Generating Signals with Multiscale Time Irreversibility: The Asymmetric Weierstrass Function

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Time irreversibility (asymmetry with respect to time reversal) is an important property of many time series derived from processes in nature. Some time series (e.g., healthy heart rate dynamics) demonstrate even more complex, multiscale irreversibility, such that not only the original but also coarse-grained time series are asymmetric over a wide range of scales. Several indices to quantify multiscale asymmetry have been introduced. However, there has been no simple generator of model time series with “tunable” multiscale asymmetry to test such indices. We introduce an asymmetric Weierstrass function \( W_A \) (constructed from asymmetric sawtooth functions instead of cosine waves) that can be used to construct time series with any given value of the multiscale asymmetry. We show that multiscale asymmetry appears to be independent of other multiscale complexity indices, such as fractal dimension and multiscale entropy. We further generalize the concept of multiscale asymmetry by introducing time-dependent (local) multiscale asymmetry and provide examples of such time series. The \( W_A \) function combines two essential features of complex fluctuations, namely fractality (self-similarity) and irreversibility (multiscale time asymmetry); moreover, each of these features can be tuned independently. The proposed family of functions can be used to compare and refine multiscale measures of time series asymmetry. © 2010 Wiley Periodicals, Inc. Complexity 16: 29–38, 2011

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I. INTRODUCTION

Time irreversibility (asymmetry with respect to time reversal) is an important property of many observed time series. Such asymmetry is evidence of the nonlinearity of a time series, as linear Gaussian processes are time reversible [1]. Several statistical tests have been
developed toward detection and quantification of irreversibility in time series (see e.g., [2, 3]). The irreversibility of natural processes reflects the ‘arrow of time’ and is a fundamental property of nonequilibrium systems [4]. Many complex time series (e.g., heart rate) demonstrate an even more complex, multiscale irreversibility such that not only the original but also coarse-grained time series are asymmetric within a range of scales. Several quantitative measures (indices) of multiscale irreversibility have been developed [5–10]. However, the relationships among these indices have not been studied, and it is possible that each of them measures a different aspect of multiscale time asymmetry. Besides their theoretical importance, such indices have practical applications. For example, indices of heart rate and electroencephalogram (EEG) time asymmetry (both single and multiscale) can be used as diagnostic tools (see e.g., [5–7, 11–18]).

Thus, it is important to investigate the properties of these indices of time asymmetry.1 Note, that experimental and observational time series are not very suitable for such an analysis, since for example, they may contain other (both known and possibly unknown) types of ‘complexity,’ which may affect the results of the asymmetry analysis and comparison of different asymmetry measures. Thus, there is a need to develop a simple deterministic time series with exactly known properties and variable multiscale asymmetry.

In this article, we introduce an asymmetric Weierstrass function $W_\lambda$ (constructed from asymmetric sawtooth functions instead of cosine waves) that can be used to construct time series with any prescribed value of the multiscale asymmetry. The article is organized as follows. In Section II, we define the multiscale asymmetry index [5,6] used in this study. In Section III, we define the classical and asymmetric Weierstrass functions and in Section IV, we calculate their multiscale asymmetry indices. We summarize and conclude in Section V.

II. DEFINITION OF MULTISCALE ASYMMETRY

To calculate the asymmetry index, an original time series $x(n)$, $n = 1, \ldots, N$ (where $N$ is the number of points in the time series) is transformed into a new time series of coarse-grained differences (for every scale $s = 1, \ldots, S_{\text{max}} \ll N$) defined as:

$$y_s(k) = x(k + s) - x(k) \quad k = 1, \ldots, N - s$$  

Individual terms (increments and decrements) in each new time series Eq. (1) quantify transitions between two values in the original time series: an increase (activation) or a decrease (relaxation). For a perfectly symmetric time series, the number of increments is equal to the number of decrements. Thus, the time asymmetry can be defined at every scale $s$ as a difference between the percentages (probabilities) of increments and decrements [6]:

$$A(s) = P^+(s) - P^-(s) = \frac{\sum_{k=1}^{N-s} \theta[-y_s(k)]}{N-s} - \frac{\sum_{k=1}^{N-s} \theta[y_s(k)]}{N-s}$$  \hspace{1cm} (2)

Here, $\theta$ is the Heaviside function.

