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Intra-Day Arbitrage Opportunities in Foreign Exchange and Eurocurrency Markets

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ABSTRACT

We have two primary objectives in this study. First, we examine the frequency of attaining simultaneous equilibrium on spot and forward foreign exchange markets and on domestic and foreign securities markets. Second, we measure the profitability of covered interest arbitrage and one-way arbitrage. Our empirical analysis has been conducted using real-time quotations. The empirical results indicate that: (a) the markets are efficient in the sense that profit opportunities from traditional covered interest arbitrage are rarely available; and (b) the frequency of attaining simultaneous market equilibrium is surprisingly low, thus opening the door for one-way arbitrage.

THE ROLE OF TRANSACTION costs in explaining the deviation of the actual forward price from the interest parity forward price has been studied extensively. Based on covered interest arbitrage, Frenkel and Levich (1975, 1977) have shown that the interest parity line is bound by a neutral band defined as:

$$(F - F_0)/F_0 = t + t^* + t_f + t_s, \tag{1}$$

where t, t^* = proportional transaction costs in domestic and foreign security markets; t_s, t_f = proportional transaction costs in spot and forward exchange markets; F = the actual forward price defined as units of home currency per unit of foreign currency; and F_0 = the interest parity forward price. By taking into account equilibrium conditions on both spot and forward exchange markets, Deardorff (1979) has demonstrated that one-way arbitrage causes the neutral band to be narrower than commonly perceived on the basis of covered interest arbitrage as indicated below:

$$(F - F_0)/F_0 = t + t^* - t_f - t_s. \tag{2}$$

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More recently, Callier (1981) and Bahmani-Oskooee and Das (1985) have demonstrated that the neutral band is narrowed further when equilibrium conditions are considered in the foreign exchange and securities markets:

$$(F - F_0)/F_0 = \min\left(t + t^*_{\cdot} - t_f - t_s,\ t_f + t_s - t - t^*\right), \tag{3}$$

where the second term in the parentheses is obtained from the equilibrium conditions on the domestic and foreign securities markets.[1]

Two empirical questions are raised by this narrower band. First, is the role of transaction costs diminished in explaining the observed divergences from the interest parity line? Bahmani-Oskooee and Das have documented empirical evidence in support of this hypothesis. Second, what is the frequency of attaining simultaneous equilibrium on spot and forward foreign exchange markets and on domestic and foreign securities markets? The frequency of market equilibrium (or disequilibrium) is virtually unknown because of the limitations of empirical methodology employed in the past. In the absence of direct measures of transaction costs, Frenkel and Levich have used: (a) the concept of triangular arbitrage to indirectly estimate transaction costs in the foreign exchange markets and (b) Demsetz's (1968) estimate to approximate the cost of transacting in securities markets while assuming transaction costs are the same for the domestic and foreign securities markets, i.e., $t = t^*$. Unfortunately, indirect measures of transaction costs are inappropriate for the examination of the frequency of market equilibrium for at least three important reasons. First, equilibrium conditions tend to be violated when the markets are unstable. In contrast, the validity of indirect measures of transaction costs requires strictly that the cost structure built into triangular arbitrage remains stable. Second, the indirect measures simply represent an average cost that does not capture the degree of uncertainty associated with each and every arbitrage transaction. The frequency of market disequilibrium should be compiled based upon individual transactions. Third, Demsetz's estimate may not be the best proxy measure for short-term securities markets because it was originally obtained using New York Stock Exchange stocks. Additionally, the simplifying assumption that $t = t^*$ also fails to capture the degree of volatility of short-term interest rates that affect domestic and foreign securities markets.

This study has two primary objectives. First, it examines the frequency of attaining simultaneous equilibrium on spot and forward foreign exchange markets and on domestic and foreign securities markets. Second, it measures arbitrage profitability and its persistence over time. Neither of these objectives has been examined in the past. Our empirical analysis is conducted using real-time quotations drawn from Eurocurrency markets and interbank foreign exchange markets. To avoid the difficulties associated with using indirect measures of transaction costs, our empirical investigation uses direct

[1] Clinton (1988) has shown that the introduction of swap markets further reduces the neutral band.

measures embedded in the bid/ask spread.[2] The choice of external Eurocurrency markets over traditional markets for short-term securities such as treasury bills is intended to meet the comparability criterion originally suggested by Aliber (1973). The selection of interbank foreign exchange markets is justified by large transaction volume. A study conducted in April 1989 by the Federal Reserve Bank of New York indicates that foreign exchange turnover in the interbank markets is approximately six times greater than all the transactions by nonbank institutions.[3] In addition, real-time quotations observed for both foreign exchange and securities markets satisfy McCormick's (1979) simultaneity criterion.

The paper is organized as follows. Section I presents a brief review of simultaneous equilibrium conditions, contrasting one-way arbitrage with traditional covered interest arbitrage. Section II summarizes the empirical data and results. Concluding comments are presented in Section III.

I. Simultaneous Equilibrium Conditions

Figure 1, adapted from Deardorff (1979), presents a schematic illustration of arbitrage transactions that link interbank foreign exchange markets and Eurocurrency markets. The following notations are used for bid and asked prices quoted: S_b and S_a = the bid and asked prices of spot foreign exchange and F_b and F_a = the corresponding forward prices; r_b and r_a = the bid and asked interest rates on Eurodollar deposits and r_b^* and r_a^* = the corresponding rates on Euro-FC deposits, where FC denotes foreign currency; additionally, \$(0), \$(1) and FC(0), FC(1) are the spot and future dollars and the spot and future foreign currencies, respectively. Arbitrageurs in the interbank markets buy or borrow at the other party's asked price, while they sell or lend at the bid price.

