# The Effect of High-Frequency Market Making on Option Market Liquidity

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The widespread development of electronic order execution systems, which allow for automatic trading systems and high-frequency trading, has transformed financial markets. These rule changes have caused exchanges to compete based on trading fees, the speed of order handling, and the quality of execution in order to obtain a greater share of trading volume. Similarly, the proliferation of electronic trading has forced option market makers to generate electronic quoting programs in order to avoid losing money on mispriced quotes arising from the speed and cost advantages of high-frequency traders (Hendershott and Moulton [2007]).[1]

Options markets are unique and powerful channels to examine the effects of high-frequency market making (HFMM) because different options exchanges compete by trading the same product, and options quotation procedures and practices differ from equity markets. In particular, option market makers are obligated to make quotes on most exchanges, unlike equity market makers. Moreover, option market makers *must* revise quotes frequently to be competitive because new quotes are required as the underlying spot price changes frequently.[2] Thus, options markets are primarily considered quote driven markets, whereas stock markets are order driven by the dominance of high-frequency traders. Here, we emphasize the effect of high-frequency option market-making activity on the bid–ask quotes and depth in options in order to examine liquidity. Given the distinctions between equity and options markets, such an examination of options liquidity provides a unique extension to the literature on the effects of high-frequency market making.

The recent media and academic focus of high-frequency electronic trading is the algorithmic trading implemented by equity traders. The resultant growth of such equity algorithmic trading spurred interest in its potential effects on market dynamics (Hendershott and Riordan [2009]). Empirically for stocks, Hendershott, Jones, and Menkveld [2011] and Hendershott and Riordan [2009] found that the net effect of algorithmic trading is to reduce bid–ask spreads and aid in the pricing efficiency in the stock market. Our investigation differs in that we examine high-frequency market making activity in options; thus, we employ a different market, with different characteristics and a different factor driving quotes (i.e., market making activity).

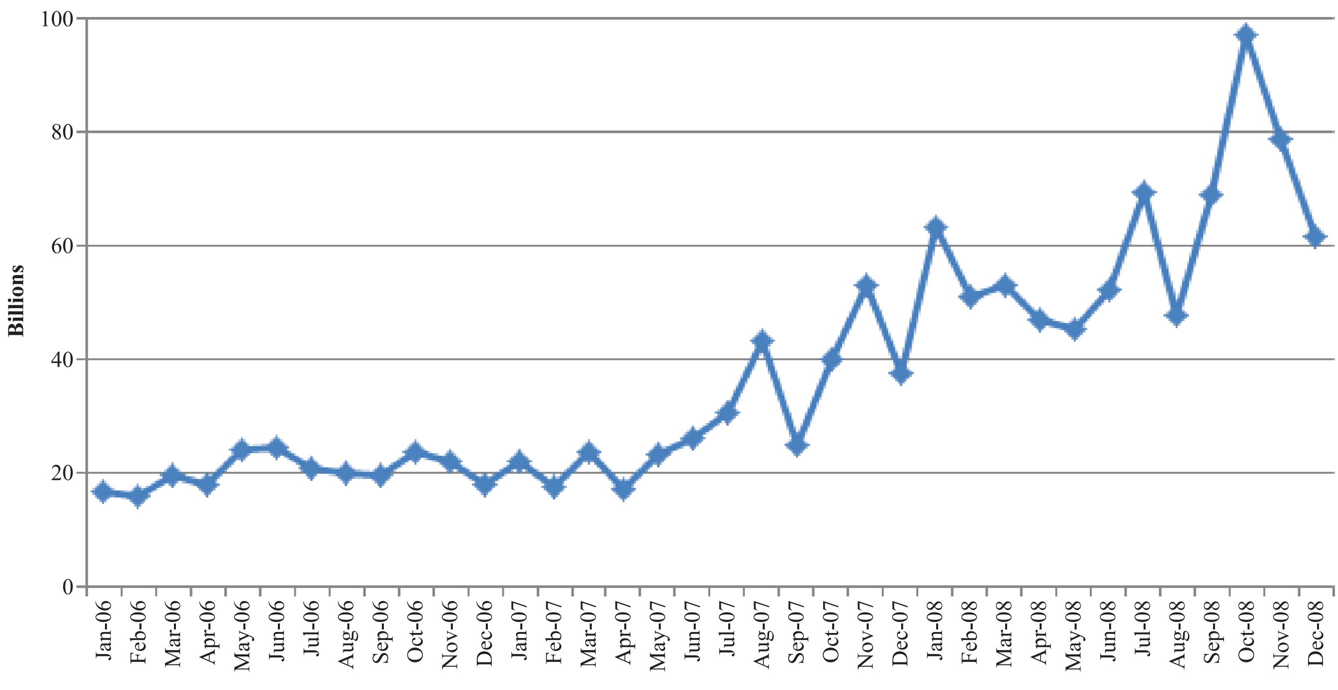
The options market possesses unique factors that affect the demand and supply of liquidity. On the demand side, the importance of trading and quote revisions for the liquidity of options is enhanced by the *smart routing* of option orders and the execution of price improving multileg orders. In addition, options are unique in their spread-enhancing, market-making activities across option-specific characteristics and simultaneous trade activities on as many as seven options exchanges at once. On the supply side, the multitude of option choices challenges the ability of this market mechanism to generate across-the-board liquidity for supply-side activities. Supply-side traders require execution of positions at current bid–ask prices, causing bid–ask spreads to widen and depth to decline. Consequently, large supply-side option orders challenge the ability of a potentially thin market across option characteristics to consistently provide liquidity. Thus, options markets need a deeper analysis of liquidity than that provided by examining stocks. Our examination of option HFMM activity provides such an analysis.

Our study contributes to two related strands of academic literature: (1) the broad impact of electronic trading on financial markets, and (2) the specific impact of option market making on liquidity. The literature on the impact of electronic and high-frequency trading in general is still at its infancy (see Hasbrouck and Saar [2013] for stocks). In addition, the area of option market liquidity is a relatively nascent area compared to liquidity research on the equity and debt markets (Cao and Wei [2010]; Goyenko, Ornthanalai, and Tang [2014]). The benefit of examining exchange-traded options is that it provides a natural laboratory for studying how the quotation and trading mechanisms affect market liquidity, given the large number of option characteristics (Mayhew [2002]). Thus, our examination of high-frequency market making is relevant, including investigating the coincident effect of the introduction of penny quotes in 2007 on options market liquidity.

Exhibit 1 shows our preliminary evidence on the growth in quote revisions on the options markets for our analysis period of 2006 to 2008. The existence and growth of quote revisions is obviously significant in 2007 and increases in 2008. We examine the relation between market maker quote revisions and liquidity by analyzing the bid–ask spread and the best bid–ask depth values from the Options Price Reporting Authority (OPRA) data feed. We employ the rate of electronic message traffic as a proxy for the amount of market-making quote revisions taking place, since option quote revisions are directly associated with market maker activity.[3] In our analysis we differentiate between call and put options, and among in-, near-, and out-of-the-money options.

## EXHIBIT 1

**Growth in OPRA Option Message Traffic per Month in Billions of Messages**



We also provide separate results according to underlying stock capitalization, option volume, and stock volatility quintiles. Given the substantial liquidity differences among the various options groupings and characteristics, we have the advantage of providing more definitive conclusions concerning liquidity for options than exists for stock algorithmic trading, thereby determining the benefits of non-human intervention on bid–ask spread and depth over the range of these characteristics. In fact, Christoffersen et al. [2014] showed that the degree of liquidity affects the size of the option bid–ask spread, thus supporting the importance of examining different strike price categories (also see George and Longstaff [1993]).

We find broad evidence to support the benefits of option HFMM to reduce the bid–ask spread measure of liquidity for options; our results help to clarify the role of depth related to high-frequency markets. We extend our analysis by employing the introduction of penny quotes for certain options classes to examine the interrelated effects of a new option tick size with high-frequency option quote revisions on liquidity, which is especially beneficial to explain the behavior of depth. Moreover, our spread and depth analysis of the different options-specific characteristics provides unique results concerning the breadth of liquidity in options markets. We also find differential impacts from the underlying asset capitalization and volatility, as well as from options volume, on the option bid–ask spread and depth. Thus, we provide evidence concerning liquidity commonalities in the options market. Overall, our results add to the developing literature on options liquidity and substantiate the beneficial liquidity effects of HFMM (see Vijh [1990]; Cao and Wei [2010]; Christoffersen et al. [2014]). Consequently, we show the importance of considering the benefits of electronic quotation procedures and trading before imposing regulatory restrictions on such activities, especially for complex markets such as options.

## ELECTRONIC AND HIGH-FREQUENCY TRADING RESEARCH

An initial area of electronic and high-frequency trading research was the examination of trading characteristics and strategies, especially the effect of speed of transmission on the markets and the effect of reducing latency, although this research employed only stocks.[4] Another area of research is the impact high-frequency trading has on the market environment, such as information dissemination, price discovery, and volatility (again with stocks).[5] However, it is critical to emphasize that both of these branches of research examine equity markets only, which are order driven, whereas our study is on quote driven option markets.

Only two market quality studies using options exist. Cao and Wei [2010] showed the existence of a material common liquidity factor in the options market, although they do not relate this common factor to high-frequency trading; thus, option liquidity does have a factor that flows across the option-specific characteristics of an option series and affects the different categories such as calls and puts to differing extents. Goyenko, Ornthanalai, and Tang [2014] examined factors affecting market makers in determining option spreads and found that hedging-related costs, option demand pressures, and information asymmetry all increase spreads. Alternatively, we examine how high-frequency market making can offset these costs.

Research on liquidity emphasizes how high-frequency trading in general affects the bid–ask spread and depth of markets, particularly for equity markets. Hendershott, Jones, and Menkveld [2011] conducted a parallel study to ours involving stocks wherein they examined message traffic (attributed to algorithmic traders) and stock market liquidity, finding lower bid–ask spreads with greater message traffic but varying patterns for depth versus the number of messages. However, they only found a significant relation between liquidity and quote messages for their largest two (one) quintiles of firm size for price spread (depth).[6]

In conclusion, the research to date on high-frequency and algorithmic trading is centered on equities and futures markets. Such research provides a foundation for the association between high-frequency trading and liquidity, especially regarding the bid–ask spread and depth. However, our article examines a different market (options) with a much richer environment of characteristics and a market centered on market maker quote activity rather than algorithmic strategy trading. Moreover, options research can shed light on the indirect consequences of equity algorithmic trading, since high-frequency quote revisions in options markets are affected by high-frequency stock trading.

## DATA

Options microstructure research provides several challenges related to data structure. First, the number of strike prices and expiration dates exponentially multiplies the number of data series, with the different strikes/expirations possessing differing price response characteristics. Second, the number of quote revisions has geometrically increased since the development of electronic markets, creating data analysis issues. Finally, data availability for all quotations for all stock options for all exchanges is limited. Thus, unlike the rich body of literature supported by organized equity microstructure data, the dearth of comprehensive options microstructure research reflects a lack of similar data for listed options.

The data for this study originate with the Options Price Reporting Authority (OPRA) data feed. The OPRA feed consists of trade execution as well as the best bid and offer quotes and associated sizes from each of the seven U.S. equity options exchanges. OPRA flags each quote with an indicator stating the quote's bid–ask relative to the national best bid and offer (NBBO). We employ the Baruch Options Data Warehouse database of options, which processes the full OPRA feed and generates data extracts and statistics on trade and quote messages.

