Index-futures arbitrage before and after the introduction of sixteenths on the NYSE

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Keywords: Index-futures arbitrage, program trading.
JEL classification: G13, G14

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Abstract
On June 24, 1997, the New York Stock Exchange reduced the minimum change for stock prices and quotes from an eighth to a sixteenth of a dollar. This study investigates the impact of the resulting decrease in spreads on S&P 500 index-futures arbitrage. For the period after June 24, 1997, we find that there is a substantial increase in the number of arbitrage trades reported to the Securities and Exchange Commission. The average number of stocks and the average dollar amount underlying each arbitrage trade increase and decrease respectively. The average index-futures mispricing error that triggers arbitrage is lower after sixteenths.

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1. Introduction

On June 24, 1997 the New York Stock Exchange (NYSE) reduced the minimum change for stock prices and quotes from an eighth to a sixteenth of a dollar. The change resulted in a decline in the quoted spread, especially for frequently traded stocks (Goldstein and Kavajecz, 2000). This study investigates the impact of the decrease in spreads on S&P 500 index-futures arbitrage. The arbitrage portfolio requires a long (short) position in the 500 stocks underlying the S&P 500 index, and a short (long) position in the S&P 500 index-futures contract. Since the narrower spreads reduce transaction costs for trading stocks, one would expect to find an increase in the number of arbitrage opportunities and a decrease in the index-futures mispricing error (MPE) that triggers arbitrage.

There are, however, a number of reasons why this may not be the case. First, Goldstein and Kavajecz (2000) find that the depth of the best bid and ask quotes has decreased after sixteenths, that is, only small quantities of stocks are available at the reduced spread. Second, Neal (1996) finds that arbitrageurs earn on average around half the quoted spread for each round-trip arbitrage trade. Hence, for arbitrage to be profitable, arbitrageurs must be able to trade at prices inside the quoted spread. This supposition is not surprising as most arbitrageurs are both NYSE member firms and brokers at the same time, and Madhavan and Sofianos (1998) report that NYSE specialists on average participate in only 30% of all stock trades. Therefore, the majority of trades take place between traders, not through the specialist. On the other hand, arbitrage requires obtaining a stock position in a very short period of time, so some of the 500 stocks may have to be purchased from the specialist. These considerations imply that whether the reduction of the minimum price increment affects the level of the mispricing error that triggers arbitrage is an interesting empirical question.

This study is different from existing studies in that it uses a unique combination of data sets. First, following Neal (1996), we use a data set of actual S&P 500 index arbitrage trades to examine the impact of the decrease in the minimum price increment on the MPE. Numerous studies of stock index arbitrage[1] analyze the prediction that the observed mispricing between the cash index and the futures should not exceed the hypothesized transaction costs of arbitrage. These studies produce potentially spurious results and conclusions since non-synchronous trading may create the illusion of arbitrage opportunities (Miller, Muthuswamy, and Whaley, 1994). In addition to NYSE data reporting index arbitrage trading activity, we obtained information from the NYSE stating when Rule 80A[2] was triggered during 1997. Overdahl and McMillan (1998) show that Rule 80A significantly curtails index arbitrage activity, hence the MPE is expected to increase when the rule is in effect.

Second, existing studies use the S&P 500 index that is supplied to financial markets approximately every 15 seconds by Standard and Poors (S&P). This index is based on the last available transaction price at the primary exchange for each of the 500 constituent stocks. We compute two new indices based on the last available bid-ask quote for each constituent stock. Similar to Standard and Poors, we calculate these indices in 15-second intervals. Subsequently, the midpoint of the quotes is used to create a quote-based S&P 500 index. This index has three advantages over the trade-based index. First, our index is less susceptible to the effects of stale prices. Although our quote-based index may still lag actual developments, the lag problem inherent in the trade-based index will be reduced, since the market maker must provide firm quotes at which she stands ready to transact at any time[3]. Second, the bid-ask bounce problem is eliminated. Therefore, the index-futures MPE should be close to zero in stable market conditions, even if more (less) than half of the stocks in the index last traded at the ask or at the bid. Third, the bid and ask indices provide a measure of time varying transaction costs for the index.

[1] For example MacKinlay and Ramaswamy (1988), Stoll and Whaley (1990), Chung (1991), Chan (1992), and Dwyer, Locke and Yu (1996).

[2] In 1997, Rule 80A was activated when the Dow Jones Industrial Average changed by 50 points from the previous day's close. Once activated on the sell (buy) side, it requires arbitrage orders to sell (buy) any component stock of the S&P 500 index to be entered with the instruction "sell plus" ("buy minus"). This implies a sell (buy) order can only be executed at a price above (below) the price of the preceding sale (buy). Note that currently there is a new version of Rule 80A which is activated by relative, rather than absolute, price changes and therefore is triggered less often.

[3] Of course in special circumstances such as a trading halt firm quotes are not available.

The NYSE daily reports on program trading show that the number of index-futures arbitrage trades increased from 3,827 before the introduction of sixteenths (January 3 to June 23, 1997) to 5,102 afterwards (June 24 to December 23, 1997). We subsequently exclude the first 30 minutes and the last ten minutes of each trading day from the sample in order to avoid biasing the results by activity related to the opening and the closing of the market. This exclusion reduced the number of arbitrage opportunities in our sample to 3,158 and 4,311 respectively. The average dollar amount underlying each reported arbitrage trade dropped significantly from 16.5 million to 13.8 million, and the average number of stocks per arbitrage trade increased significantly from 355 to 379 after the introduction of sixteenths. These statistics are consistent with the findings of Goldstein and Kavajecz (2000), who report that the quoted spread and the depth of the inside spread both decreased. Similarly, Ricker (1998) reports that the average quoted size for the S&P 500 dropped from 408 million to 224 million dollars.

