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PRICING EFFICIENCY IN THE LONG-TERM INDEX OPTIONS MARKET: AN EMPIRICAL INVESTIGATION

presented by

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has been accepted towards fulfillment
of the requirements for

PH.D. degree in BUSINESS ADMINISTRATION

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Date 10/29/1999

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PRICING EFFICIENCY IN THE LONG-TERM INDEX OPTIONS MARKET: AN EMPIRICAL INVESTIGATION

By

Anuradha Kandikuppa

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Finance and Insurance

1999

ABSTRACT

PRICING EFFICIENCY IN THE LONG-TERM INDEX OPTIONS MARKET: AN EMPIRICAL INVESTIGATION

By

Anuradha Kandikuppa

This dissertation studies pricing efficiency in the S&P 500 index Long-term Equity Anticipation Securities (LEAPS) market. This market exhibits several several sources of market friction that make arbitrage difficult and costly, due to which pricing inefficiencies may arise and persist. First, a large order imbalance typically results, due to a disproportionately high number of public LEAPS put purchases, especially out-of-the-money puts, probably for portfolio insurance. Given such an uneven distribution in public orders, market makers may face persistent inventory imbalances. Second, dynamic arbitrage in the S&P 500 LEAPS market may be more difficult than in other options markets, due to the complexity and cost of replicating the basket of 500 stocks. Third, LEAPS maturities extend up to three years, making dynamic hedging strategies potentially very costly if pricing errors persist for long periods.

Put-call parity and box spread arbitrage restrictions in S&P 500 LEAPS option prices over 1994-96 are first tested. The tests reveal that puts are overpriced with respect to calls 80% of the time, while box spread restrictions are

violated infrequently, with insignificant pricing errors. This suggests that LEAP prices are internally consistent within the S&P 500 LEAPS market, but that LEAP puts are overpriced relative to the spot index market.

Next, an intra-day analysis of bid-ask quotes and trades, employing a methodology that separates information effects of trades from inventory effects, reveals that LEAPS puts prices are revised upward upon a positive trade imbalance and downwards upon a negative trade imbalance by more than is explained by information effects of trading, suggesting that LEAPS puts prices are subject to inventory effects.

Taken together with the features of the S&P 500 LEAPS market discussed earlier, these results suggest that market frictions can be important in the pricing of options, at least when where arbitrage is particularly costly and public demand leans toward one type of order. However, trading strategies based on these observed anomalies are found to generate insignificant profits over holding periods of one and five trading days. One implication of the latter result is that the pricing deviations tend to be short-lived intra-day inventory effects.

To my father and the memory of my mother

ACKNOWLEDGEMENTS

I wish to thank Dr. James B. Wiggins, Chair of my Dissertation Committee for his invaluable guidance and discussions during the preparation of this dissertation. I would also like to thank the other members of my committee Dr. John Gilster, Dr. Asssem Safieddine and Dr. Mark Schroder for their suggestions. I thank Dr. Richard Simonds and Dr. Geoffrey Booth for their support in acquiring the data for the empirical work in this thesis. I am also grateful to the other Finance Ph.D. students for helpful discussions. Finally, I thank my husband and his family for their firm support through the past five years of my studies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 Introduction

The state of option pricing theory today owes a lot to the Black-Scholes (1973) option pricing formula, which was derived under assumptions of a log-normal stock price distribution, and frictionless markets. Subsequently, many empirical option pricing studies, including MacBeth and Merville (1979, 1980) and Rubinstein (1985) examined deviations between market prices of options and Black-Scholes model predictions. The results of these studies showed that the market prices away-from-the-money options higher than does the Black-Scholes model, a phenomenon come to be known as the implied volatility smile or smirk. Although the results of most of the studies agree that the smile exists, there is some evidence that the direction of the pricing bias has changed over time

Research has progressed in two major directions in an effort to explain these empirical anomalies. One branch of the literature, including Merton (1973, 1976), Hull and White (1987), Wiggins (1987), relaxes the distributional assumptions of the BS model and incorporates stochastic interest rates, stochastic volatility and jumps in the underlying stock price process.

Bakshi, Chen and Cao (1997, 1998) study the performance of these generalized models in the S&P 500 index options market using three different yardsticks of performance. They find that stochastic volatility models improve hedging and out-of-sample pricing performance significantly over a BS model. However, even a stochastic volatility model is still significantly mis-specified. With a stochastic volatility model, BCC find that index option prices imply a much higher correlation between volatility and returns than is present in the actual index time series. Their results suggest that away-from-the-money options are priced higher by the market than justified by the underlying asset's return distribution, even after accounting for higher moments in the distribution.

A parallel branch of the option pricing literature relaxes the frictionless markets assumption, allowing for trading discreteness and transaction costs in implementing a dynamic hedging strategy (Boyle and Emanuel (1980), Leland (1985)). This literature suggests that in imperfect markets, no-arbitrage conditions can only place bounds on option prices. Longstaff (1995) examines the impact of market frictions on option prices by comparing the value of the S&P 100 index implied by the prices of call options to the actual index market value, which should be equal under no-arbitrage conditions. He finds that the implied index value exceeds the actual index value more than 99% of the time in the sample, indicating that call option prices exceed their frictionless-market replication cost. The difference between the implied and actual index value is negatively related to open interest, total trading volume, and to the average index/strike price ratio, and positively related to the average option bid-ask spread and time to maturity, among other influences. These results suggest a role for liquidity-related variables in options pricing. As the cost of implementing a dynamic arbitrage strategy increases, the difference between prices of listed call options and their frictionless market also increases.

The aim of this dissertation is to study more closely the role of market prices in the pricing of options, for which purpose the long-term index options market provides an attractive setting. Relative to short-term options, little work has been done exclusively on long-term options, excepting for a recent study by Bakshi, Chen and Cao (1998) in the S&P 500 index LEAPS market. The work done in this thesis fills this gap in the empirical option pricing literature.

The S&P 500 LEAPS market is an attractive focus for this study because of market imperfections that cause dynamic arbitrage in the S&P 500 LEAPS market to be more difficult than in other options markets. First, dynamic trade in the basket of 500 stocks is costly. Trading in Standard and Poor's Depository Receipts (SPDRs) on the AMEX or S&P 500 futures contracts are viable alternatives, but strategies using either of these contracts involve basis risk. Most importantly, LEAPS maturities extend up to three years, making dynamic hedging strategies potentially very costly if pricing errors persist for long periods of time.

Second, an inherent order imbalance typically exists in the market for LEAPS due to a disproportionately high demand for LEAPS puts, probably for portfolio insurance. Of the put trades that can be identified as either purchases or sales from January 1994 through December 1996, 81.7% are purchases. Trading volume is concentrated in out-of-the-money rather than at- or in-the money puts.

Given this uneven distribution in public orders, market makers may face persistent inventory imbalances, which makes hedging with put-call parity conversion or other arbitrage rules more difficult. The imbalance is more severe for options with remaining maturities exceeding 6 months, where orders are more likely to be opening rather than closing trades. Market makers could hedge the put trade imbalance with relative ease if there was a corresponding public demand to sell calls with the same strike, permitting static hedging using a put-call parity conversion trade. But the total number of put purchases is more than 40 times the number of call sales in the sample.

I employ several different methods to examine the efficiency of pricing in the S&P 500 LEAPS market under these conditions. First, I empirically examine two efficiency conditions in the S&P 500 LEAPS market, the put-call parity and the box spread relations. The advantage of using this approach is that these efficiency conditions do not depend on a specific option-pricing model or assumption about the underlying asset's return distribution. The box spread tests have the additional advantage that they are not subject to a dividend-forecasting problem, since they do not involve the underlying asset.

Following the convention in the literature, I use actual dividends as a proxy for expected dividends in the put-call parity tests. In practice, the futures contract is the instrument most likely to substitute for the index. Therefore, I augment tests of the put-call parity condition using the underlying index with tests using the S&P futures contract closest in maturity to the LEAP.

I find many incidences of violations of put-call parity over the 1994-1996 sample period, when the underlying index value is used to test the relationship. Most often, puts are overpriced relative to calls, consistent with the observed pattern of public trade, even after accounting for bid-ask spreads. Since put-call parity violations are calculated using actual future dividends, unknown at the time the options are priced, they do not represent pure arbitrage opportunities. Yet, put overpricing for maturities of less than 60 days is at least as large as for longer maturities, implying that errors in dividend forecasting do not completely explain the results. The results are somewhat different when the put-call parity relation is tested using prices of futures contracts on the underlying asset. These results show no significant violations of futures put-call parity, but suggest instead that the futures price violates its own arbitrage condition.

Violations of the box spread relation are much less frequent. After accounting for option spreads, there are no consistent box spread arbitrage opportunities in the market.

Second, I examine the impact of intra-day trade imbalances on the pricing of long-term S&P 500 index options. In a sample of intra-day bid-ask quotes and trades on S&P 500 index LEAPS from 1994-96, I find evidence of inventory effects of trading on put prices, while such effects are not detectable in call prices. These results indicate that quoted put prices are sensitive to order imbalances. LEAPS put prices are revised upward after a buy order and downwards after a sell order by more than explained by information effects of trading. However, price effects appear to be related only to the trade direction and not to trade size. The results of these tests contribute to the option market microstructure and empirical options pricing literature by highlighting the role that market factors play in the pricing of options.

Third, I employ methods similar to Longstaff (1995) and test the martingale restriction in the sample of long-term index options. If there are no arbitrage opportunities in the price system, the value of the index implied from a set of synchronous LEAPS prices should be equal to the actual value of the index at that time. Evidence of the tests described earlier indicates that LEAPS puts are overpriced, in which case the result should obtain that the implied index is less than the actual index. I obtain mixed results with the martingale restriction tests. For LEAP puts, there is a highly significant difference between the actual and the implied index, but the implied index is most often higher than the actual, which result has no obvious explanation. However, consistent with Longstaff's (1995) findings, the difference between the two increases with the bid-ask spread and measures of trade imbalances, and decreases with the open interest in the options.

Fourth, I test the profitability of two trading strategies designed to exploit temporary price pressure effects in LEAPS puts prices. The strategies essentially involve buying an under-priced put, selling an overpriced put, and reversing the position at a later date. Over- and under-priced puts are identified using four different trading rules based on implied volatility of the options, trade imbalances, bid-ask quotes, and open interest. If the strategies are significantly profitable on average, it is an indication of inefficiency in the LEAPS market.

After adjusting for risk, the average profit from these strategies risk is not significantly different from zero. The results of these tests thus do not reject a hypothesis of market efficiency. The intra-day analysis showed the presence of intra-day inventory effects due to trade imbalances. However, from the results of the trading strategies, it appears that the effects either persist for intervals longer than the holding intervals used in these tests, or that marketmakers adjust prices such that the anomalies reverse by the end of trading day.

In Chapter 2, I review important results in the theoretical and empirical option pricing literature. In chapter 3, I describe the S&P 500 index LEAPS market and the data used for this study. Chapters 4 through 7 describe the individual empirical tests and the results. Chapter 8 concludes.

2 Literature Review

2.1 Option-pricing Theory

The Black-Scholes option-pricing model has had perhaps the greatest impact of all theories in finance in the world of financial markets. The Black and Scholes (1973) model is based on an arbitrage argument. Under its assumptions, an option can be combined with the underlying asset into a risk-less hedge portfolio that must therefore earn a risk-free rate of return. The set of simplifying assumptions that the authors make includes a log-normal stock price distribution, constant interest rates, constant volatility, and frictionless markets, with continuous trading and no transaction costs.

Subsequently, numerous studies have examined whether market prices of options empirically support the Black-Scholes options pricing formula. Among the first empirical studies were Black and Scholes (1973) and Galai (1977). These studies indicated that the BS model priced options quite accurately. One of the first to document BS pricing biases was MacBeth and Merville (1979, 1980), which used CBOE daily closing prices over the year 1976. The main finding of this study was that the BS model on average under (over) prices in-the-money (out-of-the-money) calls, and that the extent of the bias was proportional to the amount by which the call is in or out of the money. These pricing biases result in the implied volatility 'smile' or skew, the existence of which is one indication of the inadequacies of the constant-volatility BS model.

More results about the nature of biases in the BS model were provided by Rubinstein (1985), which study showed that the direction of the BS model pricing biases appears to have varied through time. Rubinstein (1985) used non-parametric tests and tick-by-tick transactions data from the CBOE's MDR tape to study BS pricing biases over the period August 1976 to August 1978. He finds that the BS model under-priced in-the-money options during the 1976-1977 interval, but the direction of the bias reversed during the 1977-78 interval. The reason for the change in direction is still not understood.

Given these strong indications of systematic pricing biases, two branches of research have developed in parallel since the introduction of the BS model, each of which attempts to explain the anomalies by relaxing the chief assumptions of the model. The BS model assumes a log-normal underlying asset distribution. It is widely known, however that stock returns do not always conform to a normal distribution. Non-normal skewness and kurtosis coefficients in the actual asset distribution can result in away-from-the-money options being underpriced by the BS model. In turn non-zero skewness and kurtosis could be implied by the presence of jumps and/or stochastic volatility in the price process of the underlying asset. Examples of option pricing models based on alternate stochastic processes are the pure jump model of Cox and Ross (1976), the combined jump-diffusion model of Merton (1976), the stochastic volatility models of Hull and White (1987) and Wiggins (1987).

Bakshi, Chen and Cao (1997) is a very comprehensive study of the competing option pricing models and compares their performance with respect to explaining market prices of options and hedging performance. The empirical part of their study is based on transactions data on S&P 500 index calls from 1988-1991. Their theoretical model allows for stochastic volatility and interest rates, and jumps in stock prices, and nests many other known option-pricing formulas as special cases. The BCC model performs significantly better than the base BS model in explaining market prices of options, but there still remain unexplained pricing biases.

In particular, to explain the volatility 'smile' present during their sample period across options with different strike prices and a common expiration date (in-the-money calls (puts) have higher (lower) implied volatilities than at-the-money and out-of-the-money calls (puts)), each model with stochastic volatility that they study requires implausible levels of volatility-return correlation (-0.64) when compared with the actual correlation between volatility and stock returns (-0.28) displayed by the time series of S&P 500 index returns. An interpretation of these findings is that other factors than the underlying asset's distribution play a role in determining prices of options.

The parallel branch of the option pricing literature relaxes the frictionless markets assumption, allowing for trading discreteness and transaction costs in implementing a dynamic hedging strategy. With non-zero transaction costs, rebalancing a hedge continuously is infinitely expensive. However, rebalancing at discrete intervals, while limiting transaction costs, leads to hedging errors. Leland

(1985) develops pricing bounds around the BS value in the presence of transaction costs. The bounds create a range around the theoretical price within which the market price may fall without giving rise to a profitable arbitrage opportunity large enough to cover the cost of exploiting it. The pricing bounds are a function of the level of transaction costs, the discrete portfolio revision period, and the strike price and maturity of the option.

Figlewski (1989) observes that market imperfections such as indivisibility, discreteness of trading and transaction costs are too complex to be incorporated analytically into theoretical pricing models. His approach is to simulate market imperfections to see the impact on option prices. He documents detailed results on the impact of these market imperfections on option prices in a simulated trading environment, and concludes that the impact, especially of transactions costs, is much larger than even suspected earlier by researchers. The bounds on the option prices are found to increase as the time to maturity of the options increases, consistent with Leland's (1985) prediction.

In a recent study, Longstaff (1995) examines the impact of market frictions on option prices by comparing the value of the S&P 100 index implied by the prices of call options to the actual index market value. In the no-arbitrage framework pioneered by Black and Scholes, the return of the underlying asset plays no part in the value of the option. In essence, the option can be valued as if the world was risk-neutral, and the underlying asset's distribution can be replaced by an equivalent risk-neutral distribution. In a formal exposition, Harrison and

Kreps (1979) show that in the absence of arbitrage opportunities, at least one such equivalent risk-neutral distribution must exist.

Longstaff (1995) uses these insights to derive a martingale restriction on the underlying asset. When no-arbitrage conditions are satisfied, the underlying asset price process should be a martingale, i.e., its actual value should be equal to the implied price in the options market, which is given by the mean of the equivalent risk neutral distribution. However, in markets with transaction costs, no-arbitrage conditions only place bounds on the difference between the two values. Longstaff finds that the implied index value exceeds the actual index value more than 99% of the time in his sample of S&P100 index calls, indicating that call option prices exceed their frictionless-market replication cost. The difference between the implied and actual index value is negatively related to open interest, total trading volume, and to the average index/strike price ratio, and positively related to the average option bid-ask spread and time to maturity, among other influences.

The Longstaff (1995) results suggest a role for liquidity-related variables in options pricing. One explanation for the results could be that there was greater investor demand to purchase than to sell S&P 100 call options in the sample, driving the prices of call options above their BS replication values. As the cost of implementing a dynamic arbitrage strategy increases, whether from higher option spreads or a longer time to maturity, the difference between prices of listed call options and their frictionless market also increases.

Some more supporting evidence of the importance of market frictions is presented by Long and Officer (1997) who study the relationship between the deviations from the Black-Scholes option pricing model and volume in the equity options market. Their results indicate that heavily traded call options are priced more efficiently (have lower mis-pricing errors) than thinly traded options. However, on high volume days, Black-Scholes mis-pricing errors are larger than on normal volume days. The authors suggest that new and changing information may cause the rapid increase in volume. If the information is differently reflected in the equity and option markets, Black-Scholes mis-pricing errors may result.

2.2 Put-call Parity Tests

The earlier section described some of the empirical evidence of biases in the Black-Scholes pricing models and the possible reasons for them. Several papers study the efficiency of options markets by testing for violations of arbitrage relationships, such as lower bounds, put-call parity and the box-spread arbitrage restriction. The advantage of studying deviations from arbitrage relationships is that the approach is independent of the underlying asset's distribution, and any specific option-pricing model. The put-call parity relationship for instance, arises because any two of three securities, the underlying asset and a put-call pair on the underlying asset with the same strike and maturity, may be combined to yield the payoff pattern of the third in a frictionless market. If the price of a put or a call deviates from its no-arbitrage value, an arbitrage opportunity is created where investors can step in to construct a position that earns more than the risk-free rate of return. Market frictions such as non-zero transaction costs may cause such deviations to arise and persist.

Klemkosky and Resnick (1979) was one of the first studies of put-call parity in the exchange-traded equity options markets and uses data on fifteen equity option series over the period 1977-1978. They report results that are consistent with a put-call parity relation after adjusting for the early exercise feature. They use transactions data and an algorithm to make sure that the time of the put, call and the underlying asset are within a minute of each other.