This article considers data for the calendar years 2007 and 2008, representing 2,328,185 unique options *series* on 5,100 underlying equities, exchange traded funds (ETFs) and indexes. The two years of data contain 311,567,675 trades and approximately 1.3 trillion quotes, requiring 65 terabytes of disk storage. The analysis is completed only on the shorter-term expirations. Trades and quotes for each stock (and ETF) used in this study are summarized according to standard microstructure metrics into daily data. We focus on 2007 and 2008 because the frequency of quote activity for options markets increased significantly starting in 2007 (as shown in Exhibit 1), whereas 2008 provides a unique opportunity to examine how the growth of quote activity and an increase in volatility affect both the spread and depth of options markets and to examine the interactive effects on liquidity of a change in tick size (to penny quotes) in relation to quote activity.

We compute the percentage and quoted spreads for each option series for each stock employed in this study by identifying the NBBO bid–ask spread for each new quote over each trading day. We further calculate the total dollar value traded for each option series. In this process we use the traditional filters for spreads and depth.[7] The data on market capitalization and equity returns (the latter for the calculation of the daily volatility) are obtained from COMPUSTAT and CRSP, respectively. Data are sorted into groups to examine the effect of capitalization, option volume, and stock volatility.[8] For each sorted group, the first quintile represents stocks with the highest values for that variable, whereas the fifth quintile represents stocks with the lowest quintile values. For each sort we classify the option series into call and put options and further into in-, near- and out-of-the-money options.[9]

We designate the previous sample as the general sample; we exclude from the general sample stocks that change to penny quotes during the time period of this analysis in order to provide inferences on the impact of quote revisions independent of the effects of the penny pilot activity. A subsequent section describes the procedure to examine the penny quote sample.

## LIQUIDITY MEASURES, METHODOLOGY, AND POTENTIAL LIQUIDITY CONSEQUENCES

Our experimental design employs the number of quotes as an accurate representation of market maker activity to study this activity's impact on liquidity since quote changes for options are associated with market makers. We also include the introduction of penny quotes as an exogenous instrument to examine the interaction of quote activity and a change in tick size.

### Liquidity, Market Maker Activity, and Control Measures

We examine the relation between the number of quotes (message traffic) and both the bid–ask spread and depth measures of liquidity by employing cross-sectional panel regressions, while controls are established for the underlying firm size, volatility of the underlying stock, and the dollar volume of option trading.[10] We employ every intraday NBBO bid–ask quote and depth observation and accumulate this data into the number of daily messages and related liquidity values for each of the option-specific characteristics. The percentage spread for each quote is calculated as:

$$Percentage\ Spread = \left( \frac{[Ask - Bid]}{0.5\,[Ask + Bid]} \right)(100) \qquad (1)$$

where the bid and ask prices are the NBBO values. The percentage spread is referred to as the *quoted spread* in this article. Depth is calculated as:

$$Depth = \left( \frac{[Best\ Ask\ Size + Best\ Bid\ Size]}{2} \right) \qquad (2)$$

We employ the Garman–Klass (Garman and Klass [1980]) measure to calculate the daily stock volatility:

$$Vol_{GK} = \frac{1}{2}[\ln(High) - \ln(Low)]^2 - [2\ln(2) - 1][\ln(Open) - \ln(Close)]^2 \qquad (3)$$

The Garman–Klass measure allows for an examination of volatility within a time interval as opposed to the traditional measures that examine volatility between or across intervals. The Garman–Klass measure is eight times more efficient than using a close-to-close measure of volatility, with efficiency referring to the reduction in the error of the estimate.

### Potential Liquidity Consequences of High-Frequency Market-Maker Quote Revisions

Previous studies on the relation between high-frequency trading and liquidity implicitly suggest, but do not directly state, basic hypotheses for liquidity and trade/quote activity. We present four potential liquidity consequences (*outcomes*) of the impact of high-frequency market-maker quote activity on options markets.

**Outcome I.** An increase in the message traffic in options markets decreases the bid–ask spread. Outcome I relies on the economically consistent effect of increased quote activity of option market makers, with control variables for market capitalization, volume, and the underlying stock volatility.

**Outcome II.** The sign and significance of the relation between message traffic and the bid–ask spread is consistent across stock quintiles, calls and puts, and option strike prices and expirations. Outcome II states the hypothesis that the effect of market maker activity on the bid–ask spread is consistent regardless of the factor. Such a conclusion reflects an efficient market. Thus, this study extends the literature by examining the consistency of the decrease in the bid–ask spread across differing sizes of firms, option activity, and underlying stock volatility, as well as for different option-specific characteristics.

Previous studies examining the relation between message traffic and depth have generated conflicting results, both across and within studies (see Hendershott, Jones, and Menkveld [2011] and Karagozoglu [2011]). We state our expectation of the relation in terms of a positive coefficient between message traffic and depth in order to be consistent with the option market design. Our expectation is based on the following economic logic: Options market makers adjust their option *prices* in relation to the underlying stock price. In fact, market makers possess low-cost benefits for placing orders, encouraging them to make a market; these incentives are consistent with this study's focus on high-frequency market making. Moreover, they change their quoted option *sizes* in relation to their underlying (desired) hedged inventory size. Such a procedure allows them to remain delta neutral in their positions. However, this can be overshadowed by supply and demand factors if the market-making firm possesses other positions it needs to (cross) hedge (see Battalio, Hatch, and Jennings [2004] on the microstructure characteristics of options markets). Finally, an increase in depth can occur if market makers place duplicate orders on different exchanges (van Kervel [2012]). These observations provide the following potential outcomes.

**Outcome III.** An increase in the message traffic in options markets increases the depth of the options market.

**Outcome IV.** The sign and significance of the relation between message traffic and depth is consistent across stock quintiles, calls and puts, and option categories (strikes).

A conclusion opposite to this was reached by Hendershott, Jones, and Menkveld [2011], who argued that depth for stocks can *decrease* as the number of messages increases due to the slicing and dicing of orders by institutional algorithmic trading programs. Their results on depth, however, are inconclusive due to inconsistencies across the different equity quintiles. Karagozoglu [2011] disagreed with Hendershott, Jones, and Menkveld by reporting a positive depth–algorithmic trading relation for futures (except when volatility increases, in which case depth declines), although he does not provide a justification for these results. Our results and analysis of the relation between message traffic and depth helps to clarify the direction of this relation for the options market.

### Panel Regressions

For the general sample we estimate the following generalized method of moments (GMM) regression for each category as follows:

$$l_{it} = \alpha_i + \beta_i A_{it} + \delta_{it} X_{it} + \varepsilon_{it} \quad (4)$$

where $l_{it}$ is the liquidity variable (either the bid–ask spread or the depth), $A_{it}$ is the message traffic arising from the quote revision, and $X_{it}$ is the set of control variables (i.e., market capitalization, the volatility of the underlying stock, and the dollar trading volume of the options).

We conduct our tests of option-quote revision in two parts. We first examine the relation between message traffic and liquidity for the general sample of options. For this analysis we exclude the penny quote options so as to provide inferences concerning message traffic and market quality of options independent of the consequences of moving to penny quotes. The second part of the analysis examines the effect of quote revision and penny quotes on the liquidity variables by employing the 30 days before and after the three phases of penny quote implementation on an industry-determined select sample of large stocks whose stock option quotes changed to pennies.

### The Penny Pilot as an Integrative Analysis and Robustness Check

For the three phases of the penny pilot analysis we design a model that provides us the opportunity to examine the integrated effect quote revisions and a change in tick size while functioning as a robustness check for the general sample. Options affected by the introduction of penny quotes in 2007 and 2008 should a priori decrease the bid–ask spread substantially, given the smaller tick size available. Although the effect on depth a priori would be to provide less depth at the best bid–ask size, since traders can spread their limit orders over more quotation points, the effect of market maker activity is unclear. Thus, a related question is whether market-maker quote activity affects the liquidity variables independently of the change in tick size. We examine this issue by both determining the before/after regressions of the implementation of penny quotes and the interaction indicator variable regressions. To examine the effect of the change to penny quotes and therefore separate the quoting size from the quote frequency we use the "difference-in-difference approach" used in the literature. We employ what is given on the UCLA website.[11] Thus, we introduce an interaction dummy that is the product of message traffic and the dummy variable for indicating whether it is before or after the penny pilot. Essentially, the interaction dummy will show the difference before and after the penny pilot in the relation between the liquidity proxy, such as the spread or depth, and the message traffic. This way, for the same group of options, the difference in the strength of the relation between liquidity and message traffic (HFMM) is tested.

Although the original reason to change to penny quotes was not related to high-frequency activity, a smaller tick size theoretically should create more frequent quote messages for options with penny quotes since more option price points are available as underlying stock prices change, especially for the more active stock options that were the beneficiaries of the original penny pilot experiment (Saraoglu, Louton, and Holowczak [2014]). In general, frequent underlying asset price revisions are especially crucial for options in terms of the number of quote revisions.

Our initial approach to verifying the relevance of HFMM activity is to explore the relation between message traffic and option market liquidity by analyzing the option penny quote data before and after the initiation of the new tick size. The separation of the general sample and the penny quote sample provides the opportunity to interpret these results and present inferences independently. Note that the transition to option penny quotes occurred in three phases during this time period; we examine each phase independently.

In addition to applying Equation (4) to the before and after periods of the penny quote initiation, we also estimate the following regression, which includes an indicator variable (as well as the typical before/after time dummy variable) for the sample with penny quotes:

$$l_{it} = \alpha_i + \gamma_t + \beta_i A_{it} + \delta_i X_{it} + \lambda_i INT_{it} + \varepsilon_i \quad (5)$$

where $l_{it}$, $A_{it}$, and $X_{it}$ are defined as in Equation (4). Equation (5) includes the additional variable $\gamma_t$ to represent the time dummy variable for before versus after each set of penny quotes were introduced. The variable $INT_{it}$ is defined as the interaction indicator variable that is a product of the message traffic variable and the time dummy variable. The coefficient on this interaction indicator variable describes the difference in the message traffic coefficient after the penny quote is initiated relative to the coefficient before the penny quote is initiated. Thus, we can show the change in the impact of high-frequency quote revisions on liquidity following the change in tick size. As with the general sample, Equation (5) is determined using the GMM procedure, and the variables are measured equivalently.

## RESULTS

Exhibit 2 provides the basic statistics for the call and put options in the general sample. The data are separated by option-specific characteristics (in-, near-, and out-of-the-money), and averages are provided for each option volume-sized quintile for the spread; depth; number of quotation messages; and the control variables of market capitalization, volatility, and volume. The average percentage quoted spread is smallest for the in-the-money options, next largest for the near-the-money options, and largest for the out-of-the-money options. This is consistent with the size of the prices for these categories.

Alternatively, the absolute size of the higher-priced, in-the-money spreads is larger due to less demand, which also causes these options to have fewer messages, since larger spreads mean the underlying stock prices must move more for the fair option price to be outside the existing spread. In addition, in-the-money options are less frequently traded given their high cost, lower leverage, and lower liquidity. Moreover, the spread generally increases substantially for the higher-numbered (smaller volume) stock quintiles. An interesting characteristic of these results is that the spreads are almost always higher for 2008 compared to 2007 for the same quintile/option category, especially for the call options, thus showing the effect of volatility. Spreads for smaller market cap equity quintiles in 2008 versus 2007 (not shown here), however, are narrower or reversed, implying that the financial crisis in 2008 affected the liquidity of options on the larger market cap stocks more than the smaller ones.

