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Arbitrage in the foreign exchange market: Turning on the microscope

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ABSTRACT

This paper provides real-time evidence on the frequency, size, duration and economic significance of arbitrage opportunities in the foreign exchange market. We investigate deviations from the covered interest rate parity (CIP) condition 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. The analysis unveils that: i) short-lived violations of CIP arise; ii) the size of CIP violations can be economically significant; iii) their duration is, on average, high enough to allow agents to exploit them, but low enough to explain why such opportunities have gone undetected in much previous research using data at lower frequency.

1. Introduction

Arbitrage is one of the fundamental pillars of financial economics. It seems generally accepted that financial markets do not offer risk-free arbitrage opportunities, at least when allowance is made for transaction costs. While the assumption of no arbitrage is likely to be reasonably mild or valid in several contexts in finance, its violations 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 of 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, segmented or with an imperfect degree of transparency (O'Hara, 1995; Lyons, 2001).[1]

Empirical studies have 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. Such data are, however, 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.

This paper investigates empirically the existence of arbitrage and the properties of potential departures from no-arbitrage conditions using a microstructure perspective. Specifically, we study the foreign exchange (FX) market, for which the no-arbitrage condition is well known and relatively easy to test. This condition is covered interest rate parity (CIP), which states that net returns

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

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on an investment that borrows at home and lends abroad (or vice versa) in similar interest-bearing assets will be zero when exchange rate risk is hedged through forward or swap contracts. The CIP condition is the cornerstone riskless no-arbitrage condition in the FX market. The relevant literature suggests that CIP arbitrage opportunities do not generally arise in the FX market and mispricing is negligible when one accounts for estimated transaction costs.[2]

The key advantages of this study relative to all previous empirical analyses of arbitrage are our data set, and a precise account of transaction costs as well as pricing and trading conventions. A rigorous empirical examination of no-arbitrage interest rate conditions in the FX market places stringent requirements on the data used. Contemporaneous, tradable (firm) quotes of comparable domestic and foreign interest rates and spot and forward exchange rates are needed 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 also important to have a sufficiently long sample to draw general conclusions. Our data set is the first in this literature that possesses these characteristics to a large extent, mainly because such data have been unavailable to researchers until recently. The move to electronic trading platforms in the 1990s has made it possible to obtain long data samples of real-time quotations for rigorous empirical work. The move itself provides a motivation for a fresh analysis of arbitrage opportunities because of changes in trading practices and market characteristics induced by electronic platforms.[3]

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 spot exchange rates: euro, UK sterling and Japanese yen. It also includes ask and bid quotes for exchange rate swaps and for interest rates on deposits in quoting and base currencies. The tick quotes cover a period of more than seven months spanning from February 13 to September 30, 2004, and is the longest and highest-frequency data set ever used for examining FX arbitrage. The data have been collected through Reuters trading system on special order.

To anticipate our key results, we find that trading aimed at exploiting no-arbitrage conditions is, on average, not profit-making. However, we document numerous short-lived profitable deviations from CIP. The size of the profitable deviations can be economically significant and is comparable across different maturities of the interest rates examined. Their duration is, on average, high enough to allow agents to exploit these opportunities, but low enough to explain why such CIP violations have gone undetected in much previous research using data at lower frequencies. 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 and increase with market volatility.

Overall, the evidence is consistent with the Grossman–Stiglitz view of financial markets, where efficiency is not interpreted as a statement about prices being correct at each point in time but the notion that in efficiently-functioning financial markets very short-term arbitrage opportunities can arise and invite traders to exploit them, which makes it worthwhile to watch the relevant markets. This is the arbitrage mechanism that restores the arbitrage-free prices we observe on average. Nevertheless, the lack of predictability of arbitrage and the fast speed at which arbitrage opportunities are exploited and eliminated imply that a typical researcher in international macro-finance using data at the daily or lower frequency can safely assume that CIP holds.

The paper is organized as follows. Section 2 presents the concept of CIP and a brief review of the literature. Section 3 discusses quoting conventions, transaction costs and their implications for calculations of gains and losses from arbitrage. This section also describes the data set. Section 4 presents the main empirical findings, relating to frequency, size, duration and economic significance of returns from arbitrage opportunities. Section 5 reports the results from the sensitivity analysis of the core results, and an analysis of whether and how characteristics of profitable arbitrage opportunities vary with market pace and market volatility. Section 6 briefly summarizes and concludes. Finally, the Appendix presents further details on a variety of relevant FX microstructure details and on the construction of the limit order book used in part of our empirical work.

2. Arbitrage in the FX market

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

$$(1+r_\mathrm{d}) = \frac{F}{S}(1+r_\mathrm{f}) \tag{1}$$

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

[2] Studies of FX arbitrage include Branson (1969), Frenkel (1973), Frenkel and Levich (1975, 1977), Taylor (1987, 1989), Clinton (1988), Rhee and Chang (1992), Fletcher and Taylor (1996), Aliber et al. (2003) and Juhl et al. (2006). We briefly review this literature in the next section.

[3] The growing literature on high-frequency exchange rate behavior and FX market microstructure has not–to the best of our knowledge–studied 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, 2002, 2005; Payne, 2003; Bjønnes and Rime, 2005; Lyons and Moore, 2005).

The expression in Eq. (1) neglects transaction costs, however. Such costs may be largely captured by the market buying (ask) and selling (bid) quotes of interest rates and exchange rates. The spread between ask and bid quotes for an asset covers inventory, information and order processing costs associated with the trading of the asset (see e.g. O'Hara, 1995).[4]

Taking into account ask–bid spreads of interest rates and exchange rates, CIP arbitrage is not profitable under the following conditions:

$$\left(1+r_{\mathrm{d}}^{a}\right) \geq \frac{F^{b}}{S^{a}}\left(1+r_{\mathrm{f}}^{b}\right) \tag{2}$$

$$\left(1+r_{\mathrm{f}}^{a}\right) \geq \frac{S^{b}}{F^{a}}\left(1+r_{\mathrm{d}}^{b}\right) \tag{3}$$

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.[5]

Finally, it can be shown that loss on borrowing in, for example, the domestic currency to invest in foreign currency deposits does not necessarily imply a profitable arbitrage opportunity in the reverse direction. That is, the validity of condition (2) does not necessarily imply violation of condition (3), and vice versa.

2.1. A brief review of the literature

A landmark study in the literature on testing no-arbitrage conditions in the FX market is Taylor (1987), which questioned the published evidence of deviations from CIP as it was not based on contemporaneously sampled real-time quotes of comparable domestic and foreign interest rates and spot and forward exchange rates. Accordingly, it was not possible to know whether an apparent deviation from CIP actually represented a profitable opportunity to agents at a given time or not. Taylor (1987) employed interest rate and exchange rate data points that were recorded within approximately 1 min of each other, by phoning several London brokers at ten-minute frequency during the most active hours (9.00–16.30) over three days in 1985. This study found strong evidence of CIP, not observing a single profitable CIP arbitrage opportunity.

