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# FX ARBITRAGE AND MARKET LIQUIDITY: STATISTICAL SIGNIFICANCE AND ECONOMIC VALUE

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# FX Arbitrage and Market Liquidity: Statistical Significance and Economic Value[1]

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## Abstract

This paper studies covered interest parity arbitrage violations in foreign exchange markets and their relationship with market liquidity using a novel and unique dataset of tick-by-tick firm quotes for all financial instruments involved in the arbitrage strategy. The statistical analysis reveals that arbitrage opportunities are larger in size and slower to dissipate when market liquidity is poorer. Furthermore, their economic value is sizable but arbitrage profits only accrue to traders who are able to obtain low trading costs. These findings are consistent with a competitive equilibrium with real frictions when some traders have a comparative advantage in arbitrage trading.

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# 1. 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 foreign exchange (FX) markets, exhibit in real time few arbitrage opportunities which are generally not profitable 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 necessarily hold when markets are illiquid. 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 as well as 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 large equity markets or other mature financial markets. However, it is generally acknowledged among market practitioners that arbitrage opportunities are more pronounced in size and more persistent over time in smaller and comparatively less liquid markets than in mature and larger markets.[3] Furthermore, to the best of our knowledge, there are no existing studies which have investigated the relationship between deviations from the law of one price and market liquidity in the context of FX markets.

This paper fills this gap by revisiting the issue of FX arbitrage for a single currency market (i.e. Hong Kong dollar) which is among the ten largest currency markets in terms of daily average turnover (Bank for International Settlement, 2007) but where market liquidity is a more important issue than in major currency markets usually investigated in the recent FX microstructure literature. Using a novel and unique dataset of tick-by-tick 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 we carry out an extensive statistical analysis of covered interest parity (CIP) deviations and their relationship with market liquidity. Furthermore, given the issues plaguing statistical tests of deviations from the law of one price, we move

3 Furthermore, 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 higher liquidity. 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), no previous studies have explored the relationship between arbitrage opportunities and liquidity in emerging markets. Notable exceptions are Lesmond (2005) who investigated liquidity in emerging equity markets and Yeyati *et al.* (2007) who focused on emerging markets liquidity during crises. However neither study investigates the relationship between market liquidity and arbitrage opportunities.

beyond the pure statistical perspective and provide evidence on the economic value of arbitrage opportunities in the FX market. Distinguishing between statistical analysis and economic evaluation is crucial since statistical rejections of a hypothesis do not necessarily imply economic rejections. This suggests that an economic assessment of CIP deviations is desirable to complement the statistical tests.

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 statistically significant deviations from CIP. Second, we find that these deviations are larger in size and slower to converge to equilibrium when the liquidity of the HKD/USD spot, forward and deposit markets is poor. Third, the economic value of these arbitrage opportunities is sizable even after bid-ask spreads are taken into account, especially for longer maturity tenors. However, since additional trading costs (i.e. brokerage fees and settlement costs) are generally not included in quoted and transaction prices, their explicit consideration is likely to offset any profits that arise from arbitrage activities at short maturities. For longer maturities only the traders who are able to obtain low trading costs can reap genuine arbitrage profits. These findings are consistent with competitive equilibrium where there are real frictions and some traders have a comparative advantage in arbitrage trading.

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 rely on the computation of arbitrage deviations using data in which the relevant prices are collected from markets located in different time zones. McCormick (1979) and Taylor (1987, 1989) solve 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. Furthermore, 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) revisit the issue of FX arbitrage profitability by using tick-by-tick data for three major currencies *vis-à-vis* the US dollar. Their findings are supportive of existing, but very short-lived, arbitrage opportunities.[4]

[4] A related paper which does not address the issue of CIP arbitrage but empirically investigates triangular arbitrage in the FX market is Marshall *et al.* (2008). The authors report findings which are supportive of existing arbitrage opportunities in major currency market traded in an electronic setting.

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 may be related to FX 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 where liquidity is not as high as in major currency markets, it is plausible to hypothesize that market liquidity dynamics may affect arbitrage opportunities in the FX market.

This study 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-by-tick frequency for all financial instruments involved in the 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 rates and exchange rates data that are 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 employ datasets exhibiting various limitations. One of the most relevant limitations is that all or some of the prices used to compute arbitrage deviations are purely indicative[5], hence evidence of arbitrage opportunities recorded using these datasets may not necessarily imply glaring profitable opportunities. The dataset employed in this paper is therefore unique and allows us to carry out a thorough economic 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 differ from Akram *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 FX markets. Our paper is also different from Cheung and Daniel (1994), which is, to the best of our knowledge, the only existing study on FX arbitrage in the Hong Kong FX market. In that paper, the authors employ daily indicative quotes over a shorter period of time (3 months) recorded over an interval of 30 minutes (between 10:45am and 11:15am Hong Kong time). Further, their data are collected from two commercial banks (i.e. Tokyo Forex and Tullett and Hua Chiao Commercial Bank Limited), while our tradable quotes are provided by ICAP, the world's largest voice and electronic interdealer broker.

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

Third, our work is related to 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 necessarily be economically profitable.[6]

The remainder of this paper is organized as follows. In Section 2 we discuss the theoretical underpinnings and our hypotheses, while in Section 3 we describe the data used in our empirical investigation. Sections 4 and 5 report and discuss the results of empirical analysis. Section 6 contains some robustness checks and a final section concludes.

## 2. CIP and Arbitrage in the FX Markets

The CIP theorem states that the *covered* interest rate differential between two identical risk-free securities denominated in two different currencies should be zero. Put differently, interest rate differentials over any maturity tenor should be equal to the forward premium/discount 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 tenor $k$, $S$ is the prevailing spot exchange rate and $F_k$ is the forward exchange rate with maturity tenor $k$.

