ANO 2005/12

Oslo
October, 2005

Working Paper

Research Department

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by

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ISSN 0801-2504 (printed) 1502-8143 (online)

ISBN 82-7553-328-7 (printed), 82-7553-329-5 (online)

Arbitrage in the Foreign Exchange Market: Turning on the Microscope*

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This version: October 2005

Abstract

This paper investigates the presence and characteristics of arbitrage opportunities in the foreign exchange market 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, obtained from Reuters on special order. We provide evidence on the frequency, size and duration of round-trip and one-way arbitrage opportunities in real time. The analysis unveils the existence of numerous short-lived arbitrage opportunities, whose size is economically significant across exchange rates and comparable across different maturities of the instruments involved in arbitrage. The duration of arbitrage opportunities is, on average, high enough to allow agents to exploit deviations from the law of one price, but low enough to explain why such opportunities have gone undetected in much previous research using data at lower frequency.

JEL classification: F31; F41; G14; G15.
Keywords: exchange rates; arbitrage; foreign exchange microstructure.

*__Acknowledgments:__ This work was partly undertaken when Lucio Sarno was a Visiting Scholar at Norges Bank. The authors are grateful to a number of people who kindly offered constructive comments at various stages of this paper, including Magnus Dahlquist, Martin Evans, Rich Lyons, Michael Melvin, Michael Moore, Mark Salmon, Mark Taylor, in addition to participants in presentations at the Econometric Society World Congress 2005; the 2005 Foreign Exchange Microstructure Conference, Aix-en-Provence; the Stockholm Institute for Financial Research; the University of Oslo; Norges Bank; and the 2005 High-Frequency Econometrics and Microstructure Workshop, University of Warwick. The authors also thank several foreign exchange traders and colleagues in the departments for market operations and interbank settlements at Norges Bank for insightful conversations, especially Jan Engebretsen and Thor Kristiansen. The authors alone are responsible for the views expressed in the paper and for any errors that may remain.

1 Introduction

Arbitrage is one of the fundamental pillars of financial economics. It seems to be generally accepted that financial markets do not offer risk-free arbitrage opportunities, at least when allowance is made for transaction costs. This notion is directly related to the law of one price, which postulates that in well-functioning, efficient financial markets identical securities must have the same price, no matter how they are created. For example, if a derivative instrument can be created using two different sets of underlying securities, then the total price for each derivative instrument would be the same or else an arbitrage opportunity would exist. Arbitrage is the mechanism that should ensure the validity of the law of one price.

While the assumption of no arbitrage is likely to be reasonably mild or valid in several contexts in finance, violations of the law of one price can be rationalized on several grounds. In general terms, the absence of arbitrage opportunities gives rise to the so-called 'arbitrage paradox', first pointed out by Grossman and Stiglitz (1976, 1980). That is, if arbitrage 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. Also, microstructure theory shows how price differences may occur for identical assets in markets that are less than fully centralized or with an imperfect degree of transparency (O'Hara, 1995; Lyons, 2001).[1]

Empirical studies have, however, been unable to detect short-term arbitrage opportunities in a variety of financial markets. Given the high activity level in major financial markets, such short-term arbitrage opportunities can only be adequately studied using real-time quotations on all asset prices involved, which are notoriously difficult to obtain. Furthermore, one must take into account all relevant aspects of the microstructure of the markets in order to capture the opportunities and transaction costs that market participants face. Yet, if present, the existence and properties of riskless arbitrage opportunities are of great interest to both academics and participants in financial markets, given the central role of no-arbitrage conditions in the theory and practice of financial economics.

The prime motivation of this paper is to investigate empirically the existence of arbitrage and the properties of potential departures from no-arbitrage conditions using a

[1] See also the theories related to limits to arbitrage and speculation (Shleifer and Vishny, 1997; Lyons, 2001).

microstructure perspective. Specifically, we choose to study the foreign exchange (FX) market, where no-arbitrage conditions are well known and relatively easy to test. In currency markets net returns on similar interest-bearing domestic and foreign assets are believed to be equal when exchange rate risk is hedged through derivative contracts, implying that it is neither profitable to earn nor save money by exploiting differences in lending or borrowing rates across domestic and foreign security markets while avoiding exchange rate risk through forward or swap contracts–this condition is termed covered interest rate parity. Another form of arbitrage which has received less attention by the relevant literature is the related concept of one-way arbitrage–in the form of both owner arbitrage and borrower arbitrage. These are violations of the law of one price in the sense that they represent violations of the condition 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.

A key advantage of this study relative to all previous empirical analyses of arbitrage is our data set. A rigorous empirical examination of no-arbitrage conditions in the FX market requires high-frequency, contemporaneous, tradable (firm) quotes of comparable domestic and foreign interest rates and spot and forward exchange rates. This requirement is necessary in order to establish whether an apparent deviation from no-arbitrage conditions actually represented a profitable opportunity to agents at a given time or not. Moreover, the high level of activity in FX and international capital markets demands use of high-frequency, real-time quotes to characterize the properties of arbitrage opportunities, especially their duration. Finally, it is equally important to have a sufficiently long sample to obtain robust results. Our data set is the first data set in this literature that possesses these characteristics to a large extent.

Empirical studies of arbitrage in the FX market so far have not employed data sets that meet the above-noted strict requirements, mainly because such data sets have been unavailable to researchers. This literature suggests that arbitrage opportunities do not generally arise in the FX market and mispricing is unimportant when one accounts for estimated transaction costs.[2] On the other hand, the growing literature on high-frequency exchange rate behavior and FX market microstructure has not–to the best of our knowledge–studied

[2] Studies of FX arbitrage–primarily based on tests of covered interest parity–include Branson (1969), Frenkel (1973), Frenkel and Levich, (1975, 1977), Callier (1981), Taylor (1987, 1989), Rhee and Chang (1992), Fletcher and Taylor (1993), Aliber, Chowdhry and Yan (2003), and Juhl, Miles and Weidenmier (2005).

arbitrage, focusing instead on a variety of other issues relating to international currency patterns, trading behavior, and the role of order flow in explaining exchange rate movements (e.g. Lyons, 1995, 2001; Osler, 2000, 2003, 2005; Covrig and Melvin, 2002; Evans, 2002; Evans and Lyons, 2002a,b, 2005; Payne, 2003; Bjønnes and Rime, 2005; Lyons and Moore, 2005).

Use of real-time quotations can also shed light 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 offer counterparts riskless profit opportunities–i.e. prices that violate the law of one price. 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. Accordingly, the presence of profitable arbitrage opportunities in real-time would point towards possible inefficiencies in information gathering, profit maximization and/or other constraints on parts of quote-providers.

Our data set 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 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 FX arbitrage. The data have been collected through Reuters trading system on special order.

To anticipate our key results, we find evidence of numerous short-lived arbitrage opportunities, especially in the form of one-way arbitrage. The size of arbitrage opportunities is economically significant across exchange rates and comparable across different maturities of the instruments involved in arbitrage. The duration of arbitrage opportunities is, on average, high enough to allow agents to exploit deviations from the law of one price, but low enough to explain why such opportunities have gone undetected in much previous research using data at lower frequency. We find little 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. Finally, our results suggest that frequency, size and duration of apparent arbitrage opportunities decline with the pace of markets.

The paper is organized as follows. Section 2 presents the concepts of round-trip and one-way arbitrage in the FX market and describes the relationships between these various forms of arbitrage. Section 3 briefly discusses quoting conventions, transaction costs and their implications for calculations of gains and losses from arbitrage of the different forms. In addition, this section describes the data set and notes some basic properties of interest rates and exchange rate quotes. Section 4 presents the main empirical findings, relating to frequency, size and durations of returns from arbitrage opportunities. Section 5 reports the results from a sensitivity analysis of the core results, and an analysis of whether and how characteristics of profitable arbitrage opportunities vary with market pace. 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 Riskless Arbitrage in the FX Market

2.1 Round-trip, Covered Arbitrage

Covered interest rate parity (CIP) postulates that it is not possible to earn positive returns by borrowing domestic assets for lending abroad (or vice versa) while covering the exchange rate risk through a forward contract of equal maturity. 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. Commonly, CIP is expressed as

$$(1 + i_d) = \frac{1}{S}(1 + i_f)F, \tag{1}$$

where i_d and i_f denote domestic and foreign interest rates on similar assets, respectively; S is the spot nominal exchange rate; and F is the forward exchange rate of maturity equal to that of the interest-bearing assets. The spot exchange rate is expressed in units of domestic currency per unit of foreign currency.

The common expression of CIP in equation (1) neglects transaction costs, however. Such costs may be largely captured by market quotes of interest rates and exchange rates which are expressed in terms of ask and bid quotes. The spread between ask and bid rates/quotes for an asset is assumed to take into account inventory, information and processing costs associated with the trading of the asset (see e.g. O'Hara, 1995).[3]

[3]In addition, fixed settlement costs may be incurred to settle and implement a trade. Also, the

Taking into account ask–bid spreads of interest rates and exchange rates, round-trip (or covered) arbitrage is not profitable under the following conditions:

$$(1 + i_d^a) \quad \geq \quad 1/S^a(1 + i_f^b)F^b \tag{2}$$

$$(1 + i_f^a) \quad \geq \quad S^b(1 + i_d^b)/F^a \tag{3}$$

where the superscripts a and b symbolize ask and bid rates, respectively. A trader faces ask rates when borrowing funds, and bid rates when lending. Similarly, a trader receives the exchange rate at its bid rate when selling a currency (spot or forward) but pays the ask rate when buying. Needless to say, ask rates are higher than bid rates.