Linking the exact times of the arbitrage trades reported to the NYSE to the spot and futures data, we find that, considering all arbitrage trades between 10:00 a.m. and 3:50 p.m. (Eastern Standard Time, or EST), the average percentage MPE that triggers arbitrage is similar before and after sixteenths. Although this is contrary to our expectations, a closer examination of the data reveals that this is most likely due to increased stock market volatility in the second half of 1997. Higher volatility results in an increase in timing risk and in tracking error risk (incurred if the arbitrageur does not buy or sell all the stocks underlying the index). When we condition all arbitrage trades on futures volatility in the 30 minutes prior to the arbitrage trade, we find a significant decrease in the average percentage MPE that triggers arbitrage. We also find that the mean-reversion in the MPE is stronger after sixteenths, which may be explained by the significant increase in the average number of arbitrageurs active at the same time. Finally, the MPE has to be significantly larger to trigger arbitrage when Rule 80A impedes the stock trade required for the arbitrage position. This is irrespective of the change in the minimum price increment.

The remainder of this study is organized as follows. The next section describes the data, the S&P 500 ask and bid index construction, and the calculation of the index-futures MPE. Section 3 reports on the identification of arbitrage opportunities and the sample characteristics of arbitrage opportunities before and after the introduction of sixteenths at the NYSE. Section 4 investigates the mean reversion in the MPE and section 5 concludes.

2. Data

2.1. Construction of the bid, ask, and trade-based S&P 500 index

The Trades and Quotes (TAQ) tapes from the NYSE include all trades and quotes for the 540 stocks[4] that were included in the S&P 500 index for all or part of 1997. For these 540 stocks, the last trade and bid and ask quotes from the primary exchange for each 15-second interval is extracted from the TAQ tapes[5]. For each day we have 1,561 observations, as the NYSE trades from 9:30 a.m. to 4:00 p.m. EST. To produce the last price or quote for each 15-second interval the original data (i.e. the TAQ tapes containing all trades and quotes) are filtered for data errors. The main filter eliminates large errors in trades and quotes, as these will seriously affect the index computation[6]. Not all stocks have trades and/or quotes available immediately at the start of the trading day. In these cases, the prices and quotes of the previous trading day are carried forward until the stock opens for trading. In the case of a stock split, the first available transaction price and quotes of the current trading day are used.

[4] More accurately, we should say that all trades and quotes for 540 stock codes were extracted from the TAQ database. The number of stock codes is larger than 500 due to index additions and deletions, company mergers, and changes to the ticker symbol (the ticker symbol changes, for example, when the primary exchange of a stock changes).

[5] S&P uses only prices from the primary exchange of each stock. The primary exchange for all stocks in the index for all or part of 1997 is either the AMEX (6), the NASDAQ (43), or the NYSE (491).

[6] For example, on April 17 at around 10:29 a.m. the trading prices for MSFT (Microsoft) are missing one digit, resulting in a price of $9.95 instead of $99.50. In addition, we exclude all prices or quotes that lead to immediate reversals (up-down or down-up) in excess of $0.75, all cases where the bid exceeds the ask, and all observations for which the TAQ recording shows a trading halt, an (unrepaired) time stamp error, or another recording error. Potential smaller remaining errors will have little impact on the index calculation as the index is a weighted average of 500 prices or quotes.

Standard & Poors provided the 500 index constituents for each trading day, as well as the number of shares used for each stock in the index calculation[7] and the daily divisor for the index. The latter is adjusted daily so that the index returns are not affected by removals or additions to the index or by mergers. The S&P bid and ask indices are calculated every 15 seconds as:

$$S_{t,i}^{ASK} = \sum_{n=1}^{500} s_{n,t} \cdot a_{n,t,i} / D_t \qquad (1)$$

$$S_{t,i}^{BID} = \sum_{n=1}^{500} s_{n,t} \cdot b_{n,t,i} / D_t \qquad (2)$$

where $s_{n,t}$ is the number of shares 'outstanding' for stock n on day t, $a_{n,t,i}$ and $b_{n,t,i}$ are the ask and bid quotes for stock n on day t in 15-second interval i (i = 1, …, 1561), and D_t is the divisor on day t. To monitor the accuracy of the index calculation procedure, we calculate a trade-based index using transaction prices and compare the results to the intraday S&P index as it is seen by futures traders in the futures trading pit[8]. The minimal deviations we find can be attributed to the fact that the S&P index as it is displayed to futures traders in the trading pit is not calculated on a precise 15-second grid Also, the S&P index lags our trade index slightly, probably due to the time it takes for S&P to process the last available transaction prices and disseminate the newly computed index to the market.

The bid and ask indices are then used to compute a 'midpoint' index:

$$S_{t,i}^{MID} = (S_{t,i}^{ASK} + S_{t,i}^{BID}) / 2 = \sum_{n=1}^{500} s_{n,t} \cdot (a_{n,t,i} + b_{n,t,i}) / (2D_t) \qquad (3)$$

[7] Note that the number of shares Standard & Poors uses for the index calculation is slightly different from the actual number of shares outstanding for each stock. Standard & Poors updates the number of shares every quarter unless the number of shares for a stock changes by more than 5%, in which case an immediate adjustment is made.

[8] These data are collected by the Futures Industry Institute (FII).

Since it takes some time before each stock has traded for the first time on a new trading day[9], and since the bid-ask spread widens and quotes are older at the end of each trading day, the first 30 minutes and the last 10 minutes of each day are excluded, leaving 1,401 observations per day.

2.2. S&P 500 Index-Futures

The Futures Industry Institute (FII) provided the transaction prices for the futures contracts on the S&P 500 index for 1997. The maturity dates for the individual contracts during 1997 are Thursday March 20th, June 19th, September 18th, and December 18th. At any given time, we consider the nearby contract until the Thursday one week prior to the maturity date of the nearby contract. From the Friday prior to the maturity date we use the next maturing contract. This schedule coincides closely with the day on which the next maturing contract surpasses the nearby contract in volume, and the day on which the Chicago Mercantile Exchange (CME) redesignates the next maturing contract as the lead contract in the main trading pit (Kawaller, Koch and Peterson, 1999). As with the stock prices and quotes, the last futures price for each 15-second interval is recorded, from 8:30 a.m. to 3:00 p.m. Central Standard Time (one hour behind EST). Excluding the first 30 minutes and the last 10 minutes of trading leaves 1,401 observations per day. For each 15-second interval we determine the futures implied index, trade index, bid index, and ask index. An example of how the futures and the different spot indexes relate to each other is presented in Figure 1.