III. WEIERSTRASS AND ASYMMETRIC WEIERSTRASS FUNCTIONS

The Weierstrass function is the first published [19] example of a continuous but nowhere differentiable function. It is defined as follows:

$$W(t) = \sum_{k=1}^{K_{\text{max}}} f_{\text{min}}^{-kh} \cos(2\pi f_{\text{min}}^k t)$$  \hspace{1cm} (3)

Here, $f_{\text{min}}$ is the minimum frequency of oscillations and $H$ is the so-called Hurst (or scaling) exponent (0<$H<$1), which is related to the fractal dimension, $D$, according to the following formula:

$$D = 2 - H$$  \hspace{1cm} (4)

The power spectrum of the Weierstrass function has a ‘power law’ shape

$$S(f) \sim 1/f^\beta$$  \hspace{1cm} (5)

where the power exponent $\beta$ is related to the Hurst exponent according to the relationship:

$$\beta = 2H + 1$$  \hspace{1cm} (6)

Note, that the detrended fluctuation analysis (DFA, [20]) exponent $\alpha$ is related to the Hurst exponent as:

$$H = \frac{\alpha}{2} - 1$$  \hspace{1cm} (7)

The Weierstrass function is also a classic model of a (multi) fractal process, and it is widely used in physics.

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1In this initial study, we consider only one index [5,6] of multiscale asymmetry. Theoretical analysis of other indices can be found, e.g., in [7, 8].
and physiology (see e.g., [21–23]). However, the Weierstrass function is a sum of cosine waves and, therefore, reversible (time symmetric) at any mode (frequency) because the cosine function is symmetric with respect to time reversal operation. Thus, it cannot be used to model irreversible time series [with the irreversibility defined according to Eq. (2)].

To overcome this restriction, we introduce a modified Weierstrass function (the “asymmetric Weierstrass” function or $W_A$ function) by substituting the cosine functions with sawtooth functions:

$$W_A(t) = \sum_{k=1}^{K_{\text{max}}} f_{k}^{\omega} \St(2\pi f_{\text{max}} t; \omega)$$  (8)

Here, $\omega(0 \leq \omega \leq 1)$ is the asymmetry parameter that determines the relative position of the maximum within one period of the sawtooth function $St(t)$ (in this study, we used the sawtooth function available in MATLAB [24]), see Figure 1. The asymmetric Weierstrass function Eq. (8) is deterministic and defined with a simple formula, so it is suitable for both theoretical analysis and numerical experiments.

The asymmetric Weierstrass function is irreversible at any mode (frequency). By varying the asymmetry parameter $\omega$, we can continuously change the multiscale time asymmetry of the signal (Figure 2). Note that the $W_A$ function constructed from fully symmetric ($\omega = 0.5$) sawtooth functions is equivalent to the “positive midpoint displacements” method of fractal time series construction (see e.g., [25]) and is a version of the Takagi function, another continuous but nowhere differentiable function [26].

IV. MULTISCALE ASYMMETRY OF THE $W_A$ FUNCTION

To assess the dependence of the multiscale asymmetry index on the asymmetry parameter $\omega$, we generated 101 $W_A$ functions (Eq. 8) with linearly increasing the asym-
metry parameter \( \omega(n) = (n-1)/100 \) \((n = 1, \ldots, 101)\) and Hurst exponent \( H = 0.5 \) (corresponds to regular Brownian motion). The length of each dataset was equal to \( T_{\text{max}} = 100 \) s, and the sampling frequency was equal to \( f_s = 5000 \) Hz (therefore each dataset had \( N = 5 \times 10^5 \) points). The maximum number of modes, \( K_{\text{max}} \), in Eq. (8) can be estimated from the Nyquist sampling theorem [27]:

\[
\frac{f_{\text{max}}}{f_{\text{Nyquist}}} = \frac{1}{2f_s}
\]

Since \( f_{\text{max}} = f_{\text{min}} \) then \( K_{\text{max}} = \frac{\log(f_{\text{min}})}{\log(f_s/2)} \). For the parameters used in this study \( (f_s = 5000 \) Hz, \( f_{\text{min}} = 1.5 \) Hz), the lower bound is \( K_{\text{max}} \approx 20 \). However, as \( M_{\text{Ai}} \) is a time-domain measure, we used a much larger value, \( K_{\text{max}} = 100 \).