2.2 One-way Arbitrage

Recognition of the fact that funds are borrowed and lent at different rates makes it important to consider the behavior of traders that are looking for the highest riskless returns on their endowments and of those who are looking for the cheapest borrowing opportunities. In the following sub-sections we consider these cases and point out their relationships with the conditions for profitable round-trip arbitrage, i.e. the case of CIP.

2.2.1 Owner Arbitrage

The concept of 'owner arbitrage' (OA) refers 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 riskless net return. Such traders weigh the option of lending own funds at the market bid 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 rate for that currency, while eliminating the exchange rate risk at the maturity of the lending contract through a forward contract.

The law of one price will prevent OA opportunities under the following conditions:

$$(1 + i_d^b) \quad \geq \quad 1/S^a(1 + i_f^b)F^b \tag{4}$$

$$(1 + i_f^b) \quad \geq \quad S^b(1 + i_d^b)/F^a. \tag{5}$$

initiator of a trade may need to pay brokerage fees if a transaction is conducted through a broker. The brokerage fee often depends on the maturity of the asset and the total volume traded by a dealer in a month. However, brokerage and settlement costs are often paid at the end of a month and are therefore generally neglected by a trader when conducting a single trade. This is particularly because a single trade is typically of a relatively large size, i.e. at least of 10 million US dollars, by formal or informal market conventions. Hence, brokerage and settlement costs per unit of currency traded become miniscule, about 10^{-5} per US dollar in sum.

The left-hand-side elements in these inequalities are lower than those in the case of CIP given in conditions (2)–(3), and hence they may be violated more easily (more often) than the CIP inequalities; see Panels I-II in Table 1. Consequently, absence of profitable OA opportunities is considered a stronger indication and test of market efficiency than absence of profitable covered arbitrage opportunities.[4,5]

Intuitively, the relation between CIP and OA is clear. One is more likely to gain from moving own funds between currency markets than borrowed funds. Thus, if it pays to move borrowed funds from one currency market to another (while covering the exchange rate risk), it will certainly pay to do so with own funds. Moreover, if one cannot earn a positive return by lending own funds in another currency market, one can rule out a positive return by lending borrowed funds in the other currency market.

2.2.2 Borrower Arbitrage

The concept of 'borrower arbitrage' (BA) refers to the case where a trader is searching for the cheapest way to finance an investment. Such traders face the option of borrowing funds in the desired currency directly, or to borrow funds in another currency and convert 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. In this case, funding costs avoided by choosing the relatively cheaper borrowing opportunity essentially represent risk-free net return.

The law of one price will prevent BA opportunities under the following conditions:

$$(1+i_d^a) \quad \leq \quad 1/S^b(1+i_f^a)F^a \tag{6}$$

$$(1+i_f^a) \quad \leq \quad S^a(1+i_d^a)/F^b. \tag{7}$$

[4] Alternatively, one may be interested in measuring the risk-free 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 because they are less stringent tests of arbitrage (since these variants require more transactions).

[5] It follows that profitable arbitrage in the case of CIP implies profitable OA while the converse may not be true–i.e. violation of conditions (2) and (3) is a sufficient but not a necessary condition for the violation of conditions (4) and (5) respectively. Moreover, if OA is not profitable, neither will CIP arbitrage be profitable while the opposite may not be the case–i.e. validity of conditions (4) and (5) is a sufficient but not a necessary condition for the validity of conditions (2) and (3) respectively. In Table 1 (Panels I-II), we summarize the relationship between CIP and OA.

The first inequality is relevant when the funds are required in domestic currency, while the second one becomes relevant when funds are required in the foreign currency.[6]

Note that when borrowing another currency than the currency eventually desired, the trader must consider how much she must borrow, and then sell, 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 $1/S^b(1+i_f^a)$, but $1/S^b(1+i_f^a)F^a$ in domestic currency is required if she enters a forward contract of that maturity to buy the foreign currency in order to settle her debt.

It appears that profitable CIP arbitrage when measured in, e.g., currency d or from the viewpoint of a domestic arbitrageur precludes profitable BA opportunities for a domestic fund raiser while the converse may not be true. That is, violation of conditions (2) and (3) is a sufficient but not a necessary condition for the validity of conditions (6) and (7) respectively; see Panel III in Table 1. In other words, if a positive riskless 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 convert. In other words, profitable CIP arbitrage from the viewpoint of a domestic (foreign) dealer implies borrower arbitrage from the viewpoint of a foreign (domestic) dealer; see Panel IV in Table 1.

[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. For example, if one 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 quoting currency is the base currency, one would need to buy the domestic currency (at the ask rate) spot as well as forward.

3 Data Issues and the Calculations of Returns from Arbitrage

We obtained data from the Reuters trading system, which embeds general market quoting and maturity conventions. In this section, we present precise formulas for calculating deviations from the different no-arbitrage conditions in light of these conventions as well as transaction costs that a trader would typically face when dealing through this system. Appendix A provides a detailed account of quoting conventions, calculations of days to maturity and transaction costs for different exchange rates and traded volumes.

3.1 Formulas Used for the Calculations

At Reuters trading system dealers trade swaps rather than (outright) forwards and, in particular, they act on so-called swap points. Swap points express a multiple of the difference between forward and spot exchange rates. By convention, all of the exchange rates are quoted with 4 decimals, except for the Japanese yen, where 2 decimals are used. Swap points 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 potential returns from arbitrage 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, (2)–(7), while taking into account relevant quoting and maturity conventions. For example, the deviation from the CIP condition (2) can be expressed as:

$$(F^b - S^a) - \frac{S^a(i_d^a \times \frac{D}{360} - i_f^b \times \frac{D}{360})}{(100 + i_f^b \times \frac{D}{360})} \times 10^4, \tag{8}$$

where the first term denotes market swap points for a given maturity obtained from Reuters, while the second term represents the corresponding derived swap points. Table 2 presents derived deviations for all of the no-arbitrage conditions pertaining to CIP, OA and BA. Deviations are profitable if equation (8), or the equivalent equation from Table 2, is positive net of other transactions costs.

In order to calculate derived swap points that are directly comparable to swap points quoted by Reuters, we adjust the interest rates, which are quoted in percent per annum, in order to obtain interest rates for maturities less than a year. Here D denotes the number of days to maturity of swap and deposit contracts. 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 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. Finally, the resulting term must be 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, e.g. (8), are expressed in pips since they are defined as the difference between quoted and derived swap points. In our empirical analysis, we treat the quoting currency as the domestic currency (d) and the base currency as the foreign currency (f), for convenience, since we overlook cases where both the quoting as well the base currencies are actually foreign currencies for a dealer. Table 3 makes explicit the quoting and base currencies for the three exchange rates examined.

In actual calculations of returns from arbitrage, we deduct 1/10 of a pip (10^{-5}) from the expressions for returns presented in Table 2 to obtain returns less brokerage and settlement costs. Appendix A.2 shows that the sum of brokerage and settlement costs are at most 1/10 of a pip per US dollar for an arbitrage deal of required size.[7] Thus, the number and size of profitable returns obtained by us are likely to represent lower bounds on the number of profitable returns through arbitrage.

3.2 Data

We employ tick data collected via a continuous feed from Reuters over the period February 13–September 30, 2004. The data set allows us to investigate both round-trip as well as one-way arbitrage for three major exchange rates at four different maturities: 1, 3, 6 and 12 months. The data set includes ask and bid spot exchange rates for the 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.

For the spot exchange rates we have firm quotes from Reuters electronic brokerage system (D3000-2). For the other instruments, only indicative ask and bid quotes were available to us through Reuters Monitor (i.e. Reuters 3000 Xtra). In light of evidence for spot exchange rates in Danielsson and Payne (2002), and conversations with users of

[7] Ideally, we should have converted 1/10 of a pip in US dollars to each of the quoting and base currencies at the appropriate exchange rate at the end of each month–see Appendix A.2. On the other hand, we are probably deducting more than the average cost for each arbitrage deal involving three trades.

the Reuters trading system, spreads between indicative ask and bid quotes for swaps as well as for interest rates may be considered wider than those for corresponding firm ask and bid quotes. It is a common perception that the difference between indicative quotes and firm quotes is smaller for swaps and interest rates than for spot rates.[8] Importantly, it can be shown that use of indicative quotes, with relatively wider ask-bid spreads than those of firm quotes, would not lead us to exaggerate the number and size of arbitrage violations.[9]

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, 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.[10] 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.

Despite ignoring numerous observations to ensure calculations of arbitrage opportunities with as high a share of fresh quotes as possible, we are still able to investigate a

[8] Indicative spot quotes may at times be quite different from firm interbank quotes because the former quotes may be used for marketing purposes to non-bank customers. The interbank market has other sources for obtaining information on spot quotes, e.g. electronic broker screens. For swaps and deposits, however, indicative quotes are regarded as a reliable information source in the market since few alternative information sources are present. It is therefore reasonable to expect that the indicative quotes are closer to firm quotes in the latter cases than in the case of spot quotes.