A. Covered Interest Arbitrage

Consider an arbitrageur who moves covered arbitrage funds from a Euro-FC deposit to a Eurodollar deposit with a one-year maturity. Figure 1 shows the entire process of covered interest arbitrage starting, for example, from the future foreign currencies, FC(1), and following the clockwise arrows to return to FC(1). The future FC cost of acquiring one unit of FC(1) is found by

[2] The examination of the spreads behavior or of the determinants of spreads is not the focus of this paper. As a result, the transaction costs in this paper are defined more broadly than in Glassman (1987). She decomposes the bid/ask spread into two components. The first component represents the narrowly defined transaction costs which include the overhead costs and the market maker's profit. The second component is the compensation for risk of assuming an open position. She provides an excellent review of recent research in studies of bid/ask spreads.

[3] The Federal Reserve Bank of New York's press release dated September 13, 1989, on "Summary of Results of U.S. Foreign Exchange Market Survey Conducted in April 1989" indicates that banking institutions' average daily volume was \$110.5 billion while that for nonbank financial institutions was \$18.4 billion. These figures were adjusted for the double counting of the same transactions.

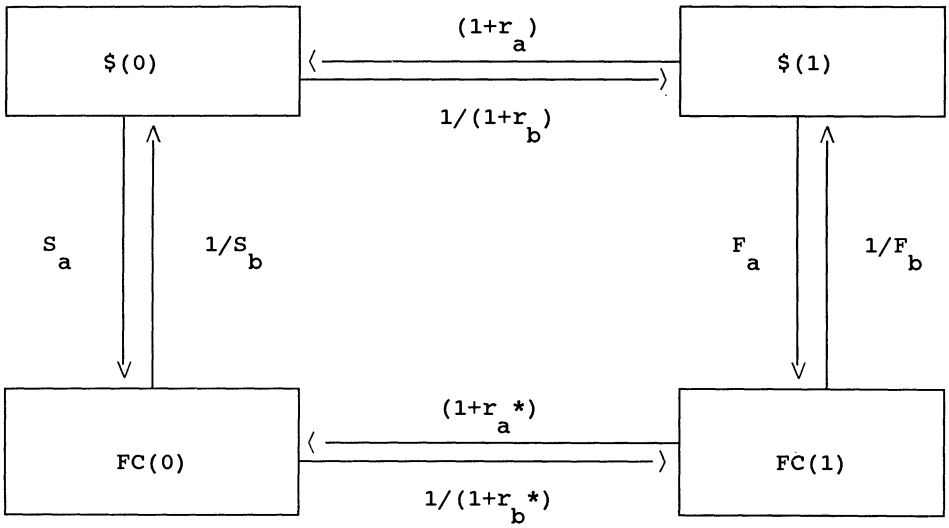

Figure 1. Arbitrage transactions. Presents a schematic illustration of arbitrage transactions that link interbank foreign exchange markets and Eurocurrency markets. S_b and S_a = the bid and asked prices of spot foreign exchange and F_b and F_a = the corresponding forward prices: r_b and r_a = the bid and asked interest rates on Eurodollar deposits and r_b^* and r_a^* = the corresponding rates on Euro-FC deposits, where FC denotes foreign currency. $(0), $(1) and FC(0), FC(1) are the spot and future dollars and the spot and future foreign currencies, respectively. Arbitrageurs in the interbank markets buy or borrow at the other party's asked price, while they sell or lend at the bid price.

multiplying the four costs associated with the four clockwise arrows. Only if that cost is greater than or equal to unity, then covered interest arbitrage stops. This condition is expressed as:

$$F_a \geq S_b W; \tag{4}$$

where $W = (1 + r_b)/(1 + r_a^*)$. In contrast, covered interest arbitrage may also be attempted in another direction when arbitrage funds are moved from a Eurodollar deposit to a Euro-FC deposit, to start and end at the future dollars, $(1), for example, following the counterclockwise arrows in Figure 1. This arbitrage stops only if the future dollar cost of acquiring one unit of $(1) is greater than or equal to unity. Thus, it follows:

$$F_b \leq S_a X; \tag{5}$$

where $X = (1 + r_a)/(1 + r_b^*)$. Thus, as a minimum requirement for market equilibrium, the above two conditions must hold simultaneously. Otherwise, foreign exchange and securities markets serve as a money machine. Profits from covered interest arbitrage are then measured by:

$$\pi_a = S_b W - F_a \text{ and} \tag{6}$$

$$\pi_b = F_b - S_a X; \tag{7}$$

where π_a and π_b denote profits from the clockwise and counterclockwise arbitrage transactions, respectively.

B. One-Way Arbitrage

The concept of one-way arbitrage was originally introduced by Deardorff (1979) as an alternative to direct market transactions for exchanging one currency for another of some maturity. The choice between the two alternatives is dictated by the costs involved. Table I summarizes eight necessary conditions for direct market transactions in foreign exchange markets as well as in securities markets. These conditions are adapted from Deardorff (1979), Callier (1981), and Bahmani-Oskooee and Das (1985) with the explicit introduction of the bid and asked prices of foreign exchange and Eurocurrency deposits to facilitate this paper's empirical analysis. Whenever one of the eight conditions is not satisfied, one-way arbitrage emerges as an alternative. Depending upon the direction of movement of the arbitrage funds, one-way arbitrage may also be classified into two categories: (a) clockwise arbitrage and (b) counterclockwise arbitrage. For example, the violation of conditions (C1), (C4), (C6), or (C7) will trigger the movement of arbitrage funds in a clockwise direction. In contrast, arbitrage funds will be moved in a counterclockwise direction if conditions (C2), (C3), (C5), or (C8) are not met. Note from Table I that conditions (C1), (C4), (C6), and (C7) define the *asked* price of forward exchange, while conditions (C2), (C3), (C5), and (C8) define the *bid* forward price.