<Insert Figure 1 about here>

2.3. Construction of the S&P 500 index-futures MPE

It almost seems that every existing study has a different way of computing the mispricing error and corresponding arbitrage opportunities. Neal (1996) points out that the outcome depends on ad hoc assumptions for short-sale restrictions, interest rates, and transaction

[9] See, for example, Aggarwal and Park (1994), for the effects of the staleness of the index at the start of the day.

costs. For the computation of the mispricing error the choice of interest rate is the major point of discussion. Chung (1991) and Miller, Muthuswamy and Whaley (1994), for example, use the Treasury bill (T-bill) rate, while MacKinlay and Ramaswamy (1988) use the higher Certificate of Deposit (CD) rate. Neal (1996) uses the data set of actual arbitrage trades to infer the interest rate such that the average mispricing error that triggers arbitrage is the same for buy programs (buy index, sell futures) and sell programs (sell index, buy futures). This approach implicitly assumes that there are no short-sale constraints. The interest rate that achieves this is 88 basis points above the T-bill rate. Whereas these studies incorporate dividends in one way or another, Dwyer, Locke and Yu (DLY, 1996) infer the entire cost-of-carry term by imposing a zero mean on the mispricing error. In this study we will follow two approaches. First, we will use actual dividends and the Eurodollar interest rate. Second, we will follow closely the approach of DLY.

2.3.1. Using actual cash dividends and risk-free rates

Miller, Muthuswamy and Whaley (MMW, 1994) use the theoretical cost-of-carry relationship between futures and spot prices

$$F_t = S_t e^{r(T-t)} - \sum_{i=1}^{n} D_i e^{r(T-t_i)} \tag{4}$$

where F_t is the futures price at time t and S_t is the index level at time t. The risk-free rate of interest, r, is assumed to be a known, constant and continuous rate. D_i represents the cash dividend paid at time t_i during the life of the futures contract ($t < t_i < T$). T is the expiration date of the futures contract.

To proxy the risk-free interest rate, MMW use the interest rate of the T-bill maturing most closely to the futures expiration, as reported in the *Wall Street Journal*. The proxy for the future cash dividends is the actual cash dividends during the futures' life, as reported by *The S&P 500 Information Bulletin*. There are two problems with this approach. First, the choice of the correct interest rate is critical, as there can be quite a difference between the T-bill, CD and LIBOR (Eurodollar) rates. Second, arbitrageurs do not actually know all dividends in advance. Even if dividends could be known with certainty, there would still be uncertainty regarding the exact stock price drop on the ex-dividend date[10]. Surprisingly, we failed to find any studies on index-futures arbitrage that consider this dividend literature. Futures and options on the index should be valued using the expected price drop as a result of the dividend, not the dividend itself. To compute the ratio of the ex-dividend day price drop to the amount of the dividend for S&P stocks, we used all actual cash dividends for all of 1997 for all stocks included in the S&P 500 index at some stage. For each dividend we determined the midpoint of the last quote for the stock (i) on the final day before the ex-dividend day, $P_{cum,i}$, the midpoint of the first firm quote for the stock on the ex-dividend day, $P_{ex,i}$, the closing midpoint index on the last day before the ex-dividend day, $S\&P_{cum,i}$, and the midpoint index at 10:00 a.m. on the ex-dividend day, $S\&P_{ex,i}$. Following Elton and Gruber (1970), the price drop dividend ratio ($PDDR$) is then computed as

$$PDDR = \frac{1}{N}\sum_{i=1}^{N}\frac{P_{cum,i} - P_{ex,i}\times\dfrac{S\&P_{cum,i}}{S\&P_{ex,i}}}{D_i} \qquad (5)$$

We calculate this ratio for 1997 to be 0.8313 with a standard error of 0.14. For the interest rate we use the 3-month Eurodollar rate. This is the rate at which banks can borrow from each other, and it is higher than the T-bill rate. We then define the mispricing error (MPE) in index-points,

$$MPE_{t,i} = \left(F_{t,i}e^{-r(T-t)} + \tilde{D}_t\right) - S_{t,i}^{MID} \qquad (6)$$

[10] It is the actual price drop as a result of the dividend that should be used when computing the present value of the dividends. In the literature there is no consensus about the ratio of the ex-dividend day price drop to the amount of the dividend, see for example Koski (1996), Elton and Gruber (1970), and Kalay (1982) who report a ratio between price drop and dividend of 0.702, 0.778, and 0.881, respectively.

where r is the 3-month Eurodollar interest rate, and $\tilde{D}_t$ is the present value of all dividends during the life of the futures contract, multiplied by the factor 0.8313. The MPE in percentage points is the MPE in index-points divided by the midpoint index. Interestingly, using this discount factor on the dividends has a similar effect to adding about 40 basis points to the Eurodollar interest rate, akin to Neal (1996) adding 88 basis points to the T-bill rate. We think our approach is more consistent with the literature on price drops on the ex-dividend day, and we also find it hard to believe the large investment banks that perform the arbitrage would have to pay such a high premium on the Treasury bill rate. From now on we will refer to the MPE in equation (6) as the cost-of-carry MPE.

2.3.2. Market-implied cost-of-carry term

DLY do not use interest rates and dividends at all. Instead they assume a zero mean for the MPE each day. Given the cost-of-carry model and using a dividend yield, q, instead of the present value of all dividends, the spot relates to the futures price as:

$$F_t = S_t e^{(r-q)(T-t)}$$

Taking the natural logarithm on both sides results in:

$$\ln F_t = \ln S_t + (r-q)(T-t)$$

DLY then define the MPE as:

$$z_{t,i} = (\ln F_{t,i} - \tfrac{1}{m}\sum_{i=1}^{m} \ln F_{t,i}) - (\ln S_{t,i}^{MID} - \tfrac{1}{m}\sum_{i=1}^{m} \ln S_{t,i}^{MID}) \qquad (7)$$

where m is the number of observations per trading day, in our case 1,401. The mean futures price and mean spot price for day t approximate the cost-of-carry term, implicitly imposing the mean MPE of zero. The assumption DLY make is that on average every trading day the market is in equilibrium.