[9] This can be seen by taking the derivative of, e.g., a deviation from CIP (dev_cip) with respect to deviations from firm quotes for an instrument, say k. Consider, as a representative example, the formula for a CIP deviation on the bid side, adjusted to allow for indicative quotes to deviate from firm quotes by an amount (x):

$$dev\_cip^b = \left[(F^b - S^a) - x^{Swap}\right] - S^a \frac{\left[\left(i_d^a + x^{i_d}\right) - \left(i_f^b - x^{i_f}\right)\right] \times D \times 10^4}{36000 + \left(i_f^b - x^{i_f}\right) \times D},$$

where, for example, $\left(i_d^a + x^{i_d}\right)$ denotes the indicative quote for the domestic borrowing interest rate at the ask. This deviation from CIP using indicative quotes refers to the case when funds are borrowed at the domestic interest rate and lent abroad at the foreign interest rate. Obviously, $\partial dev\_cip^b / \partial x^k < 0$ for k = *Swap*, i_d and i_f since the denominator in these expressions is strictly positive.

[10] 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.

large number of data points (i.e. arbitrage returns), over 2 million in the case of EUR 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). Actually, 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.

4 Frequency, Size and Duration of Arbitrage Opportunities

In this section we report our key findings regarding the frequency, size and duration of arbitrage opportunities distinguishing between round-trip/covered arbitrage and one-way arbitrage. Our basic results are mere descriptions of the observations obtained by using the formulas described in Sections 2–3.

4.1 Round-trip Arbitrage (CIP)

Table 4 presents results based on calculations of CIP arbitrage opportunities for the three exchange rates and four maturities examined. Results are given for both ask and bid sides–i.e. the outcomes of arbitrage both for the case when one borrows funds in the base currency to lend in the quoting currency and vice versa (these cases are referred to as "Ask" and "Bid" respectively, in the table).

The table gives results for the case where all of the observations are used–Panel (a), "All deviations"–and for the case where only observations consistent with profitable deviations are considered–Panel (b), "Profitable deviations." Starting from the case where all of the observations are used, let us note the large number of data points available to us: in the range of about 2–2.6 million for EUR, 2.5–2.8 million for GBP, and over 800,000 in the case of JPY. We also note that the number of observations increase with the maturity of contracts. This reflects that frequency of quote changes tends to be higher at higher maturities.

The table shows that the average return from CIP arbitrage is negative, in all of the cases–i.e. the figures in the column headed by "mean" are negative throughout the table.

Also, the median return is very close to the mean return, indicating a fairly symmetric distribution. The negative mean values imply that, *on average*, CIP arbitrage is loss-making. Furthermore, the associated t-values suggest that the losses are statistically significant at conventional levels of significance.[11] One would expect that arbitrage would eliminate any systematic negative or positive deviations from CIP and make CIP hold on average. One possible explanation for the negative mean of CIP deviations could be that market makers (quote providers) in the currency and deposit markets do not knowingly offer counterparts risk-free arbitrage opportunities and thus contribute to shift the returns towards negative values through their price offers. This would especially be the case if dealers, when pricing, say, the swap, worry about the fact that prices of other instruments, say deposits, may move in the next few seconds in a way to generate arbitrage. Accordingly, they may price more conservatively than CIP conditions imply in order to avoid arbitrage and be on the safe side. If prices are set in the deposit market in the same way, then equilibrium (average) prices will be consistent with a negative value of CIP rather than zero. An alternative explanation could be, that quote providers use the more stringent no-arbitrage conditions associated with OA and BA to set quotes; cf. Table 1. Accordingly, average returns in the case of CIP would be negative while those in the case of OA and BA will be zero. This latter explanation is consistent with the results for the case of OA in BA in Tables 6 and 8, respectively. Nevertheless, negative average return from CIP arbitrage is not sufficient to prevent arbitrage in continuous time completely since the maximum point of the distribution of returns is not zero, which is the sufficient condition that is needed to prevent any arbitrage opportunity.

The mean returns in Table 4 are period returns. It is therefore instructive to annualize them to make them more comparable across maturities. These calculations are given under the column headed "Ann. mean", which illustrates how the (negative) returns are generally comparable across different maturities. In Table 4 we also document the pace of the market by "inter-quote time", which is defined as the average time between two consecutive CIP deviations. Because at least one of the quotes involved in a CIP deviation formula must change in order to define a new CIP deviation, inter-quote time seems to be an appropriate aggregate indicator of the pace of FX and capital markets. The figures reported indicate that the pace of the market is very fast, especially at the

[11] The t-values in the case of GBP are generally smaller in absolute terms than those for the other exchange rates, but still suggest significant losses in CIP arbitrage on average at the 5% level of significance.

higher maturities. New CIP deviations occur every 2-3 seconds on average for EUR and GBP, and every 6-7 seconds for JPY.

Turning to the case where we consider only profitable CIP deviations, the column headed "Pa dev." reports the number of profitable arbitrage opportunities out of the total number of data points available ("All dev.") calculated for each of the exchange rates and maturities considered. Profitable deviations from CIP arbitrage are defined as the subset of CIP deviations with values in excess of 0.1 pip. The results suggest thousands of profitable arbitrage opportunities for all exchange rates, at most of the maturities. A round-trip arbitrage opportunity may on average arrive at least every hour when the number of profitable deviations ("Pa dev.") are greater than 1661 (= 151 ×11). As shares of the total number of data points considered, however, the profitable arbitrage opportunities are miniscule. The shares range from zero to 1.5% in the case of EUR, from 0.2% to 2.4% for GBP, and from 0.1% to 0.5% for JPY.[12]

When examining the annualized mean return from profitable arbitrage deviations, we find that these returns range from a minimum of 2 pips in the case of EUR at the one-month bid side to a maximum of 15 pips for the JPY at the three-month ask. Also, the returns show no systematic pattern with maturity of the instruments involved in arbitrage.[13,14] Finally, the average inter-quote time for profitable deviations ranges from less than 2 seconds to 15.6 seconds, except for one extreme case of 25 seconds for EUR at the one-month bid. In the latter case, the average inter-quote time is calculated only across 73 data points, which is the smallest number of arbitrage opportunities detected in Table 4.

[12]Table 4 also suggests that there are fewer profitable arbitrage opportunities with borrowed dollar funds than with borrowed funds in euro, sterling and yen. This tendency is implied by the relatively higher share of profitable arbitrage opportunities on the ask sides relative to the bid sides in the case of EUR and GBP and on the bid side relative to the ask side in the case of JPY. In the latter case, USD is the base currency (f in the formula), while USD is the quoting currency (d in the formula) in the former cases–see Table 2.

[13]The lack of relationship between size and maturity is in contrast to with the conjecture that there may be a "maturity effect" such that the size of arbitrage profits increases with maturity. Such conjecture was rationalized by Taylor (1989) on the basis of prudential credit limits that make arbitrage relatively more appealing at short maturities than at long maturities in a foreign exchange decentralized market where credit assessment is made cumbersome by lack of transparency. Of course, credit rating assessment is much easier within Reuters electronic system than in the pre-electronic, telephone-based brokerage systems studied by Taylor. We suspect that, for this reason, prudential credit limits may not provide a strong rationale for requiring larger returns for longer-maturity arbitrage activities in electronic systems such as Reuters. For a discussion of credit limits in decentralized and centralized, electronic markets, see Sarno and Taylor (2001, Ch. 2).

[14]In all cases, the median values of profits are comparable to the corresponding mean values, which also suggests fairly symmetric distributions of profits from round-trip arbitrage.

Generally, for each exchange rate and both for profitable and non-profitable CIP deviations, the average inter-quote time tends to decline with maturity, i.e. market pace is higher for longer-maturity contracts. Although this decline is not always monotonic, it seems to suggest a faster level of trading activity in the one-year forward and capital markets relative to shorter-maturity markets.

Table 5 presents information about the duration of profitable CIP arbitrage opportunities. The table reports summary statistics of the durations of clusters (sequences) of profitable CIP deviations. A cluster is defined as consisting of at least two profitable CIP deviations in a row. The number of clusters, across exchange rates and maturities, ranges from a minimum of ten to a maximum of over one thousand. Notably, most clusters of profitable CIP deviations do not seem to last beyond a few minutes. Moreover, in most of the cases, average duration falls in the range from 30 seconds to less than 2 minutes. Median values of the durations are even lower than the corresponding average durations: they are less than 1 minute in the case of EUR; at most 1:28 minutes in the case of GBP; and at most 3:34 minutes in the case of Japan. It is worth noting that durations of clusters tend to decline, albeit non-monotonically, with the maturity of contracts. This seems to be consistent with the relatively high market pace (low inter-quote time) at higher maturities noted above.

Sample standard deviations of the durations reveal large variations in the duration of profitable CIP deviations, however. The standard deviations are quite different across the cases examined: they are mostly less than a few minutes, but exceptionally they are higher than 10 minutes and as high as 89 minutes in one of the cases for GBP. Often the relatively large standard deviations occur when there are relatively few observations, i.e. clusters. It seems that, exceptionally, some clusters of profitable CIP deviations can persist for hours, but these are rare circumstances in our large sample of data. In fact, the first and third quantiles in the last two columns of Table 5 indicate that duration is not particularly high even at these quantiles of the distribution of durations, suggesting that the high standard deviations reported are potentially driven by isolated outliers.

Overall, we find a number of CIP arbitrage opportunities. However, these opportunities amount to small numbers when one compares them to the total number of observations examined. This is consistent with the widely held view that CIP holds tightly and that CIP violations occur rarely. The size of profitable CIP violations is, however, economically appealing. Their duration is relatively low but sufficiently high on average for a trader to exploit the arbitrage opportunities.

In order to exploit an arbitrage opportunity, however, a trader needs to undertake the three deals virtually simultaneously and as fast as possible.[15] Otherwise, there is a risk that prices of one or more instruments move such that an apparent arbitrage opportunity disappears before the trader has been able to seal all of the three deals. Reuters electronic trading system, which provides easy access to money and currency markets from one platform, allows a trader to undertake almost simultaneously deals with four counterparts. Alternatively, virtually simultaneous trading in the money markets and the swap markets can be accomplished through tight cooperation between money market dealers and swap market dealers, which seems to exist in a typical dealing room.

