Analysis of geodetic and model simulated data to describe nonstationary moisture fluctuations over southern Africa

by

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Abstract

Recent advances in space geodetic techniques such as Very Long Baseline Interferometry, Global Navigation Satellite Services, Satellite Laser Ranging and advanced numerical weather-prediction model simulations, provide huge tropospheric data sets with improved spatial-temporal resolution. These data sets exhibit unique fluctuations that have a spatial-temporal structure which are thought to mimic the complex behaviour of the atmosphere. As a result, the analysis of nonstationary structure in the tropospheric parameters derived from geodetic and numerical model simulations could be used to probe the extent of universality in the dynamics of the atmosphere, with applications in space geodesy. In order to identify the physical causes of variability of tropospheric parameters, parametric and nonparametric data analyses strategies which are investigated and reported in this thesis, are used to inform on the geophysical signals embedded in the data structure. In the first task of this research work, it is shown that the fluctuations of atmospheric water vapour over southern Africa are non-linear and nonstationary. Secondly, the tropospheric data sets are transformed to stationarity and the stochastic behaviour of water vapour fluctuations are assessed by use of an automatic algorithm that estimates the model parameters. By using a data adaptive modelling algorithm, an autoregressive-moving-average model was found to sufficiently characterise the derived stationary water vapour fluctuations. Furthermore, the non-linear and nonstationary properties of tropospheric delay due to water vapour were investigated by use of robust and tractable non-linear approaches such as detrended fluctuation analysis, independent component analysis, wavelet transform and empirical mode decomposition. The use of non-linear approaches to data analysis is objective and tractable because *they allow data to speak for themselves* during analysis and also because of the non-linear components embedded in the atmosphere system. In the thesis, we establish that the non-linear and nonstationary properties in the tropospheric data sets (i.e., tropospheric delay due to water vapour and delay gradients) could be triggered from strongly non-linear stochastic processes that have a local signature (e.g. local immediate topography, weather and associated systems) and/or exogenous. In addition, we explore and report on the presence of scaling properties (and therefore memory) in tropospheric parameters. This self-similar behaviour exhibit spatial-temporal dependence and could be associated with geophysical processes that drive atmosphere dynamics. Satellite Laser Ranging data are very sensitive to atmospheric conditions, which causes a delay of the laser pulse, hence an apparent range increase. A test for non-linearity is applied within specialised software for these data; it is found that the range residuals (i.e., the observed minus computed residuals) are improved when possible non-linearity of the locally measured meteorological parameters as applied to a range delay model are considered.

Preface

Geodetic time series analysis is a necessary procedure of extracting statistical properties and other characteristics of the data and is therefore an important process in modern space geodesy. In general, the analysis involves pre-processing of raw observations from various geodetic techniques, enhancing signals in the raw data, actual analysis (e.g., detection of nonlinearities and nonstationarities, statistical characterisation of the series) and prediction. While different methods are often applied to analyse the geodetic time series, estimating the deterministic (e.g., periodic variations and trend) and stochastic (mostly aperiodic variations) components as well as extracting specific oscillatory modes (which could be linked to geophysical signals) have not received much attention. In this current research work, the stochastic and multiscale properties in tropospheric parameters (hereafter Water Vapour (WV), tropospheric delay and delay gradients) derived from geodetic and numerical weather prediction models are assessed and modelled. The results indicate that WV/tropospheric delay due to WV exhibit self-similar behaviour and that their fluctuations are non-linear and nonstationary.