Still, Taylor's (1987) analysis may be improved upon in several respects. First, the data spanned a period that may be too short for inferring general conclusions. Second, the recorded quotes were not strictly contemporaneous since quotes could change during a minute. Third, the ten-minute frequency at which the observations were recorded seems to be relatively low and does not enable one to characterize dynamics of possible deviations from CIP arbitrage, which may contribute to resolve the Grossman–Stiglitz arbitrage paradox. The ten-minute interval frequency used by Taylor (1987) could, however, have been sufficiently high to provide accurate results using data from the mid-1980s, especially given that there was no centralized (electronic) market at that time.

The literature on testing no-arbitrage conditions in currency markets has been somewhat dormant in the last twenty years or so.[6] This is primarily because in the non-electronic, highly decentralized markets studied until the early 1990s, it would have been extremely difficult to improve on the quality of the data beyond Taylor's (1987, 1989) papers. Subsequent studies generally supporting the absence of arbitrage opportunities includes Rhee and Chang (1992), Fletcher and Taylor (1996), Aliber et al. (2003) and Juhl et al. (2006).

3. Data and calculations of returns from arbitrage

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

3.1. Formulas used for the calculations

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

[4] In addition, fixed settlement costs may be incurred to settle and implement a trade. Also, the initiator of a trade may need to pay brokerage fees if a transaction is conducted through a broker. See Appendix A.B for details.

[5] We assume throughout that an arbitraging trader is the liquidity-consuming, aggressive part in a trade, since execution speed is crucial to exploit an arbitrage opportunity.

[6] See Sarno (2005) for a selective review of key questions in exchange rate economics and international parity conditions.

Table 1
Base and quoting currencies

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

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

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 as the base currencies are actually foreign currencies for a dealer. Table 1 makes explicit the quoting and base currencies for the three exchange rates examined.

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, Eqs. (2) and (3), while taking into account relevant quoting and maturity conventions. Thus, the deviations from CIP on the bid side and the ask side, respectively, can be expressed as

$$\mathrm{Dev}_{\mathrm{CIP}}^{b} = \left(F^{b}-S^{a}\right) \times 10^{4} - \frac{S^{a}\left(i_{d}^{a} \times \frac{D}{360} - i_{f}^{b} \times \frac{D}{360}\right)}{\left(100 + i_{f}^{b} \times \frac{D}{360}\right)} \times 10^{4} \tag{4}$$

$$\mathrm{Dev}_{\mathrm{CIP}}^{a} = -\left(F^{a}-S^{b}\right) \times 10^{4} + \frac{S^{b}\left(i_{d}^{b} \times \frac{D}{360} - i_{f}^{a} \times \frac{D}{360}\right)}{\left(100 + i_{f}^{a} \times \frac{D}{360}\right)} \times 10^{4} \tag{5}$$

where the first term on the right-hand side of each equation represents market swap points for a given maturity obtained from Reuters, while the second term represents the corresponding derived swap points. In order to calculate derived swap points that are directly comparable to the market swap points quoted on Reuters, we adjust the interest rates i, which are quoted in percent per annum, to obtain interest rates for maturities less than a year. Specifically, 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.A for details.[7] Thereafter, the resulting term is multiplied by 10^4 (or 10^2 in the case of the Japanese yen) to obtain the derived swap points. Deviations from the no-arbitrage conditions, Eqs. (4) and (5), are expressed in pips since they are defined as the difference between quoted and derived swap points.

CIP deviations (4) and (5) are profitable if they are positive net of other transactions costs. That is, when defining a profitable arbitrage deviation, the expressions for returns presented in Eqs. (4) and (5) must be larger than 1/10 of a pip in order to cover brokerage and settlement costs. Appendix A.B shows that the sum of brokerage and settlement costs is at most 1/10 of a pip of a US-dollar pip for an arbitrage deal of required size.[8]

3.2. Data

We employ tick data collected via a continuous feed from Reuters over the period from February 13 to September 30 2004. The data set allows us to investigate CIP arbitrage for three major exchange rates at four different maturities: 1, 3, 6 and 12 months. It includes all best ask and bid spot exchange rates for three major exchange rates: USD/EUR, USD/GBP and JPY/USD—hereafter EUR, GBP and JPY, respectively (see Table 1). 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 currencies involved.

An advantage of using deposit rates for interest rates is that an arbitrageur would know when and how much she will pay or receive. The use of deposits implies, however, that we limit the pool of potential arbitrageurs to those that have credit agreements, since deposits are on-balance sheet instruments. This limitation is not particularly severe in the present context since all major banks have such credit agreements established between themselves.

For the spot exchange rates we have firm quotes from Reuters electronic brokerage system (D3000-2); these quotes are tradable as spot transactions can be carried out with a market order in the Reuters system. For swaps and euro-currency deposits only

[7] 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.

[8] 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 minuscule, about 10^{-5} per US dollar in sum. Ideally, in the case of JPY/USD we should have converted 1/10 of a pip in US dollars to JPY at the appropriate exchange rate at the end of each month—see Appendix A.B. On the other hand, 1/10 of a pip probably covers more than the average cost for each arbitrage deal involving three trades. 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.

indicative ask and bid quotes were available to us through Reuters Monitor (i.e. Reuters 3000 Xtra). This is mainly because both swaps and deposits are primarily traded bilaterally between interbank dealers, typically over telephone or Reuters D2000-1. Data from these sources is virtually impossible to obtain and has never been retrieved for empirical work in this context, to the best of our knowledge. Recently, an electronic-broker trading platform for swaps has been introduced, but this has yet to develop as the preferred platform.

However, in light of evidence for spot exchange rates in Daníelsson and Payne (2002) and our conversations with users of the Reuters trading system, one may say that spreads between indicative ask and bid quotes for swaps as well as for interest rates will not be smaller than those for corresponding firm ask and bid quotes. Thus, use of the indicative quotes would probably not lead us to exaggerate the number and size of arbitrage opportunities.[9] Actually, we may obtain results quite close to those implied by (unavailable) firm quotes for swaps and euro-currency deposits. This is because indicative quotes for swaps and deposits are also used for signaling in the dealer market, and hence regarded as a reliable indication of firm quotes in lack of other information sources. Essentially, because trading in swaps and euro-currency deposits only rarely occur on the Reuters electronic broker system, traders base their trading strategies on the posted indicative quotes, and the quotes on Reuters D2000-1 tend to be, therefore, very close to the quotes on Reuters 3000 Xtra. In contrast, indicative quotes for spot are primarily meant as advertisement towards the non-bank customers and, therefore, do not give a reliable indication of firm inter-dealer spot quotes. Thus, it is more important to have firm quotes for spot exchange rates than for exchange rate swaps and euro-currency deposits to obtain results close to those implied by firm quotes for all instruments.

Still, one drawback of using the indicative quotes is that they can become stale at times, and thereby potentially signal spurious arbitrage opportunities. Usually, dealers keep real quotes up to date, but may fail to do so when market activity is particularly high, in which case indicative quotes will be centered on previous, rather than on current, firm quotes. If so, it will be possible for the indicative ask to be lower than the true ask, or for the indicative bid to exceed the true bid, even while the indicative spread exceeds the true spread. Such cases could give rise to arbitrage opportunities in our empirical work when there are no opportunities in reality—i.e. false positives. We examine the robustness of our findings to this possibility by analyzing separately cases where an arbitrage opportunity arises because of a newly arrived spot quote in combination with existing swap quotes versus those that arise due to a newly arrived swap quote in combination with existing spot quote. The latter case is less likely to represent a stale swap quote.

