NONPARAMETRIC TESTING OF THE HIGH-FREQUENCY EFFICIENCY OF THE 1997 ASIAN FOREIGN EXCHANGE MARKETS

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Abstract. For the first time, non-parametric statistical tests, originally developed by Sherry (1992) to test the efficiency of information processing in nervous systems, are used to ascertain if the Asian FX rates followed random walks. The stationarity and serial independence of the price changes are tested on minute-by-minute data for nine currencies for the period from January 1, 1997 to December 30, 1997. Tested were the Thai baht, Indonesian rupiah, Malaysian ringgit, Philippines peso, Singapore dollar, Taiwan dollar and the Hong Kong dollar, with the Japanese Yen and German Deutschmark as benchmarks (The U.S. Dollar is the base currency). The efficiency of these FX markets before and after the onset of the Asian currency turmoil (i.e., January 1 - June 30, 1997 and July 1 - December 30, 1997) are compared. The Thai baht, Malaysian ringgit, Indonesian rupiah and Singapore dollar exhibited non-stationary behavior during the entire year, and gave evidence of a trading regime break, while the Phillipines peso, Taiwan dollar, Yen and Deutschmark remained stationary (The Hong Kong dollar was pegged). However, each half-year regime showed stationarity by itself, indicating stable and nonchaotic trading regimes for all currencies, despite the high volatilities, except the Malaysian ringgit, which exhibited non-stationarity in the second half of 1997. The Thai baht traded nonstationarily in the first half of 1997, but stationarily in the second half, while the Taiwan dollar reversed that trading pattern. Regarding Sherry s four serial independence tests of differential spectrum, relative price changes, temporal trading windows of at least 20 minutes long and price change category transitions: none of the currencies exhibited complete independence. Thus no Asian currency market - including the Yen - exhibited complete efficiency in 1997 regarding both stationarity and independence, in particular when compared with the highly efficient Deutschmark. But, remarkably, the Phillippines peso remained as efficient as the Japanese Yen throughout 1997.

1. INTRODUCTION

In the second half of 1997 the foreign exchange markets in Asia were severely shocked. Sharp volatility increases were observed and questions were raised about the markets efficiency. A financial market is considered efficient when the prices

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I thank my students Ng Guan Mean, Shih Yueh and Tan Seow Min for their tireless effort to gather and store the voluminous high-frequency data on hard disk in our on-campus Simulated Trading Room and to produce all the computations and graphs. This paper is to be presented at the 11th Annual Australasian Finance & Banking Conference, 15 - 16 December 1998, in Sydney, Australia.

of its traded instruments fully reflect all available information. Special attention is drawn to the requirements of an active trading scenario with high turnover and rapid adjustment of the prices.

Anecdotal evidence suggested that some markets continued to operate efficiently, but that others broke down, leading to abnormal trading losses. This paper quantifies, for the first time by non-parametric tests, the informational efficiency of the Asian FX markets before and after the July 2, 1997 devaluation of the Thai baht, using high frequency - minute-to-minute- observations from January 1 1997 - December 31, 1997. Such tests are necessary to come to a truly informed judgment about the efficiency of the Asian FX markets.

The tests show that none of the Asian FX markets broke down in 1997, despite the currency turmoil. They continued to trade consistently, with the exception of, perhaps, Malaysia for a short period of time. But also, none of the Asian FX markets were truly efficient and there were remarkable differences in the quality of the various markets.

Much of the early empirical research on market efficiency revolved around the random walk hypothesis. On March 29, 1900, a Ph.D. thesis by Louis Bachelier entitled Theory of Speculation was accepted by the Faculty of Sciences of the Academy of Paris, the Sorbonne, which eventually laid the foundation for the random walk hypothesis of market efficiency.

Bachelier s paper contended that (stock) market price movements are haphazard [1] and that it is not possible to employ any method to predict such market price movements in the future.[5][2] This implies that there can be no supra-normal profits made, using technical analysis of past price behavior. However, as the early work had not much theoretical content behind it, Fama organized and presented the empirical evidence in terms of a fair game model.[7] In contrast to the random walk model which deals with price movements over time, the fair game model assumes that the price of an instrument at any point in time would reflect all available information at that point in time.[3] Thus, an efficient market is represented by the following model:

$$E(\varepsilon_{j,t+1}|\Phi_t) = E(P_{j,t+1} - P_{j,t}) = E(P_{j,t+1}) - P_{j,t} = 0, \tag{1.1}$$

where $\varepsilon_{j,t+1}$ = price change, i.e., the difference between actual price P at time t and the expected price at time $t+1$ for instrument j; and Φ_t = the set of information assumed to have been reflected into the price P of instrument j at time t. This simple model implies that the market does not produce excess market value for instrument j at time $t+1$ based on the information set Φ_t at time t and therefore the market pricing process represents a fair game .

The interesting question is, of course, what is in the crucial information set Φ_t? Statisticians all too often presume to know the distribution of the price changes $\varepsilon_{j,t+1}$. For example, often it is assumed that these price changes follow a normal distribution and that therefore a parametric approach can be implemented. A normal distribution can be summarized by a mean and a variance, or standard

[1]That is: with irregular movements over a fixed time interval with in finite steps taken inbetween, similar to Brownian motion in nature.

[2]Bachelier s thesis advisor was Henri Poincaré, one of the most celebrated mathematicians of all time, who lectured on Brownian motion in 1900 at the International Congress of Physics in Paris.

[3]A fair pricing game is, mathematically speaking, a martingale, since the discrete price innovations $\varepsilon_{j,t+1}$ are martingale-differences. Cf. [10], pp 32 - 40 and [12], pp. 18 - 23.

deviation. No such distributional assumptions are made in this paper. The historically observed FX rate for currency j and its observed accumulated distribution at time t is taken as the information set Φ_t.

Foreign exchange traders tend to use technical analysis of historical price movements, summarized in the form of price charts, to forecast future price trends. However, there is only a role for technical trading rules and possible supra-normal trading profits and losses, if the foreign exchange (FX) markets are less than perfectly efficient.[4] The academic literature has so far focused on testing the efficiency of markets in the developed countries.[4] But the recent currency turmoil in Asia clearly underlines the need for more such efficiency research in the emerging markets, where inadequate risk management still prevails.

1.1. **Data.** This paper sheds some light on recent Asian currency market (in-)efficiencies by focusing on relatively high frequency data for 1997. Indicative quotes of one minute intervals were collected from Dow Jones Telerate in Singapore, covering the following seven Asian currencies for a one-year period starting from 1 January 1997 and ending on 30th December 1997:

1) Hong Kong dollar, HKD (4 decimal places)
2) Indonesian rupiah, IDR (2 decimal places)
3) Malaysian ringgit, MYR (4 decimal places)
4) Philippines peso, PHP (3 decimal places)
5) Singapore dollar, SGD (4 decimal places)
6) Taiwan dollar, TWD (3 decimal places)
7) Thai baht, THB (4 decimal places)

Besides the seven Asian currencies, also included are two major anchor currencies in our analysis, namely the Japanese Yen, JPY (2 decimal places) and the German Deutschemark, DEM (4 decimal places), as developed economy benchmarks for the seven Asian emerging market currencies. The base currency is the US dollar (USD).

Since FX trading is done on a global basis, we have round-the-clock trading and the total number of available minute-by-minute observations on each series is $T = 360 \times 24 \times 60 = 518\,400$, thus $t = 1, ..., 518400$ for $j = 1, ..., 9$ Asian FX series.[5]

1.2. **Methodology.** This paper uses the non-parametric tests originally developed by Clifford J. Sherry for the study of information processing in nervous systems.[6] These tests are superior to the conventional parametric tests, since they are very intuitive and do not require the assumption of normality, or any other parametric assumption for the underlying, observations generating pricing process.[7] The only distribution tests used are Chi-square based, which simply compare observed values with theoretically expected values.

[4]For a recent example of parametric testing of the random walk hypothesis in an emerging stock market within Europe, see [11]

[5]Due to a technical disruption in our NTU on-campus Simulated Trading Room, there was an unfortunate lapse of data availability from the 25th till the 31st of October 1997, missing ve days of trading. Thus the data points from November 1st, 1997, onwards are adjoined to the previous data stream ended on October 24th 1997.

[6]According to John Sweeney, the Editor of Technical Analysis of Stocks and Commodities, Sherry did all is computations with pencil and paper.[[13], p. xi]. We had the privilege to use EXCEL spreadsheets.

[7]For a sohisticated example of parametric testing of the volatility and autocorrelation functions of the Deutschemark/US dollar exchange rate using high frequency data, see [14]

We test for the stationarity and independence of the price changes $\varepsilon_{j,t+1}$ of the selected currencies based on Fama s formulation of the random walk model, as summarized in Table 1.

TABLE 1.	RANDOM WALK TESTS
1. Stationarity	**2. Independence**
(i) Cumulative Distributions	(i) Differential Spectra
(ii) Percentile Graphs	(ii) Relative Price Change Transition Arrays
	(iii) Category Price Change Transition Arrays
	(iv) Markow Analysis of the CPCT Arrays

1.3. **Research Limitations.** Testing the random walk model is part of testing for the weak form of efficiency under the Efficient Market Hypothesis (EMH) of financial theory. This weak form of the EMH assumes that current prices reflect fully all available past information and are thus independent of future prices. However, a rejection of the random walk model does not necessarily imply a rejection of the weak form of the EMH, since other models for the weak EMH form may be possible.

In addition, this kind of scientific research on high-frequency pricing data suffers from some serious limitations imposed by the indirect character of the available observations. There are, as yet, no regular high frequency data series on *transactions* in the Asian FX markets available for researchers. Currently available is a series of indicative quotations provided by Dow Jones Telerate, and other providers such as Reuters, on their FXFX electronic screen pages. Hence, the bulk of empirical work on the intra-day FX market has used these indicative quotations for data analysis.[8] In these data, each data point actually represents a time-stamped record of the bid-and-ask quotations attributable to a source, usually a financial institution or a bank. These individual quotations are then collated into an irregularly spaced time-series by simply ordering the quotations by time of input.

Therefore, the question arises whether one can use the series of FXFX quotations as proxy series for the price, time and volume of transactions, especially when there are certain investigations for which a researcher may want transactional data rather than quotations.[3] FXFX quotations may not be a good indicators of trades. Trading and quote-making decisions are linked, but the links are complicated and poorly understood.[6] Firstly, the quotations appearing on the FXFX screens are not firm , i.e., they are not the actually transacted prices at the actual time. These quotations may, perhaps, better be viewed as non-binding advertisements from the quoting banks. A counter argument to this criticism is the *reputation effect*: although the FXFX quotations are not technically firm, they may be seen as such due to a bank being forced to maintain a good record of honoring quotations and therefore building reputation as an honest trading partner.[2] This reputation effect could possibly lead to strong incentives for banks to honor all quotations such that the discrepancies between transactional data and the quotations are eliminated.