Evnine and Rudd (1985) provide early evidence on the efficiency of index options markets. They study put-call parity in the S&P 100 index and MMI (Major Market Index) options markets, soon after the introduction of these options. Using intra-day data and restricting their sample to options with a term to maturity of one month, they find evidence of a large number of violations of put-call parity. Their evidence is one of the first indications that index options markets may be subject to greater numbers of arbitrage condition violations than the equity options markets. Evnine and Rudd note that the difficulty of arbitraging in this market may be one reason for the large number of violations.

An alternative test of violations of the law of one price in options markets is the box spread test, first used by Billingsley and Chance (1985). A box spread is a combination of a put spread and call spread with the same strike and maturity dates, and should earn a risk free rate of return. Because a box spread does not require the underlying asset to be traded, two advantages arise: (1) Synchronicity between the recorded index prices and the option prices is not an issue, and

(2) Difficulty and cost of trying to replicate the index, which often leads to violations of put-call parity in index options markets, is not an issue.

Billingsley and Chance (1985) study the efficiency of S&P 100 index options, and find a large incidence of put-call parity violations, but fewer violations of the box-spread arbitrage restriction. Ronn and Ronn (1989) study box spread arbitrage restrictions in a sample of CBOE option prices over specific days in 1977-1984. Their results indicate that arbitrage opportunities exist only for agents with low transaction costs such as market makers, and even then only by a small amount.

More recently, Ackert and Tian (1998) study put-call parity and box spread violations in the market for Toronto 35 index options, before and after the introduction of the Toronto Index Participation Units (TIPS) in 1990.[1] They do not find conclusive evidence that option market efficiency improves when the linkage between stock and options market is thus strengthened. They find a significant number of violations both before and after the introduction of the TIPS.

The introduction of the SPDRS (S&P 500 Depository Receipts) in 1993 is a parallel to the introduction of the TIPS. Some very recent papers have studied the effects the introduction of SPDRS on the pricing efficiency of the S&P 500 index options markets. For instance, Perrakis, Switzer and Zghidi (1999) and Ackert and Tian (1999) both find that pricing efficiency within option markets

[1] Toronto Index Participation UnitS track the performance of the Toronto 35 index, and allow market participants a way of replicating the index easily and at low cost.

improves after introduction of these securities implying that a stock basket enhances the connection between markets.

Several other papers also study put-call parity in index options, although the focus of these papers is not always to test the efficiency of markets. Finucane (1991) finds a large frequency of violations in his sample of S&P 100 index options. Dubofsky, Ellis and Wagner (1996) examine the determinants of put-call parity violations in S&P 100 index options, and find a smaller fraction than Finucane (1991). The violations are found to increase significantly as dividends increase, and as the time to expiration decreases.

2.3 Trading and Prices in Options Markets

Evidence presented earlier on violations of arbitrage conditions and the relationship between deviations of market prices from arbitrage-based option-pricing model prices supports a conclusion that market imperfections that impede arbitrageurs activities play a role in pricing options. Imperfections such as asymmetric information, and risk-aversion of market makers manifest themselves as a relationship between trade imbalances and prices in financial markets. In this context, it is relevant to review here the large body of theoretical and empirical research on market microstructure issues such as the relationship between trade direction and size and prices.

Several theories have been proposed to explain the effects of trading on prices, notably the inventory control and asymmetric information models. According to the inventory control model (Amihud and Mendelson (1980,1982), Garman (1976), Ho and Stoll (1981)), market makers set quotes in order to induce buy or sell orders to achieve a certain optimal level of inventory. However, the extent to which inventory considerations influence prices varies with the prevalent market structure. In a single dealer structure such as the NYSE, the specialist may use the bid-ask midpoint as an inventory control mechanism. For example, if sustained buying results in a negative inventory in a security, the specialist may increase the bid and ask quotes to induce selling and discourage buying. In contrast, competition among market makers in a multiple dealer market such as the Chicago Board Options Exchange (CBOE) may prevent any one dealer from setting quotes to balance inventory. Collectively, a multiple dealer market may be better able to absorb inventory imbalances. However, the extent to which this is true may be market specific.

Models of information effects on trading (Bagehot (1971), Copeland and Galai (1983), Glosten and Milgrom (1985), Easley and O'Hara (1987)) suggest that security prices are affected by asymmetric information among the diverse players in a market. In these models, the market maker is faced with a positive probability that a particular trade originates from an informed trader. The outcome of these models is a role for bid-ask spreads as compensation for the market maker for losses to informed traders. The size of the spread reflects the proportion of informed trading in the market. Further, market makers will revise their bid-ask quotes to reflect the information conveyed in trading. For example, a buyer-initiated trade in a stock conveys positive information about the stock, prompting the market maker to increase his quotes, and so the bid-ask midpoint. In the index options market, an informed purchase of a call may convey information about a future increase in the index level or volatility, triggering an upward quote revision.

Empirical studies of the relation between trading and prices generally agree that trades affect stock prices, the direction and persistence of impact being determined by the nature of the trade. Holthausen and Leftwich (1987) find temporary price effects for seller-initiated transactions and permanent price effects for buyer-initiated transactions in their study of the impact of large block trades on NYSE common stock prices. Blume, Mackinlay and Terker (1989) study order imbalances during Black Monday in 1987 and conclude that there is a strong relation between stock price movements and order imbalances. Hasbrouck (1988) finds mixed evidence of inventory effects but strong evidence of information effects of trading on stocks. He finds that large trades appear to convey more information.

Previous empirical research on trading in options markets has largely focused on whether option volumes lead the underlying asset. Vijh (1990) studies the liquidity of CBOE regular equity options, specifically market depth and spreads. He finds no evidence of inventory-related price effects of large trades indicating great market depth for these options, but detects information effects of trade direction on options prices, although trade size is unimportant. He also finds that option spreads are disproportionately large compared to those of stocks. He concludes that the multiple market dealer structure is a factor responsible for the greater depth of the CBOE, though at higher costs. Chan, Chung and Johnson

(1995) study bid-ask spreads of CBOE equity options and find that options display an intra-day pattern of spreads that is very different from the U-shape spread pattern exhibited in the NYSE. This pattern appears to be related to the intra-day variations of volume and volatility, which also follow a U-shaped pattern and due to information uncertainty. Chan et al (1995) find that option spreads decline sharply after the day's open and then level off. They suggest that high uncertainty may cause the higher spreads at the open, while the different CBOE market making structure may account for spreads declining through the day.

Easley, O'Hara and Srinivas (1998) investigate the informational role of trading volume in equity options markets. They separate options volume into positive and negative volume: positive volume is the total of call buy trades and put sell trades, and negative volume is the total of call sell trades and put buy trades. They find that negative and positive option volumes are better predictors of the underlying stock prices than are volumes not separated according to their definition of volumes.

3 The S&P 500 Index LEAPS Market

The Chicago Board Options Exchange (CBOE) introduced long-term Equity Anticipation Securities (LEAPS) on indexes in 1991. Index LEAPS differ from their short-term counterparts chiefly by the length of time to maturity, which can be up to three years from the date of issue, and their contract size, which is based on one-tenth of the index level. Index LEAPS provide investors with the ability to create a long-term position in an option with the same investment horizon as their market opinion. S&P 500 LEAPS are European style, cash-settled and expire on the third Friday of December of each year. Since the underlying asset for these options is a fraction of the index, they provide the investor with the ability to control market exposure in finer increments than full-size, shorter-term index options. Like short-term index options, index LEAPS have potential uses for hedging against adverse moves in the market.[2] The volume in this contract has doubled from about 280,000 contracts in 1994 to about 510,000 contracts in 1996, showing its growing popularity.

The source of the data used in this dissertation is the Chicago Board Options Exchange (CBOE) Market Data Retrieval (MDR) tape over the years 1994-1996, which has a time-stamped record of bid-ask quotes and trade prices of all options traded on the exchange. I study LEAPS during the period 1994-96 to avoid the first few possibly inactive years after introduction of these options.

Each trade record includes the transaction price and volume of the trade while each quote record includes the bid and the ask prices. Each record also includes the value of the underlying SPX to the nearest 15 seconds, helping to minimize errors due to asynchronous measurement of the index. A separate database called the Expanded Options Summary of the CBOE includes the total daily volume and open interest for each contract, which I match with the records in the transactions database.[3]

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[2] Some of the information on LEAPS contracts is obtained from the CBOE's web site, www.cboe.com

[3] Published open interest is the level of open interest at the close of the previous trading day.

3.1 Sample Selection Criteria

From the raw sample I exclude quotes and trades that (a) have <= 6 days to expiration and bid price <= 3/8 (or transaction price <=3/8 for trades), to avoid expiration day effects and errors due to price discreteness (b) occur before 8:30 a.m. or after 3 p.m. C.S.T and (c) have obvious recording errors for prices or index values. This screening procedure results in 25407 trades and 595167 quotes in all. I use the mean of an option's bid and ask prices to proxy for its market value in my analyses, since using bid-ask quote midpoints minimizes problems of negative serial correlation due to bid-ask bounce. All the empirical work in this dissertation is done on sub-samples of this reduced data set.

Table 1 shows summary statistics for bid-ask quotes and trades of S&P 500 index LEAPS from 1994-1996 by moneyness categories, where moneyness of the option is defined as the ratio of its strike price, X, to the corresponding index value, I. Daily volume, trade frequency, and open interest are much higher for puts than for calls, and OTM puts are more frequently traded than ITM puts. Average daily volume consists of 1404.27 put contracts but only 45.71 call contracts. Over 1994-96, there were a total of 24,350 put trades but only 1,057 call trades. There were 9,767 trades in deep OTM puts, equal to 38% of the total number of trades. Average daily open interest in puts is more than 22 times the open interest in calls. Reflecting the rise in stock prices over the sample period, open interest in deep OTM puts on the last day of 1996 is 215,176 contracts, comprising 85% of the total LEAPS open interest.

Table 2 shows daily changes in open interest categorized according to an increase or decrease, for those contracts with non-zero daily volume. Of the total number of contract-days in which there was positive daily volume (533 for calls and 5,953 for puts), daily volume is exactly equal to the increase in open interest on 230 contract-days for calls and 2,377 for puts (40% of total contract-days in puts). Since speculators or day traders do not typically keep their positions open overnight these data suggest that hedging activity is responsible for much of S&P 500 LEAPS trading. On 4,698 contract-days for puts and 305 for calls, there is a net increase in open interest.[4]

Percentage bid-ask spreads decrease as the ratio of X/S increases. It is interesting to note that there are considerably more bid-ask quotes for deep ITM calls than deep OTM puts, indicating that call quotes are revised more frequently despite their lower trading volume. The frequency of quote revision for low-priced, deep OTM puts is probably limited by price discreteness. The tick size for options with prices above and below $3 are 1/8 and 1/16 respectively.

To view these statistics in perspective, I look at similar statistics for S&P 500 index short-term options, for which also I have daily closing price data. A similar pattern of heavier volumes and open interest in puts than in calls emerges, but to a much smaller extent. Average daily volume for S&P500 short-term puts is 59,470 contracts while that for calls is 42,430 contracts. Average daily put open

[4] A trade of size one in a contract will increase, decrease or have no effect on open interest in the contract depending on the positions of the two participants. If both parties are opening positions, the trade will increase open interest by one. If one party is closing a position, then there is no change in open interest. If both parties are closing positions, the trade results in a decrease in open interest by one contract.

interest is almost a million contracts, while average daily call open interest is 650,000 contracts. A comparison with corresponding statistics for LEAPS shows that a greater imbalance exists in LEAPS than in shorter-term index options.

3.2 Interest Rate Data

Daily risk-free interest rates are required to find the present value of the daily cash dividend series on the index, and as an input for the Black-Scholes option-pricing formula. Data on daily U.S Treasury Strip ask rates are collected from the Wall Street Journal for all strips maturing during the sample period from 1994-1996. Linear interpolation between the two treasury strip rates straddling a dividend payment date yields an approximate risk-free rate for discounting the dividend. Linear interpolation between the two strip rates straddling the December maturity dates of each LEAPS calendar series gives the approximate risk-free rate corresponding to each option. This procedure is repeated every day of the sample period for every dividend payment date and option maturity.

3.3 Adjusting the Index for Dividends

Since S&P 500 LEAPS are European style, the analysis in this thesis is not complicated by the need to value early exercise features. But adjusting the index for cash dividends is necessary and a challenge for LEAPS because of their long life. It is a common practice in the empirical options literature to use the present value of actual dividends over the option's life as a proxy for the expected dividends. However, over a long period such as the life of LEAPS, actual dividends may differ significantly from forecasted dividends. Using actual dividends thus leads to numerous lower bound violations for put and call options. In a sample of 23248 daily closing quotes of the LEAPS in the sample, I find 5011 (22%) violations of the lower bound when I use the present value of actual dividends to adjust the index.

One way to make a more accurate dividend adjustment is to use the implied present value of dividends from the market price of options.[5] A comparison shows that actual dividends are typically lower than the dividend forecasts impounded in option prices. So I use the implied dividends found from near-the-money put-call pairs constructed each day of the sample as a closer approximation of the dividend forecasts implicit in the price of the options, wherever an adjustment for dividends has to be made to the index. Using the implied dividends results in 1031 (4.4%) lower bound violations. I describe both methods in more detail below. Henceforth, a reference to the index means the spot index value adjusted for dividends.

3.3.1 Present Value of Actual Dividends

I obtain the S&P 500 daily cash dividend series from 1994-97 from Standard and Poor's. [6]. The latest expiration date of the option series in the sample is in December 1998 (for the series introduced in January 1996). Since at the time of writing this thesis, I cannot obtain actual cash dividends for all of

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[5] For example, Sarig (1984) studies dividend expectations implied by option prices.

[6] In a sample of S&P 100 index options, Harvey and Whaley (1992) show that it is inaccurate to assume a continuous dividend yield for the S&P 100 index, because the actual daily cash dividend series is discrete and distinctly seasonal. I find similar seasonality in S&P 500 index daily cash dividends.

1998, I forecast quarterly dividends for 1998 using 1997 dividend payout ratio and earnings forecasts, imposing the seasonal pattern in the 1994-1997 daily dividend series. Appendix A describes the methodology used for forecasting 1998 dividends. The present value of the daily dividends between day t and maturity date of each calendar series T, $PV(D)_{t,T}$, is then found by discounting each day's dividends by the appropriate risk-free interest rate and adding them up.

3.3.2 Present Value of Implied Dividends

European put-call parity is used to derive the implied present value of dividends between each day t and the maturity date of each calendar series. Define P_t as the bid-ask quote midpoint for a put on day t with strike X expiring in T days, C_t as the corresponding call quote, I_t as the closing value of the index on day t, and $PV(D)_{t,T}$ as the present value of dividends on the index paid from day t until maturity of the option T days later. By put-call parity, the following arbitrage condition holds:

$$PV(D)_{t,T} = P_t + I_t - C_t - X^*e^{-rT} \qquad (1)$$

Several empirical studies of option pricing have found that at-the-money options exhibit the smallest stock price distribution-related biases relative to options with other strikes. So I use a simple average of the implied dividends for the two nearest the money put-call pairs of a calendar series on a day as an approximation of the present value of dividends for that series on that day. I repeat this for every day and maturity and find the adjusted value of the index each day.

3.4 Classification of Trades

The MDR tape does not classify trades as buy or sell trades, while an important part of this dissertation requires data on trade classifications. It is therefore necessary to infer trade direction by comparing the trade price with the quote effective at the time of the trade. Identifying the current quote at the time of trade poses some problems. Lee and Ready (1991) compare some methods used to classify trades in studies dealing with transactions data, and discuss potential problems with the methods. They find that quote revisions due to a trade are likely to be recorded before the trade itself for NYSE stocks, causing erroneous classification of the trade. To overcome this problem, they suggest comparing the trade to the quote in effect five seconds before the trade. However, using such an interval does not appear to be necessary for the CBOE, because quote revisions caused by trades appear to be recorded most frequently at the same instant as the trade.[7] So I use the quote immediately before the trade to make the buyer- or seller-initiated classification.

The following rule is used to classify trades. A trade is classified as buyer-initiated if the transaction price is equal to the ask price and as seller-initiated if it is equal to the bid price of the quote in effect. To deal with trades that occur inside the spread, I use the rule followed in Harris (1989). A trade inside the bid-ask spread is classified as a buy trade if it is closer to the ask price and as a sell trade if it is closer to the bid price. Trades occurring at exactly the bid-ask midpoint cannot be classified by this rule. Lee and Ready (1991) discuss a tick test by which midpoint trades may be classified. However, trading in index LEAPS is too infrequent to use tick tests with an acceptable degree of accuracy. I therefore discard trades occurring at the midpoint. This should not affect the results of the study materially, as midpoint trades should not be biased towards any particular trade direction.

The number of trades at the bid-ask midpoint is 3346, equal to 13.2% of the total number of trades. These trades cannot be classified by the rule above. The incidence of these trades is more than in Easley, O'Hara and Srinivas's (1998) sample of CBOE equity options, but less than for NYSE stocks. Trades at the midpoint may occur due to limit or standing orders. A small number (228) of trades occurs at prices above the ask or below the bid of the matched quote, and cannot be classified. These unclassified trades are discarded from the analysis.

Table 3 shows summary statistics of trade classifications. There are 3,919 trades at the bid-ask midpoint, representing 15.4% of the total number of trades. A small number (228) of trades occur at prices above the ask or below the bid of the matched quote. These trades are discarded from the analysis. Of the remaining trades that can be classified, buyer-initiated trading in puts predominates during the sample period. Out of a total 25,407 trades, 17,032 trades or 67% are buy trades in puts. Of classifiable put trades, 81.7% are buys. In contrast, 53.5% of trades in LEAPS calls can be classified as buyer-initiated while 39.8% are seller-initiated, corresponding closely to previous findings for equity options. Easley, O'Hara and Srinivas (1998) classify trades in CBOE equity options from October-November 1990 in a similar fashion. Their results show that equity options

[7] Appendix B describes the procedure used to reach this conclusion.

trading is primarily buyer-initiated, with the percentage of buy and sell trades equal to 53.4% and 38.8% respectively.

3.5 Characteristics of Implied Volatility

Previous empirical research on index options, including BCC (1997, 1998), document systematic biases in the BS formula. To complete the description of the data, I compute daily BS implied volatilities for calls and puts, using the bid-ask midpoints of the last option quotes and corresponding index value on each. To aid in comparing results with previous studies (for example Bakshi, Cao and Chen (1998)), I define moneyness in a like manner as the ratio of strike price to closing index value. I divide the options into six moneyness classes, and 4 maturity groups based on the time remaining to expiration – (1) Very short term: <= 60 days, (2) Short term: >60 and <=180 days, (3) Medium term: > 180 and < 365 days, and (4) Long-term >=365 days.