We follow a similar approach with a slight variation, since we express everything in index-points. We define the futures implied index as

$$S_{t,i}^{FUT} = F_{t,i} e^{\frac{1}{m}\sum \ln(S_{t,i}^{MID} / F_{t,i})} \tag{8}$$

The MPE is then defined as

$$MPE_{t,i} = S_{t,i}^{FUT} - S_{t,i}^{MID} \tag{9}$$

From now on we will refer to the MPE in equation (9) as the market-implied MPE.

2.4. Sample statistics for the index and futures returns, and the MPE

Index and futures 15-second returns are computed using log differences. Overnight returns are excluded. The data are divided into two subsamples. The first sample, before the introduction of sixteenths, from January 3rd through June 23rd, 1997, comprises 119 trading days with 1,401 observations each (166,719 15-second intervals). The second sample, from June 24th through December 23rd, 1997, comprises 126 trading days[11] (175,166 15-second intervals[12]).

In Table 1, mean, standard deviation, and autocorrelation up to lag 4 are provided for index and futures returns and for the MPE.

<Insert Table 1 about here>

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[11] October 27 and October 28 are excluded from the sample due to extreme volatility and TAQ data recording problems. For more information on these days including arbitrage activity see Ross and Sofianos (1998).

As expected, the midpoint index volatility (0.00637 and 0.00763) is lower than the volatility of the trade index (0.00818 and 0.00843) because of the elimination of the bid-ask bounce. The difference in 15-second volatility drops from 22% in panel A to 9.5% in panel B, reflecting the decrease in spreads and therefore the bid and ask bounce. Furthermore, the autocorrelation in index returns is significantly larger for the midpoint index. The difference can be explained by the bid-ask bounce in the trade index, which renders the observed autocorrelations in the trade index a net effect of the negative autocorrelation caused by the bid-ask bounce and the positive autocorrelation of the returns of the underlying index. This explanation suggests that existing studies may underestimate the positive autocorrelation in indices.

Secondly, futures volatility is considerably higher than the index volatility. Futures volatility will overestimate the volatility due to the bid-ask bounce. Index volatility will underestimate the volatility due to the positive autocorrelation present in index returns. Miller, Muthuswamy and Whaley (1994) provide some theoretical results to support this in a simple AR(1) framework. Miller, Muthuswamy and Whaley also report that the MPE is mean-reverting regardless of the presence of an arbitrage opportunity. The statistics in Table 1 include all observations, the majority of which do not present arbitrage opportunities.

Thirdly, when comparing the cost-of-carry MPE with the market-implied MPE, there are some obvious differences. By construction, the market-implied MPE has a mean close to zero. The cost-of-carry MPE, however, has a positive mean. The difference between the cost-of-carry MPE and the market-implied MPE translates into different profits for buy and sell programs. The gap between the two MPEs is especially large after the introduction of sixteenths. The mean cost-of-carry MPE could be reduced by using higher interest rates (a procedure followed by Neal, 1996), or by using a discount factor for the dividends that is lower than the 0.8313 used here. We leave this issue as an interesting area for future research.

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[12] Note that on July 3 and November 28 trading stopped early, so for these days only 721 observations are extracted (from 10:00 a.m. through 13:00 p.m. EST).

3. Identifying arbitrage opportunities and SEC arbitrage trade reports

3.1. Identifying arbitrage opportunities and transaction costs

Arbitrage opportunities can be identified as follows:

Buy program: Buy stocks, sell futures

$$MPE_{t,i} > U_{t,i} \tag{10a}$$

Sell program: Sell stocks, buy futures

$$MPE_{t,i} < -D_{t,i} \tag{10b}$$

An arbitrage buy program is initiated when the MPE exceeds the upper bound, $U_{t,i}$. An arbitrage sell program is initiated when MPE drops below the lower bound, $-D_{t,i}$. We believe that the complexity of index arbitrage makes it impossible to determine the upper and lower bounds using statistical models[13]. Numerous factors play a role in determining the arbitrage bounds, including Rule 80A, short-selling, tracking error, time-varying transaction costs, timing risk, dividend risk, interest rate risk, and the uncertain value of the early liquidation option (see Brennan and Schwartz, 1990). Miller, Muthuswamy and Whaley (1994) indicate that for constant U and D many MPEs will be incorrectly identified as arbitrage opportunities. The identification of U and D is also made more difficult because the MPE is mean-reverting at any level, and because, as shown in Table 1, U and D also depend on the method of calculating the MPE. For these reasons the NYSE reports on the actual arbitrage trades are essential.

Relieved of the need to estimate U and D, we will focus on the potential impact of sixteenths on transaction costs, a component that is studied in every arbitrage paper. We

[13] Threshold Autoregressive models can determine a constant threshold. This tool is used, for example, by Dwyer, Locke and Yu (1996) and Martens, Kofman and Vorst (1998).

consider four different measures of the spread on the index. First, the quoted spread in index-points is defined as

$$QSPREAD_{t,i} = S_{t,i}^{ASK} - S_{t,i}^{BID} = \sum_{n=1}^{500} s_{nt} \cdot (a_{n,t,i} - b_{n,t,i}) / D_t \quad (11)$$

Second, we define the relative quoted spread,

$$QSPREAD\_REL_{t,i} = 100 \cdot (S_{t,i}^{ASK} - S_{t,i}^{BID}) / S_{t,i}^{MID}. \quad (12)$$

Neal (1996) reports that arbitrageurs earn on average less than half the quoted spread. Hence, arbitrageurs need to be able to trade inside the quoted spread. Also, Madhavan and Sofianos (1998) report that NYSE specialists on average participate in only 30% of all non-block stock trades. The participation rate of the specialist is even lower for actively traded stocks. The remaining trades are executed between market participants, and therefore they could potentially trade at zero transaction costs. For these reasons the effective spread is of interest. The effective spread for each stock is calculated as twice the deviation of the transaction price from the quote midpoint. The effective spreads are then weighted according to each stock's weight in the index, and then the spread is again computed in both index-points and percentage points:

$$ESPREAD_{t,i} = \sum_{n=1}^{500} s_{nt} \cdot abs(2 \cdot [(a_{n,t,i} + b_{n,t,i})/2 - p_{n,t,i}]) / D_t \quad (13)$$

and

$$ESPREAD\_REL_{t,i} = 100 \cdot (\sum_{n=1}^{500} s_{nt} \cdot abs(2 \cdot [(a_{n,t,i} + b_{n,t,i})/2 - p_{n,t,i}]) / D_t) / S_{t,i}^{MID} \quad (14)$$

where $p_{n,t,i}$ is transaction price for stock n on day t in 15-second interval i. The characteristics of these spread measures for the S&P 500 are provided in Table 2a.