[8] After we finished the research on this paper, in April 1998 Bruce Lehman of the University of California at San Diego brought to my attention that Martin Evans in a recent paper had studied the high frequency behavior of interbank foreign exchange markets with a newly created data set of trade transactions data, and not quote data, that provides apparently the most penetrating picture of trading activity across those markets in existence.[6]

Secondly, the quotation series may not give a clear picture of the volume of transactions. The intra-day FX market is subjected to waves of activity. Times when little happens for a matter of minutes may be followed by a 30-second period of intense activities, encompassing multiple trades and quote revisions. FX trading is actually carried out over the telephone, via brokers, or via automated broker screens.[8]. Since the FXFX quotations are not binding, in an active period, dealers are likely to be concentrating on the trades arising from the brokers, the state of transaction activity over their broker terminals, and the calls received and made over the telephone. This implies that dealers then have little time to update the FXFX quotations, so that the FXFX screens may bear little relation to the market at times when transactions most commonly occur. If FXFX quotations are comparatively less frequent during active periods, volume proxies based on these data must thus be treated with extreme caution. This could particularly be the case during the turbulent period of the currency crises in the second half of 1997.[9]

If the assumptions underlying an efficient price series are not valid, or if the return generating process is non-linear, then the use of linear models to test efficiency would not be appropriate. To cover such a possibility, we apply non-linear, non-parametric tests. Conventional methods of testing efficiency such as autocorrelation test, runs test, spectral analysis and frequency test are not capable of capturing non-linearities. The hypothesis of independence of successive price changes may erroneously be accepted, because non-linear systems, like chaotic systems, exhibit similar behavior to a random walk process. If however, the system is non-linear, the series may still be predictable.[10]

There are several reasons why non-linearities in price series may be prevalent in financial markets:[1]

Firstly, difficulties in carrying out arbitrage transactions under diverse characteristics of the market microstructure may lead to non-linearities. For instance, differing microstructures between spot markets and derivative markets may give rise to non-linear dependence. It has been shown that when price discovery takes place in futures markets and then information is carried to the spot market through the process of arbitrage, delays in transacting the spot market leg of the arbitrage reflects changes in the future prices alone, as any immediate response to the mispricing would only be partial.

Secondly, non-linearities may be examined in the light of non-linear feedback mechanisms in price movements. For example, when the price of a financial instrument gets too high, self-regulating forces usually drive the price down. If the feedback mechanism is non-linear, then the correction is seldom proportional to the amount of price deviation from the instrument s real value. Such an effect arises due to market psychology, where investors and markets over-react to bad news and under-react to good news.

Thirdly, market imperfections, such as transaction costs, may lead to non-linearities. This arises because transaction cost poses a time lag such that prices are not able to respond immediately to new information. Market players do not trade

[9]Because of their finite discontinuities, gaps and jumps, FX quotations may be parametrically analyzed by wavelets, rather than by the conventional Fourier analysis, a conjecture we currently explore at NTU.

[10]Chaotic systems can be modeled by non-linear diffusion processes, but empirical researchers have found that such models are very difficult to calibrate. Often they are approximated by linear systems.

every time new information enters the market. Instead, they trade only whenever it is economically profitable, resulting in a clustering of price changes.

Fourthly, non-linearities may also be observed when important announcements are made less often than the frequency of observations. For instance, monthly money supply announcement might cause non-linearities in minute-by-minute, hourly, daily and weekly series, but not in quarterly series.

In testing for efficiency in emerging markets, it is also important to consider the thin trading which typically describes such markets, in particular in Asia. Thin trading might lead to serial correlation and as a result, observed dependence may not necessarily imply predictability. While prices that do not follow a random walk suggest that the market is inefficient, thin trading and illiquidity actually imply that trades cannot at all be transacted at the prices shown in the data.

The remainder of this paper is organized as follows. All tests are first discussed in the form of simple recipes and then executed. The complete data set is divided into two subsets to compare the FX market efficiencies before and after the fall of the Thai baht on July 2, 1997. Section 2 graphically presents the distributional (in-)efficiencies in the various FX markets compared with those of the two main anchor currencies in the two sub-periods and includes formal Chi-square tests. This is followed by the battery of non-parametric tests for independence in Section 3. Within each section the methodology is summarized and the test results are presented. All test results are summarily tabulated in Section 4. where the main conclusions are presented. The paper concludes that the Asian FX markets continued to trade stationarily and did not break down, despite the violent Asian currency crises in the second half of 1997. However, all of these Asian FX markets were inefficient and exhibited considerable dependencies that may have led to supra-normal trading profits and losses.

2. STATIONARITY TESTS

China took over Hong Kong on July 1st, 1997 and the Thai baht was devalued on July 2nd.[11] The resulting FX trading break induced a contagion effect in all other ASEAN countries. All of a sudden a very bearish sentiment emerged towards the economic viability of Asia s emerging markets. Currencies in the region came under intense selling pressure, resulting in sharp devaluations of the Philippines peso (PHP), the Indonesian rupiah (IDR), and the Malaysian ringgit (MYR). Consequently, the usually stable Singapore dollar (SGD), which is linked by trade-weights to the surrounding Asian currencies, depreciated.

Hence, it is of interest to examine the stationarity of the Asian FX markets. There are two questions to consider. First, was there really a structural break in the middle of 1997, or did the markets exhibit the same behavior before and after the perceived breaking date? Second, if there was a structural regime shift (i.e. a non-stationarity), were the markets stationary before and after the perceived break?

A stationary time series is a data series whose statistical properties don t change over time. The trading regime remains consistent. A simple conventional parametric test for stationarity for the random walk model requires to test only for the null

[11]Only future history will tell with 20/20 hindsight if the second event was dependent on the rst.

hypothesis of constancy of the mean and variance of the first price differences:

$$H_0 : E(\varepsilon_{j,t+1}) = 0 \text{ and } Var(\varepsilon_{j,t+1}) = \text{constant} \quad (2.1)$$

However, this assumes that the statistical distributions of the FX quotations are parametrizable by these first two moments, and, effectively, that they are continuous and smooth. But this paper s non-parametric tests allow for non-parametrizability and emphasizes the broader invariance of the statistical properties of these price changes $\varepsilon_{j,t+1}$. The following methodology of [[13], pp. 12 - 20], is used to test for stationarity:

Step 1. Each data series was first divided into two equal halves (the earlier chronological half will be addressed as half 1 and the successive half as half 2).

Step 2. The data in the two halves were then separated into bins of equal interval size.

Step 3. A cumulative graph of both halves was constructed. Initially we use simple visual assessment to assess stationarity.

Step 4. Insert charts with differential spectra include data points in both halves corresponding to percentile increments of 10%, that is, we plotted the 10%, 20%, 30%, ... data value for half 2 against half 1. Using a 45^0 line to indicate equality between the two halves, we test for deviation from the 45^0 line against both halves.

Step 5. Finally, quantitative Chi-square tests were conducted on these differential spectra. To do so, the bin intervals for half 1 were obtained for cumulative percentiles of approximately 10% (i.e., we obtained the intervals for 10%, 20%, 30%, ..., 90%). These bin intervals were then used as reference bins in half 2 to nd the respective percentiles associated with each of these bin references. The difference between each percentile in the half 1 was then compared with the half 2 percentile differences using the Chi-square test.

2.1. **Analysis of Complete Data Set.** First, we investigate if there is a structural break, a regime shift and thus a non-stationarity in the complete year long data set for 1997. The cumulative distributions and percentile charts are plotted in Figures 1 - 9, followed by the Chi-square tests.

