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On how to separate random noise in time series data: Rational approach

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Abstract

A rational approach is presented to separate random noise in time series data. The approach is based on filtering the data in the frequency domain using logistic distribution function capable of removing harmonics with low amplitudes, assumed random. The removed part of data is tested by autocorrelation function to find whether it constitutes an independent and identically distributed random sequence. The remaining part of data can be modeled by discrete Fourier series. A case study is provided on solar sunspot cycle, which has impact on earth's climate.

Keywords: Stochastic model; Fourier analysis; Periodicity; White noise; Sunspot numbers

1. Introduction

The stochastic part of time series data is usually composed of a periodic correlation structure and uncorrelated random sequence. The periodic correlation structure may be estimated by autoregressive moving average (ARMA) models, which is an advantage here because dependence means in particular that past observations of the noise sequence can assist in predicting future values (Almedeij 2015). The random component can never be estimated exactly as it is considered to be made of random effects described by probability distributions (Bendat and Piersol 2010). Although all hydrologic phenomena involve some stochastic component, the resulting variability in the output may be so small that a deterministic model becomes appropriate (Haan 1977). If the random variation is large, a stochastic model is more suitable, because the actual output could be quite different from the single value a deterministic model would produce. Separating random from stochastic data allows applying different modification for the decomposed parts yielding more natural data synthesis. The aim here is to attempt separating random noise from time series data. Initially, the separation and evaluation methods will be presented. A possible application for the procedure will be presented for the case study of solar sunspot cycles, providing a comprehensive data with sufficiently wide range of records.

2. Model development

The trigonometric Fourier series for a periodic function x(t) with a fundamental period T is given by

$$x(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos\left(\frac{2\pi nt}{T}\right) + b_n \sin\left(\frac{2\pi nt}{T}\right) \quad (1)$$

and the Fourier coefficients are

$$a_n = \frac{2}{T}\int_0^T f(t)\cos\left(\frac{2\pi nt}{T}\right)dt \quad (2)$$

$$b_n = \frac{2}{T}\int_0^T f(t)\sin\left(\frac{2\pi nt}{T}\right)dt \quad (3)$$

where f is continuous function on [0,T], and n is number of harmonics in the series. The integral form of the Fourier coefficients cannot be solved analytically for discrete data, but can be approximated by Riemann sum. The Riemann states that for a continuous function f on [0,T], $\int_0^T f(t)\,dt$ always exists and is computed by

$$\int_0^T f(t)\,dt = \lim_{N\to\infty} \sum_{j=0}^{N-1} f(t_j^*)\left(\frac{T}{N}\right) \quad (4)$$

$$t_j^* = j\left(\frac{T}{N}\right) \quad (5)$$

Here, for a discrete data, N can be taken as the total number of data points. If the fundamental period is considered T=N, then the ordered pairs $(t_j^*, f(t_j^*))$ will turn to (j, f_j). Accordingly, the discrete Fourier coefficients become

$$a_n = \frac{2}{N}\sum_{j=0}^{N-1} f_j \cos\left(\frac{2\pi nj}{N}\right) \quad (6)$$

$$b_n = \frac{2}{N}\sum_{j=0}^{N-1} f_j \sin\left(\frac{2\pi nj}{N}\right) \quad (7)$$

with the series

$$x(t) = \frac{a_0}{2} + \sum_{n=1}^{N/2} a_n \cos\left(\frac{2\pi nt}{N}\right) + b_n \sin\left(\frac{2\pi nt}{N}\right) \quad (8)$$

Essentially, random noise reduces the Fourier model validity to produce forecast because of their non-periodic nature. To improve model quality, the extraneous noises can be filtered in the frequency domain by choosing a threshold amplitude value C_{min} below which harmonics are removed, assumed random. Logistic distribution is proposed here to constitute an amplitude-based filter. The logistic distribution function is given by

$$F(n) = \left(1 + e^{-(X_n - \alpha)/\beta}\right)^{-1} \quad (9)$$

where X is variable ranging -∞<X<∞, α is location parameter, and β is scale parameter with β>0. The variable X can be replaced here by the amplitude relation

$$I_n = \sqrt{a_n^2 + b_n^2} \quad (10)$$

If the location parameter is set as $\alpha = C_{min}$, then Equation (10) becomes

$$F(n) = \left(1 + e^{-(I_n - C_{min})/\beta}\right)^{-1} \quad (11)$$

For this equation, the scale parameter β should be chosen to be sufficiently small to render F nearly equal to 0 or 1 for $I_n < C_{min}$ or $I_n > C_{min}$, respectively. This filter can be implemented in Equation (8) yielding

$$x(t) = \frac{a_0}{2} + \left[\sum_{n=1}^{N/2} a_n \cos\left(\frac{2\pi nt}{N}\right) + b_n \sin\left(\frac{2\pi nt}{N}\right)\right] F(n) \quad (12)$$

The computation process can be performed quickly by using any mathematical software package.