Any deviations from Equation (1) would represent a risk-free arbitrage opportunity in a frictionless world, in which transaction costs do not exist. If we introduce transaction costs by adding bid and ask prices to Equation (1), then any deviations from CIP are profitable only if either of the following inequalities hold:

$$\begin{aligned} &\frac{F_k^b}{S^a}-\frac{\left(1+i_{d,k}^a\right)}{\left(1+i_{f,k}^b\right)}>0 \\ &\frac{S^b}{F_k^a}-\frac{\left(1+i_{f,k}^a\right)}{\left(1+i_{d,k}^b\right)}>0 \end{aligned} \tag{2}$$

6 Further, because of data limitation, Roll *et al.* (2007) employ daily observations to compute deviations from the law of one price. In this study, we use tick-by-tick data and this allows us to analyze the very short-term dynamics between arbitrage opportunities and market liquidity.

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.[7]

In order to glean insights on arbitrage activity and profitability in the HKD/USD FX market, we divide our empirical investigation into two parts. In the first part, we statistically explore the relationship between market liquidity and absolute deviations from CIP in the spirit of Roll *et al.* (2007). In the second part, we assess the economic value (i.e. profitability) of CIP deviations by explicitly incorporating bid-ask spreads and other trading costs.

# 3. Data

Our paper uses data for the HKD FX market. The triennial survey on FX market activity carried out by the Bank for International Settlements shows that in April 2007 the HKD market is the 10th-largest currency market in terms of percentage share of the daily world average turnover, together with the Swedish krona (SEK) and just above the Norwegian krone (NOK), currencies that have been investigated in recent empirical studies (Bjønnes and Rime, 2005).[8]

Our dataset is a collection of tick data obtained from ICAP for the sample period ranging between May 17th, 2005 and December 31st, 2005;[9] covering about eight months of tick-by-tick data. ICAP is the world's largest voice and electronic interdealer broker; in 2006 it covered 65% of the worldwide FX spot voice market and 35% of the FX voice forward market. Although recent market trends have exhibited a furious shift from voice broking to electronic broking, the voice-broking FX market is still very active and in certain geographical areas, especially Asia-Pacific, it is the dominant trading venue. In fact, in 2006, FX voice broking contributed a hefty 69% to the ICAP group's overall profits.[10]

[7] In the spirit of Deardorff's (1979) analysis, a different test of CIP may arise from considering one-way arbitrage opportunities in the form of owner's arbitrage (OA) and borrower's arbitrage (BA). However, 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. 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). For these reasons we consider CIP (or round-trip) arbitrage as the only proper arbitrage condition in the FX market throughout the paper.

[8] Furthermore, the HKD is the first, in terms of size, among all emerging market currencies.

[9] The sample period is chosen because of data availability (firm quotes are not available from ICAP before May 17th, 2005).

[10] 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 market coverage of our dataset, computed as in Rime (2003) and Bjønnes and Rime (2005), is about 40% of the overall HKD spot and forward FX market. We thank Dagfinn Rime for suggesting this to us.

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. A particular novelty of this unique dataset is that all of the ask and bid prices are firm (hence, directly tradable), which is different from most of the previous studies in which all or some of the quotes are indicative.[11] This difference is particularly relevant, because firm quotes allow us to accurately compute genuine real-time arbitrage opportunities and assess their economic value. All of the quotes in our dataset are retrieved from ICAP voice-broking record tapes.

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, confirming and reinforcing the argument that in the HKD FX market, liquidity is a more important issue than in major currency markets.

# 4. Statistical Significance: 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 the statistical properties of violations of the CIP condition and their relation with the underlying dynamics of market liquidity. We first compute absolute CIP deviations as follows:

$$\left| \left[ \frac{\left(1+i_{d,k}\right)}{\left(1+i_{f,k}\right)} \right]^{\frac{D}{365}} - \frac{F_k}{S} \right| \tag{3}$$

[11] 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.

where $D$ is the number of days to maturity of forward and deposit contracts over the maturity tenor $k$, 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.

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 throughout the paper is represented by proportional quoted bid-ask spreads.

The first part of Table 1 reports the proportional quoted bid-ask spreads, computed as the quoted bid-ask spread divided by bid price, for all instruments and maturity tenors. The figures reported are the average and median values together with the relative standard deviations. The proportional spreads in the HKD/USD spot and forward markets are comparable in size and very small. Furthermore, the spreads in the forward rates are increasing with maturity. The proportional spreads in both the HKD and USD deposit rates are high compared to their analogues in the spot and forward FX market and they are fairly constant across maturities. This piece of evidence is consistent with the empirical results 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 the two 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). After these adjustments the number of trading days range between 157 (four weeks maturity) and 159 (one and 12 weeks maturity). Second, we retain the active time period within each day (i.e. between 7:00 and 17:00 HK time).[12] 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 15-second interval time series to form a synchronized sample. Finally, to mitigate a possible problem of stale quotes, we delete all observations in which either the spot or forward prevailing bid and ask were quoted more than five minutes previously, or in which either the HKD or USD deposit prevailing bid and ask prices were quoted more than one hour previously. Overall, the average number of observations employed in our empirical analysis is larger than 12,000 for all four maturity tenors, with a maximum of about 28,000 observations at 12 weeks maturity. We first analyze this synchronized sample to get our baseline results. However, in Section 6, we carefully check for the robustness of these results with respect to other data synchronization filters and adjustments.

12 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.

