Market Liquidity and FX Arbitrage in Emerging Markets: Evidence from Hong Kong Tick Data[1]

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Abstract

This paper investigates FX arbitrage and its relationship with market liquidity in emerging economies using a novel and unique dataset of tradable (firm) spot and outright forward HKD/USD quotes and HK dollar- and US dollar-denominated deposit rates over four maturity tenors. We find that the HKD/USD market exhibits a non-negligible number of arbitrage opportunities which positively correlates with the illiquidity of the spot, forward and deposit markets. The economic value of these arbitrage opportunities is sizable even when transaction costs are taken into account. These findings are overall supportive of Roll *et al.* (2007) in the context of FX markets.

I. Introduction

The law of one price is a fundamental financial theory that draws the continuous attention of academics and market practitioners. However, despite a vast body of literature, its empirical validity is still a controversial issue. In general, the extant evidence suggests that the law of one price holds when markets have few frictions associated with transacting. Markets that are characterized by few frictions, for example the FX markets, exhibit few arbitrage opportunities in real-time, and, in most cases, these opportunities are unprofitable when transaction costs are taken into account (see, *inter alia*, Taylor 1987; 1989; Akram *et al.*, 2007 and the references therein). However, the law of one price does not hold when markets have significant frictions. For example, Roll *et al.* (2007) argue that aspects of the market microstructure may cause the temporary deviation of prices from their no-arbitrage values and financial market liquidity plays a key role in moving prices to eliminate arbitrage opportunities. They record a significant empirical relationship between the aggregate liquidity on the NYSE and the futures-cash basis associated with the NYSE Composite Index futures contract and a two-way causality between the short-term absolute basis and market liquidity.

Most of the current research on deviations from the law of one price, on the one hand, and market liquidity, on the other, is selectively concentrated on mature financial markets. However, in the past couple of years, emerging markets have experienced explosive growth that has caused an increasing investment interest, thus leading to substantial returns and reduced illiquidity. While the relationship between risk, return and correlation among emerging markets has been widely investigated (see *inter alia*

Bekaert and Harvey, 1995; 1997; Harvey, 1995 and the references therein), to the best of our knowledge, no previous studies have explored the relationship between the liquidity in emerging markets and its relationship with arbitrage opportunities[3].

In this paper, we fill this gap by revisiting the issue of FX arbitrage in one small emerging economy (i.e. Hong Kong) and its relationship with market liquidity using a novel and unique dataset of tradable (firm) spot and forward quotes for HK dollar *vis-à-vis* US dollar (HKD/USD henceforth) as well as tradable HKD- and USD-denominated deposit rates. This analysis is important since it is generally acknowledged among market practitioners that arbitrage opportunities use to be more pronounced in size and more persistent over time in smaller and comparatively less liquid markets than in mature and larger markets[4].

It is also worth noting that the HKD/USD market is peculiar in that it is characterized by a specific monetary regime. In fact, the Hong Kong dollar has been tied to the US dollar by means of a currency board since 1983 and in the last two decades, the value of the HKD/USD spot exchange rate has not moved substantially away from the imposed parity (7.8 HKD per USD), even under the turbulent market conditions of 1997-1998. In May 2005, the Hong Kong Monetary Authority (HKMA) introduced a currency band (labeled 'two-way convertibility undertaking') to facilitate FX arbitrage and eliminate any excessive misalignment between HK dollar- and US dollar-denominated interest rates (Yam, 2005). Our analysis of the FX arbitrage in the HKD/USD market is further enriched by the possibility of analyzing arbitrage market

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[3] Notable exceptions are Lesmond (2005) who investigated the liquidity of emerging markets and Yeyati *et al.* (2007) who focused on emerging market liquidity during crises. However neither study investigates the relationship between market liquidity and arbitrage opportunities.

[4] Evidence that is largely confirmed by private conversations with FX traders in Hong Kong.

forces at the inception of this notable change in the monetary regime. In fact, the empirical investigation carried out in this paper is based on data that span the period between May and December 2005, i.e. the aftermath of the new monetary regime.

Our main findings are as follows. First, we find that consistent with the views of market practitioners, but in contrast to the existing academic literature, the HKD/USD FX market is characterized by the presence of a non-negligible number of arbitrage opportunities. Second, in the spirit of Roll *et al.* (2007), we find that these arbitrage opportunities are positively correlated with the illiquidity of the HKD/USD spot, forward and deposit markets. Third, the economic value of these arbitrage opportunities is sizable even after realistic transaction costs are taken into account. Although brokerage fees, generally not included in quoted and transaction prices, may probably wipe out any profits that arise from arbitrage at short maturities, some, but not all traders, because of their credit worthiness or previous business relationship with their brokers, can exploit arbitrage profits net of the brokerage fees for longer maturities. Fourth, the substantial monetary regime change in the FX market introduced by the HKMA in May 2005 managed to improve the efficiency of the markets by reducing the size of the FX arbitrage opportunities over time.

This study builds on two separate bodies of literature: one that analyzes arbitrage in the FX market and another that focuses on market liquidity and its role in affecting asset prices. FX arbitrage has been investigated in the literature as part of a large research programme on the efficiency of FX markets. Early studies confirmed that FX arbitrage opportunities were merely linked to the presence of transaction costs (Frenkel and Levich, 1975; 1977; Deardorff, 1979; Callier, 1981). However, most of these contributions relied on the computation of arbitrage deviations using data in which the relevant prices were collected from markets located in different time zones. McCormick (1979) and Taylor (1987, 1989) solved this problem by constructing high-quality and high-frequency datasets where prices are contemporaneously sampled at regular intraday time intervals. Although these studies still confirm the underlying efficiency of FX markets, they do show evidence of more arbitrage opportunities in major FX markets than were previously recorded. Further, their size, persistence and frequency appear to be an increasing function of the maturity tenors of the underlying financial instruments. Similar results are confirmed by Rhee and Chang (1992) in a more recent assessment of FX arbitrage. After nearly a decade of virtually no contributions in this area of research, Akram *et al.* (2007) revisited the issue of FX arbitrage profitability by using tick data for three major currencies *vis-à-vis* the US dollar. Their findings are supportive of existing, but very short-lived, arbitrage opportunities.

The vast amount of empirical evidence of limited arbitrage opportunities in FX markets clashes with a similarly large body of evidence from market practitioners which reports that high level of resources are consistently invested in FX arbitrage strategies. This mixed story begs the question of why traders in the FX market 'seem to stage the curious spectacle of profit-seeking activity that continues indefinitely in spite of zero profits' (Deardorff, 1979; p. 361). One possible answer to this question relates to market liquidity and its dynamics over time. In fact, a recent and growing body of literature points out that market liquidity can affect financial asset prices (see, *inter alia*, Stoll, 1978, O'Hara and Oldfield, 1986; Kumar and Seppi, 1994; Chordia *et* *al.*, 2002 and the references therein). More in particular, Roll *et al.* (2007) show that market liquidity affects deviations from the law of one price in the US stock market. Following the same line of reasoning, especially for small currency markets, it is plausible to hypothesize that market liquidity may also affect arbitrage opportunities in the FX market.

In this paper, differently from the existing literature on FX arbitrage, we investigate the intertemporal association between market liquidity and deviations from the no-arbitrage relationship in the FX market. Further, this paper differs and improves upon previous studies in several other respects. First, the dataset employed in this study, to the best of our knowledge, is the first to record tradable quotes at tick frequency for all financial instruments involved in FX arbitrage over a period of eight months. Taylor (1987), a landmark study in the literature on testing no-arbitrage conditions in the FX market, employed interest rate and exchange rate data that were recorded by phoning several London brokers at ten-minutes frequency during the most active hours (9:00–16:30 GMT) over three days in 1985. Other studies which re-examined Taylor's results employed datasets exhibiting various limitations. In general in most of these studies all or some of the prices used to compute arbitrage deviations were purely indicative[5]. The dataset employed in this paper is therefore unique and allows us to carry out a better assessment of FX arbitrage since contemporaneous tradable quotes of domestic and foreign deposit rates and spot and forward exchange rates are crucial to establish whether an apparent deviation from the no-arbitrage conditions in the FX market represents a genuine profitable arbitrage opportunity. Second, we also

[5] In the most recent assessment of FX arbitrage, Akram *et al.* (2007) employ a tick dataset comprising tradable quotes for spot FX rates and indicative quotes of FX swaps and currency deposit rates.

differ from Arkam *et al.* (2007), in that we investigate an FX market where liquidity plays a much more important role than it may do in any major US dollar FX markets. Third, our work is related and builds on earlier research by Roll *et al.* (2007). However their focus is on index arbitrage in equity markets, where transaction costs are high and deviations from the law of one price may not be economically profitable[6].

The remainder of this paper is organized as follows. In Section II we discuss the theoretical underpinnings and our hypotheses, while in Section III we describe the data used in our empirical investigation. Sections IV and V report the results of the empirical tests. Finally, a discussion, with particular reference to the change that occurred in the HKD/USD market after May 2005, follows in Section VI and Section VII concludes.

[6] Further, Roll *et al.* (2007) use daily data. We use tick data and this allows us to analyze the very short-term dynamics between arbitrage opportunities and market liquidity.

II. The Covered Interest Parity and the law of one price in the FX markets

The covered interest parity (CIP) theorem states that the covered interest differential between two identical assets denominated in two different currencies should be zero. Put differently, interest rate differentials between two assets denominated in two different currencies over any maturity tenor should be equal to the forward premium/discount paid to cover the exchange rate risk over the same investment period. This parity has been widely investigated in the literature and is generally expressed as

$$\frac{\left(1+i_{d,k}\right)}{\left(1+i_{f,k}\right)}=\frac{F_k}{S} \tag{1}$$

where i_d and i_f are the domestic and foreign interest rates on similar assets of a certain maturity k, S is the prevailing spot exchange rate and F_k is the forward exchange rate with maturity k.

Any deviation from Equation (1) would represent a risk-free arbitrage opportunity in a frictionless world, as transaction costs are not taken into account. If we introduce transaction costs by adding bid and ask prices to Equation (1), then the deviations from covered interest parity are profitable only if

$$\begin{gathered}\frac{\left(1+i^a_{d,k}\right)}{\left(1+i^b_{f,k}\right)}\geq\frac{F^b_k}{S^a}\\ \frac{\left(1+i^a_{f,k}\right)}{\left(1+i^b_{d,k}\right)}\geq\frac{S^b}{F^a_k}\end{gathered} \tag{2}$$

where superscript a and b denote the ask and bid prices, respectively. Equation (2) defines the conditions for round-trip arbitrage in the FX market.

