Waiting-times and returns in high-frequency financial data: an empirical study

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Abstract

In financial markets, not only prices and returns can be considered as random variables, but also the waiting time between two transactions varies randomly. In the following, we analyse the statistical properties of General Electric stock prices, traded at NYSE, in October 1999. These properties are critically revised in the framework of theoretical predictions based on a continuous-time random walk model.

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Stochastic processes; Continuous-time random walk; Statistical finance; Econophysics; Autocorrelation function

1 Introduction

In financial markets, waiting times between two consecutive transactions vary in a stochastic fashion. From this point of view the continuous time random walk (CTRW) model of Montroll and Weiss [1] can provide a phenomenological description of tick-by-tick dynamics in financial markets [2–4]. Actually in CTRWs, two random variables are used: jumps $\xi_n = x(t_{n+1}) - x(t_n)$ and waiting times $\tau_n = t_{n+1} - t_n$. In the financial interpretation of CTRWs, $x$ represents a log-price and $\xi$ a log-return [2–4]. The physicist can think of $x$ as the position of a random walker performing discrete jumps in one dimension at randomly distributed instants. Based on [3] the evolution equation for $p(x, t)$,

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the probability of occurrence of the log-price \( x \) at time \( t \), or of finding the random walker at position \( x \) at time instant \( t \), can be written, assuming the initial condition \( p(x, 0) = \delta(x) \),

\[
p(x, t) = \delta(x) \Psi(t) + \int_0^t \int_0^{+\infty} \varphi(x - x', t - t') p(x', t') \, dx' \, dt', \tag{1.1}
\]

where \( \Psi(t) \) is the survival probability and \( \varphi(\xi, \tau) \), is the joint probability density of jumps \( \xi_n = x(t_{n+1}) - x(t_n) \) and of waiting times \( \tau_n = t_{n+1} - t_n \). Relevant quantities are the two (marginal) probability density functions (pdf’s) defined as

\[
\lambda(\xi) := \int_0^\infty \varphi(\xi, \tau) \, d\tau, \quad \psi(\tau) := \int_{-\infty}^{+\infty} \varphi(\xi, \tau) \, d\xi,
\]

called jump pdf and waiting-time pdf, respectively. If one assumes that the jump pdf \( \lambda(\xi) \) is independent of the waiting-time pdf \( \psi(\tau) \), we have the so-called ”decoupling” which leads to the factorisation \( \varphi(\xi, \tau) = \lambda(\xi) \psi(\tau) \). Eq. (1.1) is the most general master equation of the CTRW, usually derived in the Fourier-Laplace domain. The simplified form under the hypothesis of ”decoupling” is reported in [3].

The probability that a given inter-step interval is greater or equal to \( \tau \) is \( \Psi(\tau) \), which is defined in terms of \( \psi(\tau) \) by

\[
\Psi(\tau) = \int_\tau^\infty \psi(t') \, dt' = 1 - \int_0^\tau \psi(t') \, dt', \quad \psi(\tau) = -\frac{d}{d\tau} \Psi(\tau). \tag{1.2}
\]

We note that \( \int_0^\tau \psi(t') \, dt' \) represents the probability that at least one step is taken at some instant in the interval \([0, \tau]\), hence \( \Psi(\tau) \) is the probability that the diffusing quantity \( x \) does not change value during the time interval of duration \( \tau \) after a jump. We also note, recalling that \( t_0 = 0 \), that \( \Psi(t) \) is the survival probability until time instant \( t \) at the initial position \( x_0 = 0 \). A relevant choice for the survival probability is given by the Mittag-Leffler function of order \( \beta \) (\( 0 < \beta < 1 \)), which leads to a time-fractional master equation as shown in [3] (see also [5,6]). For reader’s convenience hereafter we recall the main properties of this transcendental function useful for our purposes. For more information see e.g. [7,8]. From its definition valid for any \( \beta > 0 \):

\[
\Psi(\tau) = E_\beta \left[-\frac{(\tau/\tau_0)^\beta}{\Gamma(\beta n + 1)} \right] := \sum_{n=0}^\infty (-1)^n \frac{(\tau/\tau_0)^{\beta n}}{\Gamma(\beta n + 1)}, \quad \beta > 0, \tag{1.3}
\]

one recognises that the Mittag-Leffler function generalises the simple exponential function (recovered for \( \beta = 1 \)) and, if \( 0 < \beta < 1 \), it interpolates on the positive real axis a stretched exponential and a power law according to

\[
E_\beta \left[-\frac{(\tau/\tau_0)^\beta}{\Gamma(1 + \beta)} \right] \sim \begin{cases} 
\exp\left[-\frac{(\tau/\tau_0)^\beta}{\Gamma(1 + \beta)} \right], & \tau/\tau_0 \to 0^+, \\
(\tau/\tau_0)^{-\beta}/\Gamma(1 - \beta), & \tau/\tau_0 \to \infty,
\end{cases} \quad 0 < \beta < 1. \tag{1.4}
\]
The purpose of this paper is to investigate some statistical properties of the random variables $\xi$ and $\tau$ in financial markets. This study is limited to a specific equity of a given market in a definite period. Caution is necessary and our results cannot be arbitrarily generalized. In particular, the reader will learn about General Electric stock prices, traded at NYSE, in October 1999. This preliminary presentation is part of a broader project aimed at studying the behaviour of all Dow-Jones-Industrial-Average stocks during that month.

