Predictors of triangular arbitrage opportunities: Interdependence and order book indicators

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Abstract

Recent research suggests that high-frequency triangular arbitrage opportunities arise in electronic foreign exchange (FX) markets. The deviations from the triangular parity condition are typically the result of asynchronous exchange rate adjustments to new market-wide information or country-specific shocks. This paper conducts an empirical investigation of the mechanisms and underpinnings of triangular arbitrage opportunities in the EUR/USD, EUR/JPY and USD/JPY markets, in 2010 and 2011. Two sets of variables are found statistically significant in explaining and forecasting triangular arbitrage opportunities: 1) average variance and average correlation among the exchange rates, and 2) limit order book indicators.

Keywords: Foreign Exchange Markets; Exchange Rates; Triangular Arbitrage; Limit Order Book.

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1. Introduction

Recent foreign exchange (FX) market microstructure research suggests that order flows, for instance, in the EUR/JPY market may convey relevant information and impact the EUR/USD and USD/JPY exchange rates (Lyons and Moore, 2009; Danielsson et al., 2011). Consequently, if any deviations from the triangular parity relationship arise, they likely reflect temporary market imperfections in at least one of the three markets. In this respect, the literature documents that triangular arbitrage opportunities are scarce and short-lived (Foucault et al., 2013; Fenn et al., 2009; Choi, 2011; Aiba and Hatanoa, 2004), and depend on the ability of traders to predict currency order flows (Moore and Payne, 2011). In a time series context, Ito et al. (2012) observe an erosion in the number of triangular arbitrage opportunities from 1999 to 2009.

The goal of this paper is to fill the gap in the literature concerning the nature of triangular arbitrage opportunities and their driving forces. This research avenue is pioneering relative to the previous studies that are primarily concerned with detecting violations of the triangular parity equation, but are silent about measures that may help capture patterns of fluctuations in triangular arbitrage returns. We relate arbitrage returns, first, to FX risk measures that reflect aggregate movements in volatility and correlation across three exchange rates from the triangular parity condition. Second, we extend this set of measures with electronic limit order book indicators. The key hypothesis that motivates this choice of indicators is that the order book may provide information about future price movements in FX markets. In particular, such indicators utilize the structure of a limit order book which includes levels of bid and ask FX rates, and currency order sizes. The relationship between the shape of the limit order book and arbitrage returns in FX markets has not been covered by previous research. Another advantage of our approach is that we investigate predictive relationships
and time series properties of predictors of arbitrage returns at the highest available frequency level.

It is worth noting that even when exchange rates that enable triangular arbitrage are detected, FX traders are facing problems such as the execution risk (i.e., delays in trade execution), ‘slippage’ (i.e., order execution at a worse-than-expected price) and competition from other traders. Kozhan and Tham (2012) stress the importance of execution risk in arbitrage and show by using a simulation that an increase in the number of arbitrageurs reduces arbitrage profits. Chaboud et al. (2009) show that computers have an executional advantage over humans in reacting to triangular arbitrage opportunities.

Considering the considerable risks involved in triangular arbitrage trading, scholarly efforts have centered on studying covered and uncovered interest arbitrage in FX markets to a greater extent. Akram et al. (2008) find exploitable covered interest arbitrage opportunities in a high-frequency setting. In accordance with the Grossman-Stiglitz view of financial markets (Grossman and Stiglitz, 1980), these very short-term arbitrage profits are quickly eliminated and market efficiency is restored. Similarly, at the tick-by-tick data level, Fong et al. (2010) reveal small, but positive covered interest parity arbitrage deviations that are found to represent compensation for liquidity and credit risk.\(^1\)

In regards to uncovered interest arbitrage, violations of the uncovered interest parity equation - often referred to as the “forward premium puzzle” - are discussed in works as early as Fama (1984), whereas consistent profits from ‘carry trade’ strategies have been recorded over the past 15-20 years (Brunnermeier et al., 2008).\(^2\) Typically, the observed deviations

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\(^1\)Earlier papers that include Taylor (1987), Frenkel and Levich (1975) and Rhee and Chang (1992) present evidence that does not support covered interest arbitrage opportunities. However, these studies mainly rely on low-frequency data sets that are not as detailed as the ones coming from the post-early 1990s electronic FX markets.

\(^2\)It is also important to note that carry trade strategies made substantial losses during the 2008 crisis. Even though the profits from carry trade strategies recovered during 2009, the losses may appear to have
from the uncovered interest parity equation have been attributed to volatility and liquidity fluctuations in both FX and equity markets. In this context, Menkhoff et al. (2012) find that high overall unexpected FX market volatility is negatively (positively) related to high-interest (low-interest) currencies that provide low (positive) returns during such volatility episodes. Further, Christiansen et al. (2011) show that the risk exposure of carry trade returns to stock and bond markets depends on the level of FX volatility. These findings are complemented by Hutchison and Sushko (2013) who identify a significant impact of macroeconomic surprises on carry trade activity.\(^3\) In an innovative paper, Cenedese et al. (2012) address the lack of predictability of arbitrage and show that carry trade returns can be predicted by variables such as average variance and average correlation.

While deviations from covered and uncovered interest parity conditions have received much attention by the scholars, the same cannot be stated about the triangular parity relationship. Specifically, of particular interest would be to identify high-frequency determinants as well as predictors of triangular arbitrage returns. Such explorations would not only shed light on the FX market efficiency, but also on international market microstructure mechanisms and their role in FX rate formation. Our unique high-frequency data set includes ten layers of tick quotes (at the 100 millisecond precision) on the bid and ask sides of the limit order book. This offers an unprecedented insight into the depth of the limit order book, which includes levels of unrealized currency order flows. The data are taken from Electronic Broking Services (EBS), the major interdealer platform for spot FX trading. To weakened the case for the “forward premium puzzle”. However, Jordà and Taylor (2012) demonstrate that fundamentals-augmented trading strategies would have generated robust positive profits throughout the crisis.

\(^3\)Other explanations for the forward premium puzzle include infrequent foreign currency portfolio decisions (Bacchetta and van Wincoop, 2010) while Burnside et al. (2011) view high average carry trade returns as compensation for peso-event risk. See Sarno (2005) for more information on the key parity conditions and puzzles in international economics.
the best of the authors’ knowledge this is the most comprehensive data set currently available for research in high-frequency international finance.\(^4\) Considering the vast amount of data and considerable computational requirements, we focus on three major currency pairs (EUR-JPY, EUR-USD and USD-JPY) over several time periods in 2010 and 2011.

