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The international transmission of information in Eurodollar futures markets: a continuously trading market hypothesis

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This paper studies the transmission of information in three Eurodollar futures markets, the IMM, SIMEX and LIFFE. The results show that relevant information is revealed during the trading hours of the IMM and LIFFE, but not the SIMEX. The interest rates of the three markets are cointegrated with a single common stochastic trend. Granger-causality runs from the market that is placed in the last trading order within 24 hours in the vector error correction model and this causal relationship is shorter than one day. An approach of variance decomposition and impulse response functions exploring the common factor in the cointegration system is employed. Analogous to the causality results, the common factor is driven by the last trading market in the 24-hour trading sequence. Specifically, each market, while it is trading, impounds all the information and rides on the common stochastic trend. The overall results suggest that these three markets can be considered one continuously trading market. (JEL G15, C32). Copyright © 1996 Elsevier Science Ltd

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Eurodollar futures are now the most actively traded short-term interest rate futures contracts. This paper investigates the international transmission mechanism in three Eurodollar futures markets in the Chicago, Singapore and London exchanges. These three markets trade almost identical Eurodollar futures and are participated by the same type of investors. Investors may regard the three Eurodollar futures markets as one combined market that trades on a 24-hour basis.[1] They buy and sell the futures in each trading market *segment* (i.e. the Chicago, Singapore and London markets) of the combined market to form the best portfolios. The paper examines the hypothesis that these markets can be considered one continuously trading market in the context of an information transmission mechanism.

A Eurodollar futures contract calls for the delivery (cash settlement) of a $1 million, 3-month, Eurodollar time deposit. Eurodollar futures were introduced in December 1981, by the IMM (International Monetary Market, a division of the Chicago Mercantile Exchange (CME)) in Chicago. Eurodollar futures provide a way that banks can hedge the interest rate risk associated with Eurodollar deposits, on which major international corporations increasingly have come to rely. Eurodollar futures (hereafter, ED, the ticker symbol) started trading in London, LIFFE (London International Financial Futures Exchange), and Singapore, SIMEX (Singapore International Monetary Exchange), in September 1982 and September 1984, respectively, and therefore can be traded on a global, 24-hour, basis. In Chicago time, SIMEX is open from 7:30 p.m. to 4:20 a.m., the LIFFE is open from 2:30 a.m. to 10:00 a.m., and the IMM is open from 7:20 a.m. to 2:00 p.m. Figure 1 depicts each trading period, and Figure 2 describes three possible orderings of the trading sequence within 24 hours. The importance of the latter is evinced in Sections IV and V.

A better understanding of the transmission mechanism, more specifically, the continuously trading market mechanism, may provide investors with more efficient strategies for hedging or speculating interest rate risk associated with

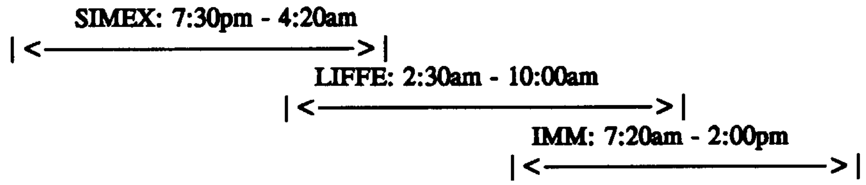
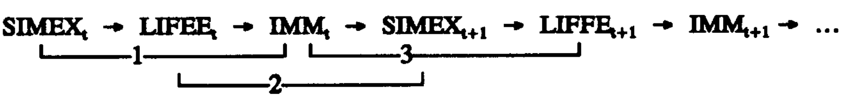


FIGURE 1. Eurodollar futures tradings hours (Chicago time).



Sequence 1: $\text{SIMEX}_t \rightarrow \text{LIFFE}_t \rightarrow \text{IMM}_t$
Sequence 2: $\text{LIFFE}_t \rightarrow \text{IMM}_t \rightarrow \text{SIMEX}_{t+1}$
Sequence 3: $\text{IMM}_t \rightarrow \text{SIMEX}_{t+1} \rightarrow \text{LIFFE}_{t+1}$

FIGURE 2. Three trading sequences with 24 hours.

Eurodollar deposits. For example, having listened to news about US inflation after the trading hours of the London markets, a British banker expects US interest rates to go up and, consequently, is worried that higher US rates will drive up his Eurodollar deposit costs. Instead of waiting for the opening of the LIFFE, he may hedge his interest rate exposure by selling Eurodollar futures during the trading hours of the SIMEX or IMM, assuming that the three Eurodollar futures markets can be considered one continuously trading market. In another context, a US treasurer analyzes his financial statements to evaluate what impact higher interest rates will have on his corporation's financial situations. Although the IMM is open at that moment, he needs several more hours to determine his hedging or speculating strategies. He does not have to rush for decisions before the Chicago market closes on that day. Instead, he can simply make the decisions during the trading hours of the next trading segment, i.e. Singapore or London segments, of the combined market.

The 1990 annual trading volume of ED traded at the IMM was 34.7 million contracts, and was about 10 times that traded on the SIMEX and 20 times that traded on the LIFFE. It is worth noting that while the trading volumes at the IMM and SIMEX were increasing during the period examined, that at the LIFFE, which bridges the gap between the trading hours of the IMM and SIMEX, was decreasing. The decreasing trading volume at the LIFFE may indicate that Eurodollar futures contracts traded there are different in some way from those traded at the other two exchanges. Inevitably, the mutual offset arrangement between the IMM and SIMEX possibly makes the contracts more flexible and less costly than those traded at the LIFFE.[2] Particularly, transaction costs incurred by the offset settlement between the IMM and SIMEX are lower than those between the LIFFE and IMM (or LIFFE and SIMEX). Examining the market structures (e.g. transaction costs and trading mechanism) of each futures market is an interesting topic, but this seems to be beyond the scope of the paper. Nevertheless, results of the paper can show whether the LIFFE still plays an equally important role as the IMM and SIMEX in the context of information transmission, though its trading volume is much smaller than the IMM and SIMEX.