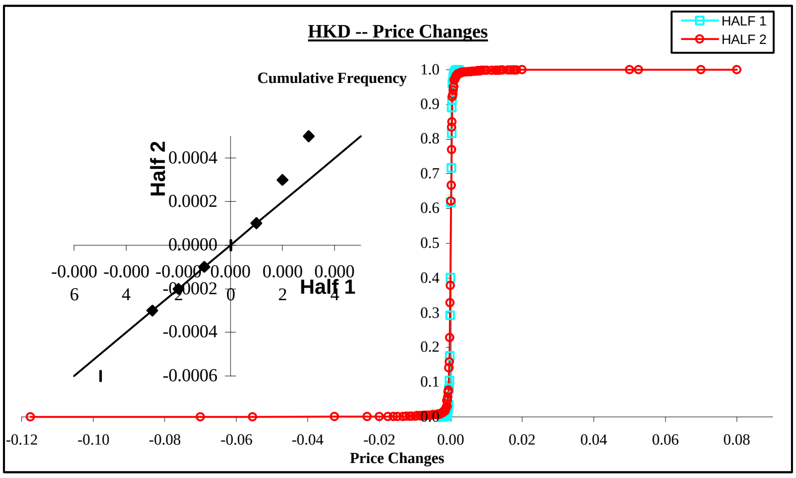

Figure 1. HKD - Price Changes, Jan-Dec 1997

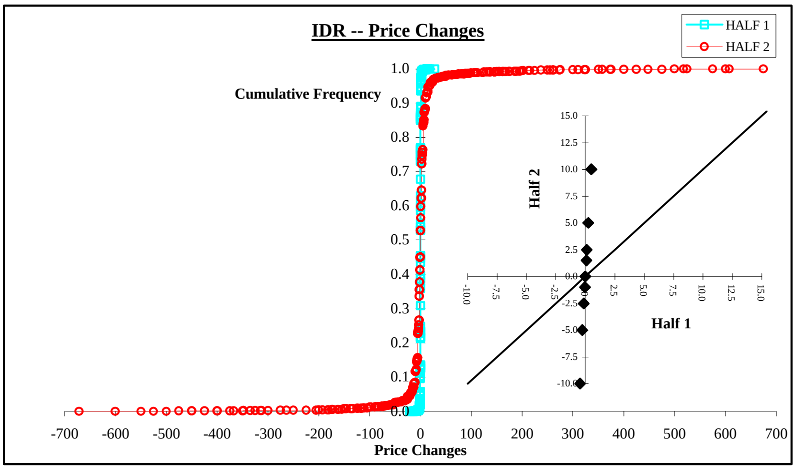

Figure 2. IDR - Price Changes, Jan-Dec 1997

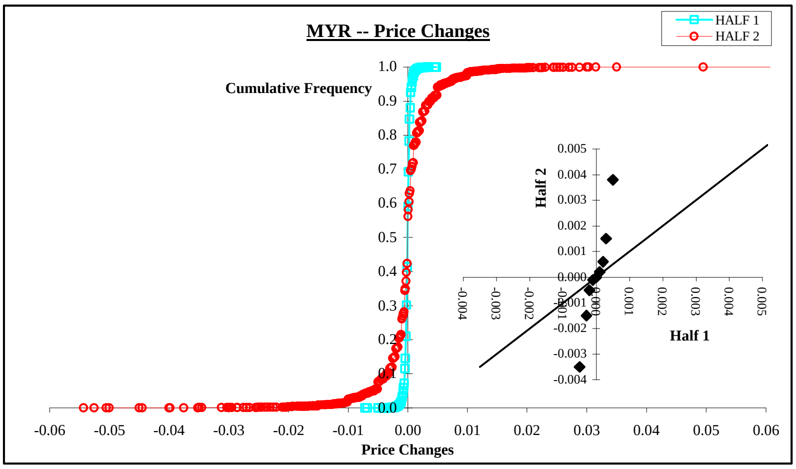

Figure 3. MYR - Price Changes, Jan-Dec 1997

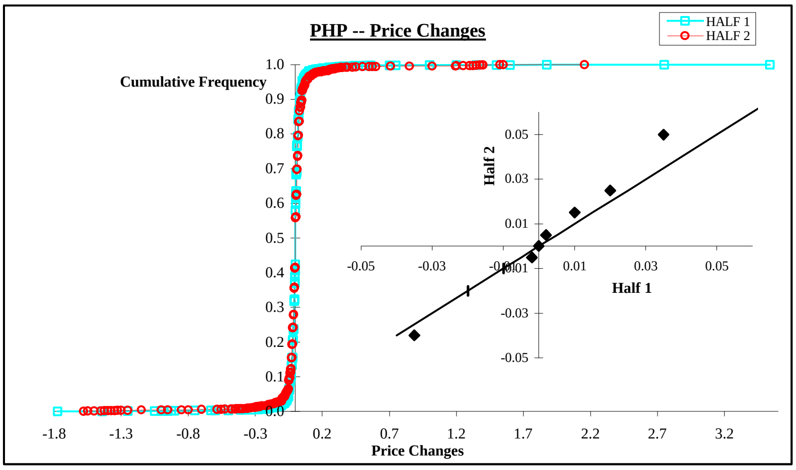

Figure 4. PHP - Price Changes, Jan-Dec 1997

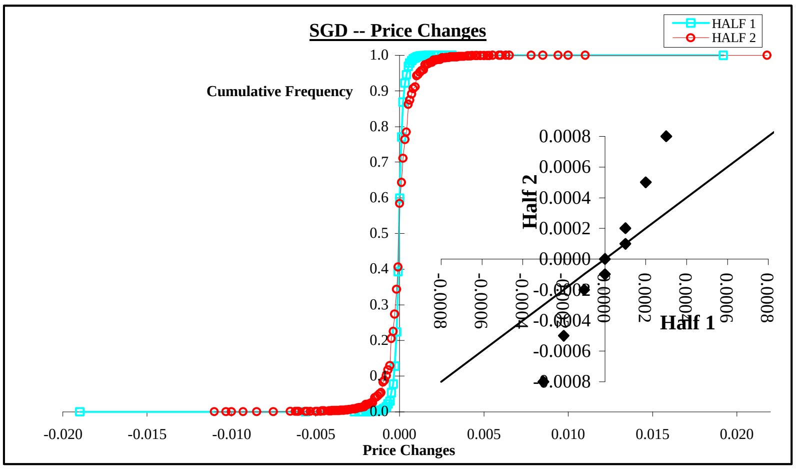

Figure 5. SGD - Price Changes, Jan-Dec 1997

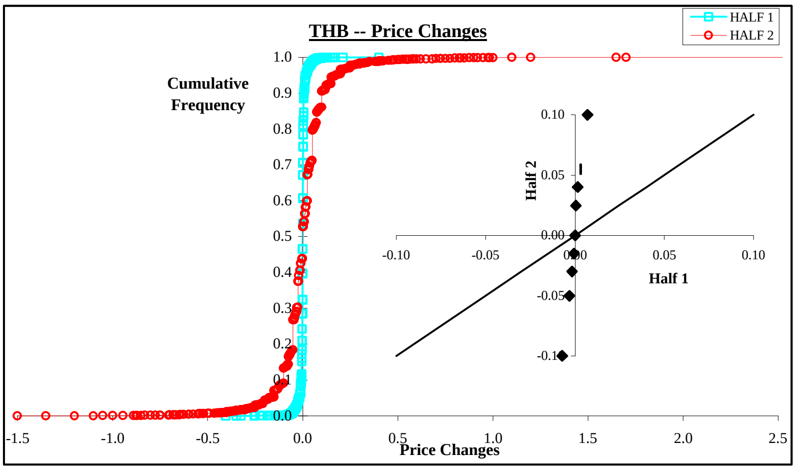

Figure 6. THB - Price Changes, Jan-Dec 1997

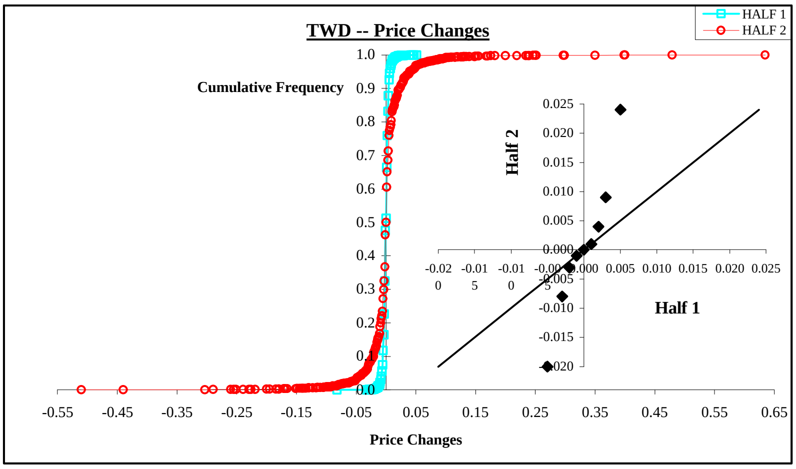

Figure 7. TWD - Price Changes, Jan-Dec 1997

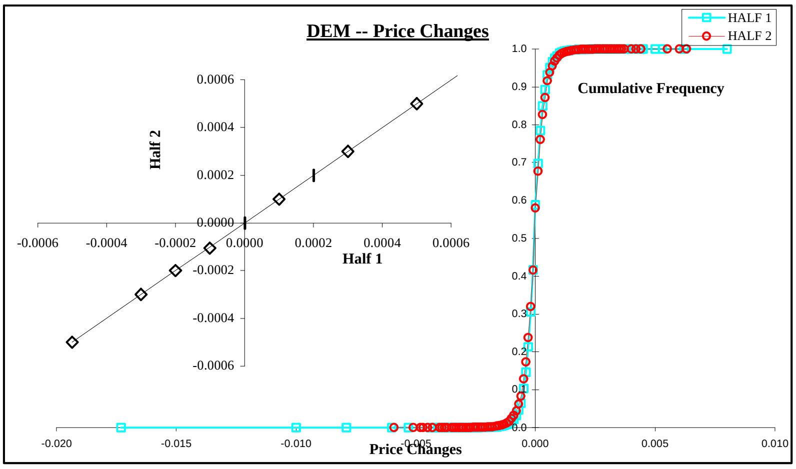

Figure 8. DEM Price Changes, Jan-Dec 1997

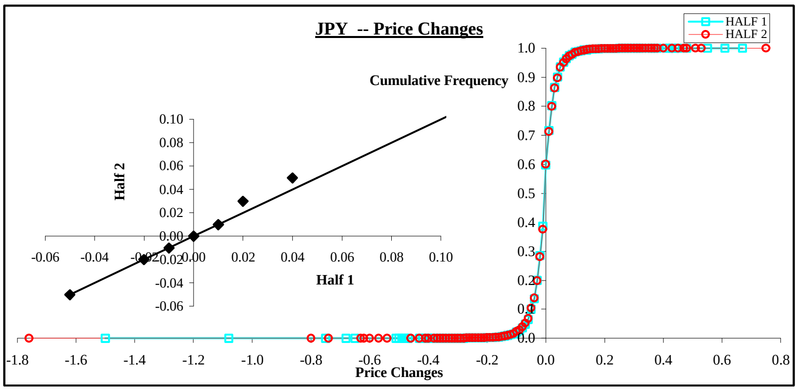

Figure 9. JPY - Price Changes, Jan-Dec 1997

2.1.1. *Cumulative Distributions and Percentile Graphs.* The insert charts in Figure 1 - 9 show that the HKD, PHP, DEM and JPY markets were overall stationary in their price changes. The price changes of the first half of the year are of about the same magnitude as those in the second half: the data points are either extremely close to, or on the 45^0 lines. This should not be surprising for the pegged HKD, but it is surprising for the PHP. It also means that the two major anchor currencies were apparently not affected by the Asian currency crisis in 1997. All the other currencies show clearly non-stationary differences.

A closer examination of the insert charts for IDR and THB shows that the data points are aligned with the y-axis in an almost vertical fashion. Besides the obvious implication that the price changes for the second half of the year are very much larger than that for the first half, it may also imply that the prices for the first half of the year were controlled, as was the case for Indonesia, which devalued its IDR only in the later half of July 1997. As for Thailand, devaluation of the THB occurred on the 2nd July 1997.

The insert chart for the MYR shows a similar pattern, since the price differences do not lie on the 45^0 line. However, it is not as vertical to the y-axis as compared to the case for the IDR. The SGD insert chart also shows a somewhat controlled regime of its price changes, as the price differences lie somewhere between the vertical and the 45^0 line. However, the SGD is not properly pegged like the HKD, as it is linked to a trade-weighted index, i.e., it exhibits passively managed oat. The TWD behavior is very similar to that of the SGD.

The DEM chart is a typical example of a perfectly efficient market as its price differences lie exactly on the 45^0 line. The JPY chart shows a very close to efficient situation, though there was apparently still some intervention in the market.

2.1.2. *Chi-square Test Results.* Table 2 shows that the Chi-square tests for the price changes of HKD, PHP, DEM and JPY are insigni cant. Thus for these four currencies, the null hypothesis of stationarity is not rejected with 99% con dence. The Chi-square result for TWD surprisingly shows it to be marginally insigni cant too, despite the fact that its chart looks similar to the SGD s. The Chi-square results for the IDR, MYR, SGD and THB con rm the conclusions obtained by visual inspection.

Currency	**Price Changes**	
	χ^2 Value	**Degree of Freedom**
HKD	6.624	6
IDR	61.437	7
MYR	32.833	6
PHP	5.378	7
SGD	15.938	5
THB	70.783	7
TWD	14.971	7
DEM	0.478	6
JPY	0.196	6

①Critical values for a confidence interval of 99% are 15.09, 16.82 and 18.48 for degrees of freedom of 5, 6 and 7 respectively.
②The shaded boxes return insignificant χ^2 results.

TABLE 2. Chi-Square Stationarity Tests - Differential Spectrum for 1997

2.2. **Before and After Analysis.**

2.2.1. *January Through June 1997.* For the structural analysis of the January to June period of 1997, the cumulative distributions and insert charts in the even numbered Figures 10-26. show that the MYR, SGD, and TWD FX markets were all stationary in the first half of 1997. The price differences for these three currencies lie exactly on the 45^0 lines.

