**Volatility Spillovers Across Stock, Call Money And Foreign Exchange Markets**

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**ABSTRACT**

The increasing integration of financial markets over the years has led to greater movement of funds between these markets and also to return and volatility spillovers. In this study, we have examined the stock market, the foreign exchange market and the call money market in India for evidence of volatility spillovers using multivariate EGARCH models which facilitate the study of asymmetric responses. The results indicate the existence of asymmetric volatility spillovers across these markets. The results also indicate that either the information assimilation across markets was slow or that the spillovers were on account of contagion. In addition, the results indicate the need to take the dynamic structure of correlation into account.

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## 1. INTRODUCTION

Since the floating exchange rate system was adopted in 1973, the world has witnessed greater integration of financial markets, increase in cross-border trade in goods and services, and attempts at risk reduction through portfolio diversification by way of cross-border investments, a substantial portion of which has gone into emerging markets. Cross-border trading in goods and services has gone up substantially in the last two decades as companies have looked outside their own countries on account of competitive pressures or in order to utilise opportunities in other countries. The liberalisation process that occurred in many countries that were hitherto relatively closed economies accelerated the growth in cross-border trading.

The liberalisation process also meant that capital could now be sourced from around the world. With growth in most of the major economies in the last two decades being primarily in single digits, the rapid growth of the South East Asian countries and emerging markets provided investors, especially institutional investors, with an opportunity to diversify their holdings and reduce risk as well as to increase returns, as the correlations of these markets with the markets in developed countries were fairly low. With investor expectations also rising because of the continuous growth in the US since the mid-80s, portfolio flows into and out of countries increased as portfolio managers searched for better risk-adjusted returns on their funds. In addition, companies have also been on the look out for cheaper sources of capital or for acquisition currencies, leading to listing on multiple exchanges.

This led to a tremendous increase in the volume of cross-border transactions in securities and currencies. For instance, since the mid-80s, international equity flows have been increasing at a rate of 34% p.a. These flows create an increased demand for and supply of currencies in which the securities are denominated, creating some degree of interdependence between stock returns and exchange rate changes.

A natural outcome of the globalisation of operations in the currency and securities markets as well as that of institutional investors has been the increase in the level of integration in these markets and more recently, consolidation, especially of securities exchanges. The process has been speeded up by the availability of technology that makes such integration possible in a seamless manner.

One of the consequences of floating rates and the increased volume of transactions has been the increase in volatility, as can be seen in the table below:

| | Annual Volatility (%) | | |
|---|---|---|---|
| | 1960-69 | 1970-79 | 1980-91 |
| Commodities | 3.6 | 13.6 | 8.6 |
| $ Interest Rate | 17.8 | 26.0 | 23.4 |
| DM/$ | 2.4 | 10.0 | 13.0 |

**Table 1 Volatility Trends**

(Source: IFC Discussion Paper 17, Glen (1993))

This increase in volatility has implications for portfolio risk and therefore on investment flows.

This has also led to an increase in the occurrence of volatility spillovers with greater integration between markets and common news impacts playing an important role. In this paper, we have looked at three markets – stock market, foreign exchange market and call money market. Section 2 contains a review of literature, section 3 covers the methodology and section 4 details the results of the study.

## 2. LITERATURE REVIEW

Linkages between financial markets across geographic boundaries as well as across asset types have been the object of many studies. One of the reasons for such studies being undertaken is the issue of impact of events in one market on another. The importance of such studies has come to the fore in recent years owing to events such as the 1987 stock market crash, the Mexican crisis, the Asian currency crisis, and so on. It has been observed that during such periods, markets tend to co-vary much more than normal, and that there are spillovers across markets and across geographical boundaries. While such occurrences would be categorised under 'contagion effects', the linkages between markets exist even otherwise and there is a growing body of literature on these linkages as well.

First and second moment linkages between markets have been studied extensively, especially since the 1987 stock market crash. The degree of interdependence between markets appears to have increased significantly since then. The works of Mandelbrot (1963) and Fama (1965) and the phenomenon of volatility clustering and asymmetric response have formed the basis for many of the studies in this area. While the focus in the early years was on international diversification, the spotlight was on shifts in correlation structure in the years following the 1987 crash, especially during crisis periods.

A variety of techniques have also been used to study these linkages including cross-market correlation coefficients, VAR, cointegration, ARCH and GARCH family of models, GMM, etc.

Phylaktis and Ravazzolo (2002) state that the portfolio balance model for exchange rate determination forms the basis for expecting volatility spillovers. The relationship between domestic stock and foreign exchange markets can be represented by

$$P_t = \alpha_0 + \alpha_1 S_t + \upsilon_t$$

where $P_t$ is the domestic stock price, $S_t$ is the real exchange rate defined as domestic prices relative to foreign prices multiplied by the nominal exchange rate and $\upsilon_t$ is a disturbance term.