Table 4 shows the mean implied volatility for options in different moneyness and maturity categories for calls and puts, and figure 1 plots the implied volatility for very short, medium and long term puts. I focus on puts in the discussion here. For very short term puts, the BS implied volatility displays the familiar U-shape known as the smile. As the put goes from being out-of-the-money to in-the-money, the implied volatility first decreases from 18.6% to about 14.5% for at-the-money options and then increases to about 22%. However, the shape of the volatility curve is dependent on the term to maturity. For short, medium and long-term puts, mean implied volatility decreases monotonically as the put goes from being out-of-the-money to in the money. For example, for longer-term options (time to expiration > 365 days) implied volatility decreases from 18.3 % for deep OTM puts to 14.1% for deep ITM puts.

These differences in shape could arise due to the property of the stock price distribution that causes the bias. Near term options may be more affected by jumps in the index which have a positive effect on the prices of both OTM and ITM options, causing a U-shaped volatility smile. Longer term options may be more prone to the effect of negative correlation between volatility and the index, causing OTM puts to be over-priced and ITM puts to be under-priced relative to ATM puts. Similar patterns are observed in call implied volatilities, except that there is some evidence of a smile in short term calls.

The term structure of implied volatility is also U-shaped for all moneyness classes. Within a moneyness class, implied volatility is higher for short and longer-term options than for the medium term options. However, the amount of variation in implied volatility with moneyness decreases as time to expiration increases. The implied volatility patterns I find are qualitatively similar to the results of Bakshi, Cao and Chen (1998) in their sample of S&P 500 index LEAPS puts from September 1, 1993 to August 31, 1994. The chief differences are a higher implied volatility in the sample for most moneyness-maturity categories, and a greater variation across moneyness categories.

These results confirm the biases in BS prices that numerous studies have documented. The results have relevance to the present study, since I analyze movements in implied volatility due to information and inventory effects of trades. It is evident that implied volatility will change as the option's moneyness changes with daily or intra-day fluctuations in the index, which must be controlled for in the study.

4 Tests of Put-call Parity and Box Spread Restrictions

In this section I first test for violations of put-call parity in a sample of S&P 500 index LEAPS put-call pairs using the spot index in the arbitrage condition. The results show a significant number of put-call parity violations in a direction that indicates that the put is overpriced. However, since the spot index is costly and difficult to trade in practice, instruments like the S&P 500 futures contracts are very likely used in practice to arbitrage pricing anomalies in index options. Therefore, I repeat the put-call parity tests using S&P 500 index futures contracts in place of the spot index. Finally, the box-spread arbitrage restriction, which does not require the underlying asset to be traded, is tested.

4.1 Put-call Parity Tests

4.1.1 Measures of Deviation from Put-call Parity

Define P and C as the bid-ask quote midpoints of a European put-call pair with strike price X and time to expiration T, I as the index value corresponding to the later of the two option quotes, and D_T as the present value of dividends. The put-call parity equation is:

$$P + I - D_T = C + Xe^{-rT} \qquad (2)$$

Define E as the amount by which the put is overpriced versus the call:

$$E = P + I - C - Xe^{-rT} - D_T \tag{3}$$

Even if $E \neq 0$, market frictions including bid-ask spreads and brokerage commissions limit arbitrage activity. But if the put is significantly overpriced with respect to the call, arbitrageurs can sell the put, buy the call, short the index and lend an amount of money equal to the present value of the strike plus the present value of the dividends. After accounting for option bid-ask spreads on the initial trade, but not for commissions, costs of closing out initial option positions, or costs of trading the cash index, the profit from this strategy will be:

$$E_1 = P^b + I - C^a - Xe^{-rT} - D_T, \tag{4}$$

where superscripts '^{a}' and '^{b}' denote ask and bid prices respectively. If the call is significantly overpriced with respect to the put, the above strategy can be reversed producing a profit of:

$$E_2 = C^b - P^a - I + Xe^{-rT} + D_T \tag{5}$$

4.1.2 Sample Construction for Put-call Parity Tests

Each day, put-call pairs are formed by pairing the last quotes of the day of puts and calls with the same strike and maturity. Using quotes avoids bid-ask bounce problems that can occur with transaction prices. The pairs are then matched with the index value corresponding to the latest of the two quotes. On average, the last of the two quotes occurs at about 12:30 PM Central Time, so issues related to potentially "artificial" quotes at the close of trading do not appear to be relevant here.

The final sample contains 10462 put-call pairs. The put quote occurs later in the day than the call quote in 6991 of these pairs, by an average of 1 hour 53 minutes. Since puts are traded more often than calls, their quotes are revised more frequently.

It is a common practice in the literature to use the present value of actual dividends over the option's life as a proxy for the market's dividend expectation. I follow that convention here, but recognize that expected dividends when the options are priced may differ significantly from the present value of actual dividends. The present value of actual dividends is obtained as described in Section 2. Daily risk-free interest rates required to find the present value of the cash dividend series on the index are collected from the *Wall Street Journal* for each day over 1994-1996, as described also in Section 2.

4.1.3 Put-call Parity Results

Table 5 presents summary statistics for the sample. As a result of the general rise in stock prices over the sample period, the index typically exceeds the present value of the strike price for the matched put-call pair. With an average maturity of 1.44 years, the mean present value of dividends is a substantial 3.5% of the mean index value. The dollar bid-ask spread tends to be higher for calls than puts, reflecting the generally higher price for calls in the pair, but the percentage spread is higher for puts.

The put-call parity test results are illustrated in Table 6 Panel A. The put option is overpriced relative to the call more than 96% of the time, and the mean value of E is \$1.16. Accounting for option bid-ask spreads, the put is overpriced versus the call almost 80% of the time. For those 8349 observations with $E_1>0$, the mean and median for E_1 are \$1.19 and \$1.07 respectively. E_2 is positive in only 39 of 10,462 cases, with a mean and median of \$0.19 and \$0.10 for those 39 cases.[8]

One explanation for put overpricing is that investors systematically overestimated future dividends on the index over the period. All else equal, from Equation (2), the higher the present value of dividends as perceived by investors, the higher is the value of the put relative to the call. This explanation becomes more convincing if actual dividends over the life of the options fell short of what could be reasonably expected based on recent experience. Over the 1989-93 and 1985-93 periods, dividends on the S&P 500 index grew at 3.3% and 6% geometric annual rates respectively, while dividends over 1993-97 grew at 5.3% annually. So, as an approximation, actual dividend growth was in line with historical experience.

Furthermore, if overestimation of future dividends were the primary cause of put overpricing, one would expect to see the size of the violation increase with option maturity. Since companies typically change their dividends only once a year, forecasting index dividends over only a few months can be performed with great accuracy, but longer term forecasting is more difficult. The second panel of Table 6 Panel B examines put-call parity violations by maturity. For measure E_1, the proportion of puts overpriced is about the same for options with less than 60

[8] The results are very similar after excluding options maturing in December 1998, where I needed to use estimated rather than actual dividends.

days to maturity as for longer maturity options. For those observations with $E_l >$ 0, average overpricing for very short-term options is \$1.23, about the same as for longer-term options. This \$1.23 mean violation is more than six times larger than the mean present value of actual dividends, suggesting that dividend forecasting errors cannot account for much of the pricing error for shorter maturities.

Put-call parity pricing errors exhibit considerable persistence from day to day. There are 8011 observations with all data available for the same option pair on the next trading day. For the 7759 of these 8011 with E>0 on day t, 7522 or 97% are again positive on day t+1. Accounting for option spreads with measure E_l, of the 6375 that are positive on day t, 5159 or 81% are again positive on day t+1.

I next estimate a regression to identify sources of deviations from put-call parity. The dependent variable is E, the overpricing of the put relative to the call using bid-ask midpoint quotes. The explanatory variables are the index/strike price ratio, the time to expiration, the time difference between put and call quotes in the pair, and both put and call open interest. The dollar change in the index between put and call quotes is also included as a control variable. A change in the index between the times of the two option quotes induces put-call parity violations, because the first of the two quotes does not reflect the subsequent index change. Regression results are presented in Table 7.

Put overpricing is positively and significantly related to the index/strike ratio. This means that out-of-the-money puts tend to be more overpriced than at-the-money or in-the-money puts. Since out-of-the-money put trading predominates in S&P 500 LEAPS market, there could be particularly severe inventory imbalances and price pressure for these options. The results support this price pressure hypothesis.

The negative coefficient on time to expiration indicates that long-term options are more efficiently priced than short-term options, consistent with results in Dubofsky, Ellis and Wagner (1996). There is no obvious explanation for this relationship. As discussed earlier, this result is particularly puzzling if inaccurate dividend forecasting is the cause of the violations. There is no significant relation between put overpricing and the time difference between put and call quotes, suggesting quote staleness per se is not driving the results.

Open interest has been used in some studies (Longstaff (1995)) as a proxy for liquidity or market depth. The more liquid the market, the easier arbitrage trading becomes, so one would expect negative coefficients on both put and call open interest. Results are mixed, with the coefficient on put open interest negative and significant but the coefficient on call open interest insignificantly different from zero.[9]

4.2 Box Spread Tests

4.2.1 Measures of Deviation from the Box Spread Arbitrage Restriction

The box spread is a position involving two pairs of puts and calls with different strike prices but a common expiration date. Let (C_1, P_1) be the bid-ask midpoints of a put and a call with strike price X_1 and (C_2, P_2) be the bid-ask midpoints of a put and a call with strike price X_2. All options expire in T years. The box spread relation is:

$$P_1 + C_2 = P_2 + C_1 - (X_2 - X_1)^* e^{-rT} \quad (6)$$

Define V as the amount by which the put P_2 is overpriced relative to the other options:

$$V = P_2 + C_1 - P_1 - C_2 - (X_2 - X_1)^* e^{-rT} \quad (7)$$

V is thus a measure of the arbitrage profit that can be realized due to overpricing of P_2 with respect to the other options.

After accounting for bid-ask spreads, a measure of the arbitrage profit available if P_2 is overpriced is:

$$V_1 = P_2^b - P_1^a + C_1^b - C_2^a + (X_1 - X_2)^* e^{-rT} \quad (8)$$

where superscripts '^{a}' and '^{b}' denote ask and bid prices respectively. A positive V_1 implies that P_2 is overpriced by enough to cover costs due to bid-ask spreads. I have not included brokerage costs, which would decrease any possible profits.

4.2.2 Sample Construction for Box Spread Tests

Testing all possible box spread combinations in the data is a Herculean task, so to keep the data manageable I always choose the first option pair (P_1, C_1) to be closest to at-the-money for that maturity. Thus, the tests evaluate the pricing of in-the-money and out-of-the-money put-call pairs (P_2, C_2) relative to the

[9] In a regression with put and call trading volumes as additional explanatory variables, the open interest coefficients were little changed and the coefficients on the volume variables were

at-the-money pair (P_1, C_1). Starting with the set of 10462 put-call pairs, I match the put-call pair that is closest to at-the-money with every other pair in the same calendar series, resulting in 8570 box spreads.

4.2.3 Results of Box Spread Tests

Table 8 illustrates the results. The mean absolute value of V is only about \$0.32, far less than the mean absolute violation of put-call parity of \$1.21 in Table 6. V is greater than zero about 50% of the time with a median value of -\$0.003, or less than one cent.

Once bid-ask spreads are incorporated, there are few profitable box spread arbitrage opportunities, even before accounting for commissions. Column 2 of Table 8 shows that V_1 is positive in only 434 (5%) cases. The mean and median violations in these 434 cases are only thirteen and eleven cents respectively. In all but one of these 434 cases, V_1 is less than 30 cents. While the put-call parity results indicate puts are generally overpriced relative to the replicating strategy of shorting the index, lending, and buying a call, the box spread results indicate options are efficiently priced relative to one another when index trading is not part of the replicating strategy.

In Table 9, I run a regression to identify sources of deviations from the box spread relation. The dependent variable is V, the overpricing of P_2 relative to the at-the-money put-call pair using quote midpoints. The explanatory variables are the index/strike ratio of the put-call pair (P_2, C_2), time to expiration, and open interest for each of the four options.

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insignificantly different from zero.

In the regression, the index/strike ratio for the (P_2, C_2) pair is positive and significant. This means that the more out-of-the-money the put is, the more overpriced it is relative to the other options, consistent with the put-call parity results in Table 7. The time to expiration variable is negative, implying that the longer the time remaining to maturity, the lower is the price of option P_2 relative to the other options.

The open interest variables are all statistically significant, with positive coefficients on P_1 and C_2 and negative coefficients on P_2 and C_1. From Equation 6, this means that the higher the open interest for an option, the lower its price relative to the others in the box spread.

4.3 Testing Put-call Parity Against S&P 500 Futures Data

The foregoing put-call parity test results raise serious questions about the joint efficiency of the S&P 500 LEAPS and stock markets. In practice, trading strategies that are in use in the real world may determine option prices more nearly than theoretical arbitrage relationships (Figlewski 1980). Since arbitrage with the underlying S&P 500 index futures contract is less expensive and easier than trading the basket of stocks, it is important to extend the study to test LEAPS put-call parity using S&P 500 index futures prices instead of the spot index.[10] This analysis is the subject of this section.

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[10] I thank Professor Mark Schroder for this suggestion.

4.3.1 S&P 500 Futures Contracts Data

I obtain transactions data on S&P 500 futures contract over the sample period of 1994-1996 from the Futures Industry Institute. These contracts expire on the third Friday of the contract month in a quarterly cycle (March, June, September and December). This is the same expiration date for LEAPS on the S&P 500, implying that no adjustment is required for a difference in time to expiration. The futures contracts may be traded until 8:30 A.M on the expiration date. The quarterly settlement is based on a Special Opening Quotation of the relevant underlying index, which is calculated using the opening price of each component stock in that index on that day.

For testing violations of put-call parity by S&P 500 LEAPS against S&P 500 futures contracts, it is required that each put-call pair in the sample be matched with the futures contracts with the same maturity month. This condition restricts the sample to put-call pairs that expire in December each year – about a third of the entire sample. For each pair and each day, the bid quote of the corresponding December futures contract is selected that is closest in time to the later of the two options in the pair. Matching futures contract records are found for a total of 2981 records, which forms the sample for this these tests. The average time difference between the futures contract quote and the latest option quote in a pair is about 9 minutes and 40 seconds.

4.3.2 Put-call Parity using S&P 500 Futures Prices

The theoretical price of a futures contract on the index at any time t, F_t is given by $F_t = (I_t - D_T) * e^{r*(T-t)}$. Here, I_t is the spot index at time t, T is the expiration date of the futures contract, D_T as before is the present value of dividends on the index over the remaining life of the contract, and r is the rate of return on the risk free security issued at time t and expiring at time T.

The measures of put-call parity violations E, E_1 and E_2 are redefined under the assumption that the futures contract is used for the spot index in equations 3, 4 and 5. Substituting for the spot index I from the futures price relationship above gives (for equation 3):

$$\begin{aligned} E_F &= P + (F*e^{-r*T} + D_T) - C - Xe^{-rT} - D_T \\ &= P + (F - X) * e^{-r*T} - C \qquad (9) \end{aligned}$$

F in this equation is the price of the futures contract at the time that the hedge is constructed.

Equation (9) says that when the LEAP put is significantly overpriced with respect to the call, arbitrageurs can sell the put, buy the call, short the futures contract of the same maturity as the put-call pair, and lend an amount of money equal to the present value of the strike. The profit from this strategy is denoted as E_F. After accounting for spreads, the profit is E_{1F}.

$$E_{1F} = P^b + (F^b - X) *e^{-r*T} - C^a \qquad (10)$$

Similarly,

$$E_{2F} = C^b - P^a - (F^a - X)*e^{-r*T} \qquad (11)$$

4.3.3 Results

Table 10 shows the results for put-call parity violations using S&P 500 futures contracts. The put-option is overpriced with respect to the call option about 80% of the time before accounting for spreads, while after accounting for spreads it is overpriced about 47% of the time. For the 1403 observations with $E_{1F} > 0$, the mean and median of E_{1F} are \$0.26 and \$0.25 respectively. In contrast, the corresponding numbers from Table 6 for put-call parity violations using the spot index are that E_1 is positive 80% of the time with a mean violation for those observations of \$1.19.

These results support a hypothesis that the ease and low cost of trading with futures contracts leads to LEAPS being priced off the futures rather than the spot index, for options where futures contracts are available with a corresponding maturity date. Taken together with the finding in the section using the spot index, the results also suggest that the futures price violates its own arbitrage condition.

Panel B shows the violations by maturity. Comparing the results in this table with Panel B of Table 6 shows that the mean E_{1F} for observations where $E_{1F} > 0$ is \$ 0.27, while mean E_1 is \$1.23 for short maturity options. This contrast is surprising because it implies that near maturity futures contract are also very much overpriced with respect to the spot index.

Put-call parity violations were found to be quite large for the long maturity LEAPS as well, for which an exactly matching maturity futures contract is not available. That anomaly remains unexplained by this analysis.

4.4 Summary

In this section I test put-call parity and box spread arbitrage conditions in the sample of S&P 500 LEAPS. Testing for these efficiency conditions is interesting in the LEAPS environment, where market makers may face persistent inventory pressures.

The put-call parity results raise questions about the joint efficiency of the S&P 500 LEAPS and stock markets. Using the present value of actual dividends in the parity equation, I find that put options are consistently overpriced relative to calls. After accounting for option bid-ask spreads, puts are overpriced about 80% of the time, with an average overpricing of $1.19 in those cases.

One possible explanation for this result is that investors overestimated future dividends when the options were priced. However, actual dividend growth over 1993-97 was in line with historical experience. Moreover, pricing errors for very short-term options, where dividend forecasting is relatively easy, are comparable to pricing errors for longer-term options.

I also test the efficiency of the LEAPS market with reference to the S&P 500 index futures market. Since these contracts have a maximum maturity of about a year, futures contracts maturing on the same day as the options in a put-call pair are available for 2981 of the total 10462 put-call pairs. Puts appear to be much less overpriced with respect to the futures price. After accounting for option bid-ask spreads, puts are overpriced only about 47% of the time, with an average overpricing of $0.27 in those cases. The low cost and ease of transacting in futures contracts are presumably the reason that the LEAPS markets are better aligned with the futures market than with the spot index. Thus, trading strategies followed by investors in the real world may determine the LEAPS prices better than theoretical arbitrage relationships. However, the large number and size of violations of put-call parity for longer-term options remain a puzzle – caused either by an overestimation of present value of dividends on the index, or overpricing of the puts due to the trade imbalances.

The results for box spreads are much more consistent with market efficiency than the results for put-call parity. After accounting for bid-ask spreads, there are very few violations in the data, and those that appear are very small.

