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Analysis of Singapore's Foreign Exchange Market Microstructure

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ANALYSIS OF
SINGAPORE'S FOREIGN EXCHANGE
MARKET MICROSTRUCTURE

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by

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Abstract

This paper analyses the Singapore foreign exchange market from a microstructure approach. Specifically, by applying and modifying the empirical methodology designed by Bollerslev and Melvin (1994), we examine the relationship between bid-ask spreads and the underlying volatility of the USD/SGD. Our data set comprises high-frequency USD/SGD tick data of three separate years (April-June 1989, April-May 2006, April-May 2009). We found that for the USD/SGD: i) the size of bid-ask spreads are positively related to the underlying exchange rate volatility; ii) the magnitude of the dependence on underlying volatility increases as tick volume increases; and iii) the size of the bid-ask spreads may also be positively related to the directional movement of exchange rates.

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1 Introduction

In "Bid-Ask Spreads and Volatility in the Foreign Exchange Market – An Empirical Analysis", an early microstructure paper in 1994, Tim Bollerslev, and Michael Melvin (henceforth, B&M), performed an empirical analysis on the USD/DEM, one of the most highly-traded currency pair in 1989, and showed that the size of the bid-ask spread of is positively related to its underlying exchange rate uncertainty. Their dataset consist of more than 300,000 continuously recorded USD/DEM quotes over a 3 month period from April to June in 1989.

In this paper, we want to examine whether B&M's result is applicable to a much lesser-traded currency belonging to a much smaller developing economy with a government-managed floating exchange rate regime – the USD/SGD. We begin with a dataset of the USD/SGD in the same 3 month period as per B&M. The volume of USD/SGD quotes from April to June in 1989 is slightly over 8,000. We also want to examine how relationship between the size of the bid-ask spreads and exchange rate volatility changes as the USD/SGD grows in volume and significance, and as Singapore evolves into a developed country. Hence, we fast-forward 17 and 20 years into the future from 1989, and repeat the analysis on over 600,000 USD/SGD quotes from April to May 2006, and on over 1 million USD/SGD quotes from the same months in 2009.

This paper examines the Singapore foreign exchange market from a microstructure approach, specifically focusing on the bid-ask spreads of the USD/SGD. We also present a review of some microstructure literature in this area. But first, we provide more background to these two underlying themes in the next two sections:

1.1 The Singapore Foreign Exchange Market

The Monetary Authority of Singapore operates a float regime for the Singapore dollar that is managed against a basket of currencies of the country's major trading partners and competitors. The various currencies are given different weights depending on the extent of trade dependence with that particular country. The composition of the basket is revised periodically to take into account changes in Singapore' trade patterns.

The trade-weighted exchange rate is allowed to fluctuate within an undisclosed policy band, which provides flexibility for the system to accommodate short-term fluctuations in the foreign exchange markets as well as some buffer in the estimation of Singapore's equilibrium exchange rate.

On a trade-weighted basis, the SGD has appreciated against the exchange rates of its major trading partners and competitors since 1981, reflected rapid economic development, high productivity growth, and high savings rate.

The following figure shows the USD/SGD, Singapore GDP, and volume of quotes over the months of April and May from 1989 to 2009.

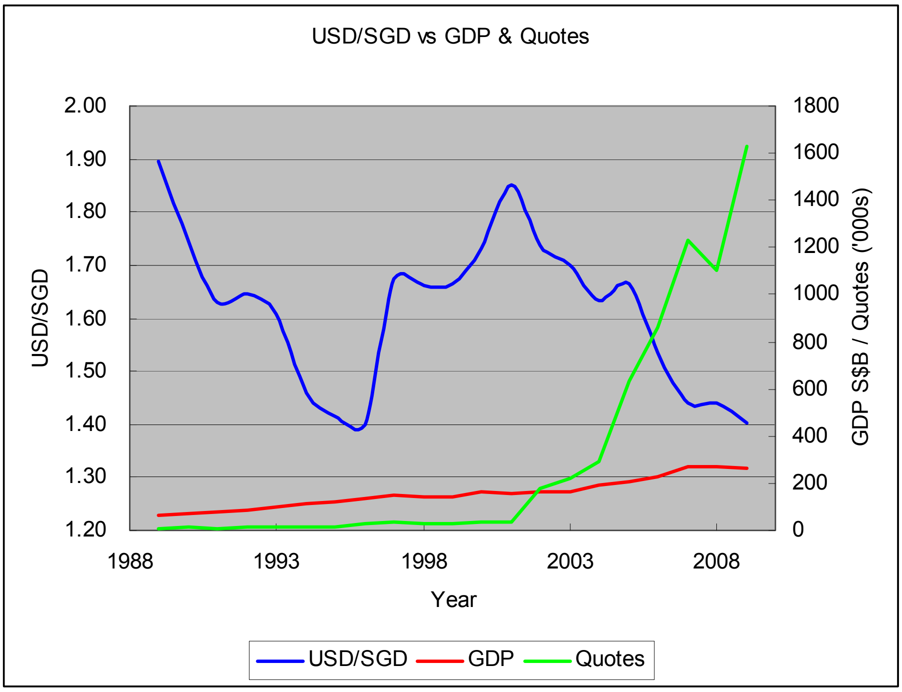

Figure 1: USD/SGD vs GDP & Quotes[1]

From 1989 to 2009, as the Singapore GDP experienced a gradual growth from SGD 61 billion in 1989 to SGD 266 billion in 2009, the USD/SGD fluctuated between 1.40 and 1.90. Interestingly though, from 2002 onwards the growth of USD/SGD quote volume for April and May experienced a sharp increase from only 33,000 quotes in 2001 to 180,000 quotes in 2002. This growth would then accelerate to 1,630,000 quotes in 2009. It is as if all of a sudden the Singapore dollar started to become more widely traded than ever before. With increasing volume, the underlying exchange rate volatility would also be expected to increase. How much effect would this have on the bid-ask spreads of the USD/SGD. We examine this using data from 1989, 2006, and 2009.

[1] USD/SGD and GDP figures obtained from Singapore Department of Statistics (singstat.gov.sg); Quotes volume obtained from Olsen Financial Technologies GmbH.

In 2006 the global economy had recorded a fourth consecutive year of strong growth despite the drag from crude oil prices, a buildup in global electronics inventories and adjustment in the US housing market. The MAS Annual Report for 2005/2006 reported that "despite higher oil prices, rising interest rates and natural disasters, the global economy expanded at a robust pace in 2005. This growth momentum continued unabated in the first quarter of 2006. The strength of the US economy was a major factor underpinning the continued growth of the world economy last year. The US economy displayed remarkable resilience against the backdrop of hurricane Katrina and 11 successive increases in the Fed funds rate from 2.25% at the beginning of 2005 to 5% in May 2006. In the first quarter of 2006, growth picked up strongly, led by a rebound in consumer spending and business investment spending on equipment and software."

The Singapore economy was also in a state of stability, as reported by the MAS Annual Report 2005/2006: "In the early months of 2006, some signs of easing in the domestic economy emerged with growth momentum slowing to 6.8% in Q1. However, this is not indicative of a broad-based slowdown, but rather a retraction to a more sustainable pace of growth."

In 2009 the world found itself in the midst of the worst global financial crisis ever since the Great Depression. The MAS Annual Report 2008/2009 reported that "2008 was a tumultuous year for the global economy. While the surge in commodity prices led to strong inflationary pressures in the first half of the year, the onset of the global financial crisis caused world growth to fall sharply in the later part of 2008 and into early 2009. The emergence of the Influenza A (H1N1) virus in recent months has added a new dimension of risk to the fragile global economy."

The global financial crisis, which saw the collapse of Lehman Brothers in September 2008, caused massive economic fallout worldwide. Amidst an erosion of confidence, global trade and industrial production collapsed in the first half of 2009, resulting in a 2.4% year-on-year contraction in world GDP over the same period. During this time, the quote volume for USD/SGD (over April and May) grew to over 1.6 million quotes, suggesting the increase in volatility in the exchange rate.

1.2 The Microstructure Approach to Exchange Rate Economics

Exchange rate economics, the branch of international economics and finance which attempt to explain the foreign exchange market, is an intriguing area of research.

There are many theories of exchange rate determination, from the open economy IS-LM models that are mandatory fare for any undergraduate economics course, to more advanced models such as the Mundell-Fleming model, the sticky/flexible-price monetary models, and the portfolio balance model. More recently, new open-economy macroeconomists attempt for formalize exchange rate in the context of dynamic general equilibrium models with explicit microfoundations, nominal rigidities and imperfect competition.

When tested against empirical evidence, these theories have various degrees of success in forecasting long-run exchange rates. All of them however are not able to convincingly explain short-run exchange rate fluctuations.

From a common-sense perspective, this is hardly surprising. If the long-run exchange rate between two countries is expected to change due to some shifting fundamental value (say productivity level, for example), how would any macro model (even one with microfoundations) designed to determine the "new" equilibrium exchange rate be able to take into account all the possible paths taken to transit from the "old" equilibrium rate to the "new" one? Some foreign exchange transactions between the two countries might be related to shifting fundamentals (e.g. import/export transactions), but others transactions may not (e.g. tourism, speculation in each others' asset markets, etc).

Macro foreign exchange models often assume that foreign exchange rates will move when fundamentals move. But foreign exchange rates can only move through a trading process in a foreign exchange market. Foreign exchange microstructurists study this trading process.

In his book, “The Microstructure Approach to Exchange Rates”, Richard Lyons (2001) defined “Order Flow” and “Bid-Ask Spreads”, two variables that are absent from the macro approach, as the two hallmarks of the microstructure approach. These are analogous to “Quantity” and “Price” in the dimension of exchange rates.

Order flow is essentially transaction volume which is “signed”, meaning it includes information if the transaction is a sale or a purchase. Such data is usually hard to come by and are proprietary to banks and other high-level participants in the foreign exchange market.

Well-connected researchers, such as Martin D. D. Evans and Richard K. Lyons managed to obtain proprietary data on all end-user EUR/USD trades received at Citibank over 6.5 years. In their 2007 paper “Exchange Rate Fundamentals and Order Flow", they tested and established four empirical results: (1) transaction flows forecast future macro variables such as output growth, money growth, and inflation, (2) transaction flows forecast these macro variables significantly better than the exchange rate does, (3) transaction flows (proprietary) forecast future exchange rates, and (4) the forecasted part of fundamentals is better at explaining exchange rates than standard measured fundamentals.

Data for the other hallmark, Bid-Ask Spreads, on the other hand, is much easier to obtain. In fact, the four datasets for this paper were purchased from Olsen Financial Technologies GmbH, while B&M obtained theirs by collecting every USD/DEM quote posted on the Reuters screen for the interbank foreign exchange market for three months in 1989. But other than being easily obtainable, Lyons highlighted that one reason spreads receive so much attention is because, being a core element of most data sets, they are a ready target for testable hypotheses. This is in contrast to other features in the trading that are not so easily measurable, such as information flow, belief dispersion, etc.

The behavior of bid-ask spreads in the foreign exchange markets offers many opportunities for research. For example, Table 1 below shows the distribution of over 600,000 USD/SGD quotes in April and May 2006, divided into nine categories of price and spread movements.

	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	32.46%	6.35%	3.53%
PRICE SAME	4.05%	7.52%	3.42%
PRICE DOWN	3.21%	6.60%	32.85%
Total	**39.73%**	**20.47%**	**39.81%**

Table 1: USD/SGD April-May 2006 Spread Behavior

Out of over 600,000 quotes over two months, the spread remained unchanged 6.35% of the time when the price moved up, and 6.60% of time when the price moved down. Though we may somewhat expect for spreads to move when prices move, what is intriguing is that when prices move up, spreads tended to widen 32.46% of the time, but yet narrowed only 3.53% of the time, Conversely, when prices move down, spreads tended to narrow 32.85% of the time but yet widened only 3.21% of the time.

Spread behavior like in the previous example may differ across different currencies within the same time period, and may also differ across different time periods within the same currency. The empirical objective of this paper is thus to examine the relationship between the bid-ask spread and the underlying exchange rate volatility from such two angles. The main currency for analysis is the USD/SGD. For comparison against a different currency within the same time period, we use B&M's results for the USD/DEM. For comparison against different time periods within the same currency, we perform this analysis for the USD/SGD from the months of April and May in 1989, 2006, and 2009. In addition, we also perform an empirical analysis on the phenomenon described above in Table 1.

1.3 Organization of Thesis

The rest of this paper shall be organized as follows: Chapter 2 begins with a review of microstructure papers which concerns bid-ask spreads, and ends with a description of B&M's model that relates volatility to bid-ask spreads. Chapter 3 describes B&M's empirical methodology and presents the empirical analyses for each dataset. Chapter 4 concludes.

2 Bid-Ask Spreads in Exchange Rates

As previously mentioned in Chapter 1, Lyons (2001) cites bid-ask spreads as one of the two hallmarks of the microstructure approach. Besides being relatively obtainable, he explained that spreads receive so much attention because they form a core element of most data sets and are a ready target for testable hypotheses. He also gave two more reasons for the heavy attention and resources focused on bid-ask spreads.

The second reason was because practitioners are "intensely concerned with managing trading costs". The third reason had to do with the history of the field of market microstructure which in its early days sought to distinguish itself from the literature on trading under rational expectations. Rational expectations models generally omit trading mechanisms when characterizing the relationship between fundamentals and price. Contrastingly market microstructure focused on how trading mechanisms affected prices, and this had led to "a focus on the determination of real-world transaction prices – spreads."

