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Does the law of one price hold in international financial markets? Evidence from tick data*

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Abstract

This paper investigates the validity of the law of one price (LOP) in international financial markets by examining the frequency, size and duration of inter-market price differentials for borrowing and lending services ('one-way arbitrage'). Using a unique data set for three major capital and foreign exchange markets that covers a period of more than seven months at tick frequency, we find that the LOP holds on average, but numerous economically significant violations of the LOP arise. The duration of these violations is high enough to make it worthwhile searching for one-way arbitrage opportunities in order to minimize borrowing costs and/or maximize earnings on given funds. We also document that such opportunities decline with the pace of the market and increase with market volatility.

JEL classification: F31 ; F41 ; G14 ; G15
Keywords: Law of one price; One-way arbitrage; Foreign exchange microstructure

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1. Introduction

Textbook finance theory is based on the law of one price (LOP), which postulates that in efficient financial markets two assets with identical cash flows must trade at the same price. Specifically, in international financial markets, the LOP for lending and borrowing services requires that the domestic lending (borrowing) interest rate should be the same as the foreign lending (borrowing) interest rate when the latter is adjusted to fully hedge for exchange rate risk. Violations of the LOP imply that the same need — desire to lend (owner arbitrage) or desire to borrow (borrower arbitrage) — can be met at two different prices at a point in time. Following the seminal work by Deardorff (1979), a number of studies refer to the LOP to describe the absence of 'one-way arbitrage', which may be stated in the form of 'owner arbitrage' and 'borrower arbitrage'.

Since Deardorff (1979) introduced the concept of one-way arbitrage, researchers often interpreted this concept as closely related to pure, round-trip arbitrage associated with deviation from the covered interest rate parity (CIP) condition. CIP states that net returns on an investment that borrows at home and lends abroad (or vice versa) in similar interest-bearing assets will be zero when exchange rate risk is hedged through forward or swap contracts. However, CIP is conceptually very different from the LOP for lending and borrowing services studied in this paper. In particular, violation of CIP is a sufficient but not a necessary condition for violation of the LOP. More importantly, violations of the LOP do not imply riskless profits since they refer to differences in the prices of the same financial service (borrowing or lending) which do not allow for a self-financing transaction (borrow and lend).[1] It seems therefore more appropriate to consider violations of the LOP as a form of 'mispricing' rather than pure arbitrage opportunities such as CIP violations, which do not require any initial endowment or borrowing need and imply riskless profits

[1] In other words, the violations of the LOP considered here are related either to borrowing capital at the lowest possible rate or lending at the highest possible rate offered by financial markets at a point in time. The violations do not generate a riskless return since agents will not be allowed to borrow at the cheaper rate and lend at the higher rate.

(e.g. see Deardorff, 1979; Akram, Rime and Sarno, 2008).

This paper investigates whether the LOP holds for borrowing and lending services and examines the frequency, size and duration of LOP deviations. A rigorous empirical examination of the LOP places stringent requirements on the data used. Contemporaneous, tradable (firm) quotes of comparable domestic and foreign interest rates and spot and forward exchange rates are needed to establish whether an apparent deviation from no-arbitrage conditions actually represented a one-way arbitrage opportunity to agents at a given time. Moreover, the high level of activity in the foreign exchange (FX) and international capital markets demands use of high-frequency, real-time quotes to characterize the properties of possible arbitrage opportunities, especially their duration. For example, Taylor (2001) shows that large biases are generated in studies of the persistence of LOP violations when researchers employ data at lower frequency than the frequency at which convergence to the LOP occurs. The direction of these biases is upward, meaning that using data that are not in real time is likely to give illusory evidence of more persistent deviations of the LOP than the true deviations. Finally, it is also important to have a sufficiently long sample to draw general conclusions.

The data set used in this paper possesses, to a large extent, the desired characteristics. It includes contemporaneous tick quotes of exchange rates and interest rates that pertain to the most liquid segments of the FX and capital markets. The sample includes ask and bid quotes for three major US dollar spot exchange rates: euro, UK sterling and Japanese yen. It also includes ask and bid quotes for exchange rate swaps and for interest rates on deposits in quoting and base currencies. The tick quotes cover a period of more than seven months spanning from February 13 to September 30, 2004, and is the longest and highest-frequency data set ever used for examining one-way arbitrage. The data have been collected through Reuters trading system on special order. We have also gathered precise information about transaction costs facing the agents.[2]

[2]Previously, some early studies have found evidence of deviations from the LOP in FX, which appear to be small and economically insignificant (e.g. Deardorff, 1979; Callier, 1981; Taylor, 1987). However,

An investigation of the validity of the LOP for borrowing and lending services can shed light on the degree of capital mobility in international financial markets and their integration, as well as being informative about the ability of financial markets to efficiently price similar assets. The investigation can also shed light on the extent to which market participants have incentives to watch financial markets to exploit mispricings and thereby ensure that they remain efficient. It may thereby also contribute to resolve the so-called 'arbitrage paradox', first pointed out by Grossman and Stiglitz (1976, 1980). That is, if mispricing is never observed, market participants may not have sufficient incentives to watch the market, in which case arbitrage opportunities could arise. A possible resolution to this paradox is for very short-term arbitrage opportunities to arise, inviting traders to exploit them, and hence be quickly eliminated.

Our use of real-time quotations can also provide evidence on the validity of another proposed resolution of the arbitrage paradox, which is the anecdote that providers of interest rate and exchange rate quotes set their quotes such that they knowingly do not misprice–i.e. set prices that do not violate the LOP. For example, if quotes are always set such that no-arbitrage conditions are ensured conditional on the latest quotes of other instruments, these conditions will hold continuously without requiring trade to actually take place. However, from the microstructure literature we know that prices can temporarily deviate from no-arbitrage values due to, for example, risk management. More generally, microstructure theory shows how price differences may occur for identical assets in markets that are less than fully centralized, segmented or with an imperfect degree of transparency (O'Hara, 1995; Lyons, 2001; Lamont and Thaler, 2003).[3]

To preview our main results, we find that the LOP holds on average. Yet, we pro-

no study has come closer than the present one to meeting the stringent data requirements discussed above and the literature has been dormant for the last two decades or so after the launch of electronic foreign exchange platforms. See also the recent research on triangular arbitrage by Lyons and Moore (2005); on convertible bond arbitrage by Hutchinson and Gallagher (2008); on the law of one price in international goods markets by Sarno, Taylor and Chowdhury (2004), Sarno and Valente (2006) and Nikolaou (2008); and on closed-end fund arbitrage by Kim and Lee (2007) and Fuertes and Thomas (2006). See Sarno (2005) for an overview of recent research on international parity conditions.

[3] See also the theories related to limits to arbitrage (Shleifer and Vishny, 1997).

vide evidence that there are numerous short-lived profitable deviations from the LOP for lending and borrowing services. The size of the profitable deviations is economically significant across exchange rates and comparable across different maturities of the interest rates examined. Their duration is, on average, high enough to allow agents to exploit these opportunities, but low enough to explain why such LOP violations can be difficult to detect using data at lower frequencies. Our results also suggest that frequency, size and duration of apparent arbitrage opportunities decline with the pace of markets, but increase with market volatility. We find scant evidence in favor of the view that prices for spot and forward rates and for money market instruments are set directly from the formulas of no-arbitrage conditions in real time. Overall, the evidence is consistent with the Grossman-Stiglitz view of financial markets, where efficiency is not interpreted as a statement about prices being correct at each point in time but the notion that in efficiently-functioning financial markets very short-term mispricings can arise and invite traders to exploit them, which makes it worthwhile to watch the relevant markets. This is the mechanism that restores the LOP we observe on average.

The paper is organized as follows. Section 2 considers the two relevant cases of one-way arbitrage in the foreign exchange market. It also relates the concept of one-way arbitrage to that of round-trip arbitrage (CIP). For the sake of consistency with existing literature on arbitrage in the FX markets, we use the terms 'one-way arbitrage', 'owner arbitrage' and 'borrower arbitrage' interchangeably with (perhaps the more appropriate terms) 'LOP', 'LOP for lending services' and 'LOP for borrowing services', respectively. Section 3 briefly discusses quoting conventions, transaction costs and their implications for calculations of gains and losses from arbitrage of the different forms. This section also describes the data set. Section 4 presents the main empirical findings, relating to frequency, size and duration of returns from LOP violations. It also undertakes a sensitivity analysis to demonstrate the robustness of the results. Section 5 analyses whether and how characteristics of profitable arbitrage opportunities vary with market pace and market volatility and sheds light on the response of the different asset prices to deviations from the LOP. Section 6 briefly summarizes the main conclusions. Finally, the appendix presents further details on quoting conventions, calculations of days to maturity and transaction costs for different exchange rates and traded volumes.

2. The LOP from the view point of fund owners and raisers

We use the term 'owner arbitrage' (OA) to refer to the case where a trader has an endowment of funds in some currency and wants to lend the funds to obtain the highest possible net return. Such traders weigh the option of lending own funds at the market bid interest rate for the endowment currency, against the option of converting the funds to another currency at the spot exchange rate and lending them at the market bid interest rate for that currency, while eliminating the exchange rate risk at the maturity of the lending contract through a forward contract.[4]

The LOP will prevent OA opportunities under the following conditions:

$$(1 + r_d^b) \geq \frac{F^b}{S^a}(1 + r_f^b), \tag{1}$$

$$(1 + r_f^b) \geq \frac{S^b}{F^a}(1 + r_d^b). \tag{2}$$

Here, r_d^b and r_f^b denote the domestic and foreign period lending interest rates, respectively; S^a and S^b are the spot exchange rates at the ask and the bid, respectively; F^a and F^b are the (outright) forward rates at the ask and the bid, respectively. A trader faces bid rates when lending funds, and ask rates when borrowing. Similarly, a trader

[4] Alternatively, one may be interested in measuring the net return in another currency than the endowment currency. In that case, if the endowment is in the domestic currency, one would weigh the option of lending it in the domestic market and converting the resulting amount at maturity to foreign currency at the forward exchange rate, against the option of converting the endowment right away to the foreign currency at the spot exchange rate and lending the resulting amount in the foreign capital market. In this case, if the domestic currency is the quoting currency, one would face the forward exchange rate at the ask in the first option, and the spot exchange rate at the ask in the second option. However, if the domestic currency was the base currency, one would be facing the bid side of both the forward and the spot exchange rates. We do not consider these alternatives in the empirical work below.

receives the exchange rate at its bid rate when selling a currency (spot or forward) but pays the ask rate when buying. Domestic and foreign interest-bearing assets can be considered similar if they are of equal maturity and share the same characteristics, such as liquidity and political and default risk. Conditions (1) and (2) refer to cases where one has an endowment in the domestic and foreign currency, respectively, and faces the choice between investing at home and abroad. In this paper, we treat the quoting currency as the domestic currency (d) and the base currency as the foreign currency (f).[5]

The concept of 'borrower arbitrage' (BA) refers to the case where a trader aims to finance an investment in the cheapest way and thereby gain by minimizing funding costs. Such traders face the option of borrowing funds in the desired currency directly, or borrowing funds in another currency and converting them to the desired currency at the spot exchange rate, while eliminating the exchange rate risk at the maturity of the borrowing contract through a forward contract.