To summarize, the evidence suggests that option prices in the S&P 500 LEAPS market are internally consistent, but that put options are overpriced relative to the replicating strategy of shorting the index, lending the proceeds, and buying a call. However, put option prices are more consistent relative to the S&P 500 futures market, whenever contracts are available with a maturity corresponding to that of the LEAPS. Put overpricing for the longer-term LEAPS could result from public demand to purchase long-term put options for portfolio insurance. Given the transaction costs involved in shorting index futures, or shorting SPDRs and lending the short sale proceeds, even large premiums on S&P 500 LEAPS puts may be difficult to arbitrage away.

5 Intra-day Analysis of Trading and Prices

In this section, I test for a relationship between trade imbalances and prices in the S&P 500 index LEAPS quotes and trades in an intra-day analysis of quotes and trades. First, I examine a sub-sample of pairs of quote revisions with a single trade between the quotes. I test whether bid-ask quotes for specific LEAP option tend to be revised upward in response to a public purchase of that option versus a public sale of the option. Next, I analyze a sample of pairs of quote revisions of an option with multiple trades between quotes. I use the difference between public buy orders and public sell orders that occur between the quotes as a measure of trade imbalance in that option. I construct samples in two different ways to check for robustness of my results. Third, I study the relationship between order imbalances over the course of the day and price changes between the first and last quotes of the day. This is to test whether intra-day inventory effects are temporary or persist into the next day.

5.1 Methodology

The objective of this part of my dissertation is to test whether order imbalances have inventory effects on S&P 500 index LEAPS prices. It is critical to separate inventory effects from information effects to make any inference about price pressure effects on options prices. An options trade can convey information about the future value of the index or the expected volatility of the index over the option's life. If a trade in a particular option conveys information about the future value or volatility of the index, the market maker should update quotes of all options on the index to incorporate the information. However, if a trade does not convey information, but creates inventory imbalances in a specific option series, quote revisions will be related only to trade in that option and not to trade in other options.[11] More generally, if inventory effects are present, quote revisions should be more sensitive to trade in the option of interest than to trade in other options. This insight is the basis of the methodology followed in this section.

Despite its empirical biases, the BS formula serves a useful purpose for the tests in this section. I test for a relation between changes in BS implied volatility with order direction and volume in both the traded option and other options with the same maturity. Since each option's implied volatility is unconstrained, the results are not dependent on the validity of the BS model, especially as changes in the BS implied volatility due to change in index are controlled for in the tests.

5.2 Single Trade between Quotes

I focus on quote revisions due to a single trade in this section and study the influence of multiple trades on prices in the next section. The change in implied volatility can be attributed to the trade with greater confidence when there is a single trade between quotes.

First, I study the relationship between changes in implied volatility and the direction and size of the trade. Evidence of a relationship will suggest the presence of inventory and/or information effects of trades. For instance, a put purchase can mean a future decrease in the index or an increase in the index implied volatility. Second, in an attempt to separate the two effects, I compare the implied volatility changes of traded options caused by a trade with that of a non-traded option due to the same trade. If implied volatility has changed because the market maker has revised the volatility estimate due to information in the trade, the implied volatility of other options should reflect the change. Significant differences in magnitudes and direction of movements in implied volatility of traded and non-traded options point to inventory effects for the traded option.

5.2.1 Sample Construction and Variable Definition

Let ($q_{i,j}^{pre}$, $q_{i,j}^{post}$) be a pair of bid-ask midpoint quotes in option i with exactly one intervening trade, $T_{i,j}$. I refer to i as the traded option and X_i is the strike price of traded option i. Let the BS implied volatility of option i before and after the trade, $IV_{i,j}^{pre}$ and $IV_{i,j}^{post}$ and the change in the implied volatility as $IV_{i,j}^{post} - IV_{i,j}^{pre} = \Delta IV_{i,j}$. Also, let $\Delta I_{i,j} = I_{i,j}^{post} - I_{i,j}^{pre}$ be the change in index between pre- and post-trade quotes.

Let ($q_{k,i,j}^{pre}$, $q_{k,i,j}^{post}$) be a pair of bid-ask midpoint quotes in any other option k with the same maturity as i but a different strike, with exactly one intervening trade, $T_{i,j}$. I refer to such options k as non-traded options with reference to trade $T_{i,j}$. Again, I find the BS implied volatility of each non-traded option k before and after the trade, $IV_{k,i,j}^{pre}$ and $IV_{k,i,j}^{post}$, and the change in the implied volatility, $IV_{k,i,j}^{post} - IV_{k,i,j}^{pre} = \Delta IV_{k,i,j}$. Note that some trades may not trigger quote revisions in any option including the traded option. In that sense, this is a restricted sample – only those trades will be selected which cause quote revisions in the traded option. I define the following trade variables: $SIGNEDNO_{i,j} = +1$ if $T_{i,j}$ is buyer-initiated and $= -1$ if it is seller-initiated, and $SIGNEDVOL_{i,j}$ is equal to volume of trade multiplied by $SIGNEDNO_{i,j}$.

This sample selection procedure isolates the cause of the change in implied volatility of option i and option(s) k. The change in implied volatility, $\Delta IV_{i,j}$, is most likely to be due to the trade $T_{i,j}$ since only one trade occurs between quotes. The interval between pre-trade and post-trade quotes is about 5 minutes on average, which strengthens this argument. The same argument holds for the implied volatility change in the non-traded option $\Delta IV_{k,i,j}$. For options that trade, quotes and hence implied volatility may change as a result of both information and inventory effects of the trade, while non-traded option quotes should only be subject to information effects. The magnitude and direction of implied volatility change of non-traded option pairs in response to a trade is therefore used as a measure of information conveyed by the trade.

The sample consists of 793 pairs of quotes (766 puts and 27 calls) on traded options with a single buy trade in the same option between the two quotes, and 238 pairs of quotes (219 puts and 19 calls) on traded options with a single sell trade in the same option between the quotes. Of the put traded option pairs (985 in all), 415 trades have at least one corresponding non-traded put option pair with which implied volatility changes of the traded option can be compared. Of the call traded option pairs (46 in all), 36 have at least one non-traded call option pair. The average time difference between pre- and post-trade quotes is 9 minutes for puts and 6 minutes for calls, while the average time interval between the trade and post-trade quote is 5 minutes for puts and 4 minutes for calls. These short intervals strengthen the argument that unobserved influences on implied volatility are likely to be minimized by the sample selection procedure. The interval between quote revisions is smaller for calls most likely because there are many more bid-ask quotes for calls than puts, even though there are far more trades in puts, probably because of the index is increasing over the sample period.

5.2.2 Relationship between Implied Volatility Changes and Trades

The relevant sample for this test is the set of traded option pairs (985 puts and 46 calls). Changes in implied volatility may be due to changes in moneyness of the option, or inventory and information effects of trading. Although it is not the aim of the analysis to completely explain the variation in implied volatility, omitting significant variables may cause a bias on other coefficients in the regression model.

It is well known that the Black-Scholes's model log-normality assumption is a simplification of the actual distribution. Excess kurtosis and/or skewness in the true distribution may cause ITM and/or OTM options to be under- or over-priced by the BS formula with reference to market prices. Table 4 shows that S&P 500 LEAPS puts and calls display a 'skew': implied volatility is the highest for deep OTM puts and decreases monotonically as the put becomes more ITM. A similar relationship obtains for LEAPS calls.

For this study, the implication is that a change in the index level between pre- and post-trade quotes will effect the price of an option differently depending on its moneyness. I control for this nonlinear impact of an index change in the empirical specification with an interaction variable between index change and moneyness of the option.

The empirical specification I test is as follows:

$$\Delta IV_{i,j} = a + b_1 * \Delta I_{i,j} + b_2 * \Delta I_{i,j} * X_i / I_{i,j}^{pre} + b_3 * SIGNEDNO_{i,j} + b_4 * SIGNEDVOL_{i,j} \qquad (12)$$

Here $X_i/I_{i,j}^{pre}$ is the moneyness of traded option i. $X_i/I_{i,j}^{pre}$ and $\Delta I_{i,j}$ together control for movements in implied volatility due to skewness and kurtosis. The shape of the volatility skew in the sample implies that b_1 should be negative (as the index increases, moneyness decreases leading to a decrease in implied volatility). However, implied volatility decreases at a lower rate for higher moneyness implying that b_2 should be positive. Information and inventory effects of trading on prices will be reflected in positive and significant coefficients for $SIGNEDNO_{i,t}$ and $SIGNEDVOL_{i,j}$.

Equation (12) is estimated separately for puts and calls and the results reported in Table 11. Durbin-Watson tests do not reveal significant serial correlation. However, White's test shows some evidence of heteroskedasticity, probably due to large differences in the independent variables $\Delta I_{i,j}$ and $X_i/I_{i,j}^{pre}$ among observations. So, I report heteroskedasticity corrected t-statistics in Table 11 to enable accurate statistical inference.

In Model I, I find a positive and significant coefficient on the trade sign variable, $SIGNEDNO_{i,j}$. The coefficients indicate that a single buy trade causes an increase of 0.16% in the implied volatility of puts, while a single sell trade causes a decrease by the same amount. This can cause quite a large change in the option's price. The size of the trade does not seem to be related to the change in volatility however. The result that trade volume is unrelated to price changes in an option is consistent with Vijh (1990), but in contrast to prior results for stocks and predictions of models such as Easley and O'Hara (1987). The changes in the index and interaction variables are not significant, possibly because the interval between quotes is short, and the index change small. Because $SIGNEDVOL_{i,j}$ is insignificant in model I, I estimate model II without it and obtain similar results. Both models have a high R^2 of 69%. This suggests that a large proportion of the change in implied volatility is explained by the trade direction. In contrast, the results for calls do not show an indication of effects of trading on the implied volatility.

The results indicate that a buyer-initiated trade in LEAPS puts increases implied volatility and prices, and a seller-initiated trade decreases implied volatility. However, this test cannot distinguish between influences due to the inventory imbalances and due to information conveyed by the trade. One way to distinguish this is to compare the change in implied volatility of a traded option with the change in implied volatility of a *non*-traded put due to the same trade. The following section describes these tests.

5.2.3 Change in Implied Volatility of Non-traded vs. Traded Options

In this section I examine LEAPS puts alone and not the calls, since the earlier tests did not reveal effects of trading on call prices. Of the traded puts in the sample used in the previous section, 415 trades (339 buy and 76 sell) have at least one corresponding (same calendar series-different strike) non-traded put option with which implied volatility changes of the traded option can be compared. Each traded put i is matched with the non-traded put, k, that has the *closest* strike price to that of put i. The aim of constructing pairs in this way is to study the relative implied volatility change of traded options i with respect to paired non-traded options k. Selecting k to be close in strike to i helps to abstract from different effects of skewness and kurtosis on the two. If the two paired puts are close together in moneyness, changes in implied volatility due to moneyness changes should be very similar. I argue that the implied volatility change of the non-traded put, $\Delta IV_{k,i,j}$, is a measure of information about volatility conveyed in the trade, T_{ij}, that triggered the quote revision. With this assumption, inventory effects on traded option i's price are suggested if $\Delta IV_{i,j}$ is more than $\Delta IV_{k,i,j}$ for a buy trade, and is less for a sell trade.

Table 12 reports the change in implied volatility of traded and non-traded puts, and the difference between them categorized by type of trade, buy or sell. The table shows mean values of $\Delta IV_{i,j}$, $\Delta IV_{k,i,j}$ and ($\Delta IV_{i,j}$ - $\Delta IV_{k,i,j}$) for all buy and sell trades.

For buy trades, implied volatility of the traded put, $\Delta IV_{i,,j}$, changes by 0.077% on average, while it changes by –0.094% on average for the paired non-traded put. The mean difference in the implied volatility change is 0.17% which is significant by t-test and by a non-parametric sign test. These results suggest that a single buy trade causes the implied volatility of the traded put to increase 0.17%

more on average than that of the non-traded put. If $\Delta IV_{k,i,j}$ is an effective proxy for the information effect of the trade on implied volatility, inventory effects of buy trades are indicated.

For sell trades, the implied volatility of the traded put changes by –0.065% on average, while that of the non-traded put changes by –0.039%. The mean difference in the implied volatility change is -0.026%, which is not statistically significant. Such a result is consistent with the presence of large positive order imbalances, which may cause asymmetrical price effects: market makers may revise quotes to encourage selling but not buying of puts.

In summary, I find that LEAPS put prices increase after a buy trade and decrease after a sell trade. Implied volatility changes for traded puts appear to be higher than for a corresponding non-traded put, indicating some inventory effects. Although these results are indicative of price pressure effects of trading on LEAPS puts, it should be noted that the results of a comparison of traded with non-traded options may be subject to the matching algorithm used. The small sample size also reduces the power of these tests. The time interval between pre- and post-trade quotes is short, which has the advantage that the implied volatility change can be isolated to a single trade. However, it may also have the disadvantage that information effects of the trades are not uniformly impounded into all options prices. Also, the applicability of the results is restricted to the set of trades that trigger quote revisions in the traded options. More frequently than not, the market maker does not revise quotes immediately after a trade. In the next section, I conduct a more general analysis of the relation between trade imbalances and prices.

5.3 Multiple Trades between Quotes

To test for evidence of inventory and information effects, I examine intra-day pairs of consecutive quotes and aggregate trading between them. For every calendar series, there are several different put and call options contracts traded in a day which differ only in strike price. If a trade conveys some information about volatility, the market maker must update the prices of all other options of the same type in the next quote revision to efficiently incorporate this information. The change in implied volatility between consecutive quotes of every option due to information effects of trading should then be related to aggregate trading in options of the same type. However if the market maker alters a quote to manage his inventory position in a specific option, the implied volatility change so caused will be related only to trade in that option and not trade in other options. I refer to this as 'own' trading. I use this insight to separate inventory effects of trading from information effects.

An issue that must be addressed in designing tests is the following. Quote revisions are made continually in all options in a series during the day. More frequently than not, there will be a time overlap among pairs of consecutive quotes in different options during the day. Since every trade can affect all option quotes to some extent, a statistical problem may result of cross-sectional correlation of an indeterminate form among implied volatility changes of different options. To eliminate this potential source of cross-correlation, I restrict the attention to the most active option each day.

5.3.1 Sample Construction and Variable Definitions

The sample consists of all pairs of consecutive quotes of the most active option each day matched with measures of aggregate and own trade direction and size between the quotes. Let $q_{t-1,i}$ and $q_{t,i}$ be two consecutive bid-ask quote midpoints at times t-1 and t for option i. $IV_{i,,t-1}$ and $IV_{i,t}$ are the corresponding BS implied volatilities of the option. Let $\Delta I_{i,t} = I_{i,t} - I_{i,t-1}$ = be the corresponding change in index value from time t-1 to time t. I use the trade classification exercise described earlier to derive measures of signed trading between quotes. Let the total number of buyer initiated trades in option i from time t-1 to time t be $NBUY_{i,t}$ and the total number of seller initiated trades be $NSELL_{i,t}$. Similarly, the total number of buyer- and seller-initiated trades in all other options of the same type (puts or calls) from times t-1 to t is denoted as $NBUY_{other,t}$ and $NSELL_{other,t}$. I can then compute the total volume of the buy and sell trades, $VBUY_{i,t}$, $VSELL_{i,t}$, $VBUY_{other,t}$ and $VSELL_{other,,t}$ from times t-1 to time t. Signed volume and number quantities are calculated as follows:

$$NDIF_{i,t} = NBUY_{i,t} - NSELL_{i,t}$$

$$NDIF_{other,t} = NBUY_{other,t} - NSELL_{other,t}$$

$$VDIF_{i.t} = VBUY_{i,t} - VSELL_{i,t}$$

$$VDIF_{other,t} = VBUY_{other,t} - VSELL_{other,t}$$

The 'DIF' variables refer to the *signed* number and volume of 'own' trades, and *signed* number and volume of 'other' trades between quotes q_t and q_{t-1} for option i. In aggregating trades, unclassified trades are ignored. Table 3 shows that about 13% of all trades are unclassified. Since there is no reason to believe that these trades are biased in one specific direction, discarding them should not affect the analysis.

The sample consists of 3732 pairs of consecutive put quotes and 697 pairs of call quotes. The mean time difference between quotes in each observation is 59 minutes for puts and 2 hours 10 minutes for calls. These time intervals contrast with corresponding figures for the restricted sample in the previous section – 6 minutes for calls and 9 for puts. LEAPS quotes are evidently not revised very frequently, even for the most active series. Mean number of trades (all) between quote revisions is 5 trades for puts and about 2 trades for calls, while the average volume is 130 contracts for puts and 23 contracts for calls. The mean time difference between the second quote in the pair and the last preceding trade is about 19 minutes for puts and 51 minutes for calls.[12]

The aim is to identify whether trading causes inventory effects on prices of options. Since prices and hence implied volatility also change with the index and with information, the model must control for these effects

The empirical specification is as follows:

$$\Delta IV_{i,t} = a + b_1 * \Delta I_{i,t} + b_2 * \Delta I_{i,t} * X_i / I_{i,t-1} + b_3 * NDIF_{i,t} + b_4 * NDIF_{other,\,t} + b_5 * VDIF_{i,t} + b_4 * VDIF_{other,\,t} \qquad (13)$$

[12] This statistic indicates that there is typically plenty of time for stock prices to adjust to any information about the true index value that might be conveyed by LEAPS trading.

Variables are as defined earlier. As in the previous section, $\Delta I_{i,t}$, and the interaction term, $X_i/I_{i,t-1}$, capture the effects of skewness and kurtosis on implied volatility. I expect a negative coefficient on $\Delta I_{i,t}$ and a positive coefficient on the interaction variable.

If trade direction does not impact prices in any way, then coefficients on both $NDIF_{i,t}$ and $NDIF_{other,\,t}$ should not be significantly different from zero. If trade direction affects prices due to information effects alone, coefficients on both should be positive but not significantly different from each other. This prediction results from the arguments presented earlier, since in this case 'own' trade and 'other' trade both convey information only. If there are both inventory and information effects, coefficients on both $NDIF_{i,t}$ and $NDIF_{other,\,t}$ should be positive and significant and b_3 should be significantly larger than b_4.

Similar predictions are expected for the volume variables $VDIF_{i,t}$ and $VDIF_{other,\,t}$ that measure the impact of trade size imbalance on prices.

5.3.2 Empirical Results

Equation (13) is estimated using OLS separately for puts and calls, and the results reported in Table 13. The Durbin-Watson test statistic does not reveal significant serial correlation. However, as in the previous section the White test reveals some evidence of heteroskedasticity, so I present consistent OLS estimates and heteroskedasticity corrected standard errors and t-statistics.

