# SEQUENTIAL AND NON-SEQUENTIAL HYPERTEMPORAL CLASSIFICATION AND CHANGE DETECTION OF MODIS TIME-SERIES

by

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# SUMMARY

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Satellites provide humanity with data to infer properties of the earth that were impossible a century ago. Humanity can now easily monitor the amount of ice found on the polar caps, the size of forests and deserts, the earth's atmosphere, the seasonal variation on land and in the oceans and the surface temperature of the earth. In this thesis, new hypertemporal techniques are proposed for the settlement detection problem in South Africa. The hypertemporal techniques are applied to study areas in the Gauteng and Limpopo provinces of South Africa. To be more specific, new sequential (windowless) and non-sequential hypertemporal techniques are implemented. The time-series employed by the new hypertemporal techniques are obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, which is on board the earth observations satellites Aqua and Terra. One MODIS dataset is constructed for each province.

A Support Vector Machine (SVM) [1] that uses a novel noise-harmonic feature set is implemented to detect existing human settlements. The noise-harmonic feature set is a non-sequential hypertemporal feature set and is constructed by using the Coloured Simple Harmonic Oscillator (CSHO) [2]. The CSHO consists of a Simple Harmonic Oscillator (SHO) [3], which is superimposed on the Ornstein-

Uhlenbeck process [4]. The noise-harmonic feature set is an extension of the classic harmonic feature set [5]. The classic harmonic feature set consists of a mean and a seasonal component. For the case studies in this thesis, it is observed that the noise-harmonic feature set not only extends the harmonic feature set, but also improves on its classification capability.

The Cumulative Sum (CUSUM) algorithm was developed by Page in 1954 [6]. In its original form it is a sequential (windowless) hypertemporal change detection technique. Windowed versions of the algorithm have been applied in a remote sensing context. In this thesis CUSUM is used in its original form to detect settlement expansion in South Africa and is benchmarked against the classic band differencing change detection approach of Lunetta et al., which was developed in 2006 [7]. In the case of the Gauteng study area, the CUSUM algorithm outperformed the band differencing technique. The exact opposite behaviour was seen in the case of the Limpopo dataset.

Sequential hypertemporal techniques are data-intensive and an inductive MODIS simulator was therefore also developed (to augment datasets). The proposed simulator is also based on the CSHO. Two case studies showed that the proposed inductive simulator accurately replicates the temporal dynamics and spectral dependencies found in MODIS data.

# OPSOMMING

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## SEKWENSIËLE EN NIE-SEKWENSIËLE HIPERTEMPORALE KLASSIFIKASIE EN VERANDERING-OPSPORING VAN MABS-TYDSREEKSE

deur

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| Sleutelwoorde: | harmoniesegeraas-kenmerkstel, Gekleurde Eenvoudige Harmoniese Ossillator, Steunvektormasjien, Matigeresolusie- Beeldskeppende Spektrale Radio-ontvanger, Kumulatiewesom, Ornstein-Uhlenbeck proses, induktiewe simulator, hipertemporale klassifikasie, hipertemporale verandering-opsporing, sekwensiële analiese |

Satelliete gee die mensdom die geleentheid om dinge van die aarde te leer wat nie ’n eeu gelede moontlik was nie. Die mensdom kan nou maklik die hoeveelheid ys op die pole, die grootte van woude en woestyne, die aarde se atmosfeer, die seisoenale veranderinge op land en in die oseane, asook die temperatuur op die aarde se oppervlak monitor. In hierdie proefskrif word nuwe hipertemporale tegnieke vir die sogenaamde nedersettingsopsporingsprobleem in Suid-Afrika beskryf. Die nuwe hipertemporale tegnieke word toegepas op studie-areas in die Gauteng- en Limpopoprovinsies van Suid-Afrika. Om meer spesifiek te wees, nuwe sekwensiële (vensterlose) en nie-sekwensiële hipertemporale tegnieke word bespreek. Die tydsreekse wat deur die hipertemporale tegnieke benodig word, word deur die Matigeresolusie- Beeldskeppende Spektrale Radio-ontvanger (MABS) sensor verskaf, wat gemonteer is op die aardobservasiesatelliete Aqua en Terra. Een MABS-datastel is saamgestel vir elke provinsie.