The depth measures shown in Exhibit 2 are substantially higher for quintile 1, which is associated with greater interest in these more active options. The depth is much smaller for the higher quintiles. Moreover, the near-the-money options possess the largest depth for quintiles 1 to 3 relative to the other strike categories. In general, the depth is similar for the different quintiles/calls/puts for 2007 and 2008, although quintile 1 does have a larger depth during 2008.

The number of quotation messages is substantially higher for the first quintile relative to the other quintiles, which is consistent with the underlying stocks for this quintile representing the largest and most active stocks/options. The number of messages substantially increases from 2007 to 2008 for most comparisons, although less than expected given the large increase in volatility during 2008 and the lower than expected growth in quotation activity during that time period.[12]

In terms of the control variables, market capitalization remains relatively stable across the two-year period for individual quintiles. The volatility for 2008 increases by a factor of six for the first quintile, and large increases exist for all but quintile 5 (which experiences a decrease). Alternatively, the behavior of option dollar volume is inconsistent. Option volume declines substantially in 2008 for quintile 1 for all categories other than the out-of-the-money puts.[13] This decline of option activity for quintile 1 during 2008, coupled with minimal volume size changes for the other quintiles, shows the special nature of the largest stock options in general and for 2008. Therefore, quintile 1 receives special attention in this analysis.

Generally, the spreads are substantially larger during the fall of 2008 compared to the 2008 data in Exhibit 2, with the exception of the largest two quintiles for puts, as would be expected during times of high volatility. Moreover, depth is smaller for the same two largest put quintiles. Alternatively, the number of messages is substantially larger in the fall of 2008 for all quintiles for both calls and puts.

The correlation matrix for the quoted spread (available upon request) shows a significant and consistently negative relation between the spread and message traffic, with larger negative correlations for the out-of-the-money options. The largest (negative) correlations exist between the spread and volume for the (active)

## EXHIBIT 2
**Summary Statistics for the General Sample**

**Panel A: Calls**

| | | CALLS 2007 | | | | | CALLS 2008 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Q1 | Q2 | Q3 | Q4 | Q5 | Q1 | Q2 | Q3 | Q4 | Q5 |
| Quoted Spread | In | 0.0291 | 0.0487 | 0.0912 | 0.1222 | 0.2391 | 0.0543 | 0.0949 | 0.1529 | 0.1623 | 0.2782 |
| | Near | 0.0713 | 0.1774 | 0.2942 | 0.4588 | 0.6599 | 0.1029 | 0.2398 | 0.3798 | 0.4939 | 0.6778 |
| | Out | 0.2287 | 0.4384 | 0.5535 | 0.7460 | 1.1499 | 0.3100 | 0.5404 | 0.7761 | 1.0172 | 1.224 |
| Quoted Depth | In | 152 | 76 | 42 | 41 | 17 | 213 | 80 | 50 | 44 | 30 |
| | Near | 308 | 141 | 59 | 39 | 23 | 399 | 170 | 77 | 46 | 40 |
| | Out | 293 | 131 | 46 | 31 | 29 | 347 | 104 | 54 | 39 | 26 |
| Quotation Messages | In | 35,538 | 8,119 | 4,544 | 1,962 | 1,069 | 35,580 | 10,483 | 4,276 | 2,546 | 1,612 |
| | Near | 39,580 | 7,356 | 3,126 | 1,055 | 1,292 | 47,233 | 10,046 | 4,224 | 1,897 | 1,163 |
| | Out | 27,510 | 4,351 | 1,699 | 886 | 2,182 | 31,874 | 6,201 | 2,932 | 1,398 | 1,057 |
| Market Cap | In, Near, Out | 16.93 | 14.93 | 13.96 | 12.69 | 13.13 | 16.38 | 14.79 | 13.78 | 13.12 | 12.70 |
| Volatility | In, Near, Out | 11.54 | 12.88 | 11.73 | 34.22 | 72.83 | 68.00 | 41.47 | 37.87 | 63.05 | 64.59 |
| Volume | In | 1043.3 | 332.8 | 133.8 | 181.0 | 41.1 | 584.6 | 330.3 | 334.0 | 127.2 | 563.6 |
| | Near | 2019.6 | 171.6 | 157.7 | 55.7 | 58.7 | 1331.8 | 191.9 | 72.7 | 42.5 | 30.7 |
| | Out | 851.0 | 62.3 | 59.8 | 22.6 | 25.6 | 600.6 | 77.6 | 29.1 | 21.5 | 13.5 |

**Panel B: Puts**

| | | PUTS 2007 | | | | | PUTS 2008 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Q1 | Q2 | Q3 | Q4 | Q5 | Q1 | Q2 | Q3 | Q4 | Q5 |
| Quoted Spread | In | 0.0329 | 0.0728 | 0.2071 | 0.3130 | 0.2760 | 0.0510 | 0.0999 | 0.1389 | 0.1707 | 0.3213 |
| | Near | 0.0751 | 0.1794 | 0.3156 | 0.4215 | 0.6111 | 0.0892 | 0.2128 | 0.3318 | 0.4362 | 0.6045 |
| | Out | 0.2309 | 0.4425 | 0.7069 | 0.8435 | 1.0075 | 0.2452 | 0.4437 | 0.6199 | 0.8719 | 1.2613 |
| Quoted Depth | In | 173 | 108 | 54 | 35 | 33 | 286 | 99 | 50 | 43 | 38 |
| | Near | 353 | 150 | 55 | 37 | 25 | 444 | 182 | 70 | 47 | 37 |
| | Out | 339 | 122 | 30 | 33 | 16 | 362 | 98 | 50 | 43 | 22 |
| Quotation Messages | In | 37,372 | 8,896 | 4,183 | 1,118 | 1,506 | 37,651 | 10,668 | 4,998 | 2,451 | 1,710 |
| | Near | 37,179 | 7,024 | 3,272 | 1,142 | 1,172 | 44,397 | 9,910 | 4,336 | 2,082 | 1,330 |
| | Out | 23,451 | 3,678 | 1,449 | 2,224 | 1,401 | 28,092 | 5,502 | 2,649 | 1,066 | 1,078 |
| Market Cap | In, Near, Out | 16.93 | 14.93 | 13.96 | 12.69 | 13.13 | 16.38 | 14.79 | 13.78 | 13.12 | 12.70 |
| Volatility | In, Near, Out | 11.54 | 12.88 | 11.73 | 34.22 | 72.83 | 68.00 | 41.47 | 37.87 | 63.05 | 64.59 |
| Volume | In | 1826.0 | 329.3 | 210.8 | 106.4 | 76.3 | 941.3 | 363.9 | 363.2 | 125.0 | 49.1 |
| | Near | 1870.6 | 217.8 | 95.5 | 52.0 | 33.0 | 1579.3 | 211.0 | 104.4 | 53.4 | 29.5 |
| | Out | 726.0 | 100.4 | 32.3 | 22.4 | 5.9 | 760.7 | 77.7 | 63.8 | 20.1 | 11.8 |

*Notes: Using the option codes to identify the underlying stocks, we divide the data into call and put options and then into in-, near-, and out-of-the-money strikes. This exhibit provides daily averages for each variable for the general sample for 2007 and 2008. Here we group/rank the options into five quintiles based on their option dollar volume of trading. For each quintile we then provide averages for the quoted spread, quoted depth, number of quotation messages, Garman–Klass volatility, stock market capitalization, and dollar option volume for each quintile for the in-, near-, and out-of-the-money options. The values for the market capitalization and volatility variables are equivalent for the in-, near-, and out-of-the-money categories since they are based on the underlying stocks. Dollar option volume is the average per strike for each stock in the category and then divided by 100 (the strikes include those without a trade but with a quote).*

out-of-the-money options. Interestingly, a positive relation exists between the number of messages and depth size for the in- and near-the-money options, and a negative relation exists for the out-of-the-money options. Consequently, the separation of options into strike categories does provide populations with different characteristics, justifying our examination of the option-specific characteristics generated in this article.

## The Effect of High-Frequency Quote Revisions on Spreads

This section examines the bid–ask spread results using the GMM regressions for the 2007 and 2008 general sample, with the goal of understanding the effects of market-maker activity on the liquidity of options. Exhibits 3 and 4 provide the bid–ask spread results sorted separately into quintiles by using each of the control variables for each option strike price category for 2007 and 2008, respectively.[14] These exhibits show that the percentage spread decreases with increasing message traffic, with these decreases existing for all strike categories and for both years when we use the market capitalization sort.[15] These results support liquidity Outcomes I and II—that is, market-making activity is related to both the decrease in bid–ask spreads and the consistency of the bid–ask results across the option specific characteristics. The number of messages is substantially smaller for the smaller capitalization firms (i.e., quintiles 2 to 5), which is related to larger reported per unit negative coefficient values for these quintiles. Consequently, as one moves from quintile 1 to quintile 5 the effect of an additional message generally has a greater effect on reducing the spread, although sometimes insignificant for quintile 5. In addition, the statistical significance of the message traffic variable is almost always larger for the larger firms, showing that the consistency and reliability of the results is stronger for quintile 1. Finally, the decrease in the size of the spread associated with the increase in message traffic is significant for all but five of the 60 quintile/option category regression coefficients for the market cap category.

The volume ranking by quintiles shows the same general negative spread versus message traffic relation as that in the market capitalization results, as well as a decline in significance from the highest volume quintile to the lower quintiles. However, quintiles 4 and 5 for the volume ranking are mostly insignificant or even possess positive coefficients, most likely due to the low option volumes in these groups in conjunction with fewer quote revisions (see Exhibit 2).

Finally, Exhibits 3 and 4 also show that the spread declines as message traffic increases for the volatility sorted groups. However, a single pattern for changes in the significance level for this sort does not emerge for these volatility results, especially for the out-of-the-money and near-the-money options. These results are consistent with the highest volatility group (quintile 1) representing active options from the highly volatile smaller cap stocks, where these stocks would be more diverse in terms of volume activity and in their response to option market-making activity (Exhibit 2), whereas the lowest volatility group in quintile 5 would represent larger capitalized firms whose stocks and options are more liquid and less volatile. What is interesting is that research on stocks associate higher volatility with larger spreads, implying that the highest volatility stocks in quintile 1 should benefit more from HFMM activity (see Stoll [2000] and Chung and Kim [2009]), which does occur in 9 of the 12 cases. We also find that the volatility sorted results are consistent because the spread effect is larger for quintile 1 than for quintile 5.

In general, the decline in spreads in Exhibits 3 and 4 is consistent with the results of Hendershott, Jones, and Menkveld [2011] for stocks and Karagozoglu [2011] for futures, although ours is associated with market makers and theirs with an increase in algorithmic trading activity. However, our results are more robust, since we are able to separate the options sample into the type of options (calls, puts), types of strikes (in-, near-, and out-of-the-money), and into quintiles by the three sorting criteria. Thus, our results emphasize the difference for options from larger versus smaller stocks and the interesting effects of volatility sorts on the strength of the spread results. In conclusion, the evidence here shows that severe restrictions on electronic market activity, and therefore on the high-frequency quote revision process, could impose artificial constraints on markets, resulting in adverse effects on the bid–ask spread of options.