Comparing the trading and non-trading time variances, the IMM and LIFFE markets are found to be more volatile when they are trading. In contrast, the Singapore market is more volatile when it is closed. These results are consistent with the fact that relevant information is revealed more during the trading hours of the IMM and LIFFE markets than those of the SIMEX market. Moreover, the magnitude of the non-trading time variance per hour of the SIMEX is similar to the size of the trading time variances per hour of the IMM and LIFFE. This result suggests that the three markets are driven by the same kind of information. Yields implied in the three markets are shown to be cointegrated with a single stochastic trend. However, none of the markets Granger-cause the others on a daily basis. Instead, causality runs from the last trading market in the 24-hour trading sequence but this causal relationship is shorter than one day. The impulse responses and the fractions of forecast error variances in each market attributed to the common stochastic trend are computed. Employing an approach that explores this common factor and allowing for the non-synchronous trading problem among markets, the paper shows that the common factor is simply driven by the last trading market in the 24-hour trading sequence. These results provide evidence that the markets are efficient on a daily basis: the responses of all markets to an innovation to the common factor are fully settled within a day. More importantly, the overall results support the notion that these three markets can be considered one continuously trading market.

The following section discusses the data and presents the summary statistics. Section II examines the trading and non-trading time variances of yield changes. Section III analyzes the transmission mechanism among markets by employing cointegration methodology. The causality relationship is studied in Section IV. Using the results in Section III and identifying the common stochastic trend, Section V investigates the variance decomposition and impulse response functions. The last section concludes the paper.

I. Data and summary statistics

Daily open and close index prices for the period after the October 1987 stock market crash—January 4, 1988 to February 22, 1994 (1585 observations)—are obtained from Commodity Systems, Inc. (CSI). Several studies report that this crash changed the structure of international movements between financial

TABLE 1. Sample statistics of yield changes (close_t–close_{t-1})

	ΔIMM	ΔSIMEX	ΔLIFFE
Mean	−0.0025 (0.185)	−0.0024 (0.219)	−0.0024 (0.206)
Median	0.00	0.00	0.00
Standard Deviation (σ)	0.074	0.077	0.077
Skewness	−0.30 (< 0.001)	−0.54 (< 0.001)	−0.40 (< 0.001)
Excess Kurtosis	11.9 (< 0.001)	13.1 (< 0.001)	11.57 (< 0.001)
Ljung–Box Q-Stat, Q(12)	25.8 (0.015)	26.9 (0.008)	18.0 (0.117)
Diebold Adjusted-Q-Stat, Q*(12)	18.0 (0.116)	16.9 (0.150)	11.5 (0.485)
LM ARCH(4) test	12.3 (0.015)	14.0 (0.007)	36.4 (< 0.001)
Correlation Coefficients			
ΔIMM		0.36	0.73
ΔSIMEX			0.58

Asymptotic p-values are contained in parentheses.

markets (see e.g. Malliaris and Urrutia, 1992; Arshanapalli and Doukas, 1993). When data are not available due to different trading days, the index price is assumed to stay the same as the previous trading day.[3]

The implied add-on yield, 100 – index price, is derived from the contract with the nearest delivery month until the first trading day of the delivery month, when it is rolled to the next nearest-to-deliver contract. Hereafter, for simplicity, IMM, SIMEX and LIFFE are used to represent the corresponding Eurodollar futures interest rates, and results are presented in this order, which is in the descending order of trading volume.

Table 1 summarizes the descriptive statistics of yield changes. Comparing the close-to-close variance, skewness and kurtosis, it shows that they give similar results—all of the yield changes exhibit moderately negative skewness, and are strongly 'heavy-tailed' (with respect to the normal distribution) and the variances are almost the same. The last result implies that the markets incorporate information at the same speed, assuming that variances are directly related to information flow (Ross, 1989). The standard Ljung-Box Q-statistics show that ΔIMM and ΔSIMEX are autocorrelated. Diebold (1988), however, points out that Q-statistics are upward biased in the presence of ARCH effects (Engle, 1982), which are indicated by the Lagrange multiplier ARCH tests. Using Diebold's ARCH-adjusted Q* test, all yield changes are then shown to be serially uncorrelated.[4] Together with insignificant means, the statistics suggest a martingale process with GARCH (Bollerslev, 1986) innovations in the Eurodollar futures markets. Not surprisingly, Table 1 also indicates that the yield changes of the three markets are highly correlated to each other with an average correlation coefficient of 0.56.

II. Volatility during trading and non-trading hours

Empirical studies that focus only on the trading and non-trading periods of the US security market fail to properly address the question of the effect of open markets in other countries on the time pattern of risk for those assets which are traded internationally. Hill *et al.* (1990) examine the trading and non-trading time variances of US Treasury bond and Eurodollar futures from 1986 to 1988. They find that variances of price changes differ both between trading and non-trading hours and between the trading hours of different markets. They conclude that the variance is related to the information arrival and the resulting impact of that information.

Koh and Tsui (1992) examine ED contracts for the period 1982–89. Although their results are generally consistent with Hill *et al.* (1990), they point out that ED prices are more volatile during exchange trading hours than non-trading hours on the IMM and the LIFFE, but not on the SIMEX. They suggest that, from a trading-strategy point of view, the times of greatest volatility, which are what speculators look for, take place during Chicago trading hours; and the times of lowest volatility, which are what hedgers look for, take place during Singapore trading hours.

The current study not only updates the results of Hill *et al.* (1990) and Koh and Tsui (1992) for the post-crash period, but also analyzes the results more explicitly in the context of information transmission among markets including the US Treasury bill futures and Eurodollar cash markets. Of particular importance, the paper indicates that the results comparing the non-trading time variance per hour of one market with the trading time variance per hour of other markets, which are not discussed in Hill *et al.* and Koh and Tsui, shed some light on the continuously trading market hypothesis mentioned previously. Note that, for example, the trading hours of the IMM overlap the non-trading hours of the SIMEX. Accordingly, if these two markets are driven by the same kind of information and can be considered one combined trading market, the trading time variance per hour of the IMM should be close to the non-trading time variance per hour of the SIMEX.