3. Application to Sunspot Cycles

Sunspots are dark spots of intense magnetic field appearing within the surface layer of the sun and providing most of the solar radiation received by the earth. The sun is typically very active when sunspot numbers are high. Since it is the solar energy that drives the earth's atmosphere creating clouds, winds, rains, droughts and ocean currents, it is obvious that the climate is affected by changes on the sun. Yet whether a significant correlation exists between sunspot numbers and our climate is a subject of debate. Researchers agree that there is a change in total irradiation accompanying shifts from solar maximum conditions when there are many sunspots present to solar minimum with basically none.

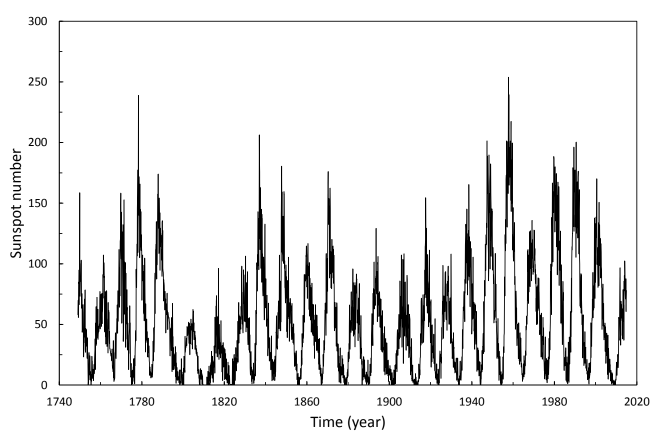

Fig. 1 Monthly average sunspot numbers for the time duration from January 1749 until December 2014. Source: World Data Center for the production, preservation and dissemination of the international sunspot number (http://www.sidc.be/silso/datafiles).

Figure (1) shows the monthly average sunspot numbers for the time duration from January 1749 until December 2014. An apparent cycle exists from one solar minimum to the next with an average duration of about 11 years. Recording of solar cycles began in 1755, the beginning of solar cycle 1 with duration about 11.3 years. Since then, subsequent cycles have been counted consecutively. The most recent one is 24, began in January 2008.

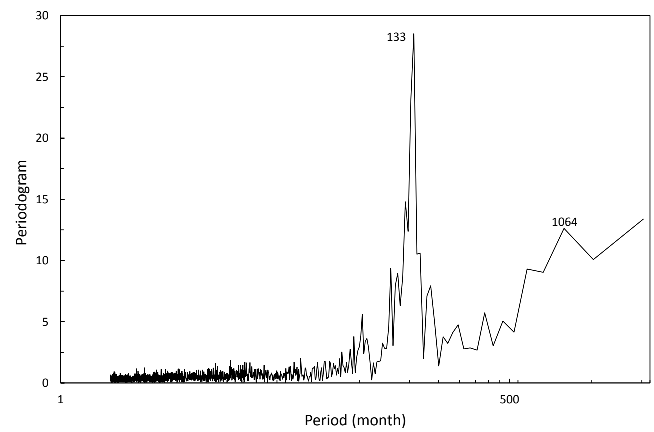

Fig. 2 Periodogram for monthly average sunspot numbers.

Figure (2) shows the amplitude spectrum plot for the sunspot numbers. A detailed review of solar cyclic activities can be found in (Hathaway 2010). The most significant period in the amplitude spectrum is the 133 months, corresponding to a pattern of nearly 11 years. The 11-year cycle is termed the Schwabe cycle, which is a periodic variation in the sun's radiation and appearance including changes in the number of sunspots, flares and other visible manifestations. When Newell et al. (1989) matched this solar cycle and temperature cycle, they found that the alternate peaks of the 11-year sunspot cycle correspond to alternate upward and downward swings of temperatures, suggesting that cooling takes place during one phase of solar magnetic polarity and warming during the other. The background for this period is the 22-year cycle, termed the Hale magnetic cycle. Hale et al. (1919) found that the polarity of sunspot magnetic fields changes in both hemispheres when a new 11-year cycle starts. Mitchell et al. (1979) reported that the 22-year solar periodicity modulates terrestrial drought-inducing mechanisms that encourage and discourage the development of major continental droughts. Both 11- and 22-year periods are important, however because nearly all manifestations are insensitive to polarity, the former remains the focus of research.

Another significant period is the 1064 months, corresponding to nearly 88 years. This one, which is termed the Gleissberg cycle (Gleissberg, 1939), concerns the height of sunspot maxima with a succession pattern that can be observed in the figure of about four strong maxima alternating with the succession of another four weak maxima. Ruzmaikin and Feynman (2015) suggest that the Gleissberg minima are associated with severe weather extremes and stimulate the current global warming hiatus. Some researchers also suggest that it is not a cycle so much as some sort of chance clustering of chaotic data with a varying timescale of 60 to 120 years. Longer cycles such as the Devries cycle of 200 years are not present in this amplitude plot because of relatively limited observations, but can be studied only indicatively by means of indirect proxies such as cosmogenic isotopes.

The amplitude spectrum plot for the model obtained with $C_{min} = 0.75$ is presented in Figure (3). This shows that the main periodicities are maintained in this model, but the pattern for higher frequencies is still complicated. Figure (4) shows however that this sunspot model is smoother than the original one.