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

Despite ignoring numerous observations to ensure calculations of arbitrage opportunities with as high a share of fresh quotes as possible, we are able to investigate a large number of data points (i.e. CIP deviations): 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 are obtained (see Table 2). 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).[11]

4. Frequency, size, duration and economic significance of arbitrage opportunities

4.1. Frequency and size

Table 2 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, we note that the number of observations increases with the maturity of contracts. This reflects the fact that the frequency of quote changes tends to be higher at higher maturities, especially for the swaps.

[9] In other words, if one cannot profit from arbitrage at the tight spread implied by firm prices, one definitely cannot profit at the worse prices in the wider spread provided by indicative quotes. The opposite is not true. In principle, therefore, there can be instances of arbitrage using firm prices that are not detected when using indicative prices.

[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.

[11] 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.

Table 2
Descriptive statistics of CIP deviations

Exchange rate			a) All deviations						b) Profitable deviations					
			All dev.	Mean	*t*-value	Median	Ann. mean	Inter-quote time (s)	Pa dev.	Share (%)	Mean	Median	Ann. mean	Inter-quote time (s)
EUR	1M	Ask	2,037,923	−0.90	−4.2	−0.9	−11	2.9	1975	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	3500	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	8559	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	8966	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	5950	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	4593	0.17	4.52	2.35	5	2.5
JPY	1M	Ask	804,885	−1.04	−3.4	−1.0	−12	7.3	1545	0.19	0.37	0.15	4	13.8
		Bid	804,885	−1.02	−3.5	−1.0	−12	7.3	2068	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	2891	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	4140	0.49	1.45	1.25	3	2.8
	1Y	Ask	892,242	−8.37	−2.3	−8.3	−8	6.6	3403	0.38	6.21	2.00	6	10.9
		Bid	892,242	−13.42	−3.4	−13.6	−13	6.6	4358	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, 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 as a percentage 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" is simply the (period) mean value divided by the respective sample standard deviation. The "Inter-quote time (s)" columns present the average time in seconds from the previous deviation. In Panel b) the "Inter-quote time" is conditioned on the current deviation being profitable.
Sample: Based on Reuters tick quotes. February 13–September 30, 2004, weekdays, between GMT 07:00 and 18:00. The following dates have been removed: April 2, 5–9, 12, May 3 and 31, June 17 and 18, August 10, 13, 24, and September 15.

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 in Panel a). Also, the median returns are very close to the mean returns, 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.[12] 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 deviation from CIP rather than zero. Nevertheless, the 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 2 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 2 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 higher maturities. New CIP deviations occur every 2–3 s on average for EUR and GBP, and every 6–7 s 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

[12] 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.

Table 3
Duration of clusters of CIP arbitrage opportunities (in minutes)

Exchange rate			# Clusters	Mean	Stdev	Median	Q1	Q3
EUR	1M	Ask	55	1:35	1:56	0:49	0:18	2:05
		Bid	8	4:03	9:33	0:39	0:09	1:35
	3M	Ask	293	4:44	12:11	1:04	0:21	3:34
		Bid	81	1:36	2:01	0:57	0:26	2:14
	6M	Ask	419	0:57	1:29	0:26	0:12	1:01
		Bid	416	0:44	2:01	0:18	0:08	0:30
	1Y	Ask	660	1:06	2:33	0:23	0:11	1:07
		Bid	518	0:36	1:01	0:14	0:06	0:36
GBP	1M	Ask	339	4:11	10:46	1:30	0:25	4:00
		Bid	70	11:02	55:16	0:39	0:14	1:23
	3M	Ask	404	5:54	13:59	1:43	0:26	5:05
		Bid	86	8:47	4:23	0:37	0:11	1:59
	6M	Ask	554	2:18	8:34	0:25	0:10	1:09
		Bid	207	1:10	2:05	0:27	0:11	1:33
	1Y	Ask	923	1:20	4:17	0:19	0:09	0:55
		Bid	232	0:48	1:46	0:18	0:08	0:46
JPY	1M	Ask	38	10:14	13:36	4:34	2:52	10:45
		Bid	60	3:28	8:07	1:36	0:54	2:53
	3M	Ask	17	5:22	13:46	0:16	0:06	1:36
		Bid	103	7:32	15:51	3:01	2:05	9:12
	6M	Ask	52	3:15	8:45	0:27	0:10	2:07
		Bid	133	1:20	3:05	0:23	0:10	1:01
	1Y	Ask	415	1:20	4:36	0:29	0:13	1:04
		Bid	183	1:47	3:26	0:41	0:16	1:51

Note: A cluster consists of at least two profitable CIP deviations in a row. The entries in the "Mean" column denote the average duration (min:s) of the clusters (based on the corresponding entries in the column "# Clusters"), while those in the "Median" column refers to the median duration of the clusters. The "Q1" and "Q3" columns present the first and the third quantiles of the duration of clusters, respectively. The "Stdev" column includes sample standard deviations of the duration of the clusters.

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 CIP arbitrage opportunity may on average arrive at least every hour when the number of profitable deviations ("Pa dev.") are greater than 1661 ($=151\times 11$). As shares of the total number of data points considered, however, the profitable arbitrage opportunities are minuscule. 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.[13]

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. The returns show no systematic pattern with maturity of the instruments involved in arbitrage.[14,15] Also, the average inter-quote time for profitable deviations ranges from less than 2 s to 15.6 s, except for one extreme case of 25 s for EUR at the one-month bid. However, 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 2.

4.2. Duration

Table 3 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 8 to a maximum of 923. 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 s to less than 4 min. Median values of the

[13] Table 2 also suggests that there are fewer profitable arbitrage opportunities with lending dollar funds than when lending 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 1. Hence, the finding of more arbitrage on the ask side of EUR and GBP and bid side of JPY might be an artifact of the reverse quoting convention of dollar per euro and sterling versus yen per dollar in Reuters system. There may be deeper microstructural reasons for this finding related to, for example, trade and execution issues, but we are not aware of any obvious reason why arbitrage opportunities occur more frequently when lending dollar funds over the sample analyzed. This is an intriguing issue which we leave for future research.

[14] The lack of relationship between size and maturity is in contrast with the conjecture that there may be a "maturity effect" such that the size of arbitrage profits increases with maturity. This 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 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. 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).

[15] In all cases, the median values of profits are comparable to the corresponding mean values, which also suggest fairly symmetric distributions of profits from CIP arbitrage.

durations are even lower than the corresponding average durations: they are generally less than 1 min in the case of EUR; at most 1:43 min in the case of GBP; and at most 4:34 min in the case of JPY. 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 lower than a few minutes, but exceptionally they can be higher than 10 min. Often the relatively large standard deviations occur when there are relatively few observations, i.e. clusters. The first and third quantiles in the last two columns of Table 3 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 relatively few outliers. They also explain the particularly long average duration of a few clusters of profitable CIP deviations. In short, the duration of profitable CIP deviations is relatively low but sufficiently high on average for a trader to exploit the arbitrage opportunities.