## The Effect of High Frequency Quote Revisions on Depth

Depth as a measure of liquidity has received minimal attention in the literature. In particular, only Hendershott, Jones, and Menkveld [2011] and Karagozoglu [2011] examined the role of depth in relation to electronic message traffic. Hendershott, Jones, and Menkveld found that depth *declines* as high-frequency trading increases for stocks, whereas Karagozoglu actually determined that depth *increases* with algorithmic trading for futures markets. The reasoning by Hendershott, Jones, and Menkveld is that their decreasing relation is based on the smaller order size created by certain algorithmic strategies, although such evidence is anecdotal.

# EXHIBIT 3

## Regression Coefficients for the Effect of Market-Maker Quote Revisions on Bid–Ask Spreads (2007)

| Group/Sorting Criteria | Q1 | Q2 | Q3 | Q4 | Q5 | Market Cap | Volume | Volatility |
|---|---|---|---|---|---|---|---|---|
| **CALLS (IN) 2007** | | | | | | | | |
| Quoted Spread for Market Cap | **–0.0001** | **–0.0011** | **–0.0024** | **–0.0049** | –0.0022 | –3.95 | –0.21 | 0.19 |
| | (–14.40) | (–13.44) | (–14.63) | (–15.52) | (–0.97) | (–28.53) | (–2.67) | (10.57) |
| Quoted Spread for Volume | **–0.00005** | **–0.0004** | **–0.0099** | 0.0078 | **0.0414** | –2.50 | 0.40 | 0.18 |
| | (–6.72) | (–7.01) | (–6.87) | (1.34) | (2.44) | (–28.64) | (6.18) | (13.49) |
| Quoted Spread for Volatility | **–0.0005** | **–0.00005** | **–0.0003** | **–0.0001** | –0.00004 | –12.36 | –1.06 | 0.47 |
| | (–17.12) | (–3.26) | (–12.18) | (–8.34) | (–1.15) | (–16.43) | (–4.05) | (2.69) |
| **CALLS (NEAR) 2007** | | | | | | | | |
| Quoted Spread for Market Cap | **–0.0007** | **–0.0014** | **–0.0115** | **–0.0234** | –0.0062 | 3.09 | –37.96 | 0.91 |
| | (–20.20) | (–8.97) | (–24.93) | (–18.71) | (–1.75) | (2.65) | (–43.56) | (7.73) |
| Quoted Spread for Volume | **–0.0006** | **–0.0064** | **–0.0300** | **–0.0500** | 0.0082 | 4.93 | –16.11 | 0.36 |
| | (–20.81) | (–18.20) | (–10.35) | (–5.12) | (1.25) | (5.91) | (–14.83) | (10.38) |
| Quoted Spread for Volatility | **0.0011** | 0.00008 | 0.0001 | **–0.0002** | **0.0004** | –34.60 | –71.82 | 1.44 |
| | (7.03) | (1.24) | (0.94) | (–2.80) | (3.28) | (–16.28) | (–39.86) | (6.45) |
| **CALLS (OUT) 2007** | | | | | | | | |
| Quoted Spread for Market Cap | **–0.0016** | **–0.0027** | **–0.0337** | **–0.0516** | –0.0015 | 24.52 | –107.51 | 2.29 |
| | (–17.75) | (–7.31) | (–13.96) | (–5.05) | (–0.21) | 11.74 | (–85.35) | (11.06) |
| Quoted Spread for Volume | **–0.0021** | **–0.0200** | **–0.0600** | **–0.0200** | **0.0035** | 25.63 | –102.32 | 1.95 |
| | (–23.40) | (–14.77) | (–4.47) | (–3.32) | (3.13) | 16.16 | (–73.41) | (12.89) |
| Quoted Spread for Volatility | **–0.0012** | **–0.0008** | **–0.0043** | **–0.0011** | **–0.0016** | –4.51 | –141.23 | 0.91 |
| | (–2.67) | (–7.51) | (–10.56) | (–4.95) | (–4.32) | (–1.17) | (–58.20) | (1.76) |
| **PUTS (IN) 2007** | | | | | | | | |
| Quoted Spread for Market Cap | **–0.0002** | **–0.0010** | **–0.0025** | **–0.0075** | **–0.0181** | –3.97 | –5.14 | 0.09 |
| | (–12.91) | (–12.35) | (–11.22) | (–5.91) | (–3.72) | (–12.14) | (–6.94) | (8.41) |
| Quoted Spread for Volume | **–0.0001** | **–0.0026** | **–0.0148** | 0.0120 | 0.0201 | –0.38 | –1.24 | 0.11 |
| | (–6.59) | (–7.65) | (–4.31) | (1.19) | (0.74) | (–1.70) | (–3.46) | (9.96) |
| Quoted Spread for Volatility | **–0.0005** | **–0.0001** | **–0.0004** | **–0.0005** | –0.00008 | –25.15 | –20.76 | –0.09 |
| | (–7.48) | (–5.58) | (–6.71) | (–6.84) | (–1.46) | (–11.05) | (–8.64) | (–0.47) |
| **PUTS (NEAR) 2007** | | | | | | | | |
| Quoted Spread for Market Cap | **–0.0006** | **–0.0014** | **–0.0113** | **–0.0208** | **–0.0194** | 0.94 | –34.35 | 0.65 |
| | (–20.48) | (–8.99) | (–16.95) | (–15.97) | (–4.17) | (0.87) | (–36.16) | (8.49) |
| Quoted Spread for Volume | **–0.0005** | **–0.0054** | **–0.0300** | –0.0143 | 0.0111 | 4.32 | –16.47 | 0.32 |
| | (–20.32) | (–14.75) | (–8.56) | (–1.74) | (1.33) | (5.44) | (–14.83) | (8.64) |
| Quoted Spread for Volatility | **–0.0003** | 0.00001 | **–0.0003** | **–0.0003** | **0.0005** | –15.81 | –55.47 | 0.31 |
| | (–2.60) | (0.16) | (–2.58) | (–3.43) | (4.15) | (–7.78) | (–30.57) | (1.45) |
| **PUTS (OUT) 2007** | | | | | | | | |
| Quoted Spread for Market Cap | **–0.0015** | **–0.0014** | **–0.0209** | **–0.0609** | –0.1092 | 6.89 | –95.98 | 1.76 |
| | (–17.36) | (–3.77) | (–6.30) | (–6.02) | (–1.73) | (3.80) | (–75.36) | (12.39) |
| Quoted Spread for Volume | **–0.0017** | **–0.0200** | **–0.1318** | –0.0011 | –0.0243 | 9.87 | –92.64 | 1.55 |
| | (–20.51) | (–5.58) | (–5.45) | (–0.10) | (–0.39) | (6.78) | (–69.34) | (14.30) |
| Quoted Spread for Volatility | **–0.0033** | **–0.0013** | **–0.0048** | **–0.0013** | **–0.0014** | –15.92 | –108.89 | 5.74 |
| | (–6.54) | (–9.87) | (–9.31) | (–6.41) | (–5.21) | (–2.89) | (–38.54) | (6.93) |

*Notes: This exhibit regresses the quoted spread on a proxy for market-maker quote revisions (message traffic) and the three control variables of market capitalization, Garman–Klass volatility of the underlying stock, and the dollar volume of the stock's options for the general sample from 2007. The control variable values given here are for quintile 1. The specification is: $l_{it} = \alpha_i + \beta_i A_{it} + \delta_{it} X_{it} + \varepsilon_{it}$, where $l_{it}$ is the liquidity variable (quoted spread in this exhibit), $A_{it}$ is the message traffic, and $X_{it}$ is the set of control variables. Option volume is the logarithm of the average volume per strike for each stock and after dividing by 100. We multiply the coefficients on the message traffic variable are by 1,000 to reduce the number of decimal places.*

*Significant coefficients at the 5% level or better are in bold.*

# Exhibit 4

**Regression Coefficients for the Effect of Market-Maker Quote Revisions on Bid–Ask Spreads (2008)**

| Group/Sorting Criteria | Q1 | Q2 | Q3 | Q4 | Q5 | Market Cap | Volume | Volatility |
|---|---|---|---|---|---|---|---|---|
| **CALLS (IN) 2008** | | | | | | | | |
| Quoted Spread for Market Cap | **–0.0006** | **–0.0025** | **–0.0007** | **–0.0020** | **–0.0085** | –17.14 | –5.62 | 0.13 |
| | (–26.16) | (–12.61) | (–14.10) | (–7.65) | (–4.04) | (–8.82) | (–5.85) | (12.31) |
| Quoted Spread for Volume | **–0.0004** | **–0.0014** | **–0.0063** | 0.0018 | 0.0123 | –4.03 | –0.58 | 0.19 |
| | (–19.89) | (–8.56) | (–5.46) | (1.56) | (1.19) | (–13.07) | (–1.47) | (5.90) |
| Quoted Spread for Volatility | **–0.0091** | **–0.0007** | **–0.0061** | **–0.0014** | **–0.0003** | –17.29 | –2.75 | 0.00 |
| | (–5.89) | (–11.06) | (–6.92) | (–8.72) | (–11.42) | (–1.62) | (–0.87) | (0.76) |
| **CALLS (NEAR) 2008** | | | | | | | | |
| Quoted Spread for Market Cap | **–0.0010** | **–0.0104** | **–0.0018** | **–0.0082** | **–0.0354** | –9.59 | –36.98 | 0.17 |
| | (–32.24) | (–29.41) | (–26.25) | (–12.82) | (–7.25) | (–4.68) | (–35.92) | (6.38) |
| Quoted Spread for Volume | **–0.0007** | **–0.0071** | **–0.0175** | **–0.0219** | –0.0026 | –3.99 | –13.70 | 0.13 |
| | (–43.85) | (–29.55) | (–14.32) | (–6.95) | (–0.43) | (–5.14) | (–18.67) | (4.48) |
| Quoted Spread for Volatility | **–0.0111** | **–0.0021** | **–0.0086** | **–0.0015** | **–0.001** | –282.57 | –61.42 | 0.00 |
| | (–3.83) | (–14.77) | (–9.97) | (–15.97) | (–10.63) | (–22.40) | (–10.84) | (–1.19) |
| **CALLS (OUT) 2008** | | | | | | | | |
| Quoted Spread for Market Cap | **–0.0033** | **–0.004** | **–0.0047** | **–0.0105** | **–0.0548** | 55.15 | –122.97 | 0.22 |
| | (–23.79) | (–26.94) | (–24.02) | (–10.24) | (–6.42) | (13.77) | (–93.79) | (11.25) |
| Quoted Spread for Volume | **–0.0031** | **–0.0222** | **–0.0376** | **–0.0500** | 0.0110 | 17.48 | –98.09 | 0.16 |
| | (–56.22) | (–23.45) | (–8.53) | (–2.31) | (0.87) | (12.63) | (–108.75) | (6.81) |
| Quoted Spread for Volatility | **–0.0200** | **–0.0025** | **–0.0326** | **–0.0066** | **–0.0048** | –232.16 | –123.37 | 0.00 |
| | (–3.24) | (–9.02) | (–6.19) | (–16.17) | (–12.17) | (–18.28) | (–18.81) | (–1.36) |
| **PUTS (IN) 2008** | | | | | | | | |
| Quoted Spread for Market Cap | **–0.0005** | **–0.0026** | **–0.0006** | **–0.0012** | 0.0041 | –7.43 | –6.92 | 0.02 |
| | (–17.86) | (–12.48) | (–7.39) | (–4.08) | (–1.18) | (–4.47) | (–8.53) | (5.47) |
| Quoted Spread for Volume | **–0.0004** | **–0.0011** | **–0.0013** | **0.0087** | **0.0074** | –1.24 | –6.12 | 0.01 |
| | (–16.79) | (–7.19) | (–2.80) | (2.11) | (4.38) | (–2.86) | (–8.46) | (4.77) |
| Quoted Spread for Volatility | **–0.0025** | **–0.0012** | **–0.0009** | **–0.0003** | **–0.0003** | –21.31 | –26.53 | 0.00 |
| | (–2.75) | (–10.75) | (–3.53) | (–5.28) | (–7.15) | (–4.67) | (–5.30) | (–1.63) |
| **PUTS (NEAR) 2008** | | | | | | | | |
| Quoted Spread for Market Cap | **–0.0007** | **–0.0091** | **–0.0015** | **–0.0052** | **–0.01339** | –16.75 | –25.22 | 0.05 |
| | (–29.47) | (–25.20) | (–23.83) | (–6.81) | (–2.28) | (–9.59) | (–30.62) | (4.81) |
| Quoted Spread for Volume | **–0.0006** | **–0.0060** | **–0.0121** | **–0.0219** | **–0.0200** | –1.90 | –10.57 | 0.03 |
| | (–40.12) | (–33.92) | (–12.57) | (–10.37) | (–3.05) | (–3.91) | (–18.56) | (3.80) |
| Quoted Spread for Volatility | **–0.0030** | **–0.0022** | **–0.0067** | **–0.0011** | **–0.0009** | 4.54 | –54.43 | 0.00 |
| | (–1.51) | (–16.91) | (–10.75) | (–12.58) | (–9.56) | (0.70) | (–13.62) | (3.68) |
| **PUTS (OUT) 2008** | | | | | | | | |
| Quoted Spread for Market Cap | **–0.0034** | **–0.0334** | **–0.0041** | **–0.0077** | **–0.0400** | 36.47 | –67.50 | 0.36 |
| | (–26.22) | (–16.03) | (–20.39) | (–6.93) | (–3.45) | (10.82) | (–50.45) | (12.93) |
| Quoted Spread for Volume | **–0.0026** | **–0.0217** | **–0.0400** | **–0.0618** | **–0.0443** | 4.84 | –73.65 | 0.24 |
| | (–54.59) | (–18.86) | (–6.47) | (–2.40) | (–2.54) | (4.91) | (–80.02) | (33.48) |
| Quoted Spread for Volatility | **–0.0800** | **–0.0032** | **–0.0140** | **–0.0070** | **–0.0046** | 62.71 | –90.06 | 0.00 |
| | (–3.17) | (–11.35) | (–10.83) | (–16.40) | (–10.40) | (0.91) | (–6.07) | (2.80) |