We envision that a dealer observing an arbitrage opportunity would, given the non-negligible duration of profitable clusters, consider it worthwhile to inquire about the relevant prevailing quotes that she would face, conditional on her (institution's) credit rating and desired trade size, from her trading partners (including electronic broker for currency trading) for the purpose of undertaking arbitrage (if it remains profitable until she is able to implement all of the required trades). *Ex ante* the trader will not know for sure whether the provided prices at her inquiry will imply profitable arbitrage or not. It is possible that she would be offered quotes that do not imply an arbitrage opportunity because of relatively poor credit rating or desire for trading a relatively larger size than recently transacted. In addition, she has to take into account that if she trades currency through the broker, prices can move in an unfavorable direction, especially if she wants to trade large volumes relative to the standard or minimum size. Danielsson and Payne (2002) observed that the likely price impact in the major currency markets can be 1-2 pips when traded volumes increase from the minimum size of 10 million USD to, say, 30 million USD.[16] Thus, a price impact in the currency markets is unlikely to remove a typical size of arbitrage profit, unless one makes an attempt to trade very large volumes. If arbitrage remains profitable at the provided quotes while making allowance for sufficiently large currency price movements, and one is able to seal the required deals at those prices, the

[15] If the three deals are conducted consecutively from a single platform, it may take above one minute; a typical deal usually takes 25 seconds on Reuters dealing system, see Reuters (p. 114, 1999). Hence, the consecutive deals will involve the risk that one has to stop short of completing all of the deals required for arbitrage owing to an unfavorable change in the price of instruments that remain to be traded.

[16] The order book at Reuters dealing system (at 16.00 GMT in 1997) depicted by Danielsson and Payne (2002) suggests that ask rates only move by about 1 pip, while the bid side hardly changes, if one buys or sells trade sizes up to 10–30 million USD.

resulting profit will be risk-free. If these two conditions are not met, a trader will be at liberty to decline trading at the provided quotes, and hence will not suffer any loss.[17] A trader may alternatively trade through the broker in currency markets by placing a limit order, i.e. a sell or buy order conditional on pre-specified prices. In this case, the trader may be faced with execution risk, that is her order may not be executed if the limit order is out-of-line with the market conditions.

Our findings suggest that arbitrage opportunities arise frequently enough and are sufficiently profitable to provide agents incentives to watch the markets and collect and analyze prices to the end of discovering and exploiting arbitrage opportunities. Moreover, these opportunities last long enough to make it worthwhile collecting and analyzing prices that one would face upon noting an arbitrage opportunity at prevailing market prices, i.e. prices provided to other market participants. Thus, one may not need to continuously collect or inquire about prices that oneself would face, but only upon noting an arbitrage opportunity at prices that has been indicated to market participants in general or have recently been transacted at by other market participants.

Furthermore, our evidence suggests that the (average) size of profits is sufficiently large to reduce the possibility that a profitable arbitrage opportunity at e.g. minimum trading size of 10 million USD at Reuters will disappear just because one wants to trade a somewhat higher amount. Thus, it would be worthwhile for a trader to ask for the required quotes even for trading higher volumes than those recently traded for the purpose of undertaking arbitrage if considered profitable at the provided quotes.

4.2 One-way Arbitrage: Owner Arbitrage (OA) and Borrower Arbitrage (BA)

We now report results for one-way arbitrage, in the form of both OA and BA. The results are presented in the same format as for the CIP arbitrage deviations reported in Tables 4-5.

Table 6 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 is in contrast with the CIP deviations, and suggests that in the case of lending services, the law

[17] It should be borne in mind that a trader is free to only act on quotes that would benefit her, and is not obliged to act on every provided quote. Also, a trader does not have to make all sell and buy orders without knowing beforehand at what prices the orders will be executed at.

of one price holds *on average*. The median returns are mostly close to the mean values, as in the case of CIP deviations. However, in contrast to the case of CIP arbitrage, 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.

As in the case of CIP arbitrage, there does not appear to be any systematic pattern linking returns to maturity. The annualized riskless mean returns from OA range from a minimum of 2 pips to a maximum of 6 pips across the three exchange rates examined. We also note that in contrast to the distributions of all deviations for OA, distributions of profitable OA opportunities seem to be slightly skewed to the left as the median values of the gains are generally lower than the corresponding mean values. 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, and the tendency of longer-maturity markets to display faster activity levels than shorter-maturity markets.

Table 7 presents information about durations of profitable OA opportunities. The summary statistics of durations are quite similar to the case of CIP violations. In particular, averages of the cluster durations are mostly less than 5 minutes, and seem to decline with the maturity of the contracts. The standard deviations of cluster durations display more variation across the different cases, in comparison with the case of CIP, while the median is always lower than the mean duration.

Let us now turn to BA opportunities, analyzed in Table 8. On average, BA mean returns are generally negatively signed and always insignificantly different from zero. This suggests that the law of one price holds on average also in the case of financing services. The median returns are mostly close to the mean values, as for CIP and OA. 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 6. Moreover, the distributions of the gains from BA is slightly skewed to the left, as the median values are generally lower than the corresponding mean values. Furthermore, the annualized riskless mean returns from BA also range from a minimum of 2 pips to a maximum of 6 pips across the three exchange rates examined. 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. Finally, Table 9 shows that the summary statistics of the cluster durations are similar to the case of CIP and especially to the results for OA.

Overall, we find a large number of opportunities for one-way arbitrage–both in the form of OA and BA opportunities. The relative higher shares of OA and BA relative to CIP arbitrage are consistent with the implied relationship between CIP and OA forms of arbitrage discussed in Section 2. They are also consistent with our impression based on conversations with several FX dealers, who were of the view that OA and BA opportunities do arise much more frequently than CIP violations. Dealers consider OA form of arbitrage whenever they receive funds to allocate, while they consider the BA form of arbitrage when looking for funding opportunities. Still, we are intrigued by the sheer numbers and shares of profitable OA and BA opportunities.

The two one-way arbitrage opportunities display similar properties in terms of both size and duration. The size is economically appealing and their duration is relatively low, consistent with the notion that arbitrage opportunities are short-lived. Duration appears to be lower for longer-maturity contracts, presumably because the market pace is higher for longer-maturity foreign and capital markets.

In sum, the frequency and economically significant size of arbitrage make it worthwhile for traders to watch the markets, collect and analyze prices in order to benefit from discrepancies in returns on assets and in funding costs across markets. Moreover, the average duration is, in general, such that a trader would find it worthwhile to collect and analyze prices she would face, given her credit rating and desired trading volume, if she wants to invest or borrow funds in e.g. foreign securities. As in the case of CIP, one way arbitrage also requires three virtually simultaneous deals in order to be risk-free. Hence, a dealer able to undertake the three deal simultaneously, or in a position to complete all of 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.

5 Robustness and Further Empirical Analysis

In this section we undertake some robustness checks on the results reported in the previous section and further empirical work designed to shed light on the properties of arbitrage violations and their relation to the pace of the market. We start by investigating two important issues in this context, namely we assess how genuine the arbitrage opportunities detected are–i.e. we examine to what extent the noted arbitrage opportunities may be caused by stale quotes–and the possibility that the law of one price in the FX market is guaranteed by prices being set directly from the no-arbitrage conditions for the cases of CIP, OA or BA.

5.1 Are Arbitrage Opportunities Genuine or Due to Stale Quotes?

As described in our data section, we restricted our 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. This was achieved by excluding weekends and days with unusually low or no trading activity, by ignoring quotes from hours with little trading and by including only quotes during the highest activity part of the trading day, namely 07:00–18:00 GMT.

In this sub-section 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 only deviations for which new quotes for *all* four instruments involved in arbitrage had appeared on the Reuters system in the previous two minutes. All deviations which did not meet this criterion were excluded from the sample.

The results, reported in Table 10, indicate that this screening of the data reduces drastically the number of observations analyzed, especially for JPY. As a consequence, the number of profitable deviations also decreases substantially. However, the frequency of occurrence of arbitrage–calculated as a share of profitable arbitrage violations out of the total number of deviations based on the particularly fresh quotes–remains fairly similar to the frequencies reported for CIP in Table 4, for OA in Table 6, and for BA in Table 8. Specifically, we find a low share for CIP violations, ranging from zero to about 3%, and high shares for both OA and BA, ranging from zero to 83%, and from zero to 76%, respectively. Interestingly, 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 in Section 4.[18]

[18] We also checked whether arbitrage opportunities occur during a specific time of the day when, for example, trading might be particularly low–e.g. at the very beginning of the trading day examined. However, we find that arbitrage violations occur throughout the trading day considered here, from 07:00

Overall, these findings corroborate the results in Section 4 and add credibility to the view that the arbitrage violations reported here are genuine arbitrage opportunities which traders would have been able to trade upon at the time of their occurrence.

5.2 Is the Forward Rate Priced Using No-arbitrage Conditions?

Given our findings that arbitrage violations exist, it is obvious that at least one of the assets involved in FX arbitrage is sometimes mispriced to an extent that is sufficient to generate arbitrage opportunities. With tick data on all four assets at our disposal, we can assess the mispricing in each asset to shed further light on how arbitrage arises.