Using this synchronized sample, the summary statistics of absolute CIP deviations, as of Equation (3), are reported at the bottom of Table 1 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.[13]

To address the question of whether CIP deviations are statistically related to liquidity in the HKD/USD FX market, we carry out, in the spirit of Roll *et al.* (2007), a simple correlation analysis by computing two sets of correlation coefficients: one between the parameters of mean-reversion of CIP deviations and market liquidity and the other between the absolute CIP deviations and market liquidity. The aggregate market liquidity measure used in this exercise, and throughout the paper, is a composite measure of liquidity summarizing liquidity conditions in all markets involved in the FX arbitrage and it is computed as the arithmetic average of all proportional quoted bid-ask spread across the four markets at each time interval.

In order to carry out the first correlation exercise, we compute the parameter of mean reversion of CIP deviations by employing a conventional Dickey-Fuller regression framework:

$$\Delta x_t = \delta_{0,T} - \delta_{1,T} x_{t-1} + e_t \qquad (4)$$

where $x_t$ denotes signed CIP deviations, i.e. deviation from Equation (1). The conventional interpretation of parameter $\delta_1$ is speed of mean reversion towards the equilibrium condition and the larger $\delta_1$ in absolute value, the faster the reversion towards the equilibrium condition.[14] Equation (4) is estimated in a rolling fashion using a sample window of T=1,500.[15] The results of this exercise are reported in Panel A of Table 2. In all cases, the estimated rolling parameters of mean reversion of CIP deviations are negatively correlated to our composite liquidity measure. This suggests that the mean reversion towards equilibrium is slower when the FX market is less liquid (or FX market liquidity is poor). The correlation coefficients are small in magnitude, about seven percent on average across maturity tenors, and they are all statistically significant at the 1% statistical level.

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13 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. Bid and ask prices are explicitly incorporated in the next section of the paper, in which the issue of the genuine profitability of arbitrage opportunities is fully addressed.

14 The empirical framework summarized by equation (4) is similar in spirit to the one proposed by Brennan and Schwartz (1990) and recently used by Roll *et al.* (2007). However, Equation (4) takes into account the fact that forward contracts are OTC instruments which are quoted for the same maturity tenor at any time during the day and for each trading day. Hence Brennan and Schwartz's (1990) approach cannot be applied in our context since it requires prices for the same futures contract over its maturity life. In fact, forward contracts, differently from futures contracts, are quoted for the same maturity tenor over any trading day and it is not possible to collect prices for the same contract over its maturity life.

15 We have experimented with rolling windows of different size and the results, not reported to save space, are qualitatively and quantitatively similar to the ones reported in Table 2.

The second correlation exercise relates absolute CIP deviations, i.e. Equation (3), with the aggregate measure of market liquidity. In this case, the hypothesis we test is that deviations from CIP are larger when market liquidity is poorer. The results of this exercise are reported in Panel B of Table 2. In all cases, our conjecture is validated by the data since absolute CIP deviations are positively correlated to the average proportional quoted spreads. This evidence is strongest at the one week maturity and weakest at the four weeks maturity, but nevertheless statistically significant in all cases at the 1% statistical level.

The above evidence suggests a strong contemporaneous relationship between CIP deviations and market liquidity. However, it is also instructive to investigate their dynamic interaction over time. For each maturity tenor we estimate a bivariate VAR, comprising both absolute CIP deviations and aggregate measures of liquidity, and the number of lags of the endogenous variables is selected by using conventional information criteria.

The results of the VAR estimations are reported in Table 3. The first two columns of the table show the *p*-values of the null hypothesis that either liquidity (column 1) or absolute CIP deviations (column 2) does not cause the other variable respectively. For all maturity tenors the null hypothesis is rejected at the 5% statistical level.

Moreover, for each VAR model, generalized impulse response functions (GIRFs), *à la* Koop *et al.* (1996), are estimated and the resulting half-lives of shocks occurring in either one of the endogenous variables are reported in the last four columns of Table 3.[16] It appears that the half-lives are sufficiently short: close to seven minutes on average across maturities and comprised within a confidence interval ranging between four and nine minutes. These findings are consistent with the fact that in a voice-broking environment shocks to either market liquidity or CIP deviations require a longer time to dissipate. Nevertheless, the figures reported in Table 3 are not unreasonably high and lie within the confidence intervals of durations of CIP deviations recorded for major currencies by Akram *et al.* (2007).

## 5. Economic Value: FX 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 related to variations in liquidity conditions of the markets involved in setting the FX arbitrage. However, these statistically significant absolute deviations from CIP represent only a necessary, but not a sufficient, condition for the existence of

16 Generalized impulse response functions 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. The confidence intervals of the GIRFs are estimated by Monte Carlo simulation setting the number of replications to 5,000.

economically profitable arbitrage opportunities, as the absolute deviations are calculated using mid-quotes and, thus, ignore transaction costs.

In this section, we investigate the profitability of deviations from CIP (round-trip) arbitrage conditions as follows:

$$CIP\ (bid): \frac{F_k^b}{S^a} - \left[\frac{\left(1+i_{d,k}^a\right)}{\left(1+i_{f,k}^b\right)}\right]^{\frac{D}{365}} > 0 \quad \text{or} \qquad (5.1)$$

$$CIP\ (ask): \frac{S^b}{F_k^a} - \left[\frac{\left(1+i_{f,k}^a\right)}{\left(1+i_{d,k}^b\right)}\right]^{\frac{D}{365}} > 0 \qquad (5.2)$$

where *D* is the number of days to maturity of the forward and deposit contracts over the maturity tenor *k*, and superscripts *a* and *b* denote the ask and bid prices respectively. Equations (5) indicate that only positive deviations are profitable.[17]

Table 4 shows the percentage of positive deviations out of all of the observations. Across maturity tenors, we find that the average percentage of positive arbitrage deviations ranges between 9% and 60%. Further, arbitrage at the bid price of CIP is roughly twice as frequent as arbitrage at the ask price. This latter finding is not novel in the literature. In fact Akram *et al.* (2007) reports for the Japanese yen (JPY)/USD CIP arbitrage a similar pattern. This phenomenon can be heuristically explained by the fact that for both JPY/USD and HKD/USD the USD is not the quoting currency. Hence, the exhibited pattern may be due to quoting practices.