The LOP will prevent BA opportunities under the following conditions:

$$(1 + r_d^a) \leq \frac{F^a}{S^b}(1 + r_f^a), \tag{3}$$

$$(1 + r_f^a) \leq \frac{S^a}{F^b}(1 + r_d^a). \tag{4}$$

Here, r_d^a and r_f^a denote the domestic and foreign period borrowing interest rates, respectively. Conditions (3) and (4) refer to cases where the funds are required at home and abroad, respectively.[6]

[5] This is for convenience, since we overlook cases where both the quoting as well the base currencies are actually foreign currencies for a dealer.

[6] Here we implicitly assume that revenues used to serve the borrowing costs flow in the same currency as that for the funds required. However, revenues used to serve the borrowing cost may flow in a different currency than that of the funds required. Take the following example: the agent needs funds to cover some costs in domestic currency, but the revenues used to serve the borrowing costs in domestic currency flow in the foreign currency. Then, the agent would weigh the option of borrowing funds in the domestic market and converting the borrowing costs at maturity at the forward exchange rate, against that of borrowing in the foreign market and converting the borrowed amount at the spot exchange rate. If the domestic currency is the quoting currency, then one would have to sell the foreign currency (at the bid rate) forward as well as spot. In contrast, if the domestic currency is the base currency, one would need to buy the domestic currency (at the ask rate) spot as well as forward.

Note that when borrowing another currency than the currency eventually desired, the trader must consider how much she must borrow of that currency to obtain one unit of the desired currency. For instance, since the borrowed amount of foreign currency must be converted to the domestic currency at the spot bid rate, a trader must borrow $1/S^b$ of the foreign currency to obtain one unit of domestic currency. At maturity, her debt in foreign currency will be $1/S^b(1+r_f^a)$, but $1/S^b(1+r_f^a)F^a$ in domestic currency would be required if she enters a forward contract of that maturity to buy the foreign currency in order to settle her debt.

It follows that any gain by lending or borrowing in one currency relative to another would imply a violation of the LOP, which states that identical securities must have the same price, irrespective of how they are created. However, it is possible that in two segmented markets for the same asset a bid (ask) rate in one market can be higher (lower) than the bid (ask) rate in the other, as long as the best bid rate is not higher than the best ask rate.

2.1. Difference between round-trip and one-way arbitrage

CIP implies absence of round-trip arbitrage opportunities. That is, it is not possible to earn positive returns by borrowing domestic assets for lending, in a similar asset, abroad (or vice versa) while covering the exchange rate risk through a forward contract of equal maturity. Taking into account ask–bid spreads of interest rates and exchange rates, round-trip arbitrage is not profitable under the following conditions:

$$(1+r_d^a) \geq \frac{F^b}{S^a}(1+r_f^b), \tag{5}$$

$$(1+r_f^a) \geq \frac{S^b}{F^a}(1+r_d^b). \tag{6}$$

It is clear that the left-hand-side elements in the OA inequalities (1)–(2) are lower than those in the case of CIP given in conditions (5)–(6), and hence they may be violated more easily, and more often, than the CIP inequalities. In Table 1 (Panels I-II), we summarize the relationship between CIP and OA.

It follows that profitable arbitrage in the case of CIP implies the existence of OA opportunities while the converse may not be true–i.e. violation of conditions (5) and (6) is a sufficient but not a necessary condition for the violation of conditions (1) and (2), respectively. Moreover, if OA opportunities are not present, neither will CIP arbitrage be profitable while the opposite may not be the case–i.e. validity of conditions (1) and (2) is a sufficient but not a necessary condition for the validity of conditions (5) and (6), respectively; see Panels I-II in Table 1.

In a similar fashion, turning to the link between CIP and BA, violation of conditions (5) and (6) is a sufficient but not a necessary condition for the validity of conditions (3) and (4), respectively; see Panel III of Table 1. In other words, if a positive return can be gained in domestic currency by borrowing domestic funds to lend abroad, it will also be relatively dearer to borrow funds abroad (when measured in domestic currency), but the converse may not be the case. However, profitable CIP arbitrage when measured in domestic currency (d) implies that it will be profitable for a foreign investor to borrow domestic currency funds, convert them to the foreign currency at the spot rate, while covering the exchange rate risk at maturity through a forward contract. In short, profitable CIP arbitrage from the viewpoint of a domestic (foreign) dealer implies BA from the viewpoint of a foreign (domestic) dealer; see Panel IV of Table 1.

In addition to the theoretical differences between round-trip arbitrage and one-way arbitrage listed in Table 1, a key difference between round-trip arbitrage and one-way arbitrage is that the latter form presuppose given funds or a need for funds, while round-trip arbitrage is 'self-financing'. However, tests of the existence of OA and BA are more stringent tests of fair pricing in the FX market than CIP tests. Given the evidence that small shares of short-lived CIP opportunities do arise (e.g. Akram, Rime and Sarno, 2008) and that the number of CIP violations provide a lower bound on OA and BA violations, a logical question is whether violations of OA and BA conditions are much more frequent than CIP violations.

3. Data and calculations of deviations from the LOP

We obtained data, on special order, from the Reuters trading system, which embeds general market quoting and maturity conventions. In this section, we present precise formulas for calculating LOP deviations in light of these conventions as well as transaction costs that a trader would typically face when dealing through this system. Appendices A.A and A.B provide a detailed account of quoting conventions, calculations of days to maturity and transaction costs for different exchange rates and traded volumes.

3.1. Calculations of deviations from the LOP

In the interbank-market dealers trade swaps rather than (outright) forwards. Swaps are denominated in so-called swap points, which express a multiple of the difference between forward and spot exchange rates. By convention, all of the spot exchange rates are quoted with four decimals, except for the Japanese yen, where two decimals are used. The smallest measure of movement for an exchange rate is called a "pip". Swap points, which are expressed in pips, are therefore obtained by multiplying the difference between forward and spot exchange rates by 10^4 in general, and by 10^2 in the case of the Japanese yen.

We investigate possible deviations from the LOP by comparing the swap points quoted through Reuters with corresponding derived (or theoretical) swap points. The derived points can be obtained by rewriting the formulas presented above, (1)–(4), while taking into account relevant quoting and maturity conventions. Specifically, the OA and BA deviations when one has an endowment in domestic currency or a need to borrow abroad can be expressed as:

$$Dev_{OA}^{b} = (F^{b} - S^{a}) - \frac{S^{a}(i_{d}^{b} \times \frac{D}{360} - i_{f}^{b} \times \frac{D}{360})}{(100 + i_{f}^{b} \times \frac{D}{360})} \times 10^{4} \tag{7}$$

$$Dev_{OA}^{a} = -(F^{a} - S^{b}) + \frac{S^{b}(i_{d}^{b} \times \frac{D}{360} - i_{f}^{b} \times \frac{D}{360})}{(100 + i_{f}^{b} \times \frac{D}{360})} \times 10^{4} \tag{8}$$

$$Dev_{BA}^{b} = (F^{b} - S^{a}) - \frac{S^{a}(i_{d}^{a} \times \frac{D}{360} - i_{f}^{a} \times \frac{D}{360})}{(100 + i_{f}^{a} \times \frac{D}{360})} \times 10^{4} \tag{9}$$

$$Dev_{BA}^{a} = -(F^{a} - S^{b}) + \frac{S^{b}(i_{d}^{a} \times \frac{D}{360} - i_{f}^{a} \times \frac{D}{360})}{(100 + i_{f}^{a} \times \frac{D}{360})} \times 10^{4} \tag{10}$$

where, in each equation, the first right-hand term denotes market swap points for a given maturity obtained from Reuters, while the second term represents the corresponding derived swap points. In order to calculate derived swap points that are directly comparable to the market swap points quoted on Reuters, we adjust the interest rate i, which is quoted in percent per annum, to obtain the interest rate for maturities less than a year.

We denote the number of days to maturity of swap and deposit contracts by D. It is calculated as the actual number of business days between the (spot) value date and the maturity date of a contract while taking into account bank holidays in the home countries of currencies and securities, and other conventions–see Appendix A.A for details. In general, the total number of days to maturity in a year are 360. For sterling contracts, however, the total number of days in a year are set at 365 in line with market conventions. Thereafter, the resulting term is multiplied by 10^4 (or 10^2 in the case of the Japanese yen) to obtain the derived swap points. Deviations from a no-arbitrage condition are expressed in pips since they are defined as the difference between quoted and derived swap points.

Dev_{OA}^{b} and Dev_{BA}^{a} express returns in domestic currency (d), while Dev_{OA}^{a} and Dev_{BA}^{b} express returns in foreign currency (f). Table 2 makes explicit the quoting and base currencies for the three exchange rates examined. Deviations are profitable if the inequalities (1)–(4) are not satisfied, or the corresponding equations (7)–(10) are positive net of other transactions costs. To obtain returns less brokerage and settlement costs we deduct 1/10 of a pip from the expressions for returns (7)–(10). In fact, Appendix A.B shows that the sum of brokerage and settlement costs are at most 1/10 of a pip of a US-dollar pip for an arbitrage deal of required size. Thus, the number and size of profitable returns obtained by us are likely to represent lower bounds on the number of profitable returns through one-way arbitrage.

3.2. Data

We employ tick data collected via a continuous feed from Reuters over the period February 13–September 30, 2004. The raw tick data are the same as employed by Akram, Rime and Sarno (2008) in the analysis of round-trip arbitrage, which allows us to make a direct comparison of their results to the one-way arbitrage results in this paper. The data set allows us to investigate one-way arbitrage for three major exchange rates at four different maturities: 1, 3, 6 and 12 months. It includes all best ask and bid spot exchange rates for three major exchange rates: USD/EUR, USD/GBP and JPY/USD–hereafter EUR, GBP and JPY, respectively. It also includes ask and bid quotes for the exchange rate swaps for the four maturities as well as for euro-currency deposits for the four currencies involved.

An advantage of using deposit rates for interest rates is that an arbitrageur would know when and how much she will pay or receive. The use of deposits implies, however, that we limit the pool of potential arbitrageurs to those that have credit agreements established between themselves, since deposits are on-balance sheet instruments. However, in principle it is possible that a quote in the Reuters system which appears as an attractive price is supplied by a counterparty with whom more creditworthy or bigger banks do not wish to transact, thereby creating a spurious arbitrage opportunity. This limitation is not particularly severe in the present context since all major banks have such credit agreements.

For the spot exchange rates we have firm quotes from Reuters electronic brokerage system (D3000-2); these quotes are tradable as spot transactions can be carried out with a market order in the Reuters system. For swaps and euro-currency deposits only indicative ask and bid quotes were available to us through Reuters Monitor (i.e. Reuters 3000 Xtra). This is mainly because both swaps and deposits are primarily traded bilaterally between interbank dealers, typically over telephone or Reuters D2000-1. Data from these sources is virtually impossible to obtain and has never been retrieved for empirical work in this context, to the best of our knowledge. Recently, an electronic-broker trading platform for swaps has been introduced, but this has yet to develop as the preferred platform.