In the spirit of Deardorff's (1979) analysis, a different test of CIP arises from considering one-way arbitrage opportunities in the form of owner's arbitrage (OA) and borrower's arbitrage (BA). Under the first scenario (OA), traders with a long position in a currency seek lending opportunities for the highest possible return. They can lend their endowment for a certain maturity at the bid rate for that currency. Alternatively, they can convert their position in another currency at the current spot rate and lend the converted currency at the bid rate of the appropriate maturity while contemporaneously buying back the same asset at the current forward rate. The exploitation of any departures from the two alternatives requires that traders already have an endowment to invest. The second scenario (BA) refers to a case in which traders want to finance an investment and seek to minimize borrowing costs. In this case, they can either finance their investment by borrowing currencies directly or by borrowing in a different currency and than converting it to the desired currency while covering the exchange rate risk at the current forward rate. Profitable deviations from the OA and BA can be defined as follows:

$$OA:\begin{cases}\dfrac{\left(1+i_{d,k}^{b}\right)}{\left(1+i_{f,k}^{b}\right)}\geq\dfrac{F_{k}^{b}}{S^{a}}\\[2ex]\dfrac{\left(1+i_{f,k}^{b}\right)}{\left(1+i_{d,k}^{b}\right)}\geq\dfrac{S^{b}}{F_{k}^{a}}\end{cases}\qquad(3)$$

$$BA:\begin{cases}\dfrac{\left(1+i_{d,k}^{a}\right)}{\left(1+i_{f,k}^{a}\right)}\leq\dfrac{F_{k}^{a}}{S^{b}}\\[2ex]\dfrac{\left(1+i_{f,k}^{a}\right)}{\left(1+i_{d,k}^{a}\right)}\leq\dfrac{S^{a}}{F_{k}^{b}}\end{cases}\qquad(4)$$

Violations of Equations (3) or (4) imply deviations from the law of one price in the FX context, i.e., the price of two identical securities must necessarily be the same, regardless of the currency of denomination. It is important to point out that round-trip and one-way arbitrage conditions differ in that violations of the latter do not necessarily prove the existence of riskless profits. In fact, if round-trip arbitrage opportunities are present, then these will also result in one-way arbitrage opportunities. The opposite link does not necessarily apply. This is due to the fact that one-way arbitrage opportunities require an excess supply or demand of funds, while round-trip arbitrage does not require funds to be lent or borrowed.[7] In other words, although one-way arbitrage opportunities may be detected more frequently, they do not imply the existence of riskless profits. They only indicate the presence of price differentials that are due to different pricing practices, market segmentation and/or different demand/supply conditions in all of the markets involved in the FX arbitrage (i.e. the FX and deposits markets).

To take into account the difference between round-trip and one-way FX arbitrage and glean different insights from the analysis of the HKD/USD FX market, we divide our analysis into two parts: In the first part, we investigate the relationship between market liquidity and absolute deviations from CIP in the spirit of Roll *et al.* (2007). Our aim is to understand how CIP violations relate to the underlying dynamics of market liquidity. It is then important to understand whether or not the CIP deviations detected in the previous analysis are also genuinely profitable. To address this issue, using realistic transaction costs, in the second part of this paper we carry out a

[7] For a more analytical treatment see, *inter alia*, Deardorff (1979), Taylor (1987) and Akram *et al.* (2007) and the references therein.

thorough analysis in which both forms of FX arbitrage (i.e., round-trip and one-way) are economically assessed.

III. Data

The dataset employed in this paper is a collection of tick data obtained from ICAP for the period from May 17th, 2005 to December 31st, 2005[8]. ICAP is the world's largest voice and electronic interdealer broker which, in 2006, covered 65% of the worldwide FX spot voice market and 35% of the FX forward market. Although recent market trends have exhibited a furious shift from voice broking to electronic broking, the voice-broking market is still very active in certain geographical areas, especially Asia Pacific, and in 2006 it contributed a hefty 69% to the formation of the ICAP group' overall profits. In the context of emerging markets (especially the HKD market), the above percentages can be considered conservative, as ICAP covers more than half of the market share in emerging market securities trading (ICAP, 2007).

The dataset comprises all of the best ask and bid prices for the HKD/USD spot exchange rate, the HKD/USD outright forward rate and all of the best ask and bid prices for the HKD- and USD-denominated deposit rates. The forward exchange rates and both the domestic- and foreign-currency denominated deposit rates are relative to four different maturity tenors: overnight, one week, four weeks, and 12 weeks[9]. A particular novelty of this unique dataset is that all of the ask and bid prices

[8] The sample period is chosen because of data availability. In fact firm quotes for all markets under investigation are not available from ICAP before May 17th, 2005.

[9] Outright forward rates are calculated by adding together the spot rate and the forward points (i.e. adjustment of the spot FX rate to reflect the current interest rate differential). In large currency markets, outrights are not traded interbank, but they are very popular with corporate customers who have the business need to settle FX trades in the future. The interbank market generally uses FX swaps. Our

are firm (hence, directly tradable), which is different from most of the previous studies in which all or some of the quotes are indicative.[10] This difference is particularly relevant in this context, because firm quotes allow us to compute accurately genuine real-time (round-trip and one-way) arbitrage opportunities and assess their economic value.

All of the quotes in our dataset are retrieved from ICAP voice-broking record tapes. The existing studies that have looked at FX arbitrage have normally relied on daily data, and only a handful of recent exceptions has looked at the intraday data obtained from electronic systems (such as Reuters D3000 or EBS), and focused exclusively on major currencies.[11] However, it is generally acknowledged among market practitioners that arbitrage opportunities used to be more pronounced in size and more persistent over time in smaller and comparatively less liquid markets than in mature and larger markets. This paper improves upon the existing literature by investigating a currency from an emerging market (i.e. the HKD market) that exhibits a relatively large turnover compared to other small currencies[12]. Further, to achieve our goal, we have chosen to investigate prices from a voice-broking platform. In fact, differently

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analysis focused on outrights for two reasons. First, as pointed out in recent studies, the customer-dealer leg of the FX market is the *locus* in which dispersed information is aggregated into prices (see *inter alia*, Evans and Lyons, 2005; Osler, Mende and Menkhoff, 2007; and the references therein). Therefore outright forward prices, although less frequently traded than FX swap prices, may carry sizable information content. Second, in the HKD/USD forward market, the outright forward transactions are more frequent when compared to larger and more liquid currency markets and are often used also by participants in the interbank market.

[10] A partial exception is represented by Akram *et al.* (2007) who used tradable firm quotes for the bid and ask prices of spot exchange rates.

[11] Notable exceptions are represented by Taylor (1987, 1989) who collected voice broking tradable quotes.

[12] BIS (2005) indicates that the HK dollar is the ninth currency in terms of the percentage share of total world average daily turnover and, most importantly, the first currency from emerging economies in terms of daily turnover.

from major currencies, which are largely traded on electronic venues, HKD/USD spot and forward trading has been most active over voice-broking platforms.[13]

As an important preliminary to the analysis in the following sections, we present in Figure 1 the average quotation activity in the markets under investigation. For all of the instruments and maturity tenors during Hong Kong trading time, we calculate the frequency of quotations over 15-minute intervals. For the HKD/USD spot market, quotation activity mainly takes place in two time periods: 7:00-11:00 and 14:00-16:00 HK time. During the morning session, the spot market has about 30 quotations every 15 minutes, while, during the afternoon session, which coincides with the morning session in London, the frequency of quotations increases to about 45 every 15 minutes. This evidence is in line with previous studies (e.g. *inter alia* Evans, 2002; Ito and Hashimoto, 2006 and the references therein) which have recorded a similar intraday seasonality for major currencies. It is also worthwhile noting that the HKD/USD intraday seasonality follows closely the seasonality of USD/JPY spot prices because of its geographical proximity and similar trading times (Lyons *et al.*, 1998; Ito and Hashimoto, 2006). For the other financial instruments over different maturity tenors, the quotation frequency is much lower. Nevertheless, it is instructive to note that the intraday seasonality is highly correlated among the markets.

[13] This evidence is also confirmed by private conversations with local traders. The situation is changing however, as EBS in April 2006 introduced (after a brief experience in 2004) a large-scale electronic trading platform for HKD/USD spot and forward trading, joining the existing electronic trading venue already provided by Reuters. This will probably shift the balance in favour of electronic trading in the near future.

IV. Absolute CIP deviations and market liquidity

In this section, we investigate the relationship between market liquidity and absolute deviations from CIP. Our aim is to understand how violations of the CIP condition relate to the underlying dynamics of market liquidity. We first compute absolute CIP deviations as follows:

(5) $$\left| \left[\frac{\left(1+i_{d,k}\right)}{\left(1+i_{f,k}\right)} \right]^{\frac{D}{365}} - \frac{F_k}{S} \right|,$$

where D is the number of days to maturity of forward and deposit contracts, and all of the variables are mid-quotes. This is a necessary adjustment as interest rates are quoted in percent per annum, and, in Equation (5), we need to obtain interest rates for maturities of less than a year.

Note that a finding of large absolute CIP deviations is a necessary, though insufficient, condition of economically profitable arbitrage opportunities. If the markets are liquid, then it is unlikely that large absolute CIP deviations will occur. It would thus be unfruitful to investigate round-trip and one-way arbitrage opportunities in subsequent analysis. In fact, according to Roll *et al.* (2007), the more liquid the markets, the smaller the deviations from the law of one price, or, put differently, there should be a significant positive correlation between absolute CIP deviations and market illiquidity.

It is important to emphasize that, because transaction data are not available, it is not possible to construct liquidity measures such as trading volume, the price impact of trades and effective bid-ask spreads. Hence, the measure of liquidity that we use in our paper is represented by quoted bid-ask spreads.