The HKD insert chart shows it to be very efficient too, saved for some small interventions in the market. This was probably necessary to maintain the peg of HKD 7.80 to each U.S. dollar.[12] The insert chart for IDR shows it to be fairly

[12]A currency peg does NOT imply a fixed exchange rate, since it requires the active intervention by the Currency Board and allows for small fluctuations.

efficient, as the price differences lie very close to the 45^0 line. It appears that there were frequent interventions in the market to maintain the IDR at the approximate level of 2400 to each USD before July 1997. The PHP also appears to be fairly efficient in this period too, despite its relatively much thinner trading volume. The price differences for the THB lie close to the 45^0 line, but it is evident that some market interventions did occur. The benchmark currencies, the DEM and the JPY, were very efficient too, although the DEM shows an outlier in the 100th percentile point.

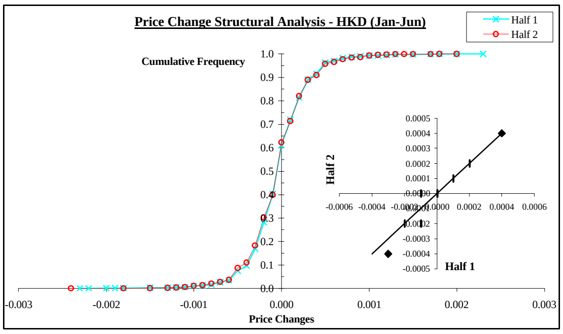

Figure 10. HKD - Price Changes, Jan-Jun 1997

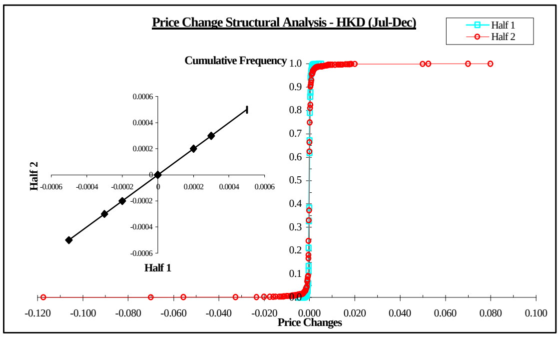

Figure 11. HKD - Price Changes, Jul-Dec 1997

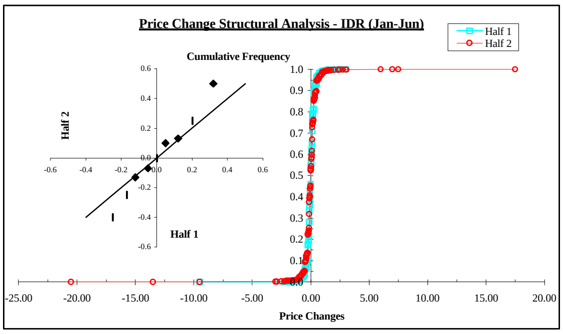

Figure 12. IDR - Price Changes, Jan-Jun 1997

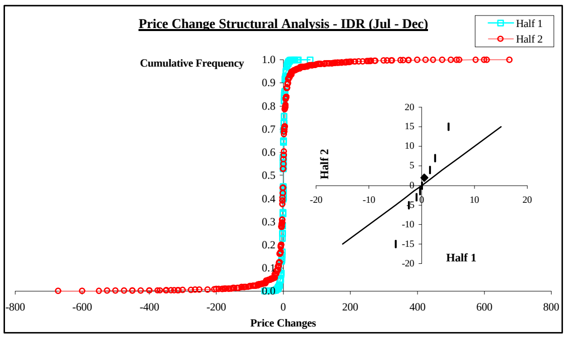

Figure 13. IDR - Price Changes, Jul-Dec 1997

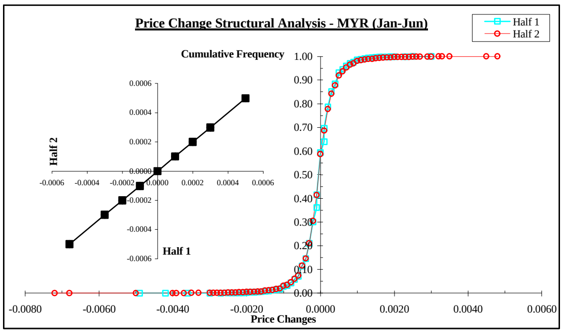

Figure 14. MYR - Price Changes, Jan-Jun 1997

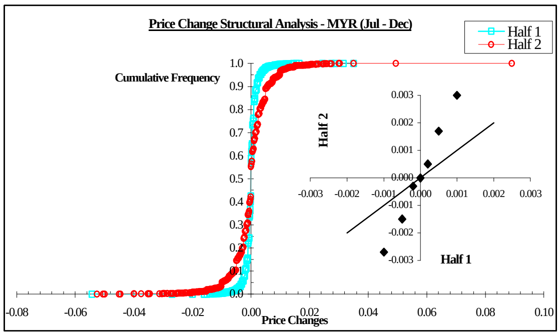

Figure 15. MYR - Price Changes, Jul-Dec 1997

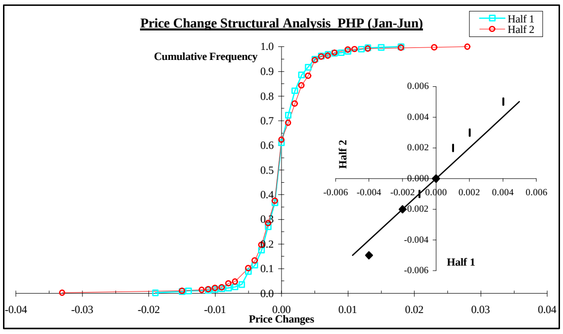

Figure 16. PHP Price Changes, Jan-Jun 1997

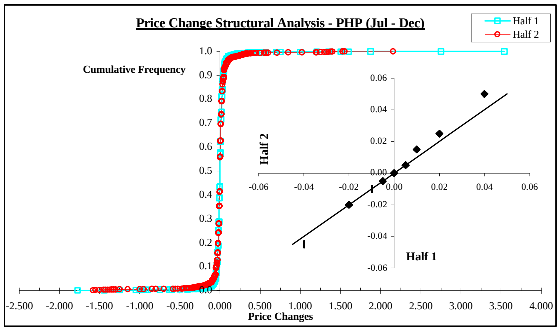

Figure 17. PHP Price Changes, Jul-Dec 1997

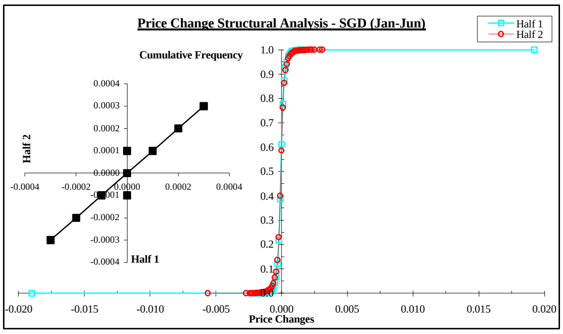

Figure 18. SGD - Price Changes, Jan-Jun 1997

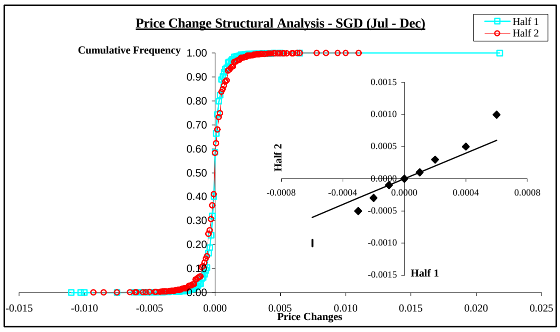

Figure 19. SGD - Price Changes, Jul-Dec 1997

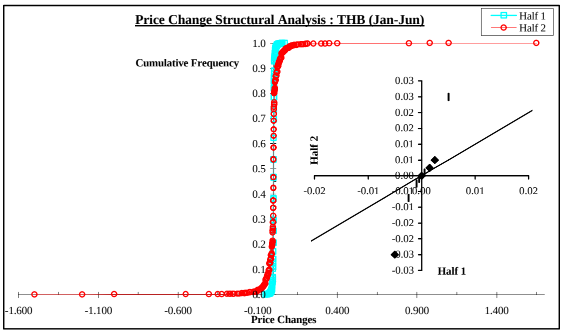

Figure 20. THB - Price Changes, Jan-Jun 1997

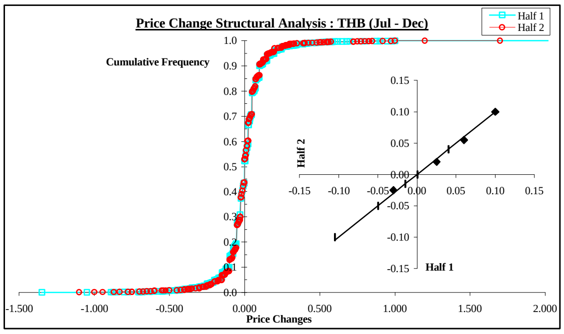

Figure 21. THB - Price Changes, Jul-Dec 1997

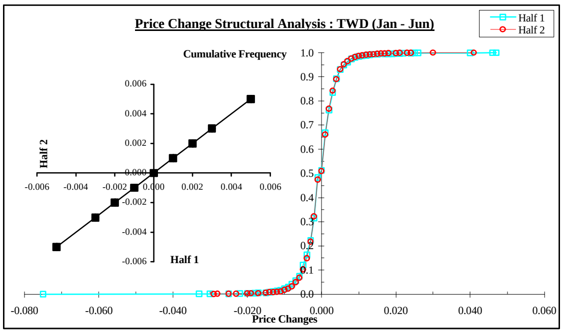

Figure 22. TWD - Price Changes, Jan-Jun 1997

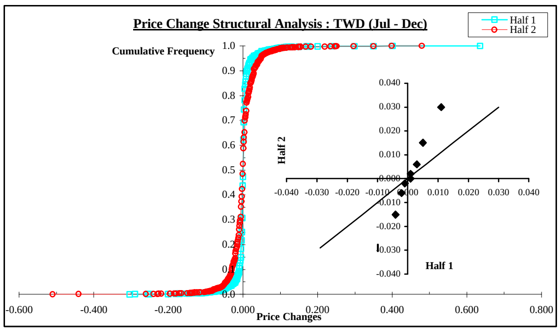

Figure 23. TWD - Price Changes, Jul-Dec 1997

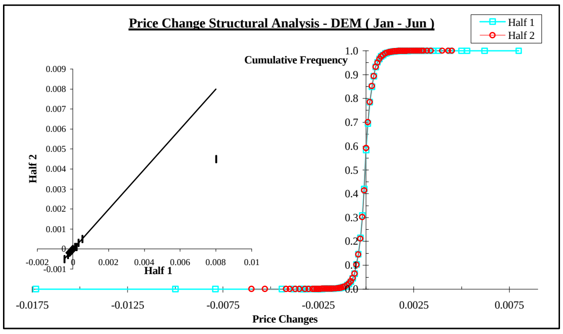

Figure 24. DEM - Price Changes, Jan-Jun 1997

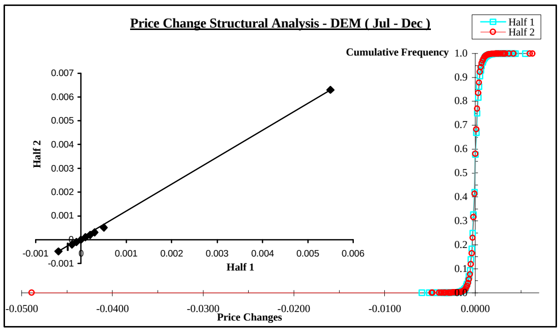

Figure 25. DEM - Price Changes, Jul-Dec 1997

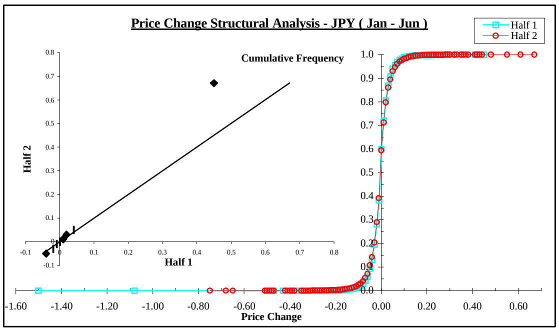

Figure 26. JPY - Price Changes, Jan-Jun 1997

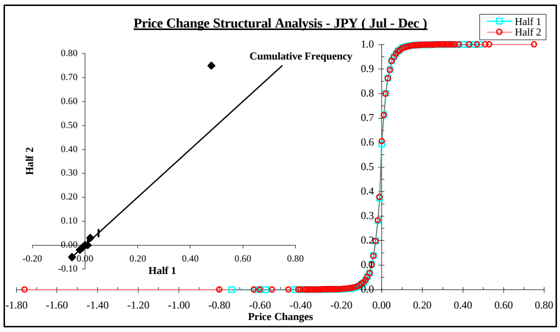

Figure 27. JPY - Price Changes, Jul-Dec 1997

2.2.2. *July Through December 1997.* The second half of 1997 shows some interesting changes in FX trading behavior and it clearly separates the sheep from the goats, i.e., the markets which remained predictably stationary and which became non-stationary and possibly chaotic, as is shown in the odd-numbered Figures 11-27. The HKD shows it to be perfectly efficient, as the price differences lie exactly on the 45^0 line. Most of the price changes fell within a bandwidth of -0.020 to 0.020, compared to the January through June period, where they mostly fell within the range of -0.002 to 0.002. This means that there was perhaps a bit greater volatility in the second half of 1997, even though the overall stationarity was not signi cantly affected.

The insert chart for the IDR shows that the price differences lie somewhat between the 45^0 line and the y-axis, though it is still comparatively closer to the 45^0 line, as we shall see when we discussed the MYR. There is a bit more market intervention here, notably by the Bank of Japan and the Monetary Authority of Singapore, both of which tried to limit the slide of the IDR in the second half of 1997. The magnitude of price changes increased dramatically. Whereas most of the price differences fell within the -5.0 to 5.0 range in the January to June 1997 period, the price differences increased 120 times to fall within a -600 to 600 range in the later half of 1997. Price changes were much more volatile. Based on the visual analysis, one is tempted to conclude that the IDR was not even stationary, and thus unpredictably inefficient, within the second half of 1997.

The MYR price differences appear to lie exactly between the 45^0 line and the y-axis. This suggests that it was not efficient, since the underlying trading rules were not stationary. This could be due to the fact that the frequent protectionist remarks made by Malaysia s policy makers sent jitters though the market, such as when short selling was curbed for a brief period in October 1997 and currency trading was deemed to be an evil (e.g. the Soros row). Anti-Jewish political remarks against international FX traders in the November period made matters only worse.

For the PHP, the magnitude of price changes also increased dramatically, as the range within which most of the price differences were found increased 150 times from a range of -0.01 to 0.01 to range of -1.5 to 1.5. Despite this, the market was fairly stationary within the second half of 1997 as the data points in the insert chart lie very close to the 45^0 line. The markets resumed normal trading, although with larger price movements, after the break. One reason could be that the Philippines President said that the way out of the currency turmoil is to embrace the markets and not to move away from it.

The SGD market was also fairly efficient. The magnitude of price changes in this period is fairly similar to the first half of 1997. The change of chairmanship at Singapore s de-facto central bank witnessed a SGD that originally depreciated along with its ASEAN neighbors , to one which saw the SGD stabilizing at less than SGD 1.7 to the U.S. dollar. But the depreciation occurred on the basis of normal, i.e., predictably stationary trading behavior.

Surprisingly, despite its sharp depreciation and larger price movements, the THB trading remained very stationary in the second half of 1997. There was no market intervention and the market sought its own course.

The TWD witnessed some market intervention and was apparently not stationary, but not signi cantly, since the Chi-square results show it to be marginally stationary. In 1997 the TWD was still able to escape with a modest depreciation of about 12.5% against the USD due to its better and healthier banking system, lighter foreign debt and the ease for rms to start and to fail.

The two benchmark currencies of the developed countries - the JPY and the DEM - remained unaffected and traded stationarily.