However, in light of evidence for spot exchange rates in Danielsson and Payne (2002) and conversations with users of the Reuters trading system, one may say that spreads between indicative ask and bid quotes for swaps as well as for interest rates will not be smaller than those for corresponding firm ask and bid quotes.[7] Thus, use of the indicative quotes may not lead us to exaggerate the number and size of arbitrage opportunities.

Actually, we may obtain results quite close to those implied by (unavailable) firm quotes for swaps and euro-currency deposits. This is because indicative quotes for swaps and deposits are also used for signaling in the dealer market, and hence regarded as a reliable indication of firm quotes in lack of other information sources. Essentially, because trading in swaps and euro-currency deposits only rarely occur on the Reuters electronic broker system, traders form their trading strategies on the posted indicative quotes, and the quotes on Reuters D2000-1 tend to be, therefore, very close to the quotes on Reuters 3000 Xtra. In contrast, indicative quotes for spot exchange rates, on the other hand, are primarily meant as advertisement towards the non-bank customers and therefore not reliable indications of firm inter-dealer quotes. Thus, it is more important to have firm quotes for spot exchange rates than for exchange rate swaps and euro-currency deposits to obtain results close to those implied by firm quotes for all instruments.

One drawback of using the indicative quotes, however, is that they can become stale,

[7]Previous studies have also shown that the indicative spot mid-point is an accurate estimate of the firm spot mid-point; see e.g. Danielsson and Payne (2002).

at times, and thereby potentially signal spurious arbitrage opportunities. Usually, dealers keep real quotes up to date, but may fail to do so when market activity is particularly high, in which case indicative quotes will be centered on previous, rather than on current, firm quotes. If so, we could report one-way arbitrage opportunities in our empirical work when there are no opportunities in reality–i.e. false positives. We examine the robustness of our findings to this possibility by analyzing separately cases where an arbitrage opportunity arises because of a newly arrived spot quote in combination with existing swap quotes versus those that arise due to a newly arrived swap quote in combination with an existing spot quote. The latter case is less likely to represent a stale swap quote.

In general, ask and bid quotes for an instrument (say the spot exchange rate) do not arrive contemporaneously with those for other instruments (e.g. euro-currency deposits for the currencies involved). In order to obtain continuous series of contemporaneous/synchronized (to the second) ask and bid quotes for different instruments, we merged all instruments according to date and time to the second into a file and then filled in missing ask and bid quotes for an instrument by using the latest quotes for that instrument. In order to severely limit the number of stale quotes, in the core empirical work we excluded weekends and days with unusually low or no trading activity (either due to a holiday or failure of the feed), which left us with quotes for 151 trading days.[8] In addition, we ignored quotes from hours with little trading and thus included only quotes that appeared during 07:00–18:00 GMT on the included days. In our robustness checks, we further limit the potential for stale quotes by imposing even more stringent constraints on how 'fresh' the quotes are and obtain largely the same results as in the core analysis.

Despite ignoring numerous observations to ensure calculations of arbitrage opportunities with as high a share of fresh quotes as possible, we are able to investigate a large number of data points (i.e. potential LOP violations), over 2 million in the case of EUR

[8]In addition to weekends, we left out the following days: April 2, 5–9, 12, May 3 and 31, June 17–18, August 10, 13, 24, and September 15, as these days were characterized by unusually low trading. Thus we were left with 151 days out of 231 days over the sample period February 13–September 30, 2004.

and around 2.5 million in the case of GBP. For JPY, however, about 0.8 million observations were obtained. The lower number of data points in the latter case can be explained on two grounds. First, our choice of trading hours allows us to cover trading in JPY taking place during the main European trading hours and partly the main US trading hours, at the expense of excluding the main Japanese trading hours. Second, the most active electronic market for trading JPY is the Electronic Broking System (EBS).[9]

4. One-way arbitrage opportunities: Empirical results

In this section we report the key findings regarding the frequency, size and duration of owner and borrower arbitrage opportunities. Our basic results are mere descriptions of the observations obtained by using the formulas presented in (7)–(10).

Table 3 reports characteristics of OA opportunities for the three exchange rates and four maturities considered. OA calculations deliver period returns that are generally negative, but always insignificantly different from zero, on the basis of t-values. This suggests that in the case of lending services, the LOP holds *on average*. However, the results indicate the presence of a large number of profitable OA opportunities in most cases. In particular, the frequency of profitable OA, calculated as shares of profitable OA opportunities out of the total number of deviations available, is in the range from about 15% to 48% in the case of EUR, 12% to 46% for GBP, and from about 11% to over 64% in the case of JPY. These figures are substantially larger than the corresponding figures reported for CIP deviations, which reach a maximum frequency just over 2% in the most extreme cases (e.g. Akram, Rime and Sarno, 2008). The average inter-quote time is in the range from about 2 seconds to 9 seconds, confirming the fast pace of FX and capital markets. It also supports the tendency of longer-maturity markets to display faster activity levels than shorter-maturity markets.

[9] The EBS is also the main trading platform for EUR. Still, we have obtained a very large number of data points for EUR, although the largest number of observations is for GBP, for which Reuters is the main trading platform.

BA opportunities are analyzed in Table 4. On average, BA returns are generally negatively signed and always insignificantly different from zero. This suggests that the LOP holds on average also in the case of financing services. The frequency of BA opportunities is largely comparable to that of OA opportunities, with the corresponding shares ranging from about 8% to 50% in the case of EUR, 13% to 50% for GBP, and from about 11% to 68% in the case of JPY. The average sizes of gains from BA opportunities are also comparable to those from OA in Table 3. In addition, the inter-quote times are similar to those in the case of OA, in the range from about 2 seconds to about 9 seconds.

In Figures 1 and 2, we present an histogram of the deviations for OA and BA, respectively. The graphs show that the distribution of all deviations is fairly symmetric around the mean.

We also examine whether the substantial shares of LOP violations are robust to the use of particularly "fresh" quotes. As described in the data section, we restricted the core analysis to the most active periods of market activity in order to limit the possibility of using stale quotes, that is quotes that may not be actually tradable even if they appear on the Reuters system.[10] We address the sensitivity of our results by further restricting the sample to quotes that may be considered particularly "fresh". To this end, we amend the data set used until now as follows: we consider a quote of an instrument as "stale" if it occurs in an inactive state of the market, i.e. when the quote has not changed within the last two minutes, and does not change within the next two minutes. When calculating deviations from OA and BA we now require that the quotes of *all* instruments involved are fresh, i.e. they are not stale according to the above definition. All deviations which did not meet this criterion were excluded from the sample. This is a very stringent condition which should ensure selection of data at very active trading times. Consequently, the results–reported in Panel c) of Tables 3 and 4 for OA and BA respectively–indicate that

[10]This was achieved by excluding weekends and days with unusually low or no trading activity (either due to a holiday or failure of the feed), and by including only quotes during the highest activity part of the trading day, namely 07:00–18:00 GMT.

this screening of the data reduces drastically the number of deviations analyzed, especially for JPY. Also, the number of profitable LOP violations decreases substantially. However, the frequency of occurrence of one-way arbitrage–calculated as the share of profitable arbitrage opportunities out of the total number of deviations based on the particularly fresh quotes–remains fairly similar to the frequencies reported for OA and BA in the core analysis–Panel b) of Table 3 and 4. Specifically, we find high shares for both OA and BA, ranging from zero to 83%, and from zero to 76%, respectively. We also note that, for some exchange rates and maturities, the frequency is lower in this selective data set, while in some cases the frequency is higher relative to the baseline data set used above.[11]

Table 5 presents information about durations of profitable OA and BA opportunities. We see that means of the cluster durations are mostly less than 5 minutes, and seem to decline with the maturity of the contracts. A cluster consists of at least two profitable deviations from no-arbitrage (LOP) in a row. The standard deviations of cluster durations display some variation across the different cases, while median durations are lower than the corresponding mean durations.

Overall, we find a large number and high share of opportunities for one-way arbitrage–both in the form of OA and BA opportunities. The two one-way arbitrage opportunities display similar properties in terms of both size and duration. The size is also economically significant, bearing in mind that, for example, the typical spread between ask and bid swap rates for major currencies is seldom larger than 1 pip. Their duration is relatively low, consistent with the notion that these opportunities are short-lived, and tends to decline with the maturity of contracts, presumably because the market pace is higher for longer-maturity contracts.

[11] We also carried out the exercise in this sub-section by using fresh quotes defined on the basis of a 1-minute (rather than 2-minute) change in price, and found results that are qualitatively identical to the ones reported in Tables 3-4. These results are not reported but remain available from the authors upon request.

5. Further analysis

This section examines the response of the different instruments to deviations from the LOP, that is whether the price of a given instrument may adjust such as to eliminate profitable deviations from the LOP. Thereafter, we examine whether deviations from the LOP can be associated with the market pace and volatility, which are both closely related to market liquidity.

5.1. On the restoration of the LOP

Given the large number of profitable deviations from the LOP, a pertinent question is whether any of the four assets involved in one-way arbitrage — spot, swap, domestic and foreign interest rates — is priced according to no-arbitrage conditions so to restore the LOP. Actually, anecdotal evidence suggests that forward contracts are priced such as to rule out LOP violations and hence OA or BA altogether. Our analysis can also be considered a test of this conjecture.

Given our data on OA and BA opportunities, we calculated the number of times an arbitrage opportunity was present at the same second when only the market swap quote was fresh (just posted), whilst the quotes entering the derived swap points were predetermined (or did not change). We then carried out the same exercise for the case when, in turn, only one of the spot exchange rate, the foreign interest rate and domestic rate were fresh quotes. We would expect that if an instrument is priced using, e.g., the OA formula, the OA condition should be valid at least whenever that instrument is priced, i.e. whenever the quote for that instrument changes. Tables 6 and 7 reports results for OA and BA, respectively.

The tables show that the shares of profitable deviations, owing exclusively to a new quote in one of the four instruments involved in arbitrage when the other instruments do not change (even if they are quoted), are comparable to the corresponding shares reported in Tables 3 and 4. The shares are also comparable across instruments. Thus, forward exchange rates–or spot exchange rates or else deposit rates–do not appear to be systematically set such that they ensure the validity of the LOP conditions using available quotes. This implies that either the practice of using the LOP conditions to set prices is not feasible at this very high frequency, and/or the providers of quotes of a given instrument do not update the formulas with the latest quotes of the other instruments.

Overall, this evidence indicates that none of the asset prices is systematically set using no-arbitrage conditions at tick frequency, and that each of them is partly responsible for the mispricing leading to the one-way arbitrage opportunities as well as for the elimination of such opportunities.

5.2. Market pace and volatility

Given the high frequency of the data employed in this study, it is difficult to design a comprehensive empirical analysis of the economic conditions under which arbitrage opportunities arise as most economic and financial variables are not available at this frequency. However, in this sub-section, we provide some evidence on whether frequency, size and duration of profitable arbitrage opportunities vary with the pace of the market and with market volatility.