General market equilibrium on the entire set of four markets requires that either (C1), (C4), (C6), or (C7) and either (C2), (C3), (C5), or (C8) hold simultaneously. Thus, the necessary and sufficient condition for a nontrivial equilibrium on the entire set of markets requires that the asked price of forward exchange be greater than or equal to the maximum of the right-hand sides of (C1), (C4), (C6), and (C7), while the bid price of forward exchange must be less than or equal to the minimum of the right-hand sides of (C2), (C3), (C5), and (C8) as indicated below:

$$F_a \geq \max\left[S_aW,\ S_bW + (F_a - F_b),\ S_bY,\ S_bZ\right] \text{ and} \tag{8}$$

$$F_b \leq \min\left[S_aX - (F_a - F_b),\ S_bX,\ S_aY,\ S_aZ\right], \tag{9}$$

where $Y = (1 + r_a)/(1 + r_a^*)$ and $Z = (1 + r_b)/(1 + r_b^*)$.

By collecting the bid and asked quotations observed simultaneously for foreign exchange and Eurocurrency deposits, one can easily determine whether the observed forward prices are mispriced. The violation of the two conditions implies mispricing in either foreign exchange markets or securities markets. Based on a series of real-time quotations, the frequency of market equilibrium (or disequlibrium) can be compiled. It must be emphasized, however, that one-way arbitrage opportunities resulting from the mispricing do not reveal the presence of a money machine as in traditional covered interest arbitrage because arbitrageurs cannot begin one-way arbitrage *de novo* in order to make money. It is the continuous flow of market

Table I

Conditions for Direct Market Transactions in Foreign Exchange Markets and Securities Markets

Whenever one of the eight conditions is not satisfied, one-way arbitrage emerges as an alternative. Depending upon the direction of movement of the arbitrage funds, one-way arbitrage may also be classified into two categories: (a) clockwise arbitrage and (b) counterclockwise arbitrage as presented in Figure 1. For example, the violation of conditions (C1), (C4), (C6), or (C7) will trigger the movement of arbitrage funds in a clockwise direction. In contrast, arbitrage funds will be moved in a counterclockwise direction if conditions (C2), (C3), (C5), or (C8) are not met. Four conditions (C1), (C4), (C6), and (C7) define the asked price of forward exchange, while conditions (C2), (C3), (C5), and (C8) define the bid forward price. S_b and S_a = the bid and asked prices of spot exchange; F_b and F_a = the bid and asked prices of forward exchange; r_b and r_a = the bid and asked interest rates on Eurodollar deposits; r^*_b and r^*_a = the bid and asked interest rates on Euro-FC deposits; \$(0) and \$(1) = spot and future dollars; and FC(0) and FC(1) = spot and future FC, where FC denotes foreign currency.

Panel A: Foreign Exchange Markets	
Demanders of FC(0) [or suppliers of \$(0)] use the spot market if	
$F_a \geq S_a(1 + r_b)/(1 + r^*_a)$	(C1)
Demanders of FC(1) [or suppliers of \$(1)] use the forward market if	
$F_b \leq [S_a(1 + r_a)/(1 + r^*_b) - (F_a - F_b)]$	(C2)
Suppliers of FC(0) [or demanders of \$(0)] use the spot market if	
$F_b \leq S_b(1 + r_a)/(1 + r^*_b)$	(C3)
Suppliers of FC(1) [or demanders of \$(1)] use the forward market if	
$F_a \geq [S_b(1 + r_b)/(1 + r^*_a) + (F_a - F_b)]$	(C4)
Panel B. Securities Markets	
Demanders of FC(0) [or suppliers of FC(1)] use the Euro-FC market if	
$F_b \leq S_a(1 + r_a)/(1 + r^*_a)$	(C5)
Demanders of \$(0) [or suppliers of \$(1)] use the Eurodollar market if	
$F_a \geq S_b(1 + r_a)/(1 + r^*_a)$	(C6)
Suppliers of FC(0) [or demanders of FC(1)] use the Euro-FC market if	
$F_a \geq S_b(1 + r_b)/(1 + r^*_b)$	(C7)
Suppliers of \$(0) [or demanders of \$(1)] use the Eurodollar market if	
$F_b \leq S_a(1 + r_b)/(1 + r^*_b)$	(C8)

participants that make one-way arbitrage work. These market participants continuously search for the least-cost route of exchanging one currency for another of some maturity, thus revealing the temporary occurrence of a redundant market.[4] One-way arbitrage profitability, however, may serve the

[4] We are grateful to Richard Levich, the referee, for his insightful comments on this issue.

useful purpose of verifying the pricing efficiency in foreign exchange and Eurocurrency markets because it can be used to examine how quickly temporary market disequilibrium disappears over time. Hence, we introduce the following profit measures for one-way arbitrage:

$$\pi_a^o = \max\left[S_aW,\ S_bW + (F_a - F_b),\ S_bY,\ S_bZ\right] - F_a \text{ and} \tag{10}$$

$$\pi_b^o = F_b - \min\left[S_aX - (F_a - F_b),\ S_bX,\ S_aY,\ S_aZ\right]. \tag{11}$$

where π_a^o and π_b^o denote profits from the clockwise and counterclockwise one-way arbitrage transactions, respectively.