The first part of Table 1 reports the percentage quoted bid-ask spreads for all instruments and maturity tenors. The figures reported are the average and median values of the bid-ask spreads together with the relative standard deviations. The spreads in the HKD/USD spot and forward markets are comparable in size and very small. Further, the spreads in the forward market are increasing with maturity. The proportional bid-ask spreads in HKD and USD deposit markets are high compared to their analogues in the spot and forward FX market. This is consistent with the empirical evidence reported in Rhee and Chang (1992) for major currency markets.

Figure 1 suggests the need for the synchronization of the quotes in different markets, as the HKD/USD forward and deposit markets are comparatively less active than the HKD/USD spot market. To obtain a time series of contemporaneous quotes for the different instruments, we construct our synchronized data as follows: First, we exclude days with few observations (such as weekends and public holidays in Hong Kong and the UK). After these adjustments the number of trading days we are left with vary according to the maturity tenor, but range between 157 (four weeks maturity) and 159 (one and 12 weeks maturity). Second, we focus on the active time period (i.e. between 7:00 and 17:00 HK time)[14]. Third, for each instrument, we generate a 15-second interval time series of prevailing quotes. Then, for each maturity tenor, we consolidate all of the time series to form a synchronized sample.

[14] It is worth noting that the market we analyze is mostly voice-intermediated; therefore trading does not necessarily occur over 24 hours as in electronic-intermediated markets. Hence, it makes sense in this context to define an opening and closing time.

Finally, to mitigate the possible problem of stale quotes, we delete all observations in which either the spot or forward bid and ask were quoted more than five minutes previously, or in which either the HKD or USD deposit bid and ask prices were quoted more than one hour previously.[15] Overall, the average number of observations employed in our empirical analysis is larger than 12,000, with a maximum of about 28,000 observations at 12 weeks maturity.

Using this synchronized sample, the absolute CIP deviations, as of Equation (5), are reported at the bottom of Table I for all maturity tenors. All figures are expressed in pips.

In line with the existing literature, the average (and median) CIP deviations are increasing with maturity tenors. Overnight instruments record an average absolute CIP deviation of about 2 pips, which goes up to 62 pips for the 12-weeks maturity tenor. These large recorded values, especially at longer maturities, may be due to the fact that absolute CIP deviations are computed using mid-quotes and do not explicitly take into account the impact of transaction costs[16].

[15] In other words, we have assumed that the spot or forward bid and ask quoted less than five minutes previously are still economically meaningful and that the deposit bid and ask quoted less than one hour previously are still valid. We have different assumptions for the spot or forward quotes compared to the deposit quotes for two reasons. First, from Figure 1, we can easily see that if we apply the five-minute deletion criterion to deposit quotes, then our final sample will be small. Second, we observe that the changes in the deposit quotes are small and infrequent, and thus we believe that the deposit bid and ask quoted less than one hour previously may not be stale. On this respect, as a preliminary robustness check, we have repeated our analysis, ignoring how long ago the prevailing deposit bid and ask were quoted. Further, we also carry out a fraction of the empirical work using data synchronized on the revision of the deposit quotes. The results, available upon request, are similar to the results reported later in the paper in which we apply the one-hour deletion criterion to deposit quotes. These results are comforting and confirm that our findings are not driven by any potential staleness of quotes in the less liquid markets.

[16] Transaction costs are explicitly incorporated in the next section of the paper, in which the issue of the genuine profitability of arbitrage opportunities is fully addressed.

To address the question of whether absolute CIP deviations are related to liquidity in the different markets, we first compute the correlation coefficients between the absolute CIP deviations and our liquidity measures in various markets, as well as a composite measure of liquidity. This composite measure is a synthetic measure of liquidity summarizing liquidity conditions in all markets involved in the FX arbitrage and it is computed as the arithmetic average of all quoted bid-ask spread across the four markets at each time interval. The results are reported in Table II. In all cases, the absolute CIP deviations are positively related to the quoted spreads. This suggests that lower the liquidity in various markets, the larger the CIP deviations are in magnitude. This evidence is stronger for deposit markets, which are less liquid, but nevertheless statistically significant in most of the cases at the 1% statistical level.

Previous empirical research has recorded that bid-ask spreads and arbitrage opportunities exhibit strong intraday and interday seasonalities (Gallant *et al.*, 1992; Chordia *et al.*, 2001; Ito and Hashimoto, 2006; Roll *et al.*, 2007). Thus, the strong correlation coefficients reported in Table II may be spurious, i.e. they may be caused by a common seasonality pattern. To investigate this potential problem, we first carry out a seasonality analysis for both the absolute CIP deviations and the liquidity measures and then we compute the correlation coefficients, as in Table II, using seasonally-adjusted variables.

The following variables are used to adjust the raw (i.e. seasonally unadjusted) series: a constant, a time trend to remove the long-term trend in the series, four daily dummy variables to take into account any day-of-the-week effect and nine intraday hourly dummy variables to take into account any intraday seasonality.[17]

The results reported in Table III show some interesting patterns. In every instance, it is possible to retrieve a statistically significant negative trend. This means that, over the sample period investigated (i.e. May-December 2005), liquidity in all of the markets increased (i.e. the spreads decreased), while the absolute CIP deviations decreased[18].

Another interesting pattern recorded in Table III is that the HKD/USD spot and forward liquidity exhibits a similar U-shaped intraday pattern: liquidity is lower (i.e. the spreads are higher) during the first and last hour of the Hong Kong trading time[19]. However, this seasonality pattern is not shared by the other two markets. Differently from previous studies (Bessembinder, 1994; Ito and Hashimoto, 2006), calendar effects do not exhibit a recognizable pattern. Some of the daily dummies are statistically significant, but they exhibit different signs and magnitudes across financial instruments and maturity tenors. Although this suggests that there is no clear day-of-the-week seasonality in the data, our estimates must be interpreted with caution, as they are obtained using a limited numbers of trading days.

Using the seasonally-adjusted series, we repeat the correlation analysis in Table II. The results of this robustness check, which are not reported to save space, exhibit

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[17] Additional robustness tests have been carried out, in which a square time trend and a dummy for the days prior to major HK, UK or US holidays have been added to the list of explanatory variables. The results, available upon request, do not differ from the results reported in Table III.

[18] This dynamic may be due to the monetary regime change induced by the HKMA in May 2005, which is discussed more in detail in Section VI.

[19] This is similar to other markets such as equity markets (see, *inter alia*, Barclay and Hendershott; 2004 and the references therein).

correlation coefficients that are qualitatively and quantitatively similar to those reported in Table II.

The empirical evidence of a strong contemporaneous correlation between absolute CIP deviations and market liquidity relies on averages over time. We glean additional insight by investigating the short-term dynamics between absolute CIP deviations and liquidity. Similarly to Roll *et al.* (2007), we study whether shocks to absolute CIP deviations have any persistent effect on liquidity and vice versa. We simply regress the absolute CIP deviations on the lagged spreads, both seasonally adjusted, and then regress the spreads on the lagged absolute CIP deviations. For parsimony, in this simple exercise we use the composite liquidity measure to approximate the overall market liquidity. Panel A (B) of Table IV shows the results when liquidity is used as a predictive variable for absolute CIP deviations (vice versa). We can see from Panel A that in all cases (with the exception of four weeks maturity) liquidity has a significant impact on the subsequent absolute CIP deviations, and this impact is larger the longer the maturity tenor. In particular, a one percent shock on overall market liquidity will have an impact on the subsequent absolute CIP deviations of 0.6, 19.6 and 62.6 pips at overnight, one week and 12 weeks maturity respectively. Similarly, the results in Panel B also suggest that a shock on absolute CIP deviations will have an impact on the subsequent overall market liquidity suggesting that there is a two-way causality between overall market liquidity and absolute CIP deviations[20].

Next, we look at the joint dynamic process that characterizes absolute CIP deviations and the composite liquidity measure using a multivariate framework. For each

[20] This finding is also confirmed when Granger-causality tests are carried out. The results, not reported to save space, are available upon request.

maturity tenor, a bivariate VAR is estimated in which the number of lags of the endogenous variables has been parsimoniously selected by using conventional information criteria. For each VAR model, generalized impulse response functions (GIRFs) are estimated, and the relative graphs are plotted in Figures 2-5.[21] The graphs report the dynamic impact of one unit standard deviation positive shock to any of the two variables on the current and future value of the endogenous variables in the VAR. The confidence intervals of the GIRFs are estimated by Monte Carlo simulation setting the number of replications to 5,000.

Figures 2-5 confirm the empirical findings reported in Table IV in that all of the responses are statistically significant at the 1% statistical level with the exception of the four week maturity tenor, in which neither GIRF is statistically significant. As for the other maturity tenors, it is interesting to note that a clear, decreasing dynamic pattern occurs after a shock in either one of the endogenous variables. The largest impact occurs in the first time-interval of 15 seconds and the impact progressively declines as the number of time-intervals increases. This implies that shocks to either liquidity or absolute CIP deviations are short-lived and that both variables revert to their average level in a relatively short period of time after a shock has occurred. Further, consistent with Roll *et al.* (2007), we find that the GIRFs are more persistent for longer maturity suggesting that arbitrage occurs more frequently and actively at shorter maturities.

[21] Generalized impulse response functions (Pesaran and Shin, 1998) are chosen, rather than traditional impulse response functions, because they allow us to construct an orthogonal set of innovations that does not depend on the VAR ordering.

With respect to the economic significance of the GIRFs, a one standard deviation shock to the aggregate composite liquidity measure (i.e. liquidity decreases in the market) causes the absolute CIP deviations to increase in the next 15 seconds by 2/100th of a pip or, *coeteris paribus*, about 46 pips on a daily basis at overnight maturity, and 2/10th of a pip (499 pips on a daily basis) at 12 weeks maturity. On the other end, a one standard deviation shock to the absolute CIP deviations has an impact on the quoted spreads of an immediate 0.01% extra overall trading cost at overnight maturity, and of 0.08% at 12 weeks maturity.

V. Arbitrage opportunities and their profitability

The evidence so far suggests that absolute deviations from CIP are statistically significant and time varying, and that one underlying reason for this time variation is the imperfect liquidity of the markets involved in setting the FX arbitrage. However, these significant absolute deviations from CIP represent only a necessary, but insufficient, condition for economically profitable arbitrage opportunities, as the absolute deviations are calculated using mid-quotes and, thus, ignoring transaction costs.