Overall, the evidence in this section has unveiled a number of CIP arbitrage opportunities. However, these opportunities amount to small numbers when one compares them to the total number of observations examined. The size of profitable CIP deviations is, however, economically appealing, with period returns (the annualized mean returns of profitable CIP arbitrage in Table 2) up to 15 pips. These are relatively large returns when compared with the typical size of spreads in the major dealer markets, usually around 2 pips. The size of the returns may seem small relative to the returns targeted by major players in the FX market, such as hedge funds, but it is not small if we bear in mind that they are riskless and require no own capital.

In order to exploit an arbitrage opportunity, however, a trader needs to undertake three deals virtually simultaneously or as fast as possible.[16] 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 several deals with 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.

4.3. Economic significance

The analysis so far has documented that profitable CIP deviations arise and may provide small, yet non-negligible profits. In order to establish whether these deviations are economically significant, we investigate whether they are worth exploring and can be acted upon. This requires information about currency volumes available for trading at quotes suggesting profitable arbitrage opportunities. Information about exact volumes available for trading is not available to us. Furthermore, for the swap and the deposit markets, where we only have indicative quotes and no information on trades, alternative measures of volume available for trading are likely to be very imprecise. For the spot market, however, for which we have both firm quotes and information on the number of trades, we can estimate orders available for trade, so-called limit orders, at ranges of spot exchange rate quotes; see Appendix A.C for details on the estimation of the limit orders. These limit orders indicate the liquidity in the spot currency market since–for a given order size–the higher the number of limit orders the more volume is available for trading. The liquidity of the spot market may give an indication about how liquidity providers in these markets behave in situations of profitable arbitrage. Since the spot exchange market is deeper than the markets for the currency deposits and exchange rate swaps, the estimated orders available for trading in the spot market can be considered as the upper bound on orders available for trading at CIP deviations.

Panel a) of Table 4 presents the average and median numbers of limit orders at best spot prices when there are profitable arbitrage opportunities. The results show that the average number of the limit orders varies from about 3 to 7, while the median numbers are in the somewhat lower range of 1 to 5. This suggests that occasionally there can be a relatively large number of limit orders at the best quotes. Moreover, since the size of profitable deviations may amount to several pips in some cases (see Table 2), the spot quotes can deviate from the best quotes without necessarily eliminating the arbitrage opportunities. The number of limit orders available when profitable arbitrage opportunities occur would therefore be higher than those available at the best quotes.

To calculate the limit orders available we need to know how much the spot exchange rate can deviate from the current level before an arbitrage opportunity will be lost. For this purpose, we reformulate the expression for CIP deviations on the bid side and ask sides as follows, while assuming that the interest rate and forward quotes remain unaltered:

$$\left(F^b - \frac{\delta}{10^4}\right) \times \frac{100 + i_f^b \times \frac{D}{360}}{100 + i_d^a \times \frac{D}{360}} - S^a = \frac{Dev_{\mathrm{CIP}}^b - \delta}{10^4} \times \frac{100 + i_f^b \times \frac{D}{360}}{100 + i_d^a \times \frac{D}{360}} \tag{6}$$

$$S^b - \left(F^a - \frac{\delta}{10^4}\right) \times \frac{100 + i_f^a \times \frac{D}{360}}{100 + i_d^b \times \frac{D}{360}} = \frac{Dev_{\mathrm{CIP}}^a - \delta}{10^4} \times \frac{100 + i_f^a \times \frac{D}{360}}{100 + i_d^b \times \frac{D}{360}} \tag{7}$$

[16] If the deals (one in the swap market and two in the money market) are conducted consecutively from a single platform, it may take above 1 min; a typical deal usually takes 25 s on the Reuters dealing system; see Reuters (1999, p. 114).

Table 4
Spot market characteristics when CIP deviations are profitable. Limit order depth (in number of orders) and deviations from arbitrage-free prices (in pips)

Exchange rate			a) Spot market limit order depth					b) Spot price deviations		
			Pa dev.	(i) Best depth		(ii) Total depth		Pa dev.	Mean	Median
				Mean	Median	Mean	Median			
EUR	1M	Ask	52	4.14	2	4.14	2	73	0.08	0.03
		Bid	1685	4.92	3	4.92	3	1975	0.16	0.14
	3M	Ask	3215	6.06	4	6.63	5	3500	0.78	0.56
		Bid	26,254	7.65	5	9.47	6	30,116	0.75	0.29
	6M	Ask	6789	6.78	4	10.30	8	8559	2.48	2.33
		Bid	10,529	5.62	3	7.64	5	12,844	1.34	1.20
	1Y	Ask	6969	6.36	4	9.72	8	8966	3.20	2.04
		Bid	17,519	7.34	4	13.36	11	21,495	5.23	4.59
GBP	1M	Ask	16,333	3.90	3	4.11	3	16,835	0.59	0.59
		Bid	34,257	4.17	3	4.22	3	35,110	0.25	0.16
	3M	Ask	23,437	5.73	4	10.95	9	24,124	2.82	3.01
		Bid	54,251	4.16	3	5.45	4	57,523	2.04	1.31
	6M	Ask	5426	3.94	3	5.28	4	5950	1.63	1.30
		Bid	34,442	4.11	3	8.11	6	37,820	4.87	3.21
	1Y	Ask	3967	4.47	3	7.62	6	4593	4.54	2.32
		Bid	32,940	4.25	3	8.26	6	37,987	9.24	7.50
JPY	1M	Ask	1885	3.65	2	3.67	2	2068	0.13	0.08
		Bid	1353	2.23	1	2.24	1	1545	0.27	0.05
	3M	Ask	2085	2.39	1	3.87	3	2891	1.74	1.63
		Bid	420	3.19	2	4.29	4	491	3.78	2.91
	6M	Ask	3838	5.58	4	8.34	7	4140	1.36	1.16
		Bid	525	2.78	2	3.98	2	718	4.66	0.80
	1Y	Ask	3602	3.32	2	5.97	5	4358	3.48	3.24
		Bid	2176	3.05	2	5.34	4	3403	6.25	1.94

Note: Panel a) shows the average and median depth (measured in number of orders) at (i) the best prices (i.e. lowest ask and highest bid), and (ii) the total depth between the current best price and the critical value (no arbitrage) of the spot price. Panel b) shows the average sizes and median values of the difference between the current spot rate and the spot rate implied by no arbitrage, both measured in pips. The columns headed by "Pa dev." present the number of profitable deviations, i.e. CIP deviations that are larger than 1/10 of a pip. In Panel a) we only use the profitable deviations where we also have observations on depth. The rows "Ask" and "Bid" refer to the spot prices, and that the spot ask (bid) price enters in the bid (ask) CIP calculation.
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.

where δ=1/10 of a pip, and F^b is the forward rate (i.e. the spot ask quote plus the swap bid quote). The first term in expression (6) and the second term in expression (7), say $\bar{S}^a$ and $\bar{S}^b$ respectively, define the spot quote at which the profit from CIP arbitrage will be zero; while S^a and S^b are the best ask and bid spot quotes, which we observe. Profitable arbitrage at the CIP bid side requires the ask spot quote S^a to be lower than the critical value defined by the first expression in (6), $\bar{S}^a$; while profitable arbitrage at the CIP ask side requires that the spot quote S^b is higher than the critical value defined by the second expression in (7), $\bar{S}^b$. The critical values $\bar{S}^a$ and $\bar{S}^b$ essentially define a band of ask and bid spot quotes, respectively, at which trading on the CIP deviation will be profitable, at given interest rates and forward rates.[17]

Panel b) of Table 4 shows how much the spot quotes can deviate from the current value without eliminating the corresponding arbitrage opportunities. Consistent with the average sizes of the profitable deviations in Table 2, the deviations from the critical spot rates (in pips) are on average between 0.08 and 5.23 in the case of EUR, between 0.25 and 9.24 in the case of GBP, and between 0.13 and 6.25 in the case of JPY.