II. Empirical Results

A. Data

The empirical analysis covers a one-month period between April 11 and May 13, 1988. The choice of this period was dictated by the availability of intra-day bid and asked quotations of foreign exchange and Eurocurrency deposits. Reuters News Service quotations during New York's morning trading hours, 8:30 A.M. to 12 noon, were collected. These quotations represent the best prices from numerous banks compiled by Reuters News Service. Although there is no assurance that transactions will be consummated at these quotes, they represent market prices. The number of trading days during the study period with complete data for both foreign exchange markets and Eurocurrency markets is 25 days with a total of 157 sets of observations. The time interval between each set of observations is approximately 35 minutes. Forward exchange rates are collected for the British pound sterling, German mark, Japanese yen, and Swiss franc. The maturities of forward exchange and of Eurocurrency deposits are one-month, two-months, three-months, six-months, and 12-months. Spot exchange rates are matched with Eurocurrency deposit rates with a one-day maturity (based on tomorrow/next price quotes).

B. Transaction Costs in Foreign Exchange and Eurocurrency Markets

Transaction costs are summarized in Tables II and III. Table II presents summary statistics of the percentage spread defined as (asked price − bid price)/bid price. Without exception, the percentage spread increases with maturity. For example, the magnitude of the 12-month forward spread is approximately two or three times larger than the spread on spot currency. Transaction costs for Swiss francs are the largest among the four currencies examined, while German marks show the smallest transaction costs during the study period.

Table III presents summary statistics on transaction costs in Eurocurrency markets. The percentage spreads are defined by $(r_a - r_b)/(1 + r_b)$ for Eurodollar deposits and $(r_a^* - r_b^*)/(1 + r_b^*)$ for Euro-FC deposits. Annualized interest rates are used for each of the six maturities for the purpose of

Table II

Transaction Costs in Foreign Exchange Markets

Transaction costs are measured by the percentage spread defined as (asked price − bid price)/bid price. Figures in parentheses denote standard deviations. Foreign currency prices are from Reuters News Service during New York's morning trading hours 8:30 A.M.–12 noon, over a one-month period from April 11 to May 13, 1988.

		Forward				
Currency	Spot	1-Month	2-Month	3-Month	6-Month	12-Month
British pound	0.0442% (0.00013)	0.0520% (0.00013)	0.0569% (0.00013)	0.0593% (0.00013)	0.0696% (0.00013)	0.0947% (0.00016)
German mark	0.0409% (0.00018)	0.0509% (0.00018)	0.0565% (0.00019)	0.0578% (0.00019)	0.0681% (0.00020)	0.0955% (0.00025)
Japanese yen	0.0563% (0.00022)	0.0707% (0.00023)	0.0732% (0.00024)	0.0768% (0.00024)	0.0916% (0.00070)	0.1369% (0.00039)
Swiss franc	0.0627% (0.00015)	0.0824% (0.00017)	0.0847% (0.00017)	0.0916% (0.00017)	0.1134% (0.00021)	0.2074% (0.00054)

Table III

Transaction Costs in Eurocurrency Markets

Transaction costs are measured by the percentage spread defined as (asked rate − bid rate)/(1 + bid rate). Figures in parentheses denote standard deviations. Interest rates are from Reuters News Service during New York's morning trading hours, 8:30 A.M.–12 noon, over a one-month period from April 11 to May 13, 1988.

	Maturity					
Currency	1-Day	1-Month	2-Month	3-Month	6-Month	12-Month
Eurodollar	0.1618% (0.0005)	0.1168% (0.0000)	0.1167% (0.0000)	0.1167% (0.0000)	0.1164% (0.0000)	0.1159% (0.0000)
Eurosterling	0.2321% (0.0000)	0.1157% (0.0000)	0.1186% (0.0001)	0.1215% (0.0003)	0.1152% (0.0000)	0.1147% (0.0000)
Euromark	0.1629% (0.0006)	0.1211% (0.0000)	0.1212% (0.0000)	0.1208% (0.0000)	0.1209% (0.0000)	0.1205% (0.0000)
Euroyen	0.1477% (0.0005)	0.1498% (0.00100)	0.1202% (0.00018)	0.1189% (0.00030)	0.1191% (0.00008)	0.1186% (0.00008)
EuroSwiss franc	0.3269% (0.0010)	0.2315% (0.0019)	0.2155% (0.0018)	0.1728% (0.0008)	0.1852% (0.0009)	0.1668% (0.0006)

comparison among different maturities. Unlike the transaction costs in foreign exchange markets, it appears that the percentage spread does not increase with maturity. Rather, the magnitude of spread on one-day maturity is greater than that reported for longer maturities. This may be attributed to the greater volatility frequently observed in short-term interest rates. The reported percentage spreads indicate that the Euro-Swiss franc deposit with a one-day maturity is the most costly among the five Eurocurrency deposits

examined, followed by Eurosterling, Euromark, Eurodollar, and Euroyen. This order, however, is not maintained consistently as maturity increases.

C. Simultaneous Equilibrium

The violation of equations (4) and (5) implies market disequilibrium from the standpoint of covered interest arbitrage, while market disequilibrium from the standpoint of one-way arbitrage is indicated by the violation of equations (8) and (9). Using a series of real-time quotations observed for foreign exchange and Eurocurrency deposits, the frequency of market equilibrium (disequilibrium) can be computed. Table IV summarizes the frequency of market equilibrium (disequilibrium) implied by covered interest arbitrage as well as one-way arbitrage. Of the 157 potential transactions, we first counted the number of violations of the interest parity conditions as defined by equations (4) and (5) for covered interest arbitrage and equations (8) and (9) for one-way arbitrage.