In Figure 3, we plot percentages of increments \((P^+)\) and decrements \((P^-)\) and their difference \([\Delta i, \text{see Eq. (2)}]\), up to the scale \( S_{\text{max}} = 5000 \) for the \( W_\alpha \) function constructed from fully asymmetric \((\alpha = 0.0)\) sawtooth functions. Note that \( N = 10^2S_{\text{max}} \) and thus, the condition \( S_{\text{max}} < N \) is satisfied.

There is no unique way to quantify multiscale asymmetry of a signal with a single number. Here, we employed one of many possible definitions. We observed that even for a "fully-asymmetric" \((\alpha = 0.0)\) \( W_\alpha \) function, the asymmetry index \( \Delta i \) crosses zero at some scale \( S^* \). Thus, we chose the sum of the asymmetry values up to the scale \( S^* \) (normalized by the value of that scale, \( S^* \)) as a quantitative measure of the signal multiscale asymmetry:

\[
M_{\text{Ai}} = \frac{1}{S^*} \sum_{s=1}^{S^*} \Delta i(s)
\]

where \( \Delta i(s) \) is the asymmetry index at scale \( s \), and \( S^* \) is the scale when the \( \Delta i(s) \) crosses zero (changes the sign) for the first time.\(^3\) The \( M_{\text{Ai}} \) index depends monotonically (approximately linearly) on the asymmetry parameter \( \omega \) (Figure 4). Thus, we can construct (by varying the asymmetry parameter \( \omega \)) a time series with any prescribed (given) value of the multiscale asymmetry. This is the main result of the paper.

Note, that multiscale asymmetry is a property of a self-similar time series that is independent from its fractal dimension \( D \) (or, equivalently, its Hurst exponent). Indeed, it has been shown (see e.g., [28] and references, therein) that any function of the form

\[
F(t) = \sum_{k=0}^{\infty} f^{-kH}g(f^k \cdot t)
\]

where \( g(f) \) is a Gaussian distribution (see Eq. (10)), \( f^k \) is the sampling frequency, and \( \tau = S^*/f_s \) is the characteristic time of asymmetry, (normalized asymmetry index \( M_{\text{Ai}} \) Eq. (9) are approximately constant for a wide range of the sampling frequencies. Thus, it would be an advantage to plot the asymmetry index versus characteristic frequency or characteristic time, instead of the scale.

**FIGURE 2**

Asymmetric Weierstrass function Eq. (8) with Hurst exponent \( H = 0.5 \) (corresponds to the classical Brownian motion), minimum frequency \( f_{\text{min}} = 2.0 \) Hz and asymmetry parameter, \( \omega \) varying from \( \omega = 0.5 \) (fully symmetric) to \( \omega = 1.0 \) (fully asymmetric).
where \( g(t) \) is a periodic function that satisfies the Lipchitz-Holder condition of order \( H \)

\[
|g(t + \Delta t) - g(t)| \leq C|\Delta t|^H
\]

(11)

has scaling (Hurst) exponent \( H \) and fractal dimension \( D = 2 - H \) (see also 'Lipchitz-Holder heuristics' in [21]).

As any sawtooth function is periodic and satisfies the condition defined by Eq. (11) for any value of the asymmetry parameter \( \omega \in (0,1) \), the asymmetric Weierstrass function Eq. (8) has the same fractal dimension \( D \) regardless of the value of \( \omega \). In two limiting cases, \( \omega = 0 \) and \( \omega = 1 \), the corresponding sawtooth functions are discontinuous, and thus, they do not satisfy the Lipchitz-Holder condition.

We also tested this statement numerically, by calculating the DFA exponent of our datasets. We calculated DFA-based Hurst exponents Eq. (7) from 101 \( W_\omega \) functions Eq. (8) with linearly increasing asymmetry parameter \( \omega(n) = (n-1)/100 \) (\( n = 1, \ldots, 101 \)) and Hurst exponent \( H = 0.5 \) (see Figure 5, top). The DFA-based Hurst exponent of the \( W_\omega \) function in the fully symmetric case (\( \omega = 0.5 \)) becomes approximately equal to the DFA-based Hurst exponent of cosine-based \( W \) function (marked as 'X' in Figure 5, top): \( H_{DFA}(W_{0.5}) = 0.4587 \) and \( H_{DFA}(W) = 0.4624 \).

The DFA-based Hurst exponents of all asymmetric (\( \omega \neq 0.5 \)) \( W_\omega \) functions are smaller than those of the symmetric \( W_0 \) (or \( W \)) function.