For the first section of this Chapter, guided by Sarno & Taylor (2002), we present a short survey on some early microstructure literature that concerns the determination of bid-ask spreads, and focus on "adverse selection" as a popular theme. We then present the views of a more contemporary paper which refutes “adverse selection” as a determinant of bid-ask spreads and proposes that asymmetric information might be a more plausible candidate.

From the second section of this Chapter we return to our main topic of interest – bid-ask spreads and exchange rate volatility. Similarly, following Sarno & Taylor (2002), we first present a short survey on the literature which analyses the proportional relationship between spreads and exchange rate volatility.

We then close this Chapter by presenting B&M’s simple asymmetric information model which forms the framework for our empirical investigation.

2.1 Bid-Ask Spreads and Asymmetric Information

Sarno & Taylor (2002) identifies three main determinants of the bid-ask spread: the cost of dealer services, inventory holding costs, and the cost of adverse selection.

Cost of Dealer Services

The cost of dealer services is formally analyzed by Demsetz (1968) who assumes the existence of some fixed costs of providing “predictable immediacy” as the service for which compensation is required by market makers. While Demsetz focused on the New York Stock Exchange, his definition for cost of dealer services could also be applicable to the foreign exchange market.

According to Demsetz, “predictable immediacy is a rarity in human actions, and to approximate it requires that costs be borne by persons who specialize in standing ready and waiting to trade with the incoming orders of those who demand immediate servicing of their orders. The ask-bid spread is the markup that is paid for predictable immediacy of exchange in organized markets; in other markets, it is the inventory markup of retailer or wholesaler”.

Inventory Holding Costs

The original argument of inventory costs as a crucial determinant of bid-ask spreads was first propositioned by Barnear & Logue (1975), who tested a modified theory of market-maker behavior first espoused by Bagehot (1971). Barnear & Logue modified the theory of the market-maker spread by distinguishing between the two major components of inventory risk. The second component, which they termed “marketability risk”, relates to the market maker's ability to make inventory adjustments when the market for an issue is "thin." They showed that volume has a negative effect on the bid-ask spread for two reasons: 1) high volume implies more competition if it implies more competition among alternative market makers; and 2) high volume implies less marketability risk, and, therefore, lower positioning costs.

Amihud & Mendelson (1980) considers the problem of a price-setting monopolistic market-maker in a Garman (1976) dealership market where the stochastic demand and supply are depicted by independent Poisson processes. The focus of their analysis is the dependence of the bid-ask prices on the market-maker's inventory position. They derived the optimal policy the results are shown to be consistent with some conjectures and observed phenomena, like the existence of a 'preferred' inventory position and the downward monotonicity of the bid-ask prices.

Ho & Stoll (1981) considers the stochastic dynamic programming problem of solving for the optimal behavior of a single dealer of a single stock who is faced with a stochastic demand for his services and return risk on his stock and on the rest of his portfolio. They show that as time unfolds and transactions occur, the dealer is able to set his bid price and ask price relative to his opinion of the "true" price of the stock so as to maximize the expected utility of terminal wealth. The bid-ask spread is given by a risk neutral spread that maximizes expected profits for the given stochastic demand functions plus a risk premium that depends on transaction size, the return variance of the stock and the dealer's attitude toward risk. The bid-ask spread does not depend on the dealer's inventory position, but the dealer's price adjustment does. When inventory increases both bid price and ask price decline, and the converse is true when inventory decreases.

Generally, inventory costs models assume that market-markers optimize their inventory holding, and generally imply that market-makers shift the spread downwards and increase the width of the spread when a positive inventory is accumulated.

Cost of Adverse Selection

Adverse selection is a common argument to explain the existence of bid-ask spreads. The origin of this argument could be traced back to Bagehot (1971), whose model includes two types of market participants – those are willing to pay the price of the spread to the market-maker in exchange for predictable immediacy and those who can speculate at the expense of the market-maker using some private insider information. An adverse selection arises because market-makers are not able to distinguish between the two types of participants and resort to widening the spreads for both types. The bid-ask spread then becomes the market-maker's defense against adverse selection in "in the form of exploitation of arbitrage opportunities". Since Bagehot, numerous microstructure papers have drawn on adverse selection as their primary interpretive framework.

Copeland & Galai (1983) analyses the determination of bid-ask spreads in organized financial markets, where the trading is done through economic agents who specialize in market-making for a limited set of securities. The commitment made by dealers to buy or sell at the bid and ask prices, respectively, is analyzed as a combination of put and call options. Given the behavior of liquidity traders and informed traders, the dealer is assumed to offer an out-of-the-money straddle option for a fixed number of shares during a fixed time interval. The exercise prices of the straddle determine the bid-ask spread. The dealer establishes his profit maximizing spread by balancing the expected total revenues from liquidity trading against the expected total losses from informed trading. They showed that a monopolistic dealer will establish a wider bid-ask spread than will perfectly competitive dealers, and that the bid-ask spread increases with greater price volatility in the asset being traded, with a higher asset price level, and with lower volume.

Glosten & Milgrom (1985) analyzed a model of a securities market in which the arrival of traders over time is accommodated by a market-maker. They showed that adverse selection, by itself, could account for the existence of a bid-ask spread, and the average magnitude of the spread depends on many parameters, including the exogenous arrival patterns of insiders and liquidity traders, the elasticity of supply and demand among liquidity traders, and the quality of the information held by insiders. They also showed that, because transaction prices are informative, bid-ask spreads tend to decline with trade.

Lyons (1995) was likely one of the first who departed from early microstructure work that focused almost entirely on stock markets and applied such theory to foreign exchange markets. He presented a model which incorporated a number of institutional features relevant to the FX market, such as the facts that major currencies are traded in decentralized dealership markets; that over 80% of the trading volume is between market-makers; that market net volume is only partially observable; and that customer order flow is an important source of private information. Lyons showed that trade size and the bid-ask spreads of a particular dealer were positively related.

Payne (2003) estimates a VAR decomposition of interdealer trades and quotes and interprets the results through the lens of adverse selection. Specifically, he used one trading week's worth of USD/DEM data derived from an electronic foreign exchange brokerage and employed the framework contained in Hasbrouck & Sofianos (1993) to test for the existence of private information effects of trading on prices. His basic results confirm the existence of private information on FX markets, indicating that adverse selection costs account for around 60% of the half-spread.

Osler, Mende & Menkhoff (2006) however shows evidence that the behavior of bid-ask spreads is inconsistent with adverse selection. They outline three factors that seem likely to be important. The first factor, fixed operating costs, can explain the negative relation between trade size and bid-ask spreads if some costs are fixed, but cannot explain the cross-sectional variation across customer types. To explain why bid-ask spreads are larger for commercial than financial customers they suggest that asymmetric information – in the broad sense of information that is held by some but not all market participants – may influence spreads through two channels distinct from adverse selection, one involving market power and a second involving strategic dealing.

The market power hypothesis suggests that firms, even in a market with hundreds of competitors like foreign exchange, gain market power from holding information. It can be costly for customer firms to search out the best available quotes in the foreign exchange market, so each individual dealer can exert a certain amount of market power despite the competition. As suggested in Green et al. (2005), dealers may quote the widest spreads when their market power is greatest, and market power in quote-driven markets depends on knowledge of current market conditions. In foreign exchange, commercial customers typically know far less about market conditions than financial customers so they might be expected to pay wider spreads, as they do.

The second channel through which asymmetric information might affect bid-ask spreads in foreign exchange involves strategic dealing. Building on abundant evidence that customer order flow carries information (e.g., Evans and Lyons

(2007), Daníelsson et al. (2002)), Osler et al argue that rational foreign exchange dealers might strategically vary spreads across customers, subsidizing spreads to informed customers in order to gain information which they can then exploit in upcoming interbank trades. In standard adverse-selection models, by contrast, dealers passively accept the information content of order flow. The idea that dealers strategically vary spreads to gather information was originally explored in Leach and Madhavan (1992, 1993). When applied to two-tier markets in Naik et al. (1999) it implies that bid-ask spreads will be narrower for trades with information, consistent with the pattern in foreign exchange.

2.2 Bid-Ask Spreads and Volatility

The directly proportional relationship between bid-ask spreads and exchange rate volatility now represents a fairly stylized fact in the microstructure literature. Early studies modeled the spread as a function of transaction costs, the bank's profit from providing liquidity services, and the market-maker's payoff for facing the exchange rate risk when assuming an open position. The main conclusions of these early studies are that exchange rate spreads are wider under floating exchange rate than under fixed-exchange rate regimes (e.g. Aliber, 1975), and that measures of exchange rate volatility are followed closely by exchange rate spreads (e.g. Fieleke, 1975; Overturf, 1982).

Glassman (1987) provides a significant contribution to this literature in that she builds a model where variables representing transactions frequency are included explicitly and the non-normality of the distribution of exchange rates is taken into account. The model not only provides additional evidence on the proportional relationship between exchange rate volatility and bid-ask spreads in the foreign exchange market, but also suggests that market-makers consider moments of the exchange rate higher than the second moment in order to evaluate the probability of large exchange rate changes.

Admanti & Pfleiderer (1988) provides another fundamental theoretical contribution to this area. In their model, there are three types of agents: informed traders, who have relatively superior information and only trade on terms favorable to them; discretionary liquidity traders, who must trade during a day but can choose when to trade during the day in order to minimize costs; and non-discretionary liquidity traders, who must trade at a precise time during the day regardless of the cost. In this model, trading volume is explained by the concentration of trade of informed traders and discretionary liquidity traders at certain points in time: the concentrations occur because it is profitable for informed traders to trade when there are many liquidity traders who do not have the same information as themselves and because discretionary liquidity traders are attracted because the larger the number of traders lowers the cost of trading.

Bollerslev & Domowitz (1993) used intradaily data to investigate the behavior of quote arrivals and bid-ask spreads. They recorded quote arrivals and bid-ask spreads over the trading day, across geographical locations as well as across market participants. They found that trading activity and the bid-ask spreads for traders whose activity is restricted to regional markets can be described by a U-shaped distribution, which is consistent with Admanti & Pfleiderer's (1989) model. The patterns of trading activity and spreads during the day also strongly suggest some degree of traders' risk aversion, given which, the more trading activity is executed by informed traders, the higher the cost of trading.

Goodhart & Figliuoli (1991) reported a study of minute bid-ask quotes on three days in 1987 at a Reuters screen and found evidence that leptokurtosis and heteroscedasticity are time-varying, and are less pronounced at the minute-by-minute frequency than at lower frequencies. They also found that trading volume is time-varying, being higher at the European and North American openings and lower at the European lunch hour. The series was also found to exhibit first-order negative serial correlation, which is especially pronounced after immediately after jumps in the exchange rate. Multivariate analysis suggested significant relationships between lagged exchange rates and the current spot rate.

2.3 Bollerslev & Melvin's Model of Volatility and Bid-Ask Spread

B&M is the main inspiration for this thesis, providing most importantly a methodology to analyze the relationship between bid-ask spreads of exchange rates and its underlying volatility.

In the early 1990's as B&M were writing their paper, the bid-ask spread component of transactions costs in the foreign exchange market had not received much attention in the literature. Earlier studies on the subject, such as Glassman (1987) and Boothe (1988), concentrated on the own statistical properties of the spread. Researchers, such as Goodhart (1990), Bossaerts and Hillion (1991), Black (1991), Melvin and Tan (1996) and Bollerslev and Domowitz (1993), had attempted to offer empirical and theoretical analyses of the determinants of foreign exchange market spreads, but no one had performed any explicit analysis of the relationship between the magnitude of foreign exchange market spreads and the underlying exchange rate volatility. Hence, B&M is likely to be the first paper to touch on this subject.

B&M opined that while unambiguous 'good' or 'bad' news regarding the fundamentals of the exchange rate should have no systematic effect on the spread, as both the bid and the ask prices should adjust in the same direction in response to the traders receiving buy or sell orders that reflect the particular news event, however greater uncertainty regarding the future spot rate, as associated with greater volatility of the spot rate, is likely to result in a widening of the spread.

We now outline B&M's simple theoretical framework that illustrates this role of volatility in determining the spread.

The formal setup for B&M's stylized market microstructure model is based on the analysis in Glosten and Milgrom (1985), Admati and Pfleiderer (1989), and Andersen (1993).

The model assumes that the foreign exchange market comprises two kinds of traders: liquidity traders and information-based traders. Liquidity traders participate in foreign exchange transactions only due to the needs of their normal business activity which require international trade of goods, services and financial assets. They are also not speculators. Information-based traders profit by intermediating the demands and supplies of foreign exchange for the liquidity traders. These traders also take positions in the foreign exchange market based on information advantages received through their dealings with the liquidity traders or, more generally, information asymmetries regarding fundamentals underlying the determination of the spot exchange rate.

The liquidity traders constitute the proportion (1—λ) of the total market participants. The liquidity traders receive a signal to either buy or sell foreign currency regardless of the actual value of the currency in comparison with the bid or ask prices prevailing at the time. Informed traders constitute the remaining λ proportion of the market. This group of traders receives some information about the true underlying fundamental value of the exchange rate s_t. This fundamental value is assumed to evolve over time according to a martingale model,

$$s_t = s_{t-1} + \varepsilon_t, \qquad (1)$$

where $E_{t-1}(\varepsilon_t)=0$, $E_{t-1}(\varepsilon_t^2)= \sigma_t^2$, and $E_{t-1}(\bullet)$ denotes the conditional expectation based on the information set generated by the past values of s_t. B&M further assumes that the standardized innovations, $\varepsilon_t\sigma_t^{-1}$, are independent and symmetrically, but not necessarily identically, distributed through time.

