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Market Making in the Options Markets and the Costs of Discrete Hedge Rebalancing

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ABSTRACT

In this paper we provide empirical evidence consistent with the hypothesis that options market makers face risks in managing inventory that are unique to the options markets. In particular, we show that risks associated with the inability to rebalance an option position continuously and uncertainty about the return volatility of the underlying stock each account for a statistically and economically significant proportion of the bid-ask spreads quoted for a sample of Chicago Board Options Exchange options.

IT IS WIDELY RECOGNIZED that securities dealers face risk associated with inventory positions taken in the course of their trading activities. For the equity dealer this has been shown both theoretically (e.g., Stoll, 1978a; Ho and Stoll, 1983) and empirically (e.g., Stoll, 1978b) to depend on the stock's return volatility and the expected duration of the risk exposure. In this paper we recognize that option dealers face an additional dimension of risk as a result of the option's stochastic return volatility and demonstrate that this option characteristic contributes to the cost of liquidity in the options market.

Ho and Stoll (1983) show that if the stock return volatility is constant, the specialist's risk exposure per dollar of investment is nonstochastic over the interval during which the inventory is held. In contrast, unless the option dealer is able to trade continuously, an option transaction's contribution to the dealer's risk exposure will be stochastic, since the volatility of an option is a function of both its (stochastic) hedge ratio as well as the underlying stock's return volatility.

The problem that arises is particularly clear in the context of a dealer attempting to maintain a delta neutral exposure; a strategy common among market makers in the options markets. Imagine a market maker who simultaneously buys 10 option contracts with a hedge ratio of 1/4 and sells 5

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contracts on the same stock with a hedge ratio of 1/2. The market's net position represents a hedge portfolio that is instantaneously riskless. Failure to rebalance the hedge continuously, however, exposes the market maker to the risk of the underlying stock. The marginal contribution of an individual option to the risk introduced by discrete rebalancing of the hedge is reflected by the option's gamma, or the sensitivity of its hedge ratio to underlying stock price changes. The greater the option's gamma, the greater its marginal contribution to *variation* in the market maker's portfolio risk exposure.

Similarly, the per dollar magnitude of an option's marginal contribution to the market maker's risk exposure will also vary with changes in the perceived volatility of the underlying stock. Following Hull and White (1987b), we use the option's sigma, or first derivative of the price with respect to volatility of the underlying stock return, to measure an option's marginal contribution to this risk exposure. We refer to this exposure as stochastic volatility risk and note that it is associated with *changes* in the volatility of the underlying stock return and is therefore distinct from the more commonly recognized risk associated with the volatility of the option itself.

Our empirical work focuses on the influence of these risks on bid-ask spreads quoted in the options markets. The practical and hence empirical importance of these risks is reduced by the degree to which market makers are able to counter their effects through diversification. There are at least two forms of diversification that market makers might employ. Black and Scholes (1973) argue that discrete rebalancing risk can be diversified across hedge portfolios and, therefore, can be ignored if hedge rebalancing occurs relatively frequently.[1] Options market making firms are particularly well positioned to achieve this form of diversification because they generally trade options on a wide range of instruments. Grossman and Miller (1988) suggest that the risk borne by any single market maker can be reduced by spreading (or diversifying) the risk across many market makers. The competitive market making system of the Chicago Board Options Exchange (CBOE) from which we draw our data provides a particularly favorable environment for this type of risk shifting.

Our empirical results indicate that both an option's gamma and sigma play a statistically and economically significant role in determining quoted bid-ask spreads. This suggests that neither form of diversification is sufficient to eliminate the impact of risk associated with discrete rebalancing and stochas-

[1] Black and Scholes (1973) note that the systematic risk in a hedge portfolio is proportional to the covariance between the hedge return and the return on the market portfolio. This covariance is zero if hedge returns and market returns are jointly normally distributed over small time intervals. Similarly, Hull and White (1987a) assume that volatility has zero systematic risk in their analysis of the consequences of stochastic volatility for option valuation. Boyle and Emanuel (1980) point out that although individual hedge returns and returns on the market portfolio are uncorrelated, they are not independent. Thus, diversification across option hedges may reduce discrete hedging risk but it will not be eliminated. Leland (1985) investigates the discrete hedging problem in the presence of transactions costs and argues that randomness in transactions costs can further increase hedging errors.

tic volatility on the options market maker's portfolio. Since both forms of diversification are particularly accessible to market makers, this conclusion is consistent with Figlewski's (1989) conclusion that arbitrage considerations impose only relatively wide bounds on option prices. The results also demonstrate that analyses of the pricing behavior of options market makers which do not account for these features of options fail to capture an important dimension of the market maker's risk management problem; a dimension which may have policy implications (Ritchie and Ginter, 1988).