In this section, we investigate the profitability of deviations from round-trip and one-way arbitrage conditions. We compute deviation from round-trip arbitrage at the bid and ask prices respectively (i.e. CIP arbitrage) as follows:

(6.1) $$CIP\ (bid): \left[\frac{\left(1+i_{d,k}^{a}\right)}{\left(1+i_{f,k}^{b}\right)} \right]^{\frac{D}{365}} - \frac{F_k^b}{S^a} \geq 0 \quad \text{and}$$

(6.2) $$CIP\ (ask): \left[\frac{\left(1+i_{f,k}^{a}\right)}{\left(1+i_{d,k}^{b}\right)}\right]^{\frac{D}{365}} - \frac{S^{b}}{F_{k}^{a}} \geq 0,$$

where D is the number of days to maturity of the forward and deposit contracts, and superscripts a and b denote the ask and bid prices respectively. Similarly, deviations from one-way arbitrage (OA and BA) at both the bid and ask prices are computed as follows:

(7.1) $$OA\ (bid): \left[\frac{\left(1+i_{d,k}^{b}\right)}{\left(1+i_{f,k}^{b}\right)}\right]^{\frac{D}{365}} - \frac{F_{k}^{b}}{S^{a}} \geq 0 \quad \text{and}$$

(7.2) $$OA\ (ask): \left[\frac{\left(1+i_{f,k}^{b}\right)}{\left(1+i_{d,k}^{b}\right)}\right]^{\frac{D}{365}} - \frac{S^{b}}{F_{k}^{a}} \geq 0,$$

(8.1) $$BA\ (bid): \frac{F_{k}^{a}}{S^{b}} - \left[\frac{\left(1+i_{d,k}^{a}\right)}{\left(1+i_{f,k}^{a}\right)}\right]^{\frac{D}{365}} \geq 0 \quad \text{and}$$

(8.2) $$BA\ (ask): \frac{S^{a}}{F_{k}^{b}} - \left[\frac{\left(1+i_{f,k}^{a}\right)}{\left(1+i_{d,k}^{a}\right)}\right]^{\frac{D}{365}} \geq 0.$$

According to Equations (6)-(8), only positive deviations can be profitable[22] [23]. Table V shows the percentage of positive deviations out of all of the

[22] To exploit an arbitrage opportunity, however, a trader needs to undertake several deals virtually simultaneously and as fast as possible. Otherwise, there is a risk that the prices of one or more instruments will move such that an apparent arbitrage opportunity disappears before the trader has been able to seal all of the deals. This may be termed 'execution risk'. Virtually simultaneous trading in the markets can be accomplished through tight cooperation between traders. This seems to be the case in a typical dealing room. See also the theories related to limits to arbitrage (Shleifer and Vishny, 1997; Lyons, 2001).

[23] Positive deviations from one-way arbitrage do not necessarily imply the existence of profitable arbitrage opportunities (see Section II). However, in this context even positive deviations from round-trip arbitrage may not necessarily denote economic profits. This is because small positive deviations

observations. Across arbitrage definitions and maturity tenors, we find that the average percentage of positive arbitrage deviations ranges between 33% and 76%. Further, arbitrage at the ask price of CIP and OA and the bid side of BA is roughly 1.8 times more frequent than arbitrage at the other side, and profitable round-trip arbitrage deviations occur slightly more frequently than do one-way arbitrage deviations[24]. If markets are very efficient, then we expect to see a high frequency of non-positive deviations, i.e. those that will not invite arbitrage activity, whereas positive deviations will be limited by arbitrage activities. Thus, positive deviations should occur much less frequently than do non-positive ones.

Notwithstanding, the unexpectedly high frequency of positive deviations reported in Table V is not sufficient evidence of substantial profitable opportunities, as deviations may have a skewed distribution, i.e. positive deviations may be frequent and small. To better quantify the economic value of these deviations, we report the mean and median values of the deviations in Table VI. We observe large positive deviations on the ask side of CIP and OA and the bid side of BA, while the average deviations are negative on the other side. This asymmetry may be due to the temporary excess demand/supply of the HKD versus the USD. In other words, the temporary excess demand/supply leads to the negative deviations on the bid side of CIP and OA and the ask side of BA, which do not invite arbitrage activities. It also leads to the positive

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may not be profitable after settlement costs and brokerage fees, which are not included in the ask and bid prices and may represent a nontrivial item in profit computations in a voice-broking environment.

[24] This last finding may be heuristically justified on the grounds that, after adjusting for all transaction costs (i.e. also including settlement costs and brokerage fees), the true frequency across round-trip or one-way may be similar.

deviations on the other side, which are profitable to, and will be worked away by, arbitrageurs.

How much do arbitragers earn from positive arbitrage deviations? An indirect answer to this question can be found in Table VII, which reports the average and median size of the positive deviations. At face value, the average profits from FX (round-trip and one-way) arbitrage are handsome, and their size increases with maturity. However, the figures reported, although they incorporate the effect of the bid and ask prices, do not include brokerage fees and settlement costs. Akram *et al.* (2007) usefully report the brokerage fees and settlement costs faced by agents trading on the Reuters D3000 platform for the three major currencies *vis-à-vis* the USD. They estimate that the total variable transaction cost per unit of base currency is equal to $1/10^{th}$ of a pip. If we borrow this figure and apply it to our findings, then we can see that in all cases our evidence still stands. However, the market we analyze is different and is not comparable in terms of brokerage costs and settlements fees to the Reuters D3000. From private conversations we had with various major traders, the voice-broking market in Hong Kong is characterized by a large variability of brokerage fees. They are applied with different magnitudes to different agents with different credit-worthiness and, in some cases, even to the same agents for different financial instruments or different market conditions. Thus, it is difficult to pin down a unique number that unambiguously represents the amount of brokerage fees and settlement costs in this market. An educated guess is that the average voice-broking fees and settlement costs are at least twice as large as those for electronic trading. In light of these considerations, it is possible to conjecture that, in the HKD/USD market the introduction of realistic voice-broking fees and settlement costs would probably wipe out any profits that arise from arbitrage in the overnight market, in which average profits are in the magnitude of 1 to 2 pips. However, for longer maturities, some, but not all, traders will be able to enjoy arbitrage profits net of the cheap brokerage fees and settlement costs they face, because of their credit-worthiness or previous business relationship with their brokers.[25]

The results reported in Tables V-VII indicate that there are substantial genuine opportunities for arbitrage profits, even when the bid-ask spreads and other transaction costs are taken into account. These findings are clearly at odds with the existing academic evidence but they suggest a possible explanation of Deardorff's (1979) paradox of perfect arbitrage. Profit-seeking activity seems to be based, at least in the context of the HKD/USD market, on sound economic considerations.[26]

VI. Discussion

The HKD/USD market has been characterized by a fixed exchange rate arrangement since 1983, and in the last two decades the value of the HKD/USD spot exchange rate has remained fairly stable, even during the turmoil of the Asian financial crisis in 1997. From 1998, the HKMA allowed for a 'weak-side convertibility undertaking' which implied an obligation for the monetary authority to sell USD when the

[25] The maximum and average positive deviations reported in Table VII may provide further insights on the amount of brokerage fees and settlement costs. The maximum deviations are profitable for most arbitrageurs. However, the average deviations are profitable for a handful number of arbitrageurs, and so they are observed frequently.

[26] However the paradox may still be valid for major currency markets in which a large arbitrage activity is claimed by market participants (trading on electronic venues), but clear evidence of positive arbitrage profits is missing or is limited to very short time intervals that can be exploited only by sophisticated investors, perhaps by relying on algorithmic trading.

HKD/USD was sharply depreciating (i.e. the current spot FX price was higher than 7.80). However, this obligation was not mirrored on the ‘strong side’. In fact there was no such mandatory intervention in the FX spot market when the HKD was appreciating. This asymmetry was the cause of uncertainty in the HKD spot FX market trading and it spurred a large inflow of speculative funds which pushed the HKD/USD spot price close to 7.70 in the third quarter of 2003. In the same period of time, the interest rate differential between USD- and HKD-denominated assets peaked at 150 basis points. This situation suggests that there were market frictions in place that did not allow arbitrageurs to exploit the existing arbitrage opportunities and bring the prices of financial assets in line with no-arbitrage equilibrium values.

On May 18th, 2005 the HKMA announced a refinement to the operation of the Linked Exchange Rate System by introducing a ‘strong-side convertibility undertaking’ at HKD 7.75 per USD. This explicitly removed the uncertainty regarding HKMA intervention in the FX market when the HKD appreciated. Simultaneously, the HKMA shifted the weak-side convertibility to 7.85, by creating a *de facto* convertibility zone or, differently, a currency band.

Our analysis of FX arbitrage in the HKD/USD market can be further sharpened by the possibility of analyzing arbitrage market forces at the inception of this new monetary regime. In fact, our empirical investigation spans the period between May and December 2005, e.g. the aftermath of the introduction of the currency band.

The evidence proposed in Table III can be revisited in light of this monetary regime change. In fact, the evidence of a negative time trend for both deviations from CIP and quoted spreads confirms the HKMA’s conjecture that ‘the strong-side convertibility undertaking will remove the uncertainty about to which the exchange rate may strengthen' and hence facilitate arbitrage forces to remove any existing (covered) interest rate differential between the HKD- and USD-denominated assets.

To provide further evidence, we investigate whether profits from FX arbitrage decreased in the aftermath of the May 18th, 2005 decision. To do so, we use the positive (round-trip and one-way) arbitrage deviations calculated in Section V and compute the averages over four different subperiods following May 18th, 2005. The results are reported in Figures 6-8[27]. As we can see the evidence reported supports the HKMA's argument in that average arbitrage profits generally decreased over time after May 2005 and the reduction in arbitrage profits was sizable (especially at longer maturities).

Overall, this evidence confirms and reinforces the findings reported in Table III and suggests that there is a significant relationship between market liquidity and arbitrage opportunities in the FX market. Further it also suggests that policy-makers can improve the efficiency of financial markets by fine-tuning the link between funding liquidity and trading liquidity.

[27] Figures 6-8 report CIP, OA and BA arbitrage profits computed at the ask prices. The equivalent arbitrage profits computed at the bid prices, not reported to save space, are qualitatively and quantitatively similar to those computed at the ask prices.