The layout of this thesis is intended to provide a logical flow of this research endeavour. After the general introduction in Chapter 1, the literature review (Chapter 2) provides an overview of space geodetic techniques, principle operation of Global Navigation Satellite System (GNSS) and Very Long Baseline Interferometry (VLBI) techniques, their applications (e.g., Earth's crustal deformation, plate tectonics, and maintenance of Terrestrial Reference Frames (TRF) as well as atmospheric remote sensing). Current measurements and analysis strategies of tropospheric parameters with application in geodetic analyses are also reviewed in this chapter. In Chapter 3, the sources of data that are studied in this thesis are explained. The spatial-temporal resolution of the geodetic (VLBI and GNSS), Numerical Weather Prediction (NWP) model simulations (e.g. NCEP/NCAR), radiosonde (e.g. the Southern Hemisphere ADditional OZonesondes (SHADOZ) network) and the HALOgen Occultation Experiment (HALOE) satellite data sets are described. The methods used to pre-process these data records are also described briefly.

Chapter 4 examines the stationarity in geodetic WV and adaptively fits a time series ARMA model that describes the stochastic pattern, to the geodetic WV transformed from nonstationary to stationary. Chapter 5 deals with the analysis of WV fluctuations. The SHADOZ radiosonde network is also used to infer the multiscale structure of WV in low- and mid-tropical Africa. Furthermore, a model for the vertical profile of WV in the southern hemisphere based on the HALOE satellite and the SHADOZ network data is developed. In Chapter 6, firstly the scaling behaviour (testing the underlying memory processes) of tropospheric WV is assessed using wavelets. Secondly, a noise-assisted data analysis methodology is applied to the geodetic tropospheric zenith delay and surface temperature to determine the dominant modes of oscillation in data. Further, WV and surface temperature have been shown to be temporally correlated because the instantaneous phase differences among the associated modes of the Intrinsic Mode Functions (IMFs) derived from the Ensemble Empirical Mode Decomposition (EEMD) of WV and surface temperature have a high degree of synchronisation. Additionally, the benefit of introducing non-linearity and nonstationarity in atmospheric correction to the Satellite Laser Ranging (SLR) range is investigated by introducing a nonlinear function to model the azimuth dependent atmospheric range correction. In Chapter 7, a summary of the findings are presented and recommendations and future research proposed.

List of publications

The following contributions have been published and/or submitted in/to various peer review journals as part of this work or related to it.

1. **Botai O. J.,** W. L. Combrinck, V. Sivakumar and C. J. de W. Rautenbach, (Submitted). Probing nonlinearity in geodetic data by hypothesis testing, Journal of Geodesy.
2. **Botai O. J.,** W. L. Combrinck and V. Sivakumar, (2011). Inferences of α-stable distribution in long-range dependent geodetic data, South African Journal of Geology (Accepted).
3. **Botai O. J.,** W. L. Combrinck and V. Sivakumar, H. Schuh and J. Boehm, (2010). Extracting independent local oscillatory geophysical signals by geodetic tropospheric delay, *In*: IVS 2010 General meeting proceedings, D. Behrend and K. D. Baver (eds). ISBN. NASA/CP-2010-215864.
4. **Botai O. J.,** V. Sivakumar , C. J. de W. Rautenbach, and W. L. Combrinck, (2010). Multiscale organisation of water vapour in the low- and mid- tropical Africa, Advances in Geosciences, 16: 241-251.
5. **Botai O. J.,** W. L. Combrinck and V. Sivakumar, (2009). Assessing the degree of synchronisation between geophysical records using the method of instantaneous phase differences, *In* 11th SAGA biennial technical meeting and exhibition. D. Vogt and S. Fourie (eds). ISBN. 978-0-620-44602-0: 588-593.
6. Sivakumar V., **O. J. Botai**, D. Moema, A. Sharma, C. Bollig and C.J. de W. Rautenbach, (2009). CSIR-NLC mobile LIDAR for atmosphere remote sensing, IEEE, Intern. geosc. Remote sens. symposium, Cape Town. ISBN. 978-1-4244-3394-0.
7. **Botai O. J.,** W. L. Combrinck and C.J. de W. Rautenbach, (2008). Nonstationary tropospheric processes in geodetic precipitable water vapour time series, Michael G. Sideris (ed). Observing our Changing Earth, International Association of Geodesy Symposia, Springer Berlin Heidelberg, 133: 625-630, doi:. 10.1007/978-3-540-85426-5.