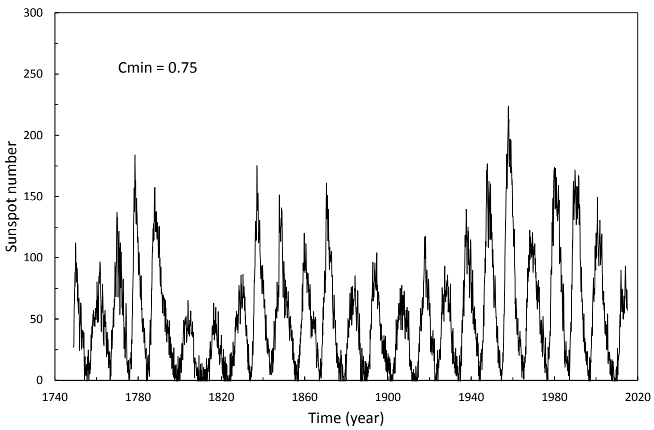

Fig. 3 Periodogram obtained for $C_{min} = 0.75$.

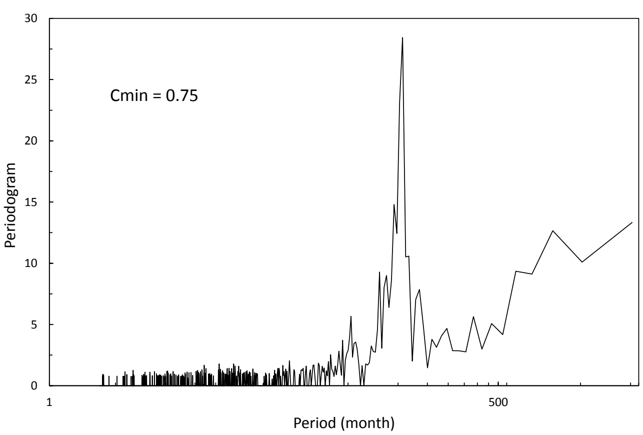

Fig. 4 Sunspot numbers obtained for $C_{min} = 0.75$.

4. Conclusions

This study provided an approach to separate random sequence from periodic data. The approach was applied to the case study of solar sunspot cycle. It should be noted that the remaining periodic data in the case study may be composed of deterministic component and stochastic correlation structure, and some periods with low amplitudes may be difficult to detect when they become virtually hidden in the random data pattern. This approach is limited to iid random sequences of white noise characterized by flat frequency spectra.

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Commonwealth Energy and Sustainable Development Network (CESD-Net)

CESD-Net is a major global initiative in energy and sustainable development. The objective of network is to promote energy and sustainable development in commonwealth countries.
Focussing on Multidisciplinary Research, Promoting Future Low Carbon Innovations, Transferring Knowledge and Stimulating Networking among Stakeholders to Ensure the UK Achieves World Leading Status in Energy and Sustainable Development. https://www.weentech.co.uk/cesd-net/

The 1st International Conference on Energy, Environment and Economics (ICEEE 2016) was held at Heriot-Watt University, Edinburgh, EH14 4AS, UK, 16-18 August 2016. ICEEE2016 focused on energy, environment and economics of energy systems and their applications. More than fifty eight delegates from 31 countries with diverse expertise ranging from energy economics, solar thermal, water engineering, automotive, energy, economics and policy, sustainable development, bio fuels, Nano technologies, climate change, life cycle analysis etc. made conference true to its name and completely international. During conference total 51 oral presentations and six posters were shared between delegates. The presentations showed the depth and breadth of research across different research areas ranging from diverse background. ICEEE2016 aimed:

- To identify and share experiences, challenges and technical expertise on how to tackle growing energy use and greenhouse gas emissions and how to promote sustainability and economical, cost effective energy efficiency measures.

In total 11 technical sessions and two invited talks both from academia and industry provided insight into the recent development on the proposed theme of the conference. Preparation, organisation and delivery of the conference started from July 2015 and further co-ordinated by vibrant team of Conference Centre, Heriot Watt University. Conference organisers would like to acknowledge support from the sponsors particularly World Scientific Publication ltd and its team members for the delivery of the conference. Organisers are also thankful to all reviewers who contributed during peer review process and their contributions are well appreciated. At the end and during vote of thanks following awards have been announced and we would like to congratulate all well deserving delegates.

- Best Paper –Academia: Amela Ajanovic, EEG, TU Vienna, Austria
- Best Paper – Student : Christian Jenne,University of Duisburg-Essen, Germany
- Best Poster – Student: Yoann Guinard, University of New South Wales, Sydney, Australia
- Best Poster – Academia: E. Salleh, Universiti Kebangsaan Malaysia, Malaysia
- Active Participation Award - Yoann Guinard, University of New South Wales, Sydney, Australia

At the end we would like to extend our gratitude to all of you for your participation and hopefully welcome you again during ICEEE2017.

Editors:
Dr. Singh is Senior Scientist at Indian Agricultural Research Institute, New Delhi, India. Her area of expertise are bio energy and bio fuels, environmental engineering, carbon accounting and renewable energy integration for rural development.
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