SURVEY OF VOLATILITY AND SPILLOVERS ON FINANCIAL MARKETS

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Abstract

In this survey article, we present a rich extent of literature on volatility and its propagation on financial markets *via* spillovers. We document how new approaches or improved existing methodologies lead to results that offer richer insights than those derived from standard econometric techniques. Moreover, the implications of the results can be related to a wide set of markets as the surveyed articles cover emerging and developed European markets as well as the United States.

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JEL Classification: C10, E44, F31, G15

1. Introduction

This survey on volatility and its spillovers is based on the papers that I worked on over several past years. These papers bring improvements to the existing methodologies or new approaches and document their use with empirical results. Moreover, a rich extent of the relevant literature is presented to provide links with the existing research in this field and to complement the contributions of the surveyed papers.

In economics and finance, volatility represents the degree of variation of the price of an asset over time, be it the price of a stock, exchange rate, or price of any asset in general. The most common measures of volatility are the standard deviation and variance of returns. Historic and implied volatilities are derived from the time series of the past market prices and the price of a derivative traded on a market, respectively. Realized volatility is computed as a sum of squared returns. Volatility also represents a measure of risk: the higher the volatility, the riskier the asset.

Economic and especially financial time series are prone to exhibit periods of high and low volatility. Therefore, it is often misleading to measure volatility by a static standard deviation or unconditional variance. However, exactly such behaviour can be modelled using conditional heteroskedastic disturbances. The solution to this problem can be found in the conditional heteroskedasticity models of Engle (1982) and Bollerslev (1987). Subsequently, it was recognized that volatility propagates in an asymmetric manner:

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this feature is formalized in an exponential GARCH model in Nelson (1991) and later formulated in a leverage-effect ARCH model in Glosten *et al*. (1993) as well as in a threshold ARCH model in Zakoian (1994). Swiftly adopted by researchers, these models have led to an expansive body of empirical evidence confirming the asymmetric effect of negative *versus* positive returns on volatility of stock markets. Specifically, it is shown to increase following negative or positive news but reacting more sensitively to bad news (see for example Koutmos and Booth, 1995; Braun *et al*., 1995).

Later, research on volatility expands from a univariate to a multivariate framework beginning with the bivariate GARCH model proposed by Engle and Kroner (1995). In the next step, Engle and Sheppard (2001) and Engle (2002) devise a Dynamic Conditional Correlation (DCC) GARCH model representing a non-linear combination of univariate GARCH models. Moreover, Cappiello *et al*. (2006) introduce the asymmetric DCC (ADCC) specification to account for asymmetries in the conditional variances and correlations in a multivariate context.

Research on volatility on financial markets has become increasingly connected with the issue of how the volatility in one asset propagates to the volatility of other asset(s), also known as volatility spillovers. Similar to volatility, much of the recent research on volatility spillovers employs versions of the GARCH model (for example Beirne *et al*., 2013; Li and Giles, 2015; and Lin, 2013, among others). However, the ability to measure spillovers by those types of models is limited, namely in their lack of spillover dynamics. Recent developments related to spillovers have introduced a new way to capture volatility spillovers more effectively. Diebold and Yilmaz (2009, 2012) develop a volatility spillover index based on forecast error variance decompositions from vector autoregressions (VARs) to measure the extent of volatility transfer among markets. The new approach has been rapidly adopted in the relevant literature (for example McMillan and Speight, 2010; Yilmaz, 2010; Bubák *et al*., 2011; Fujiwara and Takahashi, 2012; Kumar, 2013; and Fengler and Gisler, 2015).

The work surveyed in this article is firmly connected to all aforementioned issues. For the sake of consistency, the notation is kept same as in the surveyed papers.