At time $t-1$, one of the many market-making traders will set bid and ask quotes, B_t and A_t, good for trading at time t. The bid-ask spread is assumed to be set symmetrically around the known fundamental price prevailing at the time of quote formation, i.e. $A_t = s_{t-1} + k_{t,t-1}$, and $B_t = s_{t-1} – k_{t,t-1}$. Thus, the quoted spread for trades at time t, $K_t = A_t, - B_t = 2k_{t,t-1}$ depends on time $t-1$ information only.

Trades at existing quotes will generate losses, on average, for the market-maker when the opposite party an information-based trader. Information-based traders, who received the signal ε_t buy currency if $A_t < s_t$ and sell currency if $s_t, < B_t$. For values of $B_t \leqslant s_t \leqslant A_t$, the information-based traders cannot profit from knowing the true fundamental value revealed by ε_t. The liquidity traders only know s_{t-1} and expect ε_t to equal zero.

Trader positions are limited by the convention that existing quotes are only good for up to some maximum quantity of currency. Assuming that the market-makers limit trading to one unit of currency at existing quotes, the loss for the quoting trader relative to the true value s_t arising from informed trading is therefore

$$\pi_t^{\mathrm{i}} = \min[s_t - B_t, 0, A_t - s_t] = \min[\varepsilon_t + k_{t,t-1}, 0, k_{t,t-1} - \varepsilon_t]. \quad (2)$$

Let $P_{t-1}(\bullet)$ denote the probability conditional on the time $t-1$ information. Since the standardized innovations, $Z_t = \varepsilon_t \sigma_t^{-1}$, are assumed to be independent and symmetrically distributed through time, the expected loss from informed trading may be expressed as

$$\begin{aligned} \mathrm{E}_{t-1}(\pi_t^{\mathrm{i}}) &= \mathrm{E}_{t-1}(\varepsilon_t + k_{t,t-1} \mid \varepsilon_t + k_{t,t-1} < 0) P_{t-1}(\varepsilon_t + k_{t,t-1} < 0) \\ &\quad + \mathrm{E}_{t-1}(k_{t,t-1} - \varepsilon_t \mid k_{t,t-1} - \varepsilon_t < 0) P_{t-1}(k_{t,t-1} - \varepsilon_t < 0) \\ &= 2[k_{t,t-1} - \mathrm{E}_{t-1}(\varepsilon_t \mid k_{t,t-1} < \varepsilon_t)] P_{t-1}(k_{t,t-1} < \varepsilon_t) \\ &= 2[k_{t,t-1} - \sigma_t \mathrm{E}(Z_t \mid k_{t,t-1}\sigma_t^{-1} < Z_t)][1 - P(Z_t < k_{t,t-1}\sigma_t^{-1})] < 0. \end{aligned} \quad (3)$$

Assuming an equal probability of a buy or a sell order from the liquidity traders, it follows that the expected profit for the quoting trader conditional on an uninformed trade equals:

$$E_{t-1}(\pi_t^u) = E_{t-1}(\tfrac{1}{2}(A_t - s_t) + \tfrac{1}{2}(s_t - B_t)) = k_{t,t-1} > 0. \quad (4)$$

Combining the expected trading loss in Eq. (3) with the gain in Eq. (4) yields the expected profit for the market-maker conditional on time *t-1* information:

$$\begin{aligned} E_{t-1}(\pi_t) &= E_{t-1}(\pi_t^i + \pi_t^u) \\ &= 2\lambda[k_{t,t-1} - \sigma_t E(Z_t \mid Z_t > k_{t,t-1}\sigma_t^{-1})][1 - P(Z_t < k_{t,t-1}\sigma_t^{-1})] \\ &\quad + (1-\lambda)k_{t,t-1}. \quad (5) \end{aligned}$$

In equilibrium, competition from other banks or market-makers will drive this expected profit to zero. Expressing this zero profit condition in terms of the total spread, $K_t = 2k_{t,t-1}$ yields

$$\begin{aligned} K_t &= \sigma_t 4\lambda E(Z_t \mid Z_t > k_{t,t-1}\sigma_t^{-1})[1 - P(Z_t < k_{t,t-1}\sigma_t^{-1})] \\ &\quad \times [1 + \lambda - 2\lambda P(Z_t < k_{t,t-1}\sigma_t^{-1})]^{-1}. \quad (6) \end{aligned}$$

Since the conditional expectation and probabilities on the right-hand side of Eq. (6) only depend on the time *t-1* information set through $\sigma_{t-1}k_{t,t-1}$, it follows that in equilibrium the spread must move proportional to the conditional standard deviation of the true fundamental value of the exchange rate.

B&M noted that while this simple proportionality condition would no longer hold true in a more general model with endogenous information acquisition, the result that an increase in σ_t^2 leads to an increase in K_t would still remain generally valid.

Based on this relationship between exchange rate volatility and the bid-ask spread, B&M designed the empirical methodology that we will describe in the next chapter.

3 Empirical Analysis

B&M performed an empirical analysis on the USD/DEM, one of the most highly-traded currency pair between two of the largest economies in the world in 1989 and showed that the size of the bid-ask spread of the USD/DEM is positively related to its underlying exchange rate uncertainty. The USD/DEM is a free-floating exchange rate. Their dataset consist of more than 300,000 continuously recorded USD/DEM quotes over a 3 month period from April to June in 1989.

We are curious if 1) B&M's result would hold for the USD/SGD, a semi-floating currency from a much smaller economy, where over the same period from April to May 1989, there were only slightly over 8,000 quotes; 2) B&M's result would hold 17 years later for that same currency, as that country becomes a significant regional economic power in South-east Asia, and when the volume of quotes increased to over 600,000 over April and May 2006.; and 3) B&M's result would hold as that economy enters into a period of worldwide financial crisis.

For the above purposes we purchased four sets of data from Olsen Financial Technologies GmbH. Before we discuss the data and empirical results, we first describe B&M's empirical methodology and how we adapted it for this paper.

3.1 Empirical Methodology

B&M's empirical methodology comprises two major steps.

Step 1: Creating a Proxy for Exchange Rate Volatility

The first step involves using a GARCH model as an explicit proxy for the time-varying volatility of the spot rate, and as noted by Bollerslev et al. (1992), such representations have been documented by numerous studies. B&M employed a two-stage estimation procedure in which the conditional variance for the spot exchange rate is first estimated as a GARCH process. These estimates for the conditional variance are then used as the proxy for exchange rate volatility in the second-stage model for the temporal behavior of the spread.

B&M use the ask price for estimation purposes; the bid and ask prices have virtually identical higher order moments and differ only very slightly in their conditional means. They found that the MA(1)-GARCH(1,1) model of the form below seemed to fit their dataset well:

$$10{,}000\Delta \log A_t = \mu + \theta\varepsilon_{A,t-1} + \varepsilon_{A,t},$$
$$\sigma^2_{A,t} = \omega + \alpha\varepsilon^2_{A,t-1} + \beta\sigma^2_{A,t-1},$$
$$\varepsilon_{A,t} \mid I_{t-1} \sim \mathrm{N}(0, \sigma^2_{A,t}), \qquad (7)$$

where I_{t-1} denotes the time $t\text{-}1$ information set, and μ, θ, ω, α, and β are the parameters to be estimated. The time t subscript refers to the place in the order of the series of quotes, so that $\sigma_{A,t}^2$ provides an estimate of the price volatility between quotes.

The particular specification for the conditional variance in Eq. (7) may be justified by the theoretical arguments in Nelson (1990, 1992). Intuitively, if the sample path for the true unobservable volatility process is continuous, it follows that on interpreting the GARCH(1,1) model as a non-parametric estimator, or a one-sided filter, the resulting estimates for the conditional variance will generally be consistent as the length of the sampling interval goes to zero.

The primary purpose of the GARCH estimation was to create proxies for the conditional variance of the exchange rate to be used in the investigation of the determinants of the spread.

But it was 1993 then, and B&M noted that estimating a GARCH model with more than 300,000 observations in practice was not feasible in practice. Hence, they divided up their dataset into 12 weeks of data and estimated each set for the above GARCH parameters. They then saved all the estimates for the conditional variances from each of the 12 models and combined into a single time series of volatility estimates for the full set of weekday quotes. Today, we use modern econometrics software EViews to perform GARCH analysis on our datasets and to obtain the conditional variance time series.

Step 2: Estimate Relationship between Spreads and Proxy for Volatility

The second major step of the methodology involved using ordered response models to estimate the relationship between the time series of volatility estimates obtained in the first step and the bid-ask spreads.

Specifically, B&M used an Ordered Probit model with multiplicative heteroskedasticity for this purpose.

The observed spread, K_t, is assumed to take on only a fixed number of discrete values, a_1, a_2, … a_J. The unobservable continuous random variable, K*, is defined by

$$K^*_t = X_i'\beta + \varepsilon_{K,t} \qquad (8)$$

The vector X_t denotes a set of predetermined variables that affect the conditional mean of K^*_t and $\varepsilon_{K,t}$, is conditionally normally distributed with mean zero and variance, $\varepsilon^2_{K,t}$

$$\varepsilon_{K,t} \mid I_{t-1} \sim N(0, \sigma^2_{K,t}). \qquad (9)$$

B&M allowed for multiplicative heteroskedasticity in the spread by parameterizing the logarithm of $\sigma^2_{K,t}$ as a linear function of the same explanatory variables that enter the conditional mean of K^*_t.

We depart from this path in our analysis, firstly by omitting multiplicative heteroskedasticity (more due to the limitations of EViews than by choice), and secondly by estimating the relationships with both Ordered Probit models and Ordered Logit models (to allow more flexibility in the behaviour of the error term, since we omitted multiplicative heteroskedasticity).

In our analyses, the observed spread, K_t, is similarly assumed to take on only a fixed number of discrete values, a_1, a_2, … a_J, but the unobservable continuous random variable, K*, is defined by

$$K^*_t = X_i'\beta + \varepsilon \qquad (10)$$

where ε is i.i.d. standard normal for the Ordered Probit model, and takes the form of the logistic distribution for the Ordered Logit model.

The ordered response models relate the observed spreads to K^* via

$$K_t = a_j, \quad \text{iff} \quad K^*_t \in A_j, \quad j = 1, 2, \ldots, J, \qquad (11)$$

where the A_j's form an ordered partition of the real line into J disjoint intervals.

The probability that the spread takes on the value a_j is equal to the probability that K^* falls into the appropriate partition, A_j.

For tractability reasons, B&M based the empirical analysis on a classification of the spread into only four different categories. From the distribution of spreads of the USD/DEM in 1989, the four most commonly observed spreads account for 97.0 percent of the total quotes.

USD/DEM

Frequency Distribution fof Spreads		
Spread	All Quotes	
0 < . < 5	2,304	(0.8%)
5	77,856	(25.6%)
5 < . < 7	607	(0.2%)
7	34,878	(11.5%)
7 < . < 10	2,977	(1.0%)
10	170,892	(56.1%)
10 < . < 15	329	(0.1%)
15	11,534	(3.8%)
15 < . < 20	39	(0.0%)
20	2,616	(0.9%)
20 < .	572	(0.2%)
Note: Spreads converted into basis points		

Table 2: Distribution of Spreads of USD/DEM April-June 1989

We also performed the ordered response analyses with four ordered indicator values. In addition, as we will see later, because the spreads distribution for the USD/SGD 2006 and 2009 data have more converging points (certain spread sizes where there are more quotes than others) than both the USD/DEM and the USD/SGD in 1989, we used up to 10 ordered indicator values in our own ordered response analyses.

In the case of B&M where by four ordered indicator values of a_j's were used, the corresponding intervals for the unobservable latent variable K* are defined by:

$$A_1 \equiv]\infty, \mu_0],$$

$$A_2 \equiv]\mu_0, \mu_1],$$

$$A_3 \equiv]\mu_1, \mu_2],$$

$$A_4 \equiv]\mu_2, \infty[. \qquad (12)$$

The partition parameters, μ_I, are estimated jointly with the other parameters of the model.

The ordered response model defined above allows us to estimate the probability of a particular spread being observed as a function of the predetermined variables, X_t. In order to test the hypothesis that the spread is partly determined by the volatility of the spot rate, the GARCH estimate of the conditional variance for the ask prices is included as one of the elements in X_t.

B&M noted that Bollerslev and Domowitz (1993) indicated a distinct intra-day pattern in the spread distribution and tt is possible that any significant effect of the conditional variance in isolation may merely reflect this dependence rather than provide an independent influence on the spread process. In order to take account of this own temporal dependence, K_{t-1} was included as an element of the X_t vector in the estimation of the ordered response functions for K^*_t:

$$\mathbf{K_t^* = \delta_1\sigma_{A,t}^2 + \delta_2 K_{t-1} + \varepsilon} \qquad (13)$$

Given the partition boundaries determined by the data, if a higher conditional mean $\sigma' X$, is caused by a larger conditional variance of the spot rate, and this raises the probability of observing a higher spread, we will infer that the hypothesized theoretical link is supported by the empirical analysis.

We now describe each of the datasets in more details in the following section:

3.2 Description of the Data

We purchased four sets of data from Olsen Financial Technologies GmbH:

a. Dataset 1 – USD/DEM quotes from April 1989 to June 1989

b. Dataset 2 – USD/SGD quotes from April 1989 to June 1989

c. Dataset 3 – USD/SGD quotes from April 2006 to May 2006

d. Dataset 4 – USD/SGD quotes from April 2009 to May 2009

Dataset 1: USD/DEM from April 1989 to June 1989

For the first dataset we purchased the same dataset used by B&M – USD-DEM quotes from April 1989 to June 1989. We wanted to repeat the empirical analysis on the dataset again to allow for an apples-to-apples comparison between the USD/DEM 1989 and the USD/SGD 1998 results.