In Model I for puts, the coefficient of $NDIF_{i,t}$ is 0.0002 (t-statistic = 3.1) meaning that implied volatility changes by about 1% if 500 more contracts are bought than sold between quotes. A change in implied volatility of 1% will lead to significant increases in prices. I find that variables for both signed trade size and direction in *other* options, $NDIF_{other,t}$, $VDIF_{other,\,t}$, are not statistically significant. Further, an F-test of the hypothesis that coefficients of $NDIF_{i,t}$ and $NDIF_{other,t}$ are equal is rejected at the 1% level (test statistic=6.88). These results suggest that prices of put options are more sensitive to 'own' trade direction than to trade in other puts on the same underlying. This suggests inventory effects of trading: market makers increase put prices upon significant buy imbalances in the option and decrease prices if there are significant sell imbalances. Own trade size, $VDIF_{i,t\,t}$, is not a significant determinant of change in implied volatility. This result is consistent with prior research on trading and prices (Vijh 1990). I also estimate Model II without the volume variables and obtain similar results.

The coefficients of $\Delta I_{i,t}$ and $\Delta I_{i,t}*X_i/I_{i,t-1}$ have signs consistent with the implied volatility bias exhibited by the options in the sample, and are significant at the 1% level. For example, model I for puts shows a coefficient of –0.031 on $\Delta I_{i,t}$ and +0.051 for $\Delta I_{i,t}*X_i/I_{i,t-1}$. This implies that the implied volatility for ATM puts will increase by 2% for a unit increase in the index (put becoming out-of-the-money). Note that a unit increase in index means a 10 point increase in the S&P 500 index. The slope is different depending on the moneyness of the option. For options with $X_i/I_{i,t-1}>0.61$, the negative slope obtains with this specification.

The results for calls are in contrast to those for puts. For calls, coefficients of $NDIF_{i,t}$, and $NDIF_{other,\,,t}$ are significantly greater than zero but not significantly different from each other. This suggests that implied volatility changes equally with one unit of trade imbalance in 'other' options as one unit of 'own' trade. In other words, trade imbalances convey information about volatility, while inventory effects are not detectable. The results for calls suggest that the results of inventory effects for puts are caused by the considerable buying pressure for these options.

Several robustness tests are conducted to verify the results. Instead of using the change in implied volatility as the dependent variable, I use the option quote change adjusted for the delta times the change in the index, as in Vijh (1990), with similar results. Sample selection biases may result because I study only the most active options each day, which may also be more subject to inventory effects. I conduct the same test in a sample less prone to biases while ensuring that the statistical problem of overlap does not occur. I do not restrict to all pairs of consecutive quotes for the most active options. Instead, from the entire set of intra-day quotes and trades for all LEAPS on the underlying, I select those pairs that satisfy the criterion that the pre-trade quote of every pair of quotes occurs *after* the post-trade quote of the previous one. This ensures that no observations overlap in time, eliminating a source of cross-correlation among observations. OLS estimates of equation (13) (not reported) for this sample are very similar to those in table 13, confirming the results obtained earlier.

5.4 End-of-day Analysis

While the intra-day analysis in the previous sections suggests that buy-trades cause an increase in prices of put LEAPS not explained by change in implied volatility due to information, such effects may be quite temporary and may not persist even over the same day. The procedure in this section, I test the persistence of the inventory effects by studying the daily change in implied volatility.

I choose the most active option every day and match its last quote of the day with the day's opening quote. Then, I find the change in implied volatility over the day for each such pair. These traded options are each paired with an option on the same day with the same expiration date but a different strike price that is not traded. Similar to the intra-day analysis in section 1 above, the non-traded option is chosen such that it is very close in strike price to the traded option. This is to ensure that skewness and kurtosis in the index returns distribution affect the two options in the pair in a like manner. Using for comparison an option that is very close in strike mitigates the need to control for skewness and kurtosis using the change in index and moneyness interaction variable as was required in section 2 earlier.

398 traded-untraded put option pairs and 171 traded-untraded call option pairs are formed. Any information about future volatility must be reflected in the prices of all the options on the index by the end of the day, including the options that are not traded. I use this insight in controlling for the information effect of trades. In the sample of pairs, I use the change in implied volatility of the non-traded option as the control variable for the information effect of trades on implied volatility. The model is:

$$\Delta IV_{i,t} = a + b_1 * \Delta PIV_{i,t} + b_2 * NDIF_{i,t} + b_5 * VDIF_{i,t} \qquad (14)$$

where the definitions are similar to those in the section 1. The difference is that the time interval is over the whole day t rather than between consecutive quote revisions.

The empirical work in this section is based on equation (14). I run an OLS regression separately on traded-untraded option pairs of puts and calls formed as described above. If changes in implied volatility are caused by information effects, then I expect that the variables $NDIF_{i,t}$ and $VDIF_{i,t}$ will be insignificant in the regression, since information effects are controlled for by change in implied volatility of the paired untraded option. Since the paired option is chosen to be very close in moneyness to the traded option, the coefficient of $\Delta PIV_{i,t}$ should be close to 1.

Table 14 shows the OLS estimates of equation (14) for the sample of paired options. Model 1 includes only the trade imbalance variables while model II includes the control variable for information. I find that the trade imbalance variables are insignificant in these regressions, suggesting that any inventory effects caused by trading during the day are temporary and are adjusted by the day's end[13]. The variable $\Delta PIV_{i,t}$ is highly significant and its coefficient is 0.70 for puts and 0.91 for calls – this suggests that the implied volatility change in LEAPS puts options is quite similar across options whether they are traded or not. The hypothesis that the coefficient of $\Delta PIV_{i,t}$ is equal to 1 is not rejected in both puts and calls.

5.5 Summary of the Results

This section analyzes intra-day quotes and trades in S&P 500 LEAPS for evidence of trade-related information and inventory effects on prices. The approach is to relate changes in BS implied volatilities of traded options with measures of trade imbalance. I find that implied volatilities of S&P 500 LEAPS puts increase (decrease) in response to a buy (sell) trade imbalance in the same put, but are not affected by trade imbalances in other put options. This finding suggests inventory effects in the quoted prices of LEAPS puts. The results of this section suggest that the preponderance of demand for any one type of option may cause a collective inventory imbalance in the market.

The results are robust to alternative specifications and in different samples. I also study the relation between daily price changes and daily trade imbalances to test the prediction of inventory control theories that inventory effects are only temporary, and find evidence that inventory effects may not persist over the day.

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[13] In model I, one would expect the trade imbalance variables to be significant. Possibly the model is misspecified because skewness and kurtosis is not controlled for, hence they turn out insignificant.

6 Trading Profitability of Hedging Strategies

The results of put-call parity tests using the spot index value in chapter 3 showed that LEAPS puts are significantly overpriced with respect to calls, after accounting for bid-ask spreads. It was found that the amount of violation increases as the LEAP put goes more out-of-the-money. This result appears to support the hypothesis that large trade imbalances such as those in out-of-the-money LEAPS puts may lead to price pressure effects in options.
Chapter 5 directly analyzes effects of trade imbalances on the prices of puts. The tests in that chapter control for effects of non-normal skewness and kurtosis in the underlying asset distribution on put prices and information effects of trading on prices, so that the increase in price due to buy trades can be more clearly attributed to an inventory or price pressure effect. It was found that LEAPS put prices increase in response to a buy trade by more than is explained by information effects of trading.

It is interesting to examine whether an alert arbitrageur can profit from these systematic pricing anomalies in LEAPS puts. If put prices are increased temporarily in response to trade imbalances, then it may be possible to profit by taking a short position in the overpriced put and a long position in the under-priced put, and reversing the positions when the price pressure effects reverse themselves. On the other hand, if the overpricing persists over longer time intervals, then such trading strategies may not generate superior profits after adjusting for risk due to longer holding intervals.

In this chapter, I test the profitability of two trading strategies designed to exploit temporary price pressure effects in LEAPS puts prices. Mis-priced puts are identified using four trading rules: (1) Black-Scholes implied volatilities inferred from the market prices of the options (2) Strike prices of the options (3) Buy/sell volume imbalance (4) Buy/sell number of trades imbalance. If the trading strategies generate significant profits on average, inefficient pricing on the S&P 500 LEAPS market is indicated.

6.1 Using Trading Strategies to test for Efficiency in Options Markets

Many authors study the pricing efficiency of options markets by examining the profitability of trading schemes designed to exploit pricing anomalies. Ait-Sahalia, Wang and Yared (1998) find that the underlying asset state price density implied by a sample of S&P 500 index options displays excessive skewness and kurtosis compared to index-implied state price densities(SPDs). They use a market risk-adjusted Sharpe ratio to measure profitability of trading schemes designed to exploit the differences in the SPDs, and find evidence that these strategies are significantly profitable after accounting for risk. Smith, Gronewaller and Rose (1998) study the efficiency of the New Zealand Futures and Options Exchange (NZFOE) by testing the profitability of delta neutral spreads constructed with NZFOE equity options. They do not find evidence that such strategies are profitable in the presence of transactions costs, and conclude that the lack of instantaneous and synchronous trading in the equity and options markets, a characteristic of the market that they study, does not obstruct efficient option pricing.

Identifying mis-priced options is a step that precedes the construction of trading strategies. The strategies used in this chapter, the trading rules and the rationale for adopting them are described below, as well as the results. As in most of this thesis, the focus is on LEAPS puts. Four trading rules are used in this study to classify puts as overpriced or under-priced. Broadly, the strategy is to purchase the under-priced put, sell the overpriced put, and reverse the position when the prices correct themselves.

6.2 Identification of Mis-priced Options

Under the assumptions of the Black-Scholes model, all options on an underlying asset with the same expiration date should be priced using the same volatility. Black-Scholes volatilities implied by market prices of options are usually not constant across strike prices, and can be used to develop trading strategies to test pricing efficiency in option markets.

The differences in implied volatility across strike prices can be due to non-normal skewness and kurtosis in the underlying asset's distribution, which is not considered by the BS model. If cross-sectional differences in implied volatility are due only to skewness and kurtosis, a strategy based on BS implied volatilities should not be profitable on average. But if puts are overpriced due to temporary price pressures leading to a higher Black-Scholes implied volatility, which corrects in the short term, profits may be possible by buying the low IV, selling the high IV put and reversing the position after the mis-pricing is estimated to have corrected itself.

The first trading rule used in this study identifies overpriced and underpriced puts based on the Black-Scholes implied volatility. The put with the highest implied volatility each day is assumed to be overpriced, and the put with the lowest implied volatility each day is assumed to be underpriced.

Table 3 suggests that trade imbalances are highest in OTM puts. They should also display the most inventory effects on prices as a result. This result is supported by the put-call parity regressions. For the second criterion by which to identify mis-priced options, I classify the expensive put to be the OTM put (lowest strike) and the cheap put to be the ITM (highest strike) put each day.. The results of this trading rule should be consistent with those of the earlier one, because the implied volatility smile in the sample shows that BS implied volatility on average decreases with the strike price to index ratio.

Puts are also classified as expensive or cheap using the information available about buy/sell volume and number of trades during the day, which are the third and fourth trading rules used in this study. The put with the highest buy – sell imbalance (volume and number of trades), which may display the highest inventory effects, is classified the expensive put, and the one with the lowest buy-sell imbalance the cheap put.

6.3 Types of Strategies

6.3.1 Delta Neutral Put Spreads

The first strategy developed is the Black-Scholes delta neutral put spread. In this strategy, over (under) priced puts, identified using the trading rules described above, are sold (bought) in quantities such that the overall position is delta neutral. Then, risk free bonds are bought or sold in an amount to make the portfolio a zero-investment portfolio. The position is then instantaneously immune to changes in the underlying asset. The spread is created based on mid-points of closing bid-ask quotes, and held for one or five trading days.

Let P_1 be the underpriced put and P_2 be the overpriced put based on the trading rules defined above. The hedge is formed on day t, with n_1 contracts of P_1 and n_2 contracts of P_2. Let $h_{1,t}$ and $h_{2,t}$ be the deltas of puts 1 and 2 respectively on day t. Denoting the portfolio by PF, the delta of the portfolio is then

$$\text{Delta (portfolio)} = n_1 * h_1 + n_2 * h_2 \tag{15}$$

For a delta-neutral portfolio, one contract of P_1 is purchased and (h_1/h_2) contracts of P_2 are sold (written). The cost of this portfolio is $P_1 - (h_1/h_2) * P_2$. To make this a zero investment portfolio, risk free bonds maturing on the same date as the options must be bought in the quantity

$$B_t = (h_1/h_2)*P_2 - P_1. \tag{16}$$

The portfolio can then be represented as

$$PF = P_1 - (h_1/h_2)*P_2 + B_t. \tag{17}$$

Since the cost of this portfolio is zero, it is not possible to use a portfolio return to measure arbitrage profits over the period it is held. Dollar payoffs are measured and used to represent the profits instead. The dollar payoff for entering into this strategy for a holding period of n trading days is

$$\text{Dollar payoff} = P_{1,t+n} - (h_{1,t}/h_{2,t})^{*}P_{2,t+n} + B_t^{*}e^{r^{*}n}, \tag{18}$$

Spreads are held for intervals of one day and 5 trading days. Although the portfolio is instantaneously free of risk due to movements in index, this does not continue to be true throughout the holding period. This is because the assumptions under which the hedging strategy works perfectly are not likely to be satisfied.

The BS delta of each put is derived assuming a log-normal stock price distribution, and constant volatility, which are not true in practice. Non-normal skewness and kurtosis of the underlying asset's distribution need a hedge ratio different than that calculated above. Also, since the delta itself varies with the underlying index level, the hedge needs to be rebalanced continuously to maintain delta-neutrality.

Since the measure of profit used (dollar payoff) for this strategy is not risk adjusted, the risk of the portfolio becomes important to reach a conclusion about arbitrage opportunities in the market. Holding the portfolio for a shorter interval has the benefit that portfolio risk due to changes in the underlying index is minimized, while market risk can become considerable over a longer period. However, the portfolio is also subject to vega risk, which is not explicitly controlled for in this analysis.

6.3.2 Vertical Put Spread + Stock:

When the delta neutral put spreads constructed above are not rebalanced continuously, the portfolio becomes risky over time. One risk-adjusted measure of portfolio return is the Sharpe ratio. The Sharpe ratio of a portfolio is defined as the mean excess return of the portfolio divided by the standard deviation of the return. Since the investment in the strategy described above is zero (frequently negative before the bond is purchased) it is not possible to calculate a return for all portfolios so constructed. The strategy described in this section is a long position in a put spread combined with a long position in the index, which reflects a bullish attitude on the market. The investment in this portfolio is positive, therefore a portfolio return and hence a Sharpe ratio can be calculated.

Let P_1 be the underpriced put and P_2 be the overpriced put. Let I denote the index. Every day, a portfolio is formed by buying P_1, selling P_2 and buying one unit of the index. If PF denotes the portfolio, then $PF = P_1 - P_2 + I$. The portfolio is held for one or 5 trading days as before and profit is measured using a simple return. The investment in the position on day t is:

$$\text{Investment} = P_{1,t} - P_{2,t} + I_t.$$

The inflow on the day the position is reversed, t+n, is :

$$\text{Inflow} = P_{1,t+n} - P_{2,t+n} + I_{t+n} + \Sigma D_t$$

D_t is the cash dividend on the index on day t, and the summation runs over the holding period of the portfolio. The return on the portfolio is then measured as:

$$\text{PF return, } R_p = (\text{Inflow/Investment}) - 1.$$

The Sharpe ratio of the portfolios formed each day is calculated as

Sharpe ratio: (Mean (R_p) - R_f)/ SD_p

where SD_p is the standard deviation of the portfolio returns, and R_f is the risk free rate over the same holding period as the portfolio.

6.4 Holding Intervals

Delta neutrality is only instantaneous, and to maintain it the portfolio has to be rebalanced continuously, which would lead to infinite transaction costs. The holding interval must therefore achieve a balance between the two opposing factors. Methods have been developed in the literature for choosing an optimum holding interval. In this study, I do not attempt to find an optimum holding interval, but instead conduct the tests for holding intervals of one and five trading days.

The measure of arbitrage profit for the vertical put spread strategy, the Sharpe ratio, accounts for risk due to movements in the underlying index. Over the five-day interval for the delta neutral put spread some residual market risk, as well as volatility risk, may exist, implying that the gains measured may not be risk free and hence not true arbitrage profits.

6.5 Portfolio Construction

The portfolios are constructed and unwound at the end of the trading day. Therefore the last quote of the day is used in the calculation of the arbitrage profits. The following procedure is followed to select the puts to transact in each day. The puts are ordered according to each of the trading rules described in the earlier section, and one under-priced and one overpriced put in each calendar series is selected each day. For example, for the BS implied volatility trading rule, the implied volatility of each put is backed out of its last quote of the day. The puts are ordered according to the implied volatility within each calendar series, and the put with the highest and the lowest implied volatility are chosen to construct the delta neutral put spread or the vertical puts spread described above.

To calculate the BS hedge ratio of each put, the average implied volatility of the two nearest-the-money puts on the same day that the portfolios are formed is used. This is more consistent than using the put's own implied volatility, because the BS model assumes a constant volatility, and the closest to that constant volatility is the ATM puts implied volatility.

For the delta-neutral put spread strategy, the risk free security bought and sold is the US treasury strip whose expiration date is closest to the day the position is unwound (one or five trading days later). The rate of return on this security is used wherever a risk free rate is required in the calculations.
Each day, portfolios are constructed using the selected puts and the strategies described, and held for one or five trading days. Those portfolios for which quotes are not available on the day of unwinding positions (one day or 5 trading days later) are discarded. When calculating returns for one trading day intervals, weekends are accounted for as a three-day period. Arbitrage profit measures are then calculated for each portfolio as described above.

6.6 Results

6.6.1 Delta-neutral Spreads

The results for the set of delta-neutral spreads constructed are in Table 15. The table shows the number of portfolios constructed, the number with positive dollar payoffs, the mean dollar payoff, median dollar payoff, standard deviation, and other variables for each trading rule and holding interval combination. The number of portfolios constructed differs in the tables, because quotes are not always available on the day the position is unwound.

The number of spreads constructed using trading rule 1 (based on implied volatility) and held for a day is 1611, of which 948 are profitable (before bid-ask spreads and commissions). The mean dollar payoff of the portfolios is \$0.0654 (= \$6.54 for one contract), which is significant at the 1% level.

For the portfolios constructed on the basis of the strike price (trading rule 2) the mean dollar payoff, \$0.0162 is not significantly different from zero. For trading rules based on trade imbalances (trading rules 3 and 4), the mean dollar payoff is -\$0.008 and -\$0.005 respectively, neither of which is significant. These results on the mean dollar payoff do not indicate that abnormal profits can be made from this strategy on average.

6.6.2 Vertical Put Spreads

The results for this strategy are reported in Table 16. The table shows the number of portfolios constructed, the number with a positive return, the mean and median of the portfolio returns, the Sharpe ratio for the portfolio, and other variables. The table also reports the index return and Sharpe ratio for comparison with the portfolio returns. These quantities are reported for every combination of trading rules and holding period.