2. Volatility Spillovers among Stock Markets

A number of earlier papers investigate the short- and long-term linkages among the Central and Eastern European (CEE) stock exchanges both in terms of stock returns and stock market volatility (Gilmore and McManus, 2002, 2003; Voronkova, 2004; Syriopoulos, 2004; Bohl and Henke, 2003; Scheicher, 2001; Tse *et al*., 2003; Serwa and Bohl, 2005). Their findings are mostly based on data with daily or even lower frequencies; the only exception at that time was Černý and Koblas (2005). However, intraday volatility and contagion effects represent a finer detail and intraday estimates are more robust to structural breaks (Terzi, 2003).

A lack of empirical evidence on intraday stock market interlinkages between the CEE stock markets is filled by Égert and Kočenda (2007) who, moreover, investigate possible spillover effects for stock returns and stock volatilities among markets in Budapest, Prague, and Warsaw from June 2003 to February 2005, including their interactions with selected major developed markets in the EU (Frankfurt, London, and Paris—Western markets).

In order to investigate volatility spillovers, Granger causality tests are applied to stock volatility. The component GARCH (CGARCH) model of Engle and Lee (1999) is used to estimate volatility series that are then used as inputs for Granger causality tests. The *CGARCH* model contains (i) a long-term volatility component (q_t) that represents a lasting volatility with time-varying level, while (ii) the short-term volatility component ($\sigma^2_t - q_t$) captures the transitory effect from a variance innovation (for details see Engle and Lee, 1999). Specifically, Equation 1 shows the mean (level) equation, Equation 2 the short--term conditional variance equation, and Equation 3 the long-term volatility:

$$\Delta s_t = \varphi_0 + \sum_{i=1}^{m} \varphi_i \Delta s_{t-i} + \varepsilon_t \ , \tag{1}$$

$$\sigma^2_t - q_t = \overline{\omega} + \alpha \cdot \left(\varepsilon^2_{t-1} - \overline{\omega} \right) + \beta \cdot \left(\sigma^2_{t-1} - \overline{\omega} \right) \ , \tag{2}$$

$$q_t = \omega + \rho \cdot \left(q_{t-1} - \omega \right) + \delta \cdot \left(\varepsilon^2_{t-1} - \sigma^2_{t-1} \right) . \tag{3}$$

The volatility from the CGARCH model is used as the input (volatility) time-series for the Granger causality analysis. Granger causality test, specified in a standard way, enables to examine the stock volatility spillovers between pairs of markets.

Volatility spillover effects are identified among CEE markets, among Western markets and from Western to CEE markets. The uncovered link going from stock exchanges in Budapest and Warsaw to those in Frankfurt and London, respectively, bears two important implications. First, it shows that even smaller markets may impact dominant markets in terms of volatility spillovers. Second, the CEE stocks can then be considered by hedge funds and institutional investors as a separate "asset class" as compared to stocks in Western markets.

3. Exchange Rate Volatility and Regime Change

Kočenda and Valachy (2006) analyse exchange rate volatility in the four Visegrad countries, *i.e.* the Czech Republic, Hungary, Poland, and Slovakia during the period in which they were abandoning tight foreign exchange regimes in favour of more flexible ones. It is the first comprehensive analysis of exchange rate volatility that accounts for path dependency, asymmetric shocks, and movements in interest rates underlined by interest rate parity (IRP) theory.

The overall monetary policy framework has an important impact on exchange rate volatility. After eliminating constraining exchange rate regimes in the form of currency pegs, the Visegrad countries adopted direct inflation targeting (DIT). Under the DIT nominal exchange rates are likely to exhibit increasing volatility because of less importance related to exchange rate stability and rising pressure on domestic inflation (Orlowski, 2005). Other sources of exchange rate volatility are the increasing openness of the economy and instabilities related to the balance of payments (Kočenda and Valachy, 2006). Finally, degree of volatility might differ with tighter *versus* looser foreign exchange regimes as well as theoretically reflect deviation from the IRP condition.

Many early empirical studies use constant standard deviation as a proxy for exchange rate volatility (*e.g.* Hughes Hallett and Anthony, 1997; Andersen and Bollerslev, 1998; Jorion, 1995). However, they have to rely on the assumption of constant daily average returns. This is directly opposed to the IRP condition stating that changes in interest rate differential are reflected in changes in exchange rates. Solution to the above problem is the use of an augmented ARCH-type model.