From theory, the coefficient $\alpha_1$ can either take a positive or a negative value. The behaviour of the real exchange rate is one of the major determinants of economic activity. A fall in the real exchange rate has a positive effect on the competitiveness of domestic goods versus foreign goods and the balance of trade of a country. This increases the level of domestic aggregate demand and the level of output. The long-run relationship between exchange rates and economic activity has been well documented in several studies (see e.g. Cornell (1983) and Wolff (1988)).

On the other hand, economic activity also affects the level of stock prices. The stock price of a firm reflects the expected future cash flows, which are influenced by the future internal and external aggregate demand. Consequently, stock prices will incorporate present and expected economic activity as measured by industrial production, real economic growth, employment rate or corporate profits (see Fama (1981), Geske and Roll (1983)). Empirical studies have confirmed the long-run positive relationship between stock prices and economic activity (see e.g. Schwert (1990), Roll (1992) and Canova and DeNicole (1995)). Thus, a fall in real exchange rate may increase stock prices through its effect on economic activity implying that $\alpha_1 < 0$.

On the basis of the portfolio-balance approach to exchange rate determination, however, the relationship between foreign exchange and stock markets gives rise to $\alpha_1 > 0$. According to this model, agents allocate their wealth amongst alternative assets including domestic money, and domestic and foreign securities. The role of the exchange rate is to balance the asset demands and supplies. Thus, any change in the demand for and supply of assets will change the equilibrium exchange rate. For example, an increase in domestic stock prices will increase wealth and the demand for money and consequently interest rates will go up. High interest rates in turn, will attract foreign capital, resulting in an appreciation of the domestic currency and a rise in the real exchange rate. Return spillovers may also result in volatility spillovers[1].

Another view is that the volatility linkages between markets arise from two distinct sources (Fleming, Kirby and Ostdiek, 1998) – common information that affects expectations across markets and information spillover on account of cross-market hedging activities. In this study, we are looking at three markets – stock, foreign exchange and call money. We expect all three markets to be affected by common

[1] This portion is sourced from Phylaktis and Ravazzolo (2002)

information in the form of macroeconomic news, for instance. In addition, we also expect the foreign exchange and stock markets, in particular, to be influenced by information spillover on account of cross-market hedging activities as well as due to the fact that banks and FIs are major players in all three markets.

Transmission of information across financial markets has been the subject of many studies in the last few years, the focus being on the extent to which innovation in one market affects returns and volatilities in other geographically and temporally distinct markets.

A number of papers consider the role of volatility spillovers between global equity markets, with varying results. King and Wadhwani (1990) find evidence in support of their contagion model for the New York, London and Tokyo stock markets, while Hamao et al. (1990) observe volatility spillovers from the U.S. and U.K. stock markets to the Japanese stock market. Subsequently, Lin et al. (1994) find reciprocal interdependence between one market's daytime returns and the other market's overnight returns for the Tokyo and New York stock markets, while Susmel and Engle (1994) are unable to detect strong evidence of either mean or volatility spillover between the London and New York stock exchanges.

Karolyi (1995) finds short-lived price spillovers between the New York and Toronto stock markets while Theodossiou and Lee (1993) observe statistically significant mean and volatility spillovers between some of the markets in the U.S., U.K, Canada, Germany and Japan.

Previous studies on the volatility dynamics of individual asset markets indicate the presence of asymmetry in the response of conditional variances to good and bad news, with negative shocks raising volatility to a greater extent than positive ones. This phenomenon, which Black (1976) and Christie (1982) attribute, in the context of equity returns, to financial and operating leverage effects and, which Pindyck (1984), French et al. (1987), Campbell and Hentschel (1992), and Wu (2001) among others, attribute to time-varying risk premia, is captured by the exponential GARCH (EGARCH) model of Nelson (1991).

Recent research on volatility spillovers uses this method to examine the issue of asymmetric response to news. Koutmos and Booth (1995) study the linkages between the New York, Tokyo and London stock markets and conclude that the volatility transmission process was asymmetric. Kanas (1998) finds reciprocal spillovers between London and Paris and Paris and Frankfurt, along with a unidirectional spillover from London to Frankfurt; the spillovers being asymmetric in most cases. Booth et al. (1997) observe price and volatility spillovers in the Scandinavian markets, while Laopodis (1998) detects asymmetric transmission of volatility in a study of three European Monetary System (EMS) and three non-EMS exchange rates for the period prior to the reunification of Germany.

Volatility spillovers are studied in the fixed-income and derivatives markets as well, with studies by Tse and Booth (1996), Tse (1998), Ann and Alles (2000) and Fleming et al. (1998), among others. Ebrahim (2000) studies the transmission of information between the U.S. and three other markets – Canada, Germany and Japan, and finds strong evidence of price and volatility spillovers in all three models, with some volatility spillovers being asymmetric. However, pairwise contemporaneous correlations between innovations are low for all three models, indicating that common factors between markets are small. This implies that either investors process information from other markets gradually or that the spillovers are the result of contagion effects. The results also indicate that volatility spillovers from Eurocurrency to foreign exchange markets are small and that volatility in the Euro Canada market is more susceptible to exchange rate shocks that that in the Euromark and Euroyen markets.