The remainder of the paper is organized as follows. In Section I we develop an empirical model which relates quoted bid-ask spreads to risk associated with discrete hedge rebalancing and stochastic volatility while controlling for the effects of other determinants of spreads suggested by the market microstructure literature. Section II presents a description of the data and sample design used in the analyses of the model. The results of our analyses are presented in Section III. We conclude the paper with a brief summary of our results.

I. A Model of Quoted Bid-Ask Spreads

In this section we describe a set of variables designed to control for cross-sectional variation in bid-ask spreads related to factors other than discrete hedge rebalancing and stochastic volatility. The market microstructure literature suggests that variation in spreads is largely a consequence of variation in three costs faced by the market maker: inventory carrying costs, asymmetric information costs, and order processing costs. Inventory carrying costs arise because dealers routinely assume substantial security specific risk exposures in the course of providing immediate execution of market orders. We use insight from Ho and Stoll's (1983) model of spread determination by a competitive market maker in the construction of variables to control for the effects of this cost component on the quoted bid-ask spread. Ignoring order processing costs and the potential for adverse selection, Ho and Stoll (1983) demonstrate that in a two-period world the percentage spread is approximately

$$\%\text{SPREAD} = R\sigma^2 Q - R\sigma^2 Q\pi, \tag{1}$$

where σ^2 is the per period security return variance, Q is the dollar transaction size for which the market maker's reservation bid and ask quotes hold, π is the probability of a reversing transaction during the next trading interval, and R is a discounted coefficient of absolute risk aversion. Thus, Ho and Stoll's (1983) model implies that the percentage spread should be an increasing function of the dollar quantity of a trade's contribution to the market maker's risk exposure and the length of time for which the risk must be borne.

Use of Ho and Stoll's model as a guide in our empirical analyses requires attention to several issues. First, we conduct our analyses with quoted bid-ask spread data from the CBOE. CBOE regulations require only that quotes be good for a single contract. Thus, we rewrite Q as the product of the number of contracts, N, for which quotes hold and the option's price, P, and set $N = 1$.[2] Furthermore, we note that the relation between the return variance of an option and the return variance of its underlying stock, σ_s^2, is

$$\sigma^2 = \Omega^2 \sigma_s^2,$$

where the subscript s denotes the underlying stock and $\Omega = (\partial P/\partial S)(S/P)$ is the option's price elasticity with respect to the underlying stock price. Specifying the model as a function of the return volatility of the underlying stock introduces several desirable econometric properties that we discuss in more detail later. With these modifications we specify the variable

$$\mathrm{RISK} = \Omega^2 \sigma_2^2 P$$

to control for the impact on the dealer's spread of the dollar quantity of a trade's marginal risk exposure, that is, the first term in equation (1).

Assuming that the market maker's expected holding period is negatively correlated with the level of trading activity in an option, a natural candidate for proxying the second term in equation (1) is the average time between transactions in the option. Obviously, interarrival time is an endogenous function of the cost of trading. In principle one could deal with this by modeling interarrival time as part of a simultaneous system. In practice this approach presents several problems. In our empirical analyses we use data drawn across option classes as well as from within a class of options on a single stock. Unfortunately, there is not a well developed body of theory describing how the endogenous demand to trade should vary across options within a class. Further, the data set is constructed by sampling repeatedly from the options traded on a relatively small set of underlying stocks. Thus, relatively few independent observations are available when using underlying stock characteristics (Glosten and Harris, 1988) to explain variation in interarrival time across options.

The use of interarrival time is also problematic simply because in some cases we were able to measure this variable only with a high degree of imprecision. Specifically, the design of our experiment in some instances provides as the basis for calculation of the average interarrival time as few as three observations. Although calculation of a moving average over an extended time period would mitigate this problem, it would also tend to obscure variation in trading frequency that might occur as a consequence of the normal variation in option characteristics that occurs through time.

[2] Available quote data provide no information regarding the depth of the market at observed quotes. In the absence of market supply and demand schedules there is little choice but to assume that N is constant. For the analyses to follow, this assumption is important only if there are systematic differences in N across the options considered.

