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A new measurement of financial time irreversibility based on information measures method

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HIGHLIGHTS

- A new measurement of time irreversibility based on information measures is proposed to analyze the time series.
- The information measures method incorporates elements of both information-based and word statistics-based categories.
- We find that the volatility and irreversibility are not correlated.
- The new measure of time irreversibility can reveal complementary and valuable information on the evolution for the financial time series.

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ABSTRACT

In this paper, we propose a new measurement of time irreversibility based on information measures method to analyze the financial stock markets. In order to examine the effectiveness of this method, we employ it into ARFIMA models. Applying the new method to quantifying time irreversibility of 33 financial indices evolving over the period 2002–2016, we conclude that the stock daily prices of the companies are indeed time irreversible and the degree of irreversibility varies with time for each company. According to the values of irreversibility, we could rank the companies. Also we obtain that the values of annualized irreversibility may have little effect on the coefficient of variation. Moreover, in order to find patterns arising among different periods, we use the principal component analysis (PCA) and hierarchical clustering, the results obtained by these two standard techniques in data mining are in agreement.

1. Introduction

Economics has become an active research area for physicists, and many studies have employed statistical mechanics to detect the nature of an economy. The term econophysics [1–7] is used to indicate the application of statistical mechanics to economic systems. For example, Machado et al. analyze several natural and man-made complex phenomena in the perspective of dynamical systems [5]. As is well-known, in the last few decades, the quantitative analysis of financial time series [8] has obtained valuable input from nonlinear dynamics, statistical physics, and complex systems [9–12] communities. Especially the existence of long-range dependence in financial time series has been employed to measure the level of development of a given market [13]. And later this method is extended to quantify the degree of market inefficiency [14–18].

From the point of view of financial stability, one important property is the time irreversibility. In practice, time irreversibility plays an important role in characterizing natural phenomena and observing time series [19–28]. A time series $\{x(j) : 1 \leq j \leq N\}$ is said to be time irreversible if its statistical properties change after its time reversed (asymmetry with respect to time reverse). And such asymmetry is evidence of the nonlinearity of a time series, as linear Gaussian processes are

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time reversible. Moreover, it reflects the arrow of time and is used to detect the complexity of non-equilibrium systems. As a result, it is important to confirm time irreversibility because it means the influence of nonlinear dynamics, non-Gaussian noise, or both [25].

In the previous study, the time irreversibility has attracted some attention in the financial field (for example see some initial investigations on this matter [29–34]). People usually propose to employ the concept of graph-theoretical to analyze time irreversibility and Kullback–Leibler divergence has been considered as a measurement of time irreversibility. However, in this paper, we mainly propose irreversibility of financial time series based on information measures method [35], which is a kind of pattern analysis method based on symbolic sequences [36]. Therefore, we do not need to require the length of sequences should be the same, just selecting the proper values of parameters to generate a collection of patterns of fluctuations in the given time series. The financial market dynamics are influenced by a number of complex factors, such as index at the same level, the sub-index, the economic data, trading price, and so on. As a result, for this kind of intrinsically noisy system, mapping the original time series into binary sequences denoted by 1 and 0 [37] may be useful to simplify the dynamics. Peng et al. [36] proposed a definition for the weighting factor by using Shannon entropy [38,39], and they give a new definition of dissimilarity index. We here apply this new dissimilarity index to measuring time irreversibility. The novelty of this method is that it considers the underlying dynamical features of financial time series. Since our method weights the underlying information of the rank-order difference of each word statistics by Shannon entropy, it incorporates elements of both information based and word statistics-based categories. Furthermore, global information related to usage of respective elements in financial time series can be captured by the component of these basic elements. It is obvious that we could obtain more detailed and clearer information about the financial stock markets.

The rest part of this paper is organized as follows. In the following section, we introduce the analysis of time irreversibility based on information measures method in detail. In Section 3, we evaluate the effectiveness of this method with artificial time series: Autoregressive Fractionally Integrated Moving Average (ARFIMA) models [40]. Application to financial time series is shown in Section 4. The conclusion is described at Section 5.

2. Method

The information measures method was proposed by Peng et al. [37], it is the modification based on the method proposed by Yang et al. [41,42]. Here we will apply this approach to measuring time irreversibility and further study the financial stock markets.

First of all, we consider a financial time series, $\{x_1, x_2, \ldots, x_N\}$, let x_i be the closing price at day i. And then we map the original time series into binary sequences as given in Eq. (1).

$$I_n = \begin{cases} 0 & \text{if } x_n \le x_{n-1}, \\ 1 & \text{if } x_n > x_{n-1}. \end{cases} \tag{1}$$

Thus we can obtain a new symbol series I_n. Next we map m+1 successive intervals into a binary sequence of length m, called an m-bit word. Each m-bit word, w_k, represents a unique pattern of fluctuations in a given time series. Thus, this method just takes the correlation of adjacent values for the m-bit word into consideration, ignoring the relationship about every value.

In the information measures method, we usually take into account of two different time series, but in the analysis of time irreversibility, we just consider one time series. The method can be summarized as follows:

Step 1: Consider a time series, $x = \{x_1, x_2, \ldots, x_N\}$, then we translate the data into the symbols 0 or 1, respectively, based on the two states, which represents a decrease in x, or an increase in x. Therefore, we can get its corresponding binary sequence S_1 and the reversed binary sequence S_2.

Step 2: Choose the appropriate m and we map $m+1$ successive intervals to a binary sequence of length m, which is called an m-bit word. As a result, we will get a collection of m-bit words over the whole time series.

Step 3: Count the occurrences of different words after having a collection of m-bit words over the total time series, and then sort them in descending order by the frequency of occurrence. We can thus get the values of $p_1(w_k)$ and $R_1(w_k)$, which stand for the probability and rank of a specific word w_k in time series S_1, $p_2(w_k)$ and $R_2(w_k)$ for time series S_2 analogously.

Step 4: Calculate the distance I_{VG} between two symbolic sequences which incorporates the likelihood of each word, and I_{VG} can be seen as a measurement of time irreversibility in a given time series. The distance is defined as in given Eq. (2),

$$I_{VG} = \frac{1}{2^m - 1} \sum_{k=1}^{2^m} |R_1(w_k) - R_2(w_k)| F(w_k) \tag{2}$$

where

$$F(w_k) = \frac{1}{Z}[-p_1(w_k) \log p_1(w_k) - p_2(w_k) \log p_2(w_k)] \tag{3}$$

the normalization factor Z is shown by

$$Z = \sum_k [-p_1(w_k) \log p_1(w_k) - p_2(w_k) \log p_2(w_k)]. \tag{4}$$

Similarly, the sum is divided by the value $2^m - 1$ to keep the I_{VG} value in the range of [0, 1].