Kanas (2000) studies the impact of volatility spillovers between stock returns and exchange rate changes for six countries, namely, the US, the UK, Japan, Germany, France and Canada and finds evidence of volatility spillovers from stock returns to exchange rate changes for five of the six countries, Germany being the exception. All the stock return spillovers are symmetric in the sense that the effect of 'bad' stock market news on the exchange rate is the same as the effect of 'good' news. In addition, the strength of the volatility spillovers appears to have increased since the October 1987 crash.

Assoe (2001) investigates 5 developed markets and 11 emerging markets (including India) for spillovers across domestic stock markets, foreign exchange markets and a foreign stock market (USA). S&P/IFC indices and weekly return data are used for emerging markets with the exception of Singapore, and Data Stream indices are used for Singapore and the 5 developed markets. The S&P 500 index is used for the US. The return distribution for India is seen to be leptokurtic and non-normal, with a mean weekly return of 1.15%.

Assoe (2001) finds that the linkage between India's stock markets and foreign exchange markets are the least of the countries studied, with an unconditional correlation of 0.005. The maximum likelihood estimates of the parameters describing conditional means indicate that past returns have a significant impact on current returns for both the stock and foreign exchange markets. Negative mean spillovers are observed from the stock markets to the foreign exchange markets, but the absolute value of the mean spillovers from the stock markets to the foreign exchange markets is very small relative to the influence of exchange rate fluctuations on the stock market.

The study also detects the presence of significant own volatility spillovers in both stock and foreign exchange markets, implying that past own innovations increase current volatility in both markets.

Volatility spillovers from the foreign exchange markets to domestic stock markets are not significant in India, indicating that innovation in exchange rates has no significant impact on the volatility of stock markets. In contrast, Assoe (2001) finds evidence to the effect that stock market volatility has a strong impact on the rupee, with the cross-market volatility spillover from the stock market to the foreign exchange market being the second highest observed (0.461) after Mexico (1.203) and significant at 5%.

The study finds the asymmetry parameter for the stock market in India to be significantly positive (0.169), indicating that positive past innovations in these markets increase volatility more than negative innovations. On the other hand, the asymmetry parameter is significantly negative and the volatility spillover parameter is positive for the foreign exchange market. In addition, the volatility transmission from the foreign exchange market to the stock market is asymmetric, with negative shocks/news in the foreign exchange markets increasing volatilities in the stock markets more than positive shock/news do.

The volatility persistence parameters for the stock market (0.968) and the foreign exchange markets (0.894) are less than 1, suggesting that the conditional variances are not integrated and that unconditional variances are finite. However, they are still very large and significant, indicating high volatility persistence in both markets.

Assoe (2001) also finds that the conditional estimates of pairwise correlation between the two markets are substantially different from the unconditional correlations, suggesting that there is a need to account for the dynamic structure of correlation in order to design appropriate foreign exchange risk hedging strategies.

Francis, Hasan and Hunter (2002) examine the dependence in volatility between the equity and currency markets along with the extent to which changes in one market explain changes in the other on the lines of Evans and Lyons' (2001) study on the importance of order flow on exchange rate determination. The study also investigates whether the relation between international equity markets underwent a change because of changes in the volatility of the currency market. The study finds that past volatility of currency markets has a significant predictive power for the current volatility of equity securities and that greater-than-average currency volatility leads to increased correlation between equity markets. It observes that though equity markets predict the volatility of currency markets, the relationship is much weaker than the reverse, especially in the period after 1987. Additionally, except for the case of Canada, there is hardly any significant mean predictability between equity and currency markets. The cross-correlation between the U.S. and major equity markets is found to be robust to filtering for the exchange rate effect. These cross-correlations declined in the period after 1987, with the exception of Canada where it is significant only in that sub-period. The relationship between currency and equity markets is found to be bi-directional, significant, persistent and independent of the relationship between equity markets alone, and more specifically, better captured in the conditional second moments.

Apte (2001) studies the relationship between stock returns and exchange rates addressing the spillover effect in addition to that of volatility. The study finds evidence of a spillover from stock return surprises into the conditional variance of exchange rate returns. The result for one stock index (Nifty) indicates that exchange rate return surprises reduce the conditional variance of exchange rate returns, more so when the surprise is negative. There is also evidence of a spillover effect from innovations in exchange rate returns into the conditional variance of stock returns and the effect is once again asymmetric. However, the result for the other stock index (Sensex) indicates that while there is a spillover effect from exchange rate returns innovations to the stock market, the effect is symmetric in nature and in addition, there is no evidence of any spillover effects from stock returns innovations to the conditional variance of exchange rate returns.

While the study was conducted in the Indian context, the period covered, 1991 to 2000, had many gaps in the early part of the data series and the exchange rate was not market determined in the initial period. In addition, while there are a number of studies on the volatility of stock returns as well as the transmission of volatility between markets, there are very few studies on the transmission of volatility between stock markets and currency markets or volatility spillovers.