VII. Conclusions

In this paper we revisit the issue of FX arbitrage in one small but important emerging economy and its relationship with market liquidity. This analysis is motivated by the apparent incongruence, especially in the context of FX markets, between the consistent lack of evidence of profitable arbitrage opportunities reported in much empirical literature and the view by market practitioners that FX arbitrage opportunities do exist and are more pronounced in size and more persistent over time in smaller and comparatively less liquid markets than in larger and more mature markets.

We use a novel and unique dataset of tradable (firm) spot and forward HKD/USD quotes and tradable HKD- and USD-denominated deposit rates provided by the world's largest voice and electronic broker (ICAP). We construct deviations from no-arbitrage conditions and conventional measures of liquidity in all of the markets involved in FX arbitrage.

We find a host of interesting results. First we document that the HKD/USD FX market is characterized by the presence of a non-negligible number of arbitrage opportunities. Second, by applying the methodology of Roll *et al.* (2007), we find that the absolute deviations from CIP are positively correlated with the illiquidity of the HKD/USD spot and forward markets and the deposit markets. Third, we find that, consistent with the views of market practitioners, but in contrast to the existing academic literature, deviations from no-arbitrage conditions result in a number of genuinely profitable arbitrage opportunities even after taking into account realistic transaction costs. Fourth, the substantial monetary regime change in the FX market that was introduced by the HKMA in May 2005 was successful in improving the efficiency of the HKD/USD FX markets. These results are overall supportive of Roll *et al.* (2007) in the context of FX markets.

These results allow us to revisit Deardorff's (1979) paradox of perfect arbitrage. Profit-seeking activity is based, at least in the context of the HKD/USD market, on sound economic considerations. However, although realistic voice-broking fees probably wipe out any profits that arise from arbitrage at short maturities, some, but not all traders can exploit arbitrage profits net of the brokerage fees for longer maturities.

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Table I

Summary Statistics

Our tick data consist of tradable (firm) quotes of the FX spot and forward markets and the HKD and USD deposit markets from May 17th, 2005 to December 30th, 2005. The maturity tenors are overnight, one week, four weeks, and 12 weeks. Quoted bid-ask spread denotes proportional bid-ask spreads computed as percentage of the bid price. Absolute CIP deviations are expressed in pips. To calculate absolute CIP deviations for each maturity tenor, we synchronize the time series of quotes of the four markets from the raw tick data, as described in the text (Section IV).

	mean	median	standard deviation
Panel A: Quoted bid-ask spread			
1 – HKD/USD spot	0.0076	0.0064	0.0036
2 – HKD/USD forward			
overnight	0.0081	0.0077	0.0039
1 week	0.0093	0.0090	0.0034
4 weeks	0.0122	0.0116	0.0048
12 weeks	0.0148	0.0142	0.0046
3 – HK dollar deposit rate			
overnight	1.9353	1.2500	1.4157
1 week	1.3323	1.1442	0.5355
4 weeks	1.1009	1.0893	0.2056
12 weeks	1.0701	1.0482	0.1646
4 – US dollar deposit rate			
overnight	0.5209	0.5671	0.1742
1 week	0.5928	0.6198	0.1415
4 weeks	0.5095	0.4444	0.1311
12 weeks	0.5014	0.4535	0.1169
Panel B: Absolute CIP deviations			
Overnight	1.837	1.163	0.018
1 week	10.098	7.390	0.087
4 weeks	29.410	23.297	0.169
12 weeks	62.823	59.847	0.314

Table II

Correlations between absolute CIP deviations and quoted spreads

We calculate absolute CIP deviations for each of the four maturity tenors by synchronizing the time series of quotes of the four markets from the raw tick data as described in the text (Section IV). For each maturity tenor, this table reports the correlation coefficients between absolute CIP deviations and the proportional quoted spreads of the four markets (HKD/USD spot and forward FX markets, and the USD and HKD deposit markets). We also compute the correlation between the absolute CIP deviations and a composite liquidity measure (the arithmetic average of the proportional quoted spreads of the four markets). All of the figures reported are statistically significant at the 1% significance level.

	spot	forward	i_{USD}	i_{HKD}	composite
overnight	0.013	0.031	0.204	0.219	0.193
1 week	0.005	0.072	0.268	0.459	0.404
4 weeks	0.020	0.039	0.004	0.083	0.055
12 weeks	0.015	0.118	0.041	0.247	0.171
Average	*0.013*	*0.065*	*0.129*	*0.252*	*0.205*

Table III

Seasonality in absolute CIP deviations and quoted spreads

To calculate the absolute CIP deviations for each of the four maturity tenors, we synchronize the time series of quotes of the four markets from the raw tick data as described in the text (Section IV). For each maturity tenor, we compute the proportional quoted spreads of the four markets (HKD/USD spot and forward FX markets, and USD and HKD deposit markets). We also compute a composite liquidity measure (the arithmetic average of the proportional quoted spreads of the four markets). To study seasonality, dummy variables are included for the days of the week (excluding Monday) and the hours of the day (excluding 7:00 Hong Kong time), and *time* denotes a linear trend. This table reports OLS regressions with standard errors corrected for autocorrelation and heteroskedasticity (Newey and West, 1987). All of the figures reported are statistically significant at the 1% significance level, whereas insignificant figures are not reported for brevity.

(Table III continued)

Panel A: Overnight

	spot	forward	i_{USD}	i_{HKD}	composite	aCIPdev
constant	0.0089500	0.0103000	0.6999000	4.4638000	1.2950000	0.0003180
time	-0.0000001	-0.0000003	-0.0000119	-0.0004620	-0.0001180	-0.0000001
Tue	-0.0004340	-0.0009977	-0.0206000	-0.4280000	-0.1125000	0.0000653
Wed			0.0410000	-0.4890000	-0.1122740	0.0000369
Thu			0.0109000	-0.2804000	-0.0670000	0.0000370
Fri	0.0004820	0.0007200	0.0508000	-0.2908000	-0.0590000	-0.0000135
8H	-0.0013900	-0.0012600	-0.0111000	-0.4250000	-0.1240000	-0.0000246
9H	-0.0014900	-0.0014600	-0.0101000	-0.4950000	-0.1270000	-0.0000346
10H	-0.0014100	-0.0016500	0.0244000	-0.2420000	-0.0550000	-0.0000477
11H	-0.0026100	-0.0024400	0.0426000			-0.0000358
12H	-0.0023500	-0.0020220	0.0630000	-0.9460000	-0.2210000	-0.0001920
13H	-0.0033200	-0.0033700	0.0400000	-0.9050000	-0.2180000	-0.0000720
14H	-0.0025500	-0.0025900	-0.0112000			
15H	0.0028600	-0.0025500	0.0139000	0.5680000	0.1440000	
16H	-0.0030030	-0.0025500	0.0880000	0.3480000	0.1070000	-0.0000270
17H	0.0089500	0.0103000	0.6999000	4.4638000	1.2950000	0.0003180

Panel B: 1 week

	spot	forward	i_{USD}	i_{HKD}	composite	aCIPdev
constant	0.0083549	0.0118000	0.7877000	2.7806000	0.8970000	0.0014730
time	-0.0000002	-0.0000008	0.0000328	-0.0003630	-0.0000828	0.0000003
Tue	0.0002131					0.0002001
Wed	0.0008090	0.0006340	0.0272000	0.3480000	0.0942000	0.0000903
Thu	0.0004140	0.0003860	0.0273000	0.1640000	0.0481000	0.0000810
Fri	0.0006950	0.0005661	0.0140000	0.1210000	0.0342000	
8H	-0.0009170		-0.0301700	-0.1022170		
9H	-0.0010170					
10H	-0.0011600	-0.0013400	0.0351000	-0.1550000	-0.0307000	-0.0001135
11H	-0.0014100	-0.0014620	0.7860000	-0.1970000	-0.0304000	
12H	-0.0025200	-0.0027400	0.1808000	-1.0430000	-0.2169000	-0.0012730
13H	-0.0028300	-0.0029100	-0.1249000	-0.3090000	-0.1100000	-0.0003518
14H	-0.0021400	-0.0022908	0.0191000	-0.2150000	-0.0502000	-0.0001017
15H	-0.0026100	-0.0028400	0.0451000	-0.3380000	-0.0747000	-0.0002141
16H	-0.0026800	-0.0029100		-0.2050000	-0.0533000	
17H	0.0083549	0.0118000	0.7877000	2.7806000	0.8970000	0.0014730

(Table III continued)

Panel C: 4 weeks

	spot	forward	i_{USD}	i_{HKD}	composite	aCIPdev
constant	0.0088330	0.0165000	0.9560000	1.7650000	0.6868000	0.0042200
Time	-0.0000001	-0.0000005	-0.0000310	-0.0000620	-0.0000235	-0.0000005
Tue			-0.0404000	0.0265000	-0.0035300	0.0005170
Wed	0.0001855		-0.0104000	0.0341000	0.0060000	0.0006880
Thu		0.0005690	-0.0079000			0.0002430
Fri	0.0001370		-0.0128000		-0.0036800	0.0001760
8H	-0.0012500	-0.0011900	-0.0140900			
9H	-0.0011500	-0.0014900		0.0281700	0.0059100	0.0002059
10H	-0.0013110	-0.0016700		0.0452000	0.0102000	
11H	-0.0019880	-0.0023100	0.0126000	0.0532300	0.0154000	0.0007260
12H	-0.0022070	-0.0027400	0.1740000	0.0087000	0.0444000	
13H	-0.0030790	-0.0034400	-0.0417000		-0.0167000	
14H	-0.0023820	-0.0028300	-0.0218000	0.0380000	0.0027900	-0.0001600
15H	-0.0026800	-0.0031600		0.0130000		
16H	-0.0027410	-0.0032600	-0.0107000		-0.0047695	
17H	0.0088330	0.0165000	0.9560000	1.7650000	0.6868000	0.0042200