Panel a) of Table 4 also presents the average and median numbers of limit orders available at spot exchange rate quotes at which profitable deviations will not be lost. That is, we measure the depth of the limit order book within, e.g. the range $\bar{S}^a$–S^a from the best spot quote S^a. It is seen that the average number of limit orders is in the range from 4 to 13 for different currencies and maturities. The median number of the limit orders is in the range from 1 to 11. However, the depth of the limit order book at quotes different from the best quotes is likely to be underestimated. This is because, our data records all the limit orders at the best prices, but not limit orders that are entered further out in the book.

The availability of several limit orders when there are profitable arbitrage opportunities suggests that profits from exploiting arbitrage opportunities can be economically significant. Unfortunately, we do not have information about the size of the limit orders available for trading. Given the frequency and size of profitable CIP deviations recorded in Table 2, however, and given the depth of the market documented in Table 4, even relatively small profits of a few pips per arbitrage trade can accumulate to yield sizable profits over time.

As a further piece of evidence that the market is active when CIP deviations are profitable, we report in Table 5 the time between postings of limit orders at the best prices, which may or may not differ from that for previous limit orders. The results in Table 5 suggest that the spot market is quite active and limit orders are frequently posted. The time between the postings of the

[17] One can alternatively reformulate a CIP deviation such that one lets the swap quote, instead of the forward quote, remain unaltered in addition to the interest rates. In this case, the implied band around the best ask and bid spot quotes becomes wider, increasing the ranges of the spot quotes for which arbitrage will remain profitable.

Table 5
Median time since previous spot quote during CIP arbitrage opportunities (in seconds)

		EUR	GBP	JPY
1M	Ask	1	1	3
	Bid	4	1	2
3M	Ask	1	1	2
	Bid	1	1	3
6M	Ask	1	1	2
	Bid	1	1	1
1Y	Ask	1	1	2
	Bid	1	1	2

Note: The columns present the median number of seconds between two new spot quotes in a profitable CIP deviation. Rows labeled “Ask” refer to CIP arbitrage at the ask side, hence the spot at the bid. Rows labeled “Bid” refer to CIP arbitrage at the bid side, hence the spot at the ask.
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.

limit orders is mostly 1 s in the case of EUR and GBP, and around 2 s in the case of JPY. Even though the limit orders are posted frequently and the corresponding spot quotes are changed at a fast pace, they often do not change sufficiently to eliminate profitable CIP deviations. As reported in Table 3, profitable CIP deviations can last from 30 s to several minutes, on average.

Taking together the results in this section, we may envision that a dealer observing an arbitrage opportunity would, given the non-negligible duration of profitable arbitrage opportunities, consider it worthwhile to inquire from her trading partners (including the electronic broker for currency trading) about the relevant quotes that she would face, conditional on her (institution's) credit rating and desired trade size. Two important caveats are in order, however. First, *ex ante* the trader will not know for sure whether the quotes offered to her 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. Second, 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. If arbitrage remains profitable at the offered quotes while making allowance for sufficiently large currency price movements, and she is able to seal the required deals at those prices, the resulting profit will be risk-free. If these conditions are not met, the trader will be at liberty to decline trading at the provided quotes, and hence will not suffer any loss.[18]

5. Robustness and further 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 CIP violations and their relation to the pace of the market and volatility.

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 (either due to a holiday or failure of the feed), and by including only quotes during the highest activity part of the trading day, namely 07:00–18:00 GMT.

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 define a quote as “stale” if it occurs in an inactive state of the market, more precisely if the quote has not changed within the last 2 min and will not change within the next 2 min. Thereafter, when calculating deviations from CIP we require that the quotes of all instruments involved in an arbitrage opportunity are fresh, i.e. they are not stale according to the above definition. All deviations which do not meet this criterion are excluded from the sample. This a very stringent condition which should ensure that we use data from very active trading periods because, while quotes for spot exchange rates and for swap rates change at a very fast pace, quotes for euro-currency deposits change at a significantly slower pace. Consequently, the results, reported in Table 6, indicate that this screening of the data reduces drastically the number of observations analyzed, especially for JPY. Also, the number of profitable deviations decreases substantially.

However, the frequency of occurrence of arbitrage–calculated as the share of profitable arbitrage violations out of the total number of deviations based on the particularly fresh quotes–remains comparable to the frequencies reported in Table 2. Specifically, we find a low share of CIP violations, ranging from zero to about 3%. We also note that for some exchange rates and maturities the frequency is lower in this selective data set, while in some cases the frequency is higher relative to the baseline data set used in Section 4. These findings corroborate the results in Section 4 and add credibility to the view that at least some of the profitable CIP deviations reported here are genuine.[19]

[18] A trader is free to act only 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.

[19] We also carried out the exercise in this sub-section by using fresh quotes defined on the basis of a 1-minute (rather than 2-minute) change in price, and found results that are qualitatively identical to the ones reported in Table 6. These results are not reported but are available from the authors upon request.

Table 6
CIP arbitrage opportunities when controlling for stale quotes

Exchange rate			All dev.	Pa dev.	Share (%)
EUR	1M	Ask	54,806	145	0.26
		Bid	54,848	2	0.00
	3M	Ask	79,927	2645	3.31
		Bid	81,009	328	0.40
	6M	Ask	356,191	3823	1.07
		Bid	358,931	2927	0.82
	1Y	Ask	563,445	7920	1.41
		Bid	574,712	3073	0.53
GBP	1M	Ask	17,075	12	0.07
		Bid	19,285	95	0.49
	3M	Ask	40,206	1237	3.08
		Bid	43,780	438	1.00
	6M	Ask	158,986	2829	1.78
		Bid	179,055	508	0.28
	1Y	Ask	329,913	4866	1.47
		Bid	374,680	1415	0.38
JPY	1M	Ask	89	0	–
		Bid	87	0	–
	3M	Ask	146	0	–
		Bid	139	0	–
	6M	Ask	111	0	–
		Bid	100	0	–
	1Y	Ask	4,868	14	0.29
		Bid	3,791	19	0.50

Note: We consider a quote of an instrument as stale if it occurs in an inactive state of the market, more precisely when the quote has not changed within the last 2 min, and will not change within the next 2 min. When calculating CIP deviations we require that the quotes of all instruments involved in a arbitrage opportunity are fresh, i.e. are not stale according to the above definition. The column headed by "All dev." presents the number of all profitable and non-profitable deviations based on these strict criteria. The column headed by "Pa dev." presents the number of the profitable deviations, i.e. deviations that are above 1/10 of a pip, out of the possible cases in column "All dev.". Entries in the "Share" column are profitable deviations in percent 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.