2.2.3. *Chi-square Test Results.* The test results in Table 3 show that the Chi-square values increased from the first half to the second half of 1997, but all tests were insigni cant with the exception of the 99% con dence test for MYR in the July - December period. This seems to to suggest that the markets remained overall stationary and that there was not much structural change, with the exception of the MYR. When we accept slightly less stringent test criteria - 95% con dence -, nonstationarity is also observed for IDR in the second period. The point is that, although the volatility increased dramatically in the second half of the year compared with the first, within each half year stationarity remained maintained. There was a structural break in early July, but the FX markets in Asia overall did not break down and continued to trade consistently!

The only currency to show non-stationarity in the second half is the MYR, which, could be due to the frequent introduction of upsetting news into the market by Malaysia s political leaders.

Currency	Jan – Jun		Jul – Dec	
	χ^2 Value	Degree of Freedom	χ^2 Value	Degree of Freedom
HKD	1.006	6	3.057	6
IDR	1.575	7	17.805	7
MYR	0.087	6	19.167	7
PHP	2.483	6	2.013	6
SGD	0.784	4	5.313	6
THB	11.059	7	0.441	7
TWD	0.701	5	16.602	7
DEM	0.154	6	0.300	6
JPY	0.143	6	0.213	6

①Critical values for a confidence interval of 99% are 13.277, 15.086, 16.812 and 18.475 for degrees of freedom of 4, 5, 6 and 7 respectively.
②The shaded boxes return insignificant χ^2 results.

TABLE 3. Chi-Square Stationarity Tests - Half-Year Differential Spectra

3. INDEPENDENCE TESTS

The independence tests attempt to determine if the price changes $\varepsilon_{j,t+1}$ are independent of one another. If these price changes are found to be (serially) dependent, we could, based on the current FX rates, predict what the near future FX rates will be. Thus technical analysis would be possible to formulate pro table trading rules, even when dealing with minute-by-minute data. When the price changes are independent, such trading rules would not produce supra-normal pro ts and the markets would be deemed efficient pricing mechanisms. Because this is such a crucial issue for the determination of the efficiency of the FX market, a battery of tests are employed, since no scienti c test is infallible. We look at the differential spectra, the relative price changes, compute category price change transition (CPTC) arrays and conduct a Markov analysis of these CPTC arrays.

3.1. **Differential Spectra.** Following again the example of [[13], pp. 86 - 91], the following recipe to form differential spectra is used to test for independence :

Step1. The price change $\varepsilon_{j,t+1}$ are allocated to pre-speci ed bins.[13]

Step 2. The positive price change bins are paired with the negative price change bins to ensure a symmetric matching of bins.

Step 3. Using the following Chi-square test based on the frequencies of the items in the bins

$$\chi^2 = \sum_{1}^{n} \frac{(\text{Observed frequency-Expected frequency})^2}{\text{Expected frequency}}, \tag{3.1}$$

the positive price changes are used as observed values and the negative price changes as the expected values. Here n is the number of bins in the histogram/2. The critical

[13]Although the choice of the bin width is arbitrary, there is a trade-off between the sensitivity and the computational effort to conduct the test. The narrrower the bin width, the higher the sensitivity and the higher the computational effort. Of course, the bin width should never be smaller than the minimal price change that may occur.

value of the test is dependent on the number of symmetrical bins used. If the price changes $\varepsilon_{j,t+1}$ are independent, the distribution of the price changes around the zero point should be symmetrical. But if this distribution is not symmetrical, the price changes are not independent.

3.1.1. *Chi-square Test Results.* Based on the Chi-square results in Table 4, all FX price changes were signi cantly dependent in 1997, except HKD, SGD and DEM. Surprisingly, even JPY exhibits signi cant dependency according to this test.

Currency	Degree of Freedom	Confidence Level(%)	Critical Value	Chi-Square*
HKD	100	99	135.8	117.378
IDR	100	99	135.8	217.493
MYR	100	99	135.8	278.071
PHP	100	99	135.8	150.967
SGD	100	99	135.8	129.562
THB	100	99	135.8	156.105
TWD	100	99	135.8	227.380
DEM	100	99	135.8	81.144
JPY	100	99	135.8	1002.450

* Shaded boxes represent non-significant results i.e., independence.

TABLE 4. Independence Tests - Differential Spectrum 1997

Was there a difference in dependency between the first half and the second half of 1997? The difficulty in answering this question has to do with the fact that we can no longer maintain a uniform bin count as in Table 4 due to the relative size changes of the price changes. The differences in degrees of freedom for the different FX rates are dues to the different numbers of price change bins used. In the first half of 1997 the Asian FX rates were generally less volatile and the price changes were thus generally smaller. But Table 5 shows that only HKD, PHP, THB and JPY showed signi cant dependence in the first half of 1997. The price changes of IDR, MYR, SGD, TWD and DEM were independent at the 99% con dence level.

Currency	Degree of Freedom	Confidence Level(%)	Critical Value	Chi-Square*
HKD	23	99	41.6	72.074
IDR	100	99	135.8	125.078
MYR	50	99	76.2	74.929
PHP	32	99	53.5	168.318
SGD	30	99	50.9	38.000
THB	100	99	135.8	189.017
TWD	47	99	72.4	32.442
DEM	63	99	92.0	71.334
JPY	75	99	106.4	676.892

* Shaded boxes represent non-significant results i.e., independence.

TABLE 5. Independence Tests - Differential Spectrum - Jan-Jun 1997

As Table 6 shows, in the second half of 1997, only the changes in the FX rates of the HKD, SGD and PHP remained independent. This means that according to this test only the HKD and the SGD remained independent throughout 1997. It is remarkable that the PHP price changes were signi cantly dependent in the tranquil first half of 1997 but were independent in the turbulent second half.

Currency	Degree of Freedom	Confidence Level(%)	Critical Value	Chi-Square*
HKD	100	99	135.8	96.408
IDR	100	99	135.8	212.554
MYR	100	99	135.8	313.320
PHP	100	99	135.8	130.782
SGD	100	99	135.8	119.464
THB	100	99	135.8	157.476
TWD	100	99	135.8	251.063
DEM	62	99	90.8	120.878
JPY	67	99	96.8	492.842

* Shaded boxes represent non-significant results i.e., independence.

