5.2 Interaction with the Earth's surface	16
2.5.3 Interaction with a satellite-based sensor	16
2.6 MODerate resolution Imaging Spectroradiometer	20
2.7 Vegetation Indices	26
2.7.1 Normalised Difference Vegetation Index	26
2.7.2 Enhanced Vegetation Index	27
2.8 Land cover change detection methods	28
2.8.1 Hyper-temporal change detection methods	33
2.8.2 MODIS land cover change detection product	36
2.9 Summary	37
CHAPTER 3 - SUPERVISED CLASSIFICATION	38
3.1 Overview	38
3.2 Classification	38

Contents

3.3	Supervised Classification	39
3.3.1	Mapping of input vectors	40
3.3.2	Converting to feature vectors	44
3.4	Artificial Neural Networks	48
3.4.1	Network architecture	48
3.4.2	Regression using a multilayer perceptron	51
3.4.3	Classification using a multilayer perceptron	52
3.4.4	Training of neural networks	53
3.4.5	First order training algorithms	54
3.4.6	Second order training algorithms	57
3.5	Other variants of Artificial Neural Networks used for Classification	60
3.5.1	Radial basis function network	60
3.5.2	Self organising map	61
3.5.3	Hopfield networks	62
3.5.4	Support vector machine	62
3.6	Design consideration: Supervised classification	63
3.7	Summary	65
CHAPTER 4 - UNSUPERVISED CLASSIFICATION		66
4.1	Overview	66
4.2	Clustering	66
4.2.1	Mapping of vectors to clusters	67
4.2.2	Creating meaningful clusters	67
4.2.3	Challenges of clustering	70
4.3	Similarity metric	71
4.4	Hierarchical clustering algorithms	72
4.4.1	Linkage criteria	75
4.4.2	Cophenetic correlation coefficient	77
4.5	Partitional clustering algorithms	77
4.5.1	K-means algorithm	78
4.5.2	Expectation-maximisation algorithm	79
4.6	Determining the number of clusters	80
4.7	Classification of cluster labels	82
4.8	Summary	83

CHAPTER 5 - FEATURE EXTRACTION	84
5.1 Overview	84
5.2 Time series representation	84
5.3 State-space representation	86
5.4 Kalman filter	89
5.5 Extended Kalman filter	92
5.6 Least squares model fitting	97
5.7 M-estimate model fitting	101
5.8 Fourier Transform	103
5.9 Summary	107
CHAPTER 6 - SEASONAL FOURIER FEATURES	108
6.1 Overview	108
6.2 Time series analysis	108
6.3 Meaningless analysis	109
6.4 Meaningful clustering	116
6.5 Change detection method using the seasonal Fourier features	118
6.6 Summary	120
CHAPTER 7 - EXTENDED KALMAN FILTER FEATURES	121
7.1 Overview	121
7.2 Change detection method: Extended Kalman Filter	121
7.2.1 Introduction	121
7.2.2 The method	122
7.2.3 Importance of the initial parameters	125
7.2.4 Bias-Variance Equilibrium Point	130
7.2.5 Bias-Variance Search algorithm	135
7.3 Autocovariance Least Squares method	136
7.4 Summary	137
CHAPTER 8 - RESULTS	138
8.1 Overview	138
8.2 Ground truth data set	138
8.2.1 MODIS time series data set	139
8.2.2 Manual inspection of study areas	140

Contents

8.2.3	Google™Earth used for visual inspection	142
8.2.4	Simulated land cover data set	142
8.3	System outline	142
8.4	Experimental Plan	146
8.5	Parameter Exploration	148
8.5.1	Optimising the multilayer perceptron	148
8.5.2	Batch mode versus iterative retrained mode	149
8.5.3	Optimising least squares	151
8.5.4	BVEP versus autocovariance least squares	153
8.5.5	Optimisation of Kalman filter parameters	153
8.5.6	BVSA parameter evaluation	157
8.5.7	Determining the number of clusters	158
8.5.8	Results: Cophenetic correlation coefficient	159
8.6	Classification	161
8.6.1	Classification accuracy: Multilayer perceptron	161
8.6.2	Clustering experimental setup	163
8.6.3	Clustering accuracy: Single, Average and Complete linkage criterion	163
8.6.4	Clustering accuracy: Ward clustering method	164
8.6.5	Clustering accuracy: K-means clustering	166
8.6.6	Clustering accuracy: Expectation-Maximisation	168
8.6.7	Summary of classification results	168
8.7	Change detection	170
8.7.1	Simulated land cover change detection	170
8.7.2	Real land cover change detection	173
8.7.3	Effective change detection delay	175
8.7.4	Summary of change detection results	176
8.8	Change detection algorithm comparison	178
8.9	Provincial experiments	180
8.10	Computational complexity	183
8.11	Summary	184
CHAPTER 9 - CONCLUSION		186
9.1	Concluding remarks	186
9.2	Future Recommendations	188

Contents

REFERENCES	191
APPENDIX A - PUBLICATIONS EMANATING FROM THIS THESIS AND RELATED WORK	207
A.1 Papers that appeared in Thomson Institute for Scientific Information journals	207
A.2 Papers published in Refereed Accredited Conference Proceedings	208
A.3 Invited conference papers in Refereed Accredited Conference Proceedings	209
A.4 Papers submitted to Refereed Accredited Conference Proceedings	209
A.5 Best paper award	210