’n Steunvektormasjien (SVM) [1] wat ’n nuwe harmoniesegeraas-kenmerkstel gebruik om bestaande nedersettings op te spoor, is geïmplementeer. Die nuwe harmoniesegeraas-kenmerkstel is ’n nie-sekwensiële hipertemporale-kenmerkstel en is saamgestel deur die Gekleurde Eenvou-

dige Harmoniese Ossillator (GEHO) te gebruik [2]. Die GEHO bestaan uit 'n Eenvoudige Harmoniese Ossillator (EHO) [3] wat gesuperponeer is op die Ornstein-Uhlenbeck-proses [4]. Die harmoniesegeraas-kenmerkstel is 'n uitbreiding van die klassieke harmoniese-kenmerkstel [5]. Die klassieke harmoniese-kenmerkstel bestaan uit 'n gemiddelde en 'n seisoenale komponent. Aan die hand van die gevallestudies in hierdie proefskrif is daar gevind dat die harmoniesegeraas-kenmerkstel nie net 'n uitbreiding van die klassieke harmoniese-kenmerkstel is nie, maar dat die harmoniesegeraas-kenmerkstel ook die klassifikasie-vermoë van die klassieke harmoniese-kenmerkstel verbeter.

Die Kumulatiewesom- (KUMSOM) algoritme is in 1954 deur Page ontwikkel [6]. In sy oorspronklike vorm is dit 'n sekwensiële hipertemporale veranderingopsporingstegniek. Afgeknotte weergawes van die algoritme is al vantevore in 'n afstandswaarneming-konteks gebruik. In hierdie proefskrif word KUMSOM in sy oorspronklike vensterlose vorm gebruik om die vorming van nuwe nedersettings in Suid-Afrika op te spoor. Die KUMSOM-algoritme word ook met die bandaftrekkingmetode vergelyk, wat in 2006 deur Lunetta et al. ontwikkel is [7]. In die geval van die Gauteng-gevallestudie lewer KUMSOM beter resultate as die bandaftrekkingmetode. Die presiese teenoorgestelde gedrag is waargeneem in die geval van Limpopo.

Sekwensiële hipertemporale tegnieke is baie data-intensief, gevolglik is 'n induktiewe MABS-simulator ontwerp wat datastelle kan vergroot. Die nuwe simulator is ook gebaseer op die GEHO. Twee gevallestudies het gewys dat die induktiewe simulator wel die temporale dinamika en spektrale afhanklikheid kan dupliseer wat voorkom in MABS-data.

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*In die begin het God die hemel en die aarde geskep. Die aarde was heeltemal onbewoonbaar, dit was donker op die diep waters, maar die Gees van God het oor die waters gesweef. Toe het God gesê: "Laat daar lig wees!" En daar was lig.*

Genesis 1:1-3, Bybel Nuwe Vertaling, 1983

**This dissertation is dedicated to my wife and parents.**

# LIST OF ABBREVIATIONS

| | |
|---|---|
| **AG** | Asymmetric Gaussian |
| **AIRS** | Atmospheric Infrared Sounder |
| **AMSR-E** | Advanced Microwave Scanning Radiometer-EOS |
| **AMSU** | Advanced Microwave Sounding Unit |
| **ANN** | Artificial Neural Network |
| **AR** | Autoregressive |
| **ARL** | Average Run Length |
| **ASN** | Average Sample Number |
| **ASTER** | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| **ATMS** | Advanced Technology Microwave Sounder |
| **AVHRR** | Advanced Very High Resolution Radiometer |
| **B** | Blue |
| **BB** | Blackbody |
| **BFAST** | Breaks for Additive Seasonal and Trend |
| **BOB** | Bureau of Budget |
| **BRDF** | Bidirectional Reflectance Distribution Function |
| **CERES** | Clouds and the Earth's Radiant Energy System |
| **CSIR** | Council for Scientific and Industrial Research |

| | |
|---|---|
| **CrIS** | Cross-track Infrared Sounder |
| **CSHO** | Coloured Simple Harmonic Oscillator |
| **CUSUM** | Cumulative Sum |
| **CVA** | Change Vector Analysis |
| **CZCS** | Coastal Zone Color Scanner |
| **DAAC** | Distributed Active Archive Center |
| **DL** | Double Logistic |
| **DN** | Digital Number |
| **DOD** | Department of Defense |
| **DOI** | Department of the Interior |
| **EDOS** | EOS Data and Operations System |
| **EHO** | Eenvoudige Harmoniese Ossillator |
| **EOS** | Earth Observing System |
| **EOSMRWG** | EOS Science and Mission Requirements Working Group |
| **ERTS** | Earth Resources Technology Satellite |
| **ESE** | Earth Science Enterprise |
| **EUMETSAT** | European Organisation for the Exploitation of Meteorological Satellites |
| **EVI** | Enhanced Vegetation Index |
| **FFT** | Fast Fourier Transform |
| **FP** | False Positive Rate |