We undertake this investigation for all forms of arbitrage considered above to examine the generality of the findings. To this end, we estimate simple linear cross-sectional regression models with measures of frequency (share), size and duration of profitable one-way arbitrage (OA and BA) opportunities as dependent variables, regressed on an intercept, inter-quote time and a proxy for market volatility as the explanatory variables. That is, we estimate regression models of the following form:

$$y_j = \alpha_y + \beta_y IQ_{y,j} + \gamma_y DiffImplVol_{y,j} + \varepsilon_{y,j} \tag{11}$$

where y = *Share*, *Size*, or *Duration* of deviations from no-arbitrage conditions; IQ denotes inter-quote time; *DiffImplVol* is the difference between maximum and minimum implied volatility and is a measure of the degree of uncertainty (variability) in volatility; and ε is an error term. Observations on implied volatility for the relevant maturities are collected together with the rest of the data set, and is hence based on market valuations. They refer to indicative quotes of at-the-money currency options as they appear on Reuters, and are available at the same maturities as the deposits, allowing us to match the maturities exactly in estimation. Subscript j indicates an observation number; $j = 1, 2, 3, ...N_y$. The Greek letters represent time-invariant parameters.

The models are estimated by ordinary least squares (OLS) using clustered standard errors for each of the currency pairs examined, clustering on the business hour for the regression of *Share* and on the date for *Size* and *Duration*. Accordingly, values for y, IQ and *DiffImplVol* as well as the total number of observations (N) depend on the form of arbitrage and the currency pair analyzed. We have stacked observations for y, IQ and *DiffImplVol* in corresponding columns in accordance with both the arbitrage direction (i.e. stacking together ask and bid sides) and the maturity of the instruments involved. Thus, the total number of observations N_y becomes equal to the sum of the total number of observations associated with the different maturities for each y examined.

The variables are defined more precisely as follows. The y-variable *Share* also referred to as *frequency* is defined, for a given form of arbitrage and currency pair, as the share of profitable deviations out of the total number of deviations from the corresponding no-arbitrage condition that occur in a business hour over the sample period. In this case, N_y can potentially be 13,288, which is the product of the 2 potential arbitrage directions (ask and bid); the 4 maturities considered; the 11 business hours (between 07.00–18.00 GMT); and 151 working days included in the sample. However, profitable arbitrage opportunities neither occur every hour in our sample nor in both directions. Thus, N_y is expected to be much lower than 13,288. Each observation of IQ in the regressions for a specific currency pair would be equal to the average time between all of the (profitable and non-profitable) deviations used when calculating the corresponding observations for that frequency. Similarly, each observation of *DiffImplVol* for frequency for a specific currency pair would be equal to the difference between the maximum implied volatility and the minimum implied volatility for all of the (profitable and non-profitable) deviations used when calculating the corresponding observations for that frequency.

The y-variable *Size* measures the average return of profitable deviations in a profitable cluster, while *Duration* refers to the time a profitable cluster lasts. The IQ variable in the regressions for *Size* and *Duration* refers to the average time between the row of profitable deviations constituting a profitable cluster, whereas the variable *DiffImplVol* refers to the corresponding difference between the maximum implied volatility and the minimum implied volatility within each cluster. For a given form of arbitrage, the total number of observations used in a regression for size or duration for a currency pair would be equal to all profitable clusters for that currency pair.

The results from estimating regression (11) for frequency, size and duration, for all three currency pairs and no-arbitrage conditions, are given in Table 8. The results suggest that these characteristics of one-way arbitrage opportunities tend to vary with the pace of the market, as proxied by the inter-quote time, and with the variability of volatility, as proxied by the difference between the maximum implied volatility and the minimum implied volatility. In particular, frequency, size and duration are positively related both to IQ, i.e. negatively related to the market pace, and to *DiffImplVol*, i.e. positively related to variability of volatility. There are several cases where IQ does not enter the regression with a statistically significant coefficient. However, the results are particularly clear-cut in the case of *DiffImplVol*–in terms of obtaining statistically significant positive coefficients in each case. This suggests that when markets are particularly active, as described by a high number of new quotes per unit of time, and when the degree of uncertainty is relatively stable, we should observe fewer, smaller and more short-lived one-way arbitrage opportunities.

5.3. Discussion

Our analysis suggests that LOP violations reported are genuine one-way arbitrage opportunities which traders may have been able to exploit at the time of their occurrence. In practice, one-way arbitrage only requires two virtually simultaneous deals. A dealer able to undertake the two deals simultaneously, i.e. in a position to complete the required transactions at the prices implying OA or BA, will be able to obtain higher return or lower costs, respectively, through one-way arbitrage. The shares of OA and BA arbitrage are significantly higher than those observed for CIP arbitrage in Akram, Rime and Sarno (2008) and are therefore consistent with the implied relation between CIP, OA and BA discussed in Section 2.

Yet, we argue that the observed LOP violations are due to microstructure features of the FX market, as in other instances of LOP violations in financial markets (Lamont and Thaler, 2003).[12] In the following, we would like to refer to some pricing and trading practices in financial markets that can contribute to violations of the LOP, and relate these to the results provided in this section. In general, an infinite price elasticity of supply of and/or demand for funds can instantaneously eliminate deviations from the LOP. However, the lack of any clear pattern in Tables 6 and 7 suggests that FX and money markets are, to some extent, segmented. Such segmentation may lead to finite price elasticity of supply and/or demand in the separate markets. In the present context, under finite price elasticity, differences between the price of a money market security and that of a derived/synthetic security which would depend on two separate security markets– FX and money market–may arise frequently since the two markets will be governed by own supply and demand conditions (liquidity) and own speed (relatively faster in the FX market).[13] The relation between arbitrage characteristics and market pace and

[12] Quoting Lamont and Thaler (2003, p. 191): "The Law states that identical goods must have identical prices. [...] Economic theory teaches us to expect the Law to hold exactly in competitive markets with no transactions costs and no barriers to trade, but in practice, details about market institutions are important in determining whether violations of the Law can occur."

[13] Recall that one-way arbitrage requires excess supply of (desire to lend) or demand for (desire to

volatility in Table 8 suggests that time-variation in liquidity may be an important factor for understanding temporary deviations from the LOP.

Segmentation and finite price elasticity may also be due to a well-known feature of price setting in financial markets which may explain why prices may not adjust sufficiently to restore the LOP, namely inventory management through quote shading. That is, the apparent "mispricing" could partly reflect deliberate actions of well-informed rational dealers who actively manage their inventories of financial assets through their price setting, as is well known from the microstructure literature on quote shading (e.g. Garman, 1976; O'Hara, 1995). Accordingly, dealers acting as market makers may deliberately provide ask and bid quotes that are lower than the corresponding no-arbitrage quotes if they want to reduce their inventories, or provide relatively higher ask and bid quotes if they want to increase their inventories. This explanation of the apparent mispricing is not implausible given that a substantial share of trading in financial markets, and especially in the inter-dealer markets, is aimed at controlling inventories (e.g. Lyons, 2001; Bjønnes and Rime, 2005).

Another possible explanation of the observed deviations could be due to the heterogeneity of prices facing market participants. Specifically, market participants, especially those in the money markets, may face different prices that depend on their institutions' credit rating and the volumes traded. Hence, observed quotes for instruments traded directly and those used to derive similar instruments could refer to quotes facing different market participants. Unfortunately, an examination of this hypothesis does not seem to be feasible as it requires knowledge of quotes that individual dealers face over time.

Finally, if some market participants have different trading objectives than to lower the cost of borrowing or earn extra yield, one may also observe violations of the LOP. There is little evidence that treasury departments of big corporations *actively* participate in money and FX markets. Such markets are largely dominated by individual FX and

borrow) funds, in contrast with round-trip arbitrage which requires no own funds or borrowing needs.

money market desks whose capital is turned over fast with the objective of not having excess funding or borrowing needs and is used to support active trading, or 'scalping' the higher spreads faced by the broader corporate institutional market relative to those in the inter-dealer market. This interpretation of the economics of one-way arbitrage suggests that it is plausible that most dealers do not actively engage in cost minimization or yield maximization (i.e. one-way arbitrage) and this is perhaps one reason why we observe relatively high shares of OA and BA deviations. It is reasonable to expect that the development and increasing practice of algorithmic trading in recent years will make the one-way arbitrage deviations observed here more rare and short-lived.

6. Conclusions

We have employed high quality data for the major foreign exchange and money markets to investigate whether the law of one price holds for lending and borrowing services. This law implies that the domestic lending (borrowing) interest rate should be the same as the foreign lending (borrowing) interest rate when the latter is adjusted to fully hedge for exchange rate risk. Violations of the law of one price would not imply riskless profits, just that it is possible to reduce borrowing costs (net of transaction costs) by, e.g., borrowing abroad while covering the exchange rate risk through a forward contract. And that one can earn higher returns on given funds by, e.g., investing abroad while covering the exchange rate risk through a forward contract.

We report that the law of one price holds on average, while finance theory postulates that it holds continuously. We observe that substantial shares of deviations from the law of one price are profitable. The profits per unit of base currency borrowed or invested often vary in the range of 2 to 6 pips, which can be considered economically significant. Moreover, the average duration of profitable deviations from the law of one price for both lending and borrowing services is mostly around 5 minutes. Such a duration of arbitrage opportunities is low enough to suggest that markets are quite efficient and do not allow arbitrage opportunities to persist. Yet, their duration is on average high enough to enable agents to exploit deviations from the law of one price and thereby contribute to the efficiency of the markets.

Violations of the law of one price appear to increase with market volatility but decline with market activity. It follows that one-way arbitrage opportunities may differ across markets depending on their liquidity and volatility. An investigation of how arbitrage opportunities could be removed has revealed that none of the instrument quotes are set such as to eliminate fully a given deviation from the law of one price. Thus, it seems that all of the instruments are likely to change in response to a given deviation and contribute to eliminate it. In particular, these results do not support the conjecture that instrument quotes are based on the law of one price using the latest available quotes.

The substantial number of violations of the law of one price suggest short-lived mispricings, but can also be partly explained by deliberate actions of well informed rational agents operating within the given structures of the money and foreign exchange markets. We have alluded to some possible explanations in the light of the microstructure literature, but further investigation of the sources of the deviations from the law of one price in international financial markets detected here remains an avenue for future research.

A. Appendix: Details on Calculations and Transaction Costs

A.1. Calculating Days to Maturity (D)

We adjust interest rates, which are quoted in per cent per annum, by $D/360$ or $D/365$ to obtain interest rates for a period of less than a year. By convention, 365 refers to the total number of days in a year for a Commonwealth country, while 360 refers to the number of total days for other countries. D is the actual number of business days between the (spot) value date and the maturity date, which is generally the same date as the value date but in a different month.[14]

For almost all securities the value date falls on the second business day after the day of trading. The exception is the Eurosterling interest rate where the value date is the same as the trade date. Consequently, the maturity date of a sterling security that is traded on the same date as, e.g., a dollar security would, generally differ by two days. In order to ensure that both securities mature on the same day, dealers borrow or lend a sterling security forward with maturity on the value date of the other currency. Such deals are made through direct contact between dealers and, hence, do not generate transaction costs payable to Reuters.