The concept of uncovered IRP connects movements in exchange rates and interest rates and allows also to distinguish the effect of interest rates on exchange rate volatility (Golinelli and Rovelli, 2002; Svensson, 2000). The conventional notion of IRP can be expressed as:

$$s_{t+1} - s_t = i_t - i_t^* \quad , \tag{4}$$

where s_t is the log exchange rate at time t, and i_t and i^*_t are the domestic and foreign interest rates, respectively. Under the IRP condition, the exchange rate should adjust in every period so that the change is equal to the size of the interest rate differential. Bilson (1999) shows that the volatility of exchange rates is related to the annualized inflation differential ($i_t - i^*_t$). Kočenda and Valachy (2006) proceed a step further and propose to include in Equation 5 below the squared interest rate differential, *i.e.* $(i_t - i^*_t)^2$ along with the change in the interest rate differential squared, *i.e.* $(\Delta(i_t - i^*_t))^2$ to account for nonlinearity and intertemporal change in interest rate differential, respectively.

Empirical testing of the exchange rate volatility is done by employing the augmented threshold GARCH-in-mean (TGARCH-M) model:

$$\begin{aligned} \Delta s_t &= a_0 + \sum_{i=1}^{k} a_i \Delta s_{t-i} + b \ln \sigma_t^2 + \lambda \cdot SD_t + \varepsilon_t, \;\; \varepsilon_t \sim N(0, \sigma_t^2), \\ \sigma_t^2 &= \omega + \sum_{i=1}^{p} \alpha_i \varepsilon_{t-i}^2 + \sum_{j=1}^{q} \beta_j \sigma_{t-j}^2 + \xi d_{t-1} \varepsilon_{t-1}^2 + \delta_1 (i_t - i_t^*)^2 + \delta_2 (\Delta(i_t - i_t^*))^2, \end{aligned} \tag{5}$$

where Δs_t is the difference of the log exchange rate. The extension includes a conditional variance (σ^2_t) in the mean equation to analyse the process with a path-dependent rather than the zero-conditional mean. The threshold extension accounts for asymmetric information because good news and bad news do not have the same effect (Nelson, 1991). The threshold dummy d_{t-1} equals to 1 if $\varepsilon_{t-1} < 0$, and zero otherwise. Its inclusion enables to distinguish between positive and negative shocks to volatility or to allow innovations to have an asymmetric effect. The shock dummy SD_t accounts for a few infrequent outliers.

The results show that the introduction of floating regimes tends to increase exchange rate volatility in general. This is not an obvious result as Kočenda (1998) reports that volatility of an exchange rate pegged to a currency basket actually decreased after a much wider fluctuation band replaced a tight one. Moreover, under the float, the degree of volatility persistence varies across currencies but remains at a similar level, while the effect of asymmetric news tends to decrease volatility. Finally, under both regimes, only the contemporaneous effect of interest differential impacts exchange rate volatility. Hence, the type of regime is likely to be the strongest factor affecting it because of the limited role played by the interest rate.

4. Macroeconomic Sources of Foreign Exchange Risk

Research on explaining the currency risk premium using the uncovered IRP condition is widespread and has been growing since the earliest work of Hansen and Hodrick (1980) and Fama (1984). Further, Lustig *et al*. (2007) show that time-variation in large risk premia is closely related to the fundamental factors driving the risk appetite of investors.

Kočenda and Poghosyan (2009) analyse the role of macroeconomic factors as systemic determinants of currency risk in the new member states (the Czech Republic, Hungary, Poland, and Slovakia) of the European Union (EU) over the period 1999–2008. The results are derived from a multivariate framework, which has been largely neglected in the literature. Specifically, the empirical implementation is based on a multivariate GARCH model with conditional covariances in the mean of the excess returns (er_{t+1}).