After conducting an extensive search for bid and ask price misalignments from the triangular parity condition, we find on average about 80-100 such instances in the data on a daily basis. These profitable deviations are short-lived with durations between 100 and 500 milliseconds. The average triangular arbitrage strategy return is in the range from 5-7.5 basis points (bps). These ultra high-frequency findings reveal the elusiveness of triangular arbitrage profits and to a certain extent explain the relative lack of scholarly interest in the topic.

The findings also show that both volatility and correlation measures that we employ are informative for explaining and predicting triangular arbitrage returns. Specifically, higher average volatility reduces arbitrage returns both contemporaneously and in a predictive setting. Although at first sight this relationship may appear counterintuituitive, the following conclusion can be made: dealers in the interbank market are more watchful about updating their quotes when high FX volatility is observed, thus, improving the FX market efficiency. Furthermore, we find that when average correlations across the three FX rates are low, triangular arbitrage returns are expected to be higher. In other words, triangular arbitrage opportunities are more frequent in times when the average degree of interaction among the FX rates is low, which introduces potential impediments to synchronous adjustments of exchange rates to market shocks.

In addition to the empirical evidence supporting predictability of arbitrage returns by

\(^4\)Kozhan and Salmon (2012) use Reuters electronic FX trading system at the 1/100th of a second resolution, but do not present the number of layers in their limit order book.
the FX risk measures, we find limit order book indicators similarly informative and useful. Measures such as the average inside bid-ask spread and the quantity-weighted average bid-ask spread that reflect the shape of the limit order book are statistically valuable in explaining and predicting arbitrage profits. In general, we find that tighter average spread measures increase the profitability and likelihood of arbitrage trades. Intuitively, spreads are narrower during liquid periods when the volume of high-frequency trading is large and potential price misalignments are more likely. Finally, we uncover a strong level of persistence in all predictors of arbitrage returns indicating that triangular arbitrage opportunities have a long memory. By observing the predictor variables, FX traders may be able to adapt to the periodicity of arbitrage opportunities and learn when to expect them.

The remainder of the paper is laid out as follows. In Section 2, we present the concept of triangular arbitrage and define the predictor variables used in our empirical work. Section 3 contains a description of the data set. The main results are given in Section 4 while Section 5 concludes.

2. Triangular Arbitrage and Predictor Variables

2.1. Triangular Arbitrage Strategy

Triangular parity condition involves three exchange rates $S_{i/j,t}$ ($i \neq j$) that represent FX conversion rates among three currencies at time $t$ (e.g., $i, j \in \{EUR, USD, JPY\}$). When one ignores transaction costs, the triangular parity equation can be written as

$$\frac{S_{EUR/JPY,t}}{S_{USD/JPY,t}} = \frac{S_{EUR/USD,t}}{S_{USD/JPY,t}} \quad (1)$$
where \( S_{i,j,t} \) denotes the amount of currency \( j \) required to buy one unit of currency \( i \) at time \( t \). If Equation 1 does not hold, arbitrage profits may be possible, but the currency conversions have to be executed at the exact FX rates that violated the parity condition. For example, suppose that the initial endowment is one unit of EUR. Then, one can first exchange one EUR for the EUR/JPY amount of JPY. This is followed by a conversion of the JPY to the USD at the USD/JPY exchange rate. Finally, the USD amount is converted to the EUR. In a triangular arbitrage situation, this round trip should produce an amount of EUR that is greater than the initial EUR endowment (i.e., one unit). The other arbitrage route would be to convert one EUR to the USD, then to the JPY and, in the end, to the EUR.

In general, starting from \( M \) units of the EUR currency and following the first route (EUR\( \rightarrow \)JPY\( \rightarrow \)USD\( \rightarrow \)EUR), while accounting for the bid-ask spread, the triangular parity condition at time \( t \) can be written as

\[
M \times S_{EUR/JPY,t}^{b} \times \frac{1}{S_{USD/JPY,t}^{a}} \times \frac{1}{S_{EUR/USD,t}^{a}} - M = 0, \\
S_{EUR/JPY,t}^{b} \times \frac{1}{S_{USD/JPY,t}^{a}} \times \frac{1}{S_{EUR/USD,t}^{a}} - 1 = 0, 
\]

(2)

where superscript \( b \) denotes the bid quote and superscript \( a \) denotes the ask (offer) quote. To provide an illustrative example, we assume that the quotes at time \( t \) are given as follows\(^5\):

- \( S_{EUR/USD,t}^{a} = 1.3911, S_{EUR/USD,t}^{b} = 1.3909 \),
- \( S_{EUR/JPY,t}^{a} = 111.96, S_{EUR/JPY,t}^{b} = 111.94 \),
- \( S_{USD/JPY,t}^{a} = 80.48, S_{USD/JPY,t}^{b} = 80.47 \).

\(^5\)These are the actual high frequency quotes taken from EBS on November 1, 2010.
Assuming M=100 EUR, the first conversion is to the JPY, by using \( S_{EUR/JPY,t}^b = 111.94 \). The amount of JPY required to purchase 100 EUR is 11,194 JPY (100×111.94). Next, the amount of 11,194 JPY is converted to the USD as 11,194/\( S_{USD/JPY,t}^a \), which produces 139.0905 USD. Finally, we convert back to the EUR by dividing the USD amount by \( S_{EUR/USD,t}^a \): 139.0905/1.3911=99.985 EUR. In this example, the triangular parity condition does not hold, but the difference is negative (99.985 − 100 < 0), which indicates a loss to the arbitrage strategy.

The triangular parity condition for the second route (EUR→USD→JPY→EUR) can be expressed as

\[
S_{EUR/USD,t}^b \times S_{USD/JPY,t}^b \times \frac{1}{S_{EUR/JPY,t}^a} - 1 = 0. \tag{3}
\]

Equation 2 and Equation 3 represent all possible triangular arbitrage parity relationships for this set of exchange rates. If at time \( t \) the left-hand side of the two equations is greater than zero, arbitrage profits are possible.