Panel D: 12 weeks

	spot	forward	i_{USD}	i_{HKD}	composite	aCIPdev
constant	0.008300	0.021500	0.714100	1.744000	0.622000	0.012200
time	-0.000001	-0.000001	-0.000003	-0.000048	-0.000013	-0.000001
Tue	0.000175		-0.005920			-0.000302
Wed	0.000343		-0.027800	0.009481	-0.004500	
Thu	0.000321	0.000305	-0.036500		-0.008850	-0.000775
Fri	0.000378	0.000500	-0.030200	0.012625	-0.004170	-0.000674
8H	-0.000625	-0.000420		-0.022977	-0.001200	-0.000416
9H	-0.000825	-0.000724		0.012977	0.002270	-0.000516
10H	-0.000819	-0.000976				-0.000362
11H	-0.001260	-0.001650				0.000774
12H	-0.001770	-0.002166	0.125800		0.030700	
13H	-0.002210	-0.001430				-0.001670
14H	-0.002140	-0.002140		0.015617	0.003250	-0.000232
15H	-0.002300	-0.002400		0.015872	0.002120	
16H	-0.002410	-0.001970				-0.000603
17H	0.008300	0.021500	0.714100	1.744000	0.622000	0.012200

Table IV

The effect of shocks on liquidity and absolute CIP deviations

To calculate the absolute CIP deviations for each of the four maturity tenors, we synchronize the time series of quotes of the four markets from the raw tick data as described in the text (Section IV). For each maturity tenor, we compute the proportional quoted spreads of the four markets (HKD/USD spot and forward FX markets, and USD and HKD deposit markets). We then compute a composite liquidity measure (the arithmetic average of the proportional quoted spreads of the four markets). After adjusting for seasonality in Table III, we regress absolute CIP deviations on the first lag of market liquidity (Panel A) and vice versa (Panel B). This table reports the OLS estimation results with standard errors in parentheses corrected for autocorrelation and heteroskedasticity (Newey and West, 1987). R^2 denotes the adjusted coefficient of determination. In Panel B, the coefficients are divided by 100

Panel A: Dependent variable absolute CIP deviations

	const	liquidity (t-1)	R^2
overnight	0.00023	0.00006	0.02
	(0.000049)	(0.00001)	
1 week	-0.00028	0.00196	0.19
	(0.000032)	(0.00003)	
4 weeks	0.004510	0.00041	<0.01
	(0.000194)	(0.00028)	
12 weeks	0.00829	0.00626	<0.01
	(0.00036)	(0.00058)	

Panel B: Dependent variable composite liquidity measure

	const	absolute CIP deviations (t-1)	R^2
overnight	1.175	3.7592	0.02
	(0.007)	(0.2045)	
1 week	0.754	0.9647	0.19
	(0.003)	(0.0176)	
4 weeks	0.687	0.00239	<0.01
	(0.0007)	(0.00158)	
12 weeks	0.614	0.00633	<0.01
	(0.0007)	(0.00059)	

Table V

Profitable arbitrage opportunities

This table shows the frequency of profitable deviations (i.e., positive deviations) from one-way and round-trip arbitrage in the FX market. CIP denotes round-trip arbitrage, while OA and BA denote owner arbitrage and borrower arbitrage respectively. All of the definitions of arbitrage are reported in Section V. To calculate the deviations for each of the four maturity tenors, we synchronize the time series of quotes of the four markets from the raw tick data as described in the text (Section IV). Total dev represents the number of all deviations (including non-positive). Profitable dev records the number of profitable deviations. % share are the profitable deviations as the percentage of all deviations.

	CIP		OA		BA	
	bid	ask	bid	ask	ask	bid
			Overnight			
Total dev	13,300	13,300	13,300	13,300	13,300	13,300
Profitable dev	6,650	11,970	4,522	11,837	5,852	11,438
% Share	50	90	34	89	44	86
			1 week			
Total dev	12,861	12,861	12,861	12,861	12,861	12,861
Profitable dev	5,016	9,517	3,987	9,260	4,501	9,003
% Share	39	74	31	72	35	70
			4 weeks			
Total dev	22,277	22,277	22,277	22,277	22,277	22,277
Profitable dev	10,916	14,035	8,911	13,366	9,579	12,698
% Share	49	63	40	60	43	57
			12 weeks			
Total dev	28,709	28,709	28,709	28,709	28,709	28,709
Profitable dev	12,632	22,393	7,751	20,958	10,622	18,661
% Share	44	78	27	73	37	65
Average % Share	*46*	*76*	*33*	*74*	*40*	*70*

Table VI

Average deviations from one-way and round-trip arbitrage

This table shows the average of all deviations from one-way and round-trip arbitrage in the FX market. CIP denotes round-trip arbitrage, while OA and BA denote owner arbitrage and borrower arbitrage respectively. All of the definitions of arbitrage are reported in the text. To calculate the deviations for each of the four maturity tenors, we synchronize the time series of quotes of the four markets from the raw tick data as described in the text (Section IV). The values in parentheses are asymptotic standard errors calculated using autocorrelation and heteroskedasticity variance-covariance matrices (Newey and West, 1987).

	CIP		OA		BA	
	bid	ask	bid	ask	ask	bid
			Mean			
overnight	-0.17	2.41	-0.70	2.27	-0.31	1.88
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
1 week	-1.10	6.49	-3.68	5.34	-2.27	3.89
	(0.12)	(0.11)	(0.12)	(0.11)	(0.13)	(0.11)
4 weeks	7.74	7.41	-1.02	3.13	3.30	-1.52
	(0.24)	(0.22)	(0.24)	(0.23)	(0.24)	(0.23)
12 weeks	-11.79	52.51	-37.32	40.34	-24.57	26.07
	(0.39)	(0.41)	(0.46)	(0.41)	(0.41)	(0.40)
			Median			
overnight	0.0	2.05	-0.45	1.93	-0.15	1.59
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
1 week	-2.40	7.32	-4.61	6.15	-3.41	4.90
	(0.12)	(0.11)	(0.12)	(0.11)	(0.13)	(0.11)
4 weeks	-0.22	15.69	-9.15	11.14	-4.41	6.26
	(0.24)	(0.22)	(0.24)	(0.23)	(0.24)	(0.230
12 weeks	-10.30	50.65	-36.44	38.52	-22.90	24.64
	(0.39)	(0.41)	(0.46)	(0.41)	(0.41)	(0.40)

Table VII

Average profitable arbitrage deviations

This table shows the average and the maximum of all of the positive deviations from one-way and round-trip arbitrage in the FX market. CIP denotes round-trip arbitrage, while OA and BA denote owner arbitrage and borrower arbitrage respectively. All of the definitions of arbitrage are reported in Section V. To calculate the deviations for each of the four maturity tenors, we synchronize the time series of the quotes of the four markets from the raw tick data, as described in the text (Section IV). The values in parenthesis are asymptotic standard errors calculated using autocorrelation and heteroskedasticity variance-covariance matrices (Newey and West, 1987).

	CIP		OA		BA	
	bid	ask	bid	ask	ask	bid
			Maximum			
overnight	8.9	12.41	8.12	12.27	8.76	11.87
1 week	39.22	72.79	33.33	71.37	38.14	65.56
4 weeks	88.03	215.03	80.46	208.90	83.85	197.58
12 weeks	169.88	448.55	147.25	436.52	157.49	395.15
			Mean			
overnight	1.3	2.8	1.3	2.7	1.3	2.4
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
1 week	10.4	11.9	10.1	11.1	10.5	10.0
	(0.12)	(0.11)	(0.12)	(0.11)	(0.13)	(0.11)
4 weeks	36.5	30.4	35.6	27.5	36.9	24.0
	(0.24)	(0.22)	(0.24)	(0.23)	(0.24)	(0.23)
12 weeks	51.0	80.2	51.2	73.4	47.4	66.0
	(0.39)	(0.41)	(0.46)	(0.41)	(0.41)	(0.40)
			Median			
overnight	0.8	2.2	0.8	2.1	0.8	1.7
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
1 week	8.9	9.3	8.8	8.4	8.6	7.4
	(0.12)	(0.11)	(0.12)	(0.11)	(0.13)	(0.11)
4 weeks	33.9	26.9	33.8	22.8	35.2	19.8
	(0.24)	(0.22)	(0.24)	(0.23)	(0.24)	(0.23)
12 weeks	37.6	79.4	42.3	70.4	31.9	60.9
	(0.39)	(0.41)	(0.46)	(0.41)	(0.41)	(0.40)