TABLE 6. Independence Tests - Differential Spectrum - Jul-Dec 1997

3.2. **Relative Price Change Transition Arrays.** One shortcoming, perhaps, of the differential spectrum is that it only decides whether price changes are independent and fails to identify the type of serial dependence that may be present. The relative price change method assists in determining the type of serial dependence and the duration of the temporal window during which the dependency exists.

The following test recipe is used to form relative price change transition arrays to test for independence, following Sherry, who also computed all the following theoretical relative frequencies or probabilities in Tables 7, 8 and 9. [[13], pp. 93 - 112]

Step 1. The price changes $\varepsilon_{j,t+1}$ are translated into a series of arbitrary symbols using an unvarying rule. We adopt the following rule: a sequential increase in the price change is classi ed as 2 , while a sequential decrease in price change is classi ed as 1 . For example, if the string of price changes is 3,5,4,8, the translated symbols would be 2 , 1 , 2 . We exclude ties, when sequential price changes are the same, by then determining the symbol randomly, using the computers random number generation capability. As a result, the string of symbols will consists solely of either 1 s or 2 s.

Step 2. The strings of symbols of 1 s and 2 s are transformed into transition matrices. For the simple 2×2 digram transition matrix, we specify how often a symbol i is followed by a symbol j using the notation ij for a digram (cell) of the transition matrix, where i and j is either 1 or 2. There are four digrams in the transition matrix: 11, 12, 21 and 22.

Step 3. The digram series are counted to obtain the relative frequencies of the digrams ij s. The count of the digrams are the observed frequencies in the familiar Chi-square test. To obtain the expected frequency for each digram, the total number of digrams are to be multiplied by their respective theoretical frequencies as in the following corresponding theoretical probability Table 7:[14]

TABLE 7. Theoretical Probabilities of Digrams

Digram	Probability
11 or 22	1/3
12 or 21	1/6

Step 4. If the obtained Chi-square value is statistically signi cant, we proceed to generate the $2 \times 2 \times 2$ trigram transition array. Otherwise we stop. For the trigram array, the trigram is ijk , where i , j , or k are either 1 s or 2 s.

Step 5. Again the series of all possible trigrams will be counted and the results are the observed frequencies for the familiar Chi-square test. The expected frequencies are based on the following corresponding theoretical probability Table 8. These probabilities are multiplied by the total number of trigrams in the data to obtain the expected frequency for each trigram.

TABLE 8. Theoretical Probabilities of Trigrams

Trigram	Probability
111 or 222	1/24
221, 211, 122, or 112	1/8
121 or 212	5/24

Step 6. If the Chi-square test results for the trigrams are signi cant, we proceed to the $2 \times 2 \times 2 \times 2$ tetragram array. Otherwise we stop. The tetragram is ijkl , where i , j , k , or l are either 1 s or 2 s.

Step 7. Again the series of all possible tetragrams will be counted to obtain the observed frequencies for the familiar Chi-square test. The expected frequencies are based on the following corresponding theoretical probability Table 9.

TABLE 9. Theoretical Probabilities of Tetragrams

Tetragram	Probability
1111 or 2222	1/120
1112, 1222, 2111, or 2221	1/30
1121, 1211, 2122, or 2212	3/40
1122 or 2211	1/20
1212 or 2121	4/30
1221 or 2112	11/120

Step 8. In principle one can so proceed until the test results are all insigni cant and independence is ascertained. However, this paper stopped with the tetragrams, when all the results remained statistically signi cant and dependence was still signi cant within the four-minute temporal window.[15]

3.2.1. *Chi-square Test Results.* The Chi-square test results in Table 10 show that in 1997 the price changes of all nine currencies were not independent, with 99%

[14] The cells of this theoretical relative frequency or probability table sum up to unity.

[15] It requires special programming and considerable computer capacity to pursue this test further and nd the true duration of the temporal windows for these high-freqquency minute-by-minute data.

con dence, up to and including temporal windows of at least four minutes.[16]. This means that, according to this non-parametric test, all nine FX markets - including the DEM and JPY markets - were inefficient in 1997. This means that the sequential strings of up to four symbols (i.e., ve price changes) could have been used to detect invariant trading patterns, that could have been used for pro table FX trading strategies.

	Digram	Trigram	Tetragram
Degree Of Freedom	3	7	15
Confidence Level(%)	99	99	99
Critical Value	11.34	18.48	30.58

Currency	Chi-Square*		
	Digram	Trigram	Tetragram
HKD	144.724	327.760	510.815
IDR	209.016	479.904	758.780
MYR	304.363	697.763	1088.616
PHP	103.310	238.021	376.364
SGD	161.166	376.133	595.264
THB	92.824	212.274	341.336
TWD	16.969	37.661	66.845
DEM	2440.665	5604.532	8701.776
JPY	2143.419	4899.492	7651.705

TABLE 10. Independence Test - Relative Price Changes - 1997

Interestingly, when we proceed to test for independence in each of the two half years, we find first in Table 11 that in the first half of 1997 the price changes of the PHP and TWD were independent, with 99% confidence and that these FX markets operated efficiently.

[16]Fast FX traders would nd this a very long time. They tend to trade in bursts of 30 seconds or less. Some caution is required however. We use minute-by-minute data, which are averages of the actual FX quoted rates. Furthermore the quoted rates may not change as rapidly as the actual transaction rates. Cf. Section 2 for a discussion of the limitations of the data.

	Digram	Trigram	Tetragram
Degree Of Freedom	3	7	15
Confidence Level(%)	99	99	99
Critical Value	11.34	18.48	30.58

Currency	Chi-Square*		
	Digram	Trigram	Tetragram
HKD	96.992	219.792	347.053
IDR	68.900	159.497	257.233
MYR	165.257	377.552	591.792
PHP	8.221	-	-
SGD	109.614	254.332	403.918
THB	40.345	92.613	155.091
TWD	2.697	-	-
DEM	1077.127	2465.410	3826.991
JPY	894.508	2048.178	3208.595

* Shaded boxes represent non-significant results i.e., independence.

TABLE 11. Independence Tests - Relative Price Changes - Jul-Dec 1997

However, Table 12 shows that in the second half of 1997 these two currencies also lost their independence of price changes and that thus none of the Asian FX rates showed serial independence. Thus pro table trading strategies could have been developed in the second half of 1997, most likely because of the general depreciation of all currencies versus the US dollar (like a train rolling down hill). By continuing to purchase US dollars and to sell non-US currencies one could not avoid making a supra-normal trading pro t.

	Digram	Trigram	Tetragram
Degree Of Freedom	3	7	15
Confidence Level(%)	99	99	99
Critical Value	11.34	18.48	30.58

Currency	Chi-Square*		
	Digram	Trigram	Tetragram
HKD	72.973	167.094	262.005
IDR	141.461	326.960	514.464
MYR	132.470	306.637	479.923
PHP	108.375	249.526	395.546
SGD	63.051	146.060	231.320
THB	63.258	144.105	231.087
TWD	38.464	89.241	144.278
DEM	1385.009	3188.141	4959.522
JPY	1275.628	2920.197	4565.045

TABLE 12. Independence Tests - Relative Price Changes - Jul-Dec 1997

3.3. **Length of Temporal Trading Windows.** The relative price change transition arrays can be used to determine the existence as well as the duration of a temporal window during which the price changes exhibit serial dependencies. A lag-n window examines the existence of serial dependencies between a price change with the nth price change. This would mean if a temporal window is identi ed, a reasoned trading strategy based on technical analysis methods can be devised within the limits of this window. If no such window can be identi ed, technical analysis is useless.

The following recipe is used to test for such temporal windows:

Step 1. Using the same procedure as in the preceding section, the symbol 1 or 2 is assigned to each price change.

Step 2. A lag-n window is generated by pairing the first symbol with the nth, the second with the (n+1)th, and so on.

Step 3. A lag-n temporal window is determined by tabulating the frequency associated with each transition matrix. These frequencies are used as observed values.

Step 4. The observed values are compared to the temporal windows under independence. The theoretical probability of a 1,1 or a 2,2 occurrence is 0.1667 and the probability of a 2,1 or a 1,2 is 0.3333, as before.

Step 5. The Chi-square test is carried out. If the Chi-square value is signi cant, the series is not independent and higher order temporal windows will be developed, otherwise the procedure stops.

Although all lags up to and including 20 were computed, we report here only the tests for temporal windows of lag 5, 10, 15 and 20.

3.3.1. *Chi-square Test Results.* As Tables 13, 14 and 15 show, all nine currencies exhibit signi cant serial dependencies in their price changes for up to the lag-20 temporal window at the 99% con dence level. There is no difference between the first or second half of 1997. Since a lag-20 temporal window represents only 20 minutes of trading, this kind of analysis should be extended to larger intra-day windows or even to intra-week windows. Unfortunately, the capacity of processing these massive amounts of data in MS-EXCEL spreadsheets prevented us to pursue this path further at this moment. One thing is clear though: this analysis establishes that there exist temporal windows of at least 20 minutes in which technical analysis can lead to supra-normal FX trading pro ts. Thus although FX trading has become more efficient over time, currently it is still a pro table business, considering the existence of such signi cant inefficiencies.

	Lag-5	Lag-10	Lag-15	Lag-20
Degree Of Freedom	3	3	3	3
Confidence Level(%)	99	99	99	99
Critical Value	11.34	11.34	11.34	11.34

Currency	Chi-Square*			
	Lag-5	Lag-10	Lag15	Lag-20
HKD	2463.668	2058.113	2062.821	2135.321
IDR	2839.306	2866.258	3247.455	2832.306
MYR	6085.042	6219.063	5949.874	6167.510
PHP	1151.888	1085.292	1059.252	1247.528
SGD	6188.571	5864.202	6064.615	6292.940
THB	2293.228	2347.818	2326.606	2161.627
TWD	1680.707	1664.090	1531.088	1699.185
DEM	36197.96	32009.72	33628.80	32993.60
JPY	34526.31	29294.63	32230.91	31067.03

TABLE 13. Tests for Length of Temporal Windows - 1997

	Lag-5	Lag-10	Lag-15	Lag-20
Degree Of Freedom	3	3	3	3
Confidence Level(%)	99	99	99	99
Critical Value	11.34	11.34	11.34	11.34

Currency	Chi-Square*			
	Lag-5	Lag-10	Lag15	Lag-20
HKD	1278.342	1053.294	1101.235	1044.466
IDR	1297.532	1367.214	1453.154	1208.114
MYR	3313.468	3357.771	3193.361	3326.008
PHP	127.237	79.994	105.460	119.594
SGD	3114.608	2764.661	3145.683	3067.713
THB	1297.862	1220.451	1368.466	1119.693
TWD	775.856	773.009	761.324	733.242
DEM	18547.41	16784.77	17188.82	17005.34
JPY	16592.20	14851.95	15926.03	15110.09

TABLE 14. Tests for Length of temporal Windows - Jan-Jun 1997

	Lag-5	Lag-10	Lag-15	Lag-20
Degree Of Freedom	3	3	3	3
Confidence Level(%)	99	99	99	99
Critical Value	11.34	11.34	11.34	11.34

Currency	Chi-Square*			
	Lag-5	Lag-10	Lag15	Lag-20
HKD	1167.801	971.077	965.408	1047.902
IDR	1506.979	1609.044	1716.034	1651.041
MYR	2777.890	2904.570	2749.498	2755.634
PHP	1095.255	1027.179	964.166	1083.397
SGD	3189.139	3026.816	3111.420	3220.291
THB	1021.973	1118.702	1005.976	1046.076
TWD	969.485	889.909	764.218	890.654
DEM	17628.73	15202.13	16376.66	16181.20
JPY	17846.74	14296.32	16169.78	15932.29

TABLE 15. Tests for Length of Temporal Windows - Jul-Dec 1997

3.4. **Category Price Change Transition Arrays.** Using category price change transition (CPCT) arrays, the underlying FX time series can be examined in greater detail than with the relative price change transition arrays of Section 3.2. One determines if relatively large or small price changes deviate from independence by categorizing these time series according to a set of predetermined criteria. One can have as many categories as one desires and the categories can be in any fashion, as long as some non-varying rule for categorization is used. It is important to emphasize that if a series categorized by one set of criteria is determined to be independent, this does not imply that a categorization by different criteria also leads to independence. Thus, in principle, there is an in nite number of ways of categorizing FX time series to test for independence. This issue raises deep philosophical problems about the possible subjectivity of this approach, which we ll not discuss in this paper, considering the demonstration purpose of this paper.