5.2. Is any of the assets involved in arbitrage priced using no-arbitrage conditions?

Given our findings that arbitrage opportunities arise, at least one of the assets involved in FX arbitrage must sometimes be 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. Moreover we also test the widely held view that forward contracts are priced according to the CIP condition. If this is the case, then price setting would be carried out in such a way as to prevent arbitrage opportunities from arising. More generally, we can test whether any of the four assets involved in arbitrage–spot, swap, domestic and foreign interest rates–is priced according to no-arbitrage conditions in continuous time. Using data on profitable CIP deviations, we calculate the number of times an arbitrage opportunity was present at the same second when only the market swap quote was fresh (just posted), whilst the quotes entering the derived swap points were predetermined (or did not change). We then carry out the same exercise for the case when, in turn, only one of the spot exchange rate, the foreign interest rate and domestic interest rate are fresh quotes. We would expect that if an instrument was priced using the CIP formula, the CIP condition should be valid at least whenever that instrument is priced, i.e. whenever a new quote for that instrument is posted.

The results, reported in Table 7, show that the profitable deviations owing exclusively to a new quote in one of the four instruments involved in arbitrage when the other instruments do not change (even if they are quoted) as a share of all such possible cases is comparable across instruments and also comparable to the corresponding shares reported in Table 2. These results do not support the view that forward rates–or spot rates or else deposit rates–are systematically set such that they ensure the validity of the CIP condition using all available information. Thus, apparently, either the practice of using the CIP formulas to set prices is not feasible at this very high frequency, and/or the providers of quotes do not update the formulas with all available information when offering quotes.

This evidence indicates that none of the asset prices is systematically set using no-arbitrage conditions at tick frequency, and that each of them is partly responsible for the short-term CIP violations reported here.

5.3. Day of the week and hours of the day effects

To further examine the properties of CIP violations, we investigate whether they occur during a specific time of the day when, for example, trading might be particularly low—e.g. at the very beginning of a trading day. We also examine whether CIP arbitrage occurs more frequently in some days of the week than others. The results for day-of-the-week and hours-of-the-day effects are reported in Tables 8 and 9, respectively.

Table 7
Descriptive statistics of CIP arbitrage opportunities induced exclusively by change in one instrument

Exchange rate			a) Swap		b) Spot		c) Foreign interest rate		d) Domestic interest rate	
			Pa dev.	Share (%)	Pa dev.	Share (%)	Pa dev.	Share (%)	Pa dev.	Share (%)
EUR	1M	Ask	302	0.18	1621	0.09	26	0.21	8	0.04
		Bid	17	0.01	52	0.00	1	0.01	1	0.01
	3M	Ask	1777	0.91	25,498	1.41	186	1.12	3399	13.43
		Bid	255	0.13	2990	0.17	66	0.40	67	0.26
	6M	Ask	2492	0.56	9544	0.55	223	0.59	237	0.76
		Bid	1716	0.38	6056	0.35	303	0.80	150	0.49
	1Y	Ask	3239	0.49	16,105	0.96	540	1.08	629	1.56
		Bid	1710	0.25	6157	0.37	389	0.80	205	0.52
GBP	1M	Ask	817	1.27	30,274	1.51	36	0.28	257	1.32
		Bid	498	0.79	16,144	0.70	13	0.10	123	0.64
	3M	Ask	1444	2.10	48,312	2.42	129	1.18	2797	10.30
		Bid	689	1.02	23,036	1.00	130	1.20	182	0.69
	6M	Ask	3589	1.51	26,566	1.37	243	1.21	589	1.67
		Bid	449	0.19	5223	0.23	42	0.21	162	0.47
	1Y	Ask	5369	1.32	21,414	1.11	446	1.55	991	2.16
		Bid	587	0.15	3714	0.17	65	0.23	148	0.33
JPY	1M	Ask	75	0.13	1340	0.19	58	0.29	0	–
		Bid	134	0.24	1864	0.26	43	0.21	10	0.47
	3M	Ask	63	0.10	404	0.06	12	0.04	0	–
		Bid	370	0.57	2049	0.29	420	1.54	8	0.25
	6M	Ask	132	0.18	501	0.07	63	0.17	2	0.05
		Bid	182	0.24	3746	0.53	169	0.46	10	0.26
	1Y	Ask	806	0.69	2003	0.29	432	0.90	15	0.25
		Bid	518	0.44	3420	0.49	301	0.63	14	0.23

Note: The columns headed by "Pa dev." present the number of all profitable deviations (i.e. deviations that are larger than 1/10 of a pip) that are exclusively due to changes in only one instrument. Their numbers are a subset of the profitable deviations analyzed in Table 2. The columns headed by "Share" present the profitable deviations (owing exclusively to changes in the instrument in question) as shares of all the deviations when only one instrument changes quote.

Sample: Based on Reuters tick quotes. February 13–September 30, 2004, weekdays, between GMT 07:00 and 18:00. The following dates have been removed: April 2, 5–9, 12, May 3 and 31, June 17 and 18, August 10, 13, 24, and September 15. The profitable CIP deviations refer to those where only one of the instruments in the formula is quoted.

Table 8
CIP arbitrage opportunities by day of week

Exchange rate			Monday		Tuesday		Wednesday		Thursday		Friday		All
			Pa dev.	Share (%)	Pa dev.	Share (%)	Pa dev.	Share (%)	Pa dev.	Share (%)	Pa dev.	Share (%)	
EUR	1M	Ask	96	5	662	34	369	19	294	15	554	28	1975
		Bid	5	7	25	34	1	1	5	7	37	51	73
	3M	Ask	4506	15	882	3	18,546	62	817	3	5365	18	30,116
		Bid	202	6	1360	39	132	4	1607	46	199	6	3500
	6M	Ask	1941	15	1609	13	3106	24	2530	20	3658	28	12,844
		Bid	1156	14	956	11	692	8	3421	40	2334	27	8559
	1Y	Ask	3576	17	9062	42	2621	12	3115	14	3121	15	21,495
		Bid	2057	23	935	10	877	10	1468	16	3629	40	8966
GBP	1M	Ask	8982	26	951	3	11,188	32	12,977	37	1012	3	35,110
		Bid	29	0	923	5	782	5	1149	7	13,952	83	16,835
	3M	Ask	12,867	22	4101	7	18,265	32	8156	14	14,134	25	57,523
		Bid	405	2	90	0	21,312	88	869	4	1448	6	24,124
	6M	Ask	12,276	32	2878	8	6202	16	10,100	27	6364	17	37,820
		Bid	181	3	4485	75	358	6	78	1	848	14	5950
	1Y	Ask	7499	20	9387	25	7719	20	6794	18	6588	17	37,987
		Bid	265	6	340	7	397	9	118	3	3473	76	4593
JPY	1M	Ask	1	0	161	10	1358	88	25	2	0	–	1545
		Bid	61	3	5	0	20	1	0	–	1982	96	2068
	3M	Ask	2	0	259	53	0	–	22	4	208	42	491
		Bid	2240	77	176	6	119	4	19	1	337	12	2891
	6M	Ask	112	16	43	6	53	7	162	23	348	48	718
		Bid	1052	25	134	3	563	14	439	11	1952	47	4140
	1Y	Ask	381	11	610	18	886	26	390	11	1136	33	3403
		Bid	1261	29	1926	44	55	1	327	8	789	18	4358

Note: The columns headed by "Pa dev." record the number of the profitable deviations, i.e. deviations that are larger than 1/10 of a pip. Entries in the "Share" columns are profitable deviations in percent of all of the profitable deviations (reported in column "All").