Under the uncovered IRP the log excess returns are defined in the following way. The r_t and r^*_t are domestic and foreign log nominal gross returns on risk free assets. Further, s_t is the log domestic price of the foreign currency unit at time t. The excess return (er_{t+1}) to a domestic investor at time t+1 from investing in a foreign financial instrument at time t can be expressed in logarithmic form as:

$$er_{t+1} = r^*_t - r_t + \Delta s_{t+1} \quad . \tag{6}$$

In the absence of arbitrage opportunities, excess return should be equal to zero if agents are risk neutral, and to a time-varying element ϕ_t if they are risk averse. The term ϕ_t is given the interpretation of a foreign exchange risk premium required at time t for making an investment through period t+1.

Kočenda and Poghosyan (2009) show that the non-arbitrage specification for the excess return (er_{t+1}) can be derived as a function of its own variance plus its dynamic covariance with macroeconomic factors (z_i). The specification takes the form:

$$E_t[er_{t+1}] = \beta Var[er_{t+1}] + \sum_{i=1}^{K+1} \beta_i Cov_t[z_{i,t+1}; er_{t+1}] \quad , \tag{7}$$

where the β_i (i = 1, 2, ..., K+1) are the coefficients to be determined.

The estimation is performed based on the multivariate GARCH-in-mean model in a BEKK-form proposed by Engle and Kroner (1995) with a sandwich estimator that is robust to the distributional assumptions of variables (Huber, 1967; White, 1982). Moreover, two macroeconomic factors (z_i) derived from the C-CAPM model (for details see Kočenda and Poghosyan, 2009) are used: inflation rate (π; log difference in consumer prices) and consumption growth (Δc; proxied by a log difference in deflated retail sales). Hence, the nominal (inflation) and real (consumption) shocks can arrive from both sides of an economy.

The estimation results suggest that the real factor (consumption) plays a role in explaining the conditional variability in foreign exchange returns. This finding is in line with the evidence coming from more developed economies (Hollifield and Yaron, 2001; Lustig and Verdelhan, 2007). The impact of consumption (real factor) is quite levelled across the countries since they were well integrated among themselves and with respect to the Eurozone. Inflation is found to be a significant (nominal) factor for the risk premium in all countries but seems to be sensitive to the differences in inflationary history experienced by each country and the monetary policy regimes adopted in the examined countries. This finding supports the idea of the optimality of monetary policies based on inflation targeting for the nominal convergence process of the new EU members towards the Eurozone (Orlowski 2005, 2008).

5. Volatility Transmission in Foreign Exchange Markets

Motivated by the impact of the 2007–2008 financial crisis, Bubák *et al*. (2011) analyse the dynamics of volatility transmission to, from, and among CEE Forex markets. In particular, volatility spillovers among the Czech, Hungarian and Polish currencies together with the U.S. dollar are analysed during the period 2003–2009 as well as the extent to which shocks to foreign exchange volatility in one market transmit to current and future volatility in other currencies.

In terms of volatility transmission, European emerging markets have been under-researched despite their growing integration with developed markets – the volatility of CEE currencies has been of key importance for international investors (Jotikasthira *et al*., 2012; de Zwart *et al*., 2009) and foreign exchange risk has been pronounced in new EU members (Kočenda and Valachy, 2006; Kočenda and Poghosyan, 2009).

The exchange rate volatility in Bubák *et al*. (2011) is modelled with a multivariate generalization of the HAR-GARCH model of Corsi *et al*. (2008). Volatility spillovers are formally tested for by running simple pairwise Granger causality tests. A dynamic version of the Diebold and Yilmaz (2009) spillover index (DY index) is constructed as a more advanced approach in order to properly assess the overall magnitude and dynamics of the volatility spillovers.