The recipe to form category price *change* transition matrices to test for independence is adapted from [[13], pp. 131 - 140]:

Step 1. The cumulative frequency distribution of the price changes $\varepsilon_{j,t+1}$ of Section2. is divided into three parts: the lowest 10% of the series, the next 80% and the highest 10%.

Step 2. Determine in which third each price change $\varepsilon_{j,t+1}$ belongs. If a price change belongs to the ith portion, we encode it with symbol i =1,2, or 3, i.e. 1 represents the lowest 10% portion, 2 represents the 80% portion, and 3 the highest 10% portion of the cumulative frequency distribution of the FX series.

Step 3. The digram category price transition (CPT) matrix is generated by specifying how often a 1 , 2 or 3 is followed by 1 , 2 or 3 . The frequency of occurrence of a symbol i is the number of price changes in the i portion

Step 4. The theoretical probability of occurrence of each component in the digram is computed and the result is multiplied with the total number of price changes to obtain the expected frequency for that digram. For example, a digram

13 has the following expected frequency:

$$\text{(3.2)} \qquad \text{expected frequency} = (\text{theoretical probability of 1}) \times (\text{theoretical probability of 3}) \times (\text{total number of price changes})$$

Step 5. The usual Chi-square test is again carried out by comparing the observed frequencies with the expected values obtained in Step 4.

Step 6. If the Chi-square result obtained is signi cant, it implies that the series is not digram independent when categorized in a 10%-80%-10% pattern. Hence, we will continue with the trigram and tetragram transition arrays as in Section 3.2.

Again it should be emphasized that the categorization in the 10%-80%-10% pattern is arbitrary. One could choose another pattern, e.g., 20%-70%-10% and construct the digram matrices, followed by the trigram, tetragram, etc.

3.4.1. *Chi-square Test Results.* Again, Tables 16, 17 and 18 show that all nine currencies exhibit signi cant serial dependencies in their price changes for the 10%-80%-10% categorization. This means that relatively small and large price changes of the nine FX series diverge signi cantly from independence at the 99% con dence level. Furthermore, there is no discernible difference between the test results for the first or for the second half of 1997.

	Digram	Trigram	Quadgram
Degree Of Freedom	8	26	80
Confidence Level(%)	99	99	99
Critical Value	20.09	45.64	112.33

Currency	Chi-Square*		
	Digram	Trigram	Quadgram
HKD	2005.092	5197.620	11035.879
IDR	8833.400	30425.001	86728.179
MYR	13685.588	47072.459	125656.791
PHP	1810.354	5491.304	14431.692
SGD	5627.301	14869.107	31347.136
THB	4063.306	12487.213	30601.117
TWD	2606.145	8799.218	22433.433
DEM	20444.464	544469.654	122242.063
JPY	21740.199	63817.548	159276.579

TABLE 16. Tests on Category Price Change Transition Arrays - 1997

	Digram	Trigram	Quadgram
Degree Of Freedom	8	26	80
Confidence Level(%)	99	99	99
Critical Value	20.09	45.64	112.33

Currency	Chi-Square*		
	Digram	Trigram	Quadgram
HKD	815.04336	1839.048	3194.083
IDR	1090.854	2839.602	6286.163
MYR	1475.993	3478.930	6141.304
PHP	49.482	129.386	296.447
SGD	1470.245	3198.562	5517.440
THB	4293.919	16863.325	56464.217
TWD	176.166	507.088	1083.883
DEM	9744.277	26470.785	64282.558
JPY	9812.874	26640.379	56904.773

TABLE 17. Tests for Category Price Change Transition Arrays - Jan-Jun 1997

	Digram	Trigram	Quadgram
Degree Of Freedom	8	26	80
Confidence Level(%)	99	99	99
Critical Value	20.09	45.64	112.33

Currency	Chi-Square*		
	Digram	Trigram	Quadgram
HKD	1131.981	3741.681	11908.384
IDR	3173.167	12049.282	40510.877
MYR	3015.105	8453.448	18893.919
PHP	1882.002	6199.153	17521.221
SGD	1160.051	2909.095	5779.620
THB	1015.092	2314.694	4593.103
TWD	710.123	1917.331	4049.121
DEM	8306.650	23805.948	58249.435
JPY	11946.925	37761.903	107267.148

TABLE 18. Tests for Category Price Change Transition Arrays - Jul-Dec 1997

3.5. **Markov Analysis of CPCT Arrays.** Markov analysis was developed by a Russian statistician Andrei A. Markov about a century ago.[17] While in the

[17]The Russian mathematician Andrei Andreyevich Markov (1856 - 1922) studied sequences of mutually dependent variables, hoping to establish the limiting laws of probability in their most general form. Markov gave particular emphasis to Markov chains sequences of random variables in which the future variable is determined by the present variable, but is independent of the way in which the present state arose from its predecessors. A random walk is a special case of a Markov

preceding section, we looked with the digram transition matrices at zero-order Markov processes, in this section we examine higher order Markov processes. An rth-order Markov process means that the probability of occurrence of a speci c price change depends on the immediately preceding r price changes. When the price changes $\varepsilon_{j,t+1}$ follow a Markov process of the first order, their dependence would have the form:

$$P_{j,t+1} - P_{j,t} = \varepsilon_{j,t+1} = A\varepsilon_{j,t} + \eta_{j,t+1}, \tag{3.3}$$

where $\eta_{j,t+1}$ is some form of, unspeci ed, residual.[18]

Our recipe for the Markov analysis of the CPCT matrices follows again [[13], pp. 140 - 160]:

Step 1: We start with the test for a zero-order Markov process, as in the preceding section. Since their are, in principle, an in nite number of ways of categorizing a time series for non-parametric independence tests, in this section a slightly different categorization is used. Now the time series of the price changes $\varepsilon_{j,t+1}$ is divided in approximately equal thirds, i.e., with $33.33\% - 66.67\%$ categories.

Step 2: The category price change transition analysis is performed as before with the Chi-square test to determine if a zero-order Markov process is signi cant. The degrees of freedom for a zero-order Markov process is $(C-1)^2$, where C is the number of states . For example, digrams have two states so that the degrees of freedom is $(C-1)^2 = 1$, while trigrams have three states and the degrees of freedom is $(C-1)^2 = 4$.

Step 3: If the value obtained is statistically signi cant, it means that the price changes $\varepsilon_{j,t+1}$ are not independent and a higher order Markov process (order-1) should be modeled. For an order-1 Markov process, the Chi-square test statistic is calculated as follows:

$$\chi^2 = \sum_{ijk} \frac{(O_{ijk} - E_{ijk})^2}{E_{ijk}}, \tag{3.4}$$

where O_{ijk} is the observed number of occurrences of trigram ijk . E_{ijk} is the expected number of occurrences of the trigram ijk , de ned as follows:

$$E_{ijk} = \frac{O_{.jk}O_{ij.}}{O_{.j.}}. \tag{3.5}$$

In case of $O_{.jk}$ the trigram will begin with any symbol (that is 1, 2 or 3), but will end with a speci c digram jk. In case of $O_{ij.}$ the trigram begins with a speci c digram ij , but ends with any symbol. Finally, in case of $O_{.j.}$ the trigram begins and ends with any symbol, but has a speci c symbol in the middle. The degrees of freedom for this order-1 Markov process test is $C(C-1)^2 = 3(3-1)^2 = 12$. If the calculated Chi-square value is still signi cant, we perform an order-2 Markov analysis.

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chain, where the transition matrix is an identity. In 1923, the American mathematician Norbert Wiener (1894 - 1964) became the first to treat rigorously a continuous Markov process (= Wiener process). A special case is the continuous random walk or Brownian motion, which is a continuous-time martingale [Cf. [12], p. 25]. The theoretical foundation of a general theory of stochastic processes was provided during the 1930s by another Russian mathematician, Andrei Nikolaevich Kolmogorov (1903 - 1987), who de ned the (now conventional) Kolmogorov probability.

[18]Interestingly, this approach can lead to a seemingly in nite Chinese box approximation, where the next question is if these unspeci ed shocks $\eta_{j,t+1}$ independent of each other, etc., except that there is no self-conformity.

Step 4: For an order-2 Markov process, the Chi-square test statistic is calculated as follows:

$$\chi^2 = \sum_{ijk} \frac{(O_{ijkl} - E_{ijkl})^2}{E_{ijkl}}, \tag{3.6}$$

where E_{ijkl}, the expected number of occurrences of the tetragram $ijkl$ is de ned as:

$$E_{ijkl} = \frac{O_{.jkl}O_{ijk.}}{O_{.jk.}}. \tag{3.7}$$

The degrees of freedom for this order-2 Markov process Chi-square test on trigrams is $C^2(C-1)^2 = 3^2(3-1)^2 = 36$. If the calculated Chi-square value is statistically signi cant, an order-3 Markov process would be performed, etc.

3.5.1. *Chi-square Test Results.* Again, since the objective of this paper was to test the null hypothesis that the Asian FX price changes are independent, we did not continue this process until all Markov orders for all nine currencies were completely established. But three conclusions can be drawn. First, most of the nine currencies exhibit price change behavior, which can be described by higher-order Markow processes. Second, most of these price changes can be described by Markov processes of orders 2 and 3 or higher, indicating a considerable dependence and thus persistence, which can be pro tably exploited by FX traders. Third, there was more such complex dependence in the second half year after the currency break in mid 1997 than in the first half year.

Table 19 provides the results for the whole of 1997 for order-0, -1 and -2 Markov processes. All results are signi cant at the 99% con dence level.