<Insert Table 2a about here>

As previously documented in Ricker (1998) and Goldstein and Kavajecz (2000) the introduction of sixteenths reduced bid and ask spreads and therefore trading costs. Ricker reports for April to September 1997 a drop of the average quoted spread in cents per share from 14.78 to 10.59, and a drop of the percentage spread from 0.277% to 0.187%. These numbers are comparable to the results in Table 2a where we report a reduction in relative quoted spreads from 0.300% to 0.213%. In index-points the quoted spread decreased from 2.40 to 2.00. Interestingly, the volatility of the spread increased, from 10.3% to 19.4% for the quoted spread. Similar to the quoted spreads, after the introduction of sixteenths the effective spread decreases from 1.59 index-points to 1.15 index-points. Comparing the quoted and effective spreads shows how much can be saved if a substantial number of the stocks underlying the index are traded outside the specialist. For example, the 'after sixteenths' quoted spread is 2.00 index-points, compared to an effective spread of 1.15 index-points. This is a large difference, especially if one considers that the gross return on an 'after sixteenths' round-trip arbitrage[14] is only about 1.84 index-points for the cost-of-carry MPE and 1.53 index-points for the market-implied MPE.

The potential cost reduction is further investigated by considering the case in which an arbitrageur buys a sub-sample of the stocks underlying the S&P 500 index. The NYSE data shows that for many trades, arbitrageurs do indeed buy or sell a subset of the stocks in the index. Although this strategy leads to a tracking error, it can also lead to a cost reduction. Equally importantly, it also enables arbitrageurs to buy only the most liquid stocks, guaranteeing the speed necessary to acquire the arbitrage position. Finally, Rule 80A at times allows arbitrageurs to buy or sell only a limited number of stocks within a reasonable amount of time. Overdahl and McMillan (1998) find that Rule 80A has little impact on trading costs and intermarket arbitrage, but there is a significant curtailment of index arbitrage volume. Table 2b shows the spread related transaction costs of buying the *N* cheapest (panel A) or the *N* largest stocks (panel B) from the S&P index universe.

[14] A round-trip arbitrage would involve setting up, for example, a buy program (buy stocks, sell futures) when the MPE is positive, and liquidating this position prior to maturity when the MPE is negative.

<Insert Table 2b about here>

The results show that substantial cost savings are possible by trading a sub-sample of the 500 stocks underlying the S&P 500 index. For example, for arbitrageurs buying only the cheapest 150 stocks, the average quoted spread in index-points reduces from 2.40 to 1.41 prior to sixteenths, and from 2.00 to 1.07 after sixteenths. These 150 stocks have a combined weight of over 50% in the index, and this portfolio could well be sufficient to obtain an acceptable level of tracking error. The decrease in the effective spread with the introduction of sixteenths is of similar relative magnitude. In panel B, the stock portfolios are formed by market capitalization rather than by the spread. The results are qualitatively similar to those in panel A, but smaller gains are obtained with regard to the effective spread.

3.2. Sample characteristics of arbitrage trades

As argued in Section 3.1, relying solely on price data to identify arbitrage opportunities is an impossible task. Although transaction costs have decreased after sixteenths, too many other factors play a role in determining an arbitrage opportunity.

The Securities and Exchange Commission (SEC) requires the reporting of all program trades (a trade in which 15 stocks or more are traded at the same time) by member firms of the exchange. We obtained these daily program trading records from the NYSE[15] for 1997. For each index arbitrage trade, the data contain the submission time (to the nearest minute or to the nearest second) for both the stock and corresponding futures trade, and whether the trade is a buy (buy stocks, sell futures) or a sell (sell stocks, buy futures), or short sell (short sell stocks, buy futures). In addition, the data show the number of stocks

(Liquidating the position is the equivalent of to setting up a new position that involves selling stocks and buying futures).

[15] Note that member firm identifiers were removed by the NYSE. We report results aggregated across firms.

involved in the trade[16], the dollar volume of the stock position, the number of futures contracts, and the maturity of the futures contracts.[17]

The total number of arbitrage trades between 10:00 a.m. and 3:50 p.m. before and after the introduction of sixteenths is presented in the last column of Table 3.

<Insert Table 3 about here>

The daily program trading reports show there are 4,311 index-futures arbitrage trades after the introduction of sixteenths compared to 3,158 before. Even when taking into account the slightly larger size of the second sample (126 days versus 119 days) this indicates a substantial increase in arbitrage activity after the introduction of sixteenths. The average dollar amount underlying each trade drops significantly from 16.5 to 13.8 million dollars, with a t-statistic of 10.6. These numbers corroborate findings by Ricker (1998), who reports that quoted size for the stocks of the S&P 500 dropped from 408 million to 224 million dollars, and by Goldstein and Kavajecz (2000), who report that the depth of the cheapest quotes decreased after the introduction of sixteenths. The average number of stocks underlying each arbitrage trade increased significantly from 355 to 379, with a t-statistic of 8.0. With the reduced spreads it is possible to buy more stocks at lower costs, thereby reducing the tracking error. The lower total dollar amount and higher number of stocks per arbitrage trade also indicates that on average fewer shares are purchased of each stock, probably due to the reduced depth of the cheapest quotes. Similar conclusions apply to the various categories of arbitrage trades, i.e., buy programs, sell programs and in periods when rule 80A is inactive and active. The only exception is for short-sell programs, where there is little difference in the average dollar value and

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[16] Often an arbitrage trade has two separate entries that directly follow each other. Generally the first entry specifies the trade for the stocks on the NYSE, whereas the second (smaller) trade specifies the trade of the NASDAQ stocks that are part of the S&P 500 index. These related entries are aggregated for the analysis.