Anecdotal evidence suggests that forward contracts may be priced according to the CIP condition, or even more stringent no-arbitrage conditions (e.g. OA or BA). If this is the case, then price setting would be carried out in such a way as to prevent arbitrage opportunities from arising. We are in a position to test this conjecture in continuous time for the first time in this literature. Given our data on profitable CIP, 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. We would expect that if forwards were priced using, e.g., the CIP formula, the CIP condition should be valid at least whenever the forward is priced, i.e. whenever the swap quote changes.

Our results, reported in Table 11 for all of the three forms of arbitrage, do not support this conjecture. The table shows that the percentage of total CIP, OA and BA arbitrage opportunities that occur when there is only a swap price change varies from about 2% to 27%. The presence of a potentially large number of profitable arbitrage opportunities does not support the view that forward rates are systematically set such that they ensure the validity of the CIP, OA or BA formulas using all available information. Thus, apparently, either the practice of using the no-arbitrage conditions to set prices is not particularly common or feasible at this high frequency, and/or the providers of quotes do not update the formulas with all available information when offering forward quotes.

We also carried out this exercise for each of the other instruments involved in arbitrage (spot rate, and the two interest rates), recording similar results to the ones reported in Table 11 for the forward rate–not reported but available upon request. This evidence

to 18:00 GMT, and there is no evidence of clustering at a particular time of the day. These results are not reported to conserve space but they are available from the authors upon request.

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 arbitrage violations reported here.

5.3 The Role of Market Pace

In this sub-section, we provide some illustrative evidence on whether frequency, size and duration of profitable arbitrage opportunities vary with the pace of the market. 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, size and durations of profitable arbitrage opportunities as dependent variables, regressed on an intercept and inter-quote time as the explanatory variable. That is, we estimate regression models of the following form:

$$y_i = \alpha_y + \beta_y IQ_{y,i} + \varepsilon_{y,i} \tag{9}$$

where y = *frequency*, *size*, or *duration* of deviations from no-arbitrage conditions; IQ denotes inter-quote time; and ε_y is an error term. Subscript i indicates an observation number; $i = 1, 2, 3, ...N_y$. The Greek letters represent time-invariant parameters.

The models are estimated by ordinary least squares (OLS) for all of the three forms of arbitrage, for each of the currency pairs examined. Accordingly, values for y and IQ as well as the total numbers of observations (N) depend on the form of arbitrage and the currency pair analyzed. We obtained observations for y and IQ, and stacked these 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.[19] 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_i examined.

The variables are defined more precisely as follows. The y-variable *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

[19] Alternatively, we could have formulated separate models for the ask and the bid sides and for each of the four maturities examined.

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, especially in the case of CIP arbitrage. Each observation of inter-quote time (IQ) in the regressions for frequency 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.

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 inter-quote time (IQ) in the regressions for size and durations refers to the average time between the row of profitable deviations constituting a profitable 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 (9) for frequency, size and duration, for all three currency pairs and no-arbitrage conditions, are given in Table 12. The results confirm our previous conjectures that these characteristics of arbitrage opportunities tend to vary with the pace of the market, as proxied by the inter-quote time. In particular, frequency, size and duration are positively related to inter-quote time, i.e. negatively related to the market pace. This suggests that when markets are particularly active, as described by a high number of new quotes per unit of time, we should observe fewer arbitrage opportunities, smaller arbitrage profits, and more short-lived arbitrage.

For frequency and size there are a few instances where inter-quote time does not enter the regression with a statistically significant coefficient and occasionally we observe a counterintuitive negative sign. However, the results are particularly clear-cut in the case of duration–in terms of both obtaining correctly signed and statistically significant positive coefficients. This suggests that high market pace is intimately related to arbitrage opportunities that are more short-lived, as one would expect.

6 Conclusions

Finance theory postulates that in well-functioning markets no-arbitrage conditions hold in continuous time, not just on average. This paper provides evidence that short-lived arbitrage opportunities exist in three major FX and capital markets. These opportunities represent violations of the law of one price linking spot and forward exchange rates to interest rates across countries. The size of arbitrage opportunities is economically significant for the three exchange rates and across all of the different maturities of the instruments involved in arbitrage. The duration of arbitrage opportunities is, on average, high enough to allow agents to exploit deviations from the law of one price. However, duration is low enough to suggest that markets exploit arbitrage opportunities rapidly. The high speed of arbitrage recorded in this paper can explain why such opportunities have gone undetected in much previous research using data at lower frequency.

We could detect the existence and measure the duration of a number of short-lived arbitrage opportunities only by using a unique data set at tick frequency for quotes of comparable domestic and foreign interest rates and spot and forward exchange rates. These features of the data set have proven essential to establish whether deviations from no-arbitrage conditions actually represented a profitable opportunity to agents at a given time or not, and to shed light on the time the market requires to restore no-arbitrage prices in an electronic trading platform such as Reuters. In turn, this emphasizes why studies of arbitrage require the analysis of tick, carefully matched data on the assets involved in arbitrage with meticulous attention to the finest institutional details.

We find the results in this paper, at the same time, comforting and puzzling. On the one hand, it is comforting that the observed short-lived arbitrage opportunities provide evidence in support of the resolution proposed for the Grossman-Stiglitz 'arbitrage paradox'. If arbitrage was never observed, market participants may not have sufficient incentives to watch the market, in which case arbitrage opportunities could arise. In turn, very short-term arbitrage opportunities invite traders to exploit them and hence will be quickly eliminated. While this view of arbitrage is appealing, previous empirical studies have been unable to detect such short-term arbitrage opportunities in a variety of financial markets, and this paper explains why that can occur when aggregate data are used. To reiterate, arbitrage is indeed very short-lived, and requires turning on the microscope on high-quality tick data to be detected.

On the other hand, the results in this paper raise further questions. Specifically, it seems puzzling that the frequency of one-way arbitrage can be as high as 50% or 68% of the observations examined. This indicates that at the high frequency at which markets operate, i.e. in real-time, mispricing is indeed quite common. One would normally think that offering a price that allows arbitrage is indicative that a dealer is ill-informed and/or irrational.

Alternatively, the apparent "mispricing" could 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 relatively lower ask quotes and bid 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). A further exploration of this and alternative explanations of the numerous arbitrage opportunities observed in our data set is left to 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.

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.

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.

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 2000-D1).

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.[20]

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

[20] Restrictions on traded quantity are generally provided in the base currency. The requirement refers to swaps with maturity of one month to one year (inclusive), except in the case of GBP.

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.[21]

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 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.

[21] 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.

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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 for Borrower Arbitrage arbitrage. Case I is read as follows: CIP-arbitrage profitable ("Pa" is abbreviation for profitable arbitrage) in the domestic currency (d denote domestic, f foreign) implies OA-arbitrage profitable in the domestic currency. Foreign currency is the base currency. Superscripts a and b denotes ask and bid prices.

Table 2: Definitions of returns on arbitrage of CIP, OA and BA

I.	CIP, bid (return in currency d)	$\equiv$	$(F^b - S^a) - \frac{S^a(i_d^a \times \frac{D}{360} - i_f^b \times \frac{D}{360})}{(100 + i_f^b \times \frac{D}{360})} \times 10^4$
II.	CIP, ask (return in currency f)	$\equiv$	$-(F^a - S^b) + \frac{S^b(i_d^b \times \frac{D}{360} - i_f^a \times \frac{D}{360})}{(100 + i_f^a \times \frac{D}{360})} \times 10^4$
III.	OA, bid (return in currency d)	$\equiv$	$(F^b - S^a) - \frac{S^a(i_d^b \times \frac{D}{360} - i_f^b \times \frac{D}{360})}{(100 + i_f^b \times \frac{D}{360})} \times 10^4$
IV.	OA, ask (return in currency f)	$\equiv$	$-(F^a - S^b) + \frac{S^b(i_d^b \times \frac{D}{360} - i_f^b \times \frac{D}{360})}{(100 + i_f^b \times \frac{D}{360})} \times 10^4$
V.	BA, bid (return in currency f)	$\equiv$	$(F^b - S^a) - \frac{S^a(i_d^a \times \frac{D}{360} - i_f^a \times \frac{D}{360})}{(100 + i_f^a \times \frac{D}{360})} \times 10^4$
VI.	BA, ask (return in currency d)	$\equiv$	$-(F^a - S^b) + \frac{S^b(i_d^a \times \frac{D}{360} - i_f^a \times \frac{D}{360})}{(100 + i_f^a \times \frac{D}{360})} \times 10^4$

Note: The expressions $(F^b - S^a)$ and $(F^a - S^b)$ denote market quotes of swap points at bid (superscript b) and ask (superscript a), respectively, in each of the cases. The right-hand expressions are formulas for the corresponding derived swap points obtained by obeying market conventions. The Japanese yen and pound sterling differ from the above expressions in the following way: In the former case, 10^4 is replaced by 10^2, while in the latter case, the number of days in a year are set to 365 instead of 360.

Table 3: 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 Table 2. The final column shows the notation used for the three exchange rates (in the first column) in the paper.