IIA. Empirical results[5]

Table 2 Panel A demonstrates that the trading time (open-to-close) variance per hour, σ_T^{2*}, of ΔSIMEX (0.052) is much smaller than those of ΔIMM (0.596) and ΔLIFFE (0.336). Note that σ_T^{2*} of ΔSIMEX is six times less than ΔLIFFE, though the trading volume of the former is twice higher. In contrast, in Panel B, the Singapore market gives the greatest non-trading time (close-to-open) variances per hour, σ_N^{2*}. The per hour trading and non-trading time variance rations, $\sigma_T^{2*}/\sigma_N^{2*}$, are presented in Panel C. It shows that the trading time variances are greater than the non-trading time variances in the US and London markets with the ratios of 4.17 and 1.56, respectively; but the opposite is true for the Singapore market with a ratio of 0.124.

TABLE 2. A comparison of trading time (open-to-close) variances, σ_T^2, and non-trading time (close-to-open) variance, σ_N^2

	ΔIMM	ΔSIMEX	ΔLIFFE
Panel A: Trading time variance (10^{-3})			
Total variance, σ_T^2	3.98	0.515	2.52
Variance per hour, σ_T^{2*} σ_T^2/(No. of trading hours)	0.596	0.524	0.336
Panel B: Non-trading time variances (10^{-3})			
Total variance, σ_N^2	2.48	5.96	3.57
Variance per hour, σ_N^{2*} σ_N^2/(No. of non-trading hours)	0.143	0.421	0.216
Panel C: Trading time and non-trading time variances ratio			
Total variance ratio, σ_T^2/σ_N^2	1.61	0.086	0.706
Variance per hour ratio, $\sigma_T^{2*}/\sigma_N^{2*}$	4.17	0.124	1.56

IMM: Open for 6 hrs 40 mins, closed for 17 hrs 20 mins;
SIMEX: Open for 9 hrs 50 mins, closed for 14 hrs 10 mins;
LIFFE: Open for 7 hrs 30 mins, closed for 16 hrs 30 hrs.

The results are in general consistent with Hill *et al.* (1990) and Koh and Tsui (1992). The different result of the Singapore market from the other two markets may be explained by the information hypothesis that volatility changes in response to the arrival and assimilation of public information that is not uniform across trading and non-trading hours.[6] That is, Eurodollar interest rates are driven by the economic information concerning the US and European countries that is revealed in Chicago and London times. Moreover, Fung and Leung (1993) find that the Eurodollar cash and futures markets are cointegrated and bidirectionally Granger-cause each other. These active US and European cash markets are open during the non-trading hours of the Singapore markets.

Of particular interest, the non-trading variance per hour, σ_N^{2*}, of ΔSIMEX (0.421) is fairly similar to the trading variance per hour, σ_T^{2*}, of ΔIMM (0.596) and ΔLIFFE (0.336). This result not only supports the aforementioned argument that information is revealed during the trading hours of the IMM and LIFFE, but also implies that these three markets are driven by the same kind of information. The latter conclusion suggests that the three markets are a combined and continuously trading market in the context of information flow mechanism. This hypothesis is examined more clearly in Sections IV and V.

Furthermore, two non-exclusive reasons can explain the higher trading/non-trading variance ratio of the US market over the London market. First, the trading volume at the IMM dominates that at the LIFFE. Second, the Eurodollar interest rates are closely related to the US domestic interest rate; namely, the Treasury bill. Specifically, trading the interest rate differential between Eurodollar and Treasury bill futures, the TED spread, can be a means to speculate on general economic conditions and on the soundness of banks in particular without incurring interest rate risk.[7] (See also Tse and Booth, 1995.)

III. Unit root and cointegration

Unit root tests in Table 3 indicate that IMM_t, SIMEX_t, and LIFFE_t can be characterized as I(1) processes according to the augmented Dickey–Fuller (ADF) (Dickey and Fuller, 1979, 1981) tests and the Phillips–Perron (PP) (Phillips, 1987; Phillips and Perron, 1988) tests.

Let $X_t \equiv (\text{IMM}_t \text{SIMEX}_t \text{LIFFE}_t)'$; $N =$ the number of variables in the system three in this case. If X_t is cointegrated, it can be generated by a vector error correction model (VECM):

$$\langle 1 \rangle \qquad \Delta X_t = \mu + A_1 \Delta X_{t-1} + \ldots + A_{k-1} \Delta X_{t-(k-1)} + A_k X_{t-1} + \epsilon_t,$$

where μ is a 3×1 vector of drift, A's are 3×3 matrices of parameters, and ϵ_t is a 3×1 white noise vector. The Johansen trace test statistic of the hypothesis $H_0{:}r = r_0$ against $H_1{:}r > r_0$, with r being the cointegrating rank, is

$$\langle 2 \rangle \qquad -2\ln Q = -(T - Nk) \sum_{i=r_0+1}^{N} \ln\left(1 - \hat{\lambda}_i\right),$$

TABLE 3. Augmented Dickey–Fuller and Phillips–Perron unit root tests

	IMM	SIMEX	LIFFE
ADF1	−0.200	−0.237	−0.250
ADF2	−2.264	−2.350	−2.270
PP1	−0.235	−0.239	−0.257
PP2	−2.264	−2.352	−2.276

Note: ADF and PP denote the augmented Dickey–Fuller test and the Phillips–Perron test statistics, respectively. ADF1 and PP1 are computed with a constant term; and ADF2 and PP2 are with a constant and a linear trend. The statistics are computed with 10 lags for the ADF tests and 10 non-zero autocovariances in Newey–West (1987) correction. Results are robust for 5, 20, and 30 lags—the hypothesis that a unit root in each series is not rejected. The critical values for both statistics, which are asymptotically equivalent, are available in Fuller (1976, p. 373). The 5 percent critical values are −2.86 (no trend) and −3.41 (with trend).

where $\hat{\lambda}_i$'s are the $N - r_0$ smallest squared canonical correlations of X_{t-1} with respect to ΔX_t corrected for lagged differences and T is the sample size actually used for estimation. Following the correction suggested by Reinsel and Ahn (1992), $(T - Nk)$ instead of T is used in equation ⟨2⟩ (and equations ⟨3⟩ and ⟨5⟩ below). The Johansen maximum eigenvalue ($\lambda_{\max}$) test statistic of the hypothesis $H_0{:}r = r_0$ against $H_1{:}r = r_0 + 1$ is

$$\langle 3 \rangle \qquad \lambda_{\max} = -(T - Nk)\ln\left(1 - \hat{\lambda}_{r_0+1}\right),$$

where $\hat{\lambda}_{r_0+1}$ is the $(r_0 + 1)$th greatest squared canonical correlation.