[17] Like Neal (1996), we filtered the data for errors. Obvious typing errors have been corrected. Entries for which the futures and equity times are more than 15 minutes apart are eliminated. Trades that include 40 or fewer stocks (after NASDAQ trades are combined with NYSE trades) are eliminated. The time-stamp used for computing all arbitrage related statistics is determined by the earliest time, either the time for the stock or for the futures trade. Trades where the absolute difference between the dollar value underlying the stock and futures trades is more than 40% of the dollar value underlying the stock trade are eliminated. Lastly, trades for which the average price per share is lower than $10 or higher than $100 are eliminated.

number of stocks underlying the 176 arbitrage trades before sixteenths and the 172 trades after sixteenths.

Table 3 also reports the results for the mispricing errors defined in equations (6) and (9). Given the substantial reduction in transaction costs after the introduction of sixteenths, it is surprising to note that regardless of how the mispricing error is constructed, the average MPE that prevails when arbitrage trades are initiated is little changed. For example, the average cost-of-carry MPE (market-implied MPE) that triggers arbitrage is 0.103% (0.0794%) before sixteenths, and 0.102% (0.0817%) after sixteenths[18]. We hypothesize that the MPE is reduced by the introduction of sixteenths, but that any reduction is offset by the higher market volatility in the second half of 1997. This issue will be tested in Table 4.

In Table 3 we include all of the variations of the MPE described previously. However, we suggest that in comparing the two panels it is important to refer to the percentage mispricing error, and not to the mispricing error expressed in index points. The average S&P 500 index value before sixteenths is 801.23, whereas it is 938.77 after sixteenths. This increase in the index level explains the increase in the average MPE measured in index-points that triggers arbitrage after sixteenths. Additionally, there is a large difference between the cost-of-carry MPE and the market-implied MPE. We suspect that, for our data sample, the market-implied MPE underestimates the true MPE. The calculation of the market-implied MPE assumes that the average of the mispricing errors is zero for each day. Since futures prices lead the index, in an upward (downward) trending market the average daily MPE is expected to be positive (negative). Therefore the calculation of market-implied MPEs biases positive (negative) MPE numbers downward (upward) decreasing the absolute mispricing errors and underestimating profits from buy and sell programs alike. On the other hand, calculating the cost-of-carry MPE requires a correct interest rate and price drop to dividend ratio, both of which are subject to debate. For this reason, we will continue to discuss the results for both MPE

[18] The conclusions here and below are not affected by computing the median instead of the mean MPE.

measures, and we will only make conclusions regarding results that are robust to both of the MPE measures[19].

With the results presented in the first nine columns of Table 3 we investigate in greater detail the differences between buy and sell programs and the impact of Rule 80A. First, consider the difference between buy and sell programs. The assumptions underlying the market-implied MPE suggest that the MPEs should be symmetric, but the table shows that sell programs are executed at a significantly higher MPE than are buy programs. This result differs from the findings of DLY who observe no asymmetry[20]. For the cost-of-carry MPE, no difference is found in Panel A, but in Panel B buy programs require a significantly higher MPE than do sell programs. As mentioned in Section 2.4, using too high a price drop to dividend ratio after sixteenths may cause this. Hence, it is difficult to make any conclusion regarding asymmetry between buy and sell programs.

For both MPE measures Rule 80A has a significant impact on the arbitrageurs' decisions of when and how to initiate trades. Significantly fewer stocks are used for arbitrage trades when Rule 80A was in effect. This suggests that Rule 80A forces arbitrageurs to execute arbitrage trades with smaller portfolios of stocks, which in turn presumably results in higher tracking error and therefore increased risk for the arbitrageur. Accordingly, for all MPE measures the average MPE that triggers arbitrage

[19] We also computed the average MPEs using the Futures Industry S&P500 index tick data. As mentioned in Section 2.1, this is the index disseminated to the financial markets by Standard & Poors. For all arbitrage trades and the cost-of-carry (market-implied) MPE measure, the average MPE that triggers arbitrage is 0.110% (0.0865%) and 0.111% (0.0913%) before and after sixteenths, respectively. Comparing these results to the ones in the final column of Table 3, in general the average MPE that triggers arbitrage appears to be almost 0.01% higher when computed using the S&P 500 index as distributed to the financial markets. We think this can be attributed to the improved accuracy of our midpoint index, which is based on quotes rather than on past transaction prices. Also, our index is computed every 15 seconds, whereas S&P does not follow exactly the 15-second grid, and we use the time stamps for the quotes in the TAQ database. Presumably there is some interval between Standard & Poors collection of the last trading price for each constituent and the posting of the computed index to the financial markets. This lag would lead to an overestimation of arbitrage profits for the same reason that we think the market-implied MPE underestimates arbitrage profits. If futures lead the spot market, an older index will lead to an apparently larger mispricing error. It would be interesting to know whether arbitrage traders actually have immediate access to all quotes to compute our more accurate midpoint index, or whether they only have the trade-based index as released by S&P. In the latter case they would have to make an ad-hoc adjustment to the observed mispricing error.

[20] DLY perform a non-parametric test on the asymmetry of the mispricing error around zero regardless of whether arbitrage is possible.

is significantly higher when Rule 80A in effect. For example, the average cost-of-carry MPE for buy programs prior to sixteenths is 1.08 index-points when Rule 80A is in effect and 0.765 index-points when Rule 80A is not applicable. These results provide additional insights into the effects of Rule 80A on arbitrage.

That the introduction of sixteenths does not apparently affect MPEs merits further investigation to identify other characteristics of the two periods that may affect arbitrageurs' decisions of when to initiate arbitrage trades. An obvious candidate is the risk of initiating the position. The volatility in the two data panels is significantly different. Increased volatility of the futures and the underlying market will increase the execution risk for the position. In periods of high volatility, one would expect arbitrageurs to initiate trades only at somewhat higher MPEs to compensate for the increased price risk of non-simultaneous order execution. Table 4 conditions the data in the two panels on the 30-minute volatility of the futures returns immediately preceding the arbitrage event. We chose the futures volatility over the volatility of the underlying stocks because the bid-ask bounce in futures prices is deemed a less serious problem than the serial correlation in index returns. The bid-ask bounce is present in all volatility categories and therefore should not affect the categorization of the data. Table 4 presents the results for all arbitrage trades that were not impeded by Rule 80A.