Faced with these problems, we construct the variable MONEY to serve as a proxy for the market maker's expected holding period:

$$\text{MONEY} = \text{ABS}\{(S - X^{*}\text{EXP}(-rt))/S\}.$$

The empirical fact that options trade more heavily as they draw nearer-the-money implies that MONEY should be highly correlated with the market maker's expected holding period. Since the extent to which an option is out-of-the-money depends on the behavior of the underlying stock price and the option's strike price, MONEY is exogenous by construction. Thus, MONEY exhibits the features desirable in an instrument for an endogenous variable.

It should be noted that Ho and Stoll's specification applies strictly only to the spread quoted by a single market maker whereas the data used in the analyses reported later reflect the inside, or market, bid-ask spread. Although this problem is common to any study where market makers compete among themselves, with floor brokers, or with the limit order book, its seriousness is mitigated by the potential for interdealer trade which, as Ho and Stoll (1983) demonstrate, limits differences among the bid and ask quotes of individual dealers. While it is impossible to observe directly the degree to which trade occurs among market makers in the present sample, casual observation of trading activity on the floor of the CBOE suggests that it is common for market makers to share incoming orders. The effect of this activity is to distribute inventory across market makers immediately, and thus limit differences that might lead to divergence among individual bid and ask quotes.

Cross-sectional variation in bid-ask spreads can also arise in response to variation in the degree to which option traders are asymmetrically informed. Vijh (1990) finds, contrary to evidence from the NYSE reported by Glosten and Harris (1988), no relationship between trade size and the information content of trades and that information trading has little impact on the liquidity of CBOE options. To the extent that information trading does occur in the options markets, however, we would expect its impact to vary both across classes of options on different stocks and within classes of options on particular stocks. Variation across option classes is consistent with a market in which there is variation in the level of private information about the future cash flows of firms. Stoll (1978b) controls for this effect by assuming that the level of information trading in a stock is correlated with turnover of outstanding shares, where turnover is defined as the ratio of trading volume to dollar value of shares outstanding. Unfortunately, in the present sample we have repeated observations from options trading on only 40 underlying stocks. Thus, it is unlikely that turnover would control for variation resulting from asymmetric information in the 4644 quoted spreads used in this study.

Variation within a class of options is consistent with the conjecture made by Black (1975) that informational traders are attracted to investment vehicles providing the greatest leverage. If this is true, then the high degree of leverage implicit in out-of-the-money options makes them attractive trading vehicles for privately informed traders. In this case, holding other forces constant, an option's spread should be positively related to its implicit leverage. We control for this effect by including in our model the price elasticity of an option with respect to its underlying stock's price as a proxy for implicit leverage.

Finally, we expect option spreads to vary cross-sectionally as a consequence of variation in order processing costs. These costs include both the fixed costs of capital, labor, exchange membership, and time as well as the variable cost of clearing orders. Market makers typically pay commissions to a clearing member as compensation for order clearing and other services. Cox and Rubinstein (1985) suggest that these commissions vary with contract price and the volume of business generated by the market maker. These costs are, however, largely fixed over a fairly wide range of option price levels. Cox and Rubinstein (1985), for example, report a typical one-way schedule of $1.00 per contract for options above $1.00, and $0.75 for those trading below $1.00. Thus we treat order processing costs for the options in our sample as varying across options trading above and below $1.00 (as defined by the mean of the quoted bid and ask prices), but fixed on an absolute basis within each partition of the data. Specifically, we include a variable LOW which takes a value of one for options trading below $1.00 and zero otherwise. Obviously, this specification will not capture all of the subtle differences in order processing costs either within or across option classes. For example, if there are scale economies associated with the fixed costs of processing orders and the quotes for an option implicitly hold for more than one contract, our specification will not reveal this fact. However, given the discrete variation in clearing costs described by Cox and Rubinstein (1985) our specification should capture a large proportion of the variation in clearing costs.

If transactions in options on the same underlying stock differ only by presenting the market marker with different exposures to the underlying stock (as measured by the option's hedge ratio or "delta"). Ho and Stoll's (1983) model would capture the forces by which inventory carrying costs are reflected in quoted bid-ask spreads. Since an option's hedge ratio is a function of the underlying stock price, however, variation in the underlying stock price causes variation in the magnitude of the option's contribution to the market maker's aggregate exposure to the underlying stock. This becomes clear when it is recalled that an option's return volatility is the product of the underlying stock's return volatility and the option's price elasticity with respect to the underlying stock price. Thus, variation in the underlying stock price induces variation in an option's return volatility. This additional source of uncertainty is identical to the risk associated with discrete rebalancing of a hedge portfolio composed of stock and options. Since it is variation in the option's hedge ratio which introduces such risk, we use the partial derivative of the option's hedge ratio with respect to the underlying stock price, or its gamma, as our measure of discrete rebalancing risk.