Table 4: Round-trip, covered arbitrage (CIP). Descriptive statistics of deviations

Exchange rate			*a*) All deviations						*b*) Profitable deviations					
			All dev.	Mean	*t*-value	Median	Ann. mean	Interquote time (sec)	Pa dev.	Share	Mean	Median	Ann. mean	Interquote time (sec)
EUR	1M	Ask	2,037,923	-0.90	-4.2	-0.9	-11	2.9	1,975	0.10 %	0.26	0.24	3	2.7
		Bid	2,037,923	-1.00	-4.6	-1.0	-12	2.9	73	0.00 %	0.18	0.13	2	25.0
	3M	Ask	2,068,143	-2.67	-3.3	-2.7	-11	2.9	30,116	1.46 %	0.85	0.39	3	2.8
		Bid	2,068,143	-2.77	-3.7	-2.7	-11	2.9	3,500	0.17 %	0.88	0.66	4	2.2
	6M	Ask	2,309,197	-5.78	-3.1	-5.7	-12	2.6	12,844	0.56 %	1.44	1.30	3	1.9
		Bid	2,309,197	-5.31	-3.2	-5.3	-11	2.6	8,559	0.37 %	2.58	2.42	5	2.1
	1Y	Ask	2,560,419	-12.43	-2.9	-12.4	-12	2.3	21,495	0.84 %	5.33	4.69	5	2.0
		Bid	2,560,419	-10.64	-2.9	-10.6	-11	2.3	8,966	0.35 %	3.29	2.14	3	2.2
GBP	1M	Ask	2,445,312	-1.36	-2.5	-1.4	-16	2.4	35,110	1.44 %	0.35	0.26	4	2.4
		Bid	2,445,312	-1.72	-3.4	-1.7	-21	2.4	16,835	0.69 %	0.69	0.68	8	2.8
	3M	Ask	2,450,660	-4.06	-1.9	-4.1	-16	2.4	57,523	2.35 %	2.13	1.40	9	2.5
		Bid	2,450,660	-4.25	-2.0	-4.1	-17	2.4	24,124	0.98 %	2.90	3.09	12	1.9
	6M	Ask	2,594,610	-7.91	-2.3	-7.9	-16	2.3	37,820	1.46 %	4.91	3.27	10	2.0
		Bid	2,594,610	-9.43	-2.8	-9.3	-19	2.3	5,950	0.23 %	1.70	1.38	3	2.4
	1Y	Ask	2,746,288	-16.01	-2.6	-16.2	-16	2.2	37,987	1.38 %	9.09	7.38	9	2.0
		Bid	2,746,288	-17.85	-2.8	-17.4	-18	2.2	4,593	0.17 %	4.52	2.35	5	2.5
JPY	1M	Ask	804,885	-1.04	-3.4	-1.0	-12	7.3	1,545	0.19 %	0.37	0.15	4	13.8
		Bid	804,885	-1.02	-3.5	-1.0	-12	7.3	2,068	0.26 %	0.23	0.18	3	6.2
	3M	Ask	818,537	-2.66	-3.4	-2.6	-11	7.2	491	0.06 %	3.86	3.00	15	10.5
		Bid	818,537	-2.85	-3.3	-2.9	-11	7.2	2,891	0.35 %	1.83	1.72	7	15.6
	6M	Ask	838,047	-4.61	-2.9	-4.6	-9	7.0	718	0.09 %	4.71	0.90	9	15.0
		Bid	838,047	-5.69	-3.5	-5.6	-11	7.0	4,140	0.49 %	1.45	1.25	3	2.8
	1Y	Ask	892,242	-8.37	-2.3	-8.3	-8	6.6	3,403	0.38 %	6.21	2.00	6	10.9
		Bid	892,242	-13.42	-3.4	-13.6	-13	6.6	4,358	0.49 %	3.50	3.26	4	4.6

Note: The column headed by "All dev." presents the number of all profitable and non-profitable deviations (cf. definitions in Table 2), while the one headed by "Pa dev." records the number of the profitable deviations, i.e. deviations that are larger than 1/10 of a pip. Entries in the "Share" column are profitable deviations in percents of all of the deviations in column 'All dev.'. The "Mean" and "Median" columns present the average sizes and median values of the deviations, both measured in pips. The "Ann. mean" columns show annualized mean values of the period returns (deviations), reported in the "Mean" columns. Annualized values for the 1-month, 3-month and the 6-month maturities are obtained by multiplying the (period) mean value by 12, 4 and 2, respectively. The "*t*-value[s]" is simply the (period) mean values divided by their respective sample standard deviations. The 'Interquote time (sec)" column present the average time in seconds from the previous deviation, conditioned on the current deviation is 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.

Table 5: Round-trip, covered arbitrage (CIP): Duration of profitable clusters of arbitrage opportunities (in minutes)

Exchange rate			# Clusters	Mean	Stdev.	Median	Q1	Q3
EUR	1M	Ask	65	1:22	1:51	0:31	0:14	1:56
		Bid	10	3:16	8:35	0:20	0:08	1:33
	3M	Ask	318	3:25	6:39	0:55	0:15	3:05
		Bid	91	1:32	2:05	0:53	0:17	1:59
	6M	Ask	464	0:52	1:26	0:23	0:10	0:54
		Bid	488	0:42	2:04	0:14	0:05	0:27
	1Y	Ask	755	0:57	2:24	0:19	0:06	0:55
		Bid	651	0:30	0:58	0:09	0:03	0:27
GBP	1M	Ask	367	3:30	8:31	1:16	0:19	3:36
		Bid	75	12:37	89:15	0:33	0:12	1:13
	3M	Ask	428	5:09	12:03	1:28	0:22	4:54
		Bid	96	2:01	6:16	0:26	0:08	1:35
	6M	Ask	621	2:17	9:07	0:21	0:08	1:03
		Bid	239	1:01	1:58	0:20	0:06	1:16
	1Y	Ask	1,044	1:11	4:00	0:16	0:06	0:43
		Bid	286	0:40	1:36	0:15	0:05	0:39
JPY	1M	Ask	49	8:10	12:35	3:34	0:46	7:25
		Bid	78	2:46	7:13	1:10	0:28	2:18
	3M	Ask	17	5:22	13:46	0:16	0:06	1:36
		Bid	106	5:16	5:37	2:57	1:31	8:23
	6M	Ask	87	2:06	6:54	0:19	0:08	0:53
		Bid	153	1:26	3:47	0:19	0:08	0:54
	1Y	Ask	634	0:57	3:45	0:20	0:08	0:43
		Bid	222	1:32	3:14	0:26	0:10	1:28

Note: A cluster consists of at least two profitable deviations from no-arbitrage in a row. The entries in the "Mean" column 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 "Std.dev" column includes sample standard deviations of the duration of the clusters.

Table 6: Owner Arbitrage (OA). Descriptive statistics of deviations

Exchange rate			*a*) All deviations					*b*) Profitable deviations					
			All dev.	Mean	*t*-value	Median	Ann. mean	Pa dev.	Share	Mean	Median	Ann. mean	Interquote time (sec)
EUR	1M	Ask	2,037,923	-0.04	-0.2	-0.0	-0.4	474,531	23.29 %	0.20	0.18	2	3.1
		Bid	2,037,923	-0.09	-0.4	-0.1	-1.1	299,880	14.71 %	0.28	0.26	3	2.9
	3M	Ask	2,068,143	-0.21	-0.3	-0.2	-0.9	608,649	29.43 %	0.64	0.39	3	2.9
		Bid	2,068,143	-0.10	-0.1	-0.1	-0.4	733,902	35.49 %	0.65	0.51	3	2.9
	6M	Ask	2,309,197	-0.73	-0.4	-0.6	-1.5	676,992	29.32 %	1.13	0.78	2	2.6
		Bid	2,309,197	0.11	0.1	-0.0	0.2	1,083,080	46.90 %	1.47	1.15	3	2.5
	1Y	Ask	2,560,419	-1.72	-0.5	-1.6	-1.7	720,110	28.12 %	2.42	1.58	2	2.4
		Bid	2,560,419	0.05	0.0	-0.0	0.1	1,232,302	48.13 %	2.88	2.30	3	2.3
GBP	1M	Ask	2,445,312	0.06	0.1	-0.0	0.8	1,003,961	41.06 %	0.54	0.42	6	2.5
		Bid	2,445,312	-0.36	-0.7	-0.3	-4.3	284,005	11.61 %	0.43	0.27	5	2.4
	3M	Ask	2,450,660	-0.13	-0.1	-0.3	-0.5	967,976	39.50 %	1.51	1.08	6	2.5
		Bid	2,450,660	-0.28	-0.1	-0.1	-1.1	1,043,822	42.59 %	1.19	0.88	5	2.4
	6M	Ask	2,594,610	-0.03	-0.0	-0.2	-0.1	1,197,581	46.16 %	2.62	1.88	5	2.2
		Bid	2,594,610	-1.43	-0.4	-1.2	-2.9	788,979	30.41 %	2.00	1.58	4	2.4
	1Y	Ask	2,746,288	-1.05	-0.2	-1.6	-1.1	1,039,570	37.85 %	5.28	3.92	5	2.1
		Bid	2,746,288	-2.30	-0.3	-1.8	-2.3	993,183	36.16 %	3.78	2.94	4	2.2
JPY	1M	Ask	804,885	-0.21	-0.7	-0.2	-2.5	89,514	11.12 %	0.34	0.26	4	8.6
		Bid	804,885	-0.02	-0.1	-0.0	-0.3	275,863	34.27 %	0.27	0.23	3	6.2
	3M	Ask	818,537	-0.23	-0.3	-0.2	-0.9	251,775	30.76 %	0.61	0.51	2	7.3
		Bid	818,537	-0.26	-0.3	-0.3	-1.0	204,335	24.96 %	0.74	0.45	3	7.2
	6M	Ask	838,047	0.27	0.2	0.3	0.5	458,687	54.73 %	1.43	1.27	3	6.8
		Bid	838,047	-1.28	-0.8	-1.3	-2.6	140,145	16.72 %	1.17	0.82	2	8.0
	1Y	Ask	892,242	1.08	0.3	1.2	1.1	572,882	64.21 %	2.98	2.54	3	6.8
		Bid	892,242	-3.32	-1.0	-3.4	-3.3	116,788	13.09 %	2.52	1.44	3	6.3

Note: The column headed by "All dev." presents the number of all profitable and non-profitable deviations (cf. definitions in Table 2), while the one headed by "Pa dev." records the number of the profitable deviations, i.e. deviations that are larger than 1/10 of a pip. Entries in the "Share" column are profitable deviations in percents of all of the deviations in column 'All dev.'. The "Mean" and "Median" columns present the average sizes and median values of the deviations, both measured in pips. The "Ann. mean" columns show annualized mean values of the period returns (deviations), reported in the "Mean" columns. Annualized values for the 1-month, 3-month and the 6-month maturities are obtained by multiplying the (period) mean value by 12, 4 and 2, respectively. The "*t*-value[s]" is simply the (period) mean values divided by their respective sample standard deviations. The 'Interquote time (sec)" column present the average time in seconds from the previous deviation, conditioned on the current deviation is 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.