From the frequency of market equilibrium (disequilibrium) summarized in the third and fourth columns, we may conclude that foreign exchange and securities markets are efficient in the sense that profit opportunities from traditional covered interest arbitrage are rarely available. For example, we observe complete market equilibrium for German marks with all maturities except a six-month maturity. For the six-month maturity, two out of 157 sets of potential transactions provided covered arbitrage opportunities. Swiss francs with maturities ranging from one to six months also attained market equilibrium for all of 157 arbitrage transactions. Both German marks market with a six-month maturity and Swiss francs market with a 12-month maturity failed to reach equilibrium only twice out of 157 potential arbitrage transactions. A slightly higher frequency of market disequilibrium is observed for British pound sterling with 6- and 12-month maturities.[5] The Japanese yen markets with the maturities ranging from two- to six-months also show moderate frequency of disequilibrium.

However, one-way arbitrage renders a completely different picture of market equilibrium. Surprisingly, an extremely low-frequency of simultaneous equilibrium is observed as summarized in the last two columns. Given a total of 157 sets of price quotes simultaneously observed in both foreign exchange and securities markets, for example, the general market equilibrium conditions were satisfied on 68 potential transactions for British pound sterling with a one-month maturity. This figure implies that the observed percentage frequency is only 43.3%. The lowest equilibrium frequency of 7% is observed for Swiss francs with a one-month maturity, while the highest frequency of 77.1% for German marks with a three-month maturity. It is also noted that the one-month maturity provides more arbitrage opportunities than the other

[5] Six transactions out of 157 represents the percentage frequency of 3.8%. In fact, this percentage is greater than McCormick's (1979) results for arbitrage between external Eurocurrency markets but substantially lower than his results for arbitrage between treasury securities markets.

Table IV

Frequency of Market Equilibrium

The frequency of market equilibrium (disequilibrium) is computed using the 157 sets of intra-day real-time data observed during the study period from April 11 to May 13, 1988. Column four reports the number of violations of the covered interest parity conditions defined by (4) and (5):

$$F_a > S_b W \tag{4}$$

$$F_b < S_a X; \tag{5}$$

where $X = (1 + r_a)/(1 + r_b^*)$ and $W = (1 + r_b)/(1 + r_a^*)$. The last column reports the number of violations of the parity conditions for one-way arbitrage as defined by (8) and (9):

$$F_a > \max\left[S_a W, S_b W + (F_a - F_b), S_b Y, S_b Z\right] \tag{8}$$

$$F_b < \min\left[S_a X - (F_a - F_b), S_b X, S_a Y, S_a Z\right]; \tag{9}$$

where $Y = (1 + r_a)/(1 + r_a^*)$ and $Z = (1 + r_b)/(1 + r_b^*)$. The percentage frequency is shown in brackets.

		Covered Interest Arbitrage		One-Way Arbitrage	
Currency	Maturity	Frequency of Equilibrium	Frequency of Disequilibrium	Frequency of Equilibrium	Frequency of Disequilibrium
British pound	1-Month	157 [100.0%]	0 [0.0%]	68 [43.3%]	89 [56.7%]
	2-Month	157 [100.0%]	0 [0.0%]	86 [54.8%]	71 [45.2%]
	3-Month	157 [100.0%]	0 [0.0%]	94 [59.9%]	63 [40.1%]
	6-Month	151 [96.2%]	6 [3.8%]	86 [54.8%]	71 [45.2%]
	12-Month	152 [96.8%]	5 [3.2%]	43 [27.4%]	114 [72.6%]
German mark	1-Month	157 [100.0%]	0 [0.0%]	51 [32.5%]	106 [67.5%]
	2-Month	157 [100.0%]	0 [0.0%]	78 [49.7%]	79 [50.3%]
	3-Month	157 [100.0%]	0 [0.0%]	121 [77.1%]	36 [22.9%]
	6-Month	155 [98.7%]	2 [1.3%]	89 [56.7%]	68 [43.3%]
	12-Month	157 [100.0%]	0 [0.0%]	86 [54.8%]	71 [45.2%]
Japanese yen	1-Month	157 [100.0%]	0 [0.0%]	12 [7.6%]	145 [92.4%]
	2-Month	154 [98.1%]	3 [1.9%]	23 [14.6%]	134 [85.4%]
	3-Month	154 [98.1%]	3 [1.9%]	33 [21.0%]	124 [79.0%]
	6-Month	152 [96.8%]	5 [3.2%]	24 [15.3%]	133 [84.7%]
	12-Month	157 [100.0%]	0 [0.0%]	100 [63.7%]	57 [36.3%]
Swiss franc	1-Month	157 [100.0%]	0 [0.0%]	11 [7.0%]	146 [93.0%]
	2-Month	157 [100.0%]	0 [0.0%]	43 [27.4%]	114 [72.6%]
	3-Month	157 [100.0%]	0 [0.0%]	79 [50.3%]	78 [49.7%]
	6-Month	157 [100.0%]	0 [0.0%]	83 [52.9%]	74 [47.1%]
	12-Month	155 [98.7%]	2 [1.3%]	59 [37.6%]	98 [62.4%]

four maturities examined during the study period. Of the four foreign currencies examined, Japanese yen provided the largest number of arbitrage opportunities during the study period, while German marks provided the fewest. Of the five maturities examined for Japanese yen, the 12-month maturity is the only one with a simultaneous equilibrium frequency of over 50%. In contrast, only two maturities of one and two months show a less-than-50% equilibrium frequency for German marks.