If markets are very efficient, then we expect to see a high frequency of non-positive deviations, i.e. those that have not led to arbitrage profits, whereas positive deviations have been limited by arbitrage activities to avoid free lunch. Thus, positive deviations should have occurred much less frequently than non-positive ones. Notwithstanding, the unexpectedly high frequency of positive deviations reported in Table 4 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 positive CIP deviations in Table 5. At face value, the average profits from FX (round-trip) arbitrage are handsome, and their size increases with maturity.

[17] As pointed out in Akram *et al.* (2007), to exploit an arbitrage opportunity, 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’. See also the theories related to limits to arbitrage (Shleifer and Vishny, 1997; Abreu and Brunnermeier, 2002).

However, the figures reported, albeit incorporating the effect of the bid and ask prices, do not include additional trading costs (i.e. brokerage fees and settlement costs). Akram *et al.* (2007) usefully report that these trading costs faced by agents on the Reuters D3000 platform for the three major currencies *vis-à-vis* the USD are 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 not comparable to the Reuters D3000. In fact, the voice-broking market in Hong Kong is characterized by a large variability of trading costs. They are applied with different magnitudes to different traders with different credit-worthiness and, in some cases, even to the same trader for different financial instruments or different market conditions. Thus, it is difficult to pin down a unique number that unambiguously represents the amount of additional trading costs in this market and ready estimates are not available. We do not take a stand as to what appropriate trading costs should be. Instead, we compute the round-trip break-even costs that would make the average arbitrage profits reported in Table 5 equal to zero. We assume, in the spirit of Han (2006) and Della Corte *et al.* (2007), that trading costs are a fixed percentage of the value traded of all financial instruments involved in the CIP arbitrage strategy. Consequently the break-even average costs are computed by setting

$$E\left[(1-\tau)\left|w_t - w_{t-1}ARB_t\right|\right] = \frac{1}{T}\sum_{t=0}^{T-1}\left[(1-\tau)\left|w_t - w_{t-1}ARB_t\right|\right] = 0 \qquad (6)$$

where $w_t$ is equal to one if the CIP arbitrage deviations at time $t$ are positive and zero otherwise, $ARB_t$ are deviations from CIP either at the bid or ask prices as in Equations (5) and $\tau$ are break-even costs. Table 6 shows the estimated break-even costs per round-trip transaction, expressed in pips, which would offset the average arbitrage profits reported in Table 5. It is interesting to note that for very short maturity tenors, just a fraction of a pip paid per round-trip transaction would result in no arbitrage profits on average. In particular, the value of break-even costs reported for the overnight maturity tenor is not too far away from the value of $1/10^{th}$ of a pip on major electronic trading venues. However, the trading costs required to offset arbitrage profits at longer maturities are much higher, ranging between 9 and 17 pips per round-trip transaction.

In light of these considerations, we conjecture that in the HKD/USD market the presence of realistic voice-broking additional trading costs probably wipes out most (or all) profits that arise from arbitrage in the overnight maturity tenor. However, for longer maturities, some, but not all, traders are able to reap arbitrage profits only if they are able to obtain low trading costs, because of their credit-worthiness or previous business relationship with their counterparts. This evidence is consistent with competitive equilibrium when there are real frictions and some traders have a comparative advantage in arbitrage trading.

Table 7 reports the percentage share of profitable opportunities which would still exist when estimated break-even costs are included in the calculation of arbitrage profits. When break-even costs are computed to offset the average profits reported in Table 5 (reported in the first two column of Table 7), the average percentage of profitable opportunities is reduced by 77% at the bid prices and by 63% at the ask prices. If the break-even costs are computed to offset up to the 90$^{th}$ percentile of the arbitrage profits' distribution (reported in the last two column of Table 7), there is an obvious dramatic reduction of profitable arbitrage opportunities which reach a mere five percent at the bid prices and two percent at the ask prices.

The results reported in Tables 4-7 indicate that there is strong evidence of economic value to CIP deviations, even when the bid-ask spreads are taken into account. However, when trading costs deriving from the specific voice-broking environment are incorporated, the empirical evidence suggests that only a subset of traders – those with high credit-worthiness or longer and established business relationship with their counterparts - will be able to reap genuine arbitrage profits. This suggests 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.[18]

As a final exercise we compute half-lives of shocks to both market liquidity and positive CIP deviations defined as in Equations (5). In Section 4 we investigated the relationship between absolute CIP deviations, computed at the mid-prices, and aggregate market liquidity and we found that CIP deviations display larger size and slower reversion towards equilibrium when market liquidity is poorer. However, that exercise though useful for establishing a significantly statistical relationship between liquidity and the law of one price in the FX market, did not take into account the fact that only positive CIP deviations computed using tradable bid and ask prices imply genuine profitable opportunities.[19] Table 8 shows half-lives of shocks to either market liquidity or positive CIP deviations at both sides of the market. When shocks occur at the bid side of the market, the average half-life of shocks is close to 6 minutes, while when shocks occur at the ask side of the market, the half-life drops to about 3 minutes. When comparing these results with the ones reported in Table 5, we note that half-lives of shocks are much shorter when only positive CIP deviations are used. This suggests that shocks affecting market liquidity or positive CIP

[18] 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. However, some recent evidence indicates that positive arbitrage profits from triangular arbitrage are present also in major currency markets (Marshall *et al.* , 2008)

[19] In fact, absolute CIP deviations computed at mid-prices, by blending together profitable and unprofitable arbitrage opportunities, may blur the genuine relationship between market liquidity and deviations from the law of one price in the FX market.

deviations are quicker to revert to equilibrium, when compared to the speed of mean reversion highlighted in Table 3.[20]

# 6. Robustness

In this section we report some robustness checks carried out to assess the sensitivity of our baseline results discussed in Sections 4 and 5. 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 correlation patterns reported in Table 2 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 composite liquidity measure and then we compute the correlation coefficients, as in Table 2, using seasonally-adjusted variables.