| | |
|---|---|
| **FPAR** | Fraction of Photosynthetically Active Radiation |
| **FPAs** | Focal Plane Assemblies |
| **G** | Green |
| **GEHO** | Gekleurde Eenvoudige Harmoniese Ossillator |
| **GES DAAC** | GSFC Earth Sciences DAAC |
| **GIS** | Geographic Information System |
| **GMS** | Geostationary Meteorological Satellite |
| **GOES** | Geostationary Operational Environmental Satellite |
| **GSFC** | Goddard Space Flight Center |
| **HSB** | Humidity Sounder for Brazil |
| **HyspIRI** | Hyperspectral Infrared Imager |
| **i.i.d.** | independent and identically distributed |
| **ICA** | Independent Component Analysis |
| **IFOV** | Instantaneous Field of View |
| **IFOV** | Instantaneous Field of View |
| **INSAT** | Indian National Satellite System |
| **IPO** | Integrated Program Office |
| **IR** | Infrared |
| **IRS** | Indian Remote Sensing Satellite |
| **ISRO** | Indian Space Research Organisation |

| | |
|---|---|
| **ITOS** | Improved TIROS Operational System |
| **JAXA** | Japan Aerospace Exploration Agency |
| **JERS** | Japanese Earth Resource Satellite |
| **KDE** | Kernel Density Estimation |
| **KUMSOM** | Kumulatiewesom |
| **LAADS** | L1 and Atmosphere Archive and Distribution System |
| **LAI** | Leaf Area Index |
| **LDCM** | Landsat Data Continuity Mission |
| **LP DAAC** | Land Processes DAAC |
| **LWIR** | Long-wave Infrared |
| **MABS** | Matigeresolusie- Beeldskeppende Spektrale Radio-ontvanger |
| **MISR** | Multi-angle Imaging SpectroRadiometer |
| **MODAPS** | MODIS Adaptive Processing System |
| **MODIS** | Moderate Resolution Imaging Spectroradiometer |
| **MOPITT** | Measurements of Pollution in the Troposphere |
| **MSS** | Multispectral Scanner |
| **MTPE** | Mission to Planet Earth |
| **MWIR** | Mid-wave Infrared |
| **NASA** | National American Aeronautics and Space Administration |
| **NDVI** | Normalised Difference Vegetation Index |

| | |
|---|---|
| **NESDIS** | National Environmental Satellite Data and Information Service |
| **NIR** | Near-Infrared |
| **NOAA** | National Oceanic and Atmospheric Administration |
| **NPOESS** | National Polar Orbiting Environmental Satellite Series |
| **NPP** | NPOESS Preparatory Project |
| **NSIDC DAAC** | National Snow and Ice Data Center DAAC |
| **OA** | Overall Accuracy |
| **OC** | Operating Characteristic |
| **OCDPS** | Ocean Color Data Processing System |
| **OLS** | Ordinary Least Squares |
| **OMPS** | Ozone Mapping and Profiler Suite |
| **PCA** | Principal Component Analysis |
| **POES** | Polar-orbiting Operational Environmental Satellite |
| **PROSAIL** | PROSPECT + Scattering by Arbitrary Inclined Leaves |
| **R** | Red |
| **RBV** | Return Beam Vidicon |
| **ROC** | Receiver Operating Curve |
| **SAR** | Synthetic Aperture Radar |
| **SBRC** | Hughes/Santa Barbara Research Center |
| **SD** | Solar Diffuser |

| | |
|---|---|
| **SDSM** | Solar Diffuser Stability Monitor |
| **SEASAT** | Sea Satellite |
| **SHO** | Simple Harmonic Oscillator |
| **SMA** | Spectral Mixture Analysis |
| **SMMR** | Scanning Multichannel Microwave Radiometer |
| **SNR** | Signal-to-Noise Ratio |
| **SPOT** | Système Probatoire d'Observation de la Terre |
| **SPRT** | Sequential Probability Ratio Test |
| **SRCA** | Spectral Radiometric Calibration Assembly |
| **SSE** | Sum of Squared Error |
| **SV** | Space View |
| **SVM** | Support Vector Machine |
| **SWIR** | Short-wave Infrared |
| **TDRSS** | Tracking and Data Relay Satellite System |
| **TIROS** | Television Infrared Observation Satellite |
| **TM** | Thematic Mapper |
| **TOMS** | Total Ozone Mapping Spectrometer |
| **TP** | True Positive Rate |
| **UAV** | Unmanned Aerial Vehicle |
| **UME** | Uniformly Most Efficient |

| | |
|---|---|
| **UN** | Unitited Nations |
| **USA** | United States of America |
| **USGS** | United States Geological Survey |
| **USSR** | Union of Soviet Socialist Republics |
| **VIIRS** | Visible Infrared Imager Radiometer Suite |

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