D. Arbitrage Profits

Arbitrage profitability is presented in Table V. The reported profits are expressed in U.S. cents per unit of foreign currency except Japanese yen. The reported figures for the Japanese yen are in hundredths of a cent. Profits for differing maturities are annualized for ease of comparison.

Covered arbitrage profits are reported in the third column (with mean rates of return in parentheses below the profits) along with the minimum and maximum profits observed. Note that arbitrage profits are not reported for some maturities. For example, no profits are measured for British pound sterling with one-, two-, and three-month maturities because the number of violations of the interest parity conditions was zero for all three maturities as shown in Table IV. However, covered interest profitability is reported only for those maturities with a positive number of disequilibrium frequency. On six out of 157 sets of transactions, equilibrium conditions (4) and (5) were violated for British pound sterling with the six-month maturity as reported in Table IV. For these six sets of arbitrage opportunities, we estimated profits using (6) and (7), selecting whichever was larger. The estimated profits are 0.099 U.S. cents per one unit of British pound. This amount represents a mean return of 0.053%.[6] All reported profits under covered interest arbitrage are not significant except for the British pound sterling with a six-month maturity.

One-way arbitrage profits are reported in the last three columns. For example, there was market disequilibrium for British pound sterling with a one-month maturity in 89 out of 157 sets of possible transactions. Given the 89 sets of one-way arbitrage opportunities, we estimated profits using (10) and (11), selecting the largest of eight profit measures from eight alternative one-way arbitrage routes available. The arbitrage route with the largest profits represents the least-cost alternative. Profits averaged over the 89 sets of one-way arbitrage opportunities amount to 0.129 U.S. cents per one unit of British pound. The reported profits (cost savings) are significant at the 0.01 level. These profits may be translated into a mean return of 0.069%. Likewise, we computed profits for each currency with different maturities given one-way arbitrage opportunities identified. The profits computed for the four currencies are all significant at the 0.01 level across different maturities. During the study period, on the basis of percentage return, the Japanese yen provided the highest mean rates of return of the four currencies studied, ranging from 0.043% for a 12-month maturity to 0.207% for a one-month maturity. The next highest returns were provided by the Swiss francs. The percentage profits for the Swiss francs ranged from 0.079% for a 12-month maturity to 0.198% for a one-month maturity. German marks provided the lowest returns.

[6] To estimate the mean rate of return on British pound sterling, we used \$1.8762, which is the average midpoint quotation between the bid and asked prices observed during the study period. Likewise, we used the average midpoint quotations of \$0.5971, \$0.0080, and \$0.7201 to estimate the mean rates of return on German marks, Japanese yen, and Swiss francs, respectively.

Table V

Arbitrage Profitability

The reported profits are expressed in U.S. cents per unit of foreign currency except for the Japanese yen for which they are in hundredths of a cent. Profits for differing maturities are annualized for ease of comparison. Mean rates of return are reported in brackets below the profits. ** denotes that the estimated profits are statistically significant at the 0.01 level, while * denotes that they are significant at the 0.05 level.

		Covered Arbitrage Profits			One-Way Arbitrage Profits		
Currency	Maturity	Mean	Minimum	Maximum	Mean	Minimum	Maximum
British pound	1-Month	–	–	–	0.129** [0.069%]	0.006	0.449
	2-Month	–	–	–	0.092** [0.049%]	0.001	0.380
	3-Month	–	–	–	0.094** [0.050%]	0.005	0.459
	6-Month	0.099* [0.053%]	0.010	0.145	0.110** [0.059%]	0.001	0.372
	12-Month	0.072 [0.038%]	0.013	0.177	0.100** [0.053%]	0.001	0.395
German mark	1-Month	–	–	–	0.071** [0.119%]	0.000	0.262
	2-Month	–	–	–	0.028** [0.047%]	0.000	0.076
	3-Month	–	–	–	0.029** [0.049%]	0.000	0.107
	6-Month	0.004 [0.007%]	0.000	0.007	0.023** [0.039%]	0.000	0.082
	12-Month	–	–	–	0.022** [0.037%]	0.001	0.071
Japanese yen	1-Month	–	–	–	0.166** [0.207%]	0.007	0.347
	2-Month	0.033 [0.042%]	0.012	0.064	0.120** [0.150%]	0.000	0.331
	3-Month	0.038 [0.048%]	0.011	0.064	0.070** [0.087%]	0.000	0.215
	6-Month	0.014 [0.018%]	0.004	0.044	0.056** [0.070%]	0.001	0.175
	12-Month	–	–	–	0.034** [0.043%]	0.000	0.134
Swiss franc	1-Month	–	–	–	0.143** [0.198%]	0.003	0.417
	2-Month	–	–	–	0.110** [0.153%]	0.001	0.481
	3-Month	–	–	–	0.045** [0.062%]	0.001	0.181
	6-Month	–	–	–	0.062** [0.086%]	0.004	0.169
	12-Month	0.007 [0.010%]	0.002	0.011	0.057** [0.079%]	0.000	0.187

While the results illustrate the relative mgnitude of one-way arbitrage profits, they should be interpreted with caution. In reality, the actual returns might be lower than those reported because of: (a) the arbitrageurs' inability to always identify the least-cost arbitrage route; and (b) time delays in executing trades. Additionally, some quotations on Reuters screen may not be valid for actual transactions because they may be "for indications only." It should be useful to examine the possibility of exploiting the apparent arbitrage opportunities in the presence of non-negligible cost savings from one-way arbitrage. This question is examined in the following section.