An analysis of the transmission of information across markets is important for several reasons. First, the notion of market efficiency dictates that it should not be possible to predict returns in one market using lagged information from other market(s). To the extent that there are price and volatility spillovers across markets, they could indicate some degree of market inefficiency. On the other hand, if news about fundamentals is serially correlated, then the existence of spillovers need not indicate a failure of market efficiency. Second, it is important to understand the manner in which shocks are propagated across markets in order to determine the persistence of these innovations and the magnitudes of their effects over time. Third, the study of price and volatility spillovers is important from a risk management perspective, both in terms of understanding how markets are interrelated as well as in permitting the development of effective strategies for hedging against shocks that are propagated across markets. For example, the variance of returns on a multi-currency portfolio depends on the variance of individual stock market returns, the variance of exchange rates and their pair-wise covariances. Significant spillovers of volatility can also affect the non-systematic residual international portfolio risk faced by international investors and thereby the valuation of those stocks.

Also, as King and Wadhwani (1990) observe, different sections of investors (including market makers) have access to different sets of information, and they can obtain valuable information from price changes in other markets. This is due to the fact that although published news is expected to affect all the markets at the same time, not all information is public, nor does every participant have the same ability to process it.

Greater awareness of the nature of volatility transmission across markets is also important for policymakers, as the issue is significant from a financial stability perspective (a large shock in one market may have a destabilising effect on another market) and linkages across markets may have an impact on policy effectiveness. In addition, policymakers can design more effective policies if they are able to gauge the depth and duration of the impact of any policy initiative in one financial market on other markets.

The need to study this in the Indian context arises from the fact that international equity investment is becoming increasingly important, for both the actual investments and the signalling impact they have. International equity investment in India has shown a rising trend since they were first allowed in 1992, with the exception of 1998 when there was a net outflow. The cumulative foreign portfolio investment at the end of 2002 was around Rs. 58900 crores, which amounts to about 8.75% of the total market capitalisation of Rs. 672,862 crores (Source: SEBI & NSE). With foreign direct and portfolio investments on the increase, there is a need to understand the effect of volatility spillovers, as this can have a bearing on FII asset allocations.

In view of the differing results in the Indian context and the other shortcomings mentioned, it was felt that a fresh study was necessary. This study aims to address the issues related to the transmission of volatility between exchange rates, interest rates and stock prices using a multivariate exponential GARCH framework. The relationship is examined in terms of the conditional second moments of the distribution of stock returns and exchange rate changes known as volatility spillovers.

## 3. METHODOLOGY

The interdependence of stock returns, exchange rate changes and call money rates was investigated in terms of the conditional second moments of their distributions, termed as volatility spillovers. The methodology was based on the EGARCH specification (Nelson, 1991) and the multivariate extension proposed by Koutmos and Booth (1995). The bivariate version of the EGARCH model was used to examine spillovers across two markets while the trivariate EGARCH model was used to look at the dynamic interactions of all three markets simultaneously.

Modelling the three markets simultaneously has a number of advantages over the univariate and bivariate approaches followed in most studies carried out so far. The first is that it eliminates the two-step procedure, thereby avoiding the problems associated with the use of estimated coefficients in the second step. In addition, it improves the efficiency and the power of tests for spillovers across markets. It is also in tune with the view that spillovers are essentially manifestations of the impact of news on any given market. The multivariate approach is ideally suited to test the possibility of asymmetries in the volatility transmission mechanism as it allows own market and cross-market innovations to have an asymmetric impact on the volatility in a given market, with the news generated in one market being evaluated both in terms of size and sign by the other markets. Other variations of the multivariate EGARCH approaches as well as other variations of GARCH which allow for asymmetric transmission have been used by Kanas (2000), Braun, Nelson and Sunier (1995), Koutmos (1996,1999), Kearney and Patton (2000), and Assoe (2001), among others. Comparative studies of various approaches have come out with varying results on their efficacy, but we have adopted the multivariate EGARCH approach in line with Koutmos' (1996, 1999) findings in major stock markets and in emerging Asian stock markets and those of Kearney and Patton (2000) on exchange rate processes and based on the fact that it appears to be the most widely used of the various approaches available.

For this study, daily return data for the INR-USD exchange rate (RIU) and the S&P CNX NIFTY stock index (RNSE) along with the call money rate (CMR, levels) is used in the absence of high frequency data. Data for the period January 1993 to December 2001 is used, as a result of which, over 1600 data points are available for analysis.

A bivariate extension of the EGARCH (p,1) model is employed to ascertain whether the volatility of stock returns affects and is affected by the volatility of exchange rate changes within an economy. As stated earlier, the EGARCH specification (Nelson, 1991) is used as it allows asymmetrical responses of the conditional variance of asset returns to both positive and negative innovations in return generating process and as it ensures that the conditional variance remains non-negative without resorting to complex restrictions on parameters.