	Order -0	**Order-1**	**Order-2**
Degree Of Freedom	4	12	36
Confidence Level(%)	99	99	99
Critical Value	13.28	26.22	58.57

Currency	**Chi-Square***		
	Order -0	**Order-1**	**Order-2**
HKD	1624.926	250.866	151.248
IDR	5979.245	1230.039	867.993
MYR	3519.383	844.982	537.299
PHP	1488.094	531.220	394.382
SGD	1596.543	365.369	233.540
THB	4247.558	1125.562	882.164
TWD	380.636	318.756	200.258
DEM	17408.700	1828.356	1027.835
JPY	13859.766	2955.194	784.540

TABLE 19. Tests for Price Change Markov Processes - 1997

Table 20 shows that for the first half of 1997, the price changes of PHP and TWD exhibit independence at order-2 processes: the price changes were thus order-1 Markov and *not* independent innovations. The price changes could have been ltered and predicted supra-pro tably by an order-1 Kalman lter [9]. In addition, the price changes of HKD, MYR and SGD exhibit independence at order-3 Markov.

	Order -0	Order-1	Order-2	Order-3
Degree Of Freedom	4	12	36	108
Confidence Level(%)	99	99	99	99
Critical Value	13.28	26.22	58.57	147.0

Currency	Chi-Square*			
	Order -0	Order-1	Order-2	Order-3
HKD	608.407	103.122	63.072	135.006
IDR	788.216	181.738	119.664	169.626
MYR	1258.060	148.113	83.237	113.464
PHP	56.968	27.995	25.260	-
SGD	1150.765	218.219	77.776	117.338
THB	843.375	209.822	248.508	211.406
TWD	31.061	52.570	56.019	-
DEM	8335.133	780.843	452.423	524.952
JPY	6459.412	1246.094	352.667	516.139

* Shaded boxes represent non-significant results i.e., independence.

TABLE 20. Tests for Price Change Markov Processes - Jan-Jun 1997

This means that, on average, a price change in the PHP and TWD series at a particular time was in uenced by the price change of the preceding period (i.e., in the preceding 2 minutes), while the price changes of the HKD, MYR and SGD series were in uenced by the price changes in the preceding three periods (i.e., in the preceding 4 minutes). The results suggest longer persistence in the cases of IDR, THB and, surprisingly, DEM and JPY.

Table 21 shows that the price changes of the PHP and, perhaps surprisingly, of the THB, show order-2 Markov behavior, while those of all other currencies show order-3 or higher Markov behavior. In other words, most currencies showed even longer persistence phenomena, when they were all headed in the same downward trend versus the US dollar.

	Order -0	Order-1	Order-2	Order-3
Degree Of Freedom	4	12	36	108
Confidence Level(%)	99	99	99	99
Critical Value	13.28	26.22	58.57	147.0

Currency	Chi-Square*			
	Order -0	Order-1	Order-2	Order-3
HKD	482.500	164.925	117.583	158.538
IDR	2776.324	853.586	519.355	484.748
MYR	1681.673	703.124	440.876	348.294
PHP	833.923	123.830	111.935	133.624
SGD	673.768	220.765	130.431	192.635
THB	586.368	48.620	84.430	117.128
TWD	546.066	360.313	210.519	235.222
DEM	9012.290	1063.687	572.680	678.029
JPY	7443.499	1842.207	498.688	743.899

* Shaded boxes represent non-significant results i.e., independence.

TABLE 21. Tests for Price Change Markov Processes - Jul-Dec 1997

4. CONCLUSIONS

Table 22 summarizes the results from our extensive non-parametric testing, using high-frequency (minute-by-minute) data series to see if the Asian FX markets were efficient in 1997. In addition, we tested if there was an obvious difference in the efficiency of these Asian FX markets in the second half of 1997, after the Thai baht devaluation on July 2th, 1997, in comparison with the first half of 1997. The efficiency tests determined if the FX prices adhered to random walk behavior and thus the price changes were innovations, i.e., stationary and independent, or not.

Currency	HKD	IDR	MYR	PHP	SGD	THB	TWD	DEM	JPY
Stationarity Test									
-- 1997: Visual Inspection	✓	•	•	✓	•	•	•	✓	✓
Chi-Square	✓	•	•	✓	•	•	✓	✓	✓
-- Jan to Jun 97:Visual Insp	✓	✓	✓	✓	✓	✓	✓	✓	✓
Chi-Square	✓	✓	✓	✓	✓	✓	✓	✓	✓
-- Jul to Dec 97: Visual Insp	✓	•	•	✓	✓	✓	•	✓	✓
Chi-Square	✓	✓	•	✓	✓	✓	✓	✓	✓
Differential Spectrum									
-- 1997	✓	•	•	•	✓	•	•	✓	•
-- Jan to Jun 97	•	✓	✓	•	✓	•	✓	✓	•
-- Jul to Dec 97	✓	•	•	✓	✓	•	•	•	•
Relative Price Change									
-- 1997: Digram	•	•	•	•	•	•	•	•	•
Trigram	•	•	•	•	•	•	•	•	•
Tetragram	•	•	•	•	•	•	•	•	•
-- Jan to Jun 97: Digram	•	•	•	✓	•	•	✓	•	•
Trigram	•	•	•	--	•	•	--	•	•
Tetragram	•	•	•	--	•	•	--	•	•
-- Jul to Dec 97: Digram	•	•	•	•	•	•	•	•	•
Trigram	•	•	•	•	•	•	•	•	•
Tetragram	•	•	•	•	•		•	•	•
Temporal Windows									
-- 1997: Lag-5	•	•	•	•	•	•	•	•	•
Lag-10	•	•	•	•	•	•	•	•	•
Lag-15	•	•	•	•	•	•	•	•	•
Lag-20	•	•	•	•	•	•	•	•	•
-- Jan to Jun 97: Lag-5	•	•	•	•	•	•	•	•	•
Lag-10	•	•	•	•	•	•	•	•	•
Lag-15	•	•	•	•	•	•	•	•	•
Lag-20	•	•	•	•	•	•	•	•	•
-- Jul to Dec 97: Lag-5	•	•	•	•	•	•	•	•	•
Lag-10	•	•	•	•	•	•	•	•	•
Lag-15	•	•	•	•	•	•	•	•	•
Lag-20	•	•	•	•	•	•	•	•	•
Category Price Transition									
-- 1997: Digram	•	•	•	•	•	•	•	•	•
Trigram	•	•	•	•	•	•	•	•	•
Quadgram	•	•	•	•	•	•	•	•	•
-- Jan to Jun 97 : Digram	•	•	•	•	•	•	•	•	•
Trigram	•	•	•	•	•	•	•	•	•
Quadgram	•	•	•	•	•	•	•	•	•
-- Jul to Dec 97 : Digram	•	•	•	•	•	•	•	•	•
Trigram	•	•	•	•	•	•	•	•	•
Quadgram	•	•	•	•	•	•	•	•	•
Markov Analysis									
-- 1997: Order-0	•	•	•	•	•	•	•	•	•
Order-1	•	•	•	•	•	•	•	•	•
Order-2	•	•	•	•	•	•	•	•	•
-- Jan to Jun 97: Order-0	•	•	•	•	•	•	•	•	•
Order-1	•	•	•	•	•	•	•	•	•
Order-2	•	•	•	✓	•	•	✓	•	•
Order-3	✓	•	✓	--	✓	•	--	•	•
-- Jul to Dec 97: Order-0	•	•	•	•	•	•	•	•	•
Order-1	•	•	•	•	•	•	•	•	•
Order-2	•	•	•	•	•	•	•	•	•
Order-3	•	•	•	✓	•	✓	•	•	•

• -- Significant Result (does not exhibit stationarity or serial independence)

TABLE 22. Summary of Nonparametric Efficiency (Random Walk) Tests for Asian FX Rates

First, regarding stationarity, all nine currencies - the seven Asian currencies (Hong Kong dollar, Indonesian rupiah, Malaysian ringgit, Philippines peso, Singapore dollar, Thai baht and Taiwan dollar), plus the two benchmark currencies of the Deutschemark and the Yen - reveal stationarity before the currency turmoil started (i.e. before the 2nd of July), as indicated by the tick marks. The Malaysian ringgit (MYR) was the only non-stationary currency in the second half of 1997, as indicated by the dot. All other FX markets in the second half of 1997 were stationary, despite the much higher volatility. Thus within each half year period, there were stationary, stable trading processes and the private Asian FX markets and pricing mechanisms did *not* break down. The exception was the Malaysian ringgit in the second half of 1997, when the Malaysian government under leadership of Dr. Mahathir, intervened in the Malaysian ringgit trading, for political reasons.

However, when all the 1997 data were tested, only the Hong Kong dollar (HKD), the Philippines peso (PHP) and the Taiwan dollar (TWD) and the two benchmark currencies (DEM and JPY) showed stationarity. Thus there was a structural break in the price generating processes. The 1997 FX data set is non-homogeneous, since in the turbulent second half of the year the volatility of the FX pricing dramatically increased, in comparison with the tranquil first half of 1997.

Second, all nine currencies exhibited significant dependencies in both the whole 1997 data set and in each of the half year data sets, in particular, when they were tested for category price change transition matrices and temporal windows. Using the relative price change approach, the price changes of all nine currencies exhibited signi cant serial dependencies in the whole-year data set. The Philippines peso (PHP) and the Taiwan dollar (TWD) showed independence in the first half of 1997, using this approach, but lost it in the second half.

Signi cant trading windows of up to 20 minutes were identi able throughout 1997. Using Markov analysis, the price changes of all currencies showed signi cant higher order Markov behavior in both the whole year and half year subset data sets. While the Markov processes were mostly of order-1 and order-2 in the first half of the year, their orders increased to order-2 and order-3 or higher in the second half of the year, exhibiting more complex persistence behavior.

In summary, the rst conclusion is that the currency markets, be it Asian or European, show considerable inefficiencies in trading using high-frequency (minute-to-minute data), which can lead to supra-normal trading pro ts.

The second conclusion is that the Asian FX trading and pricing processes did not break down in the second half of 1997. All FX pricing processes continued to show stationary behavior, although the pricing volatility increased dramatically in the second half, compared with the first half. In other words, there was a dramatic structural break in volatility in the middle of the year, when the tranquility of the Asian FX markets got suddenly disturbed.

The third conclusion is that signi cant trading windows of up to 20 minutes existed. While the price changes showed in the tranquil first half of 1997 mostly order-1 to -2 (two to three minute) Markov-type behavior, they showed one or two orders higher Markov behavior in the second half. Such higher-order behavior can, in principle, be ltered and monitored by traders to obtain supra-normal pro ts. However, this last conclusion is very tentative, since the higher order Markov process behavior may be partially induced by the fact that we use minute-to-minute and not tick-by-tick data.[19] Furthermore, the data consist of quotations, which are updated with some time-lag and not of actually transaction prices. Thus more research is required using actual tick-by-tick transaction prices, whenever these are available.

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[19] Tick-by-tick data contains discontinuous behavior with gapping and the traditional forms of analysis, like Markov processes, break down. For such data wavelet analysis appears to be more appropriate.