2 Empirical analysis

In Fig. 1, a scatter plot is presented for waiting times $\tau_n$ as a function of the corresponding log-return $\xi_n$. By means of a contingency table analysis [9], we have studied the independence of the two stochastic variables. A direct inspection of Fig. 1 shows that for large values of log-returns waiting times tend to be shorter. This indicates a possible correlation. Actually, a hypothesis test has been performed on the empirical joint pdf $\varphi(\xi, \tau)$. According to the contingency table presented in Tab. 1, the two random variables cannot be considered independent. The null hypothesis of independence can be rejected with a level of significance of 1%.

In Fig. 2, an estimate of the autocorrelation function for the absolute value of log-returns is plotted. We have used the following estimator [10]

$$C(m) = \frac{1}{N - m} \sum_{n=0}^{N-m-1} (|\xi_{n+m}| - \overline{|\xi|})(|\xi_n| - \overline{|\xi|}), \quad (2.1)$$

where $N$ is the total number of points ($N = 55559$) and $\overline{|\xi|} = \frac{1}{N} \sum_{n=0}^{N-1} |\xi_n|$. The inset shows the time series of the absolute values as a function of the tick $n$. Due to scale persistence, the autocorrelation function follows a power-law decay with a slope of $-0.76$. The autocorrelation is over the noise level (conventionally $3/\sqrt{N}$) for a lag between 20 and 30 ticks, corresponding to an average time of 250s. Therefore, within that time scale, it is not safe to assume that the log-returns themselves, $\xi_n$, are independent variables. These are well-known stylised fact for tick-by-tick financial time series, see e.g. [11–13].

In Fig. 3, the autocorrelation function is shown for waiting-times $\tau_n$. As above, the inset shows the time series itself. Waiting times between trades are inherently positive random variables. For the GE stock in October 1999, there is a marked seasonality of waiting times with a 1-day period (nearly 3,000 trades). Inspection of the series shows that the trading activity is slower in the middle of the day. The seasonality is outlined by the periodic behaviour of the autocorrelation estimate, with periodicity above the conventional noise band.
<table>
<thead>
<tr>
<th>$\xi_n$</th>
<th>$\tau_n$</th>
<th>(0 \div 10)</th>
<th>(10 \div 20)</th>
<th>(&gt; 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt; -0.002)</td>
<td>25 (38.9)</td>
<td>21 (10.1)</td>
<td>9 (6.0)</td>
<td></td>
</tr>
<tr>
<td>(-0.002 \div -0.001)</td>
<td>516 (613.6)</td>
<td>230 (159.5)</td>
<td>122 (94.9)</td>
<td></td>
</tr>
<tr>
<td>(-0.001 \div 0)</td>
<td>6641 (7114.3)</td>
<td>2085 (1849.1)</td>
<td>1338 (1100.6)</td>
<td></td>
</tr>
<tr>
<td>(0 \div 0.001)</td>
<td>31661 (31008.0)</td>
<td>7683 (8059.2)</td>
<td>4520 (4797.0)</td>
<td></td>
</tr>
<tr>
<td>(0.001 \div 0.002)</td>
<td>398 (464.4)</td>
<td>179 (120.7)</td>
<td>80 (71.9)</td>
<td></td>
</tr>
<tr>
<td>(&gt; 0.002)</td>
<td>34 (36.1)</td>
<td>10 (9.4)</td>
<td>7 (5.6)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1

Contingency table between log-returns $\xi_n$ and waiting times $\tau_n$. Every cell contains the frequency observed within the values considered and (in brackets) the theoretical frequency which can be computed under the null hypothesis of independence between $\xi_n$ and $\tau_n$.

In recent times, several efforts have been devoted to find a suitable measure of time, in order to discard similar seasonalties, see e.g. [14,15]. However, as shown in Fig. 4, the survival probability $\Psi(\tau)$ can be fitted by a stretched exponential function: $\exp\left[-\left(\tau/\tau_0\right)^{\beta}/\Gamma(1 + \beta)\right]$, with $\tau_0 = 6.6s$ and $\beta = 0.7$. The reduced chi-square of the fit is 0.71. In a previous work on bond futures [3], according to theoretical considerations on the properties of continuous-time random walks, we suggested the Mittag-Leffler function with a power-law decay as a suitable fit for the empirical survival probability. The above result does not contradict our previous findings. In fact, whereas for bonds futures we found waiting times greater than 10,000s, here we have only waiting times smaller than 200s, and the Mittag-Leffler function is well approximated by the stretched exponential as $\tau$ is small enough, see Eq. (1.4).

### 3 Summary

A preliminary study of General Electric high-frequency stock prices has been performed. Some statistical properties of the log-return and waiting-time random variables have been presented. This study was inspired by previous theoretical and empirical work, based on the phenomenological CTRW model of financial markets. The main results are as follows: the two random variables cannot be considered independent from each other; the autocorrelation of log-returns absolute values exhibits a power-law decay and reaches the noise level after about 250 s; the autocorrelation of waiting times shows a 1-day periodicity, corresponding to the daily stock market activity.
References


Fig. 1. Scatter plot of waiting times $\tau_n$ as a function of the corresponding log-returns $\xi_n$.

Fig. 2. Autocorrelation function for the absolute value of log-returns $\xi_n$. The inset shows the time series.
Fig. 3. Autocorrelation function for the waiting times $\tau_n$. The inset shows the time series.

Fig. 4. Survival probability. The stretched exponential (solid line) is compared with the standard exponential (dash-dotted line).