2.2. Average Triangular Variance and Average Triangular Correlation

This set of predictors is motivated by Menkhoff et al. (2012) and Cenedese et al. (2012), and is aimed at exploring risk measures that are specific to the FX market. Our risk measures are adapted to the triangular parity setting and involve three currencies, as opposed to all market exchange rates. Thus, our risk measure captures the joint variance and correlation among the EUR-JPY (denoted by ‘1’ for the remainder of the equations in this subsection), EUR-USD (denoted by ‘2’) and USD-JPY (denoted by ‘3’) exchange rates. First, we define
‘triangular’ average return at time $t+1$ as

$$r_{T,t+1} = \frac{1}{3} \sum_{j=1}^{3} r_{j,t+1}, \quad (4)$$

where $r_{j,t+1}$ is a standard one-period return from time $t$ to time $t + 1$ on exchange rate $j$ ($j \in \{1, 2, 3\}$).

Next, we calculate the ‘triangular’ variance of the realized average return at time $t+1$ as

$$TV_{t+1} = \sum_{l=1}^{L} r_{T,t+l}^2 + 2 \sum_{l=2}^{L} r_{T,t+l} r_{T,t+2}, \quad (5)$$

where $L$ is the number of periods used in a sliding window.

We also define realized variance of the returns to exchange rate $j$ at time $t+1$ as

$$RV_{j,t+1} = \sum_{l=1}^{L} r_{j,t+l}^2 + 2 \sum_{l=2}^{L} r_{j,t+l} r_{j,t+2}, \quad j \in \{1, 2, 3\}, \quad (6)$$

The average ‘triangular’ variance (ATV) and correlation (ATC) can be written as

$$ATV_{t+1} = \frac{1}{3} \sum_{j=1}^{3} RV_{j,t+1}, \quad (7)$$

$$ATC_{t+1} = \frac{1}{6} \sum_{j=1}^{3} \sum_{j \neq i=1}^{3} TC_{ij,t+1}, \quad (8)$$

where

$$TC_{t+1} = \frac{RV_{ij,t+1}}{\sqrt{RV_{i,t+1}} \sqrt{RV_{j,t+1}}}, \quad (9)$$
\[
RV_{ij,t+1} = \sum_{l=1}^{L} r_{i,t+\frac{l}{L}} r_{j,t+\frac{l}{L}} + 2 \sum_{l=2}^{L} r_{i,t+\frac{l}{L}} r_{j,t+\frac{l-1}{L}}, \quad i,j \in \{1, 2, 3\}. \tag{10}
\]

We find it important to note that the ATV and the ATC measures are the components of the ‘triangular’ variance (TV), and this decomposition can be expressed as follows

\[
TV_{t+1} = ATV_{t+1} \times ATC_{t+1}. \tag{11}
\]

Two regressions will be of interest:

\[
r_{TR,t+1} = \alpha + \beta TV_t + \epsilon_t, \tag{12}
\]

\[
r_{TR,t+1} = \alpha + \beta_1 ATV_t + \beta_2 ATC_t + \epsilon_t, \tag{13}
\]

where \(r_{TR,t+1}\) (triangular arbitrage returns) stands for the left-hand sides of Equation 2 and Equation 3, i.e., both routes for triangular arbitrage will be explored. Hence, \(r_{TR,t+1}\) can be zero (triangular parity condition holds), and can take positive (arbitrage strategy profit) and negative (arbitrage strategy loss) values. Equation 13 separates the effects of ATV and ATC and we will establish the contribution of each component of TV in explaining and predicting triangular arbitrage returns. Our predictive regressions will employ lagged TV, ATV and ATC variables.

2.3. Limit Order Book Measures

The literature that describes the informativeness of the limit order book in equity markets is abundant, while such research in FX markets has been less intense, mainly due to the
dispersed nature of the FX market and the unavailability of detailed high-frequency FX trading information.\footnote{Kozhan and Salmon (2012) provide an extensive literature review on the topic.} We are particularly interested in the evidence that the shape of the limit order book can be used for predicting future prices. For example, Harris and Panchapagesan (2005) find that the limit order book is informative in revealing pending price changes. In a related paper, Cao \textit{et al.} (2009) confirm the findings by Harris and Panchapagesan (2005) based on data gathered from the Australian Stock Exchange. Specifically, they document that the limit order book is informative in determining the value of an asset, as its contribution beyond the best bid and offer is 22%. Overall, the research findings reveal that lagged order book information is significantly correlated to future returns. In the same vein, Bloomfield \textit{et al.} (2005) and Kaniel and Liu (2006) show that informed traders are more likely to favour limit orders over market orders. Finally, Kozhan and Salmon (2012) demonstrate the superiority of limit order book information in high-frequency out-of-sample FX rate forecasting and devising a profitable trading strategy.

The dynamics of the limit order book is such that at any point of time it contains a large number of orders over the bid and offer ranges. In general, these unrealized orders (i.e., price-quantity combinations) represent the aggregate FX market demand and supply schedules. To capture the structure of the limit order book in terms of both price and quantity, we use two measures – the quantity-weighted average bid-ask spread and the novel measure we refer to as the \textit{center of gravity quantity-weighted average bid-ask spread} – as well as the measure based on standard inside spread or the difference between the best bid and the best ask price.\footnote{By using the information share measure from Hasbrouck (1995), Cao \textit{et al.} (2009) show that the mid-quote and the quantity-weighted average mid-quote contribute to the price discovery by about 77\%. Consequently, we consider these measures as our primary choice for the limit order book predictors of triangular arbitrage returns.} Our principal hypothesis is that the shape of the limit order book,
when averaged across the three exchange rates, will have certain predictive power for future triangular arbitrage returns.

As before, if we substitute the three exchange rates (EUR/USD, EUR/JPY and USD/JPY) with ordinal numbers \((i=1,2,3)\), the average inside spread at time \(t + 1\) can be written as

\[
\overline{\text{ispread}}_{t+1} = \frac{1}{3} \sum_{i=1}^{3} \left( S_{a,i,t+1}^{a,1} - S_{b,i,t+1}^{b,1} \right),
\]

where \(S_{a,i,t+1}^{a,1}\) and \(S_{b,i,t+1}^{b,1}\) are the best ask and bid quotes of the \(i^{th}\) exchange rate, respectively. Therefore, superscript \((a, 1)\) stands for the ask price where price rank 1 represents that this is the best ask price (rank 2 is the 2\(^{nd}\) best, etc.). In the same manner, superscript \((b, 1)\) stands for the best bid price with price rank 1. Figure 1 presents the location of the inside spread for the EUR/USD limit order book. The intuition behind this and other limit order book measures that average across the three markets is that we would like to capture shocks taking place in at least one of the markets. The shocks may cause price movements in the limit order book that violate the parity condition, which will be reflected in the change of the (average) measure. We conjecture that the larger the average inside spread, i.e., the distance between the bid and offer prices, the more difficult it becomes to profit from triangular arbitrage.