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

The results reported in the Appendix to this paper (Table A.1) show some interesting patterns. In every instance, it is possible to retrieve a statistically significant linear negative trend. However, the coefficient on the quadratic trend is positive, albeit very small in magnitude. 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.[21] In contrast with previous studies (Bessembinder, 1994; Ito and Hashimoto, 2006), calendar effects do not exhibit recognizable patterns. Some of the daily and hourly 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 or hour-of-the-day seasonality in the data, our estimates must be interpreted with caution, as they are obtained using a limited numbers of trading days.

[20] We also computed the set of correlation coefficients as in Table 3 when only positive CIP deviations at both the bid and ask prices are used. The results of this exercise, not reported to save space, confirm qualitatively and quantitatively the results reported in Table 3.

[21] This dynamic may be due to the monetary regime change introduced by the HKMA in May 2005. The HKD/USD market has been characterized by a Linked Exchange Rate System since 1983. From 1998, the HKMA allowed for a 'weak-side convertibility undertaking' which implied an obligation for the monetary authority to sell USD when the 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'. 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. The negative trends in Table A.I can also be rationalized on the basis of the findings of Akram *et al.* (2007) who show that lower volatility of FX markets is generally associated with smaller and less frequent arbitrage opportunities.

Using the seasonally-adjusted series, we repeat the correlation analysis in Table 2. The results of this robustness check are reported in Table A.2 and they exhibit correlation coefficients that are qualitatively similar but quantitatively smaller in magnitude to those reported in Table 2.

Our second robustness check relates to the possible bias induced by the synchronization rule employed in Section 4. More in particular we try to assess how the percentage share of profitable arbitrage opportunities and the average CIP arbitrage profit vary when different, and more stringent, synchronization rules are used.

We construct different samples using three different synchronization or filtering rules. With filtering rule 1 (Table A.3, Panel A), we use the forthcoming quotes of deposit rates to replace the prevailing quotes of deposit rates used for our baseline results. This rule deletes observations with spot or forward rates being quoted more than five minutes previously, or with the forthcoming interest rates being missing.

When comparing Panel A with Tables 4 and 5, it appears that the results are robust no matter we use prevailing deposit rates or forthcoming deposit rates. This should not be surprising, since deposit rates rarely change significantly within a day. Thus, we feel comfortable with the baseline rule in using prevailing deposit rates that were quoted within one hour ago. On the other hand, both filtering rule 1 and the baseline rule allow observations where either spot or forward bid and ask were quoted within five minutes previously. Such quotes may be stale. To check for this, with filtering rule 2, we delete all observations in which either the spot or forward bid and ask were quoted more than two, not five, minutes previously. This further mitigates a possible problem of stale quotes, but significantly reduces the number of usable observations. To make sure that this sample has a reasonable size, we cannot (as explained above, we do not have to) impose that the forthcoming or the prevailing deposit rates must be quoted within one hour. Thus, with this filtering rule, we only insist that both the forthcoming and the prevailing deposit rates are quoted within the day. Then, we compare the results using the forthcoming quotes with the results using the prevailing quotes. These are shown in Table A.3, Panel B. We note that the results using prevailing quotes or forthcoming quotes are similar. They are also comparable with the baseline results shown in Tables 4 and 5.

A final robustness check on the computation of positive CIP deviations involves the effects of possible nonsynchronous trading in the four markets involved in the FX arbitrage. To address this issue we adopt the Jokivuolle's (1995) approach which allows us to estimate the true value of an index when some of its components are subject to stale pricing (Table A.3, Panel C). Again, the results are similar to Tables 4 and 5. Overall, the robustness exercises reported in this section indicate that the key results reached in Sections 4 and 5 are robust. These baseline results are qualitatively and quantitatively unaffected by the existence of intraday and interday seasonality in market liquidity and CIP deviations and are not due to stale pricing in the less liquid markets involved in the FX arbitrage.

# 7. Conclusions

In this paper we revisit the issue of FX arbitrage 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 tick-by-tick 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 aggregate measures of liquidity summarizing liquidity conditions 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 statistically significant deviations from CIP. Second we find that these deviations are larger in size and slower to converge to equilibrium when the aggregate liquidity of the HKD/USD spot and forward markets and the deposit markets is poorer. These results are overall supportive of Roll *et al.* (2007) in the context of FX markets. Third, we find that, consistent with the views of market practitioners, but in contrast to the most of the existing academic literature, deviations from no-arbitrage conditions result in a number of genuinely profitable arbitrage opportunities even after taking into account bid-ask spreads. However, the existence of voice-broking trading costs is likely to offset any profits that arise from arbitrage at short maturities: however, some but not all, traders can reap arbitrage profits net of all transaction costs. These results are consistent with a competitive equilibrium when there are real frictions and some traders have a comparative advantage in arbitrage trading.