Declaration

I, the undersigned declare that the thesis, which I hereby submit for the degree Doctor of Philosophy, Faculty of Natural and Agricultural Sciences at the University of Pretoria, is my own work except where acknowledged. This work has not previously been submitted by me for a degree at this or any other tertiary institution.

Botai Ondego Joel

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Acronyms

AAM	: Atmospheric Angular Momentum
ACs	: Analysis Centres
AIRS	: Atmosphere Infrared Sounder
ARMA	: Autoregressive Moving Average
BIBER	: Bound Influence by Standardised Residuals
CAM	: Community Atmosphere Model
CCAM	: Cubic Conformal Atmospheric Model
CO_2	: Carbon dioxide
DFA	: Detrended Fluctuation Analysis
DORIS	: Doppler Orbitography and Radiopositioning Integrated by Satellite
DWT	: Discrete Wavelet Transform
ECMWF	: European Centre for Medium-range Weather Forecasts
EEMD	: Ensemble Empirical Mode Decomposition
EMD	: Empirical Mode Decomposition
ENSO	: El Nino Southern Oscillation
EOP	: Earth Orientation Parameters
FFT	: Fast Fourier Transform
FT	: Fourier Transform
GGOS	: Global Geodetic Observing System
GMF	: Global Mapping Functions
GNSS	: Global Navigation Satellite Systems
GPS	: Global Positioning Satellites
gPWV	: Global PWV
HALOE	: Halogen Occultation Experiment
HartRAO	: Hartebeesthoek Radio Astronomy Observatory
HCB	: Highveld and Central Bushveld
HHT	: Hilbert-Huang Transform
HT	: Hilbert Transform
ICA	: Independent Component Analysis
IGG	: Institute of Geodesy and Geophysics

IF	: Instantaneous Frequency
IR	: Infrared
IGG	: Institute of Advanced Geophysics and Geodesy
IWV	: Integrated Water Vapour
IAG	: International Association of Geodesy
ICRF	: International Celestial Reference Frame
IGS	: International GNSS Service
IMFs	: Intrinsic Mode Functions
IMF	: Isobaric Mapping Function
ITCZ	: Inter-Tropical Convergence Zone
ITRF	: International Terrestrial Reference Frame
IVS	: International VLBI Service
LRD	: Long-Range Dependent
MI	: Mutual Information
MODWT	: Maximum Overlap Discrete Wavelet Transform
NADA	: Noise Assisted Data Analysis
NCAR	: National Centre for Atmospheric Research
NCEP	: National Centre for Environmental Prediction
NMF	: Niell Mapping Function
NO_2	: Nitrogen dioxide
NWP	: Numerical Weather Prediction
PCA	: Principal Component Analysis
PSC	: Polar Stratospheric Clouds
PRN	: Pseudorandom noise
PWV	: Precipitable Water Vapour
QQ	: Quartile-Quartile
QSO	: Quasi-Stellar Objects
RINEX	: Receiver Independent Exchange
RH	: Relative Humidity
RO	: Radio Occultation
SAWS	: South African Weather Service
SGT	: Space Geodetic Techniques
SHADOZ	: Southern Hemisphere ADditional OZoneondes

SLR	: Satellite Laser Ranging
SOI	: Southern Oscillation Index
SO_2	: Sulphur dioxide
SSA	: Singular Spectrum Analysis
SS	: Self-Similar
SSTs	: Sea Surface Temperatures
TD	: Tropospheric Delay
TEC	: Total Electron Content
US	: United States
UV	: Ultra Violet
VEOF	: Vector Empirical Orthogonal Function
VMF	: Vienna Mapping Function
VLBI	: Very Long Baseline Interferometry
WT	: Wavelet Transform
WV	: Water Vapour
WVR	: Water Vapour Radiometry
ZTD	: Zenith Tropospheric Delay
ZWD	: Zenith Wet Delay