First, B&M's results were obtained in 1993 using probably not so technologically advanced means. We wanted to repeat the estimation processes again using EViews. Furthermore, as mentioned in the previous Chapter, we departed from B&M's ordered probit procedure by omitting multiplicative heteroskedasticity. Second, B&M's data were obtained from Reuters. From their paper we were unable to ascertain the accuracy of this data, or how they presented 12 workweeks of data from an actual 13 weeks in April to June 1989. We obtained ours by purchasing from Olsen Financial Technologies GmbH and upon comparison, we found some minor differences. The differences between our purchased data and the actual data used by B&M are tabulated as follows:

a. Volume of Quotes

ORIGINAL BOLLERSLEV & MELVIN

DAY	TICKS	
Sun	887	0.29%
Mon	60,095	19.66%
Tue	66,109	21.63%
Wed	63,812	20.88%
Thu	61,521	20.13%
Fri	53,082	17.37%
Sat	98	0.03%
Grand Total	305,604	100.00%

PURCHASED FROM OLSENDATA

DAY	TICKS	
Sun	1,571	0.51%
Mon	56,600	18.25%
Tue	67,634	21.80%
Wed	66,325	21.38%
Thu	61,377	19.79%
Fri	56,646	18.26%
Sat	33	0.01%
Grand Total	310,186	100.00%

Table 3: Quote Volume differences between B&M and Purchased Data USD/DEM 1989

B&M collected 305,604 ticks of USD/DEM quotes while the dataset purchased from Olsen Financial Technologies GmbH contains 310,186 ticks. The distribution of the quotes over each workday is similar in terms of percentage in both datasets.

b. Frequency of No Spread Change

USD/DEM			
No. of Quotes, & Frequency of No Spread Change			
		No Change in Spread	
	Number	Bid-Ask Rise	Bid-Ask Fall
All quotes	304,619	8.00%	8.30%

Table 4: Frequency of No Spread Change reported by B&M USD/DEM 1989

B&M reported that 8% of all the quotes observed no change in spread when the bid-ask price rose and that 8.3% of all the quotes observed no change in spread when the bid-ask price fell. It was not clear, however, whether these percentages where calculated based on Number of Ticks with No Spread Change divided by Number of Ticks Moved, or on Number of Ticks with No Spread Change divided by Total Number of Ticks. We make this distinction clearer with the purchased data.

	NO. OF QUOTES		
	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	64384	32787	23767
PRICE SAME	13083	39422	13523
PRICE DOWN	24045	33407	64164
Grand Total	101512	105616	101454

	DIVIDED BY NO OF TICKS MOVED		
	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	53.24%	27.11%	19.65%
PRICE SAME	19.81%	59.70%	20.48%
PRICE DOWN	19.77%	27.47%	52.76%
GRAND TOTAL	32.90%	34.23%	32.88%

	DIVIDED BY TOTAL NO. OF TICKS		
	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	20.86%	10.63%	7.70%
PRICE SAME	4.24%	12.78%	4.38%
PRICE DOWN	7.79%	10.83%	20.79%
GRAND TOTAL	32.90%	34.23%	32.88%

Table 5: Frequency of No Spread Change with Olsen USD/DEM 1989

Among all ticks, we counted that 10.63% and 10.83% of all ticks observed no change in spreads when the price rose and fell respectively.

c. Frequency Distribution of Spreads

Frequency Distribution of Spreads

Spread	ORIGINAL		OLSENDATA	
0 < . < 5	2,304	(0.8%)	2,562	(0.8%)
5	77,856	(25.6%)	81,368	(26.4%)
5 < . < 7	607	(0.2%)	660	(0.2%)
7	34,878	(11.5%)	35,682	(11.6%)
7 < . < 10	2,977	(1.0%)	3,192	(1.0%)
10	170,892	(56.1%)	171,264	(55.5%)
10 < . < 15	329	(0.1%)	327	(0.1%)
15	11,534	(3.8%)	10,389	(3.4%)
15 < . < 20	39	(0.0%)	38	(0.0%)
20	2,616	(0.9%)	2,547	(0.8%)
20 < .	572	(0.2%)	553	(0.2%)
Note: Spreads converted into basis points				

Table 6: Frequency Distribution of Spreads USD/DEM 1989

It appears that the frequency distribution of spreads is quite similar between the dataset reported by B&M and the dataset purchased from Olsen Financial Technologies GmbH. The most common bid-ask spread is 10 basis points, followed by 5 basis points.

Dataset 2: USD/SGD from April 1989 to June 1989

The second dataset are USD/SGD quotes from April 1989 to June 1989.

a. Volume of Quotes

DAY	USD/SGD	
Sun	6	0.07%
Mon	1,307	15.43%
Tue	2,024	23.89%
Wed	1,876	22.14%
Thu	1,652	19.50%
Fri	1,586	18.72%
Sat	21	0.25%
Grand Total	8,472	100.00%

Table 7: Volume of Quotes of USD/SGD April-June 1989

Compared against a major currency in 1989 over the same period from April to June, there are only 8,472 USD/SGD quotes compared to over 310,000 for the USD/DEM. Distribution of the quotes over the week are however quite similar, with volume peaking during midweek.

b. Frequency of No Spread Change

Compared against the USD/DEM in 1989 over the same period from April to June, we do not observe as much spread changes in the USD/SGD when prices moves. When prices move upwards, the spread remained unchanged 89.21% of the time. When prices move downwards, the spread remained unchanged 90.62% of the time.

	NO. OF QUOTES		
	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	87	3108	289
PRICE SAME	62	1340	63
PRICE DOWN	256	3168	72
Grand Total	405	7616	424

	DIVIDED BY NO OF TICKS MOVED		
	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	2.50%	89.21%	8.30%
PRICE SAME	4.23%	91.47%	4.30%
PRICE DOWN	7.32%	90.62%	2.06%
GRAND TOTAL	4.80%	90.18%	5.02%

	DIVIDED BY TOTAL NO. OF TICKS		
	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	1.03%	36.80%	3.42%
PRICE SAME	0.73%	15.87%	0.75%
PRICE DOWN	3.03%	37.51%	0.85%
GRAND TOTAL	4.80%	90.18%	5.02%

Table 8: Frequency of No Spread Change for USD/SGD April-June 1989

c. Frequency Distribution of Spreads

Frequency Distribution of Spreads		
Spread	USD/SGD	
0 < . < 5	6	(0.1%)
5	137	(1.6%)
5 < . < 7	22	(0.3%)
7	122	(1.4%)
7 < . < 10	43	(0.5%)
10	7,854	(93.0%)
10 < . < 15	6	(0.1%)
15	76	(0.9%)
15 < . < 20	1	(0.0%)
20	164	(1.9%)
20 < .	14	(0.2%)
Note: Spreads converted into basis points		

Table 9: Frequency Distribution of Spreads USD/SGD April-June 1989

While spread changes in the USD/SGD are uncommon when prices moves, we note similar characteristics to the USD/DEM in that the most common bid-ask spread is 10 basis points. When spreads do change, they are most likely to be 5, 7 or 20 basis points.

Dataset 3: USD/SGD from April 2006 to May 2006

The third dataset are USD/SGD quotes from April 2006 to May 2006.

a. Volume of Quotes

DAY	USD/SGD	
Sun	3,832	0.63%
Mon	104,327	17.24%
Tue	126,812	20.96%
Wed	147,084	24.31%
Thu	135,037	22.32%
Fri	87,332	14.44%
Sat	555	0.09%
Grand Total	604,979	100.00%

Table 10: Volume of Quotes of USD-SGD April-May 2006

15 years later, the USD/SGD has grown to become a major currency in Southeast Asia. Compared against itself in 1989 over the period from April to May, the volume of quotes of the USD/SGD has grown from over 8,400 ticks in

3 months to over 604,000 ticks in 2 months. The distribution of quotations over the week remains consistent with volume peaking during midweek.

b. Frequency of No Spread Change

In 2006, we observed that the tendency for spreads to remain unchanged when prices move is reduced dramatically. Now, when prices move upwards, the spread remained unchanged only 14.99% of the time compared to 89.21% of the time in 1989. When prices move downwards, the spread remained unchanged only 15.46% of the time compared to 90.62% of the time in 1989.

	NO. OF QUOTES		
	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	194955	38121	21197
PRICE SAME	24340	45185	20568
PRICE DOWN	19302	39611	197313
Grand Total	238597	122917	239078

	DIVIDED BY NO OF TICKS MOVED		
	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	76.67%	14.99%	8.34%
PRICE SAME	27.02%	50.15%	22.83%
PRICE DOWN	7.53%	15.46%	77.01%
GRAND TOTAL	39.73%	20.47%	39.81%

	DIVIDED BY TOTAL NO. OF TICKS		
	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	32.46%	6.35%	3.53%
PRICE SAME	4.05%	7.52%	3.42%
PRICE DOWN	3.21%	6.60%	32.85%
GRAND TOTAL	39.73%	20.47%	39.81%

Table 11: Frequency of No Spread Change for USD-SGD April-May 2006

c. Frequency Distribution of Spreads

Frequency Distribution of Spreads

Spread	USD/SGD	
0 < . < 5	51,090	(8.5%)
5	224,763	(37.2%)
5 < . < 7	51,163	(8.5%)
7	68,377	(11.3%)
7 < . < 10	53,582	(8.9%)
10	155,466	(25.7%)
10 < . < 15	25	(0.0%)
15	17	(0.0%)
15 < . < 20	15	(0.0%)
20	1	(0.0%)
20 < .	0	(0.0%)
Note: Spreads converted into basis points		

Table 12: Frequency Distribution of Spreads USD-SGD April-June 2006

The characteristics of the frequency distribution of spreads have also changed almost completely over 15 years. The most common spread in 2006 is 5 basis points, followed by 10 basis points. Most of the spreads recorded are either 10 basis points or lower, while quotes with spreads of more than 10 basis points make up less than 0.01% of the entire spectrum of quotes.

Dataset 4: USD/SGD from April 2009 to May 2009

The fourth dataset are USD/SGD quotes from April 2009 to May 2009.

a. Volume of Quotes

DAY	**USD/SGD**	
Sun	9,336	0.87%
Mon	183,055	17.02%
Tue	217,496	20.22%
Wed	237,508	22.08%
Thu	237,604	22.09%
Fri	190,603	17.72%
Sat	32	0.00%
Grand Total	1,075,634	100.00%

Table 13: Volume of Quotes of USD/SGD April-May 2009

In the year of the 2009 economic crisis, we observed a dramatic increase in volume of USD-SGD quotes over the period of April to May 2009, as compared to the same period in 2006, although we noted earlier that the volume growth had been exponential since 2002. The volume of quotes of the USD-SGD has grown from over 604,000 ticks, to exceeding 1 million quotes over a 2 month period.

b. Frequency of No Spread Change

We now observed that in 2009, the tendency for spreads to remain unchanged when prices moved is reduced again compared to 2006. Now, when prices move upwards, the spread remained unchanged 10.17% of the time compared to 14.99% of the time in 1989. When prices move downwards, the spread remained unchanged 9.76% of the time compared to 15.46% of the time in 2006.

	NO. OF QUOTES		
	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	304279	48129	120968
PRICE SAME	59290	18050	53790
PRICE DOWN	120972	45055	295733
Grand Total	484541	111234	470491

	DIVIDED BY NO OF TICKS MOVED		
	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	64.28%	10.17%	25.55%
PRICE SAME	45.21%	13.76%	41.02%
PRICE DOWN	26.20%	9.76%	64.04%
GRAND TOTAL	45.44%	10.43%	44.13%

	DIVIDED BY TOTAL NO. OF TICKS		
	SPREAD UP	SPREAD SAME	SPREAD DOWN
PRICE UP	28.54%	4.51%	11.35%
PRICE SAME	5.56%	1.69%	5.04%
PRICE DOWN	11.35%	4.23%	27.74%
GRAND TOTAL	45.44%	10.43%	44.13%

Table 14: Frequency of No Spread Change for USD-SGD April-May 2009

c. Frequency Distribution of Spreads

Frequency Distribution of Spreads

Spread	USD/SGD	
<2.00	13	(0.0%)
2	13,684	(1.3%)
2.00 < . < 3.00	8,422	(0.8%)
3	54,432	(5.1%)
3.2	20,407	(1.9%)
3.20 < . < 3.50	6,484	(0.6%)
3.5	114,907	(10.7%)
3.50 < . < 4.00	10,882	(1.0%)
4	88,441	(8.2%)
4.00 < . < 5.00	13,748	(1.3%)
5	59,572	(5.5%)
5.00 < . < 6.00	6,932	(0.6%)
6	54,354	(5.1%)
6.00 < . < 7.00	2,903	(0.3%)
7	165,828	(15.4%)
7.00 < . < 8.00	2,080	(0.2%)
8	268,577	(25.0%)
8.00 < . < 9.00	1,158	(0.1%)
9	39,789	(3.7%)
9.00 < . < 10.00	830	(0.1%)
10	91,613	(8.5%)
10.00 < . < 11.00	579	(0.1%)
11	11,304	(1.1%)
> 11.00	38,696	(3.6%)
Note: Spreads converted into basis points		

Table 15: Frequency Distribution of Spreads USD-SGD April-May 2009

The characteristics of the frequency distribution of spreads have changed again over 3 years. The most common spread in 2006 was 5 basis points, followed by 10 basis points. In 2009, the most common spread had risen to 8 basis points, followed by 7 basis points and 3.5 basis points respectively. Most of the spreads recorded are still either 10 basis points or lower, but quotations with spreads of more than 10 basis points have increased to slightly under 5% of the entire spectrum of quotations.