Similarly, stochastic stock return volatility also causes variation in the per dollar magnitude of a trade's marginal contribution to the market maker's aggregate exposure. Following Hull and White (1987b) we model exposure to the risk of stochastic volatility with the option's sigma, that is, the partial derivative of the option's price with respect to its underlying stock's return volatility. Once again, we note that this risk is associated with *changes* in the return volatility of the underlying stock during the remaining life of the option and is therefore distinct from the risk associated with the *level* of the option's (and thus the stock's) return volatility which is captured by RISK.

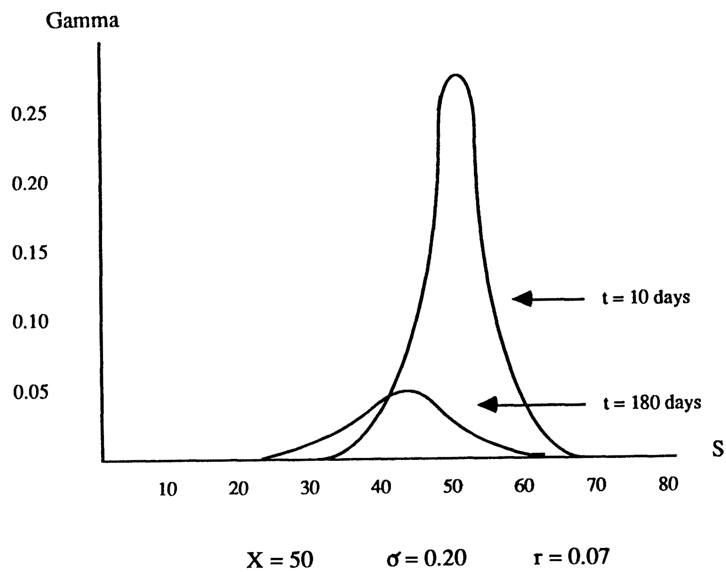
II. Data and Methodology

The data used in our empirical analyses are drawn from the resorted format of the Berkeley Options Data Base. The Data Base provides a time stamped record of all transactions and bid and ask quotes offered on the CBOE. The analyses were confined to options on the January/April/July/October expiration cycle during 1985. Of the 57 option classes listed by the 1985 CBOE expiration calendar as being on this cycle, 17 had one or more days with no trading activity and were excluded from the sample. The 40 remaining option classes are listed in Figure 1.

Our sample was designed to counter a problem likely to be encountered in any attempt to estimate the sensitivity of the bid-ask spread to an option's gamma and sigma. Figure 2 shows that both gamma and sigma peak for options near-the-money, with variation in gamma being greatest near option expiration, and variation in sigma greatest for long maturity options. As time to expiration increases, gamma approaches zero for all options, while the opposite is true for sigma. Thus there will be periods during which gamma and sigma will exhibit very little variation across options. Such lack of variation will make it difficult to estimate the independent effects of gamma or sigma on spreads. To counter this problem our sample was drawn from two 10-day trading intervals surrounding the October 19th expiration

AA	FLR	LOR	SY
ARC	FNB	MER	SQB
AVP	GWF	MMM	T
BAC	HAL	MRK	TAN
BNI	HM	MTC	TDY
CUL	IBM	NWA	TXN
DAL	IGL	PEP	UPJ
ECK	IP	PRD	WGO
EK	JNJ	PWJ	WY
FDX	KMG	PZL	XON

Figure 1. Sample Option Classes. Figure 1 contains the exchange symbols for the option classes used in the empirical analyses.