For example, for trading rule 1, based on BS implied volatility, and holding period one day, 1609 spreads are constructed of which 846 are have a positive portfolio return before accounting for bid ask spreads and commissions. The mean portfolio return is 0.075 %, which is significant at the 10% level, while the Sharpe ratio is 0.036 showing a very small excess return per unit risk. The index Sharpe ratio over the same holding period is 0.034 and the index return is 0.076%. Since the strategy includes holding one unit of the index, it appears that the portfolio gain or loss is largely due to the change in the index. There is no significant additional gain from transacting in the put spread, even when it is based on the trading rules that are hypothesized to generate higher returns than a naïve strategy.

The results are very similar for all other combinations of trading rules and holding periods. Furthermore, the Sharpe ratio measure is not adjusted for volatility risk of the portfolio. The portfolio vegas, which are shown in the table, are quite large, with the first one being about 300.8, implying a considerable volatility risk.

The premise tested in this chapter is whether two simple strategies that arbitrageurs may use to benefit from pricing anomalies in the LEAPS market are in fact profitable. Overall, the results of the tests in this chapter do not indicate no significant arbitrage profits from the strategies I describe and after accounting for market risk but not volatility risk. The results in tables 15 and 16 do not account for commissions and trading costs, which would further detract from the profits. The tests assume the validity of the Black-Scholes model in creating the delta neutral portfolios. Market prices of options may deviate from the BS model prices if index returns display skewness and kurtosis, and if price pressures affect puts. If price pressure effects exist, they either persist for longer periods than the holding intervals tested in this chapter, or reverse by end-of-day.

7 Other tests of Impact of Market Frictions on S&P 500 Index LEAPS

7.1 Implied Index Analysis

The concept of a risk neutral probability was first suggested by Cox and Ross (1976), and later formally developed by Harrison and Kreps (1979). The risk neutral probability is also sometimes called the equivalent martingale measure.[14] This term is used in describing a risk neutral probability because, as shown in Harrison and Kreps (1979), and discussed in detail Huang and Litzenberger (1988), the martingale property is one of the necessary and sufficient conditions for financial markets not to admit arbitrage opportunities.

The martingale property of the equivalent martingale measure requires that all discounted asset prices should be a martingale under the measure. Symbolically, if Q is the risk neutral probability distribution, I_T is the underlying asset at time T, and I_0 is the underlying asset value today, then the martingale

[14] A stochastic process is said to be a martingale if the expected change in the value of the process is always zero.

property requires that:

$$I_0 = \exp(-r^*T) \, {}^*E_Q\,(I_T)\,, \tag{19}$$

where r is the risk free rate, the only relevant discount rate in a risk neutral world.

Essentially, this restriction requires that the mean of the risk neutral distribution implied by option prices must equal the actual underlying asset value at every point in time. This condition is necessary and sufficient for no-arbitrage conditions to exist in the securities markets.

Longstaff (1995) tests this restriction in a sample of S&P 100 index options. He notes that variables that proxy for market friction such as bid-ask spreads and open interest should be related to the magnitude of martingale restriction violations, if these market frictions cause its violation. In his sample of S&P 100 index calls, he finds that the implied index value is nearly always higher than the actual index value on average. The percentage differences between the two are related to a number of variables that proxy for option market frictions such as open interest, trading volume and bid-ask spreads. These results may imply that market frictions have a significant effect on the prices of options. Longstaff notes however that the actual risk neutral probability distribution that determines option prices may differ from the one he assumes.

In this section, I test for the impact of market frictions in the S&P 500 index LEAPS put prices by testing the martingale restriction. Similarly to Longstaff (1995), I find that the implied index value is significantly different from the actual index value. The results are difficult to reconcile with earlier findings that put prices are overpriced, however. Overpriced puts should lead to a result that the implied index that is lower than the actual index value. On average, however, the implied index is much higher than the actual index value. However, in put sub-samples by moneyness and maturity, it is found that for short maturity and out-of-the-money options, the implied index is lower than the actual index value. The difference between implied index and actual index is related to variables that proxy for market frictions.

7.1.1 Methodology and Sample Construction

As in Longstaff (1995), I assume that the Black-Scholes assumption of log-normal underlying asset distribution is accurate. Since the log-normal distribution is completely described by two moments, testing the martingale restriction requires backing out both moments of the implicit distribution used to price S&P 500 index LEAPS, for which exercise a minimum of two option prices is required. This methodology used for inferring the moments is the minimization of sums of squared deviations procedure. The equation minimized is the following:

$$\underset{I_t, \sigma_{t,T}}{MIN} \sum_{i=1}^{N} (O_{i,t} - BS(I_t, \sigma_{i,T}, X_i, T, r_{t,T}))^2$$

Here, N is the total number of options (puts or calls) maturing in time T available to estimate the distribution at time t, $O_{i,t}$ is the market price of option i at time t, BS denotes the Black-Scholes price of the option. X_i is the strike prices of option i, T is the time to amount of time to expiration, $r_{t,T}$ denotes the ask rate at time t of the US treasury strip expiring at time T. $\sigma_{t,T}$ denotes the implied volatility at time t of options with time to expiration T, and I_t denotes the implied index value.

The objective of obtaining the actual index value is to compare it with the implied index value. Since the index changes throughout the day, it may not be valid to use market prices of options throughout the day to imply an index value. The N options that are used to estimate the moments of the distribution for a particular calendar series should be close to one another in time.

Each day in the sample period, all of the put and call bid-ask quotes that occur between 2:30 p.m. and 3:00 p.m. are collected. This time interval is chosen as being the most likely to be insulated from abnormal trading activity at the open or the close. For every calendar series each day, the implied index and implied volatility are backed out of the Black-Scholes formula using the equation above, whenever more than two option quotes are available each day. Quote midpoints are used in the equation.

Each quote includes the actual S&P 500 index value within 15 seconds of recording the quote. These actual index values are recorded for each set of options used to estimate a density and an average actual index value is computed for comparison with the implied index value. A last index value is also used which corresponds to the index value corresponding to the last recorded option quote of the set. The index is dividend-adjusted using the present value of actual cash dividends over the life of the options.

7.1.2 Results

Table 17 shows summary statistics on the differences between actual and implied index and volatility. A total of 488 densities are estimated from call options and a total of 590 from put options. On average about 4 put option quotes are used in the estimation of the put densities, while about 10 call quotes are used for the call densities. There are many more call quotes in the sample than put quotes, hence this difference.

The table shows that the implied index value is higher than the last recorded index value in 514 of the 590 densities estimated from puts. On average the difference is 6.56, which is almost 10% of the actual index value. This contrasts greatly with Longstaff's result of about 0.5% difference in the sample of calls he uses. For the calls, the average difference is –0.80 (1.2%), which is less than that for puts although still significant. The large difference between the implied index and the actual index indicates a violation of the martingale restriction. However, if puts are overpriced, the direction of the difference predicted is that the implied index should be less than the actual. The result in the sample is hence in a direction not consistent with overpricing of puts.[15]

The implied volatility is also a free parameter in the estimation of the densities, and an examination of the results on the implied volatility may throw some light on this inconsistency. Table 18 reports the differences in the implied volatility when estimated jointly with the index, versus when estimated as the

[15] It has been noted in the chapter on put-call parity tests that the present value of expected dividends is higher than the present value of actual dividends. If this contributes to the difference between the implied and the actual index values, then for both calls and puts, the implied index

only free parameter. For the puts, the average implied volatility is 23.5% when estimated individually. The volatility implied jointly with the index is on average higher than that estimated separately, and the percentage difference is 27%. A similar result obtains for the calls. Computationally, it appears that the implied index is higher than the actual for the puts to compensate for the higher jointly estimated implied volatility, while for calls the implied index is lower than the actual to compensate for the same directional difference in volatilities.

Table 18 breaks up the sample of put densities by moneyness and maturity categories. It can be observed that for shorter maturity puts the implied index is usually lower than the actual, while for longer maturity options the implied index is usually higher. An economic reason for this observation is not obvious from the current analysis.

Table 19 presents regressions of the difference between implied and actual index, and of the absolute difference on explanatory variables that proxy for market frictions in the puts sub-sample. The direction of the coefficients is very similar in the two sets of regressions, because the observations for which implied index is greater than the actual dominate. For puts with a longer term to expiration, the difference between implied and actual index values is higher, and puts that are more out-of-the-money also display more of a difference than in the money and at-the-money puts. This last result supports the results in the other parts of this thesis about the greater effect of market frictions on OTM puts because of the greater trade imbalances they are subject to.

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value should appear to be higher than the actual. The differences are in opposite directions implying that this cannot be the only cause of the deviation.

In addition, the difference between implied and actual indexes increases as the average bid-ask spread increases, and decreases as the trading volume increases. These results are consistent with Longstaff's (1995) results, and imply that market frictions affect the extent of violation of the martingale restriction. However, unlike in Longstaff (1995), the number of options used to estimate the density is important: as this number increases, the implied index value becomes closer to the actual index value.

7.2 Introduction of New Option Series

In the sample period studied in this dissertation, three new calendar series were introduced in S&P 500 index LEAPS: the series expiring in December of 1996, 1997 and 1998. A total of 26 new strike prices were introduced in these new calendar series at the time of their introduction, and a total of 66 strike prices in all were introduced.

In chapter 5, it was suggested that as trade imbalances builds up in and option series, market makers may increase the prices to offset risk due to inventory imbalances. Such a hypothesis suggests that the prices of newly introduced options should conform better to model prices, and that pricing anomalies should increase as trade starts increasing in the newly introduced options.

In this section, I examine option series that are introduced during the sample period for such indications. One way to study this is by examining the implied volatility skews of the newly introduced options on the day they are introduced. Table 20 shows the skews for the options introduced on January 24, 1994, January 23, 1995 and January 22, 1996.

Consider the skew for the options introduced on January 24, 1994. The implied volatility for each option in the new calendar series expiring in December 1996 is calculated, and the average in each category of moneyness is reported in the table. Then, the average implied volatility of all other options is calculated and reported for reference in the table. New calls have an average implied volatility of 14.2% decreasing to 13.6% as the call goes more out of the money. This is a percentage decrease of about 4%. The existing calls have an average implied volatility of 16.4% reducing to 11.9% as the call goes out of the money, which is a percentage decrease of about 27%. The skew appears to be much larger for existing calls.

For new puts, the corresponding values are 16.1% decreasing to 15.1%, and for old puts it is 16.4% decreasing to 10.7%. Once again the skews appear much deeper for existing options than for new options: 6.2% for new options versus 35% for existing options. The implied volatility level for new OTM puts, although slightly lower than for existing puts, is not very much different (16.1% to 16.4%).

For the other introduced options presented in Table 20 a similar result obtains regarding the skew: it is usually markedly less for newly introduced options than for the existing options. These results show some evidence that when newly introduced, the assumption of a single volatility across strikes is employed by market makers to price options. This assumption is modified as market makers receive information about demand for options with different strike as trading in the options commences, resulting in a higher variance of implied volatility across strikes.

8 Conclusions and Further Research

This dissertation studies the efficiency of pricing in the S&P 500 index Long-term Equity Anticipation Securities (LEAPS) market. The main goal is to study the effect of market frictions and trade imbalances in the pricing of options, specifically LEAPS. I employ tests of arbitrage restrictions such as put-call parity and box spread arbitrage restrictions, using both the S&P 500 spot and futures values, an intra-day analysis of the relationship between trade imbalances and quote revisions, and tests of the profitability of trading strategies designed to exploit pricing anomalies.

The results of put-call parity and arbitrage restriction tests provide some initial support for the hypothesis that market factors affect pricing of LEAPS options. Using the put bid price and call ask price in the equation to account for spreads, puts are overpriced 80% of the time, while the box spread restriction is violated infrequently, with no consistent or economically significant pricing errors in the data. This suggests that put and call prices in the S&P 500 LEAPS market are internally consistent, but that put options are overpriced relative to the replicating strategy of shorting the index, lending the proceeds, and buying a call. Put overpricing is higher for out-of-the-money puts and decreases with open interest in these options.

However, put option prices are more consistent relative to the S&P 500 futures market, whenever contracts are available with a maturity corresponding to that of the LEAPS.

The intra-day analysis of quote revisions and trade imbalances probe deeper into the potential causes of LEAPS put overpricing. The central result of these tests showed that LEAPS puts prices are revised upward upon a positive trade imbalance and downwards upon a negative trade imbalance by more than is explained by information effects of trading, suggesting that LEAPS puts prices are subject to inventory effects. This result is even more surprising since inventory effects are not predicted for a competitive market making system such as the CBOE.

Having obtained evidence in support of intra-day inventory effects, I proceed to verify whether abnormal profits are possible from the pricing anomalies uncovered. I test this by constructing zero-investment delta-neutral portfolios and measuring mean dollar payoffs to these portfolios over holding periods of one and five trading days. I find a mean dollar payoff that is not significantly different from zero. I also construct vertical put spreads with one share of the index, and measure average returns and Sharpe ratios of these put spreads over similar holding periods. After adjusting for market risk, I do not find evidence that arbitrageurs can gain from pricing anomalies.

Taken together with the evidence of intra-day inventory effects in LEAPS put prices, these findings suggest that pricing pressures either persist over a longer interval or reverse within the day, before the arbitrage positions are unwound. It is difficult to test for arbitrage profits over a longer holding interval due to a difficulty of distinguishing arbitrage profits from volatility or market risk premiums, and hence that task is not undertaken in this dissertation. As in Longstaff (1995), the implied index analysis in this dissertation also supports the hypothesis that no-arbitrage conditions are not satisfied in the LEAPS market, and provides evidence of open-interest and bid-ask spread biases.

Overall, the results of this dissertation suggest that market frictions can be important in the pricing of options, at least in settings where arbitrage is particularly costly and public demand is biased towards one type of order. It is important to note, however, that the intra-day analysis and the trading strategy tests use the Black-Scholes model as a reference. Although the intra-day analysis results are robust to alternative specifications and in different samples, using BS implied volatilities as the basis of comparison hinders unequivocal inferences about inventory effects due to the impact of stock price distribution effects.

Further research considers an option pricing model that assumes a more general stock price distribution as a basis for price comparison of traded and non-traded options. If the inventory effects found in this dissertation exist even in an expanded study of this nature, the conclusion that market factors are important in pricing options would be strengthened.

Reference has been made in this thesis to the S&P 500 index units called SPDRs. It would be interesting to study whether put-call parity is violated with respect to the SPDRs market as well as with the spot index (as found in this thesis). In practice, arbitrage is most likely to be done with the SPDRs or with the

S&P futures contracts; there should not be an inconsistency between the SPDRs market and the LEAPS options markets.

The findings of this thesis are for a particular market characterized by a trade that is dominated by pubic put purchases versus other types of trade. One direction for further research is to study the short-term index options markets for similar inventory effects. Though only a conjecture at this stage, the disproportionately higher demand during periods of rapid market declines for puts than for corresponding calls on other indexes as well may result in similar price effects. Such inventory effects have an implication for the cost of portfolio insurance when investors need it most. The answers to these questions can help to check the results of this dissertation for robustness, and shed further light on the effect of market factors on the pricing of options.

Table 1

Summary Statistics of quotes and trades of S&P 500 index LEAPS over the period 1994-96

Table 1 shows summary statistics for all bid-ask quotes and trades of S&P 500 index LEAPS over the period 1994-1996 that have time to expiration > 6 days, bid price >=3/8 (or transaction price >=3/8), occur at or before 3 P.M CST, and do not have any obvious recording errors. Observations are grouped by their moneyness, defined as the ratio of strike price, X, to index value, I. Panel A shows summary statistics for calls and Panel B for puts. Variables are defined as follows: quoted price is the midpoint of bid and ask prices, spread is equal to ask price – bid price, spread percentage is spread as a percentage of quoted price.

Panel A: S&P 500 Index LEAPS Calls

Variable \ Moneyness	All Calls	X/S<=0.94	0.94<X/S <=0.97	0.97<X/S <1.03	1.03<=X/S <1.06	1.06<=X/S
Mean quoted price	15.14	17.73	6.83	5.54	4.52	4.17
Mean Spread	0.72	0.79	0.49	0.42	0.38	0.40
Mean Spread %	5.9 %	4.9 %	8.3 %	9.8 %	11.1 %	13.2 %
Number of Bid-Ask Quotes	440412	346010	27477	45688	14222	7015
Number of Trades	1057	507	120	282	102	46
Average Daily Volume	45.71	23.70	4.52	13.51	1.99	1.99
Average Daily Open Interest	8950	6784	643	1307	128	90
Total Open Interest on 12/30/96	7778	7125	162	320	0	171

Panel B: S&P 500 Index LEAPS Puts

Variable \ Moneyness	All Puts	X/S<=0.94	0.94<X/S <=0.97	0.97<X/S <1.03	1.03<=X/S <1.06	1.06<=X/S
Mean quoted price	2.60	1.54	2.29	3.15	4.68	5.75
Mean Spread	0.25	0.21	0.23	0.28	0.34	0.39
Mean Spread %	12.8 %	16.4 %	12.1 %	10.2 %	7.3 %	6.9 %
Number of Bid-Ask Quotes	154755	71307	19149	41158	13301	9840
Number of Trades	24350	9767	4050	7261	1850	1422
Average Daily Volume	1404.27	681.66	183.14	358.27	91.80	89.39
Total Open Interest on 12/30/96	244560	215180	6720	18420	0	4240
Average Daily Open Interest	203410	150500	16280	28430	4140	4050

Table 2
Classification of daily open interest changes

This table summarizes the relationship between daily volume and open interest changes in the sample of S&P 500 index LEAPS trades from 1994-1996. Each day the contracts in which there was positive volume during the day are selected. For each of these contracts, the change in open interest over day t is calculated by subtracting the open interest on day t-1 from the open interest on day t. The change in open interest is compared with the volume in that contract over the day and classified according to the categories below. Columns numbered 1-5 show the number of day-contracts in that category and the percentage of total day-contracts with positive volume in parentheses.

Put/Call	Total day-contracts for which volume>0	Open interest decrease is equal to daily volume	Open interest increase is equal to daily volume	Net decrease in open interest	Net increase in open interest	No change in open interest
Calls	533	54 (10%)	230 (43%)	91 (17%)	305 (57%)	137 (26%)
Puts	5953	189 (3.2%)	2377 (40%)	876 (15%)	4698 (79 %)	379 (6%)

Table 3
Trade Classifications

This table shows results of classification of S&P 500 index LEAPS trades from 1994-1996 using the following rule. Trades occurring at or below the ask price and above the bid-ask midpoint of the quote in effect at time of trade are classified as buyer-initiated trades. Trades occurring at or above the bid price and below the bid-ask midpoint of the quote in effect at time of trade are classified as seller-initiated trades. The total number of trades during this period which satisfy the following criteria: transaction price > 3/8, trade time before 3:00 p.m. C.S.T and no obvious recording errors in price or index values is 25407, including 1057 call trades and 24350 put trades. The table shows the number of trades in each class, and its percentage of the total number of trades.