\[\text{[INSERT FIGURE 1 ABOUT HERE]}\]

Next, we use the complete limit order book information and define the quantity-weighted bid quote of an exchange rate \(i\) at time \(t + 1\) as

\[
qwb_{t+1}^{i} = \frac{\sum_{j=1}^{10} S_{i,t+1}^{b,j} \times Q_{i,t+1}^{b,j}}{\sum_{j=1}^{10} Q_{i,t+1}^{b,j}},
\]

where \(j\) is the price rank or the level of the orders on the bid side and \(Q_{i,t+1}^{b,j}\) is the corresponding order size for the price \(S_{i,t+1}^{b,j}\).
On the ask side, we define the quantity-weighted ask quote of an exchange rate $i$ at time $t+1$ as

$$qwa_{i,t+1} = \frac{\sum_{j=1}^{10} S_{i,t+1} \times Q_{a,j}^{i,t+1}}{\sum_{j=1}^{10} Q_{a,j}^{i,t+1}},$$ (16)

where the notation follows Equation 15.

Based on Equation 15 and Equation 16, we define the quantity-weighted average bid-ask spread as

$$\bar{qwspread}_{t+1} = \frac{3}{3} \sum_{i=1}^{3} \frac{qwa_{i,t+1} - qwb_{i,t+1}}{3},$$ (17)

and also the quantity-weighted average mid-quote as

$$\bar{qwmidq}_{t+1} = \frac{1}{3} \sum_{i=1}^{3} \frac{(qwa_{i,t+1} + qwb_{i,t+1})}{2}.$$ (18)

Figure 2 shows the quantity-weighted ask quote, the quantity-weighted bid quote and the quantity-weighted mid-quote for the EUR/USD limit order book. These measures provide more information about the current limit order ‘pressure’ on the price while accounting for the order size at each price level. In other words, they summarize all information contained in the order book that is relevant for future price movements. We average these measures across the three exchange rates from the triangular parity relationship.

[INSERT FIGURE 2 ABOUT HERE]

The last measure we propose is a novel limit order book indicator that is inspired by the ‘center of gravity’ concept from fuzzy logic. This predictor captures the most likely location of the bid and ask quotes by making the structure of the limit order book more ‘continuous’
relative to the simple quantity-weighted approach.

We define the center of gravity quantity-weighted bid quote of an exchange rate $i$ at time $t + 1$ as

$$cogqwb^i_{t+1} = \frac{\int_{z^b}^{z^b} Q^b_{i,t+1}(z) z \, dz}{\int_{z^b}^{z^b} Q^b_{i,t+1}(z) \, dz},$$

(19)

where $z^b$ is the total area above the bid price levels defined by the shape of the bid side and $Q^b_{i,t+1}$ terms are the corresponding order sizes for price terms $S^b_{i,t+1}$.

Then, we define the center of gravity quantity-weighted ask quote of an exchange rate $i$ at time $t + 1$ as

$$cogqwa^i_{t+1} = \frac{\int_{z^a}^{z^a} Q^a_{i,t+1}(z) z \, dz}{\int_{z^a}^{z^a} Q^a_{i,t+1}(z) \, dz},$$

(20)

where $z^a$ is the total area above the ask price levels defined by the shape of the ask side and $Q^a_{i,t+1}$ terms are the corresponding order sizes for price terms $S^a_{i,t+1}$.

We can write the center of gravity quantity-weighted average bid-ask spread as

$$cogqwspread_{t+1} = \sum_{i=1}^{3} \frac{cogqwa^i_{t+1} - cogqwb^i_{t+1}}{3},$$

(21)

and the center of gravity quantity-weighted average mid-quote as

$$cogqwmidq_{t+1} = \frac{1}{3} \sum_{i=1}^{3} \frac{(cogqwa^i_{t+1} + cogqwb^i_{t+1})}{2}.$$

(22)

[INSERT FIGURE 3 ABOUT HERE]

The center of gravity concept is illustrated by Figure 3 which shows the center of gravity
quantity-weighted ask quote, the center of gravity quantity-weighted bid quote and the center of gravity quantity-weighted mid-quote for the EUR/USD limit order book. As we will see later, the new measure, when averaged across the three exchange rates, is as successful as the simple quantity-weighted measure in capturing future triangular arbitrage returns.

3. Limit Order Book Data

The paper utilizes the latest generation of Electronic Broking Services (EBS) data called “Data Mine Level 5.0” from which we extract tick-by-tick FX transaction prices for the EUR/USD, EUR/JPY and USD/JPY exchange rates. EBS operates as an electronic limit order book and is used for global interdealer spot trading. It is dominant and most representative for the EUR-USD and USD-JPY currency trading, whereas the GBP-USD currency pair is traded primarily on Reuters. The data are recorded for ten best bid and ten best offer prices for each exchange rate over 24 hours, based on GMT time. The best bid is the highest bid price in the EBS market, while the best offer is the lowest offer price in the EBS market at the time, regardless of credit. EBS provides ten layers of prevalent (“transactable”) best bid and ask quotes as well as the corresponding order sizes. The direction of each trade is known and transaction costs are directly measured by the bid-ask spread. To demonstrate the robustness of our analysis, we choose the following non-overlapping time periods with the observation frequency of 100 milliseconds (1/10th of a second): November 1-14, 2010, February 21-27, 2011, April 4-10, 2011, October 3-16, 2011, excluding weekends. Each day contains about 25 million lines of data (quotes and transactions) for all exchange rates. Orders in the EBS market are submitted in units of millions of the base currency. For instance, if we consider EUR/USD prices, the quoted price is the amount of local currency

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8This means that the minimum order size is 1,000,000 EUR, USD or JPY.
(USD) that is required to purchase one unit of the base currency (EUR).

By testing Equation 2 and Equation 3 we find on average about 100 daily triangular arbitrage opportunities over the November 1-14, 2010 time period. Both parity equations contribute roughly equally to the violations of the parity condition. The average daily returns from triangular arbitrage are: 5 bps (Equation 2) and 7.5 bps (Equation 3). For the second two-week time period (October 3-16, 2011), the average daily number of arbitrage opportunities decreases to about 80. The contribution of both parity equations is again roughly equal. The average daily return from Equation 2 for this period is 5.6 bps, while it is 6.2 bps based on Equation 3. The weighted average return thus decreases in the second period. The arbitrage parity violations are very short-lived and last between 100-500 milliseconds.