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**Table 1. 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. Proportional quoted bid-ask spreads are computed as quoted bid-ask spreads 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 4).

| | **Mean** | **Median** | **Standard Deviation** |
|---|---|---|---|
| *Panel A: Proportional 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 – HKD 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 – USD 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 2. Correlations between CIP Deviations and Market Liquidity**

For each maturity tenor, this table reports the correlation coefficients between the coefficient of mean reversion ($\delta 1$ in Equation (4) discussed in the main text) of CIP deviations (Panel A) or absolute CIP deviations (Panel B) and market liquidity approximated by the equally-weighted proportional quoted spreads of the four markets (HKD/USD spot and forward FX markets, and the USD and HKD deposit markets). CIP deviations are computed using mid-quotes. The coefficient of mean reversion in Panel A) is computed recursively using a window of 1500 observations. Values in parentheses are p-values of the null hypothesis that the correlation coefficient is equal to zero (Ljung and Box, 1979). 0 denotes p-values lower than 10-4. See notes to Table 1.

*Panel A) CIP deviations' mean reversion and market liquidity*

| | corr ($\delta_1$,liq) | *p*-value |
|---|---|---|
| overnight | -0.080 | (0) |
| 1 week | -0.080 | (0) |
| 4 weeks | -0.060 | (0) |
| 12 weeks | -0.050 | (0) |
| *Average* | *-0.067* | |

*Panel B) absolute CIP deviations and market liquidity*

| | corr ($\vert$CIP dev$\vert$,liq) | *p*-value |
|---|---|---|
| overnight | 0.19 | (0) |
| 1 week | 0.40 | (0) |
| 4 weeks | 0.05 | (0) |
| 12 weeks | 0.17 | (0) |
| *Average* | *0.20* | |

**Table 3. Causality Tests and Half-Lives of Shocks**

The table reports the results of Granger causality tests and half-lives of shocks affecting either absolute CIP deviation, $\lvert \text{CIP dev} \rvert$, or market liquidity. The statistical tests are carried out by estimating bivariate VARs models of absolute CIP deviations and market liquidity for each maturity tenors. Values in parentheses are *p*-values of the null hypothesis that either market liquidity or absolute CIP deviations does not Granger-cause absolute CIP deviations or market liquidity respectively. HL1 and HL2 denote half-lives to shocks in market liquidity and absolute CIP deviations respectively. Half-lives are computed using generalized impulse response functions (Koop *et al.*, 1996) and the magnitude of the shocks is set equal to +1 standard deviation of the absolute CIP deviations or market liquidity respectively. Half-lives, and their confidence interval in brackets, are expressed in minutes.

| | liq g.c. $\lvert \text{CIP dev} \rvert$ | $\lvert \text{CIP dev} \rvert$ g.c. liq | HL1 | | HL2 | |
|---|---|---|---|---|---|---|
| overnight | (0) | (0.005) | 7.25 | [4.25, 10.25] | 7.25 | [4.50, 10.00] |
| 1 week | (0.026) | (0) | 8.25 | [3.75, 12.75] | 8.25 | [5.25, 11.25] |
| 4 weeks | (0.019) | (0) | 6.75 | [3.75, 9.75] | 6.75 | [5.25, 8.25] |
| 12 weeks | (0.007) | (0) | 6.25 | [3.25, 9.25] | 6.25 | [4.50, 8.00] |
| *Average* | | | | *7.13* | *[4.31, 9.94]* | |

**Table 4. Number of Profitable Arbitrage Opportunities**

This table shows the frequency of profitable deviations (i.e., positive deviations) from CIP arbitrage in the FX market as in Equations (5) in the main text. 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. See notes to Table 1.

| | CIP | |
|---|---|---|
| | Bid | Ask |
| *Overnight* | | |
| Total dev | 13,300 | 13,300 |
| Profitable dev | 6,642 | 1,207 |
| % Share | 49 | 9 |
| *1 week* | | |
| Total dev | 12,861 | 12,861 |
| Profitable dev | 7,750 | 3,266 |
| % Share | 60 | 25 |
| *4 weeks* | | |
| Total dev | 22,277 | 22,277 |
| Profitable dev | 11,208 | 8,116 |
| % Share | 50 | 36 |
| *12 weeks* | | |
| Total dev | 28,709 | 28,709 |
| Profitable dev | 15,583 | 6,128 |
| % Share | 55 | 21 |
| *Average % Share* | *53* | *22* |

**Table 5. Average Arbitrage Profits**

This table shows the average and the maximum of all of the positive deviations from round-trip arbitrage in the FX market. CIP denotes round-trip arbitrage deviations as defined in Section 5. The values in parenthesis are asymptotic standard errors calculated using autocorrelation and heteroskedasticity variance-covariance matrices (Newey and West, 1987). The values reported are expressed in pips. See notes to Table 1.

| | CIP | |
|---|---|---|
| | Bid | Ask |
| | *Maximum* | |
| overnight | 10.67 | 6.25 |
| 1 week | 62.24 | 29.72 |
| 4 weeks | 189.01 | 74.33 |
| 12 weeks | 382.18 | 132.35 |
| | *Mean* | |
| overnight | 1.6 | 1.3 |
| | (0.03) | (0.04) |
| 1 week | 8.7 | 9.3 |
| | (0.12) | (0.13) |
| 4 weeks | 20.7 | 32.7 |
| | (0.25) | (0.23) |
| 12 weeks | 62.7 | 49.6 |
| | (0.43) | (0.49) |
| | *Median* | |
| overnight | 0.6 | 0.8 |
| | (0.03) | (0.04) |
| 1 week | 5.4 | 7.2 |
| | (0.12) | (0.13) |
| 4 weeks | 15.3 | 30.2 |
| | (0.25) | (0.23) |
| 12 weeks | 57.9 | 44.5 |
| | (0.43) | (0.49) |