*Notes: The exhibit regresses the quoted spread on a proxy for market-maker quote revisions (message traffic) and the three control variables of market capitalization, the Garman–Klass volatility of the underlying stock, and the dollar volume of the stock's options for the general sample from 2008. The control variable values given here are for quintile 1. The specification is:* $l_{it} = \alpha_i + \beta_i A_{it} + \delta_{it} X_{it} + \varepsilon_{it}$, *where* $l_{it}$ *is the liquidity variable (quoted spread in this exhibit),* $A_{it}$ *is the message traffic, and* $X_{it}$ *is the set of control variables. Option volume is the logarithm of the average volume per strike for each stock after dividing by 100. We multiply the coefficients on the message traffic variable by 1,000 to reduce the number of decimal places.*

*Significant coefficients at the 5% level or better are in bold.*

Here, we provide evidence associated with the limited and conflicting results of depth in past research. In particular, the potential for depth to be reduced from frequent quote revisions is a potential adverse consequence of electronic markets that needs to be examined.

Our analysis of depth for options in Exhibits 5 and 6 shows that depth *increases* as the number of quote revisions increase for all of the in-the-money quintile 1 and 2007 near-the-money cases, across all sorting criteria. Positive coefficients also exist for two-thirds of the remaining depth regressions on message traffic, with the remaining negative coefficients not clustering by quintile.[16] Alternatively, the time series graphs made by Hendershott, Jones, and Menkveld show a consistent decline in the depth variable for 2001 and 2002 for all five quintiles, then a leveling off through 2005 (the end of their data), whereas Karagozoglu [2011] showed depth increasing with algorithmic trading and decreasing with volatility increases.

Our results for the general sample are in accordance with Outcome III (i.e., an increase in message traffic mostly increases depth rather than decreasing it); however, Outcome IV is not supported, as the results are not consistent among the various groupings. The penny pilot results for depth that are next examined provide a different perspective, namely how message activity relates to the size of the depth available in conjunction with a change in the tick size. We also discuss explanations of the inconsistent results in the literature in the subsequent discussion section.

### The Size of the Effect of High-Frequency Quote Revisions on Spread and Depth Values

Exhibit 7 examines the magnitude of the effect of quote revisions on spread and depth by multiplying the average number of messages from Exhibit 2 by the coefficient size in the volume ranked regressions in Exhibits 3 to 6. These results are needed since the coefficients for the larger quintiles are smaller due to the large number of daily messages. Thus, the results in Exhibit 7 provide the average absolute size effect by quintile. For spreads, quintiles 2 and 3 and the out-of-the-money options typically see the largest reduction in the size of the spread. Many of these sizes are large on an absolute basis. Panel B of Exhibit 6 provides the message effect on the of the depth size. Quintile 1 shows a large change in depth size, although this quintile already possessed a large average daily value of depth. The other quintiles have relatively small effects on depth size, although those effects are generally significant.[17]

### Effects of the Penny Pilot and High-Frequency Quote Revisions: Concepts

Next, we examine the effects of a change in tick size from nickels/dimes to pennies arising from the penny pilot experiment. An important element of this tick size change is its addition of an exogenous factor affecting the frequency and potentially the size of market maker orders. The penny pilot for options was a Securities and Exchange Commission (SEC) initiative to reduce the quote size for stock options with the most activity in order to decrease price spreads, provide better prices to retail customers (pricing efficiency), and reduce the payment for order flow. Phase I of the penny pilot program was adopted by six exchanges on January 26, 2007, and included 13 securities; Phase II of the penny pilot program began on September 28, 2007, and included 22 securities; and Phase III began on March 28, 2008, and covered 28 securities.

For our purposes, the introduction of penny quotes for the options market provides an opportunity to examine the effects of a factor that is exogenous to liquidity. In fact, in economic terms, penny quotations should adversely affect market makers. Moreover, the smaller tick size caused by penny quotes should create more quote changes, since options prices will change more frequently in conjunction with changes in the price of the underlying stock, especially for the more active stock options (American Stock Exchange [2007]). In our extended analysis of penny quotes, the indicator variable in the interrelated variable model (Equation (5)) separates the increase in quote revisions from the effect of the switch to penny quotes in order to determine the relative impact of these factors on spread and depth.

The introduction of the penny pilot introduces two new major factors affecting option liquidity. First, penny quotes increase the activity of institutional orders by allowing them to slice and dice their orders, since smaller-sized bid–ask quotes allow the placement of orders at (better) penny quotations. This activity, however, could create less depth at the best bid–ask price point, as typically traders would spread orders across multiple penny price points to hide their activity.

## EXHIBIT 5

**Regression Coefficients for the Effect of Market-Maker Quote Revisions on Depth (2007)**

| Group/Sorting Criteria | Q1 | Q2 | Q3 | Q4 | Q5 | Market Cap | Volume | Volatility |
|---|---|---|---|---|---|---|---|---|
| **CALLS (IN) 2007** | | | | | | | | |
| Quoted Depth for Market Cap | **0.0011** | **0.0013** | **0.0009** | **–0.0003** | **0.0211** | 54.32 | –1.59 | –0.34 |
| | (22.60) | (31.86) | (6.85) | (–2.00) | (8.95) | (40.27) | (–3.60) | (–7.20) |
| Quoted Depth for Volume | **0.0013** | 0.0001 | **–0.0017** | **0.0032** | –0.0006 | 40.79 | 0.99 | –0.25 |
| | (24.58) | (1.21) | (–4.40) | (2.17) | (–0.99) | (37.20) | (2.14) | (–5.94) |
| Quoted Depth for Volatility | **0.0011** | **0.0005** | **0.0031** | **0.0015** | **0.0041** | 7.97 | –1.65 | 1.65 |
| | (11.54) | (12.44) | (24.56) | (15.41) | (24.87) | (3.50) | (–2.73) | (1.90) |
| **CALLS (NEAR) 2007** | | | | | | | | |
| Quoted Depth for Market Cap | **0.0005** | **0.0020** | **0.0014** | 0.00008 | **0.0078** | 127.14 | 4.90 | –1.50 |
| | (7.02) | (27.11) | (14.39) | (0.30) | (2.95) | (47.31) | (6.25) | (–8.63) |
| Quoted Depth for Volume | **0.0005** | **–0.0006** | **–0.0036** | **0.0041** | –0.0003 | 89.38 | 18.43 | –1.29 |
| | (6.89) | (–4.95) | (–12.96) | (3.95) | (–1.89) | (35.83) | (20.59) | (–8.51) |
| Quoted Depth for Volatility | **0.0014** | **–0.0001** | **0.0056** | **0.0015** | **0.0046** | 30.63 | –1.20 | 2.65 |
| | (13.04) | (–3.61) | (23.18) | (10.70) | (16.56) | (24.80) | (–2.11) | (5.75) |
| **CALLS (OUT) 2007** | | | | | | | | |
| Quoted Depth for Market Cap | **–0.0003** | **0.0023** | **0.0022** | **0.0010** | 0.0034 | 127.91 | –17.40 | –0.79 |
| | (–4.59) | (17.48) | (8.02) | (2.04) | (1.46) | (40.23) | (–21.05) | (–8.12) |
| Quoted Depth for Volume | **–0.0009** | **0.0018** | **–0.0002** | 0.0006 | 0.00002 | 93.55 | –22.51 | –0.54 |
| | (–11.60) | (5.50) | (–7.48) | (1.02) | (0.40) | (35.97) | (–24.17) | (–6.65) |
| Quoted Depth for Volatility | **0.0014** | 0.00008 | **0.0066** | **–0.0003** | –0.0007 | 40.66 | –4.64 | 0.68 |
| | (9.23) | (1.72) | (15.42) | (–2.39) | (–1.82) | (26.38) | (–5.96) | (1.70) |
| **PUTS (IN) 2007** | | | | | | | | |
| Quoted Depth for Market Cap | **0.0009** | **0.0016** | **0.0006** | **–0.0001** | **0.0124** | 37.89 | –0.03 | –0.33 |
| | (14.84) | (32.34) | (3.78) | (–0.47) | (4.57) | (20.36) | (–0.05) | (–7.33) |
| Quoted Depth for Volume | **0.001** | **–0.0021** | **–0.0020** | **0.0036** | **0.0071** | 30.10 | 1.96 | –0.25 |
| | (16.11) | (–9.23) | (–4.26) | (2.57) | (7.90) | (21.95) | (3.29) | (–6.38) |
| Quoted Depth for Volatility | **0.0008** | **0.0005** | **0.0038** | **0.0018** | **0.0035** | 11.56 | 6.09 | 1.41 |
| | (8.63) | (11.17) | (23.64) | (13.69) | (11.56) | (8.92) | (7.87) | (3.38) |
| **PUTS (NEAR) 2007** | | | | | | | | |
| Quoted Depth for Market Cap | **0.0003** | **0.0024** | **0.0018** | 0.0006 | **0.0091** | 146.59 | –0.40 | –1.64 |
| | (3.30) | (25.32) | (11.30) | (1.76) | (3.38) | (43.56) | (–0.43) | (–8.35) |
| Quoted Depth for Volume | 0.0001 | **–0.0011** | **–0.0030** | **0.0027** | **0.0005** | 107.24 | 3.11 | –1.31 |
| | (1.16) | (–7.11) | (–9.67) | (2.47) | (0.71) | (34.28) | (2.90) | (–8.18) |
| Quoted Depth for Volatility | 0.0017 | **0.0003** | **0.0060** | **0.0014** | **0.0036** | 34.84 | –1.17 | 1.49 |
| | (1.87) | (–6.75) | (20.10) | (8.28) | (10.84) | (24.15) | (–1.45) | (2.23) |
| **PUTS (OUT) 2007** | | | | | | | | |
| Quoted Depth for Market Cap | **–0.0006** | **0.0022** | **0.0009** | 0.0003 | **0.0440** | 166.37 | –31.78 | –0.80 |
| | (–6.51) | (14.57) | (2.99) | (0.68) | (4.16) | (40.60) | (–30.54) | (–7.16) |
| Quoted Depth for Volume | **–0.0011** | 0.0001 | 0.0010 | 0.0003 | 0.0007 | 130.69 | –33.84 | –4.90 |
| | (–12.06) | (0.39) | (1.65) | (1.43) | (1.99) | (40.53) | (–30.85) | (–5.23) |
| Quoted Depth for Volatility | **0.0036** | –0.00004 | **0.0095** | **–0.0013** | **–0.0019** | 46.33 | –8.35 | 2.92 |
| | (11.55) | (–0.75) | (13.82) | (–7.96) | (–4.75) | (12.65) | (–8.65) | (2.77) |