Two observations are of noteworthy regarding the 2009 dataset. First, the most common spreads are no longer “significant” numbers such as 5 or 10. This could indicate advancement in the market’s ability to evaluate foreign exchange risk, and hence being able to price bids and asks more accurately. Second, the volume of quotes with spreads of more than 10 basis points increased from 0.01% in 2006 to slightly under 5% in 2009. This could be attributed to the increased amount of uncertainty in the financial markets during that period of global economic crisis. Both phenomena could warrant future research.

3.3 GARCH Analysis

The primary purpose of the GARCH estimation was to create proxies for the conditional variance of the exchange rate to be used in the investigation of the determinants of the spread. Recall from Section 3.1 that, following B&M, we estimate for each dataset with the following MA(1)-GARCH(1,1) model:

$$
\begin{aligned}
&10{,}000\Delta \log A_t = \mu + \theta \varepsilon_{A,t-1} + \varepsilon_{A,t},\\
&\sigma^2_{A,t} = \omega + \alpha \varepsilon^2_{A,t-1} + \beta \sigma^2_{A,t-1},\\
&\varepsilon_{A,t} \mid I_{t-1} \sim \mathrm{N}(0, \sigma^2_{A,t}),
\end{aligned} \tag{7}
$$

where I_{t-1} denotes the time $t-1$ information set, and μ, θ, ω, α, and β are the parameters to be estimated. The time t subscript refers to the place in the order of the series of quotes, so that $\sigma_{A,t}^2$ provides an estimate of the price volatility between quotes.

Following B&M, we first removed all weekend quotes. We then used EViews to estimate the parameters for each dataset and the full results are attached in

Appendix 1. Here we present a summary of the results:

	B&M DEM1989	DEM1989	SGD1989	SGD2006	SGD2009
μ	0.0065	0.0069	0.0452	0.0025	0.0023
	(0.0042)	(0.0013)	(0.0138)	(0.0004)	(0.0003)
θ	-0.5953	-0.5867	-0.3281	-0.7817	-0.7802
	(0.0052)	(0.0014)	(0.0114)	(0.0009)	(0.0006)
ω	0.1008	0.0500	0.6833	0.0578	0.0453
	(0.0053)	(0.0005)	(0.0256)	(0.0008)	(0.0002)
α	0.0652	0.0561	0.2650	0.0632	0.0513
	(0.0018)	(0.0003)	(0.0081)	(0.0006)	(0.0002)
β	0.9057	0.9327	0.6540	0.9025	0.9197
	(0.0030)	(0.0003)	(0.0075)	(0.0009)	(0.0003)
α+β	0.9708	0.9888	0.9190	0.9657	0.9710
T	304,608	308,748	8,444	551,355	1,006,736

Asymptotic errors are reported in parenthesis

Table 16: GARCH Estimates for all Datasets

The first column contains the average of the weekly estimates from the original B&M dataset (they only estimated these parameters per workweek, for 12 weeks). The second to fifth columns contain the EViews GARCH estimates for the parameters for the purchased USD/DEM 1989, USD/SGD 1989, USD/SGD 2006, and USD/SGD 2009 data respectively.

First we observe that the EViews estimates for the purchased USD/DEM dataset compares very well with B&M's original results, though standard errors are significantly lower. This provides confidence that the EViews results for the rest of the datasets are appropriate for comparison.

The second observation is that all estimates for θ are negative, which corresponds to B&M's results, and they noted that "the negative estimates for θ may be partly attributed to a non-synchronous quoting phenomenon; see Lo and MacKinlay (1990) for a formal analysis."

The GARCH effects for all datasets are all highly significant. Comparing GARCH effects between the USD/DEM 1989 dataset and USD/SGD 1989 dataset, it is clear that the USD/DEM dataset shows much stronger effects, and stronger $\alpha+\beta$ volatility persistence. This is expected, as the USD/DEM dataset contains at least 36 times more observations and from Table 8, the spread did not change 90.18% of the time.

As the Singapore economy grows and the USD/SGD becomes a significant regional currency, the results show that the GARCH effects and persistence of volatility is consistent with this phenomenon.

The primary purpose of the GARCH estimation was to create proxies for the conditional variance of the exchange rate to be used in the investigation of the determinants of the spread. To this end, we used EViews to obtain GARCH variance series for each dataset.

3.4 Ordered Response Analysis

Recall from Section 3.1 that we estimate for each dataset with the following ordered response model (probit and logit):

$$\mathbf{K_t^* = \delta_1 \sigma_{A,t}^2 + \delta_2 K_{t-1} + \varepsilon} \qquad (13)$$

We first use four ordered indicator values and B&M's definitions for a_j's:

a_1: <= 5 a_2: 5 < . < 10 a_3: = 10 a_4: > 10

The results for the above parameters for all four datasets are attached in Appendix 1, but a summary is presented below:

	DEM1989	SGD1989	SGD2006	SGD2009
δ1	0.0214 (73.9604)	0.0091 (10.6719)	0.0464 (29.2412)	0.0988 (113.8863)
δ2	0.3116 (135.3568)	0.0422 (22.3298)	-0.1306 -(69.4622)	0.2622 (177.1729)
T	308,748	8,444	551,355	1,006,736

Z-statistics are reported in parenthesis

Table 17: Ordered Probit Estimates for all Datasets (4 ordered indicator values)

	DEM1989	SGD1989	SGD2006	SGD2009
δ1	0.1299 (102.6436)	0.0231 (9.2342)	0.0802 (28.9306)	0.2146 (109.5740)
δ2	0.4330 (108.2955)	1.8160 (23.1592)	-0.2040 -(66.7912)	0.4395 (169.4684)
T	308,748	8,444	551,355	1,006,736

Z-statistics are reported in parenthesis

Table 18: Ordered Logit Estimates for all Datasets (4 ordered indicator values)

The positive δ_1 coefficients for both ordered probit and logit analyses above suggest that there is a significantly positive effect of exchange rate volatility on the spread for all datasets. The conditional mean of K_t* is an increasing function of $\sigma_{A,t}^2$. This is consistent with the implications drawn from B&M's theoretical model. The estimates for δ_2 are indicative of intra-day persistence in the spread process.

The magnitude of δ_1 for each dataset supports what we intuitively already know. Comparing the USD/DEM and USD/SGD in 1989, although both δ_1 values are statistically significant, volatility appears to play a much larger role in determining the size of the spread for the USD/DEM. After all, as noted above, the spread remained the same 90.18% of the time for the USD/SGD in 1989. For the same reason, the δ_2 values show that the dependence on the previous spread appears to be more significant for the USD/SGD than for the USD/DEM.

As the country grow in economic significance and the SGD becoming a major regional currency over 17 years, the magnitude of the δ_1 values almost quadrupled, coincidentally matching the growth in quote volume. It is interesting to note the negative δ_2 values for the USD/SGD 2006 dataset, but it might be due to seasonality.

In 2009, in midst of the worldwide financial crisis, we observed a higher level of volatility in the USD/SGD. The much higher δ_l values for this dataset, together with the larger distribution of spreads as shown in Table 15, supports the theory that the bid-ask spreads of foreign exchange rates is very much positively related to the underlying volatility.

We repeated the ordered response analyses using 10 ordered indicator values, due to the larger distribution of spreads as seen in the 2006 and 2009 data. The a_j's are:

a_1: < 3 a_2: 3 <= . < 4 a_3: 4 <= . < 5

a_4: 5 <= . < 6 a_5: 6 <= . < 7 a_6: 7 <= . < 8

a_7: 8 <= . < 9 a_8: 9 <= . < 10 a_9: = 10

a_{10}: > 10

Again, the results for the above parameters for all four datasets are attached in Appendix 1, but a summary is presented below:

	DEM1989	**SGD1989**	**SGD2006**	**SGD2009**
δ1	0.0345 (90.1741)	0.0106 (12.7664)	0.0296 (19.2017)	0.0964 (117.0911)
δ2	0.1124 (122.5758)	0.2933 (16.0766)	-0.0404 -(61.5938)	0.0884 (212.8967)
T	308,748	8,444	551,355	1,006,736

Z-statistics are reported in parenthesis

Table 19: Ordered Probit Estimates for all Datasets (10 ordered indicator values)

	DEM1989	SGD1989	SGD2006	SGD2009
δ1	0.1557	0.0305	0.0599	0.2047
	(115.2591)	(10.8283)	(22.1246)	(110.9948)
δ2	0.1599	0.5637	-0.0755	0.1493
	(100.3382)	(16.7295)	-(67.7863)	(205.0571)
T	308,748	8,444	551,355	1,006,736

Z-statistics are reported in parenthesis

Table 20: Ordered Logit Estimates for all Datasets (10 ordered indicator values)

Generally, the conclusions from the previous ordered response analyses with 4 ordered indicator values still holds after we attempt to be more discerning with the ordered indicator values.

3.5 Incorporating Returns

Recall that we noted (see Tables 5, 11 and 14) an interesting phenomenon regarding the behavior of bid-ask spreads of foreign exchange rates. When prices move up, and the bid-ask spreads change, they tend to widen. Conversely, when prices move down, and the bid-ask spreads change, they tend to narrow.

Previously we were examining the relationship between bid-ask spreads and the underlying volatility of exchange rates and found that positive relationships generally exists between the two. We are now curious if there is any relationship between bid-ask spreads and price movement. To examine this we repeat the ordered response analyses by including the Returns variable from the MA(1)-GARCH(1,1) model into the ordered response model:

$$K_t^* = \delta_1 \sigma_{A,t}^2 + \delta_2 K_{t-1} + \delta_3 10{,}000 * \Delta \log A_t + \varepsilon \qquad (14)$$

We repeated the ordered probit and ordered logit analyses for all four datesets using both 4 and 10 ordered indicator values. The results are attached in Appendix 1, but we summarize the results below:

	DEM1989	SGD1989	SGD2006	SGD2009
δ1	0.0148	0.0093	0.0325	0.0406
	(51.4649)	(10.9454)	(19.1288)	(44.7718)
δ2	0.0383	1.0090	0.5203	0.2606
	(16.2662)	(23.4338)	(210.7702)	(146.0215)
δ3	0.0970	0.0827	0.6241	0.4158
	(98.3419)	(12.2743)	(449.5486)	(437.6876)
T	308,748	8,444	551,355	1,006,736

Z-statistics are reported in parenthesis

Table 21: Ordered Probit Estimates (with Returns) for all Datasets (4 ordered values)

	DEM1989	SGD1989	SGD2006	SGD2009
δ1	0.1319	0.0235	0.0485	0.2225
	(101.6830)	(8.7724)	(14.8530)	(96.1127)
δ2	0.6732	1.9380	1.0532	1.9644
	(154.6104)	(24.1228)	(229.6602)	(494.6543)
δ3	0.3205	0.1796	1.2152	1.3865
	(174.0656)	(12.2520)	(409.7483)	(585.1713)
T	308,748	8,444	551,355	1,006,736

Z-statistics are reported in parenthesis

Table 22: Ordered Logit Estimates (with Returns) for all Datasets (4 ordered values)

	DEM1989	SGD1989	SGD2006	SGD2009
δ1	0.0205 (54.0252)	0.0108 (13.0826)	-0.0350 -(22.6917)	-0.0032 -(3.8439)
δ2	0.0042 (4.5016)	0.3135 (17.0041)	0.0185 (22.5621)	0.0949 (188.9157)
δ3	0.0961 (105.6836)	0.0745 (11.3375)	0.0012 (298.6273)	0.3996 (468.5108)
T	308,748	8,444	551,355	1,006,736

Z-statistics are reported in parenthesis

Table 23: Ordered Probit Estimates (with Returns) for all Datasets (10 ordered values)

	DEM1989	SGD1989	SGD2006	SGD2009
δ1	0.1592 (113.7732)	0.0317 (10.6241)	0.0673 (21.1859)	0.2688 (124.5891)
δ2	0.2532 (146.3672)	0.6059 (17.7207)	0.4030 (251.9007)	0.5755 (574.3314)
δ3	0.3182 (173.2477)	0.1677 (11.3873)	1.1891 (434.4841)	1.2835 (654.4871)
T	308,748	8,444	551,355	1,006,736

Table 24: Ordered Logit Estimates (with Returns) for all Datasets (10 ordered values)

In general (except for Ordered Probit estimates for 10 ordered values), the results for δ_1 and δ_2 values are consistent with the results in the previous section. Even when taking Returns into account, B&M's theory still holds. The results for δ_3 values show that a significant positive relationship also exists between the size of the bid-ask spread and the direction of the exchange rate movement.

One interesting result to note are the negative δ_1 and δ_2 values for the ordered probit analyses of 2006 and 2009 for 10 ordered indicator values (see Table 23). Not only does this violate B&M's prediction, the observation that the δ_1 values appear to decrease with increasing tick volume runs counter to the rest of the ordered response results. One possible explanation for this is that multiplicative heteroskedasticity, which our ordered response models omitted but has been shown to be significant by B&M, is likely to be the cause of this results.

Also since we know that the error term of equations 13 and 14 are not i.d.d. standard normal, the results for the ordered logit analyses are probably more meaningful.

3.6 Summary

B&M provided the theoretical framework and showed empirical evidence that the size of the bid-ask spread of exchange rates is positively related to the exchange rate's underlying volatility. Their empirical subject was over 300,000 USD/DEM quotes from April to June of 1989. The USD/DEM was obviously one of the most traded currency pair during that time, and both the USD and DEM belonged to floating exchange rates regimes of two of the top three largest world economies in 1989.