The model specification is as follows:

$$S_t = \alpha_{s,0} + \sum_{i=1}^{p} \alpha_{S,i} S_{t-i} + \sum_{i=1}^{q} \alpha_{E,i} E_{t-i} + \varepsilon_{s,t}$$

$$\varepsilon_{s,t} / \Omega_{t-1} \sim N(0, \sigma^2_{s,t}) \qquad (1)$$

$$E_t = \beta_{E,0} + \sum_{i=1}^{m} \beta_{E,i} E_{t-i} + \sum_{i=1}^{n} \beta_{S,i} S_{t-i} + \varepsilon_{E,t}$$

$$\varepsilon_{E,t} / \Omega_{t-1} \sim N(0, \sigma^2_{E,t}) \qquad (2)$$

$$\sigma^2_{S,t} = \exp[c_{S,0} + \sum_{j=1}^{p_S} b_{S,j} \log(\sigma^2_{S,t-j}) + \delta_{S,S}(| z_{S,t-1} | - E | z_{S,t-1} |)$$

$$+ \theta_{S,S} z_{S,t-1} + \delta_{S,E}(| z_{E,t-1} | - E | z_{E,t-1} |) + \theta_{S,E} z_{E,t-1}] \qquad (3)$$

$$\sigma^2_{E,t} = \exp[c_{E,0} + \sum_{j=1}^{p_E} b_{E,j} \log(\sigma^2_{E,t-j}) + \delta_{E,E}(| z_{E,t-1} | - E | z_{E,t-1} |)$$

$$+ \theta_{E,E} z_{E,t-1} + \delta_{E,S}(| z_{S,t-1} | - E | z_{S,t-1} |) + \theta_{E,S} z_{S,t-1}] \qquad (4)$$

$$\sigma_{S,E,t} = \rho_{S,E} \sigma_{S,t} \sigma_{E,t} \qquad (5)$$

In equations (1) to (5), $\varepsilon_{s,t}$ and $\varepsilon_{E,t}$ are the stochastic error terms, $\Omega_{t-1}$ is the information set at time t-1, $\sigma^2_{s,t}$ and $\sigma^2_{E,t}$ are the conditional (time varying) variances of stock returns and exchange rate changes, $z_{s,t}$ and $z_{E,t}$ are the standardised residuals for stock returns and exchange rate changes$[z_{s,t} = (\varepsilon_{s,t} / \sigma_{s,t}) \textit{ and } z_{E,t} = (\varepsilon_{E,t} / \sigma_{E,t})]$. Conditional on $\Omega_{t-1}$, $\varepsilon_{s,t}$ and $\varepsilon_{E,t}$ are assumed to be normally distributed with zero mean and variances of $\sigma^2_{s,t}$ and $\sigma^2_{E,t}$.

Equations (1) and (2) are the conditional mean equations for the stock returns ($S_t$) and exchange rate returns ($E_t$) respectively. The number of lags used in equations (1) and (2) are determined using the AIC criterion.

Equations (3) and (4) are the conditional variance equations for stock returns and exchange rate returns respectively, and reflect the EGARCH (p,1) representation of the variances of $\varepsilon_{s,t}$ and $\varepsilon_{E,t}$. Under the EGARCH representation, the variance is conditional on its own past values as well as on past values of the standardised residuals. The persistence of volatility is measured by $\sum_{j=1}^{p_s} b_{sj}$ for stock returns, and by $\sum_{j=1}^{p_e} b_{Ej}$ for exchange rate changes. The conditional variances are finite if $\sum_{j=1}^{p_s} b_{sj} <1$ and $\sum_{j=1}^{p_e} b_{Ej} <1$. The terms $\delta_{E,s}[|z_{s,t-1}|-E|z_{s,t-1}|+\theta_{E,s}z_{s,t-1}]$ and $\delta_{s,E}[|z_{E,t-1}|-E|z_{E,t-1}|+\theta_{s,E}z_{E,t-1}]$ capture the ARCH effect, and the parameters $\theta_{s,s}$ and $\theta_{E,E}$ allow this effect to be asymmetric. The likelihood ratio test is used to determine the lag truncation length.

The volatility spillover effect from stock returns to exchange rate changes is captured by the term $\delta_{s,E}[|z_{E,t-1}|-E|z_{E,t-1}|+\theta_{s,E}z_{E,t-1}]$ in equation (3). Similarly, the spillover effect from exchange rates to stock returns is captured by the term $\delta_{E,s}[|z_{s,t-1}|-E|z_{s,t-1}|+\theta_{E,s}z_{s,t-1}]$ in equation (4). $\delta_{s,E}$ measures spillovers from exchange rate to stock returns, and indicates whether these spillovers are asymmetric; $\theta_{s,E}<0$ implies that the negative exchange rate shocks increase the volatility of stock returns more than positive shocks. Similarly, $\delta_{E,s}$ measures spillovers from stock returns to exchange rates, and $\theta_{E,s}$ indicates whether these spillovers are asymmetric.

The conditional covariance, $\sigma_{s,E,t}$, is specified by equation (5), where the parameter $\rho_{s,E}$ is the cross-market correlation coefficient between the standardised residuals from the stock returns and exchange rate changes equations.