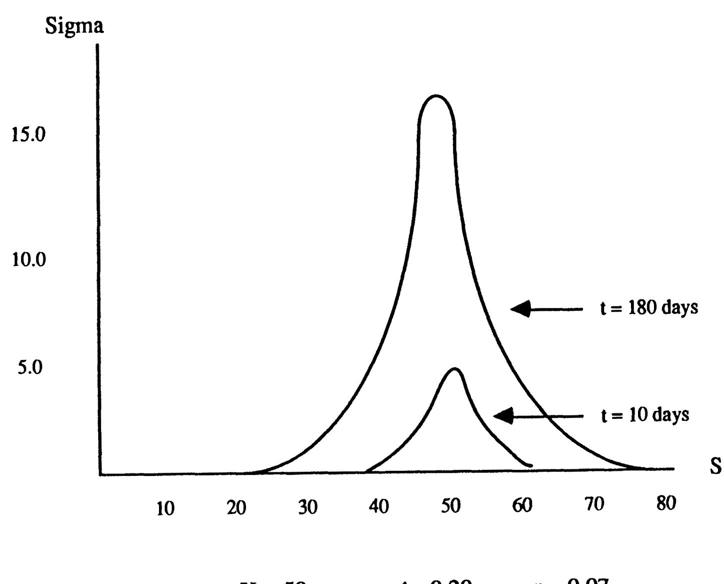


Figure 2. Variation in Option Gamma and Sigma. Figure 2 describes the variation of gamma ($\partial^2 C/\partial S^2$) and sigma ($\partial C/\partial \sigma$) across time (t) and stock price level (S) for an option with strike price $X = 50$ and volatility $\sigma = 0.20$, and a riskless rate of $r = 0.07$.

date: October 1–October 14, 1985 and October 21–November 1, 1985. Constructed in this manner the sample includes one period (pre-expiration) during which gamma for one expiration series (the near expiration and most heavily traded) for each of the 40 option classes will approach its maximum level of variation. Similarly, the post-expiration period will be one where sigma is expected to be relatively more variable.

A. Option Valuation

The calculation of option characteristics proceeded in two stages. At the first stage an implied standard deviation (ISD) for each of the 40 option classes was calculated for each day of the sample period. The ISD was then used as a proxy for σ_s and in the calculations of option deltas, gammas, and sigmas. Use of the ISD in the construction of RISK has two benefits. First, it permits σ_s to vary across the 20-day sample period. More importantly, as Neal (1987) points out, it avoids the spurious positive correlation between volatility and the bid-ask spread associated with volatility estimates from transaction prices.

The daily average ISD was calculated from the most actively traded, near-the-money, January, 1986, call option using the mean of the quoted bid and ask prices as the option price input. The daily average was based on ISDs calculated from the midpoint of each quoted spread reported during the day for the call option under consideration. Since the probability of early exercise was positive for many of the January call options, ISDs were calculated using the Roll (1977) and Whaley (1981) American call option pricing model.[3]

Table I reports the mean ISD across 40 option classes for each of the 20 days in the sample as well as summary statistics for the class of Polaroid (PRD) options. ISDs were relatively stable over the sample period, but relatively less stable within the trading day. Intraday variation in the ISD is consistent with the inventory control method suggested by Ho and Stoll (1981, 1983) by which market makers shift the location of the spread to induce market orders that will offset an undesirable inventory position. Ho and Macris (1984) and Hasbrouck (1988) provide evidence consistent with this effect of inventory control. Although it would perhaps be of some interest to model the microstructure related variation in the ISD, this is beyond the scope of the present study. Thus, the daily average ISD is used in the remainder of the analyses and is assumed to represent a more accurate estimate of the true return variance of the underlying stock than would any single intraday ISD or an intraday moving average.

Option elasticities, gammas, and sigmas and the variable RISK were obtained from either the Roll/Whaley American pricing model (for calls) or the two-point extrapolation of the Geske and Johnson (1984) American put

[3] The current 13-week T-bill rate reported by the Wall Street Journal was used as the interest rate input to the model. For stocks paying cash dividends, the model allowed for a maximum of three ex dividend dates during the life of an option (see Hull (1989) p. 131).

Table I

Descriptive Statistics for Implied Standard Deviation Estimates

Summary of the behavior of Implied Standard Deviations (ISDs) over the 20-day sample period. The first two columns report for each day in the sample the mean of the daily mean ISDs calculated for each of the 40 firms in the sample and the mean standard deviation of the daily mean ISDs. The remainder of the table provides summary statistics for the daily mean ISDs calculated for the class of Polaroid (PRD) options.