*Notes: This exhibit regresses the quoted depth on a proxy for market maker quote revisions (message traffic) and the three control variables of market capitalization, the Garman–Klass volatility of the underlying stock, and the dollar volume of the stock's options for the general sample from 2007. The control variable values given here are for quintile 1. The specification is:* $l_{it} = \alpha_i + \beta_i A_{it} + \delta_{it} X_{it} + \varepsilon_{it}$, *where* $l_{it}$ *is the liquidity variable (quoted depth in this exhibit),* $A_{it}$ *is the message traffic, and* $X_{it}$ *is the set of control variables. Option volume is the logarithm of the average volume per strike for each stock after dividing by 100. We multiply the coefficients on the message traffic variable by 1,000 to reduce the number of decimal places.*

*Significant coefficients at the 5% level or better are in bold.*

## EXHIBIT 6

**Regression Coefficients for the Effect of Market Maker Quote Revisions on Depth (2008)**

| Group/Sorting Criteria | Q1 | Q2 | Q3 | Q4 | Q5 | Market Cap | Volume | Volatility |
|---|---|---|---|---|---|---|---|---|
| **CALLS (IN) 2008** | | | | | | | | |
| Quoted Depth for Market Cap | **0.0013** | **0.0009** | **0.0027** | **–0.0007** | **0.0040** | 77.07 | 0.32 | –0.11 |
| | (13.66) | (7.73) | (26.55) | (–13.68) | (5.27) | (18.37) | (0.27) | (–12.01) |
| Quoted Depth for Volume | **0.0015** | **–0.0002** | **–0.0007** | **–0.0006** | –0.0006 | 28.18 | –4.47 | –0.06 |
| | (25.06) | (–2.16) | (–2.83) | (–3.95) | (–1.61) | (29.06) | (–6.79) | (–4.67) |
| Quoted Depth for Volatility | **0.0120** | 0.00008 | **0.0039** | **0.0015** | **0.0018** | 13.92 | 3.84 | 0.00 |
| | (7.90) | (1.08) | (7.45) | (11.42) | (10.98) | (2.69) | (1.54) | (–1.73) |
| **CALLS (NEAR) 2008** | | | | | | | | |
| Quoted Depth for Market Cap | **–0.0003** | **0.0020** | **0.0049** | –0.0003 | **0.0016** | 205.15 | 2.02 | –0.08 |
| | (–5.08) | (11.09) | (48.68) | (–1.33) | (5.02) | (47.07) | (2.36) | (–3.25) |
| Quoted Depth for Volume | **0.0003** | –0.0002 | **–0.0019** | 0.0002 | –0.0008 | 59.77 | 4.07 | –0.07 |
| | (6.29) | (–1.64) | (–10.32) | (1.43) | (–1.86) | (36.42) | (5.65) | (–2.33) |
| Quoted Depth for Volatility | **–0.0300** | **0.0009** | **0.0055** | **0.0010** | **0.0025** | –73.87 | 46.82 | –0.16 |
| | (–5.78) | (7.05) | (16.41) | (6.05) | (12.22) | (–6.35) | (7.65) | (–2.29) |
| **CALLS (OUT) 2008** | | | | | | | | |
| Quoted Depth for Market Cap | **–0.0003** | **0.0027** | **0.0060** | **–0.0006** | **0.0017** | 162.18 | –6.09 | –0.01 |
| | (–3.37) | (10.73) | (27.76) | (–11.13) | (3.51) | (40.18) | (–7.67) | (–0.68) |
| Quoted Depth for Volume | **–0.0005** | –0.0001 | **–0.0009** | 0.0003 | **–0.0009** | 35.99 | –10.43 | –0.01 |
| | (–10.27) | (–0.75) | (–4.11) | (1.03) | (–2.46) | (23.63) | (–17.79) | (–0.62) |
| Quoted Depth for Volatility | **–0.0124** | –0.0001 | **0.0049** | **0.0024** | **0.0035** | –45.22 | 24.74 | 0.00 |
| | (–3.50) | (–1.87) | (5.46) | (9.16) | (13.19) | (–5.75) | (3.67) | (–1.89) |
| **PUTS (IN) 2008** | | | | | | | | |
| Quoted Depth for Market Cap | 0.00008 | **0.0012** | **0.0028** | **–0.0008** | 0.0013 | 113.64 | 3.97 | 0.15 |
| | (0.73) | (7.17) | (8.65) | (–13.35) | (1.56) | (23.74) | (2.86) | (10.44) |
| Quoted Depth for Volume | **0.0008** | **–0.0006** | **–0.0005** | **–0.0006** | **–0.0003** | 14.81 | –0.61 | 0.12 |
| | (11.69) | (–4.96) | (–5.05) | (–3.31) | (–3.99) | (7.13) | (–0.61) | (12.80) |
| Quoted Depth for Volatility | **0.0005** | **0.0002** | **0.0018** | **0.0014** | **0.0019** | –28.02 | 18.27 | 0.00 |
| | (5.82) | (2.16) | (4.24) | (9.21) | (12.90) | (–3.69) | (7.58) | (–4.71) |
| **PUTS (NEAR) 2008** | | | | | | | | |
| Quoted Depth for Market Cap | **–0.0005** | **0.0021** | **0.0048** | –0.0001 | 0.0012 | 230.90 | 3.76 | –0.06 |
| | (–6.62) | (10.22) | (40.48) | (–1.49) | (1.45) | (48.62) | (4.02) | (–2.27) |
| Quoted Depth for Volume | **0.0001** | –0.00007 | **–0.0013** | 0.0002 | **–0.0007** | 65.19 | 2.89 | –0.06 |
| | (1.99) | (–0.34) | (–9.03) | (1.57) | (–3.19) | (35.51) | (3.51) | (–1.94) |
| Quoted Depth for Volatility | **–0.0022** | **0.0007** | **0.0060** | **0.0006** | **0.0021** | –13.57 | 25.20 | 0.00 |
| | (–2.16) | (4.84) | (15.23) | (3.43) | (9.57) | (–3.16) | (13.05) | (–6.29) |
| **PUTS (OUT) 2008** | | | | | | | | |
| Quoted Depth for Market Cap | **0.0007** | **0.0030** | **0.0058** | **–0.0005** | 0.0014 | 178.96 | –5.88 | –0.27 |
| | (4.79) | (8.10) | (22.60) | (–6.43) | (1.95) | (33.93) | (–5.68) | (–12.65) |
| Quoted Depth for Volume | **–0.0005** | **0.0004** | **–0.0008** | 0.0006 | 0.0002 | 41.00 | –12.71 | –0.24 |
| | (–8.27) | (2.05) | (–2.89) | (0.82) | (0.73) | (24.49) | (–17.02) | (–7.60) |
| Quoted Depth for Volatility | **0.0002** | **–0.0014** | **0.0062** | **0.0029** | **0.0029** | 29.90 | (–3.25) | 0.00 |
| | (5.10) | (–7.98) | (13.35) | (7.83) | (7.92) | (5.94) | (–1.42) | (–2.35) |

*Notes: This exhibit regresses the quoted depth on a proxy for market maker quote revisions (message traffic) and the three control variables of market capitalization, the Garman–Klass volatility of the underlying stock, and the dollar volume of the stock's options for the general sample from 2008. The control variable values given here are for quintile 1. The specification is:* $l_{it} = \alpha_i + \beta_i A_{it} + \delta_{it} X_{it} + \varepsilon_{it}$, *where* $l_{it}$ *is the liquidity variable (quoted depth in this exhibit),* $A_{it}$ *is the message traffic, and* $X_{it}$ *is the set of control variables. Option volume is the logarithm of the average volume per strike for each stock after dividing by 100. We multiply the coefficients on the message traffic variable by 1,000 to reduce the number of decimal places.*

*Significant coefficients at the 5% level or better are in bold.*

## EXHIBIT 7
**Unit Effect of Market Maker Quote Revisions on Spread and Depth**

| Group/Sorting Criteria | | Q1 | Q2 | Q3 | Q4 | Q5 | Q1 | Q2 | Q3 | Q4 | Q5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Panel A: CALLS 2007 | | | | | Panel B: PUTS 2007 | | | | |
| Quoted Spread | In | –1.78 | –3.25 | –44.99 | 15.30 | 44.26 | –3.74 | –23.13 | –61.91 | 13.42 | 30.27 |
| | Near | –23.75 | –47.08 | –93.78 | –52.75 | 10.59 | –18.59 | –37.93 | –98.16 | –16.33 | 13.01 |
| | Out | –57.77 | –87.02 | –101.94 | –17.72 | 7.64 | –39.87 | –73.56 | –190.98 | –2.45 | –34.04 |
| Quoted Depth | In | 46.20 | 0.81 | –7.72 | 6.28 | –0.64 | 37.37 | –18.68 | –8.37 | 4.02 | 10.69 |
| | Near | 19.79 | –4.41 | –11.25 | 4.33 | –0.39 | 3.72 | –7.73 | –9.82 | 3.08 | 0.59 |
| | Out | –24.76 | 7.83 | –0.34 | 0.53 | 0.04 | 39.87 | –1.10 | 8.69 | 3.11 | 5.04 |
| | | Panel C: CALLS 2008 | | | | | Panel D: PUTS 2008 | | | | |
| Quoted Spread | In | –14.23 | –14.68 | –26.94 | 4.58 | 19.83 | –15.06 | –11.73 | –6.50 | 21.32 | 12.65 |
| | Near | –33.06 | –71.33 | –73.92 | –41.54 | –3.02 | –26.64 | –59.46 | –52.47 | –45.60 | –26.60 |
| | Out | –98.81 | –137.66 | –110.24 | –69.90 | 11.63 | –73.04 | –119.39 | –105.96 | –65.88 | –47.76 |
| Quoted Depth | In | 53.37 | –2.10 | –2.99 | –1.53 | –0.97 | 30.12 | –6.40 | –2.50 | –1.47 | –0.51 |
| | Near | 14.17 | –2.01 | –8.03 | 0.38 | –0.93 | 4.44 | –0.69 | –5.64 | 0.42 | –0.93 |
| | Out | –15.94 | –0.62 | –2.64 | 0.42 | –0.95 | –14.05 | 2.20 | –2.12 | 0.64 | 0.22 |

*Notes: This exhibit examines the size effect of the number of quotation messages on spread and depth by multiplying the average number of messages from Exhibit 2 by the coefficient size in the volume ranked regressions in Exhibits 3 to 6. The results here provide the average absolute size effect by quintile.*

Second, option market makers are more active due to the smaller differences between option price points; in particular, changes in the underlying stock price create more frequent changes in the market makers' bid–ask prices when penny quotes exist. This change in price revision activity could also thin out the size of options orders, since a higher risk of larger size executions over multiple exchanges would exist, as shown by Saraoglu, Louton, and Holowczak [2014]. Such changes are enhanced by the speed of electronic markets. Consequently, a reduction in depth could occur at the best bid and ask quotes due to the existence of penny quotes.