Trade occurs	All Trades	Trades in Calls	Trades in Puts
At or below ask price and above bid-ask midpoint (Buyer-initiated)	17597 (69.3 %)	565 (2.2 %)	17032 (67.0 %)
At midpoint (Unclassified)	3919 (15.4 %)	636 (2.5 %)	3283 (12.9 %)
At or above bid price and below bid-ask midpoint (Seller-initiated)	4236 (16.7 %)	420 (1.7 %)	3816 (15 %)
Above ask or below bid (Indeterminate or errors)	228 (0.9 %)	9 (0.04 %)	219 (0.9 %)

Table 4
Implied volatility corresponding to the last quote of each day of S&P 500 Index LEAPS

This table shows mean Black-Scholes implied volatilities corresponding to the bid-ask midpoint of the last quote of each day for a sample of S&P 500 index LEAPS from 1994-1996. The sample for which mean implied volatility is found consists of 23248 last quotes for options over the sample period (12680 calls and 10568 puts)The options are grouped according to moneyness where moneyness is defined as the ratio of strike price to closing index value, and their time to expiration. The table shows mean implied volatility as a decimal for the options in each moneyness-maturity class.

Moneyness Strike/ Closing value of Index	Calls Very short-term Expiration<=60 days	Calls Short-term Expiration from 60 – 180 days	Calls Medium-term Expiration from 180 - 365 days	Calls Long-term Expiration >=365 days	Puts Very short-term Expiration<=60 days	Puts Short-term Expiration from 60 – 180 days	Puts Medium-term Expiration from 180 - 365 days	Puts Long-term Expiration >=365 days
<0.94	0.184	0.258	0.191	0.185	0.186	0.180	0.175	0.183
0.94-0.97	0.158	0.150	0.146	0.160	0.164	0.145	0.146	0.159
0.97-1.00	0.152	0.140	0.139	0.156	0.145	0.138	0.140	0.156
1.00-1.03	0.120	0.133	0.131	0.151	0.154	0.138	0.132	0.153
1.03-1.06		0.140	0.132	0.147	0.193	0.129	0.122	0.144
>1.06		0.143	0.138	0.148	0.220	0.112	0.114	0.141

Figure 1
Implied Volatility of S&P 500 index LEAPS puts

Figure 1 plots the implied volatility of very short-term, medium-term and long-term LEAPS puts by moneyness categories. The diamond legend is for very short-term, square is for medium-term and triangle denotes long-term.

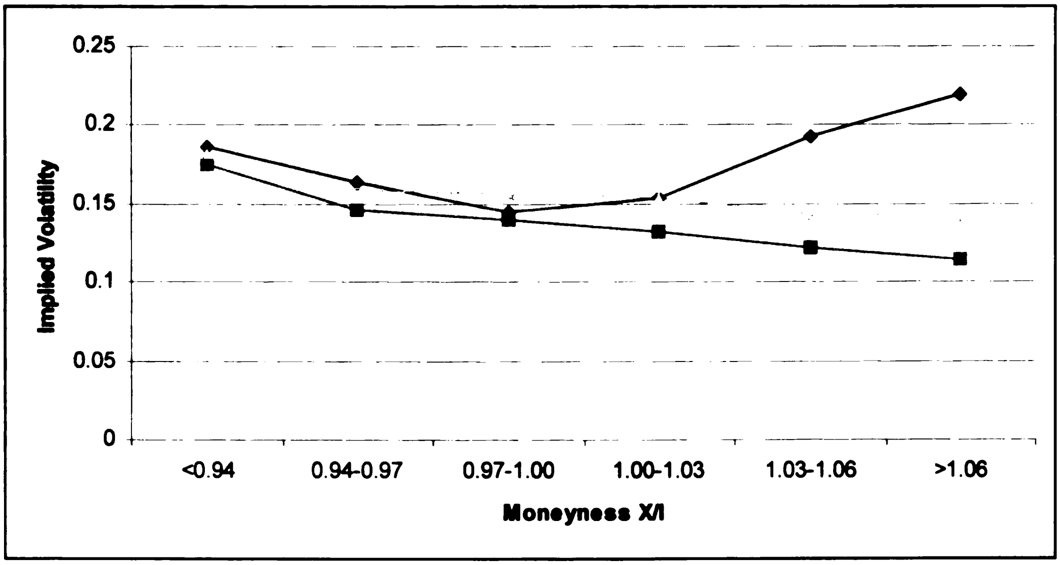

Table 5
Summary Statistics of the sample of S&P 500 index LEAPS put-call pairs

Table 4 presents summary statistics for the sample of 10462 S&P 500 LEAPS put-call pairs from 1994-96. The pairs are formed from the last quotes of the day of LEAPS puts and calls with the same strike price and expiration date. The LEAPS S&P 500 index is equal to one-tenth of the S&P 500 index. The quoted price is the midpoint of the bid and ask prices, the dollar spread is equal to the ask price minus the bid price, and the percentage spread is the dollar spread as a percent of quoted price.

Variable	Mean	Median
Quoted call price	$8.05	$7.00
Quoted put price	$2.15	$1.88
LEAPS S&P 500 index	59.75	63.41
Present value of strike price	50.57	49.89
Present value of dividends	2.07	1.99
Call dollar spread	0.48	0.50
Put dollar spread	0.23	0.25
Call percentage spread	7.83 %	6.45 %
Put percentage spread	13.88 %	11.32%
Time to maturity in years	1.44	1.39

Table 6
Put-call Parity Violations

Panel A presents data for put-call parity violations in the sample of 10462 S&P500 index LEAPS put-call pairs. E, E_1 and E_2 refer to three different measures of parity deviations from equations (3)-(5):

$$E = P + I - C - X^{*}e^{-rT} - D_T \quad (3)$$
$$E_1 = P^b + I - C^a - X^{*}e^{-rT} - D_T \quad (4)$$
$$E_2 = C^b - P^a - I + X^{*}e^{-rT} + D_T \quad (5)$$

where P (C) is the midpoint of the bid-ask spread of the put (call) in the put-call pair, and P^b (C^b), P^a (C^a) are the bid price and the ask price of the put (call) respectively, I is the index value corresponding to the later quote in the pair, and D_T is the present value of the actual cash dividends on the index. E_1 measures overpricing of the put accounting for option spreads, and E_2 measures overpricing of the call accounting for spreads. Panel B illustrates data for E_1 by maturity groups, along with the mean present value of dividends over the option's life. * indicates statistical significance at the 1% level in a two-tailed test.

Panel A:

	Absolute value of E	E	E_1	E_2
Number > 0 (% of total observations)	10462 (100 %)	10124 (96.77%)	8349 (79.80%)	39 (0.37%)
Mean Dollar Value (t-statistic)	$1.18	$1.16 (176.0)*		
Median	$1.15	$1.15		
Mean for Observations > 0			$1.19	$0.19
Median for Observations > 0			$1.07	$0.10

Panel B:

	Very short-term Expiring in <=60 days	Short-term Expiring in 60 – 180 days	Medium-term Expiring in 180 - 365 days	Long-term Expiring in >=365 days
Number of observations	131	822	2025	7484
Number (%) of observations for which E_1 is positive	112 (85.50 %)	740 (90.02 %)	1664 (82.17 %)	5833 (77.94 %)
Mean E_1 for observations > 0	$ 1.23	$ 1.13	$ 1.26	$ 1.16
Mean present value of dividends	$ 0.19	$ 0.52	$ 1.08	$ 2.54

Table 7
Determinants of Put-call Parity Violations

This table illustrates regression results for the S&P 500 LEAPS put-call parity sample. The dependent variables is E, the overpricing of the put relative to the call using bid-ask spread midpoint prices. Each cell contains the coefficient estimates, followed by the t-statistic in parenthesis, with * indicating statistical significance at the 1% level in a two-tailed test.

Variable	Coefficient
Intercept	0.37 (6.24)*
Index/Strike price ratio	0.94 (18.04)*
Time to expiration	-0.00033 (-14.10)*
Difference between index values corresponding to the two quotes	0.47 (49.55)*
Time difference between quotes	-0.00000049 (-0.65)
Put open interest	-0.000010 (-13.37)*
Call open interest	0.000027 (3.84)*
Number of observations Adjusted R^2	10433 23.96 %

Table 8
Box Spread Violations

This table presents data for the sample of 8570 S&P 500 LEAPS box spreads. V and V_1 refer to violations of the box spread relation defined in equations (7) and (8):

$$V = P_2 + C_1 - P_1 - C_2 - (X_2 - X_1) * e^{-rT} \quad (7)$$

$$V_1 = P_2^b - P_1^a + C_1^b - C_2^a + (X_1 - X_2) * e^{-rT} \quad (8)$$

The measure V does not account for bid-ask spreads, while V_1 measures the box-spread violation after accounting for spreads. (P_1, C_1) is the at-the-money put-call pair chosen as the reference, and (P_2, C_2) refer to the other pair in the spread. * indicates statistical significance at the 1% level in a two-tailed test.

	Absolute value of V	V	V_1
Number positive (% of total observations)	8570 (100%)	4256 (49.66%)	434 (5.06%)
Mean dollar value (t-statistic)	$0.32	-$0.016 (-3.83)*	
Median	$0.34	-$0.003	
Mean dollar value when $V_1 > 0$			$0.13
Median dollar value when $V_1 > 0$			$0.11

Table 9
Determinants of Box Spread Violations

This table illustrates regression results for the S&P 500 LEAPS box spread sample. The dependent variable is $V = P_2 + C_1 - P_1 - C_2 - (X_2 - X_1) * e^{-rT}$, the overpricing of the put P_2 relative to the other options using spread midpoint prices. (P_1, C_1) is an at-the-money pair and (P_2, C_2) is an in- or out-of-the-money pair. Each cell contains the coefficient estimates, followed by the t-statistic in parenthesis, with * indicating statistical significance at the 1% level in a two-tailed test.

Variable	Coefficient
Intercept	-0.78 (-20.84)*
Index/Strike price ratio of (P_2,C_2) pair	0.78 (24.09)*
Time to Expiration	-0.0017 (-10.86)*
Open interest of P_2 as of the close of the day	-0.000016 (-33.58)*
Open interest of C_2 as of the close of the day	0.000068 (16.01)*
Open interest of P_1 as of the close of the day	0.000026 (30.40)*
Open interest of C_1 as of the close of the day	-0.00014 (-13.06)*
Number of observations Adjusted R^2	8544 22.4 %

Table 10
Put-call Parity Violations using S&P 500 futures contracts

Panel A presents data for put-call parity violations in the sub-sample of 2981 S&P500 index LEAPS put-call pairs for which S&P 500 futures contracts exist with the same maturity. E, E_{1F} and E_{2F} refer to three different measures of parity deviations from equations (9)-(11):

$$E_F = P + (F - X) * e^{-r*T} - C \quad (9)$$
$$E_{1F} = P^b + (F^b - X) * e^{-r*T} - C^a \quad (10)$$
$$E_{2F} = C^b - P^a - (F^a - X) * e^{-r*T} \quad (11)$$

where P (C) is the midpoint of the bid-ask spread of the put (call) in the put-call pair, and P^b (C^b), P^a (C^a) are the bid price and the ask price of the put (call) respectively, F is the midpoint of the same maturity futures bid-ask spread for the futures quote closest to the later option in the pair, F^b (F^a) is the futures bid (ask) price. E_{1F} measures overpricing of the put accounting for option spreads, and E_{2F} measures overpricing of the call accounting for spreads. Panel B illustrates data for E_{1F} by maturity groups.
* indicates statistical significance at the 1% level in a two-tailed test.

Panel A:

	Absolute value of E	E	E_1	E_2
Number > 0 (% of total observations)	2981 (100 %)	2373 (79.6 %)	1403 (47.1%)	73 (2.45 %)
Mean Dollar Value (t-statistic)	\$0.32	\$0.27 (49.09)*		
Median	\$0.27	\$0.24		
Mean for Observations > 0			\$0.26	\$0.16
Median for Observations > 0			\$0.25	\$0.08

Panel B:

	Very short-term Expiring in <=60 days	Short-term Expiring in 60 – 180 days	Medium-term Expiring in 180 - 365 days	Long-term Expiring in >=365 days
Number of observations	131	819	2003	28
Number (%) of observations for which E_{1F} is positive	50 (38.2%)	405 (49.5%)	940 (46.9%)	8 (28.6%)
Mean E_{1F} for observations > 0	0.274	0.250	0.260	0.186

Table 11
Relationship between quote revisions due to a single trade in option i and trade characteristics

This table shows OLS estimates of equation (12) (reproduced below) in a sample of quote revisions triggered by trades in S&P 500 index LEAPS. The sample consists of pairs of quotes ($q_{i,j}^{pre}$, $q_{i,j}^{post}$) for option i where $q_{i,j}^{pre}$ is the current quote before trade $T_{i,j}$ and $q_{i,j}^{post}$ is the quote after the trade. $\Delta IV_{i,j}$ is the change in implied volatility of option i due to trade $T_{i,j}$, $\Delta I_{i,j}$ is the change in index before and after the trade. X_i is the strike of option i, $I_{i,j}^{pre}$ is the value of index corresponding to the quote immediately before the trade $q_{i,j}^{pre}$, $SIGNEDNO_{i,j}$ is equal to 1 if trade $T_{i,j}$ is buyer-initiated and equal to –1 if it is seller-initiated, $SIGNEDVOL_{i,j}$ is equal to $SIGNEDNO_{i,j}$ multiplied by volume of trade $T_{i,j}$. Model I includes both sign and volume variables while Model II includes only the sign variable. The table shows coefficient estimates and heteroskedasticity corrected t-statistics.

$$\Delta IV_{i,j} \quad = \quad a + b_1{*}\Delta I_{i,j} + b_2{*}\Delta I_{i,j}{*}X_i/I_{i,j}^{pre} + b_3{*}SIGNEDNO_{i,j} + b_4{*}SIGNEDVOL_{i,j} + e_{i,j} \qquad (12)$$

Variable	Puts Model I	Puts Model II	Calls Model I	Calls Model II
Intercept	-0.00042 1.73**	-0.00044 -1.79**	0.0023 0.90	0.0021 0.81
$\Delta I_{i,j}$	-0.0069 -0.31	-0.0067 -0.30	-0.222 -0.85	-0.205 -0.79
$\Delta I_{i,j}{*}X_i/I_{i,j}$	0.0305 1.29	0.0303 1.27	0.181 0.69	0.165 0.63
$SIGNEDNO_{i,j}$	0.0016 6.16*	0.0016 6.51*	0.0042 1.62***	0.0038 1.49***
$SIGNEDVOL_{i,j}$	0.0000014 1.39		-0.0000015 -0.85	
Number of observations R^2	985 67.8 %	985 67.8 %	46 12.7 %	46 13.2 %

*,**,*** indicate significance of the coefficient at the 1%, 5% and 10% levels.

Table 12
Changes in implied volatility of traded vs. non-traded S&P 500 LEAPS puts in response to buyer- and seller-initiated trades

This table compares trade-related movements in implied volatility of traded S&P 500 index LEAPS puts with those of paired non-traded puts with the same maturity as the traded put and closest in strike to it. The notation is as follows: $\Delta IV_{i,j}$ is the change in implied volatility of traded put i due to the j^{th} trade in the i^{th} put $T_{i,j}$, $\Delta IV_{k,i,j}$ is the change in implied volatility due to trade $T_{i,j}$ in the non-traded put k with the closest strike to i with the same maturity and ($\Delta IV_{i,j}$ - $\Delta IV_{k,i,j}$) is the difference in the implied volatility impact of trade $T_{i,j}$ on the two options. There are 339 buyer-initiated trades and 76 seller-initiated trades for which pairs of non-traded and trades puts are formed. Various summary statistics are shown in the table for these three quantities, in categories by buyer- or seller-initiated trades. N refers to number of observations, N^+ refers to number positive.

	Buyer-initiated Trades	Seller-Initiated Trades
Change in implied volatility of traded put, $\Delta IV_{i,j}$		
N	339	76
N^+	191	29
Mean($\Delta IV_{i,j}$)	0.00077	-0.00039
t-stat(p-value)	1.52 (0.13)	-0.41 (0.68)
Median($\Delta IV_{i,t}$)	0.00079	-0.00083
Change in implied volatility of non-traded put, $\Delta IV_{k,i,j}$		
N	339	76
N^+	157	25
Mean($\Delta IV_{i,j}$)	-0.00094	-0.00065
t-stat(p-value)	-1.98 (0.05)	-0.7 8(0.44)
Median($\Delta IV_{i,t}$)	-0.00022	-0.0013
Differential impact of trade $T_{i,j}$ on implied volatility of traded put, ($\Delta IV_{i,j}$ - $\Delta IV_{k,i,j}$)		
N	339	76
N^+	189	29
Mean($\Delta IV_{i,j}$)	0.001706	0.00026
t-stat(p-value)	3.54(0.00)	0.22 (0.82)
Median($\Delta IV_{i,t}$)	0.000726	0.00078
Sign (p-value)	2.12 (0.003)	1.84 (0.08)

Table 13
Intra-day inventory and information effects of trading in S&P 500 index LEAPS

This table shows OLS estimates of equation (13) (reproduced below) in a sample of pairs of consecutive intra-day quotes ($q_{t-1,i}$, $q_{t,i}$) for the most active S&P 500 index LEAPS from 1994-1996. The sample consists of 3732 pairs of quotes for puts and 697 for calls. Variable definitions are as follows: $\Delta IV_{i,t} = IV_{i,t} - IV_{i,t-1}$ is the change in IV of option i from time t-1 to time t, $\Delta I_{i,t} = I_{i,t} - I_{i,t-1}$ = change in corresponding index value from time t-1 to time t, $NDIF_{i,t}$ is the number of buy trades less sell trades in option i from time t-1 to time t, $VDIF_{i,t}$ is the buy volume less sell volume in option i from time t-1 to time t, $NDIF_{other,t}$ is number of buy trades less number of less trades in all other options of the same type (puts or calls) from time t-1 to time t, $VDIF_{other,t}$ is buy volume less sell volume for all other options of the same type from time t-1 to time t. The table show coefficient estimates and heteroskedasticity corrected t-statistics.

$$\Delta IV_{i,t} = a + b_1 * \Delta I_{i,t} + b_2 * \Delta I_{i,t} * X_i / I_{i,t-1} + b_3 * NDIF_{i,t} + b_4 * NDIF_{other,t} + b_5 * VDIF_{i,t} + b_4 * VDIF_{other,t} + e_{i,j} \quad (13)$$

Variable	Puts Model I	Puts Model II	Calls Model I	Calls Model II
Intercept	0.00011 0.82	0.0001 0.75	0.007 1.57***	0.007 1.57***
$\Delta I_{i,t}$	-0.031 -7.05*	-0.031 -7.08*	-0.313 -2.79*	-0.314 -2.80*
$\Delta I_{i,t} * X_i / I_{i,t-1}$	0.051 10.2*	0.051 10.2*	0.292 2.49*	0.293 2.49*
$NDIF_{i,t}$	0.0002 3.15*	0.0002 3.41*	0.0032 3.10*	0.003 3.00*
$NDIF_{other,t}$	0.0000006 0.02	0.000011 0.02*	0.0028 3.63*	0.003 4.51*
$VDIF_{i,t}$	-0.0000003 -0.94		-0.0000023 -0.27	
$VDIF_{other,t}$	0.0000005 0.91		0.0000069 1.45	
Number of observations R^2	3732 66 %	3732 66 %	697 37 %	697 37 %
F-statistic for test of difference between coefficients of $NDIF_{i,t}$ and $NDIF_{other,t}$	6.88*	6.06*	0.02	0.04

*,**,*** indicate significance of the coefficient at the 1%, 5% and 10% levels.