Again, as the theory predicts, this deviation becomes significant at the regions close to the two limiting cases, \( \omega = 0 \) and \( \omega = 1 \), where the Lipchitz-Holder condition is not valid. However, within a wide range of \( \omega(0.2 \leq \omega \leq 0.8) \) the Hurst exponent is relatively independent from the asymmetry parameter, in agreement with the theory.

Besides fractal dimension, multiscale asymmetry appears to be independent of some other multiscale complexity indices. As another numerical test, we computed multiscale entropies (MsEn) [29] of both cosine-based \( W \) function and 101 \( W_\omega \) functions with varying asymmetry parameter (again, in all the cases \( H = 0.5 \)). The results demonstrate that for all values of \( \omega \), MsEn curves lie very close to each other (Figure 5, bottom). Again, we found that MsEn of the symmetric (\( \omega = 0.5 \)) \( W_\omega \) function is practically indistinguishable from MsEn of the corresponding \( W \) function, whereas MsEn of fully asymmetric (\( \omega = 0.0 \) and \( \omega = 1.0 \)) \( W_\omega \) functions are outliers at small scales.

Thus, MsAi is independent (within a wide range of asymmetry parameter values) from other multiscale measures. The asymmetry parameter can be varied continua-

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As shown in Figure 5, all DFA-based exponents lie below the 'theoretical' value (\( H = 0.5 \)). We found that our DFA calculations systematically underestimate values of Hurst exponent Eq. (7) as compared with 'theoretical' Hurst exponents used to construct \( W \) functions [both for cosine-based \( W \) Eq. (2) and \( W_\omega \) functions Eq. (8)]. This may be due to a finite number of modes (\( K_{max} \)) in Eqs. (2) and (8) or because the summation started with \( k = 1 \) (not with \( k = -K_{max} \)), so these functions are not truly 'scale free.' Anyway, a detailed analysis of why the DFA method underestimates values of the Hurst exponents \( W \)-type functions is outside the scope of the article. Our goal was to demonstrate, via numerical calculations [in addition to the formal analysis, Eq. (11)], that the fractal dimension of the \( W_\omega \) function (measured by DFA exponent) remains approximately constant (regardless of the specific value of this constant) within a wide range of asymmetry parameter. Underestimation leads to a 'systematic error,' which is nevertheless the same for all the datasets.
ously (to construct a time series with any prescribed value of multiscale asymmetry) while preserving other multiscale properties. More detailed analysis is needed to determine the origin of the weak dependence of other multiscale properties (e.g., scaling exponent and multiscale entropy) from the asymmetry parameter $\omega$ around two limiting cases ($\omega = 0.0$ and $\omega = 1.0$).

The proposed modification of the Weierstrass function permits one important generalization. Note, that if the Hurst exponent is time dependent, $H = H(t)$ (a time varying scaling exponent is usually referred as Holder exponent [30]), the Weierstrass function demonstrates multifractal properties [31, 32]. In a similar manner, we can introduce time-dependent (local) multiscale time asymmetry (irreversibility) $\omega = \omega(t)$. Such time dependent asymmetry may exist, for example in long-term (e.g., Holter monitor) recordings [33] of the heart rate, as its time asymmetry may depend on the level of physical activity (rest vs. intensive exercise or sleep vs. wake). An example of time-dependent (piecewise constant) multiscale time asymmetry is given below (where $T$ is the length of time series), see Figure 6:

$$\omega(t) = \begin{cases} 0 & 0 \leq t < T/3 \\ 0.5 & T/3 \leq t < 2T/3 \\ 1 & 2T/3 \leq t < T \end{cases}$$ (12)

In this extreme case, multiscale time asymmetry has opposite signs in two parts of the time series. While multiscale asymmetry of whole time series is zero, it is possible to recover such a time-dependent multiscale time asymmetry by dividing the initial time series into overlapping windows and applying the same algorithm [Eqs. (2) and (9)] to each window (Figure 6, bottom).

V. DISCUSSION

In this article, we introduced a new method of constructing a simple deterministic function (asymmetric Weierstrass function, $W_A$) with any prescribed value of multiscale asymmetry (irreversibility). Then, we provided evidence (both analytical and computational) that multiscale asymmetry index is independent of other multiscale complexity measures of time series (such as MsEn or DFA...
Finally, we generalized the concept of the multiscale asymmetry by introducing time-dependent (local) multiscale asymmetry and constructed examples of such time series. Thus, the $W_A$ function combines two essential features of complex time series (e.g., healthy heart rate), namely fractality (multiscale self-similarity or long-range correlations) and irreversibility (multiscale time asymmetry); moreover, each of these features can be tuned independently.