	Mean		PRD				
Date	ISD	SD	Mean	SD	Max	Min	N
10/1/85	0.2599	0.0135	0.3131	0.0128	0.3476	0.2753	50
10/2/85	0.2596	0.0152	0.3023	0.0056	0.3286	0.2624	109
10/3/85	0.2650	0.0117	0.3289	0.0012	0.3666	0.2635	144
10/4/85	0.2997	0.0113	0.3293	0.0124	0.3535	0.2983	49
10/7/85	0.2728	0.0127	0.3448	0.0113	0.3704	0.3149	88
10/8/85	0.2735	0.0142	0.3274	0.0143	0.3554	0.2938	34
10/9/85	0.2670	0.0108	0.3319	0.0164	0.3797	0.2917	82
10/10/85	0.2670	0.0146	0.3156	0.0043	0.3325	0.3001	21
10/11/85	0.2633	0.0114	0.2958	0.0153	0.3242	0.2632	26
10/14/85	0.2636	0.0119	0.2985	0.0021	0.3293	0.2781	45
10/21/85	0.2534	0.0138	0.3040	0.0206	0.3283	0.2602	32
10/22/85	0.2518	0.0102	0.2840	0.0044	0.3021	0.2600	25
10/23/85	0.2501	0.0105	0.2721	0.0004	0.3051	0.2426	50
10/24/85	0.2535	0.0124	0.2821	0.0191	0.3020	0.2585	33
10/25/85	0.2535	0.0116	0.2853	0.0190	0.3354	0.2486	26
10/28/85	0.2564	0.0111	0.2785	0.0051	0.3007	0.2495	20
10/29/85	0.2523	0.0183	0.2972	0.0111	0.3278	0.2517	29
10/30/85	0.2500	0.0123	0.2701	0.0194	0.3020	0.2389	14
10/31/85	0.2547	0.0169	0.2776	0.0038	0.2913	0.2707	6
11/1/85	0.2538	0.0163	0.2715	0.0140	0.3219	0.2323	20

SD = standard deviation.

option pricing model using the daily average ISD as the volatility input.[4] The sample described below was drawn from a population containing in excess of 100,000 bid-ask quotes. Taking the midpoint of the bid-ask quote as a benchmark, we find only small deviations (less than 5%) in model prices from the benchmark for all but very deep-out-of-the-money options. For options trading at less than \$0.50, deviations from the benchmark exceed 43% for puts and 20% for calls.[5] This result is at least partially a consequence of the minimum quote of 1/16th on low priced options. Quote discreteness will

[4] Gamma and sigma were calculated numerically using the central difference formula for the first derivative of a function:

$$f'(x) = \big(f(x+h) - f(x-h)\big)/2h + O(h^2),$$

where for gamma, $f(S+h)$ is the option's hedge ratio evaluated at the stock price $S+h$.

[5] A detailed analysis of the performance of the option pricing models as well as summary statistics for the variables used in the empirical analyses are provided in an earlier draft of the paper which is available from the authors upon request.

result in large percentage deviations from the benchmark for model prices close to zero. Given the extreme sensitivity to quote discreteness of such low priced options and the fact that they are subject to trading restrictions that limit arbitrage activity (Philips and Smith, 1980), options with spread midpoints below \$0.50 are excluded from the remainder of the analyses.

B. Sample Construction

The regression analyses reported in the next section were conducted with data drawn from seven intraday trading intervals for each day during the 20 day sample period: Open–9:30, 9:30–11:00, 11:00–12:00, 12:00–1:00, 1:00–2:00, 2:00–3:00, and 3:00–Close. The sampling procedure involved drawing a single quote record for each firm and day yielding seven cross-sections with a maximum of 800 observations each (40 option classes · 20 days). The seven intraday cross-sections were then pooled to obtain a final sample of 4644 observations. The number of observations in each subsample ranged from a maximum of 740 (opening) to a minimum of 472 (closing). Each of the seven subsamples contained fewer than the maximum number of observations because of the exclusion of options for which there were fewer than two transactions during a trading day, and the fact that it was common for one or more of the 40 option classes to have no quotes reported during a particular trading interval. From a practical perspective this sampling procedure reduced a massive amount of data to a manageable dimension. Given the large number of identical quotes associated with the same underlying stock value, especially for the most active option classes (e.g., IBM, NWA, SY, and TXN), the exclusion of independent observations is limited.

The single quote drawn for each firm was the first quote recorded during the trading interval for an option with at least two transactions during that trading day. The opening of options in order of their strike and maturity implies that applying this sampling procedure to the opening of the market would lead to systematic selection of options that were first to open. This selection bias was avoided by randomly selecting a single quote record from the opening interval.

C. Model Specification and Hypotheses

The regression model estimated in the following section is:

$$\begin{aligned}\%\text{SPREAD} = {}& \alpha(1/P) + \alpha'\text{LOW}(1/P) + \beta_1\text{RISK} + \beta_2\text{GAMMA} \\ & + \beta_3\text{SIGMA} + \beta_4\text{ELASTICITY} + \beta_5\text{MONEY} + \epsilon,\end{aligned} \tag{2}$$

where P is the option's price. Since LOW is included to control for the possibility that options trading below \$1.00 will be subject to lower order processing costs, we predict that α' will be negative. RISK, MONEY, and ELASTICITY are included to control for variation in inventory carrying costs and adverse selection costs, and thus we hypothesize that the coefficients associated with each will be positive. Finally, we predict that the coefficients associated with both GAMMA and SIGMA will be positive.