E. Persistance of One-Way Arbitrage Opportunities

In practice, arbitrageurs may require time to process market data and they face the risk that market prices may move against them during this period. To reflect this possibility, Frenkel and Levich (1975, 1977) have introduced a simple trading rule under which arbitrageurs receive a profit signal at time t and execute their transactions at time $t + 1$ (at the prices prevailing at time $(t + 1)$. Frenkel and Levich suggest that data on consecutive transactions would be ideal to test this trading rule. In our opinion, our data on the 157 sets of potential arbitrage transactions provide an ideal setting for the test even though they do not represent truly consecutive transactions. The minimum and maximum lengths of time between the receipt of the profit signal and the execution of arbitrage transactions are 12 and 43 minutes, respectively, with an average length of 35 minutes as reported earlier. We introduce three lags in transactions to test the Frenkel and Levich trading rule, i.e., $t + n$ where $n = 1$, 3, and 5, corresponding to an average of 35 minutes, 105 minutes, and 175 minutes.

Table VI summarizes the results of applying this trading rule whenever the markets are in disequilibrium from the one-way arbitrageurs' standpoint. If arbitrageurs were able to transact in quoted prices at time t, there would be 106 arbitrage opportunities out of 157 for German marks with a one-month maturity. When transactions are executed at $t + 1$, $t + 3$, and $t + 5$, the number of these opportunities declines to 92, 83, and 79, respectively. For all four currencies of differing maturities, the frequency of market disequilibrium as well as the percentage frequency consistently show a declining trend. This result is consistent with the empirical evidence documented by Frenkel and Levich (1975, 1977), suggesting that lags between observing a profit opportunity and executing the transactions reduce the number of profit opportunities.

In general, the magnitude of arbitrage profits also declines as the lagged transactions are introduced even though it does not decline as fast as the number of arbitrage opportunities. However, it is noted that the profits either decline very slowly or show little change. In some unusual cases such as British pound sterling with a one-month maturity and German marks with a three-month maturity, the profits even increase with the lagged transactions. The results are in direct contrast to those reported by Frenkel

Table VI

Lags in Transactions: Arbitrage Frequency and Profits

This table reports the one-way arbitrage profits for the trading rule under which arbitrageurs receive a profit signal at time t and execute their transactions at time $t + n$. Top figures are the frequency of market disequilibrium with the percentage frequency in brackets and bottom figures represent arbitrage profits. Profits [losses] are expressed in U.S. cents per unit of foreign currency with the exception of the Japanese yen which are expressed in hundredths of a cent. **denotes that the estimated profits are statistically significant at the 0.01 level.

		Lags in Transactions			
Currency	Maturity	t	$t+1$	$t+3$	$t+5$
British pound	1-Month	89 [56.7%] 0.129**	81 [51.9%] 0.133**	74 [48.1%] 0.136**	68 [44.7%] 0.145**
	2-Month	71 [45.2%] 0.092**	68 [43.6%] 0.090**	67 [43.5%] 0.091**	67 [44.1%] 0.091**
	3-Month	63 [40.1%] 0.094**	59 [37.8%] 0.083**	56 [36.4%] 0.089**	54 [35.5%] 0.092**
	6-Month	71 [45.2%] 0.110**	59 [37.8%] 0.101**	56 [36.3%] 0.107**	55 [36.2%] 0.107**
	12-Month	114 [72.6%] 0.100**	111 [71.1%] 0.096**	110 [71.4%] 0.099**	107 [70.4%] 0.097**
German mark	1-Month	106 [67.5%] 0.071**	92 [59.0%] 0.074**	83 [53.9%] 0.069**	79 [52.0%] 0.066**
	2-Month	79 [50.3%] 0.028**	74 [47.4%] 0.028**	73 [47.4%] 0.026**	66 [43.4%] 0.027**
	3-Month	36 [22.9%] 0.029**	34 [21.8%] 0.029**	29 [18.8%] 0.031**	25 [16.4%] 0.034**
	6-Month	68 [43.3%] 0.023**	49 [31.4%] 0.024**	45 [29.2%] 0.023**	42 [27.6%] 0.023**
	12-Month	71 [45.2%] 0.022**	59 [37.8%] 0.022**	49 [31.8%] 0.021**	38 [25.0%] 0.024**
Japanese yen	1-Month	145 [92.4%] 0.166**	143 [91.7%] 0.167**	138 [89.6%] 0.167**	134 [88.2%] 0.164**
	2-Month	134 [85.4%] 0.120**	134 [85.9%] 0.120**	134 [87.0%] 0.120**	133 [87.5%] 0.121**
	3-Month	124 [79.0%] 0.070**	122 [78.2%] 0.069**	123 [79.9%] 0.069**	123 [80.9%] 0.069**
	6-Month	133 [84.7%] 0.056**	125 [79.6%] 0.056**	123 [79.9%] 0.054**	121 [79.6%] 0.053**
	12-Month	57 [36.3%] 0.034**	45 [29.0%] 0.035**	41 [26.6%] 0.034**	34 [22.4%] 0.035**
Swiss franc	1-Month	146 [93.0%] 0.143**	139 [89.1%] 0.143**	129 [83.8%] 0.143**	122 [80.3%] 0.145**
	2-Month	114 [72.6%] 0.110**	106 [67.9%] 0.111**	101 [65.6%] 0.102**	98 [64.5%] 0.092**
	3-Month	78 [49.7%] 0.045**	70 [44.9%] 0.042**	60 [39.0%] 0.042**	54 [35.5%] 0.039**
	6-Month	74 [47.1%] 0.062**	68 [43.6%] 0.061**	58 [37.7%] 0.053**	48 [31.6%] 0.048**
	12-Month	98 [62.4%] 0.057**	88 [56.4%] 0.058**	74 [48.1%] 0.060**	71 [46.7%] 0.056**

and Levich who showed that some unexploited profit opportunities prove to be illusionary. Unfortunately, direct comparison is impossible between this study's results and those of Frenkel and Levich because of different sample periods, weekly versus intra-day observations, different methods of estimating transaction costs, etc.