Figure 1. Frequency of Quotations

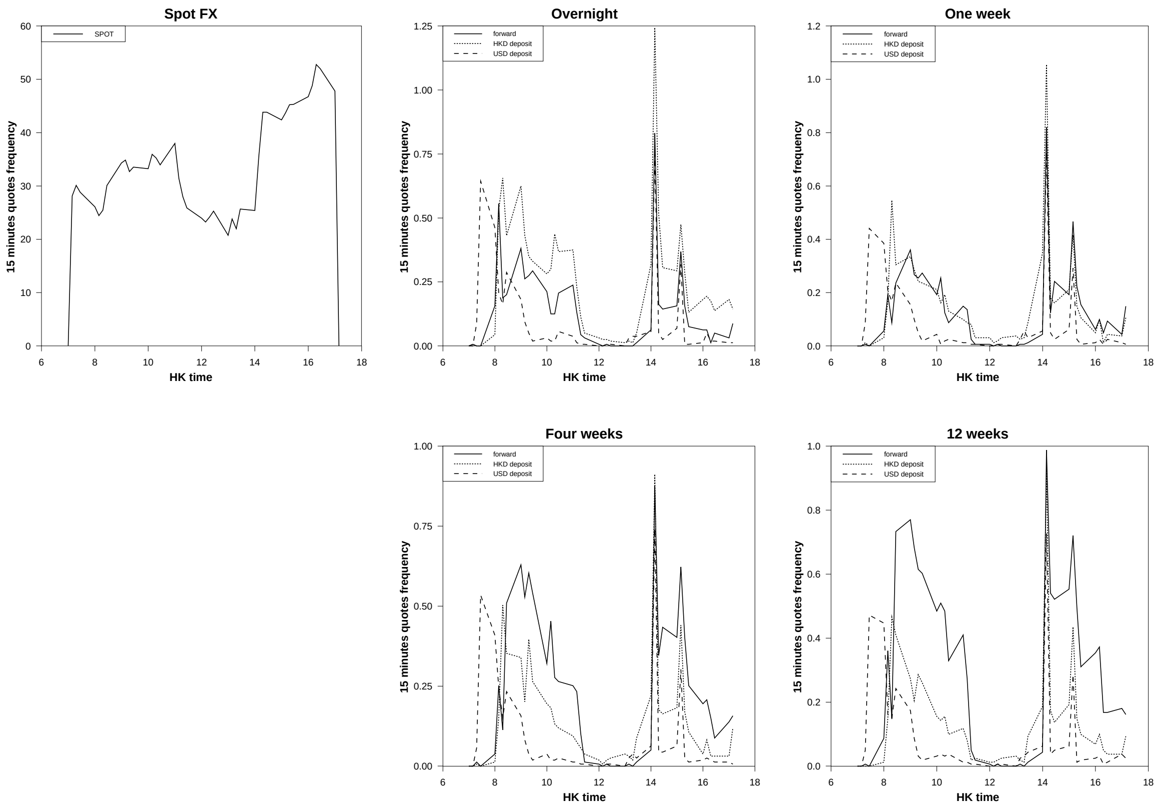

Figure 2. Responses to innovations: Overnight

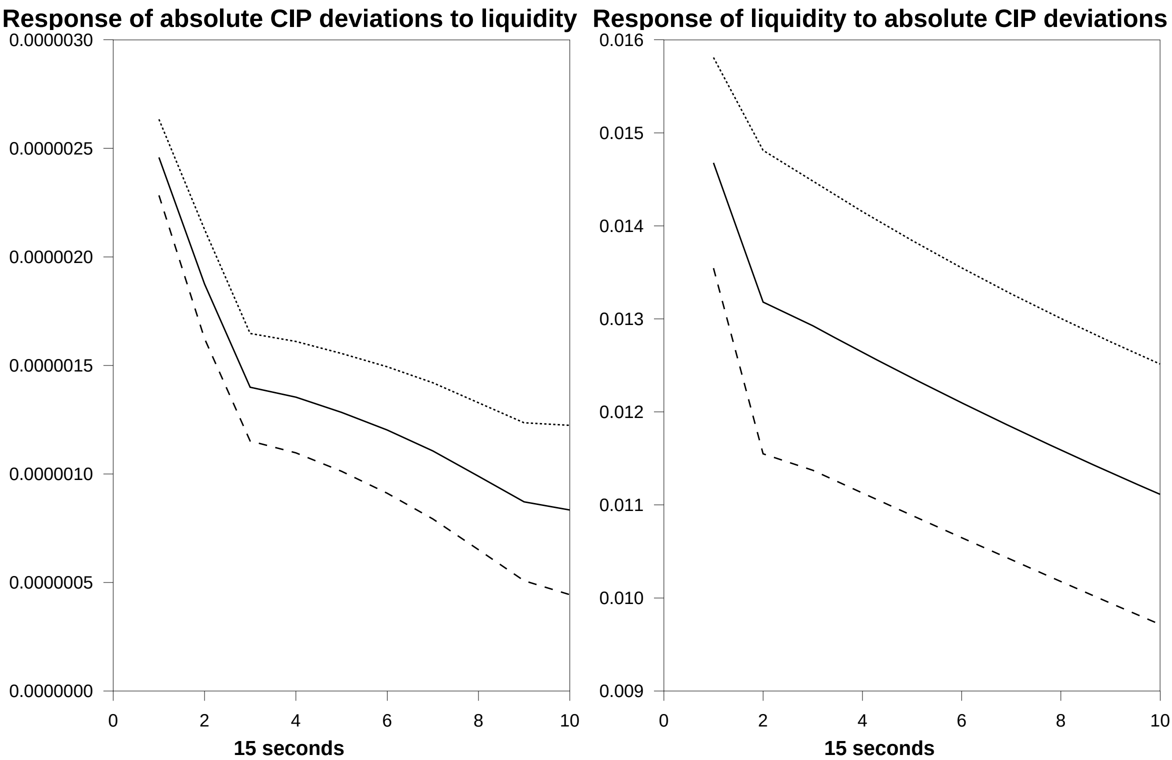

Figure 3. Responses to innovations: one week

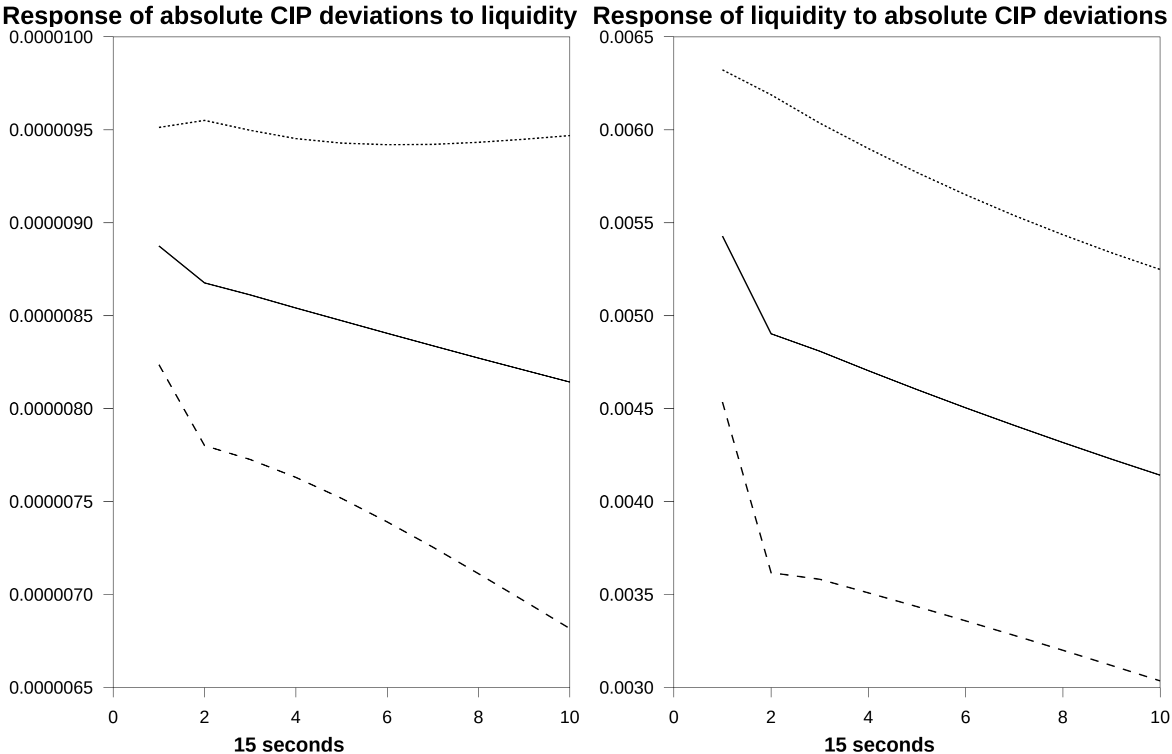

Figure 4. Responses to innovations: four weeks

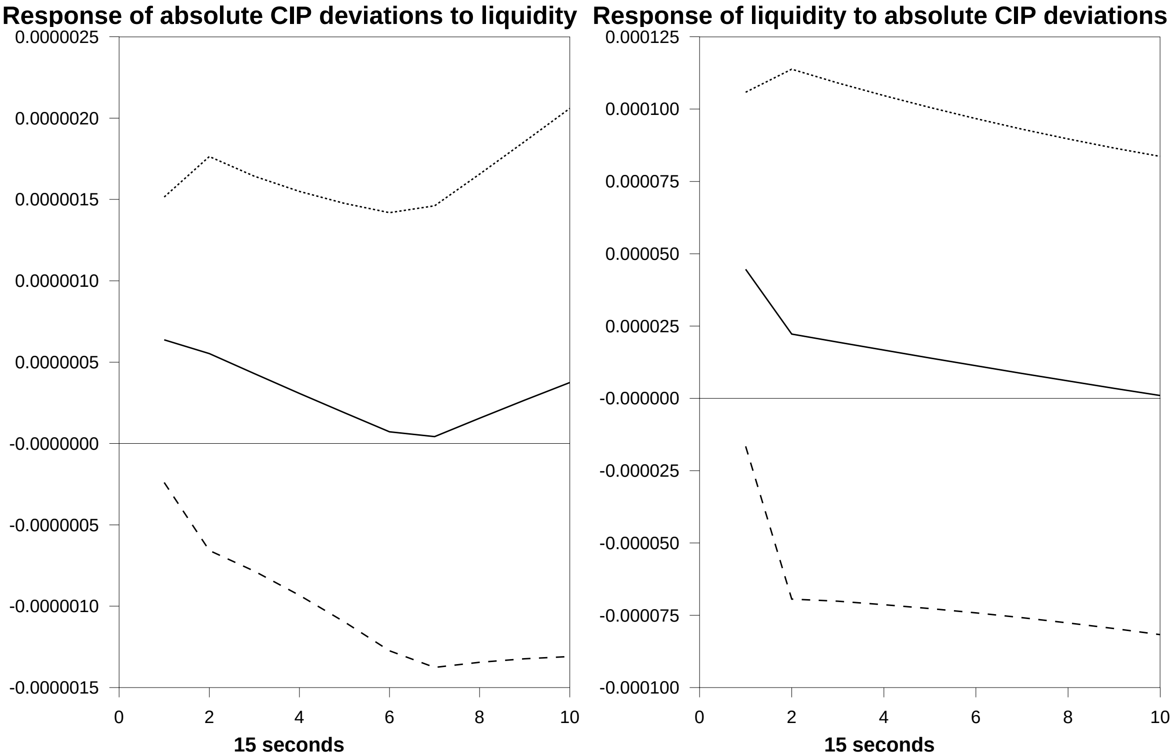

Figure 5. Responses to innovations: 12 weeks