Assuming conditional normality and given a sample of T observations, the log likelihood function for the bivariate EGARCH model is:

$$L(\Theta) = -0.5(NT)\log(2\pi) - 0.5\sum_{i=1}^{T}(\log|Q_t| + \varepsilon_t^{'}Q_t^{-1}\varepsilon_t) \qquad (6)$$

where N is the number of equations, $\Theta$ is the parameter vector to be estimated, $\varepsilon_t$ is the 1 x 2 vector of residuals at time t, $Q_t$ is the 2 x 2 conditional variance-covariance matrix with diagonal elements given by (3) and (4) and cross-diagonal elements given by (5). The BFGS (Broyden, Fletcher, Goldfarb and Shanno) algorithm is used to maximise $L(\Theta)$.

Constant conditional correlations are assumed over time, as in Bollerslev (1990). This assumption results in a significant reduction in the number of parameters that have to be estimated (also see Koutmos and Booth (1995)). As detailed in Bollerslev (1990), this simplifies the estimation and inference procedures. Under normal conditions, the ML estimation of $\Theta$ requires one NxN matrix inversion for each time period and the maximization of $L(\Theta)$ can be quite costly even for moderate values of T and N.

The constant conditional correlation assumption reduces this computational complexity considerably by reducing the number of inversions of the NxN matrix to just 1. Other terms are also concentrated out of the likelihood function, reducing the complexity further.

The same models are used to study volatility spillovers between stock and call money markets & foreign exchange and call money markets as well.

In order to investigate the volatility spillovers across the three markets, a trivariate EGARCH model is posited for the joint processes. By jointly modelling movements in these three markets, it is possible to examine the nature of interdependence and interaction across these markets, that is, whether innovation and volatility in a given market are indicative of the conditional mean and variances in the other markets. The trivariate EGARCH Model is an extension of the bivariate model and is as shown below:

$$S_t = \alpha_{S,0} + \sum_{i=1}^{p} \alpha_{S,i} S_{t-i} + \sum_{i=1}^{q} \alpha_{E,i} E_{t-i} + \varepsilon_{S,t}$$

$$\varepsilon_{S,t} / \Omega_{t-1} \sim N(0, \sigma_{S,t}^2) \qquad (7)$$

$$E_t = \beta_{E,0} + \sum_{i=1}^{m} \beta_{E,i} E_{t-i} + \sum_{i=1}^{n} \beta_{S,i} S_{t-i} + \varepsilon_{E,t}$$

$$\varepsilon_{E,t} / \Omega_{t-1} \sim N(0, \sigma_{E,t}^2) \qquad (8)$$

$$I_t = \chi_{I,0} + \sum_{i=1}^{r} \chi_{I,i} E_{t-i} + \sum_{i=1}^{r} \chi_{I,i} S_{t-i} + \varepsilon_{I,t}$$

$$\varepsilon_{I,t} / \Omega_{t-1} \sim N(0, \sigma_{I,t}^2) \qquad (9)$$

$$\begin{aligned}\sigma_{S,t}^2 = \exp[c_{S,0} &+ \sum_{j=1}^{p_S} b_{S,j} \log(\sigma_{S,t-j}^2) \\ &+ \delta_{S,S}(|z_{S,t-1}| - E|z_{S,t-1}|) + \theta_{S,S} z_{S,t-1} \\ &+ \delta_{S,E}(|z_{E,t-1}| - E|z_{E,t-1}|) + \theta_{S,E} z_{E,t-1} \\ &+ \delta_{S,I}(|z_{I,t-1}| - E|z_{I,t-1}|) + \theta_{S,I} z_{I,t-1}] \qquad (10)\end{aligned}$$

$$\begin{aligned}\sigma_{E,t}^2 = \exp[c_{E,0} &+ \sum_{j=1}^{p_E} b_{E,j} \log(\sigma_{E,t-j}^2) \\ &+ \delta_{E,S}(|z_{S,t-1}| - E|z_{S,t-1}|) + \theta_{E,S} z_{S,t-1} \\ &+ \delta_{E,E}(|z_{E,t-1}| - E|z_{E,t-1}|) + \theta_{E,E} z_{E,t-1} \\ q \quad &+ \delta_{E,I}(|z_{I,t-1}| - E|z_{I,t-1}|) + \theta_{E,I} z_{I,t-1}] \qquad (11)\end{aligned}$$

$$\begin{aligned}\sigma_{I,t}^2 = \exp[c_{I,0} &+ \sum_{j=1}^{p_I} b_{I,j} \log(\sigma_{I,t-j}^2) \\ &+ \delta_{I,s}(|z_{s,t-1}| - E|z_{s,t-1}|) + \theta_{I,s} z_{s,t-1} \\ &+ \delta_{I,E}(|z_{E,t-1}| - E|z_{E,t-1}|) + \theta_{I,E} z_{E,t-1} \\ &+ \delta_{I,I}(|z_{I,t-1}| - E|z_{I,t-1}|) + \theta_{I,I} z_{I,t-1}] \qquad (12)\end{aligned}$$

$$\sigma_{x,y,t} = \rho_{x,y} \sigma_{x,t} \sigma_{y,t} \qquad x, y = S, E, I \ \& \ x \neq y \qquad (13)$$