A.2. Transaction Costs: Brokerage Fees and Settlement Costs

There are two types of variable transaction costs associated with trading in the FX market, in addition to those captured by ask-bid spreads: brokerage fees and settlement costs. In our case, the brokerage fees refer to the costs of trading swap contracts through the Reuters electronic broking system, Reuters Dealing 3000. At present, the Reuters system does not allow for trading of deposits in the security markets. Such trading is conducted via direct contact between dealers or through voice brokers. The variable broker costs of trading in deposits may therefore be assumed to be zero. Settlement costs, however, are incurred on trades of both swap contracts and deposits.

[14] Exceptionally, if the maturity date is a holiday in the home country of a security, the maturity date becomes the first business day after that holiday. If the value date is the last business day in a month, the maturity date will also be the last business day but in a different month. This is commonly referred to as the "end-of-month end-of-month rule." For swap contracts, the value date and the maturity date must not be a holiday in the US and in the home countries of the quoting and the base currencies. We took holidays, i.e. days that are not settlement dates, for the different currencies from Bloomberg to account for this convention.

The brokerage fee is paid by the initiator of a trade (aggressor) at the end of a month in the Reuters trading system for swaps. Such fees increase with the maturity of a traded swap contract, but are inversely related to the total volume traded by the aggressor in a month. Table A.1 presents a recent fee schedule for Reuters dealing system, where we report deal fees charged when dealing swaps through Reuters Dealing 3000. When a volume band has been reached, the (lower) deal fee per million (mill) USD in the subsequent band is applied to the total volume. It appears that a small trader with a total trade volume of 1 billion (bn) USD or less incurs a fee of at most 10 USD for a trade of 1 mill USD at maturities of one month to one year (inclusive). If one trades more than 5 bn a month in this maturity range, the fee falls to 5 USD for a trade of 1 mill USD.

Table A.1. Schedule of fees in Reuters dealing system for swap contracts

Total volume per month in USD	Costs per million USD
$< 0 - 1bn]$	10
$< 1bn - 2bn]$	9
$< 2bn - 3bn]$	8
$< 3bn - 4bn]$	7
$< 4bn - 5bn]$	6
$< 5bn - 10bn]$	5
$< 10bn- >$	5

Source: Reuters on request of the authors in 2004.

The brokerage fee per unit of a base currency becomes negligible since the electronic dealing/matching system of Reuters places restrictions on the minimum size of a currency trade. Moreover, it is only possible to trade multiples of the minimum quantity of a currency. The matching system does not accept trading orders that violate these restrictions. Deposits, however, do not face such restrictions on quantity traded as they are traded at other venues, e.g. at Reuters direct dealing system (Reuters D2000-1).

Table A.2 presents the minimum trading size for four currencies, where the euro, US dollar and UK sterling are base currencies. We note that the minimum quantity of swaps that is tradable in Reuters is 10 mill of the base currency. The brokerage fee per unit of a currency, therefore, becomes negligible.[15]

[15]Restrictions on traded quantity are generally provided in the base currency. The requirement refers

Table A.2. Minimum tradable quantity of swaps in base currency

Currency pair	Minimum tradable volume
USD/EUR	10 mill €
JPY/USD	10 mill $
USD/GBP	10 mill £
USD/GBP	5 mill £ when 1 year

Source: Reuters on request of the authors in 2004.

The settlement costs are associated with messages/notices that are sent to counterparts of a trade. In our case, a trade is settled and implemented through the SWIFT (Society for Worldwide Interbank Financial Telecommunication) network. There are three notices associated with each transaction: notice of confirmation, payment instructions and notice of incoming payments. Confirmation of a deal is sent to both sides of the deal on the trading date. This is followed by payment instructions to the banks where both parties have accounts that will be debited. Finally, a notice of incoming payments may be sent to the banks where both parties want the incoming payments to be credited.

The cost of a notice is $14 - 28$ cents and is the same for transactions in the FX and security markets. The cost does not depend on the venue of trading, i.e. it is the same for trading directly or via a broker (voice or electronic). Thus each party incurs a total cost of $0.42 - 0.84$ cents for the three messages per transaction. These costs are charged at the end of each month. SWIFT invoices its customers either in dollars or euros, depending on the country in which the customer is located irrespective of the invoicing address.[16]

An arbitrage deal using a currency swap leads to three transactions, one in the FX market and two in the security markets, and thus for a total of 9 ($= 3 \times 3$) notices. Hence, the total (variable) settlement costs vary in the range of $1.26 - 2.52$ ($= 3 \times 0.42 - 3 \times 0.84$) USD. In extraordinary situations, a trade may require more than three notices and, therefore, entail higher costs.

Overall, even the total of variable transaction costs (brokerage fees and settlement costs) per unit of a base currency becomes negligible. For example, the sum of brokerage

to swaps with maturity of one month to one year (inclusive), except in the case of GBP.

[16]Customers located in the Americas and in Asia are in principle invoiced in dollars. All other customers are invoiced in euros. Where fees are denominated in another currency, they are converted to dollars or euros at the market spot selling rate at 15.00 Belgian time at the end of the period for which the invoice is issued.

fee and settlement costs of a minimum-size swap of 10 mill USD of, e.g., maturity one month to one year (inclusive), would at most be $(10 \times 10 + 0.84) = 100.84$ USD, i.e. 10.084 per 1 mill USD or about 1/10 of a pip per USD. If we add the SWIFT costs associated with lending and borrowing, the total cost associated with an arbitrage deal involving a minimum-size swap, would still be about 1/10 of a pip, or more precisely $(100.84 + 2 \times 0.84) = 10.252$ per 1 mill USD or 0.1025 of a pip per USD.

References

Akram, Q.F., Rime, D., Sarno, L., 2008. Arbitrage in the foreign exchange market: Turning on the microscope. Journal of International Economics, forthcoming.

Bjønnes, G.H., Rime, D., 2005. Dealer behavior and trading systems in the foreign exchange market. Journal of Financial Economics 75, 571–605.

Callier, P., 1981. One way arbitrage, foreign exchange and security markets: A note. Journal of Finance 36, 1177–1186.

Danielsson, J., Payne, R., 2002. Liquidity determination in an order driven market. Typescript, Financial Markets Group, London School of Economics.

Deardorff, A.V., 1979. One-way arbitrage and its implications for the foreign exchange markets. Journal of Political Economy 87, 351–364.

Fuertes, A.-M., Thomas, D.C., 2006. Large market shocks and abnormal closed-end-fund price behaviour. Journal of Banking and Finance 30, 2517–2535.

Garman, M., 1976. Market microstructure. Journal of Financial Economics 3, 257–275.

Grossman, S.J., Stiglitz, J.E., 1976. Information and competitive price systems. American Economic Review 66, 246–252.

Grossman, S.J., Stiglitz, J.E., 1980. On the impossibility of informationally efficient markets. American Economic Review 70, 393–407.

Hutchinson, M., Gallagher, L.A., 2008. Simulating convertible bond arbitrage portfolios. Applied Financial Economics 18, 1247–1262.

Kim, Y., Lee, B.S., 2007. Limited participation and the closed-end fund discount. Journal of Banking and Finance 31, 381–399.

Lamont, O.A., Thaler, R.H., 2003. The law of one price in financial markets. Journal of Economic Perspectives 17, 191–202.

Lyons, R.K., 2001. The Microstructure Approach to Exchange Rates. MIT Press, Cambridge MA.

Lyons, R.K., Moore, M., 2005. An information approach to international currencies. Working Paper 11220, NBER.

Nikolaou, K., 2008. The behaviour of the real exchange rate: Evidence from regression quantiles. Journal of Banking and Finance 32, 664–679.

O'Hara, M., 1995. Market Microstructure Theory. Blackwell Publishers, Oxford UK.

Reuters, 1999. An Introduction to Foreign Exchange & Money Markets. Reuters Financial Training Series, Wiley, Singapore and New York.

Sarno, L., 2005. Towards a solution to the puzzles in exchange rate economics: Where do we stand? Canadian Journal of Economics 38, 673–708.

Sarno, L., Taylor, M.P., Chowdhury, I., 2004. Nonlinear dynamics in deviations from the law of one price: A broad-based empirical study. Journal of International Money and Finance 23, 1–25.

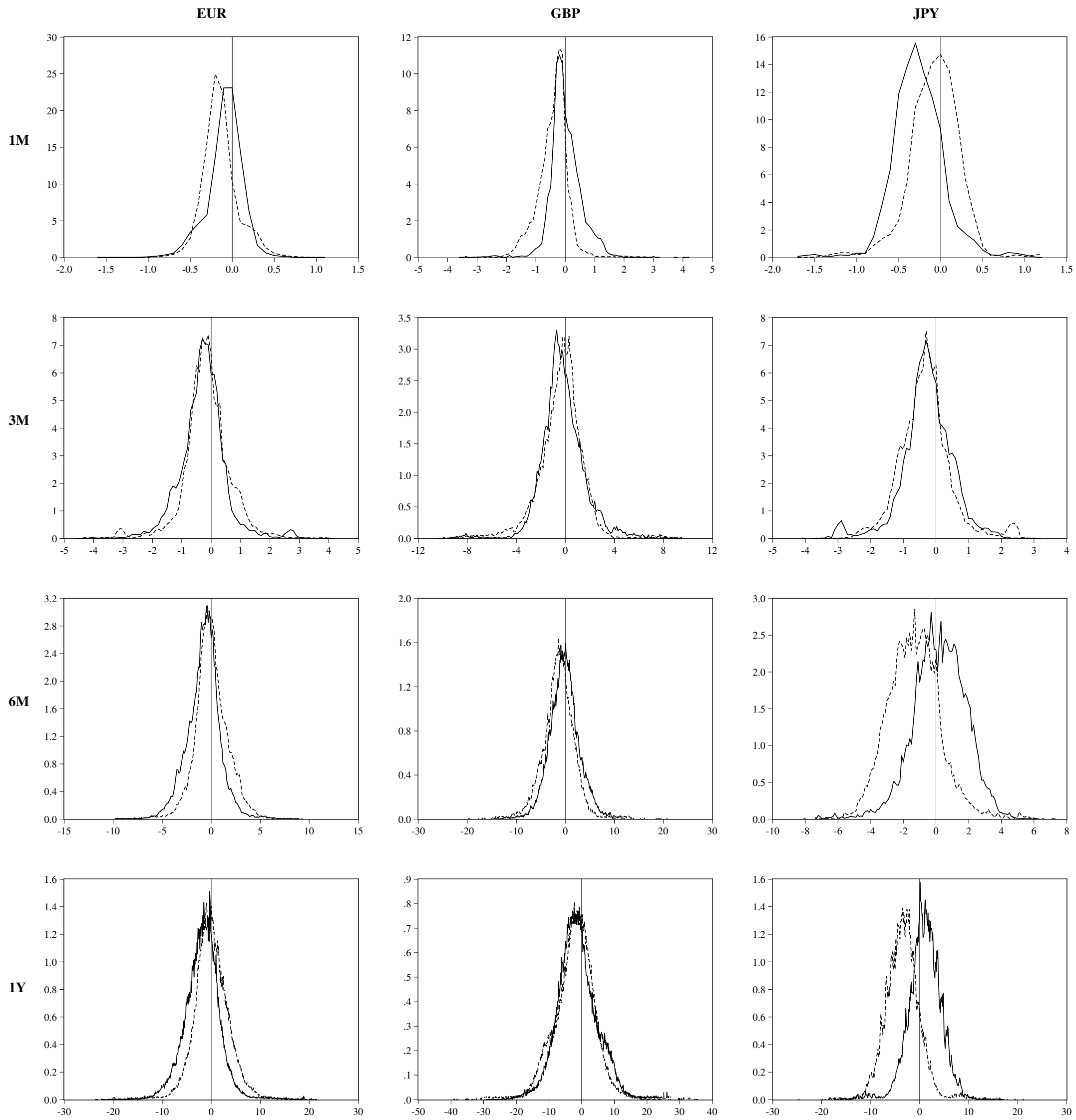
Sarno, L., Valente, G., 2006. Deviations from purchasing power parity under different exchange rate regimes: Do they revert and, if so, how? Journal of Banking and Finance 30, 3147–3169.