Table 4 Panel A shows that the lag lengths k in the VECM ⟨1⟩ chosen by the Akaike and Schwarz information criteria (AIC and SIC) are 4 and 2, respectively. Reimers (1991) finds that the SIC does well in selecting k. However, since the role of the lagged differences of X_t in the VECM is to whiten the error ϵ_t, it is not certain that the SIC will select $k = 2$ (i.e. one lag of ΔX_t in the VECM ⟨1⟩) so that ϵ_t is white. Hence residual diagnostics for the estimated model using the k selected by the SIC are examined. In the first row of Panel B the asymptotic p-values for the Ljung-Box test for up to the 20th order serial correlation in the residuals indicate that the serial correlation is insignificant for all equations in the system.[8] The results reported in this paper are qualitatively the same for $k = 4$, the lag length chosen by AIC.

The results of the Johansen (1991) cointegration tests are reported in Panel C. It demonstrates that the interest rates implied in the futures contracts of the three futures markets are cointegrated with $r = 2$, indicating that there is one common trend. To ensure that this cointegration result is not biased by a non-synchronous trading problem among the three markets, the Johansen test are conducted for the following two adjusted data sets: (1) one day lag of IMM; (2) one day lags of IMM and LIFFE. (The non-synchronous problem is discussed in the next two sections.) The cointegration results remain unchanged.

TABLE 4. VECM specification and Johansen cointegration tests

$$\Delta X_t = \mu + A_1 \Delta X_{t-1} + \ldots + A_{k-1} \Delta X_{t-(k-1)} + A_k X_{t-1} + \epsilon_t$$

Panel A: Lag selection in VECM[a]

	$k = 2$	$k = 3$	$k = 4$	$k = 5$
AIC	-18.59	-18.60	-18.61	-18.60
SIC	-18.53	-18.50	-18.48	-18.44

Panel B: Residual diagnostic[b]

	IMM	SIMEX	LIFFE
Ljung–Box tes	0.292	0.734	0.055
Skewness test	< 0.001	< 0.001	< 0.001
Excess kurtosis test	< 0.001	< 0.001	< 0.001

Panel C: Johansen cointegration tests[c]

	Trace	Critical values at the 1% level	$\lambda_{\max}$	Critical values at the 1% level
$r = 2\ (m = 1)$	0.0606	11.65	0.0606	11.65
$r = 1\ (m = 2)$	658.5**	23.52	658.42**	19.19
$r = 0\ (m = 3)$	1457.1**	37.22	798.6**	25.75

[a] For Panel A,

$$\text{AIC} = \ln|\hat{\Sigma}_{r,N}| + 2q/T, \text{ and SIC} = \ln|\hat{\Sigma}_{t,N}| + q \ln(T)/T,$$

where $\hat{\Sigma}_{r,N}$ denotes the Johansen ML estimate of the residual covariance matrix and $q = N^2(k-1) + N + 2Nr - r^2$ is the number of freely estimated parameters of the VECM.

[b] For Panel B, p-values are reported for $k = 2$.

[c] For Panel C, $m \equiv N - r$ is the number of common trends. The critical values are obtained from Osterwald-Lenum (1992). Results reported for $k = 2$ are qualitatively the same for $k = 3$ to 5.

** significant at the 1 percent level.

IV. Granger causality among markets

To examine the directions of causation in the Granger sense among the yield change of the three markets, the following VECM is estimated:

⟨4a⟩

$$\begin{aligned}\Delta \text{IMM}_\tau = a_1 &+ \pi_{11}(\text{IMM}_{\tau-1} - \text{SIMEX}_{\tau-1}) + \pi_{12}(\text{IMM}_{\tau-1} - \text{LIFFE}_{\tau-1}) \\ &+ d_{11}\Delta \text{IMM}_{\tau-1} + d_{12}\Delta \text{SIMEX}_{\tau-1} + d_{13}\Delta \text{LIFFE}_{\tau-1} + \epsilon_{1\tau}\end{aligned}$$

⟨4b⟩

$$\begin{aligned}\Delta \text{SIMEX}_\tau = a_2 &+ \pi_{21}(\text{SIMEX}_{\tau-1} - \text{IMM}_{\tau-1}) + \pi_{22}(\text{SIMEX}_{\tau-1} - \text{LIFFE}_{\tau-1}) \\ &+ d_{21}\Delta \text{IMM}_{\tau-1} + d_{22}\Delta \text{SIMEX}_{\tau-1} + d_{23}\Delta \text{LIFFE}_{t-1} + \epsilon_{2\tau}\end{aligned}$$

⟨4c⟩

$$\begin{aligned}\Delta \text{LIFFE}_\tau = a_3 &+ \pi_{31}(\text{LIFFE}_{\tau-1} - \text{IMM}_{\tau-1}) + \pi_{32}(\text{LIFFE}_{\tau-1} - \text{SIMEX}_{\tau-1}) \\ &+ d_{31}\Delta \text{IMM}_{\tau-1} + d_{32}\Delta \text{SIMEX}_{t-1} + d_{33}\Delta \text{LIFFE}_{\tau-1} + \epsilon_{3\tau},\end{aligned}$$

where π_{ij}, $i = 1$, 2 or 3 and $j = 1$ or 2, are parameters for the two error correction terms of each equation.[9] Note that the subscript τ refers to the index of trading-market series in each of the three 24-hour trading sequences illustrated in Figure 2 instead of the calendar trading day denoted by t. That is, for Sequence 1 with the SIMEX (IMM) as the first (last) trading market within a particular 24-hour trading hour, τ is the same as t for each market. But for Sequence 2, τ corresponds to $t+1$ for the SIMEX; and for Sequence 3, τ corresponds to $t+1$ for the SIMEX and LIFFE.