4. Results

4.1. Correlations

To explore in further detail the relationship between the proposed predictors and triangular arbitrage returns, Table 1 presents correlation coefficients for the ATC, ATV and TV variables. Significance probabilities under the null hypothesis of no correlation are $p=0.000$ for all cells in the correlation matrix, i.e., all predictors exhibit statistically significant correlation coefficients both contemporaneously and lagged. The contribution of the ATC measure in explaining and predicting triangular arbitrage returns is much smaller relative to the ATV predictor variable. Also, all the measures are negatively correlated to triangular arbitrage returns. This suggests that triangular arbitrage profits are more likely when the average price volatility and the average interaction among the exchange rates are low. An interesting result is the relatively weak correlation between triangular arbitrage returns $r_{TR,t+1}$ and
Table 1: Correlations between triangular arbitrage returns and predictors (November 1-14, 2010).

Notes: The table reports the average daily correlation coefficients between triangular arbitrage returns \(r_{T_R,t+1}^1\) and \(r_{T_R,t+1}^2\) for the left-hand sides of Equation 2 and Equation 3, respectively) and the average triangular variance (ATV) and correlation (ATC), and triangular variance (TV) measures.

\[
\begin{array}{cccccccc}
\text{Nov. 1-14, 2010} & r_{T_R,t+1}^1 & r_{T_R,t+1}^2 & TV_{t+1} & ATV_{t+1} & ATC_{t+1} & TV_t & ATV_t & ATC_t \\
r_{T_R,t+1}^1 & 1 & & & & & & & \\
r_{T_R,t+1}^2 & 0.07 & 1 & & & & & & \\
TV_{t+1} & -0.36 & -0.23 & 1 & & & & & \\
ATV_{t+1} & -0.35 & -0.22 & 0.99 & 1 & & & & \\
ATC_{t+1} & -0.04 & -0.03 & 0.11 & 0.04 & 1 & & & \\
TV_t & -0.36 & -0.23 & 0.99 & 0.99 & 0.11 & 1 & & \\
ATV_t & -0.35 & -0.22 & 0.99 & 0.99 & 0.04 & 0.99 & 1 & \\
ATC_t & -0.04 & -0.03 & 0.11 & 0.04 & 0.99 & 0.11 & 0.04 & 1 \\
\end{array}
\]

\(r_{T_R,t+1}^2 (0.07)\), which points to differential nature of the two arbitrage routes.

Next, we construct the correlation matrix for triangular arbitrage returns and the limit order book measures. The basic predictors that we use are the average inside spread (Equation 14) and the quantity-weighted average bid-ask spread (Equation 17). In addition, we calculate original measures based on substituting the bid and ask quotes in Equations 2 and 3 for the quantity-weighted bid quote \(q_{wb}^i_{t+1}; i=1,2,3\) from Equation 15 as well as the quantity-weighted ask quote \(q_{wa}^i_{t+1}; i=1,2,3\) from Equation 16. We denote these measures \(r_{TRqw,t}^1\) and \(r_{TRqw,t}^2\) for Equations 2 and 3, respectively. The intuition behind these predictors is that the quantity-weighted bid and ask quotes may represent future realizations of the actual, transactable bid and ask quotes in the order book. In turn, the triangular arbitrage returns received by using the quantity-weighted bid and ask quotes represent forecasts of future triangular arbitrage returns.
Table 2: Correlations between triangular arbitrage returns and order book predictors (November 1-14, 2010).

Notes: The table reports the average daily correlation coefficients between triangular arbitrage returns ($r_{T,R,t+1}^i; i=1,2$ indices stand for the left-hand sides of Equation 2 and Equation 3, respectively) and the following variables: quantity-weighted average bid-ask spread ($qwspread_t$), inside spread ($ispread_t$), left-hand side of Equation 2 when bid and ask prices are calculated by Equations 15 and 16 ($r_{T,Rqw,t+1}^i$) and left-hand side of Equation 3 when bid and ask prices are calculated by Equations 15 and 16 ($r_{T,Rqw,t}^i$).
Table 2 reveals a strong negative contemporaneous correlation between the standard inside spread measure and triangular arbitrage returns (-0.57 and -0.52). Similarly, triangular arbitrage profits diminish as the quantity-weighted average bid-ask spread among the exchange rates widens. The corresponding correlation coefficients are -0.40 and -0.41. In a predictive setting, however, the lagged quantity-weighted average bid-ask spread becomes more dominant (correlation coefficients: -0.33 and -0.34) while the lagged average inside spread displays weaker correlation coefficients with $r_{TR,t+1}^1$ (-0.30) and $r_{TR,t+1}^2$ (-0.31). The two new measures appear to be the most useful in forecasting triangular arbitrage returns: the correlation coefficient between $r_{TRqw,t}^1$ and $r_{TR,t+1}^1$ is 0.36, and the corresponding figure for $r_{TRqw,t}^2$ and $r_{TR,t+1}^2$ is 0.35. Based on the above findings, our predictive regressions will not utilize the average inside spread and the quantity-weighted average bid-ask spread will be used instead.\footnote{The correlations based on the center of gravity quantity-weighted average measures are similar to Table 2. For brevity reasons, we do not include another table to this section. It is available by request from the authors.}

4.2. Triangular arbitrage predictors

First, we test whether TV, ATV and ATC predictors can provide insight into forecasting triangular arbitrage returns. We run linear regressions from Equation 12 and Equation 13, and report our findings in Table 3 and Table 4. The results indicate statistically significant forecast ability of the predictors. In summary, higher average triangular variance and average triangular correlation predict lower returns from triangular arbitrage. Put differently, high average exchange rate volatility makes triangular arbitrage profits more elusive. Similarly, triangular arbitrage opportunities require low average correlation across the three exchange rates from the triangular parity condition. These findings are intuitive and in accord with the evidence from Cenedese et al. (2012) that focus on gains from carry trade strategies. However,
Table 3: Predictive power of average variance and correlation measures (November 1-14, 2010).