## 4. RESULTS

The multivariate EGARCH tests for volatility spillover are conducted for two markets at a time using a bivariate EGARCH routine based on Koutmos and Booth (1995) and for all the markets together using a trivariate EGARCH routine. The results for the bivariate tests are presented first, followed by the results for the trivariate test.

| Variable | Coefficient | Std Error | T-stat | Signif |
|---|---|---|---|---|
| B11 | 0.000137 | 2.5E-05 | 5.48849 | 4E-08 |
| B21 | 0.000623 | 0.000259 | 2.40202 | 0.016305 |
| VC(1,1) | -0.28901 | 0.053964 | -5.35564 | 9E-08 |
| VC(2,1) | -0.07481 | 0.027014 | -2.76944 | 0.005615 |
| VC(2,2) | -0.80585 | 0.171669 | -4.69421 | 2.68E-06 |
| VA(1) | 0.971913 | 0.004364 | 222.737 | 0 |
| VA(2) | 0.899236 | 0.020478 | 43.91255 | 0 |
| VB(1,1) | 0.363562 | 0.025411 | 14.30746 | 0 |
| VB(2,1) | 0.200905 | 0.017273 | 11.63083 | 0 |
| VB(2,2) | 0.190546 | 0.026657 | 7.14818 | 0 |
| VD(1) | 0.286772 | 0.054776 | 5.23535 | 1.6E-07 |
| VD(2) | -0.52726 | 0.077565 | -6.79765 | 0 |

**Table 2 Bivariate EGARCH Test Results – RIU & RNSE**

| Variable | Coefficient | Std Error | T-stat | Signif |
|---|---|---|---|---|
| B11 | 0.000186 | 3.62E-05 | 5.14695 | 2.6E-07 |
| B21 | 7.699214 | 0.033767 | 228.0097 | 0 |
| VC(1,1) | -0.62148 | 0.075881 | -8.19018 | 0 |
| VC(2,1) | -0.00998 | 0.024034 | -0.41541 | 0.677838 |
| VC(2,2) | 0.183399 | 0.024954 | 7.34944 | 0 |
| VA(1) | 0.94519 | 0.006534 | 144.6531 | 0 |
| VA(2) | 0.928048 | 0.009686 | 95.81051 | 0 |
| VB(1,1) | 0.315284 | 0.031577 | 9.98468 | 0 |
| VB(2,1) | 0.068701 | 0.020007 | 3.43392 | 0.000595 |
| VB(2,2) | 0.771746 | 0.043762 | 17.63516 | 0 |
| VD(1) | 0.362085 | 0.0768 | 4.71466 | 2.42E-06 |
| VD(2) | 0.027006 | 0.027923 | 0.96715 | 0.333468 |

**Table 3 Bivariate EGARCH Test Results – RIU & CMR**

| Variable | Coefficient | Std Error | T-stat | Signif |
|---|---|---|---|---|
| B11 | 0.000445 | 0.000332 | 1.34124 | 0.179843 |
| B21 | 7.702143 | 0.03355 | 229.5697 | 0 |
| VC(1,1) | -0.67782 | 0.134482 | -5.0402 | 4.7E-07 |
| VC(2,1) | -0.00764 | 0.023731 | -0.3219 | 0.747527 |
| VC(2,2) | 0.183609 | 0.027994 | 6.55895 | 0 |
| VA(1) | 0.9185 | 0.016047 | 57.23881 | 0 |
| VA(2) | 0.921645 | 0.010793 | 85.39105 | 0 |
| VB(1,1) | 0.245492 | 0.031112 | 7.89067 | 0 |
| VB(2,1) | -0.06955 | 0.023551 | -2.95296 | 0.003147 |
| VB(2,2) | 0.794991 | 0.04418 | 17.99433 | 0 |
| VD(1) | -0.16281 | 0.068482 | -2.37734 | 0.017438 |
| VD(2) | 0.036826 | 0.025599 | 1.43858 | 0.150269 |

**Table 4 Bivariate EGARCH Test Results – RNSE & CMR**

| Variable | Coefficient | Std Error | T-stat | Signif |
|---|---|---|---|---|
| B11 | 0.000127 | 2.8E-05 | 4.52111 | 6.15E-06 |
| B21 | 0.000517 | 0.000358 | 1.44413 | 0.148702 |
| B31 | 8.009904 | 0.004977 | 1609.367 | 0 |
| VC(1,1) | -0.30708 | 0.020888 | -14.7015 | 0 |
| VC(2,1) | -0.07576 | 0.02438 | -3.10746 | 0.001887 |
| VC(2,2) | -0.74807 | 0.096643 | -7.74059 | 0 |
| VC(3,1) | -0.0086 | 0.022977 | -0.37423 | 0.708234 |
| VC(3,2) | -0.00489 | 0.022601 | -0.21637 | 0.828701 |
| VC(3,3) | 0.275755 | 0.027914 | 9.87892 | 0 |
| VA(1) | 0.970362 | 0.00188 | 516.1238 | 0 |
| VA(2) | 0.906417 | 0.011648 | 77.81894 | 0 |
| VA(3) | 0.893415 | 0.010414 | 85.7922 | 0 |
| VB(1,1) | 0.358301 | 0.029289 | 12.23312 | 0 |
| VB(2,1) | 0.204079 | 0.018067 | 11.2959 | 0 |
| VB(2,2) | 0.17425 | 0.026679 | 6.53146 | 0 |
| VB(3,1) | 0.065372 | 0.019443 | 3.3623 | 0.000773 |
| VB(3,2) | -0.04819 | 0.019115 | -2.52084 | 0.011708 |
| VB(3,3) | 0.78991 | 0.045171 | 17.48696 | 0 |
| VD(1) | 0.268009 | 0.061578 | 4.35236 | 1.35E-05 |
| VD(2) | -0.55439 | 0.084543 | -6.55749 | 0 |
| VD(3) | 0.081779 | 0.024841 | 3.29213 | 0.000994 |