The cointegrating vectors for the error correction terms are $(1 - b)'$ with $b = 1$, i.e. the interest rate differentials. These are verified by the results shown in Table 5 Panels A and B, respectively, that every two markets in a bivariate system, (IMM,SIMEX), (IMM,LIFFE) and (SIMEX,LIFFE), are cointegrated with a cointegrating vector $(1 - 1)'$. The Johansen cointegration tests used in Panel A are the same as in the previous section. The hypotheses that H_0: $b = 1$ against H_a: $b \neq 1$ in Panel B are tested following Johansen (1991), and the test statistic is given as

$$\langle 5 \rangle \qquad Q_H = (T - Nk) \sum_{i=1}^{r} \ln\left[\left(1 - \hat{\lambda}_i^*\right)/\left(1 - \hat{\lambda}_i\right)\right],$$

where $\hat{\lambda}_i^*$ and $\hat{\lambda}_i$ are the eigenvalues associated with the H_0 and H_a specifications. In these bivariate cointegration systems, $r = 1$ and Q_H is distributed asymptotically as a $\chi^2(1)$. The null hypothesis that $b = 1$ is not rejected in each case.

Results of Sequences 1, 2 and 3 are respectively presented in Panels A, B and C of Table 6. Panel A shows that the error correction terms including $\mathrm{IMM}_{\tau-1}$ in the ΔSIMEX and ΔLIFFE models (π_{21} and π_{31} in equations $\langle 4b \rangle$ and $\langle 4c \rangle$, respectively) are stongly significant at any conventional significance

TABLE 5. Johansen tests and cointegrating vectors for bivariate systems

	(IMM, SIMEX)	(IMM, LIFFE)	(SIMEX, LIFFE)
	Panel A: Johansen tests[a]		
Trace			
$r = 1\ (m = 1)$	0.06	0.07	0.06
$r = 0\ (m = 2)$	793.0**	668.4**	794.5**
$\lambda_{\max}$			
$r = 1\ (m = 1)$	0.06	0.07	0.06
$r = 0\ (m = 2)$	792.9**	668.3**	794.4**
	Panel B: Cointegrating Vectors, $(1 - b)'$		
$\hat{b}$	1.00	1.00	0.99
p-value of H_0: $\hat{b} = 1$	(0.10)	(0.49)	(0.25)

[a] The critical values are presented in Panel C of Table 4. Results reported for $k = 2$ in the VECM are qualitatively the same for $k = 3$ to 5.

** significant at the 1 percent level.

TABLE 6. Estimation of VECM

$$\Delta \mathrm{IMM}_\tau = a_1 + \pi_{11}(\mathrm{IMM}_{\tau-1} - \mathrm{SIMEX}_{\tau-1}) + \pi_{12}(\mathrm{IMM}_{\tau-1} - \mathrm{LIFFE}_{\tau-1}) + d_{11}\Delta \mathrm{IMM}_{\tau-1} + d_{12}\Delta \mathrm{SIMEX}_{\tau-1} + d_{13}\Delta \mathrm{LIFFE}_{\tau-1} + \epsilon_{1\tau}$$

$$\Delta \mathrm{SIMEX}_\tau = a_2 + \pi_{21}(\mathrm{SIMEX}_{\tau-1} - \mathrm{IMM}_{\tau-1}) + \pi_{22}(\mathrm{SIMEX}_{\tau-1} - \mathrm{LIFFE}_{\tau-1}) + d_{21}\Delta \mathrm{IMM}_{\tau-1} + d_{22}\Delta \mathrm{SIMEX}_{\tau-1} + d_{23}\Delta \mathrm{LIFFE}_{\tau-1} + \epsilon_{2\tau}$$

$$\Delta \mathrm{LIFFE}_\tau = a_3 + \pi_{31}(\mathrm{LIFFE}_{\tau-1} - \mathrm{IMM}_{\tau-1}) + \pi_{32}(\mathrm{LIFFE}_{\tau-1} - \mathrm{SIMEX}_{\tau-1}) + \mathrm{d}_{31}\Delta \mathrm{IMM}_{\tau-1} + d_{32}\Delta \mathrm{SIMEX}_{\tau-1} + d_{33}\Delta \mathrm{LIFFE}_{\tau-1} + \epsilon_{3\tau},$$

where π_{ij}, $i = 1, 2$ or 3 and $j = 1$ or 2, are the parameters for the two error correction terms of each equation.

	ΔIMM		ΔSIMEX		ΔLIFFE	
Panel A: Sequence 1 ($\mathrm{SIMEX}_t \rightarrow \mathrm{LIFFE}_t \rightarrow \mathrm{IMM}_t$)						
a_i	−0.002	(−1.03)	0.000	(0.14)	−0.004**	(−2.59)
π_{i1}	−0.007	(−0.08)	−0.799**	(−11.8)	−0.864**	(−8.29)
π_{i2}	−0.165*	(−2.06)	−0.170**	(−2.72)	−0.005	(−0.06)
d_{i1}	0.121	(1.47)	0.122**	(3.04)	0.140	(1.83)
d_{i2}	−0.030	(−0.63)	0.013	(0.82)	−0.037	(−0.70)
d_{i3}	−0.020	(−0.35)	−0.058	(−1.71)	−0.026	(−0.49)
Panel B: Sequence 2 ($\mathrm{LIFFE}_t \rightarrow \mathrm{IMM}_t \rightarrow \mathrm{SIMEX}_{t+1}$)						
a_i	−0.002	(−1.20)	−0.002	(−1.02)	−0.004**	(−3.34)
π_{i1}	−0.801**	(−8.85)	0.015	(0.16)	−0.154	(−1.90)
π_{i2}	−0.052	(−0.78)	−0.142	(−1.72)	−0.828**	(−11.5)
d_{i1}	0.010	(0.13)	0.059	(0.73)	0.023	(0.35)
d_{i2}	0.059	(0.76)	0.062	(0.76)	0.070	(1.06)
d_{i3}	−0.007	(−0.17)	−0.039	(−0.80)	−0.017	(−0.43)
Panel C: Sequence 3 ($\mathrm{IMM}_t \rightarrow \mathrm{SIMEX}_{t+1} \rightarrow \mathrm{LIFFE}_{t+1}$)						
a_i	0.002*	(2.32)	0.002	(1.49)	−0.002	(−1.12)
π_{i1}	−0.021	(−0.31)	0.144*	(2.21)	0.141	(1.62)
π_{i2}	−0.987**	(−12.2)	−1.079**	(−11.8)	−0.020	(−0.21)
d_{i1}	−0.003	(−0.12)	0.015	(0.51)	−0.010	(−0.29)
d_{i2}	−0.005	(−0.19)	−0.008	(−0.23)	−0.036	(−0.62)
d_{i3}	−0.046	(−1.16)	−0.100	(−1.82)	−0.071	(−1.14)

t-statistics calculated by White (1980) are in parentheses.
*significant at the 5 percent level. **significant at the 1 percent level.