The results indicate that arbitrageurs fail to search systematically for the least-cost arbitrage method. This conclusion supports the recent findings of Woodward (1988). He reports that many of the observed deviations of actual forward prices from the interest parity prices do not fall within the neutral band defined by one-way arbitrage: the reported percentage of deviations explained by arbitrage transaction costs ranges from 22.2% for British pound sterling to 53.6% for Japanese yen.[7]

The reported results should be interpreted with caution for at least the following two reasons. First, the results may be peculiar to our study period, April 11 to May 13, 1988, due to some notable announcements, including: (a) the U.S. trade deficit figures for February; (b) the U.S. GNP growth rate for the first quarter; and (c) an increase in the U.S. prime rate.[8] Second, the nature of our data may explain the apparent persistence of one-way arbitrage profits. Since the quotations used in our study represent the "best prices" from numerous banks, it may be that the banks quoting at time t are not necessarily the same banks quoting at $t + n$. This has two effects: (a) it raises uncertainty about which banks to call for execution of the transactions; and (b) it is not possible for an arbitrageur to capture the cost savings from a one-way arbitrage transaction because he may not be able to transact with all of the banks.[9] One may argue that the reported arbitrage profits may not be large enough to compensate for search costs and brokerage fees, when applicable. For example, Woodward (1988, p. 651) suggests that search costs may be negligible for relatively large-size transactions under covered interest arbitrage, but they are likely to be non-negligible for one-way arbitrageurs dealing with small-size transactions. Although Woodward's suggestion makes sense for covered interest arbitrage, his argument does not necessarily hold for one-way arbitrage. A substantial portion of search costs represent sunk cost because one-way arbitrage entails transactions that were to occur any-

[7] Woodward (1988) does not use simultaneously observed data. Additionally, he assumes that: (a) $t_s = t_f$; and (b) FC futures prices = FC forward prices.

[8] Although the announcements made during the study period are not extraordinary, an unanticipated portion of the announced figures might have affected both foreign exchange and Eurocurrency markets. Shown below are examples of the important announcements:

(a) *April 15* The U.S. trade deficit widened from $12.44 billion in January to $13.83 billion in February.
(b) *April 16–17* Central banks of Japan, Germany, and Switzerland intervened in foreign exchange markets to keep U.S. dollars from declining.
(c) *April 27* The U.S. GNP grew during the first quarter of 1988 at an annual rate of 2.30% which was below expectations.
(d) *April 30* The U.K. trading figures for March turned out to be better than expected.
(e) *May 12* The U.S. prime rate was increased from 8.50 percent to 9%.

[9] We would like to thank Richard Levich, the referee, for his discussion of these points.

way. Normally, arbitrageurs do not pay brokerage fees for interbank transactions, but they frequently rely on foreign exchange brokers to cover their large open positions and, as a result, pay brokerage fees. However, in the absence of information about brokerage fees, it is difficult to conclude that profit opportunities would disappear as these fees are taken into account.

III. Conclusion

Deardorff (1979) and two follow-up studies by Callier (1981) and Bahmani-Oskooee and Das (1985) have evaluated conditions for simultaneous equilibrium on spot and forward exchange markets as well as on the domestic and foreign securities markets. Due to their combined effort, the term "one-way arbitrage" found a unique position in studies of the interest parity theorem. This paper represents the first empirical attempt to examine the frequency of simultaneous equilibrium on the four markets using real-time quotations drawn from Eurocurrency and interbank foreign exchange markets during the morning trading hours of New York. Profit opportunities have been examined from the standpoint of not only one-way but also covered interest arbitrageurs.

The findings of this study indicate that: (a) the markets are efficient in the sense that profit opportunities from traditional covered interest arbitrage are rarely available; (b) the frequency of attaining market equilibrium is surprisingly low, thus opening the door for one-way arbitrage; and (c) profits from one-way arbitrage persist, thus indicating the failure of one-way arbitrageurs in searching for the least-cost arbitrage routes. The last two findings are interesting but puzzling. In interpreting the results, several factors must be taken into account. First, New York's morning trading hours represent a "good time" of the day for an empirical examination since the New York and London markets are both open, providing more depth to foreign exchange markets. At this time of the day, one expects that there should be enough order flow to remove one-way arbitrage profits. Second, the results may be peculiar to our study period since some important announcements might have affected foreign exchange and Eurocurrency markets. However, the study period was relatively "tranquil" except for several days surrounding the announcements cited in footnote 8. Third, the nature of our data may in part explain the apparent one-way arbitrage profits. Since the Reuters quotations used in our study represent the "best prices" from numerous banks, it may be that the banks quoting at t are not always the same banks quoting at $t + n$ and arbitrageurs are not able to consistently identify these prices. Additionally, some quotes may be "for indications only." Thus, actual transactions may not be conducted at the quoted prices.

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