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
Shares of CIP arbitrage opportunities by hour of day

Exchange rate			[07–08) (%)	[08–09) (%)	[09–10) (%)	[10–11) (%)	[11–12) (%)	[12–13) (%)	[13–14) (%)	[14–15) (%)	[15–16) (%)	[16–17) (%)	[17–18) (%)	All
EUR	1M	Ask	40.2	15.6	5.5	2.5	10.3	11.1	14.8	0.1	–	–	–	1975
		Bid	–	54.8	12.3	–	–	–	6.8	–	–	8.2	17.8	73
	3M	Ask	4.8	6.4	8.8	6.6	8.2	15.6	12.2	14.0	12.7	6.7	4.0	30,116
		Bid	78.5	11.2	1.8	1.6	2.2	1.4	–	1.9	0.8	0.2	0.2	3500
	6M	Ask	20.6	3.8	2.6	1.0	4.3	22.6	19.8	18.7	6.4	0.1	0.0	12,844
		Bid	48.9	4.1	4.6	2.8	4.2	12.3	9.5	8.0	2.9	1.8	1.0	8559
	1Y	Ask	21.8	3.7	3.4	0.9	3.1	19.0	15.2	19.0	10.6	1.5	1.9	21,495
		Bid	20.8	8.9	7.7	3.3	2.7	10.0	6.6	18.4	16.5	3.8	1.4	8966
GBP	1M	Ask	3.3	8.4	2.6	5.0	7.0	18.4	17.5	16.6	9.9	8.3	3.0	35,110
		Bid	5.6	5.2	9.2	5.4	6.5	20.9	15.8	11.8	10.3	5.4	3.9	16,835
	3M	Ask	7.0	6.0	7.8	1.5	7.4	15.4	17.5	14.3	11.5	7.7	3.9	57,523
		Bid	12.0	11.5	8.6	10.6	9.5	9.9	9.1	10.9	9.4	4.5	4.1	24,124
	6M	Ask	14.1	12.9	2.6	1.7	9.0	24.5	17.7	13.0	4.4	0.0	–	37,820
		Bid	12.7	10.8	28.2	14.9	14.9	6.6	1.7	2.0	3.3	2.2	2.8	5950
	1Y	Ask	17.9	6.9	4.0	3.4	6.5	23.0	12.4	14.6	6.6	2.3	2.4	37,987
		Bid	9.5	2.2	11.9	0.2	0.5	16.4	2.5	15.2	18.2	17.2	6.1	4593
JPY	1M	Ask	3.8	9.8	4.1	9.7	3.0	17.2	27.7	19.2	2.6	2.1	0.7	1545
		Bid	11.5	7.8	23.2	13.7	4.8	27.6	3.7	5.6	2.2	–	0.0	2068
	3M	Ask	1.4	40.5	–	–	–	35.8	11.8	4.7	–	3.1	2.6	491
		Bid	29.1	14.5	11.3	12.5	2.4	9.2	5.6	4.8	7.0	2.4	1.2	2891
	6M	Ask	6.7	44.8	–	–	–	14.2	4.6	13.2	10.6	2.6	3.2	718
		Bid	61.1	0.2	0.1	0.8	1.9	11.9	9.2	13.2	1.1	0.1	0.2	4140
	1Y	Ask	6.6	7.0	3.3	4.6	3.3	16.7	13.8	22.5	11.8	7.3	3.1	3403
		Bid	36.1	0.9	0.6	1.0	1.2	10.5	15.6	18.2	13.7	0.9	1.2	4358

Note: The table presents the share of all profitable deviations (i.e. deviations that are larger than 1/10 of a pip) that has occurred during in indicated hour out of all profitable deviations, reported in the “All” column.
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.

Upon examining the share of profitable CIP opportunities across days (Table 8), we find that arbitrage violations occur throughout the week (Monday to Friday), suggesting the absence of a systematic pattern of CIP violations during the week days. Specifically, it is never the case that CIP arbitrage is more frequent across maturities or exchange rates in any given day relative to another. Similarly, the results in Table 9, reporting the share of profitable CIP opportunities during a trading day from 07:00 to 18:00 GMT, do not indicate obvious clustering at a particular time of the day. However, in general, CIP opportunities appear to be somewhat more frequent early in a trading day and around the middle of the day, presumably because market pace is lower and quotes are updated less frequently at those times.

Overall, these results suggest that arbitrage opportunities may occur at any time and cannot be easily predicted.

5.4. The role of market pace and volatility

Given the high frequency of the data employed in this study, it is difficult to undertake a comprehensive empirical analysis of the economic conditions under which arbitrage arises as most economic and financial variables are not available at this frequency. However, 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 and with market volatility. To this end, we estimate simple linear cross-sectional regression models with measures of frequency (share), size and duration of profitable CIP violations as dependent variables, regressed on an intercept, inter-quote time and a proxy for market volatility as the explanatory variables. That is, we estimate regression models of the following form:

$$y_j = \alpha_y + \beta_y \mathrm{IQ}_{y,j} + \gamma_y \mathrm{DIVol}_{y,j} + \varepsilon_{y,j} \tag{8}$$

where y = Share, Size, or Duration of deviations from no-arbitrage conditions; IQ_y denotes inter-quote time; DIVol_y is the difference between maximum and minimum implied volatility and is a measure of the degree of uncertainty (variability) in volatility; and ε_y is an error term. Subscript j indicates an observation number; $j=1,2,3,\ldots,N_y$. The Greek letters represent time-invariant parameters.

The models are estimated by ordinary least squares (OLS) for each of the currency pairs examined. Accordingly, values for y, IQ_y and DIVol_y as well as the total numbers of observations (N_y) depend on the currency pair analyzed. We obtained observations for y, IQ_y and DIVol_y and stacked these in corresponding columns in accordance with both the arbitrage directions (i.e. ask and bid sides) and the maturity of the instruments involved.[20] Thus, the total number of

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

observations N_y becomes equal to the sum of the total number of observations associated with the different maturities for each y modelled.