The daily quadratic variation of the intra-day log spot exchange rates is measured with the realized variance (RV) designed by Andersen *et al*. (2001) and Barndorff-Nielsen (2002). They propose to measure the variation as the sum of squared returns. Realized variance is a critical building block of the DY index and is formally defined along with the spillover index in Section 6. In plain language, the DY index measures the proportion of the forecast error of its own volatility (on a specific market or in a specific asset) that can be attributed to shocks coming from other markets or assets. Intuitively, the value of the spillover index increases with the extent of volatility coming from other markets or assets. In the case when there are no spillovers, the index is equal to zero.

The empirical results (i) document the existence of volatility spillovers between CEE Forex markets on an intraday basis, and (ii) show that each CEE currency has a different volatility transmission pattern. The volatility spillovers have a greater effect on the volatility of the Czech and Polish currencies – this result correlates with the fact that during 2003–2009 both currencies exhibited very similar pattern of floating. This contrasts with the managed regime of the Hungarian currency and its volatility being irresponsive to spillovers.

During the post-2008 period, volatility increases in general but the volatilities of all currencies reflect chiefly their own history. The dynamic version of the DY index shows that the magnitude of the volatility spillovers increases significantly during periods of market uncertainty. From a medium-term perspective, volatility increases for Hungary, a country with troubled financial sector development. Finally, a general difference in the *pre*- and *post*-crisis patterns is an increase in the strength of the short-term volatility spillovers within a trading day. This seems to indicate a generally faster response of the market to volatility dynamics after the crisis.

6. Asymmetries in Volatility Spillovers

The basic notion of the DY index was introduced in previous section. Baruník *et al*. (2016, 2015) extend the spillover index methodology of Dieboled and Yilmaz (2009, 2012) by employing the concept of realized semivariances from Barndorff-Nielsen *et al*. (2010). This new approach enables to account for asymmetries in volatility spillovers.

The presence of asymmetric volatility in financial markets has long been recognized in the literature (Black, 1976; Christie, 1982; Pindyck, 1984; French *et al*., 1987). However, asymmetries in volatility spillovers have not yet received the same attention, despite their relevance to risk valuation and portfolio diversification strategies (Garcia and Tsafack, 2011). Asymmetry in volatility on financial markets implies that past returns are negatively correlated with present volatility (Bekaert and Wu, 2000). Since volatility is transferred across markets via spillovers, it is worth assuming that volatility spillovers also exhibit asymmetries which might stem from qualitative differences due to bad and good uncertainty (Segal *et al*., 2015).

A new measure of volatility has been introduced by Andersen *et al*. (2001) and Barndorff-Nielsen (2002) who propose estimating quadratic variation as the sum of squared returns (r^2_i) and coin the term "realized variance" (RV):

$$RV = \sum_{i=1}^{n} r_i^2 \ . \tag{8}$$

Diebold and Yilmaz (2009, 2012) use the realized variance as the total volatility measure. Then, realized variances of N assets, that are modelled by a covariance stationary vector autoregression VAR(p), are inputs to compute the (total) Diebold-Yilmaz spillover index S^H defined as:

$$S^H = 100 \times \frac{1}{N} \sum_{\substack{i,j=1 \\ i \neq j}}^{N} \tilde{\omega}_{ij}^H \, . \qquad (9)$$

In the Equation 9, $\tilde{\omega}_{ij}^H$ are the elements of the H-step-ahead generalized forecast error variance decomposition matrix (for H = 1, 2, ..., h). It records how much of the H-step-ahead forecast error variance of some variable i is due to innovations in another variable j. It provides a simple way of measuring volatility spillovers across assets or markets. In addition to the total spillover index, directional index and net index can be computed to provide more details on propagation of spillovers among assets or markets. Because the detailed formal exposition of the DY index is beyond the scope of this survey, original papers of Diebold and Yilmaz (2009, 2012) are recommended as an authoritative source.