Table 7: Owner Arbitrage (OA): Duration of profitable clusters of arbitrage opportunities (in minutes)

Exchange rate			# Clusters	Mean	Stdev.	Median	Q1	Q3
EUR	1M	Ask	9,059	2:29	6:44	0:48	0:14	2:25
		Bid	5,715	2:24	4:38	0:50	0:10	2:55
	3M	Ask	11,936	2:15	7:58	0:37	0:13	1:59
		Bid	12,784	2:34	5:35	0:40	0:09	2:49
	6M	Ask	21,834	1:17	3:45	0:24	0:08	1:14
		Bid	25,454	1:40	3:32	0:29	0:08	1:41
	1Y	Ask	32,098	0:52	2:27	0:13	0:04	0:41
		Bid	42,836	1:03	2:25	0:12	0:04	0:50
GBP	1M	Ask	6,824	5:16	19:59	1:03	0:18	3:17
		Bid	4,880	2:05	5:57	0:32	0:12	2:01
	3M	Ask	7,217	5:44	25:38	0:53	0:15	3:32
		Bid	8,327	4:34	10:52	1:18	0:16	4:57
	6M	Ask	20,819	2:11	9:03	0:29	0:09	1:29
		Bid	18,310	1:38	5:25	0:28	0:09	1:28
	1Y	Ask	23,271	1:34	5:28	0:23	0:08	1:09
		Bid	26,176	1:22	3:33	0:23	0:07	1:12
JPY	1M	Ask	2,461	4:08	8:42	1:51	0:29	4:40
		Bid	4,079	5:40	17:08	1:32	0:23	3:46
	3M	Ask	6,562	4:35	13:39	1:41	0:27	4:44
		Bid	5,483	3:45	11:02	0:45	0:14	2:40
	6M	Ask	8,283	6:24	48:33	1:55	0:31	5:56
		Bid	5,486	2:59	9:34	0:36	0:12	2:01
	1Y	Ask	14,137	4:42	35:09	1:00	0:17	3:49
		Bid	7,761	1:30	4:56	0:24	0:08	1:09

Note: A cluster consists of at least two profitable deviations from no-arbitrage in a row. The entries in the "Mean" column 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 "Std.dev" column includes sample standard deviations of the duration of the clusters.

Table 8: Borrower Arbitrage (BA). Descriptive statistics of deviations

			a) All deviations					*b*) Profitable deviations					
Exchange rate			All dev.	Mean	*t*-value	Median	Ann. mean	Pa dev.	Share	Mean	Median	Ann. mean	Interquote time (sec)
EUR	1M	Ask	2,037,923	0.01	0.1	0.0	0.2	621,115	30.48 %	0.22	0.19	3	2.9
		Bid	2,037,923	-0.14	-0.7	-0.1	-1.7	172,451	8.46 %	0.24	0.21	3	3.0
	3M	Ask	2,068,143	-0.01	-0.0	-0.0	-0.0	812,189	39.27 %	0.58	0.42	2	2.9
		Bid	2,068,143	-0.31	-0.4	-0.3	-1.2	466,835	22.57 %	0.47	0.36	2	2.9
	6M	Ask	2,309,197	-0.37	-0.2	-0.2	-0.7	916,229	39.68 %	1.10	0.85	2	2.5
		Bid	2,309,197	-0.26	-0.2	-0.4	-0.5	838,837	36.33 %	1.39	1.05	3	2.5
	1Y	Ask	2,560,419	-1.74	-0.4	-1.7	-1.7	798,025	31.17 %	2.66	2.02	3	2.3
		Bid	2,560,419	0.08	0.0	0.1	0.1	1,286,227	50.24 %	3.14	2.52	3	2.3
GBP	1M	Ask	2,445,312	-0.01	-0.0	-0.0	-0.1	869,166	35.54 %	0.47	0.33	6	2.5
		Bid	2,445,312	-0.29	-0.6	-0.3	-3.5	325,846	13.33 %	0.42	0.24	5	2.4
	3M	Ask	2,450,660	-0.10	-0.0	-0.1	-0.4	1,022,279	41.71 %	1.17	0.78	5	2.4
		Bid	2,450,660	-0.32	-0.2	-0.3	-1.3	864,150	35.26 %	1.08	0.75	4	2.5
	6M	Ask	2,594,610	0.08	0.0	0.1	0.2	1,286,415	49.58 %	2.13	1.56	4	2.3
		Bid	2,594,610	-1.54	-0.5	-1.5	-3.1	614,680	23.69 %	1.75	1.31	4	2.3
	1Y	Ask	2,746,288	-0.48	-0.1	-0.7	-0.5	1,170,922	42.64 %	4.25	3.01	4	2.2
		Bid	2,746,288	-2.88	-0.5	-2.6	-2.9	736,587	26.82 %	3.17	2.41	3	2.2
JPY	1M	Ask	804,885	-0.04	-0.1	-0.0	-0.5	224,944	27.95 %	0.28	0.24	3	9.5
		Bid	804,885	-0.20	-0.7	-0.2	-2.4	87,679	10.89 %	0.27	0.20	3	7.1
	3M	Ask	818,537	-0.08	-0.1	-0.0	-0.3	332,831	40.66 %	0.56	0.43	2	8.3
		Bid	818,537	-0.42	-0.5	-0.5	-1.7	158,389	19.35 %	0.65	0.43	3	6.4
	6M	Ask	838,047	-0.21	-0.1	-0.3	-0.4	339,893	40.56 %	1.16	0.94	2	7.1
		Bid	838,047	-0.80	-0.6	-0.8	-1.6	212,646	25.37 %	0.96	0.72	2	6.5
	1Y	Ask	892,242	1.71	0.4	1.9	1.7	606,464	67.97 %	3.67	3.35	4	6.7
		Bid	892,242	-3.95	-1.1	-4.2	-4.0	127,668	14.31 %	2.00	1.51	2	6.6

Note: The column headed by "All dev." presents the number of all profitable and non-profitable deviations (cf. definitions in Table 2), while the one headed by "Pa dev." records the number of the profitable deviations, i.e. deviations that are larger than 1/10 of a pip. Entries in the "Share" column are profitable deviations in percents of all of the deviations in column 'All dev.'. The "Mean" and "Median" columns present the average sizes and median values of the deviations, both measured in pips. The "Ann. mean" columns show annualized mean values of the period returns (deviations), reported in the "Mean" columns. Annualized values for the 1-month, 3-month and the 6-month maturities are obtained by multiplying the (period) mean value by 12, 4 and 2, respectively. The "*t*-value[s]" is simply the (period) mean values divided by their respective sample standard deviations. The 'Interquote time (sec)" column present the average time in seconds from the previous deviation, conditioned on the current deviation is 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.

Table 9: Borrower Arbitrage (BA): Duration of profitable clusters of arbitrage opportunities (in minutes)

Exchange rate			# Clusters	Mean	Stdev.	Median	Q1	Q3
EUR	1M	Ask	10,326	2:46	7:48	0:53	0:15	2:42
		Bid	4,289	1:52	3:48	0:41	0:11	2:05
	3M	Ask	13,548	2:48	10:42	0:38	0:12	2:17
		Bid	10,689	2:00	4:24	0:37	0:10	2:02
	6M	Ask	23,853	1:34	3:28	0:27	0:08	1:30
		Bid	21,481	1:31	3:04	0:26	0:07	1:33
	1Y	Ask	30,221	0:59	2:14	0:15	0:04	0:51
		Bid	36,044	1:19	3:39	0:13	0:04	0:54
GBP	1M	Ask	8,384	3:36	12:24	0:41	0:16	2:31
		Bid	4,577	2:40	8:09	0:39	0:09	2:13
	3M	Ask	8,431	4:27	13:30	0:48	0:14	3:13
		Bid	8,248	4:01	16:35	0:57	0:12	3:25
	6M	Ask	23,379	2:01	6:53	0:28	0:09	1:26
		Bid	16,866	1:21	4:09	0:25	0:08	1:10
	1Y	Ask	26,746	1:32	4:38	0:22	0:08	1:07
		Bid	24,966	1:03	3:28	0:20	0:07	0:58
JPY	1M	Ask	4,003	7:31	31:17	1:59	0:32	5:58
		Bid	1,942	4:03	12:01	0:58	0:18	3:00
	3M	Ask	7,226	6:07	48:50	1:34	0:25	4:06
		Bid	3,656	3:44	11:30	0:44	0:15	2:29
	6M	Ask	8,662	4:24	17:06	1:20	0:23	3:37
		Bid	6,460	3:21	9:50	0:45	0:17	2:45
	1Y	Ask	10,330	6:36	55:09	0:56	0:17	3:12
		Bid	6,729	2:02	5:42	0:28	0:10	1:32

Note: A cluster consists of at least two profitable deviations from no-arbitrage in a row. The entries in the "Mean" column 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 "Std.dev" column includes sample standard deviations of the duration of the clusters.