**Table 5 Trivariate EGARCH Test Results – RIU, RNSE & CMR**

Volatility spillovers across markets are measured by the parameters VB(i,j) for $i \neq j$. A significant positive VB(i,j) coupled with a negative VD(j) implies that negative innovations in market j have a greater impact on the volatility of market i than positive innovations. A positive VD(j), on the other hand, implies that positive innovations in market j have a greater impact on the volatility of market i than negative innovations.

The volatility spillover mechanism is, in either case, asymmetric. The volatility spillover mechanism is symmetric if and only if VD(j)=0.

As can be seen from the above tables, the volatility spillover mechanism in each case is asymmetric, with the degree of asymmetry varying across markets. In the case of the foreign exchange market and the stock market, the volatility spillover mechanism is significant and asymmetric. The positive coefficient of VD(1) indicates that the volatility spillover to the stock market increases when there is a rise in the exchange rate (i.e., the rupee depreciates). The degree of asymmetry between volatility spillovers is given by the ratio |-1+VD(j)|/(1+VD(j)), which in this case, works out to 0.5543, indicating that volatility spillover increases by 55.43% in case of a depreciation of the rupee as compared to that during an appreciation of the rupee.

Similarly, the negative coefficient of VD(2) indicates that the volatility spillover from the stock market to the foreign exchange market is higher when there is a negative innovation (i.e., the stock index falls) as compared to that during a positive innovation (i.e., the stock index rises). The degree of asymmetry in this case works out to 323.06%.

The volatility persistence parameters, VA(1) and VA(2), are both close to, but less than unity. This implies that while the unconditional variances are finite (as per Hsieh, 1989), the hypothesis that there is a unit root in both the series cannot be rejected. Current innovations, therefore, may retain their importance for all future forecasts of conditional variances. In addition, the hypothesis that the series' are homoskedastic (VB(i,i)=VA(i)=VD(i)=0) is rejected at any sensible level of significance.

The results for the other two bivariate tests are similar to that for the foreign exchange market and the stock market, with the exception that the spillover from the call money markets to the other two markets is not asymmetric, with the respective VD(j) values not significantly different from 0. The degree of asymmetry w.r.t. volatility spillover from the foreign exchange market to the call money market works out to 46.83%, while that for the volatility spillover from the stock market to the call money market works out to

138.89%.

| To<br>From | Foreign Exchange Market | Stock Market | Call Money Market |
|---|---|---|---|
| Foreign Exchange Market | N.A. | 55.43% | 46.83% |
| Stock Market | 323.06% | N.A. | 138.89% |
| Call Money Market | Symmetric | Symmetric | N.A. |

**Table 6 Degree of Asymmetry of Volatility Spillover**

As can be seen from Table 6, the degree of asymmetry is the highest for spillovers from the stock market to the foreign exchange market, followed by the spillovers from the stock market to the call money market. Spillovers from the foreign exchange market to the stock market and the call money market, in that order, follow.

The results from the trivariate tests (Table 5) are also similar in nature to those of the bivariate tests, with one major change. The degree of asymmetry w.r.t. volatility spillover in this case turns out to be 57.73% from the foreign exchange market to the other two markets, 348.83% from the stock market to the other two markets, and 84.88% from the call money market to the other two markets. Thus, the stock market appears to have the greatest impact on the other two markets, followed by the call money market and the forex market, in that order. Also, unlike in the bivariate case, the results indicate asymmetric transmission exists between all markets, with VD(3), the asymmetry coefficient, turning out to be significant. As in the bivariate case, the volatility persistence parameters, VA(i), are all significant and less than unity, but close to it. This indicates that while the unconditional variance is finite, the hypothesis of a unit root in all three series cannot be rejected either.

The above results clearly indicate that there are significant volatility spillovers across the three markets. These findings suggest that each of these financial markets are sensitive to news originating in the other two markets. However, as seen in the Ebrahim (2000) study, pairwise contemporaneous correlations between innovations are low for all three markets, indicating that either the common factors between markets are small, with investors from one market processing information from other markets gradually or, that the spillovers are the result of contagion effects. In addition, conditional estimates of pairwise correlation between two markets are substantially different from the unconditional correlations, indicating that there is a need to account for the dynamic structure of correlation in order to design appropriate risk hedging strategies.

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