<table>
<thead>
<tr>
<th>Nov. 1-14, 2010</th>
<th>Eq 12(2)</th>
<th>Eq 12(2)</th>
<th>Eq 13(3)</th>
<th>Eq 13(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td></td>
<td>(0.000)</td>
<td>(0.000)</td>
<td>(0.000)</td>
<td>(0.000)</td>
</tr>
<tr>
<td>$TV_t$</td>
<td>-35.38</td>
<td></td>
<td>-20.62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.000)</td>
<td></td>
<td>(0.000)</td>
<td></td>
</tr>
<tr>
<td>$ATC_t$</td>
<td>-0.011</td>
<td></td>
<td>-0.011</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.000)</td>
<td></td>
<td>(0.000)</td>
<td></td>
</tr>
<tr>
<td>$ATV_t$</td>
<td>-17.53</td>
<td></td>
<td>-9.76</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.000)</td>
<td></td>
<td>(0.000)</td>
<td></td>
</tr>
<tr>
<td>$R^2$</td>
<td>[0.102]</td>
<td>[0.061]</td>
<td>[0.070]</td>
<td>[0.082]</td>
</tr>
</tbody>
</table>

Notes: The table presents the daily averages for ordinary least squares regression results for one-step-ahead forecasting of triangular arbitrage returns (Equations 12 and 13): “Eq 12(2)” denotes that Equation 2 was used for the calculation of triangular returns (i.e., $r_{TR,t+1}$ from the first triangular arbitrage route) and “Eq 13(3)” denotes that Equation 3 was used for the calculation of triangular returns (i.e., $r_{TR,t+1}$ from the second triangular arbitrage route). The numbers in parentheses are Newey and West (1987) p-values with ten lags for the estimates and the numbers in square brackets are the $R^2$ values for each predictive regression. The regressors are the average triangular variance (ATV) and correlation (ATC), defined in Equation 7 and Equation 8, respectively.

in contrast to this paper, we find that average triangular variance is a substantially better predictor of triangular profits than average triangular correlation that appears to provide a smaller contribution to total triangular variance and thereby to the predictability of arbitrage profits. It can also be observed that the predictors are more successful in predicting triangular arbitrage returns in 2010 relative to 2011.

To confirm the predictive power of our measures relative to the random walk model, we also perform a directional test that determines the percentage of correctly forecasted signs of the change in triangular arbitrage returns: $PERCTA = 1/T \sum_{t=1}^{T} \rho_t$, where $\rho_t = 1$ if $\Delta r_{TR,t+1} \Delta \hat{r}_{TR,t+1} = 1$, and zero, otherwise. The significance of the difference in the performance of the model given by Equation 13 and the random walk model is tested by the Diebold and Mariano (1995) (DM) test statistic. The null hypothesis is that there is no difference in the percentage of correctly predicted directional movements in triangular
Table 4: Predictive Power of Average Variance and Correlation Measures (October 3-16, 2011).

Notes: The table presents the daily averages for ordinary least squares regression results for one-step-ahead forecasting of triangular arbitrage returns (Equations 12 and 13): “Eq 12(2)” denotes that Equation 2 was used for the calculation of triangular returns (i.e., $r_{TR,t+1}^i$ from the first triangular arbitrage route) and “Eq 13(3)” denotes that Equation 3 was used for the calculation of triangular returns (i.e., $r_{TR,t+1}^i$ from the second triangular arbitrage route). The numbers in parentheses are Newey and West (1987) p-values with ten lags for the estimates and the numbers in square brackets are the $R^2$ values for each predictive regression. The regressors are the average triangular variance (ATV) and correlation (ATC), defined in Equation 7 and Equation 8, respectively.

<table>
<thead>
<tr>
<th>Oct. 3-16, 2011</th>
<th>Eq 12(2)</th>
<th>Eq 12(2)</th>
<th>Eq 13(3)</th>
<th>Eq 13(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td></td>
<td>(0.000)</td>
<td>(0.000)</td>
<td>(0.000)</td>
<td>(0.000)</td>
</tr>
<tr>
<td>$TV_t$</td>
<td>-9.53</td>
<td>-9.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.000)</td>
<td>(0.000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ATC_t$</td>
<td>-0.009</td>
<td></td>
<td>-0.009</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.000)</td>
<td></td>
<td>(0.000)</td>
<td></td>
</tr>
<tr>
<td>$ATV_t$</td>
<td>-4.82</td>
<td></td>
<td>-5.96</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.000)</td>
<td></td>
<td>(0.000)</td>
<td></td>
</tr>
<tr>
<td>$R^2$</td>
<td>[0.042]</td>
<td>[0.048]</td>
<td>[0.035]</td>
<td>[0.036]</td>
</tr>
</tbody>
</table>

arbitrage returns of the two alternative forecasting models. We average our findings for each day over the period from November 1-14, 2010 and use the expanding sample one-step-ahead forecasting. The DM statistic in Table 5 shows statistically significant forecast improvements over the random walk model at the 1% significance level. This exercise demonstrates the difficulties of forecasting the directional movements in triangular arbitrage returns accurately and the added value of utilizing the proposed predictors.

Next, based on our conclusions from Table 2, we run the following predictive regressions:

$$r_{iTR,t+1}^i = \alpha_i + \beta_{1i}qwspread_{t} + \beta_{2i}r_{TR qw,t}^i + \epsilon_{i,t}, \quad i = 1, 2 \tag{23}$$

$$r_{iTR,t+1}^i = \alpha_i + \beta_{1i}cogqwspread_{t} + \beta_{2i}r_{TR cog,t}^i + \psi_{i,t}, \quad i = 1, 2 \tag{24}$$
Table 5: **Directional forecast performance (November 1-14, 2010).**

Notes: The table presents the daily averages for the percentage of correctly forecasted signs of the change in triangular arbitrage returns ($PERCTA$) for the random walk model ($RW$) and the model specification given by Equation 13. The Diebold and Mariano (DM) (1995) test is used to measure the statistical significance of the sign forecasts of Equation 13 over the random walk model.