**Table 6. Break-Even Trading Costs**

This table shows the overall trading costs, per round-trip transaction, that are required to offset the average positive arbitrage profits reported in Table 7. We computed the break-even brokerage fees per maturity tenor at both ask and bid prices as discussed in Section 5. All values reported are expressed in pips.

| | |
|---|---|
| *CIP deviations (bid)* | |
| overnight | 0.28 |
| 1 week | 0.53 |
| 4 weeks | 1.85 |
| 12 weeks | 17.62 |
| *CIP deviations (ask)* | |
| overnight | 0.51 |
| 1 week | 2.17 |
| 4 weeks | 3.50 |
| 12 weeks | 9.56 |

**Table 7. Number of Profitable Arbitrage Opportunities Net of Break-Even Trading Costs**

This table shows the frequency of profitable CIP deviations higher than the estimated break-even trading costs computed to offset the average arbitrage profits reported in Table 7 (τ(average)) or to offset up to the 90$^{th}$ percentile of the arbitrage profit distribution (τ(90$^{th}$ percentile)). 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. See notes to Tables 1 and 4.

| | τ(average) | | τ(90$^{th}$ percentile) | |
|---|---|---|---|---|
| | Bid | Ask | Bid | Ask |
| | *Overnight* | | | |
| Total dev | 13,300 | 13,300 | 13,300 | 13,300 |
| Profitable dev>τ | 1,463 | 266 | 532 | 133 |
| % Share | 11 | 2 | 4 | 1 |
| | *1 week* | | | |
| Total dev | 12,861 | 12,861 | 12,861 | 12,861 |
| Profitable dev>τ | 1,672 | 1,286 | 643 | 257 |
| % Share | 13 | 10 | 5 | 2 |
| | *4 weeks* | | | |
| Total dev | 22,277 | 22,277 | 22,277 | 22,277 |
| Profitable dev>τ | 2,673 | 2,673 | 1,114 | 668 |
| % Share | 12 | 12 | 5 | 3 |
| | *12 weeks* | | | |
| Total dev | 28,709 | 28,709 | 28,709 | 28,709 |
| Profitable dev>τ | 3,732 | 2,297 | 1,435 | 574 |
| % Share | 13 | 8 | 5 | 2 |
| *Average % Share* | *12* | *8* | *5* | *2* |

**Table 8. Half-Lives of Shocks and Positive CIP Deviations**

The table reports the results of half-lives of shocks affecting either positive CIP deviation, or market liquidity (i.e. the arithmetic average of all financial instruments proportional quoted spread). The statistical tests are carried out by estimating bivariate VARs models of positive CIP deviations (at both bid and ask prices) and market liquidity for each maturity tenors. See notes to Tables 1 and 3.

*Panel A) Positive CIP deviations (bid)*

| | HL1 | | HL2 | |
|---|---|---|---|---|
| overnight | 6.25 | [3.50, 8.75] | 6.25 | [3.75, 8.50] |
| 1 week | 7.25 | [3.25, 11.00] | 7.25 | [4.50, 9.75] |
| 4 weeks | 5.25 | [2.75, 7.50] | 5.25 | [4.00, 6.25] |
| 12 weeks | 5.00 | [2.50, 7.25] | 5.00 | [3.50, 6.25] |
| *Average* | | *5.94 [3.47, 8.16]* | | |

*Panel B) Positive CIP deviations (ask)*

| | HL1 | | HL2 | |
|---|---|---|---|---|
| overnight | 2.75 | [1.50, 3.75] | 2.75 | [1.50, 3.75] |
| 1 week | 3.25 | [1.25, 5.00] | 3.25 | [2.00, 4.25] |
| 4 weeks | 4.25 | [2.25, 6.00] | 4.25 | [3.25, 5.00] |
| 12 weeks | 2.75 | [1.25, 4.00] | 2.75 | [1.75, 3.50] |
| *Average* | | *3.25 [1.84, 4.41]* | | |

# Appendix

**Table A.1 Seasonality in Absolute CIP Deviations and Quoted Spreads**

For each maturity tenor, we compute absolute CIP deviations and a composite liquidity measure (the arithmetic average of the proportional quoted spreads of the four markets). To study seasonality, as in Gallant *et al.* (1992), a linear regression is estimated using dummy variables for the days of the week (excluding Monday) and the hours of the day (excluding 7:00 Hong Kong time), and time and $time^2$ denote a linear and quadratic trend respectively. This table reports OLS estimates of the parameters that are statistically significant at the 1% significance level. Standard errors of the parameters are computed using autocorrelation and heteroskedasticity consistent variance-covariance matrix (Newey and West, 1987). Parameters estimates relative to absolute CIP deviations have been multiplied by $10^4$.

| | Overnight | | 1 week | |
|---|---|---|---|---|
| | Liquidity | \|CIPdev\| | Liquidity | \|CIPdev\| |
| constant | 1.4940 | 3.1290 | 0.8896 | 13.1610 |
| time | -0.0001 | -0.0008 | -0.0001 | -0.0031 |
| $time^2$ | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| Tue | -0.1112 | 0.6528 | | 2.0003 |
| Wed | -0.1123 | 0.3699 | 0.0945 | 0.9184 |
| Thu | -0.0677 | 0.3696 | 0.0478 | 0.8119 |
| Fri | -0.0573 | -0.1373 | 0.0339 | |
| 8H | -0.2105 | | | |
| 9H | -0.3233 | | | |
| 10H | -0.2516 | | | |
| 11H | -0.1699 | | | |
| 12H | -0.4212 | -1.8679 | -0.2099 | -11.1750 |
| 13H | -0.4128 | -0.6636 | -0.1032 | |
| 14H | -0.2128 | | | |
| 15H | | | | |
| 16H | -0.0872 | | | |
| 17H | -0.1164 | | | |