levels, but both error correction terms in the ΔIMM model (π_{11} and π_{12} in equation ⟨4a⟩) are insignificant with *t*-statistics = −0.08 and −2.06, respectively. Moreover, the coefficient of the lag ΔIMM in the ΔSIMEX model (d_{21}) is significant, while the coefficients of the lag ΔSIMEX and ΔLIFFE in the ΔIMM model (d_{12} and d_{13}, respectively) are insignificant. The overall results indicate a unidirectional causality—the IMM Granger-causes SIMEX and LIFFE. Nevertheless, these results are shown to be induced by the problem of non-synchronous trading simply by examining the results of Sequences 2 and 3 as follows.

Note that the IMM is the last trading market in Sequence 1. When the SIMEX is the last trading market as in Sequence 2, Panel B demonstrates that the error correction terms including $\text{SIMEX}_{\tau-1}$ in the ΔIMM and ΔLIFFE models (π_{11} and π_{32} in equations ⟨4a⟩ and ⟨4c⟩, respectively) are highly significant. However, none of the terms (both the error correction terms and cross- and own-market lagged yield changes) in the ΔSIMEX model are significant. Similarly, Panel C showing Sequence 3 with the LIFFE as the last trading market indicates that the error correction terms including $\text{LIFFE}_{\tau-1}$ are highly significant in the ΔIMM and ΔSIMEX models, and all terms in the ΔLIFFE model are insignificant.

In sum, none of the markets Granger-cause the others on a daily basis. Causality possibly runs from the last trading market in the sequence but this causal relationship is shorter than one day. These results again support the previously discussed continuous market hypothesis that each trading *segment* of the combined market (i.e. each trading market in the sequence) incorporates the information that will affect the next trading segment sequentially within a day.

V. Variance decomposition and impulse response analysis

Since Sims (1980), variance decomposition and impulse response analysis based on VAR models have been widely used to examine how much movement in one market can be explained by innovations in different markets and how rapidly the price movements in one market are transmitted to other markets. (See Eun and Shim, 1989; and Jeon and Furstenberg, 1990, for the international transmission of stock market movements, and Booth *et al.*, 1993, for stock index futures markets.)

In this paper, variance decomposition and impulse reponse analysis are examined by exploring the single common stochastic trend within the cointegration system. The cumulative impulse functions of ED interest rates and the fractions of the forecast error variances attributed to the shocks to the common factor are computed. Note that the shock is innovation to the common factor, instead of each individual series as the usual way done in the conventional VAR literature. Since a common factor naturally exists among markets for an identical product, this approach may provide a more in-depth analysis of international transmission mechanism for ED markets.

V.A. Identification of the common stochastic trend

Since there is only one common factor in $X_t \equiv (\text{IMM}_t\ \text{SIMEX}_t\ \text{LIFFE}_t)'$, X_t may be considered to be generated from the following common factor representation

$$\langle 6\rangle \qquad \mathrm{X}_t = \mathrm{X}_0 + \mu t + Jf_{1t} - \tilde{X}_t,$$

where $X_0 = (\text{IMM}_0\ \text{SIMEX}_0\ \text{LIFFE}_0)'$, μ is a 3×1 vector of drift, $J = (1\ 1\ 1)'$, f_{1t} is a scalar I(1) common stochastic trend, and $\tilde{X}_t$ is a 3×1 vector of I(0) transitory components with zero long-run multiplier.

Let $\omega_{1t} = \Delta f_{1t}$. The response of X_t to the shock ω_{1t}, i.e. $\partial X_t/\partial\omega_{1,t-h}$ for $h = 0, 1, 2, \ldots$, is computed as follows. From equation ⟨6⟩,

$$\langle 7\rangle \qquad \lim_{h\to\infty} \partial X_t/\partial\omega_{1,t-h} = J,$$

as $f_{1t} = \Delta^{-1}\omega_{1t} = \Sigma_{(i=0\text{ to }\infty)}\omega_{1,t-i}$. Thus the long-run multiplier of ω_{1t} is unity. Since ω_{1t} is the innovation process to the common permanent component, it may be considered the permanent shock. The fractions of forecast error variances of ΔX_t due to the permanent shock which yields information about the relative importance of the common stochastic trend in each series are also estimated.

The VECM ⟨1⟩ is estimated and transformed to a vector moving average (VMA) model

$$\langle 8\rangle \qquad \Delta X_t = \mu + C(B)\epsilon_t,$$

where $C(B)$ is a 3×3 matrix polynomial in B. Since there is only one common factor in X_t, $C(1)$ is of rank 1 and there exists a 3×1 vector D such that $C(1) = JD'$.

To identity the common factor f_{1t}, some identifying restrictions are imposed. The following procedures are similar to King *et al.* (1991). Rewrite equation ⟨8⟩ as

$$\langle 9\rangle \qquad \Delta X_t = \mu + \Gamma(B)\omega_t,$$

where $\Gamma(B) = C(B)\Gamma_0$, Γ_0^{-1} exists, and $\omega_t = (\omega_{1t}\ \omega_{2t}\ \omega_{3t})' = \Gamma_0^{-1}\epsilon_t$. As $\Gamma(1) = C(1)\Gamma_0 = JD'\Gamma_0$ is of rank one, Γ_0 may be chosen so that

$$\langle 10\rangle \qquad \Gamma(1) = \begin{pmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}.$$

Thus, ω_{1t} is the persistent shock with the long-run multiplier J. Moreover, ω_{2t} and ω_{3t} are transitory shocks with the long-run multiplier equal to 0, though they have non-zero impact in the short-run. (See also the Appendix.) Since $C(1)\epsilon_t = \Gamma(1)\omega_t$, it can be shown that $\omega_{1t} = D'\epsilon_t$. The impulse responses associated with ω_{1t} are given by the first column of $\Gamma(B)$.