Shleifer, A., Vishny, R., 1997. The limits of arbitrage. Journal of Finance 52, 35–55.

Taylor, A.M., 2001. Potential pitfalls for the purchasing-power-parity puzzle? Sampling and specification biases in mean-reversion tests of the law of one price. Econometrica 69, 473–498.

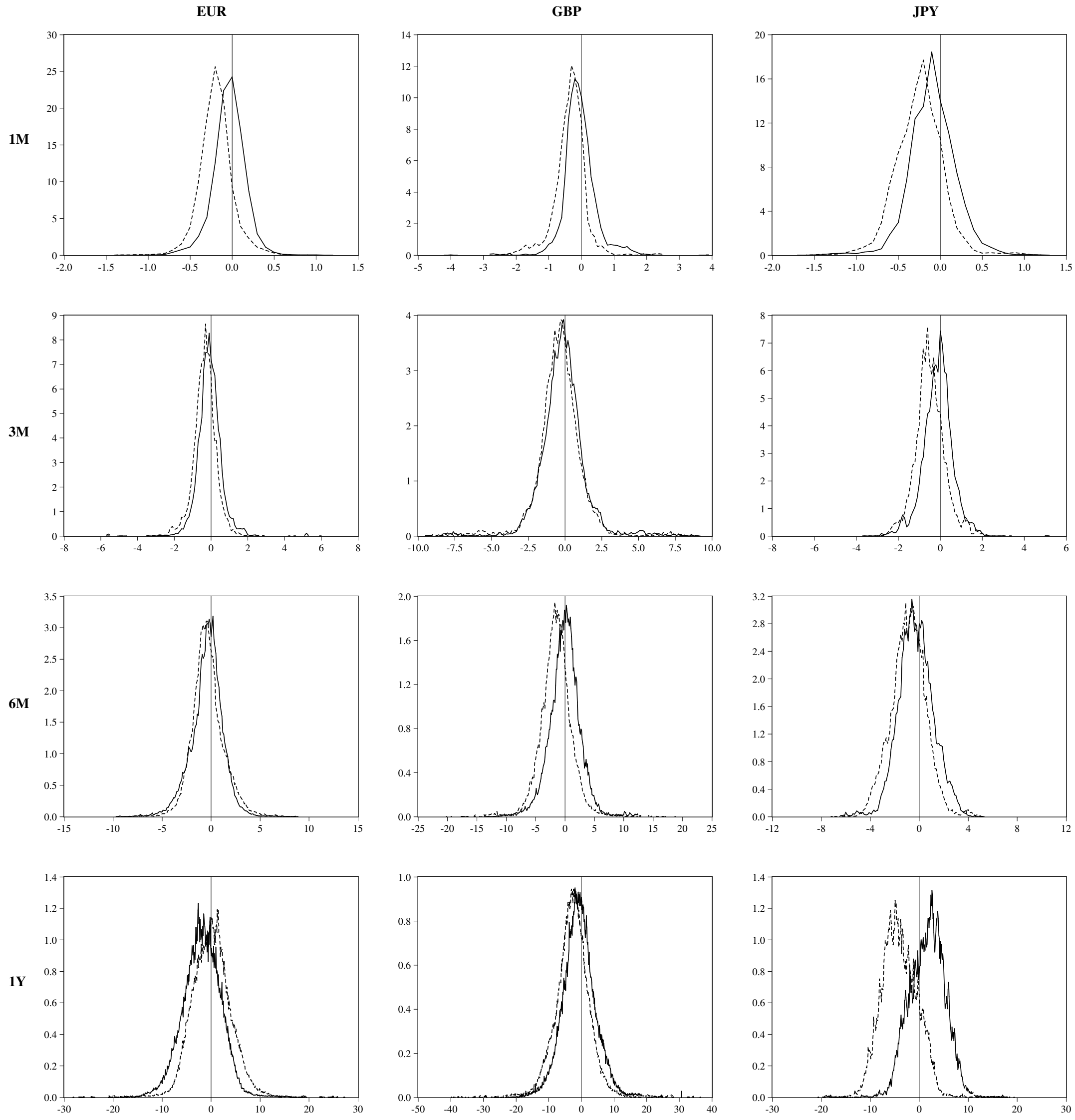
Taylor, M.P., 1987. Covered interest parity: A high-frequency, high-quality data study. Economica 54, 429–438.

Figure 1: Frequency of Owner Arbitrage (OA) deviations



Note: Each graph shows the frequency (in percent, vertical axis) of deviations at the bid (dashed line) and the ask (solid line) within bins of 1/10 of a pip (horizontal axis).
Sample: Based on Reuters tick quotes. February 13 – September 30, 2004, weekdays, between GMT 07:00 and 18:00. The following dates have been removed: April 2, 5–9, 12, May 3 and 31, June 17 and 18, August 10, 13, 24, and September 15.

Figure 2: Frequency of Borrower Arbitrage (BA) deviations



Note: Each graph shows the frequency (in percent, vertical axis) of deviations at the bid (dashed line) and the ask (solid line) within bins of 1/10 of a pip (horizontal axis).
Sample: Based on Reuters tick quotes. February 13 – September 30, 2004, weekdays, between GMT 07:00 and 18:00. The following dates have been removed: April 2, 5–9, 12, May 3 and 31, June 17 and 18, August 10, 13, 24, and September 15.

Table 1: Relationships between CIP, OA and BA

I. CIP Pa in d (f) $\Longrightarrow$ OA Pa in d (f)
$(1+i_d^a) \leq 1/S^a(1+i_f^b)F^b \Longrightarrow (1+i_d^b) \leq 1/S^a(1+i_f^b)F^b$
$(1+i_f^a) \leq S^b(1+i_d^b)/F^a \Longrightarrow (1+i_f^b) \leq S^b(1+i_d^b)/F^a$
II. OA not Pa in d (f) $\Longrightarrow$ CIP not Pa in d (f)
$(1+i_d^b) \geq 1/S^a(1+i_f^b)F^b \Longrightarrow (1+i_d^a) \geq 1/S^a(1+i_f^b)F^b$
$(1+i_f^b) \geq S^b(1+i_d^b)/F^a \Longrightarrow (1+i_f^a) \geq S^b(1+i_d^b)/F^a$
III. CIP Pa in d (f) $\Longrightarrow$ BA not Pa in d (f)
$(1+i_d^a) \leq 1/S^a(1+i_f^b)F^b \Longrightarrow (1+i_d^a) \leq 1/S^b(1+i_f^a)F^a$
$(1+i_f^a) \leq S^b(1+i_d^b)/F^a \Longrightarrow (1+i_f^a) \leq S^a(1+i_d^a)/F^b$
IV. CIP Pa in d (f) $\Longrightarrow$ BA Pa in f (d)
$(1+i_d^a) \leq 1/S^a(1+i_f^b)F^b \Longrightarrow (1+i_d^b) \leq 1/S^a(1+i_f^a)F^b$
$(1+i_f^a) \leq S^b(1+i_d^b)/F^a \Longrightarrow (1+i_f^b) \leq S^b(1+i_d^a)/F^a$

Note: "CIP" refers to Covered Interest Parity (round-trip) arbitrage; "OA" to Owner Arbitrage; "BA" to Borrower Arbitrage arbitrage; while "Pa" denotes profitable arbitrage opportunity. The letters "d" and "f" denotes domestic and foreign currency, respectively. Foreign currency is the base currency. Superscripts "a" and "b" denotes ask and bid prices. Case I is read as follows: CIP-arbitrage profitable in the domestic (foreign) currency implies OA-arbitrage profitable in the domestic (foreign) currency.

Table 2: Base and quoting currencies

Exchange rates	Quoting currency (d)	Base currency (f)	Notation used
USD/EUR	USD	EUR	EUR
USD/GBP	USD	GBP	GBP
JPY/USD	JPY	USD	JPY

Note: The "base currency" is the currency being priced in units of another currency, which would be the "quoting currency". The base and quoting currencies correspond to the foreign (f) and the domestic (d) currencies in the formulas. The final column shows the notation used in the paper for the three exchange rates (in the first column).

Table 3: Owner Arbitrage (OA). Descriptive statistics of deviations

Exchange rate			a) All deviations			b) Profitable deviations				c) Only "fresh" quotes		
			All dev.	Mean	t-value	Pa dev.	Share	Mean	Interquote time (sec)	"Fresh" obs.	Pa dev.	Share
EUR	1M	Ask	2,037,923	-0.04	-0.2	474,531	23.29 %	0.20	3.1	54,864	15,850	28.89 %
		Bid	2,037,923	-0.09	-0.4	299,880	14.71 %	0.28	2.9	54,864	10,769	19.63 %
	3M	Ask	2,068,143	-0.21	-0.3	608,649	29.43 %	0.64	2.9	80,001	26,965	33.71 %
		Bid	2,068,143	-0.10	-0.1	733,902	35.49 %	0.65	2.9	79,999	30,398	38.00 %
	6M	Ask	2,309,197	-0.73	-0.4	676,992	29.32 %	1.13	2.6	356,611	107,232	30.07 %
		Bid	2,309,197	0.11	0.1	1,083,080	46.90 %	1.47	2.5	356,612	173,484	48.65 %
	1Y	Ask	2,560,419	-1.72	-0.5	720,110	28.12 %	2.42	2.4	564,772	169,266	29.97 %
		Bid	2,560,419	0.05	0.0	1,232,302	48.13 %	2.88	2.3	574,180	285,742	49.77 %
GBP	1M	Ask	2,445,312	0.06	0.1	1,003,961	41.06 %	0.54	2.5	17,076	2,971	17.40 %
		Bid	2,445,312	-0.36	-0.7	284,005	11.61 %	0.43	2.4	19,302	4,415	22.87 %
	3M	Ask	2,450,660	-0.13	-0.1	967,976	39.50 %	1.51	2.5	40,206	13,645	33.94 %
		Bid	2,450,660	-0.28	-0.1	1,043,822	42.59 %	1.19	2.4	43,444	20,906	48.12 %
	6M	Ask	2,594,610	-0.03	-0.0	1,197,581	46.16 %	2.62	2.2	158,986	67,659	42.56 %
		Bid	2,594,610	-1.43	-0.4	788,979	30.41 %	2.00	2.4	178,113	59,291	33.29 %
	1Y	Ask	2,746,288	-1.05	-0.2	1,039,570	37.85 %	5.28	2.1	329,914	120,542	36.54 %
		Bid	2,746,288	-2.30	-0.3	993,183	36.16 %	3.78	2.2	374,132	141,128	37.72 %
JPY	1M	Ask	804,885	-0.21	-0.7	89,514	11.12 %	0.34	8.6	89	62	69.66 %
		Bid	804,885	-0.02	-0.1	275,863	34.27 %	0.27	6.2	93	4	4.30 %
	3M	Ask	818,537	-0.23	-0.3	251,775	30.76 %	0.61	7.3	146	116	79.45 %
		Bid	818,537	-0.26	-0.3	204,335	24.96 %	0.74	7.2	149	-	0.00 %
	6M	Ask	838,047	0.27	0.2	458,687	54.73 %	1.43	6.8	111	92	82.88 %
		Bid	838,047	-1.28	-0.8	140,145	16.72 %	1.17	8.0	116	11	9.48 %
	1Y	Ask	892,242	1.08	0.3	572,882	64.21 %	2.98	6.8	4,868	3,585	73.64 %
		Bid	892,242	-3.32	-1.0	116,788	13.09 %	2.52	6.3	4,875	418	8.57 %