Here, we have considered only the simplest case, where all modes in $W_A$ function have the same value of the asymmetry parameter $\omega$. Possible generalizations can include, for example, scale (mode)-dependent time asymmetry $\omega(k) = (k/K_{\text{max}}) - 1$, so that the asymmetry is different for each mode (for every basis function) or $\omega = \text{rand}(1, K_{\text{max}})$ (the asymmetry of every mode is chosen randomly). In general, the asymmetry parameter can depend on both time and mode, $\omega = \omega(k,t)$. Thus, a large
variety of test signals can be created to test different aspects of proposed asymmetry indices.

Interestingly, most of the classical continuous but nowhere differentiable (fractal or self-similar) functions are symmetric even on a single scale (for a historical review, see [34]). Also, the Takagi function is not the only fractal (continuous but nowhere differentiable) function constructed using the symmetric sawtooth function. Other examples include McCarthy [35] and Knopp [36] functions. Thus, multiscale asymmetric functions (with any prescribed degree of asymmetry) can be constructed from these functions as well.

Note, that the ‘power law’ frequency dependence (logarithmic scale) in the Weierstrass function is somewhat inconvenient for numerical analysis, because both multiscale entropy MsEn and multiscale asymmetry MsAi use linear scales. Similarly, the Fourier transform [27] (in contrast to, e.g., Wavelet [37] or Constant-Q [38] transforms), which is used for calculation of scaling exponent from power spectrum, employs a linear sequence of frequencies. A simple example of multiscale asymmetric function (which we refer to as multiscale sawtooth function, MsSt) with linear sequence of frequencies is given below:

\[
MsSt(t) = \sum_{k=1}^{K_{\text{max}}} St(2\pi f_k t; \omega)
\]  
(13)

Here, \(St\) is a periodic sawtooth function with a frequency \(f_k = f_{\text{max}}/k\), \(k = 1, \ldots, K_{\text{max}}\). Thus, the signal generated by Eq. (13) is time-asymmetric for every frequency component (mode) from \(f_{\text{min}} = f_{\text{max}}/K_{\text{max}}\) to \(f_{\text{max}}\). Multiscale properties (those discussed in this article) of MsSt function are similar to those of the \(W_\lambda\) function. Namely, by varying the asymmetry parameter \(\omega\) we can continuously change the multiscale time asymmetry of the MsSt function. Other multiscale measures (DFA and MsEn) of the MsSt function are also independent from its asymmetry parameter (except around two limiting cases \(\omega = 0.0\) and \(\omega = 1.0\)). It is also possible to construct piecewise nonlinear multiscale asymmetric functions of the forms Eqs. (8) or (13). One example is a multiscale asymmetric function constructed from repeated exponents instead of the linear functions used in the sawtooth function.

The applications of the proposed asymmetric Weierstrass function are not limited to physiological signals. For example, \(W_1\)-type signal is very similar to the multiscale fluctuations of temperature during long-term climate change [39] and fluctuations of TCP flow dynamics in communication networks (see e.g., [40, 41]). Note that a modified version (‘piecewise-linear analog’) of the Weierstrass function constructed from fully asymmetric \((\omega = 0.0)\) sawtooth functions with logarithmically decreasing frequencies (which is somewhat similar to both \(W_\lambda\) and MsSt functions introduced in this article) was used to construct a deterministic model of Burgers turbulence [42]. We note possible applications of the \(W_\lambda\) function as a model of rough surfaces (see e.g., [43, 44]) and of fractally asymmetric ratchet potentials (see e.g., [45, 46]).

Further, formal analysis is required to analytically derive the properties of the asymmetric Weierstrass function and to understand the behavior of multiscale asymmetry index. Specifically, the (in)dependence of MsAi from fractal dimension (and other ‘complexity measures’) has to be studied rigorously. It is interesting to investigate possible connections between \(W_\lambda\) functions and so-called ‘asymmetric fractals’ introduced in [47]. Finally, we need to reemphasize that all the results of this article were obtained by using only one specific definition (MsAi index [5, 6]) of multiscale asymmetry. One should calculate other indices of multiscale asymmetry [7–9] for the \(W_\lambda\) function to systematically compare the results and clarify whether different indices capture different aspects of multiscale asymmetry.

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