V.B. Empirical results

As previously mentioned, three possible orderings of trading sequence exist. Consider Sequence 1 in Figure 2, i.e. the IMM is the last trading market within a 24-hour interval. The percentage of the forecast error variances of ΔX_t attributed to innovations ω_{1t} in the common stochastic trend is presented in Table 7 Panel A. In computing these, the permanent shock is assumed to be uncorrelated with the transitory shocks, i.e. $E\omega_{1t}\omega_{2t} = E\omega_{1t}\omega_{3t} = 0$. The point estimates suggest that at the end of a 50-day horizon, 90 percent of the forecast error variance in ΔIMM, 52 percent in ΔSIMEX, and 66 percent in ΔLIFFE can be attributed to innovations in the common stochastic trend, ω_{1t}. Moreover, even at the end of a 1-day horizon, the innovations in the common factor explain 99 percent of the fluctuations in ΔIMM, but only 33 percent and 80 percent in ΔSIMEX and ΔLIFFE, respectively.

TABLE 7. Forecast error variance decomposition

Horizon	ΔIMM_t	$\Delta SIMEX_t$	$\Delta LIFFE_t$
	Panel A: Sequence 1 ($SIMEX_t \rightarrow LIFFE_t \rightarrow IMM_t$)		
1	0.9938	0.3259	0.7973
2	0.9902	0.5189	0.6632
3	0.9897	0.5184	0.6621
4	0.9897	0.5183	0.6621
5	0.9897	0.5183	0.6621
10	0.9897	0.5183	0.6621
50	0.9897	0.5183	0.6621
	Panel B: Sequence 2 ($LIFFE_t \rightarrow IMM_t \rightarrow SIMEX_{t+1}$)		
1	0.6739	0.9950	0.4984
2	0.5878	0.9907	0.5208
3	0.5872	0.9905	0.5191
4	0.5870	0.9905	0.5190
5	0.5870	0.9905	0.5190
10	0.5870	0.9905	0.5190
50	0.5870	0.9905	0.5190
	Panel C: Sequence 3 ($IMM_t \rightarrow SIMEX_{t+1} \rightarrow LIFFE_{t+1}$)		
1	0.2031	0.5284	0.9965
2	0.6185	0.4824	0.9919
3	0.6174	0.4823	0.9916
4	0.6173	0.4826	0.9916
5	0.6173	0.4826	0.9916
10	0.6173	0.4826	0.9916
50	0.6173	0.4826	0.9916

Note: Entries are the fractions of forecast error variance to forecast ΔX_t that are due to shocks to the common factor.

The impulse responses of X_t to an innovation to the common stochastic trend are reported in Table 8. In response to a shock generated at day 0 (the same day), all markets fully respond in day 1 (next day). Specifically, at day 0, the Chicago market responds 96 percent, the Singapore market 35 percent, and the London market 78 percent. Note that the long-run multiplier of the permanent shock is unity as shown in equation ⟨7⟩, i.e.

$$\langle 11 \rangle \quad \lim_{h \rightarrow \infty} \partial x_{it} / \partial \omega_{1,t-h} = 1, \qquad \text{where } x_{it} = IMM_t, SIMEX_t \text{ or } LIFFE_t.$$

These results may imply that the common factor is mainly derived from the Chicago market, and the Chicago market drives the information transmission mechanism among markets, assuming that the common factor impounds all the long-run information.

Nevertheless, the non-synchronous trading problem discussed in Section IV is found to carry over to this section. In fact, the results in Panels B and C of Table 8, which follow Sequences 2 and 3 respectively in Figure 2, show that whichever is the last trading market in the 24-hour trading sequence is the

TABLE 8. Responses to innovation to the common factor

h	IMM_t	SIMEX_t	LIFFE_t
	Panel A: Sequence 1 ($\text{SIMEX}_t \rightarrow \text{LIFFE}_t \rightarrow \text{IMM}_t$)		
0	0.9615	0.3478	0.7761
1	1.0173	0.9877	1.0357
2	1.0028	1.0196	0.9970
3	1.0001	1.0026	0.9997
4	1.0002	0.9987	1.0000
5	1.0004	0.9994	1.0001
10	1.0003	0.9996	1.0000
50	1.0003	0.9996	1.0000
	Panel B: Sequence 2 ($\text{LIFFE}_t \rightarrow \text{IMM}_t \rightarrow \text{SIMEX}_{t+1}$)		
0	0.6501	0.9864	0.4666
1	0.9723	0.9991	1.0015
2	0.9964	0.9986	0.9945
3	0.9990	0.9996	0.9992
4	1.0002	0.9996	0.9999
5	1.0003	0.9996	1.0000
10	1.0003	0.9996	1.0001
50	1.0003	0.9996	1.0001
	Panel C: Sequence 3 ($\text{IMM}_t \rightarrow \text{SIMEX}_{t+1} \rightarrow \text{LIFFE}_{t+1}$)		
0	0.2276	0.5600	1.0104
1	0.9571	0.9913	1.0171
2	1.0127	1.0307	1.0001
3	1.0021	1.0029	0.9990
4	0.9996	0.9986	0.9999
5	1.0002	0.9994	1.0001
10	1.0003	0.9996	1.0001
50	1.0003	0.9996	1.0001

Note: Entries are the impulse responses of x_{it} to shocks to the common stochastic trend, $\partial x_{it}/\partial \omega_{1,t-h}$, where ω_{1t} is the permanent shock.

'dominant' market driving the common factor. That is, when Singapore is the last trading market as in Sequence 2, the Singapore market responds 99 percent at day 0, but 65 percent and 47 percent for the Chicago and London markets, respectively. Similarly, when London is the last trading market as in Sequence 3, it responds 100 percent at day 0, but 23 percent and 56 percent for the Chicago and Singapore markets respectively. Analogous results of forecast error variance decomposition presented in Table 7 are also obtained. That is, if the last trading market in the 24-hour trading sequence is Singapore in Panel B or London in Panel C of Table VII, at the end of a 1-day or 50-day horizon, 99 percent of its forecast error variance can be explained by ω_{1t}.