<Insert Table 4 about here>

Volatility increased substantially in the second part of 1997, as is evidenced by the much larger number of observations in the three highest volatility brackets in Panel B than in Panel A. Table 4 also shows that the higher the (index-futures) volatility, the higher the average MPE that triggers arbitrage. For example, the cost-of-carry MPE in Panel B averages 0.0793% for the lowest volatility range, and increases to 0.114% for the highest volatility range. The higher volatility after the introduction of sixteenths creates the impression in Table 3 that the reduction of transaction costs had little impact on the average MPE that triggers arbitrage.

After we control for the increased volatility we find a significant reduction in the average MPE that triggers arbitrage after the introduction of sixteenths. The mean of the average market-implied MPE for the five middle volatility ranges (0.015-0.020, …, 0.035-0.040) is 0.0843% before and 0.0748% after sixteenths. For the cost-of-carry MPE the mean is 0.0922% before and 0.0869% after sixteenths[21]. If we construct a new series by computing the difference in average MPE for each volatility category before and after sixteenths, we find that for both the cost-of-carry MPE and the market-implied MPE there is a significant drop in the average MPE that triggers arbitrage. The t-statistics are 2.6 and 3.3 for the cost-of-carry and market-implied MPE, respectively. For the market-implied MPE we find larger differences before and after sixteenths when considering sell programs separately (results not reported in Table 4). The mean of the average MPE for the five middle volatility ranges is –0.0939% before sixteenths, and –0.0777% after sixteenths. This translates into a reduction of 0.0162%, or 0.1458 index-points for an S&P index level of 900.

Hence, when conditioning upon volatility we do find evidence of a reduction in the average MPE that triggers index-futures arbitrage. The magnitude of the difference is less than half the reduction in transaction costs as measured by the quoted and effective spreads. This again illustrates the ability of arbitrageurs to trade inside the quoted spread and to avoid the market makers for at least part of the stocks, which in turn reduces the benefit of the decreased spreads. The cost benefits from the reduction in the minimum price increment are potentially larger for institutional arbitrageurs. However, they face higher commission costs and a lower ability to internally match client orders and trade with other member firms to reduce transaction costs incurred by trading through the market makers. In spite of these qualifications, the reduction in the minimum price increment does have the expected effect of reducing the magnitude of mispricing errors.

[21] To get a feeling for these differences in economic terms consider the situation where the S&P index is at 900. A difference of 0.0922% – 0.0869% = 0.0053% translates into 0.0477 index-points. Compare this to a 0.40 index-points reduction in the average quoted spread, or 0.20 index-points for a one-way trip. For the market-implied MPE the difference of 0.0843% – 0.0748% = 0.0095% translates into 0.0855 index-points.

4. Mean-reversion of the MPE

The premise of index arbitrage is that taking arbitrage positions dissipates any mispricing between the futures price and the index value. To evaluate the validity of this statement and to gain additional insight into the process of mean reversion of the market-implied MPE, Figure 2 presents an event study type plot of mispricing[22]. The graph centers on the event of index arbitrage trades. The deviation from fair value is examined for the interval from 10 minutes (40 periods) prior to the arbitrage trade to 10 minutes after the arbitrage trade.

<Insert Figure 2 about here>

Figure 2 is similar in format to Figure 2 in Neal (1996), except that we represent the MPE before and after sixteenths separately and in percentage points rather than index points.[23] Consistent with our expectations, we find clear evidence of mean reversion. Within five minutes after the arbitrage trade event the mean mispricing decays more than 75%. The speed of decay accelerates for the period after the introduction of sixteenths particularly for the sell programs. An indication for increasing competition among arbitrageurs in 1997 is that after sixteenths were introduced it took an average of 2.25 (4) minutes, or 45 seconds (1 minute) less than before, for market-implied (cost-of-carry) MPEs to half after arbitrage transactions were initiated. Regardless of the method of MPE calculation the acceleration in mean reversion is pervasive.

Comparing our results to those of Neal, we see an apparent dramatic improvement in market efficiency. Mean MPEs 10 minutes after arbitrage events are very close to zero. The MPEs triggering arbitrage transactions, i.e. those at or around the event, arise and dissipate much more quickly than during the period Neal studied[24]. Whether these results

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[22] Using the cost-of-carry MPE instead of the market-implied MPE does not materially change Figure 2.

[23] Graphs of the MPE in index points have the same shape as our percentage graph. However, as mentioned in Section 3.2, the large difference in the level of the S&P 500 index before and after sixteenths would result in an apparently larger MPE after sixteenths.

[24] Neal reports that for buy programs the mean MPE (in index-points) falls from 0.54 to 0.31 in the 10 minutes after the arbitrage trade, whereas for sell programs the mean MPE drops from –0.54 to –0.32. In our data, the mean market-implied MPE (in percentage points) before sixteenths drops from 0.071% to 0.010% within 10 minutes for buy programs, and from –0.083% to –0.017% for sell programs. The cost-

are indeed due to increased market efficiency and the increased presence of arbitrageurs or are due to improved data quality cannot be determined with certainty.

To quantify the mean reversion of the MPE more accurately, we calculate the coefficients of a variation of a standard threshold auto-regressive (TAR) model,[25]

$$MPE_t = a_0 + \sum_{k=1}^{K} a_k \cdot MPE_{t-k} + e_t \,. \tag{15}$$

Coefficient estimates for a_1 are reported in Table 5. Existing studies rely on an estimated constant threshold variable to divide the data into three regimes ('buy programs', 'no arbitrage', and 'sell programs'). This assumption leads to many observations being incorrectly identified as arbitrage opportunities (MMW 1994). Rather than following this static approach, we use the SEC data listing actual arbitrage transactions to categorize the data into the three regimes.