Barndorff-Nielsen *et al*. (2010) decompose the realized variance Equation 8 into estimators of realized semivariance (RS) that capture the volatility due to negative or positive movements in returns. The negative and positive realized semivariances (RS^- and RS^+) are defined as follows:

$$RS^- = \sum_{i=1}^{n} \mathrm{II}(r_i < 0) \, r_i^2 \, , \qquad (10)$$

$$RS^+ = \sum_{i=1}^{n} \mathrm{II}(r_i \geq 0) \, r_i^2 \, . \qquad (11)$$

Realized semivariance provides a complete decomposition of the realized variance, as $RV = RS^- + RS^+$. It can serve as a measure of downside and upside risk or bad and good volatility as termed by Segal *et al*. (2015). The realized semivariances were quickly adopted by Feunou *et al*. (2013), Patton and Shepard (2015), and Segal *et al*. (2015) to provide finer points in volatility assessment.

In order to better quantify the extent of volatility spillovers, Baruník *et al*. (2015, 2016) suggest to employ realized semivariances to compute the DY indices in a way that would distinguish asymmetries in the volatility source and the extent of their propagation in terms of volatility spillovers. They introduce a spillover asymmetry measure (SAM) that is defined as the difference between negative and positive spillovers:

$$SAM = S^+ - S^-, \qquad (12)$$

where S^+ and S^- are (modified) volatility spillover indices (Equation 9) due to negative and positive semivariances RS_- and RS_+ (Equation 10, Equation 11), respectively. When SAM takes the value of zero, spillovers coming from RS^- and RS^+ are equal. When SAM is positive, spillovers coming from RS^+ are larger than those from RS^- and the opposite is true when SAM is negative. This new approach effectively enables accounting for dynamics of the asymmetries in volatility spillovers (time subscripts are omitted). As in the case of the DY index, directional and net effects are available as well (for details see Baruník *et al*., 2016).

The presented framework to measure asymmetries in volatility spillovers has been applied on financial and commodity markets. First, Baruník *et al*. (2016) employ it for the analysis of individual U.S. stocks and detect ample asymmetric connectedness at the sectoral level, While there is no universal pattern that would hold across sectors, the consumers, telecommunications, and health sectors exhibit visibly larger asymmetries in spillovers than the financial, information technology, and energy sectors, with marked differences how asymmetries in spillovers propagate between specific assets and within sectoral portfolios. Finally, negative asymmetries in spillovers are frequent but they do not strictly dominate the U.S. stock market.

Second, Baruník *et al*. (2015) detect and quantify asymmetries in volatility spillovers of petroleum commodities. They show that overall volatility spillovers due to negative (price) returns materialize to a greater degree than those due to positive returns. The occurrence of negative volatility spillovers correlates with low levels of crude oil inventories in the U.S. and often with world events that hamper crude oil supply. Thus, negative spillovers frequently indicate the extent of real or potential crude oil unavailability. In this respect, the advent of the tight oil production after 2008 and ongoing financialization of commodities actually coincide with lower volatility of spillovers as well as their asymmetries.

Third, Baruník *et al*. (2017) use high-frequency, intra-day data of the most actively traded currencies over 2007–2015 and document the dominating asymmetries in spillovers that are due to bad, rather than good, volatility. They also show that negative spillovers are chiefly tied to the dragging sovereign debt crisis in Europe while positive spillovers are correlated with the subprime crisis, different monetary policies among key world central banks, and developments on commodities markets. It seems that a combination of monetary and real-economy events is behind the positive asymmetries in volatility spillovers, while fiscal factors are linked with the negative spillovers.

7. Summary

The surveyed papers bring contributions that are both methodological and empirical. They enable a better gauge of economic and financial links based on a better understanding and quantification of volatility and its spillovers. The methodological contributions rest either on improvements to the existing models or the development of new approaches. Because of the methodological advances, the empirical results offer richer insights than those derived from standard econometric techniques. Finally, the geographical coverage of the markets spreads from the emerging European markets to developed markets in Europe as well as the U.S. Hence, despite the fact that much of the findings come from the assessment of the Central European countries, the implications of the results contained in the surveyed papers are relevant for a much wider set of markets.

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