In short, none of the three markets can be described as the main source of information flow. Instead, each trading market is informationally efficient, on a daily basis, and embodies all the information that will affect the other two non-trading markets when they open several hours later. More importantly, these results reinforce the continuously trading market hypothesis. In particular, the markets are driven by the same information which flows around each trading market (or each trading market segment of the combined market).[10] It is worth mentioning that these results are not inconsistent with the results obtained in Section II. Section II merely indicates that information is revealed during the non-trading hours of the Singapore market; here the results demonstrate that the Singapore market, and the other two markets, incorporate all the information when there is information flow.

VI. Conclusions

This paper investigates the international transmission of information in Eurodollar futures markets. It analyzes the hypothesis that the three Eurodollar futures markets can be considered one combined market in the context of information transmission mechanism. Comparing the volatility of interest rate changes in each market during trading and non-trading hours, it is found that, in contrast to the other two markets, the non-trading time variance of the Singapore market is higher than the trading time variance. These results are consistent with the fact that Eurodollar interest rates are driven by the economic news concerning the US and European countries. Moreover, the non-trading time variance per hour of the SIMEX is close to the trading time variance per hour of the IMM and LIFFE. This result suggests that the three markets are driven by the same kind of information. Yields implied in the three markets are shown to be cointegrated with a single stochastic trend. However, none of the markets Granger-cause the others on a daily basis. Instead, causality runs from the last trading market in the 24-hour trading sequence but this causal relationship is shorter than one day. In particular, the markets are driven by the same information mechanism which flows around each trading market (or each trading market segment of the combined market).

An approach exploring the common factor in the cointegration system is employed to examine the variance decomposition and impulse response functions of interest rates. All markets respond to the shock generated from the common factor rapidly. Comparing the results with different orderings of the trading sequence, each trading market is evinced to impound all the information that will influence the two non-trading markets when the open later in the day. Each market in turn drives the common factor and information flow. In this way, none of the three markets can be considered the main source of information flow, and each trading market is extremely informationally efficient. In conclusion, the overall results do not reject the hypothesis that these three Eurodollar futures markets can be considered one continuously trading market.

Appendix

The common factor representation in equation ⟨6⟩ can also be represented by the structural

VMA ⟨9⟩. Using a expansion $\Gamma(B) = \Gamma(1) + \Delta\Gamma^*(B)$, equation ⟨9⟩ can be rewritten as

$$\Delta X_t = \mu + \Gamma(1)\omega_t + \Delta\Gamma^*(B)\omega_t, \tag{9a}$$

and thus equation ⟨6⟩ as

$$X_t = X_0 + \mu t + \Gamma(1) f_t + \tilde{X}_t, \tag{6a}$$

where $f_t = \Delta^{-1}\omega_t$ is a 3 × 1 vector with the common factor f_{1t} as the first element, and $\tilde{X}_t = \Gamma^*(B)\omega_t$. Equation ⟨9a⟩ will be the same as the common factor representation ⟨6⟩ if equation ⟨10⟩ holds. Each element of $\tilde{X}_t$ is idiosyncratic to each market if $\Gamma^*(B)$ is not a diagonal matrix.

Since $\tilde{X}_t = \Gamma^*(B)\omega_t$ is a linear combination of present and past shocks of ω_t, $\tilde{X}_t$ depends on the permanent shock ω_t. But the long-run multiplier of the permanent shock on the transitory components $\tilde{X}_t$ is zero, i.e. $\lim_{h\to\infty} \partial\tilde{X}_t/\partial\omega_{1,t-h} = 0$. If the second and the third columns of $\Gamma^*(B)$ are not zero, the transitory shocks ω_{2t} and ω_{3t} have non-zero impact on $\tilde{X}_t$ in the short run while they have zero effects in the long run.

Notes

1. Eurodollar futures contracts traded in Tokyo (TIFFE), which are introduced in October 1990, are not considered in the paper because of the insufficient trading history.
2. The mutual offset arrangement means that Eurodollar futures positions established at the IMM may be offset at the SIMEX with the same contract, and vice versa. In contrast, if an investor has bought (sold) a contract at the LIFFE and wants to offset his position at the SIMEX or IMM, he needs to sell (buy) a new contract at the SIMEX or IMM.
3. The results are virtually the same if these 91 different trading days are deleted.
4. Lo and MacKinlay's (1988) variance ratio test, which is heteroskedasticity-consistent (including ARCH), also gives no evidence of serial correlation.
5. For simplicity, the results reported do not consider the effects of weekends and holidays. Results are qualitatively the same when these effects are taken into account, and are available upon request.
6. If yield change volatility is mainly derived from noise trading, the volatility is related to trading activities when the markets are open. However, if volatility is caused by the release of public information, volatilities during trading and non-trading hours are only related to the information flow instead of trading activities. See French and Roll (1986), Ross (1989), and Barclay *et al.* (1990) for more information.
7. In general, events that jeopardize the soundness of the banking system tend to widen the spread. Slentz (1987) analyzes the incident of Continental Illinois Bank in May 1984 and its effects on the TED spread.
8. Moderate skewness and strong excess kurtosis are found in all equations. As the Johansen tests are constructed under the Gaussian assumption, Cheung and Lai (1993) examine the bias in the size of the Johansen tests due to non-normal innovations, including leptokurtic and non-symmetric ones. They find that both the *trace* and $\lambda_{\max}$ test statistics are reasonably robust. Furthermore, Lee and Tse (in press) report that both the size and power performance of the Johansen tests are robust to the GARCH innovations.
9. If only one error correction term that incorporates all the three markets is included in the ECM, collinearity may be induced because the system contains two cointegration vectors.
10. To examine whether the crisis of the exchange rate mechanism (ERM) of the European Monetary System (EMS) in September 1992 may bias the results or induce any structural changes, the same analysis is conducted for the pre-crisis period, January 4, 1988 to August 31, 1992, and the post-crisis period, October 1, 1992 to February 22, 1994. Results of both of the subperiods (available upon request) are qualitatively the same as the whole period.

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