<table>
<thead>
<tr>
<th>Model</th>
<th>PERCTA</th>
<th>DM (p-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RW</td>
<td>0.30</td>
<td>10.17 (0.000)</td>
</tr>
<tr>
<td>Equation 13</td>
<td>0.54</td>
<td></td>
</tr>
</tbody>
</table>

where $r^i_{TR,t+1}$ (triangular arbitrage returns) stands for the left-hand sides of Equation 2 ($i=1$) and Equation 3 ($i=2$), and the predictor variables are defined as follows:

- $qws\text{spread}$ is the quantity-weighted average bid-ask spread defined by Equation 17;

- $cogqws\text{spread}$ is the center of gravity quantity-weighted average bid-ask spread defined by Equation 21;

- $r^i_{TRqw,t}$ is the left-hand side of Equation 2 (when $i=1$) or Equation 3 (when $i=2$) when bid and ask prices are calculated by Equations 15 and 16;

- $r^i_{TRcog,t}$ is the left-hand side of Equation 2 (when $i=1$) or Equation 3 (when $i=2$) when bid and ask prices are calculated by Equations 19 and 20.

Table 6 and Table 7 report the estimates of slope coefficients from Equations 23 and 24. Although all limit order book indicators are informative for predicting triangular arbitrage returns, it can be observed that the standard quantity-weighted indicators ($r^i_{TRqw,t}$) are dominant and have the highest predictive power. The spread measures ($qws\text{spread}$ and $cogqws\text{spread}$) suggest that the lower the average spread, the larger future triangular arbitrage
returns are expected. In particular, triangular arbitrage returns are forecasted to increase by between 10-100 bps on average when the average spread declines by one pip. Specifically, 100 bps increase in the returns on triangular arbitrage according to the limit order book measures forecasts an average increase in the actual triangular arbitrage strategy profits by 1-7 bps. This evidence demonstrates the usefulness of limit order book information to arbitrage traders. In addition, these measures are more effective in forecasting triangular arbitrage returns relative to the average covariance and correlation measures.

Table 6: Predictive Power of Limit Order Book Measures (November 1-14, 2010; Daily Averages).

<table>
<thead>
<tr>
<th>r_{TR,t+1}^i (i = 1)</th>
<th>qwspread_t</th>
<th>cogqwspread_t</th>
<th>r_{TRqw,t}^i</th>
<th>r_{TRcog,t}^i</th>
<th>R^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>β_{1i}, β_{2i}</td>
<td>-0.003</td>
<td>0.036</td>
<td></td>
<td></td>
<td>0.212</td>
</tr>
<tr>
<td>p-value</td>
<td>(0.000)</td>
<td>(0.000)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>β_{1i}, β_{2i}</td>
<td>-0.006</td>
<td>0.065</td>
<td></td>
<td></td>
<td>0.263</td>
</tr>
<tr>
<td>p-value</td>
<td>(0.000)</td>
<td>(0.000)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>r_{TR,t+1}^i (i = 2)</th>
<th>qwspread_t</th>
<th>cogqwspread_t</th>
<th>r_{TRqw,t}^i</th>
<th>r_{TRcog,t}^i</th>
<th>R^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>β_{1i}, β_{2i}</td>
<td>-0.010</td>
<td>0.047</td>
<td></td>
<td></td>
<td>0.249</td>
</tr>
<tr>
<td>p-value</td>
<td>(0.000)</td>
<td>(0.000)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: r_{TR,t+1}^i (triangular arbitrage returns) stands for the left-hand sides of Equation 2 (i=1) and Equation 3 (i=2). The predictors are the quantity-weighted average bid-ask spread (qwspread), the center of gravity quantity-weighted average bid-ask spread (cogqwspread), triangular arbitrage returns obtained from the quantity-weighted average bid and ask prices (r_{TRqw,t}^i), and triangular arbitrage returns obtained from the center of gravity quantity-weighted average bid and ask prices (r_{TRcog,t}^i). The numbers in parentheses are Newey and West (1987) p-values (p-value) with ten lags for the estimates of β_i, and the numbers in square brackets are the R^2 values of each predictive regression.
Table 7: Predictive power of limit order book measures (October 3-16, 2011; daily averages).

Notes: $r_{TR,t+1}^i$ (triangular arbitrage returns) stands for the left-hand sides of Equation 2 ($i=1$) and Equation 3 ($i=2$). The predictors are the quantity-weighted average bid-ask spread ($\text{qwspread}$), the center of gravity quantity-weighted average bid-ask spread ($\text{cogqwspread}$), triangular arbitrage returns obtained from the quantity-weighted average bid and ask prices ($r_{TRqw,t}^i$), and triangular arbitrage returns obtained from the center of gravity quantity-weighted average bid and ask prices ($r_{TRcog,t}^i$). The numbers in parentheses are Newey and West (1987) p-values (p-value) with ten lags for the estimates of $\beta_i$, and the numbers in square brackets are the $R^2$ values of each predictive regression.

<table>
<thead>
<tr>
<th></th>
<th>$\text{qwspread}_t$</th>
<th>$\text{cogqwspread}_t$</th>
<th>$r_{TRqw,t}^1$</th>
<th>$r_{TRcog,t}^1$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{TR,t+1}^i$ ($i = 1$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_{1i}, \beta_{2i}$</td>
<td>-0.013</td>
<td>0.009</td>
<td></td>
<td>[0.082]</td>
<td></td>
</tr>
<tr>
<td>(p-value)</td>
<td>(0.000)</td>
<td>(0.000)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_{TR,t+1}^i$ ($i = 2$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_{1i}, \beta_{2i}$</td>
<td>-0.002</td>
<td>0.039</td>
<td></td>
<td>[0.099]</td>
<td></td>
</tr>
<tr>
<td>(p-value)</td>
<td>(0.000)</td>
<td>(0.000)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3. Decimal pip pricing

Decimal pip pricing refers to the addition of a fifth decimal place to the prices in the EBS platform.\(^{10}\) The policy was introduced to accommodate the platform’s high-frequency traders (HFT) and to respond to the potential threat from competing platforms such as the ones from Barclays and Deutsche Bank. Although the move to decimal pips accelerated a decline in the market share for EBS and the policy was subsequently scraped in September, 2012, it would be interesting to test the impact of pip pricing on our results.

The goal of this subsection is to observe the frequency and predictability of triangular arbitrage opportunities before and after the introduction of decimal pip pricing by EBS in

\(^{10}\)In the context of basis points, considering that currencies are typically quoted to four decimal places, one pip corresponds to one basis point.
mid March, 2011. In the week of February 21-27, 2011 the whole pip pricing was still in use, while from April 4-10, 2011, the new decimal pip pricing was in effect. In what follows, we will apply our framework to the last week of February, 2011 and the first week of April, 2011.