We then wanted to see if both theory and empirical results would hold for a much lesser traded subject currency, if the currency belonged to a small country and from a semi-floating exchange rate regime – the USD/SGD.

We applied a modified version of B&M's methodology on the USD/SGD from the same months of April to June 1989 and found that the evidence (as documented in the previous section) supported their theory. Furthermore, we repeated the analysis on the USD/SGD 17 years later in 2006 when the world economy was at a point of stability, and again in 2009 when the world economy was somewhat in disarray. We found that B&M's theory was still supported by the evidence.

Along the way we also noted the interesting phenomenon regarding the behavior of bid-ask spreads of foreign exchange rates. When prices move up, and the bid-ask spreads change, they tend to widen. Conversely, when prices move down, and the bid-ask spreads change, they tend to narrow. We repeated the analyses on the datasets and included Returns as additional variable in the ordered response models. We found that the relationship between bid-ask spreads and price direction is positive and significant.

4 Conclusion

This paper has set out to empirically test B&M's theory against a lesser-traded currency from a developing country with a managed floating rate regime. The results generally hold, and we found that the effects of the tested parameters grew in strength as that currency grew in economic significance in its region. We departed from B&M's methodology by omitting multiplicative heteroskedasticity, but we tested our data using both Ordered Probit and Ordered Logit models. The generally "better-behaving" results from the Logit models suggests that the disturbances are indeed not standard normal, and that future work in this area using the same methodologies should include multiplicative heteroskedasticity.

We also noted the interesting phenomenon regarding the behavior of bid-ask spreads of foreign exchange rates. We included returns as additional variable in the ordered response models and found that the relationship between bid-ask spreads and price direction is positive and significant. Future work in this area should attempt to build a model which links bid-ask spreads not only to volatility and also returns.

We provided a simple survey on microstructure literature. We first touched on those which analyses bid-ask spreads and asymmetric information, and also presented snapshots of research involving bid-ask spreads and volatility. Bid-ask spreads, one of two “hallmarks” of the microstructure approach, remain a popular theme for research today.

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Appendix 1 – EViews Results

A.1.1 Dataset 1: USD-DEM April 1989 to June 1989:

A.1.1.1 MA(1)-GARCH(1,1) Results:

Dependent Variable: 10000*DLOG(ASK)
Method: ML - ARCH (Marquardt) - Normal distribution
Sample (adjusted): 2 304131
Included observations: 304130 after adjustments
Convergence achieved after 86 iterations
MA Backcast: 1
Presample variance: backcast (parameter = 0.7)
GARCH = C(3) + C(4)*RESID(-1)^2 + C(5)*GARCH(-1)

Variable	Coefficient	Std. Error	z-Statistic	Prob.
C	0.007732	0.001186	6.518723	0
MA(1)	-0.586985	0.00129	-455.0911	0
	Variance Equation			
C	0.04555	0.000523	87.1623	0
RESID(-1)^2	0.055817	0.00029	192.773	0
GARCH(-1)	0.934608	0.000278	3358.51	0
R-squared	0.237055		Mean dependent var	0.00087
Adjusted R-squared	0.237053		S.D. dependent var	2.379553
S.E. of regression	2.078464		Akaike info criterion	4.102756
Sum squared resid	1313837		Schwarz criterion	4.102931
Log likelihood	-623880.6		Hannan-Quinn criter.	4.102807
Durbin-Watson stat	1.942352			
Inverted MA Roots	0.59			

A.1.1.2 Ordered Probit Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 304131
Included observations: 304130 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 4 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.021372	0.000289	73.96036	0
AJ(-1)	0.311626	0.002302	135.3568	0
	Limit Points			
LIMIT_2:C(3)	0.190472	0.005775	32.98297	0
LIMIT_3:C(4)	0.557843	0.005798	96.21363	0
LIMIT_4:C(5)	2.633627	0.007509	350.7163	0

Pseudo R-squared	0.041442	Akaike info criterion	2.077312
Schwarz criterion	2.077487	Log likelihood	-315881.5
Hannan-Quinn criter.	2.077363	Restr. log likelihood	-329538.1
LR statistic	27313.29	Avg. log likelihood	-1.03864
Prob(LR statistic)	0		

A.1.1.3 Ordered Probit (with Returns) Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 304131
Included observations: 304130 after adjustments
Number of ordered indicator values: 4
Failure to improve Likelihood after 12 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.014821	0.000288	51.46485	0
AJ(-1)	0.038314	0.002355	16.26616	0
10000*DLOG(ASK)	0.096973	0.000986	98.34188	0
	Limit Points			
LIMIT_2:C(4)	-0.569596	0.005843	-97.47589	0
LIMIT_3:C(5)	-0.204094	0.005933	-34.39776	0
LIMIT_4:C(6)	1.828335	0.007386	247.5462	0
Pseudo R-squared	0.041202		Akaike info criterion	2.077839
Schwarz criterion	2.078049		Log likelihood	-315960.6
Hannan-Quinn criter.	2.0779		Restr. log likelihood	-329538.1
LR statistic	27155.04		Avg. log likelihood	-1.0389
Prob(LR statistic)	0			

A.1.1.4 Ordered Probit Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 308749
Included observations: 307943 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 7 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.034469	0.000382	90.17413	0
AJ(-1)	0.112367	0.000917	122.5758	0
	Limit Points			
LIMIT_2:C(3)	-2.206482	0.01721	-128.2094	0
LIMIT_3:C(4)	-1.756869	0.010998	-159.7475	0
LIMIT_4:C(5)	-1.538779	0.00944	-162.9984	0
LIMIT_5:C(6)	0.322974	0.006894	46.85067	0
LIMIT_6:C(7)	0.329696	0.006894	47.8258	0
LIMIT_7:C(8)	0.666276	0.006924	96.2254	0
LIMIT_8:C(9)	0.693844	0.006929	100.1396	0
LIMIT_9:C(10)	0.694678	0.006929	100.2579	0
LIMIT_10:C(11)	2.788901	0.008505	327.928	0

Pseudo R-squared	0.037526	Akaike info criterion	2.258734
Schwarz criterion	2.259114	Log likelihood	-347769.7
Hannan-Quinn criter.	2.258844	Restr. log likelihood	-361329
LR statistic	27118.64	Avg. log likelihood	-1.129331
Prob(LR statistic)	0		

A.1.1.5 Ordered Probit (with Returns) Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 308749
Included observations: 307943 after adjustments
Number of ordered indicator values: 10
Failure to improve Likelihood after 9 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.020522	0.00038	54.02521	0
AJ(-1)	0.004221	0.000938	4.501637	0
10000*DLOG(ASK)	0.096148	0.00091	105.6836	0
	Limit Points			
LIMIT_2:C(4)	-3.04669	0.017039	-178.812	0
LIMIT_3:C(5)	-2.605993	0.011008	-236.7287	0
LIMIT_4:C(6)	-2.393098	0.00953	-251.1147	0
LIMIT_5:C(7)	-0.605194	0.006997	-86.49427	0
LIMIT_6:C(8)	-0.598756	0.006998	-85.56097	0
LIMIT_7:C(9)	-0.277872	0.007077	-39.26293	0
LIMIT_8:C(10)	-0.251959	0.007086	-35.55753	0
LIMIT_9:C(11)	-0.251127	0.007086	-35.43857	0
LIMIT_10:C(12)	1.820135	0.008402	216.6283	0

Pseudo R-squared	0.034829	Akaike info criterion	2.26507
Schwarz criterion	2.265485	Log likelihood	-348744.3
Hannan-Quinn criter.	2.26519	Restr. log likelihood	-361329
LR statistic	25169.41	Avg. log likelihood	-1.132496
Prob(LR statistic)	0		

A.1.1.6 Ordered Logit Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 304131
Included observations: 304130 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 4 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.129908	0.001266	102.6436	0
AJ(-1)	0.432993	0.003998	108.2955	0
	Limit Points			
LIMIT_2:C(3)	0.483887	0.009847	49.14077	0
LIMIT_3:C(4)	1.100335	0.009948	110.6037	0
LIMIT_4:C(5)	4.89648	0.014927	328.0225	0

Pseudo R-squared	0.051821	Akaike info criterion	2.05482
Schwarz criterion	2.054994	Log likelihood	-312461.1
Hannan-Quinn criter.	2.05487	Restr. log likelihood	-329538.1
LR statistic	34153.96	Avg. log likelihood	-1.027393
Prob(LR statistic)	0		

A.1.1.7 Ordered Logit (with Returns) Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 3 304131
Included observations: 304128 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 5 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.131878	0.001297	101.683	0
AJ(-1)	0.673158	0.004354	154.6104	0
10000*DLOG(ASK)	0.320523	0.001841	174.0656	0
	Limit Points			
LIMIT_2:C(4)	0.955897	0.010468	91.31565	0
LIMIT_3:C(5)	1.626336	0.010676	152.3301	0
LIMIT_4:C(6)	5.78533	0.016938	341.5674	0

Pseudo R-squared	0.102908	Akaike info criterion	1.944117
Schwarz criterion	1.944327	Log likelihood	-295624.3
Hannan-Quinn criter.	1.944178	Restr. log likelihood	-329536.2
LR statistic	67823.94	Avg. log likelihood	-0.972039
Prob(LR statistic)	0		

A.1.1.8 Ordered Logit Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 308749
Included observations: 307943 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 7 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.155742	0.001351	115.2591	0
AJ(-1)	0.159926	0.001594	100.3382	0
	Limit Points			
LIMIT_2:C(3)	-5.137085	0.053891	-95.32363	0
LIMIT_3:C(4)	-3.762068	0.028652	-131.3013	0
LIMIT_4:C(5)	-3.158783	0.022402	-141.0075	0
LIMIT_5:C(6)	0.717831	0.011771	60.98525	0
LIMIT_6:C(7)	0.729267	0.011771	61.95536	0
LIMIT_7:C(8)	1.29396	0.011879	108.9279	0
LIMIT_8:C(9)	1.339747	0.011894	112.6399	0
LIMIT_9:C(10)	1.341132	0.011895	112.7518	0
LIMIT_10:C(11)	5.194799	0.016561	313.6803	0

Pseudo R-squared	0.04758	Akaike info criterion	2.23514
Schwarz criterion	2.23552	Log likelihood	-344136.9
Hannan-Quinn criter.	2.23525	Restr. log likelihood	-361329
LR statistic	34384.2	Avg. log likelihood	-1.117534
Prob(LR statistic)	0		

A.1.1.9 Ordered Logit (with Returns) Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 308749
Included observations: 307943 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 7 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.15917	0.001399	113.7732	0
AJ(-1)	0.253184	0.00173	146.3672	0
10000*DLOG(ASK)	0.318154	0.001836	173.2477	0
	Limit Points			
LIMIT_2:C(4)	-4.663842	0.053994	-86.37753	0
LIMIT_3:C(5)	-3.286633	0.028848	-113.9311	0
LIMIT_4:C(6)	-2.681408	0.022654	-118.3644	0
LIMIT_5:C(7)	1.308867	0.012554	104.2614	0
LIMIT_6:C(8)	1.321246	0.012556	105.2298	0
LIMIT_7:C(9)	1.93451	0.012762	151.5792	0
LIMIT_8:C(10)	1.984385	0.012786	155.2056	0
LIMIT_9:C(11)	1.985893	0.012786	155.3148	0
LIMIT_10:C(12)	6.194035	0.018747	330.3986	0

Pseudo R-squared	0.093349	Akaike info criterion	2.127739
Schwarz criterion	2.128154	Log likelihood	-327599.2
Hannan-Quinn criter.	2.127859	Restr. log likelihood	-361329
LR statistic	67459.66	Avg. log likelihood	-1.063831
Prob(LR statistic)	0		

A.1.2 Dataset 2: USD-USD April 1989 to June 1989:

A.1.2.1 MA(1)-GARCH(1,1) Results:

Dependent Variable: 10000*DLOG(ASK)
Method: ML - ARCH
Sample (adjusted): 2 8445
Included observations: 8444 after adjustments
Convergence achieved after 37 iterations
MA Backcast: 1
Presample variance: backcast (parameter = 0.7)
GARCH = C(3) + C(4)*RESID(-1)^2 + C(5)*GARCH(-1)

Variable	Coefficient	Std. Error	z-Statistic	Prob.
C	0.045205	0.013771	3.282516	0.001
MA(1)	-0.3281	0.011435	-28.693	0
	Variance Equation			
C	0.683349	0.025552	26.7437	0
RESID(-1)^2	0.265029	0.008055	32.9008	0
GARCH(-1)	0.653991	0.007513	87.05354	0

R-squared	0.046483	Mean dependent var	0.001809
Adjusted R-squared	0.04637	S.D. dependent var	2.611027
S.E. of regression	2.549771	Akaike info criterion	4.444882
Sum squared resid	54884.24	Schwarz criterion	4.449051
Log likelihood	-18761.29	Hannan-Quinn criter.	4.446305
Durbin-Watson stat	1.819609		
Inverted MA Roots	0.33		

A.1.2.2 Ordered Probit Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 8445
Included observations: 8444 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 5 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCH01	0.009127	0.000855	10.67187	0
AJ(-1)	0.942999	0.042231	22.3298	0
	Limit Points			
LIMIT_2:C(3)	0.61897	0.123303	5.019921	0
LIMIT_3:C(4)	1.002232	0.121611	8.241273	0
LIMIT_4:C(5)	4.898957	0.134626	36.38941	0
Pseudo R-squared	0.115395		Akaike info criterion	0.581462
Schwarz criterion	0.585632		Log likelihood	-2449.933
Hannan-Quinn criter.	0.582885		Restr. log likelihood	-2769.524
LR statistic	639.1806		Avg. log likelihood	-0.290139
Prob(LR statistic)	0			