Note: The column headed by "All dev." in panel *a*) presents the number of all profitable and non-profitable deviations (cf. definitions in Table 1), while the column "Fresh obs." in panel *c*) presents the same using only "fresh" (non-stale) quotes. We consider a quote of an instrument as *stale* if it occurs in an inactive state of the market, more precisely that the quote has not changed within the last two minutes, and does not change within the next two minutes. When calculating deviations from OA and BA we require that the quotes of *all* instruments involved in an arbitrage opportunity are fresh, i.e. are not stale according to the above definition. The columns headed by "Pa dev." in panels *b*) and *c*) record the number of the profitable deviations, i.e. deviations that are larger than 1/10 of a pip. Panel *b*) show such deviations out of all deviations in panel *a*) ("All dev."), while panel *c*) shows such deviations out of the possible cases in column "Fresh obs.". Entries in the "Share" columns in panels *b*) and *c*) are profitable deviations in percents of all possible cases from panels *a*) and *c*), respectively. The "Mean" columns present the average sizes of the deviations, measured in pips. The "*t*-value[s]" are the (period) mean values divided by their respective sample standard deviations. The "Inter-quote time (sec)" column in panel *b*) presents the average time in seconds from the previous deviation, conditioned on the current deviation being profitable.
Sample: Based on Reuters tick quotes. February 13 – September 30, 2004, weekdays, between GMT 07:00 and 18:00. The following dates have been removed: April 2, 5–9, 12, May 3 and 31, June 17 and 18, August 10, 13, 24, and September 15. Only "fresh" quotes are used in panel *c*).

Table 4: Borrower Arbitrage (BA). Descriptive statistics of deviations

Exchange rate			a) All deviations			b) Profitable deviations				c) Only "fresh" quotes		
			All dev.	Mean	t-value	Pa dev.	Share	Mean	Interquote time (sec)	"Fresh" obs.	Pa dev.	Share
EUR	1M	Ask	2,037,923	0.01	0.1	621,115	30.48 %	0.22	2.9	54,790	19,508	35.61 %
		Bid	2,037,923	-0.14	-0.7	172,451	8.46 %	0.24	3.0	54,790	6,700	12.23 %
	3M	Ask	2,068,143	-0.01	-0.0	812,189	39.27 %	0.58	2.9	80,937	35,437	43.78 %
		Bid	2,068,143	-0.31	-0.4	466,835	22.57 %	0.47	2.9	80,935	18,862	23.31 %
	6M	Ask	2,309,197	-0.37	-0.2	916,229	39.68 %	1.10	2.5	358,533	152,196	42.45 %
		Bid	2,309,197	-0.26	-0.2	838,837	36.33 %	1.39	2.5	358,534	129,952	36.25 %
	1Y	Ask	2,560,419	-1.74	-0.4	798,025	31.17 %	2.66	2.3	564,010	202,443	35.89 %
		Bid	2,560,419	0.08	0.0	1,286,227	50.24 %	3.14	2.3	573,363	269,926	47.08 %
GBP	1M	Ask	2,445,312	-0.01	-0.0	869,166	35.54 %	0.47	2.5	17,058	5,327	31.23 %
		Bid	2,445,312	-0.29	-0.6	325,846	13.33 %	0.42	2.4	19,284	1,924	9.98 %
	3M	Ask	2,450,660	-0.10	-0.0	1,022,279	41.71 %	1.17	2.4	40,542	16,307	40.22 %
		Bid	2,450,660	-0.32	-0.2	864,150	35.26 %	1.08	2.5	43,780	16,488	37.66 %
	6M	Ask	2,594,610	0.08	0.0	1,286,415	49.58 %	2.13	2.3	159,746	73,616	46.08 %
		Bid	2,594,610	-1.54	-0.5	614,680	23.69 %	1.75	2.3	179,055	50,082	27.97 %
	1Y	Ask	2,746,288	-0.48	-0.1	1,170,922	42.64 %	4.25	2.2	330,374	133,186	40.31 %
		Bid	2,746,288	-2.88	-0.5	736,587	26.82 %	3.17	2.2	374,679	116,713	31.15 %
JPY	1M	Ask	804,885	-0.04	-0.1	224,944	27.95 %	0.28	9.5	83	49	59.04 %
		Bid	804,885	-0.20	-0.7	87,679	10.89 %	0.27	7.1	87	-	0.00 %
	3M	Ask	818,537	-0.08	-0.1	332,831	40.66 %	0.56	8.3	136	53	38.97 %
		Bid	818,537	-0.42	-0.5	158,389	19.35 %	0.65	6.4	139	41	29.50 %
	6M	Ask	838,047	-0.21	-0.1	339,893	40.56 %	1.16	7.1	95	56	58.95 %
		Bid	838,047	-0.80	-0.6	212,646	25.37 %	0.96	6.5	100	-	0.00 %
	1Y	Ask	892,242	1.71	0.4	606,464	67.97 %	3.67	6.7	3,784	2,894	76.48 %
		Bid	892,242	-3.95	-1.1	127,668	14.31 %	2.00	6.6	3,791	293	7.73 %

Note: The column headed by "All dev." in panel *a*) presents the number of all profitable and non-profitable deviations (cf. definitions in Table 1), while the column "Fresh obs." in panel *c*) presents the same using only "fresh" (non-stale) quotes. We consider a quote of an instrument as *stale* if it occurs in an inactive state of the market, more precisely that the quote has not changed within the last two minutes, and does not change within the next two minutes. When calculating deviations from OA and BA we require that the quotes of *all* instruments involved in an arbitrage opportunity are fresh, i.e. are not stale according to the above definition. The columns headed by "Pa dev." in panels *b*) and *c*) record the number of the profitable deviations, i.e. deviations that are larger than 1/10 of a pip. Panel *b*) show such deviations out of all deviations in panel *a*) ("All dev."), while panel *c*) shows such deviations out of the possible cases in column "Fresh obs.". Entries in the "Share" columns in panels *b*) and *c*) are profitable deviations in percents of all possible cases from panels *a*) and *c*), respectively. The "Mean" columns present the average sizes of the deviations, measured in pips. The "*t*-value[s]" are the (period) mean values divided by their respective sample standard deviations. The "Inter-quote time (sec)" column in panel *b*) presents the average time in seconds from the previous deviation, conditioned on the current deviation being profitable.
Sample: Based on Reuters tick quotes. February 13 – September 30, 2004, weekdays, between GMT 07:00 and 18:00. The following dates have been removed: April 2, 5–9, 12, May 3 and 31, June 17 and 18, August 10, 13, 24, and September 15. Only "fresh" quotes are used in panel *c*).

Table 5: Owner Arbitrage (OA) and Borrower Arbitrage (BA): Duration of profitable clusters (in minutes)

Exchange rate			Owner Arbitrage						Borrower Arbitrage					
			# Clusters	Mean	Stdev	Median	Q1	Q3	# Clusters	Mean	Stdev	Median	Q1	Q3
EUR	1M	Ask	8,052	3:01	8:25	1:05	0:21	2:49	9,159	3:18	9:08	1:11	0:22	3:07
		Bid	4,805	3:00	6:17	1:15	0:22	3:36	3,699	2:20	5:52	0:56	0:19	2:29
	3M	Ask	10,588	2:45	9:12	0:47	0:18	2:19	11,986	3:15	10:25	0:49	0:18	2:47
		Bid	11,001	3:09	7:15	0:59	0:17	3:27	9,114	2:26	5:42	0:51	0:17	2:30
	6M	Ask	18,716	1:34	4:15	0:32	0:13	1:30	20,550	1:52	4:19	0:36	0:14	1:50
		Bid	21,616	2:05	4:57	0:41	0:14	2:06	18,133	1:56	4:46	0:38	0:14	1:58
	1Y	Ask	25,616	1:06	3:08	0:20	0:08	0:57	24,522	1:13	2:47	0:22	0:08	1:10
		Bid	33,746	1:22	3:20	0:21	0:07	1:15	28,879	1:44	4:57	0:21	0:07	1:20
GBP	1M	Ask	6,287	6:39	24:50	1:19	0:23	3:48	7,566	4:42	18:48	0:53	0:21	3:00
		Bid	4,324	2:41	12:55	0:43	0:18	2:19	4,051	3:20	13:59	0:55	0:18	2:39
	3M	Ask	6,588	6:01	17:43	1:09	0:21	4:13	7,697	5:20	15:51	1:01	0:20	3:58
		Bid	7,664	5:28	15:05	1:40	0:25	5:44	7,435	4:44	16:21	1:17	0:20	4:00
	6M	Ask	18,654	2:21	7:11	0:35	0:14	1:44	20,927	2:19	7:13	0:34	0:13	1:41
		Bid	16,330	1:54	5:31	0:35	0:13	1:43	14,886	1:35	5:13	0:31	0:12	1:24
	1Y	Ask	20,708	1:45	4:48	0:28	0:12	1:21	23,786	1:45	5:04	0:28	0:12	1:20
		Bid	23,307	1:35	4:12	0:29	0:11	1:27	22,032	1:13	3:11	0:25	0:10	1:07
JPY	1M	Ask	2,075	5:59	22:32	2:16	0:51	5:47	3,365	10:27	32:38	2:33	1:03	7:28
		Bid	3,357	8:14	27:50	2:00	0:44	4:50	1,632	6:18	27:40	1:29	0:29	3:48
	3M	Ask	5,450	5:39	14:16	2:07	0:49	6:07	6,137	7:22	26:45	2:00	0:45	5:32
		Bid	4,247	5:33	19:46	1:19	0:26	3:44	2,863	5:47	21:13	1:12	0:27	3:43
	6M	Ask	7,317	7:12	20:47	2:33	0:52	6:55	7,452	5:18	16:22	1:49	0:37	4:31
		Bid	4,121	4:13	12:55	1:01	0:24	3:01	5,201	4:20	11:31	1:10	0:26	3:43
	1Y	Ask	11,831	5:30	17:36	1:29	0:30	5:06	8,747	7:41	28:54	1:19	0:27	4:16
		Bid	5,679	2:01	6:01	0:36	0:16	1:37	5,047	2:40	6:40	0:44	0:18	2:13

Note: A cluster consists of at least two profitable deviations from no-arbitrage in a row. The entries in the "Mean" columns denote the average duration (min:sec) of the clusters (based on the corresponding entries in the column "# Clusters"), while those in the "Median" columns refer to the median duration of the clusters. The "Q1" and "Q3" columns present the first and the third quantiles of the duration of clusters, respectively. The "Stdev" column includes sample standard deviations of the duration of the clusters.