Since we have shown before that an improved predictability of triangular arbitrage by using the ATC and ATV predictors implies forecast gains from the order book indicators, for consistency, we employ only ATC and ATV as regressors. Table 8 presents the daily average estimates from our predictive regressions. The average daily return from triangular arbitrage in the week of Feb. 21-27, 2011 is 3.4 bps, while this figure for the week of Apr. 4-10, 2011 is 4.6 bps. It is worthwhile to mention that both figures are lower than the averages for Nov. 1-14, 2010 (6.3 bps) and Oct. 3-16, 2011 (5.9 bps). A somewhat surprising finding is that the number of average triangular arbitrage opportunities plunges to about 34 before the

Table 8: Predictive power of ATV and ATC for the event study.

<table>
<thead>
<tr>
<th></th>
<th>Feb. 21-27, 2011</th>
<th>Apr. 4-10, 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq</td>
<td>34</td>
<td>120</td>
</tr>
<tr>
<td>$ATC_t$</td>
<td>-0.001 (0.000)</td>
<td>-0.004 (0.000)</td>
</tr>
<tr>
<td>$ATV_t$</td>
<td>-11.63 (0.000)</td>
<td>-5.78 (0.000)</td>
</tr>
<tr>
<td>$\overline{R^2}$</td>
<td>[0.032] [0.015]</td>
<td>$\overline{R^2}$</td>
</tr>
</tbody>
</table>

Notes: The table presents the daily averages for ordinary least squares regression results for one-step-ahead forecasting of triangular arbitrage returns as specified in Equation 13. $r_{TR,t+1}$ (triangular arbitrage returns) stands for the left-hand sides of Equation 2 ($i=1$) and Equation 3 ($i=2$). The numbers in parentheses are Newey and West (1987) p-values with ten lags for the estimates and the numbers in square brackets are the average $\overline{R^2}$ values for each predictive regression for the weeks Feb. 21-27, 2011 and Apr. 4-10, 2011. The regressors are the average triangular variance (ATV) and correlation (ATC), defined in Equation 7 and Equation 8, respectively. “Freq” is the average number of daily triangular parity violations over the two periods.
structural change and then increases to very high levels (120, on average) after the change. In addition, we observe that both trading volume and trading frequency were lower than average before the regulation. This can be explained by the potential behavior of market participants that may have pulled back due to uncertainty to absorb the structural change. This also caused the reduced predictability of triangular arbitrage opportunities.

After the change to decimal pip pricing, the new platform setting attracted HFT and this resulted in an increase in trading volume, number of arbitrage opportunities, average profitability and a better regression fit as measured by the $R^2$. Following that, the average predictability and profitability slightly improved later in 2011, but the number of triangular arbitrage situations fell below the 2010 levels (to roughly 80 in October, 2011, which is the last available month in our data set). According to Reuters, the average daily cash FX volume on the EBS platform dropped by 49% from August 2011 to August 2012, when it was $95.5 billion. This decline in trading activity, likely caused by the departure of traders and banks that used slower technology relative to HFT, is consistent with our results.

5. Conclusions

Triangular arbitrage strategy involves exploiting mispricing in the FX market when a currency is traded at two different prices, a direct price and an indirect price (i.e., a cross FX rate that is constructed by using a third currency). As the literature shows, triangular arbitrage situations are difficult to profit from due to delays in trade execution, technological advances that promote price transparency and efficiency, competition from other traders, relatively small size (and frequency) of the profits, and the inability to predict arbitrage opportunities.
This paper makes an important contribution in regards to our understanding and predicting triangular arbitrage. We demonstrate empirically the existence of triangular arbitrage in three major exchange rates (EUR/USD, EUR/JPY and USD/JPY) in 2010 and 2011. Although such opportunities are relatively frequent, their duration is, on average, very short to allow agents to easily exploit them. The observed short durations indicate that markets are efficient in terms of exhausting arbitrage profits rapidly and that they can only be detected in ultra high-frequency data sets at tick-by-tick frequencies.

The quality of our unique data coming from the EBS platform enables us to go one step further and identify the variables that may be used to predict triangular arbitrage profits. This research objective is pioneering and fills an important gap in the international finance literature. Two sets of predictors are found statistically informative: 1) average variance and average correlation among the exchange rates, and 2) limit order book indicators averaged across the three exchange rates from the triangular parity condition. Our original limit order book measures are based on the quantity-weighted average bid/ask prices and the center of gravity quantity-weighted average bid/ask prices. These measures are dominant in predicting arbitrage profits relative to the average variance and correlation measures. Specifically, we report that when the average FX volatility and average correlations among the FX rates are low, triangular arbitrage returns are expected to increase. Also, triangular arbitrage returns obtained from the quantity-weighted average bid and ask prices are useful for predicting the actual triangular arbitrage returns.

Lastly, we find that all predictors are highly persistent, which suggests that currency mispricings are not a random occurrence, but are the result of long-memory forces that accumulate over time. In this context, reaching an arbitrage situation can be viewed as a “wave” of trading activity that builds up and periodically becomes profitable.
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Cenedese, G., Sarno, L., and Tsiakas, I. (2012). Average variance, average correlation and 


Figure 1: Example: inside spread.

The data are taken by a random draw from the limit order book for the EUR/USD transactions at a given point in time at the highest frequency [100ms]. All ten levels on the bid and ask sides are visible with the height of the individual columns corresponding to the limit order size in the EUR currency.
Figure 2: Example: Quantity-weighted measures.
The data are taken by a random draw from the limit order book for the EUR/USD transactions at a given point in time at
the highest frequency [100ms]. All ten levels on the bid and ask sides are visible with the height of the individual columns
corresponding to the limit order size in the EUR currency. The quantity-weighted ask quote ($qwa$), the quantity-weighted bid
quote ($qwb$) and the quantity-weighted mid-quote ($qwmidq$) values for the snapshot of the EUR/USD limit order book are
marked with arrows.
Figure 3: Example: center of gravity quantity-weighted measures.
The data are taken by a random draw from the limit order book for the EUR/USD transactions at a given point in time at the highest frequency [100ms]. All ten levels on the bid and ask sides are visible with the height of the individual columns corresponding to the limit order size in the EUR currency. The center of gravity quantity-weighted ask quote (\textit{cogqwa}), the center of gravity quantity-weighted bid quote (\textit{cogqwb}) and the center of gravity quantity-weighted mid-quote (\textit{cogqwmidq}) values for the snapshot of the EUR/USD limit order book are marked with arrows.