| | 4 weeks | | 12 weeks | |
|---|---|---|---|---|
| | Liquidity | \|CIPdev\| | Liquidity | \|CIPdev\| |
| constant | 0.69740 | 44.5610 | 0.61740 | 120.0000 |
| time | -0.00002 | -0.0045 | -0.00001 | -0.0102 |
| $time^2$ | 0.00001 | 0.0001 | 0.00001 | 0.0001 |
| Tue | -0.00351 | 5.2065 | | -3.0143 |
| Wed | 0.00600 | 6.8968 | -0.00451 | |
| Thu | | 2.3965 | -0.00891 | -7.8237 |
| Fri | -0.00369 | 1.7241 | -0.00427 | -6.8661 |
| 8H | | | | |
| 9H | | | | |
| 10H | | | | |
| 11H | | | | |
| 12H | | | 0.03520 | |
| 13H | -0.02730 | | | |
| 14H | | | | |
| 15H | | | | |
| 16H | | | | |
| 17H | | | | -16.3590 |

**Table A.2 Seasonal Adjustment and Correlations**

This table reports the correlation coefficients computed between the seasonally adjusted measures of market liquidity and the coefficients of mean reversion of seasonally adjusted CIP deviations (panel A) and between the seasonally adjusted measures of market liquidity and the seasonally adjusted CIP deviations (panel B). See notes to Tables 1, 2 and 3.

*Panel A) CIP deviations' mean reversion and market liquidity*

| | corr ($\delta_1$,liq) | *p*-value |
|---|---|---|
| overnight | -0.01 | (0) |
| 1 week | -0.01 | (0) |
| 4 weeks | -0.06 | (0) |
| 12 weeks | -0.02 | (0) |
| *Average* | *-0.02* | |

*Panel B) Absolute CIP deviations and market liquidity*

| | corr ($\lvert$CIP dev$\rvert$,liq) | *p*-value |
|---|---|---|
| overnight | 0.16 | (0) |
| 1 week | 0.43 | (0) |
| 4 weeks | 0.01 | (0.14) |
| 12 weeks | 0.06 | (0) |
| *Average* | *0.16* | |

**Table A.3 Data Synchronization and Arbitrage Opportunities**

This table shows the frequency of profitable deviations from round-trip arbitrage in the FX market (*% Share*) and the average positive CIP deviation (*Mean*) under different synchronization schemes involving the four financial instruments as discussed in Section 6 of the main text. See notes to Tables 1, 4 and 5.

*Panel A) Synchronization based on filtering rule 1*

| | CIP Forthcoming Quotes | |
|---|---|---|
| | Bid | Ask |
| | *Overnight* | |
| Total dev | 9,198 | 9,198 |
| % Share | 46 | 12 |
| Mean | 1.8 | 1.4 |
| | *1 week* | |
| Total dev | 7,443 | 7,443 |
| % Share | 61 | 30 |
| Mean | 10.0 | 10.0 |
| | *4 weeks* | |
| Total dev | 14,098 | 14,098 |
| % Share | 50 | 42 |
| Mean | 22.1 | 36.1 |
| | *12 weeks* | |
| Total dev | 17,161 | 17,161 |
| % Share | 55 | 32 |
| Mean | 66.9 | 51.2 |
| *Average % Share* | *53* | *29* |

**(Table A.3 continued)**

*Panel B) Synchronization based on filtering rule 2*

| | CIP | | | |
|---|---|---|---|---|
| | Prevailing Quotes | | Forthcoming Quotes | |
| | Bid | Ask | Bid | Ask |
| | | *Overnight* | | |
| Total dev | 2,000 | 2,000 | 2,000 | 2,000 |
| % Share | 48 | 10 | 49 | 9 |
| Mean | 1.8 | 1.3 | 1.8 | 1.3 |
| | | *1 week* | | |
| Total dev | 1,565 | 1,565 | 1,565 | 1,565 |
| % Share | 73 | 18 | 72 | 19 |
| Mean | 8.9 | 9.8 | 9.1 | 9.5 |
| | | *4 weeks* | | |
| Total dev | 3,119 | 3,119 | 3,119 | 3,119 |
| % Share | 55 | 41 | 52 | 42 |
| Mean | 20.9 | 37.0 | 21.1 | 36.4 |
| | | *12 weeks* | | |
| Total dev | 3,332 | 3,332 | 3,332 | 3,332 |
| % Share | 46 | 38 | 48 | 40 |
| Mean | 50.5 | 53.3 | 47.8 | 52.4 |
| *Average % Share* | *55* | *26* | *55* | *27* |

**(Table A.3 continued)**

*Panel C) CIP deviations corrected as in Jokivuolle's (1995)*

| | CIP | |
|---|---|---|
| | Bid | ask |
| | *Overnight* | |
| Total dev | 13,300 | 13,300 |
| % Share | 50 | 9 |
| Mean | 1.6 | 1.3 |
| | *1 week* | |
| Total dev | 12,861 | 12,861 |
| % Share | 60 | 25 |
| Mean | 8.7 | 9.3 |
| | *4 weeks* | |
| Total dev | 22,277 | 22,277 |
| % Share | 50 | 36 |
| Mean | 20.6 | 32.7 |
| | *12 weeks* | |
| Total dev | 28,709 | 28,709 |
| % Share | 55 | 21 |
| Mean | 62.6 | 49.5 |
| *Average % Share* | *54* | *23* |

**Figure 1. Frequency of Quotations**