A.1.2.3 Ordered Probit (with Returns) Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 8445
Included observations: 8444 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 5 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.00933	0.000852	10.94538	0
AJ(-1)	1.008975	0.043056	23.43378	0
10000*DLOG(ASK)	0.08268	0.006736	12.27428	0
	Limit Points			
LIMIT_2:C(4)	0.775747	0.125149	6.198581	0
LIMIT_3:C(5)	1.166192	0.12345	9.446642	0
LIMIT_4:C(6)	5.148438	0.138288	37.22976	0

Pseudo R-squared	0.142475	Akaike info criterion	0.563936
Schwarz criterion	0.568939	Log likelihood	-2374.936
Hannan-Quinn criter.	0.565644	Restr. log likelihood	-2769.524
LR statistic	789.1746	Avg. log likelihood	-0.281257
Prob(LR statistic)	0		

A.1.2.4 Ordered Probit Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 8445
Included observations: 8444 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 7 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.010588	0.000829	12.7664	0
AJ(-1)	0.293255	0.018241	16.07658	0
	Limit Points			
LIMIT_2:C(3)	-1.046148	0.251299	-4.162967	0
LIMIT_3:C(4)	-0.925167	0.225398	-4.104586	0
LIMIT_4:C(5)	-0.71307	0.195539	-3.646689	0.0003
LIMIT_5:C(6)	0.463308	0.159031	2.91332	0.0036
LIMIT_6:C(7)	0.525466	0.158821	3.308537	0.0009
LIMIT_7:C(8)	0.77686	0.158252	4.908998	0
LIMIT_8:C(9)	0.837742	0.158161	5.296765	0
LIMIT_9:C(10)	0.843638	0.158153	5.334317	0
LIMIT_10:C(11)	4.644992	0.167892	27.66655	0

Pseudo R-squared	0.069425	Akaike info criterion	0.65859
Schwarz criterion	0.667763	Log likelihood	-2769.568
Hannan-Quinn criter.	0.661721	Restr. log likelihood	-2976.191
LR statistic	413.2452	Avg. log likelihood	-0.327992
Prob(LR statistic)	0		

A.1.2.5 Ordered Probit (with Returns) Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 8445
Included observations: 8444 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 7 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.010826	0.000828	13.08258	0
AJ(-1)	0.313473	0.018435	17.00409	0
10000*DLOG(ASK)	0.074509	0.006572	11.33749	0
	Limit Points			
LIMIT_2:C(4)	-0.920766	0.2527	-3.643716	0.0003
LIMIT_3:C(5)	-0.799597	0.226892	-3.524124	0.0004
LIMIT_4:C(6)	-0.586622	0.197098	-2.976292	0.0029
LIMIT_5:C(7)	0.609972	0.160333	3.804416	0.0001
LIMIT_6:C(8)	0.673407	0.160125	4.205514	0
LIMIT_7:C(9)	0.92919	0.159566	5.823252	0
LIMIT_8:C(10)	0.991005	0.159477	6.214104	0
LIMIT_9:C(11)	0.996988	0.159469	6.251929	0
LIMIT_10:C(12)	4.866967	0.170386	28.56432	0

Pseudo R-squared	0.09087	Akaike info criterion	0.64371
Schwarz criterion	0.653717	Log likelihood	-2705.745
Hannan-Quinn criter.	0.647126	Restr. log likelihood	-2976.191
LR statistic	540.8901	Avg. log likelihood	-0.320434
Prob(LR statistic)	0		

A.1.2.6 Ordered Logit Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 8445
Included observations: 8444 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 7 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.023145	0.002506	9.234157	0
AJ(-1)	1.816022	0.078415	23.15919	0
	Limit Points			
LIMIT_2:C(3)	1.151811	0.221143	5.208446	0
LIMIT_3:C(4)	2.052707	0.215518	9.524505	0
LIMIT_4:C(5)	9.285628	0.252771	36.73541	0
Pseudo R-squared	0.11296		Akaike info criterion	0.583059
Schwarz criterion	0.587229		Log likelihood	-2456.677
Hannan-Quinn criter.	0.584483		Restr. log likelihood	-2769.524
LR statistic	625.6929		Avg. log likelihood	-0.290938
Prob(LR statistic)	0			

A.1.2.7 Ordered Logit (with Returns) Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 8445
Included observations: 8444 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 8 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.023498	0.002679	8.772378	0
AJ(-1)	1.937969	0.080338	24.12276	0
10000*DLOG(ASK)	0.179594	0.014658	12.25201	0
	Limit Points			
LIMIT_2:C(4)	1.431605	0.224685	6.371611	0
LIMIT_3:C(5)	2.341427	0.219477	10.66822	0
LIMIT_4:C(6)	9.770045	0.261472	37.36562	0

Pseudo R-squared	0.139367	Akaike info criterion	0.565974
Schwarz criterion	0.570977	Log likelihood	-2383.542
Hannan-Quinn criter.	0.567682	Restr. log likelihood	-2769.524
LR statistic	771.9628	Avg. log likelihood	-0.282276
Prob(LR statistic)	0		

A.1.2.8 Ordered Logit Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 8445
Included observations: 8444 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 6 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.030535	0.00282	10.82827	0
AJ(-1)	0.563651	0.033692	16.72951	0
	Limit Points			
LIMIT_2:C(3)	-3.399721	0.756259	-4.495444	0
LIMIT_3:C(4)	-2.993661	0.63663	-4.702359	0
LIMIT_4:C(5)	-2.298438	0.488651	-4.703637	0
LIMIT_5:C(6)	0.926596	0.286528	3.233876	0.0012
LIMIT_6:C(7)	1.076884	0.285436	3.77277	0.0002
LIMIT_7:C(8)	1.66173	0.282811	5.875773	0
LIMIT_8:C(9)	1.797737	0.282485	6.364009	0
LIMIT_9:C(10)	1.810792	0.282458	6.41083	0
LIMIT_10:C(11)	8.845043	0.310773	28.46145	0

Pseudo R-squared	0.068507	Akaike info criterion	0.659237
Schwarz criterion	0.66841	Log likelihood	-2772.3
Hannan-Quinn criter.	0.662368	Restr. log likelihood	-2976.191
LR statistic	407.7821	Avg. log likelihood	-0.328316
Prob(LR statistic)	0		

A.1.2.9 Ordered Logit (with Returns) Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 8445
Included observations: 8444 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 8 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.031698	0.002984	10.62409	0
AJ(-1)	0.605872	0.03419	17.72067	0
10000*DLOG(ASK)	0.167709	0.014728	11.38731	0
	Limit Points			
LIMIT_2:C(4)	-3.108606	0.756454	-4.109446	0
LIMIT_3:C(5)	-2.702375	0.63687	-4.243211	0
LIMIT_4:C(6)	-2.004677	0.48917	-4.098116	0
LIMIT_5:C(7)	1.236004	0.289368	4.271391	0
LIMIT_6:C(8)	1.387414	0.288368	4.811259	0
LIMIT_7:C(9)	1.976024	0.286018	6.908731	0
LIMIT_8:C(10)	2.112879	0.285744	7.394317	0
LIMIT_9:C(11)	2.126018	0.285722	7.440867	0
LIMIT_10:C(12)	9.336144	0.318108	29.349	0

Pseudo R-squared	0.09058	Akaike info criterion	0.643914
Schwarz criterion	0.653921	Log likelihood	-2706.607
Hannan-Quinn criter.	0.64733	Restr. log likelihood	-2976.191
LR statistic	539.1676	Avg. log likelihood	-0.320536
Prob(LR statistic)	0		

A.1.3 Dataset 3: USD-USD April 2006 to May 2006:

A.1.3.1 MA(1)-GARCH(1,1) Results:

Dependent Variable: 10000*DLOG(ASK)
Method: ML - ARCH (Marquardt) - Normal distribution
Sample (adjusted): 2 551356
Included observations: 551355 after adjustments
Convergence achieved after 14 iterations
MA Backcast: 1
Presample variance: backcast (parameter = 0.7)
GARCH = C(3) + C(4)*RESID(-1)^2 + C(5)*GARCH(-1)

Variable	Coefficient	Std. Error	z-Statistic	Prob.
C	0.002535	0.000358	7.075531	0
MA(1)	-0.781719	0.000858	-911.204	0
	Variance Equation			
C	0.057826	0.000813	71.15628	0
RESID(-1)^2	0.063219	0.000558	113.2785	0
GARCH(-1)	0.902484	0.000889	1015.04	0

R-squared	0.372225	Mean dependent var	-0.000425
Adjusted R-squared	0.372224	S.D. dependent var	1.657286
S.E. of regression	1.313106	Akaike info criterion	3.302185
Sum squared resid	950669.3	Schwarz criterion	3.302287
Log likelihood	-910333.2	Hannan-Quinn criter.	3.302214
Durbin-Watson stat	1.97678		
Inverted MA Roots	0.78		

A.1.3.2 Ordered Probit Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 551356
Included observations: 551355 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 4 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.046421	0.001588	29.24124	0
AJ(-1)	-0.130554	0.001879	-69.46221	0
	Limit Points			
LIMIT_2:C(3)	-0.267391	0.004557	-58.67524	0
LIMIT_3:C(4)	0.497267	0.004577	108.652	0
LIMIT_4:C(5)	3.624999	0.036661	98.87791	0

Pseudo R-squared	0.00466	Akaike info criterion	2.122714
Schwarz criterion	2.122815	Log likelihood	-585179.4
Hannan-Quinn criter.	2.122742	Restr. log likelihood	-587919.3
LR statistic	5479.851	Avg. log likelihood	-1.061348
Prob(LR statistic)	0		

A.1.3.3 Ordered Probit (with Returns) Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 551356
Included observations: 551355 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 6 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.032475	0.001698	19.12882	0
AJ(-1)	0.520271	0.002468	210.7702	0
10000*DLOG(ASK)	0.624067	0.001388	449.5486	0
	Limit Points			
LIMIT_2:C(4)	0.803072	0.005446	147.4683	0
LIMIT_3:C(5)	1.84724	0.00582	317.4066	0
LIMIT_4:C(6)	6.264271	0.051481	121.682	0

Pseudo R-squared	0.202812	Akaike info criterion	1.700133
Schwarz criterion	1.700255	Log likelihood	-468682.4
Hannan-Quinn criter.	1.700167	Restr. log likelihood	-587919.3
LR statistic	238473.8	Avg. log likelihood	-0.850056
Prob(LR statistic)	0		

A.1.3.4 Ordered Probit Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 551356
Included observations: 530382 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 5 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.029623	0.001543	19.20169	0
AJ(-1)	-0.040361	0.000655	-61.5938	0
	Limit Points			
LIMIT_2:C(3)	-2.770052	0.008137	-340.4275	0
LIMIT_3:C(4)	-2.123895	0.005776	-367.693	0
LIMIT_4:C(5)	-1.541017	0.005154	-299.0033	0
LIMIT_5:C(6)	-0.292156	0.004841	-60.34619	0
LIMIT_6:C(7)	-0.076775	0.004831	-15.89255	0
LIMIT_7:C(8)	0.218854	0.004827	45.33503	0
LIMIT_8:C(9)	0.463249	0.00484	95.70278	0
LIMIT_9:C(10)	0.472672	0.004841	97.63469	0
LIMIT_10:C(11)	3.593189	0.037289	96.36043	0

Pseudo R-squared	0.00228	Akaike info criterion	3.351617
Schwarz criterion	3.351849	Log likelihood	-888807.6
Hannan-Quinn criter.	3.351682	Restr. log likelihood	-890838.9
LR statistic	4062.696	Avg. log likelihood	-1.675788
Prob(LR statistic)	0		

A.1.3.5 Ordered Probit (with Returns) Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 551356
Included observations: 530382 after adjustments
Number of ordered indicator values: 10
Failure to improve Likelihood after 17 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	-0.035043	0.001544	-22.69168	0
AJ(-1)	0.01852	0.000821	22.56212	0
10000*DLOG(ASK)	0.365238	0.001223	298.6273	0
	Limit Points			
LIMIT_2:C(4)	-2.768453	0.008501	-325.6782	0
LIMIT_3:C(5)	-2.089688	0.006173	-338.5115	0
LIMIT_4:C(6)	-1.484632	0.00565	-262.7437	0
LIMIT_5:C(7)	-0.148442	0.005549	-26.74997	0
LIMIT_6:C(8)	0.084178	0.005598	15.03649	0
LIMIT_7:C(9)	0.395925	0.005688	69.60886	0
LIMIT_8:C(10)	0.648621	0.005789	112.0419	0
LIMIT_9:C(11)	0.659757	0.005795	113.8488	0
LIMIT_10:C(12)	4.041679	0.025918	155.9393	0

Pseudo R-squared	0.101511	Akaike info criterion	3.018282
Schwarz criterion	3.018535	Log likelihood	-800409.1
Hannan-Quinn criter.	3.018353	Restr. log likelihood	-890838.9
LR statistic	180859.6	Avg. log likelihood	-1.509118
Prob(LR statistic)	0		

A.1.3.6 Ordered Logit Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 551356
Included observations: 551355 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 4 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.080152	0.00277	28.93061	0
AJ(-1)	-0.204018	0.003055	-66.79117	0
	Limit Points			
LIMIT_2:C(3)	-0.41091	0.007581	-54.20336	0
LIMIT_3:C(4)	0.830244	0.007658	108.4198	0
LIMIT_4:C(5)	9.135262	0.144521	63.21045	0