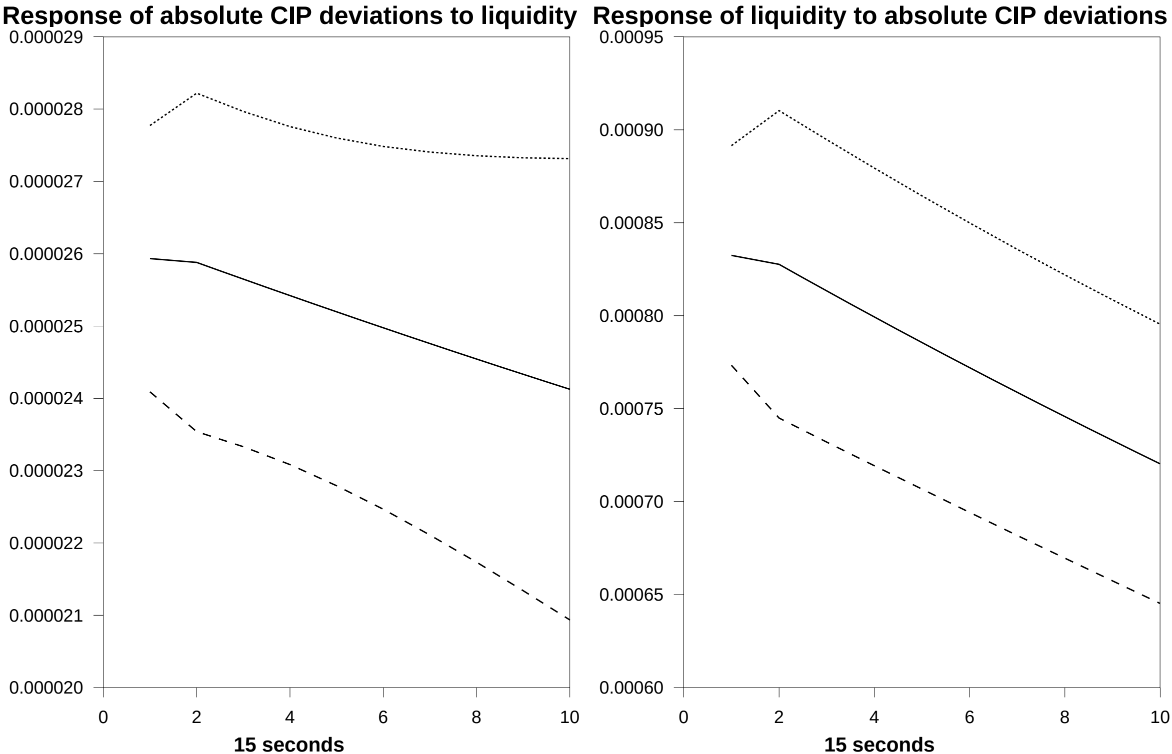

Figure 6: Average Positive Arbitrage Deviations
Round-trip arbitrage (ask prices)

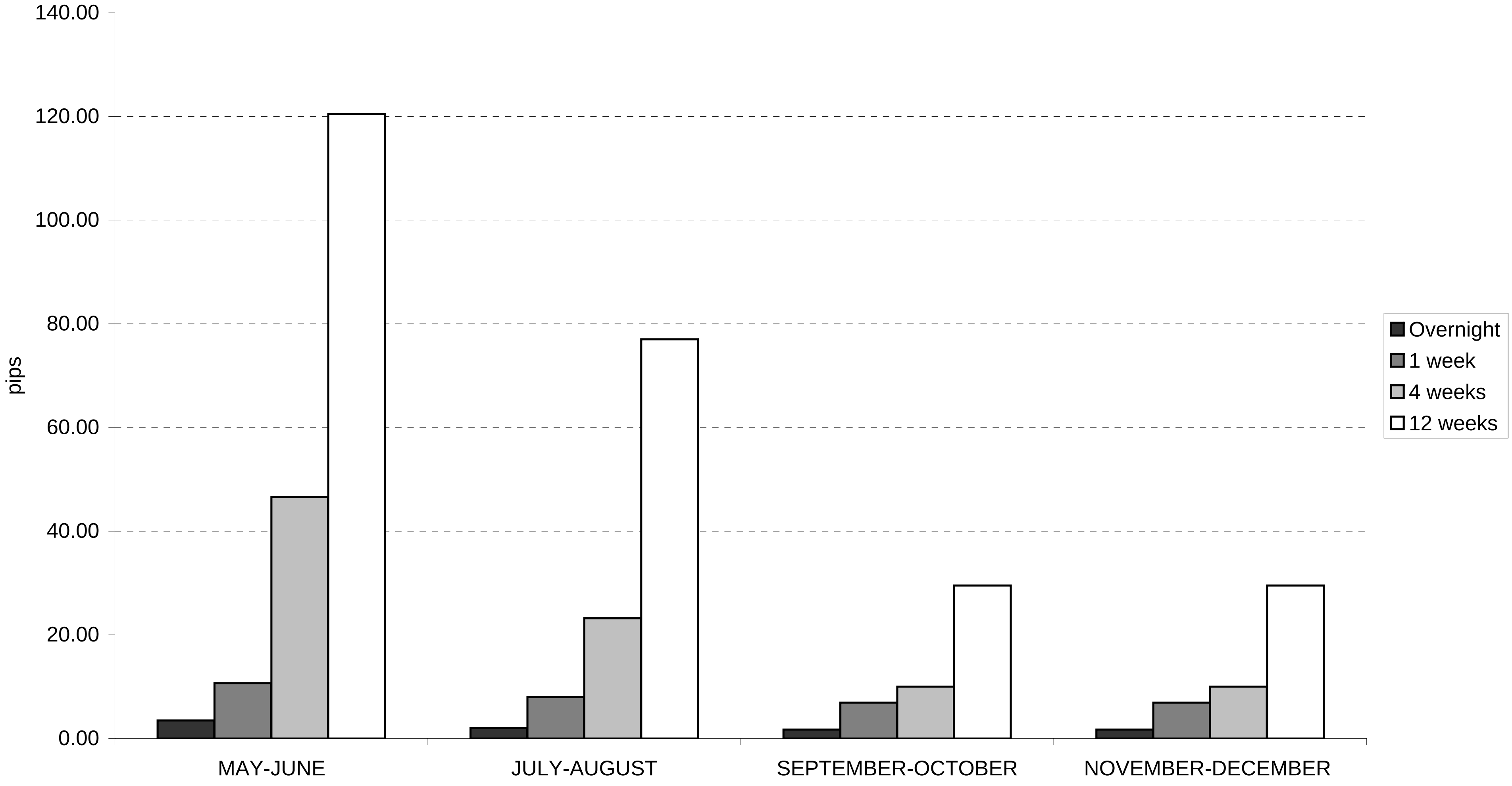

Figure 7: Average Positive Arbitrage Deviations
One-way (OA) arbitrage (ask prices)

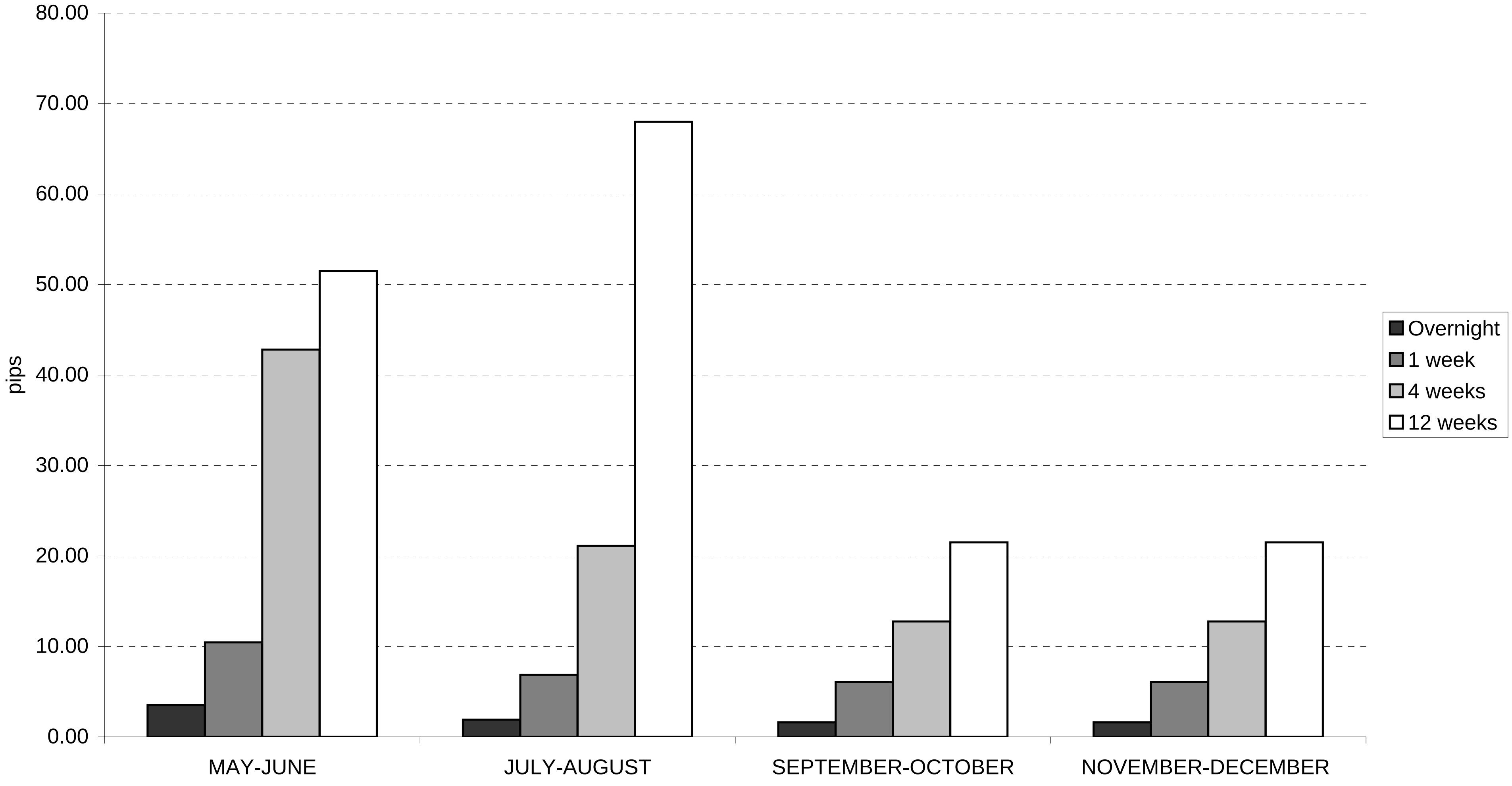

Figure 8: Average Positive Arbitrage Deviations

One-way (BA) arbitrage (ask prices)