III. Empirical Analysis

Estimation of the regression model yields:

$$
\begin{aligned}
\%\text{SPREAD} = {} & \underset{(17.25)}{0.1345(1/P)} - \underset{(-4.44)}{0.0233\text{LOW}(1/P)} + \underset{(2.53)}{0.00016\text{RISK}} \\
& + \underset{(3.51)}{0.1205\text{GAMMA}} \\
& + \underset{(6.67)}{0.0007\text{SIGMA}} + \underset{(4.99)}{0.0016\text{ELASTICITY}} + \underset{(13.80)}{0.1882\text{MONEY}} + \epsilon
\end{aligned}
$$

$$R^2 = 0.74$$
$$F = 1922.87.$$

The t-statistics reported in parentheses reflect asymptotic standard errors obtained from the heteroskedasticity-consistent covariance matrix proposed by White (1980).[6] The coefficients associated with LOW, RISK, ELASTICITY, and MONEY have the predicted signs and are significantly different from zero at the 0.0001 level except in the case of RISK which is significantly different from zero at the 0.01 level. After controlling for the cross-sectional variation in spreads produced by other cost determinants of the spread, both GAMMA and SIGMA are positive and statistically significant at the 0.001 and 0.0001 levels, respectively. Given the sample mean percentage spread of 13.02% and the sample mean of 0.0850 for GAMMA, this estimate indicates the mean percentage spread is roughly 8% ([0.1205 · 0.0850]/0.1302) higher than it would be if discrete rebalancing risk were not a factor. This corresponds to a \$0.02 increase in the mean absolute spread of \$0.261. Similarly, risk associated with stochastic volatility accounts for about 4.5% of the quoted percentage spread or about \$0.01 of the mean absolute spread.[7] Taken as a whole, the results are consistent with the hypothesis that the risks associated with discrete hedge rebalancing and stochastic volatility are not easily diversifiable, and thus contribute to the cost of obtaining immediate

[6] The test results to follow should be interpreted with some care given the large sample on which they are based. Leamer (1978) discusses the problems associated with hypothesis testing at fixed levels of significance and suggests that significance levels should be a decreasing function of sample size. Neal (1987) suggests a posterior odds ratio test to control for type 1 errors which roughly translates into doubling the t-statistic required for a "significant" effect. Use of this strategy would have little qualitative effect on our conclusions.

[7] A sense of the amount of sample variation in the percentage spread explained by gamma can be gained by noting that a one standard deviation increase in gamma leads to a 0.08 standard deviation increase in the percentage spread. Likewise, a one standard deviation in sigma results in a 0.06 standard deviation increase.

execution of market orders in the options market. The absolute importance of each will vary through time with discrete rebalancing risk being most pronounced for near maturity options and stochastic volatility risk being greatest for longer term options for which price sensitivity to variation in the return volatility of the underlying stock is greatest.

To examine the sensitivity of our results to model specification we also estimate an absolute spread specification of the model; the approach employed by Demsetz (1968), Tinic and West (1972), Benston and Hagerman (1974), and Neal (1987). We respecify the regression model by multiplying the right hand side of equation (2) by the option price, P. This specification eliminates any potential for spurious correlation resulting from the presence of the option price in both the dependent and independent variables. Estimation of the model yields:

$$\begin{aligned}
\text{SPREAD} = {} & \underset{(22.0)}{0.1687} - \underset{(-14.18)}{0.0726}\text{LOW} + \underset{(5.06)}{0.00016}P \cdot \text{RISK} + \underset{(3.63)}{0.1069}P \cdot \text{GAMMA} \\
& + \underset{(11.18)}{0.0005}P \cdot \text{SIGMA} - \underset{(4.50)}{0.0009}P \cdot \text{ELASTICITY} \\
& + \underset{(15.17)}{0.6433}P \cdot \text{MONEY} + \epsilon \\
R^2 = {} & 0.28 \\
F = {} & 297.44.
\end{aligned}$$

The absolute spread specification produces similar parameter estimates and leads to identical conclusions regarding the role of discrete rebalancing and stochastic volatility in the determination of quoted spreads.

IV. Summary

The goal of this paper was to examine the unique features of the inventory risk management problem faced by options market makers. After controlling for variation in spreads produced by the costs of making markets generally cited in the market microstructure literature, we find that risks associated with discrete rebalancing of the market maker's portfolio and stochastic stock return volatility explain a statistically significant proportion of the remaining variation in option spreads. This result is especially striking in light of the fact that options market makers face a rich set of opportunities for diversifying such risks.