Table 6: Profitable Owner Arbitrage (OA) opportunities induced exclusively by one instrument

			a) Swap		b) Spot		c) Foreign interest rate		d) Domestic interest rate	
Exchange rate			Pa dev.	Share	Pa dev.	Share	Pa dev.	Share	Pa dev.	Share
EUR	1M	Ask	38,655	23.40 %	426,277	23.34 %	3,067	24.91 %	3,134	17.20 %
		Bid	28,471	17.25 %	261,191	14.32 %	2,598	21.11 %	4,147	22.91 %
	3M	Ask	56,469	29.06 %	531,490	29.45 %	4,441	26.84 %	9,391	37.11 %
		Bid	69,032	35.62 %	636,319	35.32 %	7,545	45.64 %	9,716	38.37 %
	6M	Ask	130,488	29.13 %	512,972	29.45 %	10,450	27.48 %	8,123	26.22 %
		Bid	211,614	47.23 %	807,195	46.48 %	20,262	53.56 %	16,257	52.75 %
	1Y	Ask	175,338	26.58 %	483,268	28.73 %	13,403	26.93 %	11,607	28.85 %
		Bid	327,433	47.79 %	797,902	47.83 %	26,914	55.20 %	20,086	50.80 %
GBP	1M	Ask	24,875	38.52 %	806,146	40.31 %	2,823	21.61 %	9,338	47.82 %
		Bid	8,398	13.26 %	264,274	11.41 %	1,952	15.33 %	2,745	14.33 %
	3M	Ask	28,459	41.44 %	766,755	38.41 %	3,791	34.72 %	12,328	45.41 %
		Bid	27,151	40.32 %	985,917	42.64 %	4,996	46.30 %	11,011	41.57 %
	6M	Ask	108,060	45.40 %	903,699	46.54 %	8,803	43.92 %	14,719	41.82 %
		Bid	70,878	30.41 %	679,795	30.24 %	6,132	31.21 %	12,548	36.46 %
	1Y	Ask	151,031	37.17 %	724,700	37.70 %	10,200	35.42 %	17,171	37.37 %
		Bid	147,126	36.86 %	795,339	35.90 %	10,512	37.56 %	17,426	38.98 %
JPY	1M	Ask	6,678	11.77 %	75,777	10.75 %	3,141	15.76 %	188	8.86 %
		Bid	14,635	25.68 %	252,146	35.13 %	6,387	31.91 %	579	27.34 %
	3M	Ask	19,165	29.70 %	215,811	30.70 %	9,022	33.13 %	900	28.71 %
		Bid	15,823	24.51 %	176,584	24.68 %	9,635	35.36 %	812	25.81 %
	6M	Ask	41,792	55.98 %	378,954	54.18 %	21,234	57.86 %	1,940	50.36 %
		Bid	13,028	17.43 %	117,081	16.45 %	7,022	19.08 %	815	21.19 %
	1Y	Ask	76,932	65.42 %	443,973	64.02 %	30,046	62.76 %	3,667	61.37 %
		Bid	15,334	13.02 %	90,601	12.86 %	7,710	16.11 %	635	10.63 %

Note: The columns headed by “Pa dev.” present the number of all profitable deviations that are exclusively due to quote changes in only one instrument. Their numbers are a subset of the profitable deviations analyzed in Table 3. The columns headed by “Share” present the profitable deviations (owing exclusively to changes in the instrument in question) as shares of all the deviations when only one instrument changes quote.
Sample: Based on Reuters tick quotes. February 13 – September 30, 2004, weekdays, between GMT 07:00 and 18:00. The following dates have been removed: April 2, 5–9, 12, May 3 and 31, June 17 and 18, August 10, 13, 24, and September 15. Deviations are limited to those where only one of the instruments in the formula is quoted.

Table 7: Profitable Borrower Arbitrage (BA) opportunities induced exclusively by one instrument

			a) Swap		b) Spot		c) Foreign interest rate		d) Domestic interest rate	
Exchange rate			Pa dev.	Share	Pa dev.	Share	Pa dev.	Share	Pa dev.	Share
EUR	1M	Ask	49,235	29.81 %	557,841	30.54 %	4,918	39.94 %	4,627	25.39 %
		Bid	16,629	10.07 %	149,480	8.20 %	1,113	9.04 %	3,864	21.35 %
	3M	Ask	75,872	39.04 %	707,131	39.19 %	8,291	50.11 %	10,895	43.05 %
		Bid	43,669	22.53 %	406,312	22.55 %	3,081	18.64 %	6,741	26.62 %
	6M	Ask	181,357	40.49 %	686,017	39.39 %	19,532	51.36 %	9,682	31.25 %
		Bid	160,418	35.80 %	630,826	36.32 %	11,434	30.22 %	14,328	46.49 %
	1Y	Ask	200,629	30.42 %	524,432	31.18 %	22,816	45.84 %	9,689	24.08 %
		Bid	339,168	49.51 %	842,471	50.50 %	19,006	38.98 %	23,945	60.56 %
GBP	1M	Ask	20,379	31.55 %	668,925	33.45 %	5,223	39.97 %	6,866	35.16 %
		Bid	9,955	15.72 %	304,525	13.15 %	861	6.76 %	2,506	13.08 %
	3M	Ask	29,176	42.48 %	810,285	40.59 %	5,302	48.56 %	12,322	45.39 %
		Bid	22,988	34.14 %	815,582	35.28 %	3,088	28.62 %	9,727	36.72 %
	6M	Ask	114,672	48.18 %	967,754	49.84 %	10,930	54.54 %	14,842	42.17 %
		Bid	55,855	23.96 %	527,030	23.45 %	3,899	19.85 %	11,330	32.92 %
	1Y	Ask	170,666	42.01 %	817,382	42.53 %	13,219	45.90 %	17,451	37.98 %
		Bid	110,516	27.69 %	585,059	26.41 %	6,885	24.60 %	15,412	34.47 %
JPY	1M	Ask	21,825	38.45 %	190,267	26.98 %	6,467	32.44 %	972	45.78 %
		Bid	5,844	10.25 %	79,010	11.01 %	1,892	9.45 %	110	5.19 %
	3M	Ask	29,452	45.64 %	283,586	40.35 %	11,332	41.61 %	1,523	48.58 %
		Bid	10,206	15.81 %	138,771	19.39 %	8,029	29.47 %	493	15.67 %
	6M	Ask	28,886	38.69 %	282,208	40.35 %	18,144	49.44 %	1,618	42.00 %
		Bid	17,415	23.30 %	183,738	25.81 %	8,065	21.92 %	826	21.47 %
	1Y	Ask	78,967	67.15 %	468,603	67.58 %	33,646	70.28 %	4,655	77.91 %
		Bid	18,983	16.12 %	99,420	14.11 %	6,394	13.36 %	384	6.43 %

Note: The columns headed by "Pa dev." present the number of all profitable deviations that are exclusively due to quote changes in only one instrument. Their numbers are a subset of the profitable deviations analyzed in Table 4. The columns headed by "Share" present the profitable deviations (owing exclusively to changes in the instrument in question) as shares of all the deviations when only one instrument changes quote.
Sample: Based on Reuters tick quotes. February 13 – September 30, 2004, weekdays, between GMT 07:00 and 18:00. The following dates have been removed: April 2, 5–9, 12, May 3 and 31, June 17 and 18, August 10, 13, 24, and September 15. Deviations are limited to those where only one of the instruments in the formula is quoted.

Table 8: Effects of market pace and volatility on characteristics of arbitrage opportunities

		Owner Arbitrage (OA)			Borrower Arbitrage (BA)		
		EUR	GBP	JPY	EUR	GBP	JPY
a) Share	IQ time	0.0019	0.0000	0.0002	0.0007	0.0001	0.0002
		(4.37)	(0.21)	(1.71)	(3.19)	(1.00)	(2.12)
	DiffImpVol	3.8997	3.2249	1.7204	4.5776	3.8197	2.4495
		(9.18)	(11.94)	(3.17)	(11.09)	(11.40)	(9.17)
	Obs	5,688	5,470	4,304	5,810	5,471	4,354
b) Size	IQ time	0.0034	0.0015	0.0006	(0.0004)	0.0083	0.0007
		(2.06)	(0.94)	(0.86)	(-0.35)	(2.33)	(0.72)
	DiffImpVol	8.9786	18.4368	8.1620	7.5050	15.9539	7.8690
		(14.59)	(14.43)	(4.62)	(12.57)	(10.81)	(3.53)
	Obs	134,092	103,821	44,032	126,014	108,333	40,403
c) Duration	IQ time	8.05	0.76	3.75	5.94	3.56	3.93
		(5.41)	(1.14)	(8.78)	(7.71)	(3.34)	(10.33)
	DiffImpVol	5,107.0	12,455.2	17,881.7	6,077.1	11,372.8	22,655.4
		(12.64)	(10.05)	(10.37)	(10.58)	(8.95)	(9.54)
	Obs	134,092	103,821	44,032	126,014	108,333	40,403

Note: Panel *a*) reports estimation results for the relationship between share (frequency), and interquote time ("IQ time") and the difference between maximum implied volatility and minimum implied volatility ("DiffImpVol"). The dependent variable "Share" (frequency) is defined as the share of profitable deviations out of the total number of deviations in an business hour (containing profitable deviations) over the sample period, while "IQ time", measured in seconds, is the average time between all of the (profitable and non-profitable) deviations used when calculating the corresponding observation for the frequency. Panels *b*) and *c*) report estimation results for the relationships between the average size of profitable deviations (in pips) from clusters of profitable deviations and IQ-time and DiffImpVol, and duration of clusters of profitable deviations and IQ-time and DiffImpVol. A cluster consists of at least two profitable arbitrage opportunities in a row. The interquote time in the regressions for size and durations is the average time between the rows of profitable deviations constituting a profitable cluster. The coefficients have been estimated by OLS while their standard errors have been adjusted for clustering of errors based on business hours in panel *a*) and date in panels *b*) and *c*). The OLS estimates of the intercept terms (positive, and statistically significant at the 5% level in all cases) have not been reported for the sake of brevity. Associated t-values are reported in parenthesis below the coefficient estimates. The t-values are based on the adjusted standard errors. The rows "Obs" denotes the numbers of observations used in estimation.
Sample: Based on Reuters tick quotes. February 13 – September 30, 2004, weekdays, between GMT 07:00 and 18:00. The following dates have been removed: April 2, 5–9, 12, May 3 and 31, June 17 and 18, August 10, 13, 24, and September 15.

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