Table 14
Daily inventory and information effects of trading in S&P 500 index LEAPS

This table shows OLS estimates of model 3 (reproduced below in a sample of daily traded-untraded option pairs for the most active S&P 500 index LEAPS from 1994-1996. The sample consists of 399 put pairs and 171 call pairs. Notation is as follows: $\Delta IV_{i,t}$ is the change in implied volatility of traded put i over day t, $\Delta PIV_{i,t}$ is the change in implied volatility over day t of the untraded put with the closest strike to i with the same maturity, $NDIF_{i,t}$ is the number of buy trades less sell trades in option i over day t, $VDIF_{i,t}$ is the buy volume less sell volume in option i over day t. The table shows coefficient estimates and heteroskedasticity corrected t-statistics (p-values are indicated in parentheses when significant)

$$\Delta IV_{i,t} = a + b_1{*}\Delta PIV_{i,t} + b_2{*}NDIF_{i,t} + b_5{*}\ VDIF_{i,t} + e_{i,t} \qquad (14)$$

Variable	Puts Model I	Puts Model II	Calls Model I	Calls Model II
Intercept	-0.0022 -1.46	-0.003 -2.10(0.04)**	-0.0049	-0.0013 -0.85(0.40)
$\Delta PIV_{i,t}$		0.70 8.69(0.00)*		0.91 24.2 (0.00)*
$NDIF_{i,t}$	0.00024 0.95	0.00028 1.24	0.00035	0.0016 1.19
$VDIF_{i,t}$	0.0000016	0.0000013 0.47(0.64)	-0.000014	0.0000028 0.18
Number of observations R^2	399 0.5 %	399 15.8 %		171 0.12 %

*,** indicate significance of the coefficient at the 1% and 5% levels.

Table 15
Profitability of delta neutral strategy using two put options

This table shows summary results on the profitability of zero-cost delta-neutral portfolios constructed according to different trading rules described in the text. Portfolios are held for one and five trading days. All calculations use the bid-ask midpoint of the last quote of each option every day. The dollar payoff is calculated described in the text and repeated here:

Dollar payoff for n-day holding interval = $P_{1,t+n} - (h_{1,t}/h_{2,t})*P_{2,t+n} + B_t*e^{r*n}$
where $B_t = (h_{2,t}/h_{1,t})*P_{12t} - P_1$

Panel A: Trading rule 1 – Black-Scholes Implied Volatility

Variable	1 day holding interval	5 day holding interval
N (N^+)	1611 (948)	1495 (879)
Mean (T-stat)	0.0654 (3.47)	-0.00256 (-0.08)
Median (Sign Rank test p-value)	0.016 (0.00)	0.063 (0.00)
Standard Deviation	0.757	1.258
Delta on day t+1	0.0142	0.0229
Gamma (Vega) on day t	0.0028 (-492.03)	-0.0028 (-492.61)

Panel B: Trading rule 2 – Option Strike Prices

Variable	1 day holding interval	7 day holding interval
N (N^+)	1709 (865)	1491 (809)
Mean (T-stat)	0.0162 (0.83)	-0.0531 (-1.6)
Median (Sign Rank test p-value)	0.000165 (0.51)	0.020 (0.08)
Standard Deviation	0.785	1.28
Delta on day t+1	0.0164	0.0245
Gamma (Vega) on day t	-0.0032 (-521.40)	-0.00308 (-530.69)

Panel C: Trading rule 3 – Trading Volumes

Variable	1 day holding interval	7 day holding interval
N (N^+)	1053 (475)	1003 (475)
Mean (T-stat)	-0.00805 (-1.68)	-0.01162 (-1.53)
Median (Sign Rank test p-value)	-0.00004 (0.01)	-0.00206 (0.34)
Standard Deviation	0.155	0.241
Delta on day t+1	0.00256	0.00177
Gamma (Vega) on day t	-0.00017 (-13.14)	-0.00015 (-8.38)

Panel D: Trading rule 4 – Number of trades

Variable	1 day holding interval	7 day holding interval
N (N^+)	1079 (496)	1023 (491)
Mean (T-stat)	-0.00523 (-1.35)	-0.00392 (-0.77)
Median (Sign Rank test p-value)	-0.00003 (0.16)	-0.00033 (0.88)
Standard Deviation	0.127	0.1633
Delta on day t+1	0.0029	0.00068
Gamma (Vega) on day t	-0.0007 (9.84)	-0.00003 (15.69)

Table 16
Profitability of vertical put spread strategies using two put options – 1 day interval

This table shows summary results on the profitability of strategy 2 described in the text, constructed according to different trading rules. Portfolios are held for one and five trading days. All calculations use the bid-ask midpoint of the last quote of each option every day. Returns, Sharpe ratios, and portfolio characteristics such as gamma and vega are reported for each holding period and trading rule. Index returns and Sharpe ratios are also reported for comparison.

Panel A: Trading rule 1 – Black-Scholes Implied Volatility

Variable	1 day holding interval	5 day holding interval
N (N^+)	1609 (846)	1296 (707)
Mean (T-stat)	0.00075 (1.98)	0.002104 (4.19)
Median (Sign Rank test p-value)	0.00089 (0.02)	0.0023 (0.00)
Standard Deviation	0.0152	0.018
Sharpe Ratio	0.036	0.065
Index return (Sharpe ratio)	0.000757 (0.034)	0.00269 (0.0826)
Delta on day t	-0.299	-0.299
Gamma (Vega) on day t	0.00159 (300.8)	0.00158 (301.93)

Panel B: Trading rule 2 – Option Strike Prices

Variable	1 day holding interval	7 day holding interval
N (N^+)	1607 (825)	1294 (694)
Mean (T-stat)	0.00038 (1.00)	0.00166 (3.35)
Median (Sign Rank test p-value)	0.00065 (0.18)	0.001622 (0.00)
Standard Deviation	0.015	0.018
Sharpe Ratio	0.011	0.041
Index return (Sharpe ratio)	0.000733 (0.014)	0.00269 (0.08)
Delta on day t	-0.32	-0.32
Gamma (Vega) on day t	0.00167 (312.71)	0.00167 (313.32)

Panel C: Trading rule 3 – Trading Volumes

Variable	1 day holding interval	7 day holding interval
N (N^+)	1051 (529)	876 (470)
Mean (T-stat)	0.00261 (0.50)	0.0018 (2.34)
Median (Sign Rank test p-value)	0.000041 (0.33)	0.00196 (0.01)
Standard Deviation	0.017	0.023
Sharpe Ratio	0.0032	0.039
Index return (Sharpe ratio)	0.000394 (-0.01125)	0.0016 (0.030)
Delta on day t	0.075	0.075
Gamma (Vega) on day t	-0.00035 (-92.49)	-0.00036 (-97.55)

Panel D: Trading rule 4 – Number of trades

Variable	1 day holding interval	7 day holding interval
N (N^+)	1077 (536)	893 (492)
Mean (T-stat)	0.000254 (0.49)	0.00235 (3.02)
Median (Sign Rank test p-value)	-0.00017 (0.39)	0.0025 (0.00)
Standard Deviation	0.017	0.023
Sharpe Ratio	0.0026	0.062
Index return (Sharpe ratio)	0.000308 (-0.01125)	0.00173 (0.0379)
Delta on day t	0.111	0.111
Gamma (Vega) on day t	-0.00057 (-144.88)	-0.00057 (-149.46)

Table 17
Implied Index Analysis

This table shows summary statistics on the differences between actual and implied index and volatility. Each day in the sample period, all of the put and call bid-ask quotes that occur between 2:30 p.m. and 3:00 p.m. are collected. For every calendar series each day, the implied index and implied volatility are estimated wherever more than two option quotes are available each day using a minimization of sums of squares deviations procedure. The notation is as follows: LASTIND = Index value corresponding to the latest option quote of the options used in the estimation, INDDIF = Implied index value – LASTIND, MEANIV = Average implied volatility of all options used in the estimation, IVDIF = Implied volatility estimated – MEANIV.

	Calls	Puts
Number of densities estimated	488	590
Number with INDDIF positive	70	514
Mean INDDIF	-0.80	6.56
T-stat	-23.50*	24.75*
Mean % INDDIF	-1.2%	9.95%
T-stat	-22.84*	24.39*
Median INDDIF	-0.78	6.32
Mean Absolute INDDIF	0.90	7.19
T-stat	31.7*	30.11*
Mean moneyness of options used in the estimation	0.84	0.94
Mean number of options used	9.6	4.11
Mean IVDIF	0.022	0.046
T-stat	12.48*	16.18*
Mean % IVDIF	22.86%	27%
T-stat	14.95*	19.00*
Mean Implied volatility estimated, MEANIV	15.45	0.235

* indicates significance of the coefficient at the 1% level.

Table 18
Implied index and volatility by moneyness and maturity groups.

This table shows summary statistics by moneyness and maturity groups for the total of 2422 put quotes used to estimate the densities described in table 17. The table shows (1) the total number of options in that category (2) the implied volatility estimate with index free (unrestricted), (3) the implied volatility estimated with index restricted to equal the actual index, (4) the implied index, (5) the actual index for each moneyness and maturity group.

Moneyness Strike/ Closing value of Index		Very short-term Expiration<=60 days	Short-term Expiration from 60 – 180 days	Medium-term Expiration from 180 -365 days	Long-term Expiration >=365 days
<0.94	(1)	4	102	171	929
	(2)	0.082	0.196	0.249	0.263
	(3)	0.229	0.211	0.198	0.199
	(4)	68.42	64.93	68.0	76.6
	(5)	71.7	65.12	63.7	68.9
0.94-0.97	(1)	14	57	51	175
	(2)	0.184	0.178	0.225	0.255
	(3)	0.242	0.195	0.174	0.179
	(4)	64.5	64.5	61.77	74.60
	(5)	65.5	65.1	58.3	67.45
0.97-1.00	(1)	15	64	51	207
	(2)	0.203	0.192	0.224	0.252
	(3)	0.263	0.184	0.169	0.174
	(4)	63.7	64.9	63.23	73.54
	(5)	64.01	64.9	60.9	66.99
1.00-1.03	(1)	7	45	48	159
	(2)	0.217	0.173	0.219	0.249
	(3)	0.353	0.193	0.170	0.172
	(4)	53.8	63.05	62.0	73.1
	(5)	54.34	64.08	60.06	67.27
1.03-1.06	(1)	5	30	26	129
	(2)	0.140	0.215	0.218	0.250
	(3)	0.39	0.186	0.153	0.167
	(4)	53.9	64.17	63.88	72.35
	(5)	55.6	63.64	61.7	66.96
>1.06	(1)	7	22	20	84
	(2)	0.211	0.204	0.211	0.244
	(3)	0.393	0.195	0.158	0.163
	(4)	47.5	59.54	56.1	69.6
	(5)	48.12	59.73	54.8	64.8

Table 19
Implied Index Analysis Regression Analysis

The table shows regressions of the difference between implied and actual index (INDDIF), and of absolute INDDIF on explanatory variables in the puts sub-sample. The number of observations is 585. Columns 1 and 2 show results for dependent variable absolute INDDIF, and columns 3 and 4 show results for dependent variable INDDIF (defined above). Average moneyness is average strike/index ratio of the options used in the estimation. Similarly, average spread. Total OI is total open interest of the options used in the estimation, similarly total daily volume.

Variable	Coefficient 1	T-stat 2	Coefficient 3	T-stat 4
Intercept	25.42	7.60* (0.00)	21.03	5.89* (0.00)
Expiration Time	0.00633	9.66* (0.00)	0.0073	10.45* (0.00)
Average Moneyness	-27.4	-8.26* (0.00)	-24.81	-7.01* (0.00)
Average Spread	3.42	1.33 (0.18)	5.58	2.03** (0.04)
Total OI	0.0000903	10.46* (0.00)	0.000107	11.66* (0.00)
Total daily Volume	-0.0006	-3.14* (0.00)	-0.000596	-3.12* (0.00)
Number of options	-0.463	-6.50* (0.00)	-0.499	-6.16* (0.00)
Adjusted R^2	33.6%		37.5%	

*, ** indicate significance of the coefficient at the 1% and 5% levels.

Table 20
Analysis of newly introduced options

This table shows results on the newly introduced option series. Panel A shows summary statistics on the new S&P 500 index LEAPS series introduced in the sample period. Panel B shows the average implied volatility of the newly introduced options for each moneyness category by date introduced compared with the average implied volatility of all existing options on the same date. IV refers to implied volatility.

Panel A

Description	Number
Number of new calendar series introduced in the sample period	3
Total number of new calendar series options introduced	26
Number of new strikes introduced in existing calendar series*	66**
Number of new strikes which have lowest IV of all other strikes in same calendar series	53

*All new strike prices are highest strikes of all, because index is going up in this time.
** Of the 66, 55 have implied volatility lower than implied volatility of the closest existing strike price.

Panel B: IV skews of new maturity options:

24/1/94 Introduction of Dec 1996 expiration options

Moneyness	Calls IV of old options	Calls IV of new options	Puts IV of old options	Puts IV of new options
X/S <=0.94	0.164	0.142	0.164	0.161
0.94<X/S<=0.97	0.148	0.153	0.144	0.146
0.97<X/S<=1.03	0.125	0.136	0.146	0.151
1.03<X/S<1.06	0.119		0.107	0.151
X/S>=1.06				

23/1/95 Introduction of Dec 1997 expiration options

Moneyness	Calls IV of old options	Calls IV of new options	Puts IV of old options	Puts IV of new options
X/S <=0.94	0.164	0.185	0.167	0.175
0.94<X/S<=0.97				
0.97<X/S<=1.03	0.139	0.159	0.149	0.169
1.03<X/S<1.06	0.138	0.168	0.128	0.159
X/S>=1.06				

22/1/96 Introduction of Dec 1998 expiration options

Moneyness	Calls IV of old options	Calls IV of new options	Puts IV of old options	Puts IV of new options
X/S <=0.94	0.155	0.155	0.166	0.157
0.94<X/S<=0.97				
0.97<X/S<=1.03	0.131	0.146	0.140	0.152
1.03<X/S<1.06	0.122	0.142	0.124	0.139
X/S>=1.06				

Appendix A Dividend Forecasting Methodology

Dividend forecasting models such as Fama and Babiak's (1968) model relate the change in dividends to past lagged dividends, earnings and current earnings. After a model has been fitted using historical dividends and earnings data, 1998 dividends may be predicted using the fitted parameters. At the time of working on the thesis, only annual earnings forecasts for 1998 were available, therefore an annual dividend forecasting model was chosen (since quarterly earning forecasts for 1998 are more difficult to come by.

The model I estimate is Fama and Babiak (1968):

$$\Delta D_t = \beta_1 D_{t-1} + \beta_2 E_{t-1} + \beta_3 E_t + \varepsilon_t$$

where $\Delta D_t = D_t - D_{t-1}$= change in dividends from year t-1 to year t and E_t is the earnings at year t. Annual data on dividends and earnings are used to estimate the model.

I estimate the model with data from 1970 to 1997, omitting available data from 1935-1970, as being too far in the past. The regression results are:

Table 21
Regression results for the dividend forecasting model

Variable	Estimate	t-stat (p-value)
D_{t-1}	-0.0507	-1.63 (0.11)
E_t	0.0208	0.92 (0.36)
E_{t-1}	0.028	1.48 (0.15)

Annual 1998 dividends are then forecast using the estimates in the table, and the last available earnings forecast from the S&P Outlook for E_t. This gave an annual dividend of $16.99 for 1998[16].

[16] To check the accuracy of these results, 1997 annual dividends were forecast using this model and were predicted to be $15.333, while actual 1997 annual dividends were $14.9. This implied a reasonably accurate forecast (error of 3%) in that year.

Seasonalization of the 1998 annual dividends so forecast was done using the following procedure. Using the 1994-1997 daily cash dividend series, I find the average dividend paid on each day, find what fraction the average daily dividend is to the average annual dividend during this period. Then, I use these fractions to distribute the 1998 dividend forecast in the same proportions.

Appendix B CBOE Quote Revision Frequencies

Similar to the procedure in Lee and Ready (1991), I select one trade per contract per day: the first trade after 10 a.m. and before 3 p.m. with no trade at least two minutes before and after it. This results in 4509 trades in all. For each of these trades, I find the timing of all quotes in an interval of five minutes around it. I then find the frequency of quotes for every time distance in seconds away from the trade. The assumption is that the trade triggers the quote. The data are plotted in a histogram showing the time distance between the quote and the trade and the number of quotes at that distance away.

The pattern observed, reported in figure 2, is different from that obtained by Lee and Ready (1991) for NYSE transactions data. Unlike in the NYSE, it appears that the quote revision due to the trade is most often made in the same instant (a frequency of111). This implies that the quote recorded five seconds prior to the trade need not be taken as the reference bid-ask quote for trade classification, but that the earliest quote before the trade can be chosen as the reference.

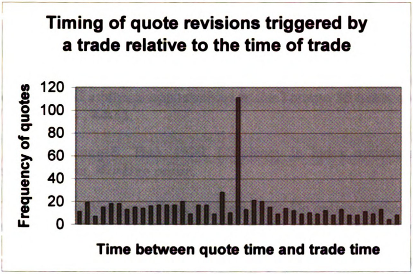

Figure 2: Timing of CBOE traded options quote revisions triggered by a trade

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