Table 10: Arbitrage opportunities when controlling for stale quotes

Exchange rate			*a*) CIP			*b*) OA			*c*) BA		
			All dev.	Pa dev.	Share	All dev.	Pa dev.	Share	All dev.	Pa dev.	Share
EUR	1M	Ask	54,806	145	0.26 %	54,864	15,850	29 %	54,790	19,508	36 %
		Bid	54,848	2	0.00 %	54,864	10,769	20 %	54,790	6,700	12 %
	3M	Ask	79,927	2,645	3.31 %	80,001	26,965	34 %	80,937	35,437	44 %
		Bid	81,009	328	0.40 %	80,001	30,399	38 %	80,937	18,862	23 %
	6M	Ask	356,191	3,823	1.07 %	356,611	107,232	30 %	358,533	152,196	42 %
		Bid	358,931	2,927	0.82 %	356,611	173,458	49 %	358,533	129,926	36 %
	1Y	Ask	563,445	7,920	1.41 %	564,772	169,266	30 %	564,010	202,443	36 %
		Bid	574,711	3,073	0.53 %	564,772	281,476	50 %	564,010	265,853	47 %
GBP	1M	Ask	17,075	12	0.07 %	17,076	2,971	17 %	17,058	5,327	31 %
		Bid	19,285	95	0.49 %	17,076	4,110	24 %	17,058	1,784	10 %
	3M	Ask	40,206	1,237	3.08 %	40,206	13,645	34 %	40,542	16,307	40 %
		Bid	43,780	438	1.00 %	40,206	19,500	49 %	40,542	15,405	38 %
	6M	Ask	158,986	2,829	1.78 %	158,986	67,659	43 %	159,746	73,616	46 %
		Bid	179,055	508	0.28 %	158,986	52,946	33 %	159,746	44,340	28 %
	1Y	Ask	329,913	4,866	1.47 %	329,914	120,542	37 %	330,374	133,186	40 %
		Bid	374,680	1,415	0.38 %	329,914	127,204	39 %	330,374	105,074	32 %
JPY	1M	Ask	89	-	0.00 %	89	62	70 %	83	49	59 %
		Bid	87	-	0.00 %	89	4	4 %	83	-	0 %
	3M	Ask	146	-	0.00 %	146	116	79 %	136	53	39 %
		Bid	139	-	0.00 %	146	-	0 %	136	41	30 %
	6M	Ask	111	-	0.00 %	111	92	83 %	95	56	59 %
		Bid	100	-	0.00 %	111	11	10 %	95	-	0 %
	1Y	Ask	4,867	14	0.29 %	4,867	3,584	74 %	3,783	2,893	76 %
		Bid	3,791	19	0.50 %	4,867	418	9 %	3,783	293	8 %

Note: We consider a quote of an instrument *stale* if it has not changed for more than two minutes. When calculating deviations from CIP, OA and BA (cf. definitions I-VI in Table 2) we require that the quotes of *all* instruments involved in a arbitrage opportunity is more recent than two minutes, i.e. is fresh. The column headed by "All dev." presents the number of all profitable and non-profitable deviations based on exclusively non-stale (fresh) quotes. The columns headed by 'Pa dev." record the number of the profitable deviations/returns, i.e deviations that are above 1/10 of a pip. Entries in the "Share" columns are profitable deviations in percents of all of the deviations in column "All dev.'.
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 considered.

Table 11: Descriptive statistics of profitable arbitrage opportunities induced exclusively by changes in market swap points

Exchange rate			*a*) CIP			*b*) OA			*b*) BA		
			Pa dev.	Share of dev.	Mean	Pa dev.	Share of dev.	Mean	Pa dev.	Share of dev.	Mean
EUR	1M	Ask	303	15.3 %	0.27	38,661	8.1 %	0.21	49,249	7.9 %	0.22
		Bid	17	23.3 %	0.21	28,636	9.5 %	0.29	16,669	9.7 %	0.24
	3M	Ask	1,779	5.9 %	1.16	56,486	9.3 %	0.60	75,889	9.3 %	0.57
		Bid	263	7.5 %	0.96	71,115	9.7 %	0.64	45,383	9.7 %	0.44
	6M	Ask	2,491	19.4 %	1.34	130,443	19.3 %	1.14	181,383	19.8 %	1.13
		Bid	1,740	20.3 %	2.38	217,940	20.1 %	1.51	164,656	19.6 %	1.40
	1Y	Ask	3,242	15.1 %	4.62	175,307	24.3 %	2.27	200,656	25.1 %	2.47
		Bid	1,756	19.6 %	3.35	332,112	27.0 %	2.89	345,188	26.8 %	3.13
GBP	1M	Ask	817	2.3 %	0.36	24,865	2.5 %	0.53	20,382	2.3 %	0.47
		Bid	498	3.0 %	0.68	8,458	3.0 %	0.43	10,069	3.1 %	0.43
	3M	Ask	1,445	2.5 %	5.47	28,452	2.9 %	1.67	29,177	2.9 %	1.28
		Bid	689	2.9 %	2.91	27,917	2.7 %	1.15	24,012	2.8 %	1.07
	6M	Ask	3,591	9.5 %	9.93	108,035	9.0 %	2.83	114,679	8.9 %	2.27
		Bid	450	7.6 %	1.54	73,358	9.3 %	2.01	58,443	9.5 %	1.72
	1Y	Ask	5,369	14.1 %	13.41	150,956	14.5 %	5.38	170,678	14.6 %	4.32
		Bid	599	13.0 %	2.48	150,759	15.2 %	3.80	114,059	15.5 %	3.10
JPY	1M	Ask	75	4.9 %	3.22	6,689	7.5 %	0.35	21,843	9.7 %	0.25
		Bid	134	6.5 %	0.29	15,386	5.6 %	0.30	6,005	6.8 %	0.34
	3M	Ask	63	12.8 %	14.08	19,182	7.6 %	0.63	29,475	8.9 %	0.56
		Bid	370	12.8 %	1.65	16,367	8.0 %	0.67	10,656	6.7 %	0.69
	6M	Ask	132	18.4 %	15.13	41,808	9.1 %	1.45	28,907	8.5 %	1.25
		Bid	188	4.5 %	1.53	13,495	9.6 %	1.14	17,945	8.4 %	0.89
	1Y	Ask	806	23.7 %	14.36	77,005	13.4 %	2.92	79,001	13.0 %	3.64
		Bid	557	12.8 %	3.65	17,206	14.7 %	2.30	20,152	15.8 %	2.01

Note: The columns headed by "Pa dev." present the number of all profitable deviations that are exclusively due to changes in the swap points quoted; cf. the left-hand sides of the definitions I-VI in Table 2. Their numbers are a subset of the profitable deviations analyzed in Tables 4 (CIP), 6 (OA) and 8 (BA). The columns headed by "Share of dev." present the profitable deviations (owing exclusively to changes in the swap points) as shares of all of the profitable deviations analyzed in Tables 4, 6 and 8, respectively. The entries in the "Mean" columns are average values of the profitable deviations recorded in the "Pa dev." columns.
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 the swap is quoted.

Table 12: Estimation results for bivariate relationships between the characteristics of arbitrage opportunities and market pace

		a) Frequency		*b*) Size		*c*) Duration	
		IQ time	Obs	IQ time	Obs	IQ time	Obs
CIP	EUR	0.0045	834	0.0156	2,895	18.9986	2,895
		(5.47)		(1.85)		(25.16)	
	GBP	0.0025	894	0.0536	3,227	2.9681	3,227
		(2.87)		(2.14)		(1.84)	
	JPY	0.0025	386	0.0567	1,355	6.0933	1,355
		(8.67)		(5.69)		(20.24)	
OA	EUR	-0.0001	11,341	0.0017	163,457	3.2868	163,457
		(-0.65)		(4.75)		(47.81)	
	GBP	0.0001	10,829	0.0011	117,518	0.5300	117,518
		(0.66)		(2.17)		(5.40)	
	JPY	0.0002	8,232	0.0002	55,250	2.2333	55,250
		(2.85)		(0.73)		(22.36)	
BA	EUR	-0.0003	10,923	-0.0005	152,370	1.9772	152,370
		(-2.28)		(-1.65)		(30.13)	
	GBP	0.0002	10,523	0.0057	123,256	1.7557	123,256
		(1.35)		(7.62)		(11.42)	
	JPY	0.0002	7,569	0.0004	50,210	2.1745	50,210
		(2.64)		(1.60)		(17.35)	

Note: Panel a) reports estimations for the bivariate relationship between frequency and interquote time ('IQ time'). The dependent variable '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) reports estimations for the bivariate relationships between the average size of profitable deviations (in pips) from clusters of profitable deviations and IQ-time, and duration of clusters of profitable deviations and IQ-time. 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. OLS estimates of the intercept terms (positive, and statistically significant at the 5% level in all but one case) have not been reported for the sake of brevity. Associated *t*-values are reported in parenthesis below the coefficient estimates. The column '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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Exchange rates
Arbitrage
Foreign exchange microstructure

Working Paper 2005/12