Pseudo R-squared	0.004388	Akaike info criterion	2.123295
Schwarz criterion	2.123397	Log likelihood	-585339.7
Hannan-Quinn criter.	2.123324	Restr. log likelihood	-587919.3
LR statistic	5159.321	Avg. log likelihood	-1.061638
Prob(LR statistic)	0		

A.1.3.7 Ordered Logit (with Returns) Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 551356
Included observations: 551355 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 6 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.048475	0.003264	14.85304	0
AJ(-1)	1.053246	0.004586	229.6602	0
10000*DLOG(ASK)	1.215211	0.002966	409.7483	0
	Limit Points			
LIMIT_2:C(4)	1.600267	0.009958	160.7016	0
LIMIT_3:C(5)	3.453473	0.011048	312.5789	0
LIMIT_4:C(6)	13.6294	0.167398	81.41909	0

Pseudo R-squared	0.216154	Akaike info criterion	1.671678
Schwarz criterion	1.671801	Log likelihood	-460838.1
Hannan-Quinn criter.	1.671713	Restr. log likelihood	-587919.3
LR statistic	254162.3	Avg. log likelihood	-0.835828
Prob(LR statistic)	0		

A.1.3.8 Ordered Logit Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 551356
Included observations: 530382 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 5 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.059869	0.002706	22.12459	0
AJ(-1)	-0.07549	0.001114	-67.78632	0
	Limit Points			
LIMIT_2:C(3)	-5.681481	0.021378	-265.7677	0
LIMIT_3:C(4)	-3.965107	0.011679	-339.4939	0
LIMIT_4:C(5)	-2.690845	0.009268	-290.3316	0
LIMIT_5:C(6)	-0.512979	0.008257	-62.12349	0
LIMIT_6:C(7)	-0.168038	0.008229	-20.41918	0
LIMIT_7:C(8)	0.3095	0.008227	37.61812	0
LIMIT_8:C(9)	0.714603	0.008278	86.32978	0
LIMIT_9:C(10)	0.73051	0.008281	88.22038	0
LIMIT_10:C(11)	9.036028	0.147643	61.20197	0

Pseudo R-squared	0.0028	Akaike info criterion	3.34987
Schwarz criterion	3.350102	Log likelihood	-888344.5
Hannan-Quinn criter.	3.349936	Restr. log likelihood	-890838.9
LR statistic	4988.841	Avg. log likelihood	-1.674915
Prob(LR statistic)	0		

A.1.3.9 Ordered Logit (with Returns) Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 551356
Included observations: 530382 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 6 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.067262	0.003175	21.18593	0
AJ(-1)	0.402995	0.0016	251.9007	0
10000*DLOG(ASK)	1.189108	0.002737	434.4841	0
	Limit Points			
LIMIT_2:C(4)	-3.894364	0.022026	-176.8036	0
LIMIT_3:C(5)	-2.114505	0.012808	-165.0968	0
LIMIT_4:C(6)	-0.7165	0.010767	-66.54475	0
LIMIT_5:C(7)	2.04924	0.010738	190.8341	0
LIMIT_6:C(8)	2.528082	0.010914	231.6353	0
LIMIT_7:C(9)	3.225475	0.011271	286.1774	0
LIMIT_8:C(10)	3.846774	0.011692	329.0122	0
LIMIT_9:C(11)	3.872262	0.011712	330.6322	0
LIMIT_10:C(12)	13.94908	0.170499	81.81305	0

Pseudo R-squared	0.146499	Akaike info criterion	2.867156
Schwarz criterion	2.867409	Log likelihood	-760331.9
Hannan-Quinn criter.	2.867227	Restr. log likelihood	-890838.9
LR statistic	261014.1	Avg. log likelihood	-1.433555
Prob(LR statistic)	0		

A.1.4 Dataset 4: USD-USD April 2009 to May 2009:

A.1.4.1 MA(1)-GARCH(1,1) Results:

Dependent Variable: 10000*DLOG(ASK)
Method: ML - ARCH
Sample (adjusted): 2 1006737
Included observations: 1006736 after adjustments
Convergence achieved after 21 iterations
MA Backcast: 1
Presample variance: backcast (parameter = 0.7)
GARCH = C(3) + C(4)*RESID(-1)^2 + C(5)*GARCH(-1)

Variable	Coefficient	Std. Error	z-Statistic	Prob.
C	0.002329	0.000251	9.274136	0
MA(1)	-0.78024	0.000611	-1276.001	0
	Variance Equation			
C	0.045284	0.000225	201.6421	0
RESID(-1)^2	0.051345	0.00021	244.0686	0
GARCH(-1)	0.919658	0.000263	3502.001	0
R-squared	0.36927		Mean dependent var	-0.000386
Adjusted R-squared	0.369269		S.D. dependent var	1.602816
S.E. of regression	1.272934		Akaike info criterion	3.196957
Sum squared resid	1631271		Schwarz criterion	3.197016
Log likelihood	-1609241		Hannan-Quinn criter.	3.196973
Durbin-Watson stat	1.970126			
Inverted MA Roots	0.78			

A.1.4.2 Ordered Probit Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 1006737
Included observations: 1006736 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 3 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.098754	0.000867	113.8863	0
AJ(-1)	0.262245	0.00148	177.1729	0
	Limit Points			
LIMIT_2:C(3)	0.300383	0.003019	99.50314	0
LIMIT_3:C(4)	1.797373	0.003373	532.8891	0
LIMIT_4:C(5)	2.392075	0.003801	629.366	0

Pseudo R-squared	0.024794	Akaike info criterion	2.069774
Schwarz criterion	2.069833	Log likelihood	-1041853
Hannan-Quinn criter.	2.069791	Restr. log likelihood	-1068342
LR statistic	52977.45	Avg. log likelihood	-1.034882
Prob(LR statistic)	0		

A.1.4.3 Ordered Probit (with Returns) Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 1006737
Included observations: 1006736 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 12 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.040619	0.000907	44.7718	0
AJ(-1)	0.260624	0.001785	146.0215	0
10000*DLOG(ASK)	0.415817	0.00095	437.6876	0
	Limit Points			
LIMIT_2:C(4)	0.072632	0.003441	21.10602	0
LIMIT_3:C(5)	1.741812	0.004059	429.1621	0
LIMIT_4:C(6)	2.420409	0.004675	517.7516	0

Pseudo R-squared	0.176356	Akaike info criterion	1.748103
Schwarz criterion	1.748173	Log likelihood	-879933.1
Hannan-Quinn criter.	1.748122	Restr. log likelihood	-1068342
LR statistic	376817.7	Avg. log likelihood	-0.874046
Prob(LR statistic)	0		

A.1.4.4 Ordered Probit Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 1006737
Included observations: 1006736 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 4 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.096416	0.000823	117.0911	0
AJ(-1)	0.088372	0.000415	212.8967	0
	Limit Points			
LIMIT_2:C(3)	-1.466867	0.003573	-410.4852	0
LIMIT_3:C(4)	-0.169471	0.002717	-62.38151	0
LIMIT_4:C(5)	0.142757	0.00271	52.67088	0
LIMIT_5:C(6)	0.32063	0.002718	117.9753	0
LIMIT_6:C(7)	0.463947	0.002729	170.0266	0
LIMIT_7:C(8)	0.855945	0.002774	308.5626	0
LIMIT_8:C(9)	1.630826	0.002965	549.9868	0
LIMIT_9:C(10)	1.799457	0.003034	593.0574	0
LIMIT_10:C(11)	2.394888	0.003495	685.2099	0

Pseudo R-squared	0.016257	Akaike info criterion	4.058805
Schwarz criterion	4.058934	Log likelihood	-2043062
Hannan-Quinn criter.	4.05884	Restr. log likelihood	-2076824
LR statistic	67525.47	Avg. log likelihood	-2.029392
Prob(LR statistic)	0		

A.1.4.5 Ordered Probit (with Returns) Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Probit (Quadratic hill climbing)
Sample (adjusted): 2 1006737
Included observations: 1006736 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 9 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	-0.003187	0.000829	-3.843887	0.0001
AJ(-1)	0.094896	0.000502	188.9157	0
10000*DLOG(ASK)	0.399614	0.000853	468.5108	0
	Limit Points			
LIMIT_2:C(4)	-1.889585	0.00377	-501.2568	0
LIMIT_3:C(5)	-0.540899	0.002964	-182.4773	0
LIMIT_4:C(6)	-0.211211	0.003013	-70.09902	0
LIMIT_5:C(7)	-0.014555	0.003062	-4.753915	0
LIMIT_6:C(8)	0.153294	0.003113	49.24206	0
LIMIT_7:C(9)	0.615502	0.003255	189.0877	0
LIMIT_8:C(10)	1.481455	0.003579	413.8783	0
LIMIT_9:C(11)	1.676514	0.003697	453.4845	0
LIMIT_10:C(12)	2.40264	0.004378	548.8559	0

Pseudo R-squared	0.096012	Akaike info criterion	3.729748
Schwarz criterion	3.729889	Log likelihood	-1877424
Hannan-Quinn criter.	3.729787	Restr. log likelihood	-2076824
LR statistic	398801.1	Avg. log likelihood	-1.864862
Prob(LR statistic)	0		

A.1.4.6 Ordered Logit Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 1006737
Included observations: 1006736 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 4 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.214626	0.001959	109.574	0
AJ(-1)	0.43948	0.002593	169.4684	0
	Limit Points			
LIMIT_2:C(3)	0.593662	0.00533	111.3912	0
LIMIT_3:C(4)	3.114943	0.006332	491.9238	0
LIMIT_4:C(5)	4.301442	0.007555	569.3761	0
Pseudo R-squared	0.024601		Akaike info criterion	2.070184
Schwarz criterion	2.070243		Log likelihood	-1042059
Hannan-Quinn criter.	2.0702		Restr. log likelihood	-1068342
LR statistic	52565.01		Avg. log likelihood	-1.035087
Prob(LR statistic)	0			

A.1.4.7 Ordered Logit (with Returns) Results: 4 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 1006737
Included observations: 1006736 after adjustments
Number of ordered indicator values: 4
Convergence achieved after 5 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.222491	0.002315	96.11273	0
AJ(-1)	1.964362	0.003971	494.6543	0
10000*DLOG(ASK)	1.38648	0.002369	585.1713	0
	Limit Points			
LIMIT_2:C(4)	2.992082	0.007366	406.2264	0
LIMIT_3:C(5)	6.796605	0.010304	659.6204	0
LIMIT_4:C(6)	8.504201	0.012206	696.7327	0

Pseudo R-squared	0.27793	Akaike info criterion	1.532523
Schwarz criterion	1.532594	Log likelihood	-771417.2
Hannan-Quinn criter.	1.532543	Restr. log likelihood	-1068342
LR statistic	593849.5	Avg. log likelihood	-0.766256
Prob(LR statistic)	0		

A.1.4.8 Ordered Logit Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 1006737
Included observations: 1006736 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 4 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.204722	0.001844	110.9948	0
AJ(-1)	0.149279	0.000728	205.0571	0
	Limit Points			
LIMIT_2:C(3)	-2.795295	0.007967	-350.8518	0
LIMIT_3:C(4)	-0.187268	0.004866	-38.48186	0
LIMIT_4:C(5)	0.339075	0.004839	70.07788	0
LIMIT_5:C(6)	0.630813	0.004859	129.8187	0
LIMIT_6:C(7)	0.863371	0.004891	176.5268	0
LIMIT_7:C(8)	1.496184	0.005024	297.8132	0
LIMIT_8:C(9)	2.804875	0.005538	506.4991	0
LIMIT_9:C(10)	3.112486	0.005723	543.812	0
LIMIT_10:C(11)	4.297395	0.007016	612.4985	0

Pseudo R-squared	0.01601	Akaike info criterion	4.059823
Schwarz criterion	4.059952	Log likelihood	-2043574
Hannan-Quinn criter.	4.059859	Restr. log likelihood	-2076824
LR statistic	66500.5	Avg. log likelihood	-2.029901
Prob(LR statistic)	0		

A.1.4.9 Ordered Logit (with Returns) Results: 10 Ordered Values

Dependent Variable: AJ
Method: ML - Ordered Logit (Quadratic hill climbing)
Sample (adjusted): 2 1006737
Included observations: 1006736 after adjustments
Number of ordered indicator values: 10
Convergence achieved after 5 iterations
Covariance matrix computed using second derivatives

Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCHVAR	0.268841	0.002158	124.5891	0
AJ(-1)	0.575528	0.001002	574.3314	0
10000*DLOG(ASK)	1.283457	0.001961	654.4871	0
	Limit Points			
LIMIT_2:C(4)	-1.499334	0.008444	-177.5703	0
LIMIT_3:C(5)	1.549476	0.005795	267.3935	0
LIMIT_4:C(6)	2.288018	0.005979	382.6506	0
LIMIT_5:C(7)	2.734323	0.006163	443.6451	0
LIMIT_6:C(8)	3.100859	0.006343	488.8769	0
LIMIT_7:C(9)	4.034615	0.006789	594.2899	0
LIMIT_8:C(10)	5.85286	0.007889	741.9462	0
LIMIT_9:C(11)	6.285226	0.008209	765.6376	0
LIMIT_10:C(12)	7.959922	0.010167	782.9249	0

Pseudo R-squared	0.158021	Akaike info criterion	3.473909
Schwarz criterion	3.47405	Log likelihood	-1748643
Hannan-Quinn criter.	3.473948	Restr. log likelihood	-2076824
LR statistic	656363.1	Avg. log likelihood	-1.736943
Prob(LR statistic)	0		