Exhibit 8 presents the basic statistics for the penny quote sample. The penny quote sample possesses basic characteristics that are almost identical to the first quintile market capitalization sort for the general sample. The explanation for this similarity is that the stocks used for the penny pilot sample are large capitalization stocks that possess very actively traded options. As with the general sample, the average spread as a percentage of the price for the penny pilot sample is smallest for in-the-money options, next largest for near-the-money options, and largest for out-of-the-money options. The depth is largest for the near-the-money options for calls and the out-of-the-money options for puts. Finally, the number

## EXHIBIT 8
**Summary Statistics for the Penny Quote Sample**

| | | CALLS | PUTS |
|---|---|---|---|
| Quoted Spread | In | 0.0213 | 0.0348 |
| | Near | 0.0989 | 0.1050 |
| | Out | 0.6063 | 0.5353 |
| Quoted Depth | In | 692 | 584 |
| | Near | 1,322 | 1,447 |
| | Out | 1,126 | 1,593 |
| Quotation Messages | In | 37,958 | 37,689 |
| | Near | 42,756 | 39,396 |
| | Out | 22,561 | 18,696 |
| Market Cap | In, Near, Out | 16.99 | 16.99 |
| Volume | In | 556.5 | 708.2 |
| | Near | 1,767.2 | 1,960.5 |
| | Out | 367.4 | 358.3 |
| Volatility | In, Near, Out | 5.43 | 5.43 |

*Notes: Based on the option code, we divide the data into call and put options and then into in-, near-, and out-of-the-money options. The exhibit provides the averages for the call and put options for the penny quote sample for 2007 and 2008 for the variables of interest. The dollar option volume is the average per strike price for each stock in the category then divided by 100 (the strikes include those without a trade but with a quote).*

of quote revisions is substantially higher for the near-the-money group.

For each phase we examine one month before and after the implementation of penny quoting. The correlation statistics for the penny sample (available upon request) of the messages versus the spread are similar to the general sample correlations. The correlations between messages and depth are very small (for the sample size) for the penny quote sample (typically smaller than −0.10), whereas in the general sample, they are often positive and much larger.

We next generate daily panel regressions using (1) separate GMM regression for before versus after the implementation of the penny quotes in order to directly compare the coefficients and significance levels of the two periods using Equation (4); and (2), we generate one integrated regression that includes an interaction indicator variable to examine the change in significance of the relation between the algorithmic messages and liquidity before versus after the penny quotation periods using Equation (5).

The spread regression results described by (1) for calls and puts for all three phases of the penny pilot show that the quote-revision message variable is consistently negative and significant, as it is with the general sample.[18] More importantly, the coefficients on the message variables are largely significant after the penny quotes started, showing that even with a much lower tick size, the frequent quote revisions reduce the spread size. In fact, the size of the significance values for the message variable is larger for half of the regression coefficients after the penny quotes started. The control variables are consistent in their sign and relative significance before versus after the implementation of penny quotes. These results support Outcomes I and II and are important as they show that market maker high-frequency quote revisions reduce the bid–ask spread *exclusive* of the switch to penny quotes, and the spread decreases for calls and puts, different strikes, and all three phases of the penny quote pilot.

The depth results for the before and after penny quote sample shows that the quote revision (message) variable possesses positive coefficients with depth for three-quarters of the significant coefficients for the calls and puts, further supporting the positive relation between increasing quote revisions and depth, even after the penny quotes took effect.[19] Thus, Outcome III is supported by the results in these exhibits, but Outcome IV is not. Moreover, these results exist even though it was anticipated that (1) depth would decline due to the slicing of institutional orders into smaller sizes, which would exist to obtain better execution prices and a faster execution of trades in conjunction with penny quotes; (2) depth would decline due to smaller-sized orders placed by market makers due to the penny quote increments since market-maker quotations need to revise these quotes more frequently as the underlying prices change, and execution risk exists from institutional traders placing trades across exchanges; thus, the previous depth that was aggregated at the five- and ten-cent quotes is spread out over the penny prices (see Saraoglu, Louton, and Holowczak [2014]).

Exhibit 9 provides the integrated regression results for the penny quotes for spreads using Equation (5). This exhibit shows that the message traffic variable itself is still significant and negative, as with the general sample. The key addition in these regressions is the *interaction indicator variable*, which shows the difference in the *slopes* of the message traffic effect for the after versus before change in the tick size (to penny quotes). Given the expected negative relation between the number of messages and the bid–ask spread, a positive and significant coefficient on the interaction indicator variable would show a weaker negative coefficient value between spreads and message activity after the initiation of penny quotes relative to before the initiation of penny quotes. In fact, the indicator variable in Exhibit 9 clearly shows that after the penny quotes were implemented, the quote revisions had a weaker effect on spreads than before the implementation, as overall the coefficient on the interaction indicator variable is (in fact) positive and significant.

Exhibit 10 illustrates the integrated regression results for depth. In over 80% of the cases, the strongly positive message traffic coefficients support the positive quote revision versus depth relation, just as in the general sample. Given the expected positive relation between message traffic and depth, a negative and significant coefficient on the interaction indicator variable is consistent with a weaker relation between depth and quote revisions after the initiation of penny quotes.

In conclusion, the penny quote sample provides results consistent with the general sample, regardless of the intervening factor of the change to a much smaller tick size. In particular, the positive relation between messages and depth is confirmed by the penny quote sample. Thus, the a priori expectation that depth would become negatively related to message traffic because of

## EXHIBIT 9

**Regression Coefficients for the Effect of Market Maker Quote Revisions on Bid–Ask Spreads for Penny Quotes (before vs after integrated sample for calls and puts)**

| | CALLS | | | PUTS | | |
|---|---|---|---|---|---|---|
| | **Messages** | **Dum** | **IntInd** | **Messages** | **Dum** | **IntInd** |
| **IN** | | | | | | |
| Quoted Spread for phase 1 | **–0.0002** | –0.0031 | –0.0000 | **–0.0002** | –0.0015 | **–0.0001** |
| | (–7.02) | (–4.53) | (–0.12) | (–4.08) | (–1.18) | (–2.07) |
| Quoted Spread for phase 2 | **–0.0003** | –0.0062 | **0.0001** | **–0.0003** | –0.0034 | 0.0000 |
| | (–13.55) | (–5.55) | (2.01) | (–4.54) | (–0.60) | (0.18) |
| Quoted Spread for phase 3 | **–0.0002** | –0.0077 | 0.0000 | **–0.0002** | –0.0072 | –0.0000 |
| | (–15.27) | (–10.25) | (0.12) | (–14.86) | (–11.56) | (–0.02) |
| **NEAR** | | | | | | |
| Quoted Spread for phase 1 | **–0.0022** | –0.0539 | 0.0007 | **–0.0012** | –0.0537 | 0.0002 |
| | (–7.17) | (–4.22) | (1.81) | (–4.40) | (–4.68) | (0.49) |
| Quoted Spread for phase 2 | **–0.0020** | –0.0662 | **0.0014** | **–0.0017** | –0.0507 | **0.0010** |
| | (–18.52) | (–9.80) | (9.90) | (–16.31) | (–7.49) | (7.51) |
| Quoted Spread for phase 3 | **–0.0019** | –0.0791 | **0.0011** | **–0.0015** | –0.0739 | **0.0010** |
| | (–15.95) | (–8.96) | (7.65) | (–14.75) | (–10.11) | (7.72) |
| **OUT** | | | | | | |
| Quoted Spread for phase 1 | **–0.0200** | –0.2290 | **0.0140** | **–0.0075** | –0.0421 | –0.0056 |
| | (–11.90) | (–7.92) | (6.14) | (–3.04) | (–1.31) | (–1.90) |
| Quoted Spread for phase 2 | **–0.0046** | –0.1347 | **0.0034** | **–0.0033** | –0.1156 | **0.0022** |
| | (–11.58) | (–11.13) | (7.93) | (–11.04) | (–10.58) | (6.37) |
| Quoted Spread for phase 3 | **–0.0044** | –0.262 | **0.0034** | **–0.0030** | –0.1435 | **0.0018** |
| | (–11.63) | (–15.42) | (8.09) | (–9.66) | (–11.07) | (4.26) |

*Notes: This exhibit provides the regression results for the interaction sample (using the before and after penny pilot sample combined) for the quoted spread for calls and puts with the proxy for market maker quote revisions (message traffic) and various control variables as the independent variables. The specification is* $l_{it} = \alpha_i + \gamma_t + \beta_i A_{it} + \delta_{it} X_{it} + \lambda_i INT_{it} + \varepsilon_i$. *The key addition in these regressions is the interaction indicator (IntInd), which shows the difference in the slopes of the message traffic effect for the after versus before change in the tick size to penny quotes. To reduce the number of decimal places, we multiply coefficients on message traffic and IntInd variables by 1,000.*

*Significant coefficients at the 5% level or better are in bold.*

penny quotes, primarily due to the enhanced slicing and dicing of institutional orders as well as the likelihood that market makers would reduce their own risk by posting smaller orders, is not supported by the evidence presented in this section.

## CONCLUSIONS

Empirical research on electronic markets and high-frequency activity is important for both policymakers and market participants due to their effects on the bid–ask spread and the depth of the market. We extend previous research on algorithmic trading for stocks and futures to the study of market-making activity in the options market, which has the advantage of examining a quote-driven market and the effects of different strikes and other option-specific characteristics, as well as the importance of a multitude of exchanges to place orders.

Our analysis of the general sample for 2007 and 2008 and examination of the effect of the option-specific and stock-specific characteristics show a highly significant (and stronger) narrowing of the spread than that given in the literature for other markets with substantial high-frequency activity. In fact, the spread declines even when a smaller tick size exists. These results are persistent over all quintile rankings for all ranking variables. We also find a positive message–depth relation in both the general and penny samples, with two-thirds and three-quarters, respectively, of the regression coefficients being positive and significant.