These results have two important implications. First, they suggest that failure to account for these unique features of options when studying option spreads ignores an important dimension of the market maker's risk management problem. In addition to offering further explanation for the relatively large percentage spreads observed in the options markets (Vijh, 1990), they carry important implications for efforts to develop risk-based position limits for market makers. Our results also provide further evidence that the inability to costlessly and continuously rebalance an option portfolio imposes undiversifiable risks on market participants that may influence the theoretical bounds on option prices.

REFERENCES

Benston, George and Robert Hagerman, 1974, Determinants of bid-ask spreads in the over-the-counter market, *Journal of Financial Economics* 1, 353-364.

Black, Fischer, 1975, Fact and fantasy in the use of options, *Financial Analysts Journal* 31, 36-41, 61-72.

—— and Myron Scholes, 1973, The pricing of options and corporate liabilities, *Journal of Political Economy* 81, 637-659.

Boyle, Phelim and David Emanuel, 1980, Discretely adjusted option hedges, *Journal of Financial Economics* 8, 259-282.

Cox, John C. and Mark Rubinstein, 1985, *Options Markets*, (Prentice-Hall, Englewood Cliffs, NJ).

Demsetz, Harold, 1968, The cost of transacting, *Quarterly Journal of Economics* 82, 33-53.

Figlewski, Stephen, 1989, Options arbitrage in imperfect markets, *Journal of Finance* 44, 1289-1312.

Geske, Robert and Herb Johnson, 1984, The American put option valued analytically, *Journal of Finance* 39, 1511-1524.

Glosten, Lawrence and Lawrence Harris, 1988, Estimating the components of the bid-ask spread, *Journal of Financial Economics* 21, 123-142.

Grossman, Sanford and Merton Miller, 1988, Liquidity and market structure, *Journal of Finance* 43, 617-633.

Hasbrouck, Joel, 1988, Trades, quotes, inventories and information, *Journal of Financial Economics* 22, 229-252.

Ho, Thomas and Richard Macris, 1984, Dealer bid-ask quotes and transaction prices: An empirical study of some AMEX options, *Journal of Finance* 39, 23-45.

—— and Hans Stoll, 1981, Optimal dealer pricing under transactions and return uncertainty, *Journal of Financial Economics* 9, 47-73.

—— and Hans Stoll, 1983, The dynamics of dealer markets under competition. *Journal of Finance* 38, 1053-1074.

Hull, John, 1989, Options, futures, and other derivative securities, (Prentice-Hall, Englewood Cliffs, NJ).

Hull, John and Alan White, 1987a, The pricing options on assets with stochastic volatilities, *Journal of Finance* 42, 281-300.

—— and Alan White, 1987b, Hedging the risks from writing foreign currency options, *Journal of International Money and Finance* 6, 131-152.

Leamer, Edward, 1978, Specification searches: Ad hoc inference with nonexperimental data, (John Wiley, New York, NY).

Leland, Hayne E., 1985, Option pricing and replication with transactions costs, *Journal of Finance* 40, 1283-1301.

Neal, Robert, 1987, Potential competition and actual competition in equity options, *Journal of Finance* 42, 511-533.

Phillips, Susan M. and Clifford W. Smith, Jr., 1980, Trading costs of listed options: The implications for market efficiency, *Journal of Financial Economics* 8, 179-201.

Ritchie, Joseph and Gary Ginter, 1988, Why market maker position limits should be delta-based, *Futures*, 42-43.

Roll, Richard, 1977, An analytic valuation formula for unprotected American call options on stocks with known dividends, *Journal of Financial Economics* 5, 251-258.

Stoll, Hans R., 1978a, The supply of dealer services in securities markets, *Journal of Finance* 33, 1133–1151.

——, 1978b, The pricing of security dealer services: An empirical study of NASDAQ stocks, *Journal of Finance* 33, 1153–1172.

——, 1989, Inferring the components of the bid-ask spread: Theory and empirical tests, *Journal of Finance* 44, 115–134.

Tinic, Seha and Richard West, 1972, Competition and the pricing of dealer services in the over-the-counter market, *Journal of Financial and Quantitative Analysis* 7, 1707–1728.

Vijh, Anand M., 1990, Liquidity of the CBOE equity options, *Journal of Finance* 45, 1157–1180.

Whaley, Robert, 1981, On the valuation of American call options on stocks with known dividends, *Journal of Financial Economics* 9, 207–212.

White, Halbert, 1980, A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity, *Econometrica* 48, 817–838.