The variables are defined more precisely as follows. The y-variable Share is defined, for a given currency pair, as the share of profitable deviations out of the total number of CIP deviations that occur in a business hour over the sample period. In this case, N_y can potentially be 13,288, which is the product of the 2 potential arbitrage directions (ask and bid), the 4 maturities considered, the 11 business hours (between 07.00–18.00 GMT), and 151 working days included in the sample. However, profitable arbitrage opportunities neither occur every hour in our sample nor in both directions. Thus, N_y is expected to be much lower than 13,288. Each observation of IQ_y in the regressions for a specific currency pair would be equal to the average time between all of the (profitable and non-profitable) deviations used when calculating the corresponding observations for Share. Similarly, each observation of $DIVol_y$ for Share of a specific currency pair would be equal to the difference between the maximum implied volatility and the minimum implied volatility for all of the (profitable and non-profitable) deviations used when calculating the corresponding observations for Share.

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

The results from estimating regression (8) for frequency, size and duration, for all three currency pairs and no-arbitrage conditions, are given in Table 10. The results suggest that these characteristics of CIP arbitrage violations tend to vary with the pace of the market, as proxied by the inter-quote time, and with the variability of volatility, as proxied by the difference between the maximum implied volatility and the minimum implied volatility. In particular, frequency, size and duration are positively related both to IQ, i.e. negatively related to the market pace, and to DIVol, i.e. positively related to variability of volatility. This suggests that when markets are particularly active, as described by a high number of new quotes per unit of time, and when the degree of uncertainty is relatively more stable, we should observe fewer arbitrage opportunities, smaller arbitrage profits, and more short-lived arbitrage opportunities.

For Size there are a few instances where IQ and/or DIVol do not enter the regression with a statistically significant coefficient. However, the results are particularly clear-cut in the case of Share and Duration—in terms of both obtaining correctly signed and statistically significant positive coefficients. This suggests that high market pace and stable volatility are closely related to arbitrage opportunities that are more short-lived, as one would expect.

Table 10
Estimated relationships between the characteristics of CIP arbitrage opportunities and market pace and volatility

		IQ-time	DIVol	Obs
a) Share	EUR	0.0064	1.7973	514
		(5.77)	(2.17)	
	GBP	0.0085	2.2536	696
		(4.26)	(5.66)	
	JPY	0.0028	1.5365	184
		(9.54)	(4.64)	
b) Size	EUR	0.0219	−0.0482	2448
		(1.03)	(−0.00)	
	GBP	0.1348	4.4103	2812
		(3.51)	(0.48)	
	JPY	0.0628	89.1078	1000
		(4.77)	(5.47)	
c) Duration	EUR	21.23	3,087.5	2448
		(25.09)	(5.65)	
	GBP	7.19	13,333.3	2812
		(2.02)	(15.73)	
	JPY	7.46	3,755.0	1000
		(20.38)	(8.29)	

Note: Panel a) reports estimation results for the relationship between frequency ("Share"), inter-quote time ("IQ time") and the difference between maximum implied volatility and minimum implied volatility ("DIVol"). The dependent variable "Share" is defined as the share of profitable deviations out of the total number of deviations in an business hour (containing profitable deviations) over the sample period, while "IQ time", measured in seconds, is the average time between all of the (profitable and non-profitable) deviations used when calculating the corresponding observation for the frequency. Panels b) and c) report estimation results for the relationships between the average size of profitable deviations (in pips) from clusters of profitable deviations and IQ-time and DIVol, and duration of clusters of profitable deviations and IQ-time and DIVol. A profitable deviations is a deviation that is larger than 1/10 of a pip. A cluster consists of at least two profitable deviations in a row. The inter-quote 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 cases) have not been reported for the sake of brevity. Associated t-values are reported in parenthesis below the coefficient estimates. The column "Obs" presents 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.

6. Conclusions

Finance theory postulates that in well-functioning markets no-arbitrage conditions hold continuously, not just on average. This paper provides evidence that short-lived arbitrage opportunities arise in the major FX and capital markets in the form of violations of the CIP condition. The size of CIP arbitrage opportunities can be economically significant for the three exchange rates examined and 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 CIP condition. However, duration is low enough to suggest that markets exploit arbitrage opportunities rapidly. These results, coupled with the unpredictability of the arbitrage opportunities, imply that a typical researcher in international macro-finance can safely assume arbitrage-free prices in the FX market when working with daily or lower frequency data.

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 carefully matched tick data on the assets involved in arbitrage with meticulous attention to the finest institutional details.

We find it 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 would 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 are quickly eliminated. To reiterate, arbitrage is indeed very short-lived, and requires turning on the microscope on high-quality tick data to be detected. This is because arbitrage-free prices are restored rapidly, generally consistent with the notion of market efficiency.

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Appendix A

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

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

Source: Reuters on request of the authors in 2004.

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

Table B.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.[21]

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

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

Source: Reuters on request of the authors in 2004.

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

The cost of a notice is 14–28 cents and is the same for transactions in the FX and security markets. The cost does not depend on the venue of trading, i.e. it is the same for trading directly or via a broker (voice or electronic). Thus each party incurs a total cost of 0.42–0.84 cents for the three messages per transaction. These costs are charged at the end of each month. SWIFT invoices its customers either in dollars or euros, depending on the country in which the customer is located irrespective of the invoicing address.[22]

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 ($=3\times3$) notices. Hence, the total (variable) settlement costs vary in the range of 1.26 to 2.52 ($=3\times0.42$ to 3×0.84) 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 ($10\times10+0.84=100.84$ USD, i.e. 10.084 per 1 mill USD or about 1/10 of a pip per

[21] 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.

[22] 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.

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 $(100.84+2\times0.84)=10.252$ per 1 mill USD or 0.1025 of a pip per USD.

A.C. The spot limit order book

Using information on the number and prices of recently quoted limit orders we have been able to create a measure of the depth of the limit order book for the spot market. Given the data quality, we expect that the depth measure is quite accurate for depth at the best prices, but underestimates depth at other prices further out in the book, i.e. prices inferior to the best prices. The reason is that our data records all the limit orders at the best prices, but not limit orders that are entered further out in the book. We have implemented the following algorithm in SAS to derive the limit order book. It carries out the following steps for each day (e.g. for the ask side):

1. Accumulate all limit orders and assign them to their price level in the book, i.e. create a variable for each price observed in the book containing the accumulated limit orders.
2. Correct this accumulated level in the following cases:
   (a) If a limit order at quote or price level k enters the book, we set the depth at all prices below k to zero. Since we observe all limit orders at the best prices, recording a limit order at price k implies that there cannot be any depth in the book at ask prices lower than k.
   (b) If a trade is entered at the best price then this trade removes one order from the book. If a trade enters at a price l higher than the current best price k, then one order is removed from the level l. Level l is set as the best price, and all depth at price k is assumed withdrawn.
   (c) For all levels with non-zero depth we subtract the orders in the book that we believe should be cancelled. We do this by removing the depth lagged by 2 min.
3. Create variables that relate to the current best price, measured either by the last limit order or the last trade. Specifically, we create depth at the best price and for the next 10 prices in the book. We also create a variable that sums the depth at all prices above the current ask.

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