# EXHIBIT 10

**Regression Coefficients for the Effect of Market-Maker Quote Revisions on Depth for Penny Quotes (before vs after integrated sample for calls and puts)**

| | CALLS | | | PUTS | | |
|---|---|---|---|---|---|---|
| | **Messages** | **Dum** | **IntInd** | **Messages** | **Dum** | **IntInd** |
| **IN** | | | | | | |
| Quoted Depth for phase 1 | **0.0680** | 0.1124 | **–0.0700** | **0.0220** | 0.0375 | **–0.0100** |
| | (8.76) | (0.81) | (–8.12) | (4.65) | (0.39) | (–2.64) |
| Quoted Depth for phase 2 | **0.0180** | 0.0060 | **–0.0100** | **0.0060** | –0.7165 | **–0.0027** |
| | (15.88) | (0.23) | (–9.69) | (9.50) | (–5.38) | (–2.52) |
| Quoted Depth for phase 3 | **0.0034** | –0.0435 | **–0.0021** | **0.0025** | –0.1505 | **–0.0015** |
| | (9.64) | (–2.33) | (–4.83) | (6.50) | (–6.37) | (–3.19) |
| **NEAR** | | | | | | |
| Quoted Depth for phase 1 | **0.2090** | 1.1606 | **–0.1800** | **0.1820** | 1.0446 | **–0.1900** |
| | (18.03) | (4.42) | (–14.71) | (14.40) | (3.52) | (–14.26) |
| Quoted Depth for phase 2 | **0.0260** | –0.3937 | **–0.0200** | **0.0210** | –0.5401 | **–0.0200** |
| | (15.55) | (–9.63) | (–12.54) | (12.97) | 12.93) | (–11.00) |
| Quoted Depth for phase 3 | **–0.0024** | –0.8194 | **0.0028** | **–0.0031** | –0.8889 | **0.0032** |
| | (–6.04) | (–29.86) | (6.74) | 6.9(–7) | (–30.90) | (7.02) |
| **OUT** | | | | | | |
| Quoted Depth for phase 1 | **0.1220** | 0.1632 | **–0.0900** | 0.4050 | 1.2604 | **–0.3900** |
| | (5.34) | (0.66) | (–3.94) | (8.87) | (2.89) | (–8.00) |
| Quoted Depth for phase 2 | **0.0160** | –0.9043 | **–0.0096** | **0.0280** | –0.8404 | **–0.0300** |
| | (7.24) | (–17.36) | (–4.33) | (8.17) | (–13.63) | (–7.62) |
| Quoted Depth for phase 3 | –0.0007 | –0.5847 | 0.0002 | **0.0017** | –0.4877 | **–0.0024** |
| | (–1.62) | (–26.57) | (0.37) | (2.62) | (–22.81) | (–3.63) |

*Notes: This exhibit provides the regression results for the interaction sample (using the before and after penny pilot sample combined) for the depth for calls and puts with the proxy for market maker quote revisions (message traffic) and various control variables as the independent variables. The specification is* $l_{it} = \alpha_i + \gamma_t + \beta_i A_{it} + \delta_i X_{it} + \lambda_i INT_{it} + \varepsilon_i$*. The key addition in these regressions is the interaction indicator (IntInd), which shows the difference in the slopes of the message traffic effect for the after versus before change in the tick size to penny quotes. We multiply the coefficients on message traffic and IntInd variables by 1,000 to reduce the number of decimal places.*

*Significant coefficients at the 5% level or better are in bold.*

Consequently, the behavior of our depth conflicts with the stock results of Hendershott, Jones, and Menkveld [2011], as well as being more consistent and possessing higher *t*-values across the quintiles. Other research on high-frequency activity does not examine quintiles or other factors available for options.

A key conclusion to our results is that the options results are stronger and more consistent than previous studies on algorithmic trading for stocks. Such results are consistent with options markets being quote-driven markets dominated by the revision of bid–ask quotes, whereas stock markets are order-driven markets driven by high-frequency traders placing and canceling limit orders.

The issue of liquidity in financial markets is a timely and crucial factor. Additional analysis of more complicated and integrated markets such as options provides crucial information to aid appropriate regulatory interests in making the markets fair and efficient. Moreover, further investigation of the impacts of high-frequency activity on the markets is essential to determine the trade-offs between the additional liquidity that market makers provide in normal markets versus the potential for market crashes when high-frequency traders remove their liquidity, as evidenced during the flash crash of 2010.

## ENDNOTES

[1]In particular, the promulgation of Order Protection Rule 611 promoted the use of electronic trading and

computerized algorithms. On April 6, 2005, Regulation NMS leveled the playing field across U.S. exchanges regarding order executions. Disagreement exists regarding how to refer to market making activities in high-frequency electronic markets. In fact, the common usage of algorithmic and high-frequency trading often overlap in general, creating disagreements in identifying whether a particular trading activity is algorithmic trading or high-frequency trading. Fabozzi, Focardi, and Jonas [2011] defined high-frequency trading as orders held for 10 milliseconds to 10 seconds. Algorithmic trading is explained as computerized quantitative models designed to identify when to trade an instrument, as well as its best quantity, price, timing, and trade location. Moreover, algorithmic trading often is associated with specific profit-oriented strategies that take positions. Whereas some consider market making to be a type of algorithmic (or high-frequency) trading, others deem the activity a different process.

[2]Alternatively, the general perception of high-frequency trading in equity markets is algorithmic trading in which orders are placed and canceled in rapid succession to generate trading profits, including multiple orders over many exchange venues and millisecond trade execution for fractional profits. For exchanges with "payment for order flow," option market makers are not allowed to participate in the placement of trade orders unless they provide competitive quotes. Overall, quote activity in options is caused by different determinants than those that dominate equity markets, although typical institutional terminology employs "algorithmic trading" as the general term for all markets with frequent quote revisions. Thus, although option market makers use computerized programs to create revised quotes as underlying asset prices and other factors change, they have different motives than equity algorithmic traders.

[3]Biais and Weill [2009] presented a theoretical model on how algorithmic trading relates to message traffic, showing that message traffic is a good proxy for algorithmic trading. Consultants at the Aite Group and the Tabb Group, as well as exchanges and other market venues (Hendershott, Jones, and Menkveld [2011]) commonly use message traffic by market participants for high-frequency activity.

[4]For example, Riordan and Storkenmaier [2008] stated that algorithmic stock traders increase liquidity by reducing latency in order transmission from 50 milliseconds (ms) to 10 ms, thereby reducing trading costs by one to four basis points. Easley, Hendershott, and Ramadorai [2014] examined an upgrade in the New York Stock Exchange, which was implemented to improve information dissemination on the trading floor and reduce latency in reporting trades and costs. They showed that the portion of the upgrade that reduced the latency and transparency of electronic orders has significant impacts on liquidity, turnover, and returns. Hasbrouck and Saar [2013] used order book data from NASDAQ to show that increased low latency improves market quality in terms of reduced spread, increased depth in the limit order book, and lowered short-term volatility.

[5]In particular, Hendershott and Riordan [2009] examined the 30 DAX stocks and found that algorithmic trades create a larger price impact than non-algorithmic trades; therefore, algorithims tend to contribute more to price discovery. Brogaard [2010] investigated the impact of equity algorithm trading on market quality by showing that such trading improves price discovery more than trades by other market participants and that their activity appears to lower volatility.

[6]Karagozoglu [2011] examined algorithmic trading in relation to five futures contracts, finding that spreads are decreased and market depth is increased. Frino, Lepone, and Wearin [2008] associated an increase in depth with a decrease in the spread for a dealer market in futures. Finally, Egginton, Van Ness, and Van Ness [2012] showed that individual equity *quote stuffing* (intense episodic spikes in quoting activity in which orders are placed and canceled within milliseconds) decreases liquidity and increases trading cost and short-run volatility.

[7]For example, we remove negative spreads and stub quotes (a quote with a zero bid and a very large ask, such as 199,999). Thus, only executable quotes are employed. Also, "non-firm" quotes at the start of the day are removed. The messages include both quotes and trades, with more than 99.95% of the option messages representing quotes.

[8]We generate stratified quintile groupings for the option characteristics representing the largest 40 stocks possessing options for each quintile grouping. We sort the options into quintiles based on three different criteria and then analyze each group separately. The three groups are (1) market capitalization of the underlying stocks for the year; (2) dollar volume traded for the options generated by all of the exchanges for the entire year for each option category for each stock; and (3) the volatility for each of the underlying stocks for the entire year. The stocks from each quintile are employed to generate separate quintile panel regressions in terms of call and put options and in-, near-, and out-of-the-money strike prices of these options.

[9]The in-, near-, and out-of-the-money option groups are created using the following procedure: First, we calculate the difference between the stock price of the last trade and the strike price—that is, the *stock-strike difference*. A call option is grouped as a near-the-money option if the stock-strike difference is within 2.5 (5) points for stocks below (above) \$20. It is grouped as an out-of-the-money option if the stock-strike difference is −2.5 to −10 (−5 to −20) for stocks below (above) \$20, and an in-the-money option if the difference is 2.5 to 10 (5 to 20) for stocks below (above) \$20. Opposite sign criteria

are used for puts. Options outside these ranges possess little trading interest and therefore are removed from the analysis.

[10]Hendershott, Jones, and Menkveld [2011] suggested using either a measure of message traffic normalized by volume or using raw message traffic to represent high-frequency trading. Although we employ raw message traffic, we do control for the volume of trading in the regression analysis. The results are unchanged when the volume of trading is normalized by message traffic. The volume and volatility control variables are total values for the day.

[11]The interaction dummy procedure is designed following the procedure described in UCLA [2016].

[12]Results from the fall of 2008 alone possess higher spreads (except for quintile 5 for puts), lower call depth, consistently lower put depth, more messages (except for quintile 1 for calls), and lower (generally higher) call (put) volume. These 2008 results are available upon request.

[13]This could be due to various regulatory changes happening during the post-crisis period, such as the short-sale ban (see, e.g., Hayunga et al. [2012])

[14]We also employ each of the control factors as independent variables in the equation. However, as done by Hendershott, Jones, and Menkveld [2011], we only present the coefficients (and significance) of the control variables for quintile 1 for space reasons. Results are available upon request. The Newey–West standard errors correction is employed for the analysis.

[15]We also examine the spread (and depth) results for 2008 using only the periods before and during the financial crisis by employing the procedures used by Anand et al. [2011] to determine the crisis period. The regression results for these samples are essentially equivalent to the entire 2008 year. More specifically, the results for the crisis period show the same pattern for spreads as for the non-crisis period, although the *t*-values are mostly substantially lower. These results are available upon request.

[16]From the spread results in Exhibits 2 and 3 we know that the quintile 1 results are the most important and most consistent of all the quintiles. Results from the fall of 2008 show that two-thirds of the coefficients are positive, which is consistent with the remainder of the year. However, the *t*-values are mostly lower for these results.

[17]We reran the entire analysis (a type of robustness test) by including the time to expiration of the options as a variable to determine if time to expiration was an important factor. Time to expiration did not significantly affect the results. Since the separation of time to expiration was unimportant, we only report it in a footnote.

[18]The GMM panel regression results for spreads and depth are not provided here for space considerations. Exhibits 8 and 9 show more sophisticated results in the integrated regression results.

[19]Also note that our penny quote results for both spread and depth possess larger *t*-values than those Hendershott, Jones, and Menkveld [2011] obtained for equity high-frequency algorithm trading. Moreover, Hendershott, Jones, and Menkveld depth results for quintiles 2 and 3 are insignificant and their quintile 4 and 5 results are positive.

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