<Insert Table 5 about here>

Based on the evidence in Figure 2 of the duration of arbitrage opportunities, we calculate the mean reversion coefficient for time intervals ranging from 15 seconds to two minutes. The coefficient estimates show that increasing the data frequency does not necessarily translate into more accurate estimates for the mean reversion of the MPE. On the contrary, for very short intervals the MPE does not decay much at all since it takes some time for arbitrage trades to reverse MPEs. Additionally, the time series in the no-arbitrage regime displays mean reversion in the MPE for reasons explained in MMW (1994). Therefore, the coefficients for mean reversion should not be considered independently, but rather relative to the no-arbitrage regime. Considering the 2-minute frequency, we observe that the MPE decays more quickly in the outer regimes when arbitrage is possible than it does in the no-arbitrage regime. Comparing the two panels,

of-carry MPE (in percentage points) before sixteenths drops from 0.101% to 0.039% within 10 minutes for buy programs, and from –0.101% to –0.034% for sell programs.

the coefficient estimate for a_1 at the two minute frequency drops from 0.360 (0.441) to 0.247 (0.333) for the buy (sell) regime after the introduction of sixteenths[26]. Hence, the mean-reversion of the MPE is faster after the introduction of sixteenths. Since the average dollar size of arbitrage trades has decreased after sixteenths, one possible explanation is that more arbitrage traders are active at the same time. The average number of arbitrage trades per 15-second interval, considering only those intervals in which arbitrage trades occurred, increased significantly from 1.086 before sixteenths to 1.130 after sixteenths, with a t-statistic of 5.0. The difference indicates that the number of parties engaging in index arbitrage trades increased with the decrease in transaction costs. Perhaps the reduction of transaction costs provides a more level playing field between the member firms that can internally match client orders with the arbitrage trades and the institutional investor who more likely need the market makers for fast execution.

5. Conclusion

On June 24, 1997, the New York Stock Exchange reduced the minimum change for stock prices and quotes from an eighth to a sixteenth of a dollar. This study investigates the impact of the resulting decrease in spreads on S&P 500 index-futures arbitrage. For the second half of 1997 we find that there is a significant increase in the number of arbitrage opportunities, verified by the increase in arbitrage trades as reported to the Securities and Exchange Commission. The average dollar amount underlying each arbitrage trade decreases and the average number of different stocks involved in each arbitrage trade increases. These averages are consistent with findings in the literature that the quoted depth of the inside spread decreased after the introduction of sixteenths.

We find that the average mispricing error that triggers arbitrage is significantly smaller after sixteenths. The reduction in the mispricing error, however, is less than half the average reduction in transaction costs. We think this is related to the ability of

[25] Time t-1 is 15 seconds after the time-stamp in the SEC files. All other MPEs are taken from the grid determined by the data frequency. For example, at the 60-second frequency t will be 75 seconds after the time-stamp in the SEC files.

arbitrageurs to circumvent the NYSE specialists for a substantial number of the stocks required for arbitrage. As a result, arbitrageurs only partly benefited from the reduced spreads. We do find a slight increase in the number of arbitrageurs active at the same time, and the speed of mean-reversion has also increased after sixteenths. This is despite the lower average dollar volume per arbitrage trade.

For future research it will be interesting to see the impact of the imminent introduction of a decimal pricing system. Only a (small) sub-sample of the stocks is quoted at the minimum spread of one sixteenth. If market makers find one sixteenth too small to be profitable, at present the next possible quote is one eighth. Decimal pricing will make it possible to quote spreads in-between one eighth and one sixteenth, potentially reducing trading costs further.

[26] Similar results are obtained for the cost-of-carry MPE. For the two-minute frequency the estimate for a_1 drops from 0.399 (0.471) to 0.200 (0.370) for the buy (sell) regime after the introduction of sixteenths.

References

Aggarwal, Raj, and Young S. Park (1994), The relationship between daily U.S. and Japanese equity prices: Evidence from spot versus futures markets, *Journal of Banking and Finance* 18, 757-773.

Bali, Rakesh, and Gailen L. Hite (1998), Ex dividend day stock price behavior: discreteness or tax-induced clienteles?, *Journal of Financial Economics* 47, 127-159.

Brennan, Michael J., and Eduardo S. Schwartz (1990), Arbitrage in stock index futures, *Journal of Business* 63, 7-31.

Chan, Kalok (1992), A further analysis of the lead-lag relationship between the cash market and stock index futures market, *The Review of Financial Studies* 5 (1), 123-152.

Chung, Y. Peter (1991), A transaction data test of stock index futures market efficiency and index arbitrage profitability, *Journal of Finance* 46 (5), 1791-1809.

Dwyer, Gerald P. Jr., Peter Locke, and Wei Yu (1996), Index arbitrage and nonlinear dynamics between the S&P 500 futures and cash, *The Review of Financial Studies* 9 (1), 301-332.

Elton, Edwin J., and Martin J. Gruber (1970), Marginal stockholder tax rates and the clientele effect, *Review of Economics and Statistics* 52, 68-74.

Goldstein, Michael A., and Kenneth A. Kavajecz (2000), Eighths, sixteenths and market depth: Changes in tick size and liquidity provisions on the NYSE, *Journal of Financial Economics* 56, 125-149.

Kalay, Avner (1982), The ex-dividend day behavior of stock prices: A re-examination of the clientele effect, *Journal of Finance* 37, 1059-1070.

Kawaller, Ira G., Paul D. Koch, and John E. Peterson (1999), Volume and volatility surrounding quarterly redesignation of the lead S&P 500 futures contract, working paper University of Kansas.

Koski, Jennifer Lynch (1996), A microstructure analysis of ex-dividend stock price behavior before and after the 1984 and 1986 tax reform acts, *Journal of Business* 69, 313-338.

MacKinlay, A. Craig, and Krishna Ramaswamy (1988), Index-futures arbitrage and the behavior of stock index futures prices, *The Review of Financial Studies* 1 (2), 137-158.

Madhavan, Ananth, and George Sofianos (1998), An empirical analysis of NYSE specialist trading, *Journal of Financial Economics* 48, 189-203.

Martens, Martin, Paul Kofman, and Anton C.F. Vorst (1998), A threshold error-correction model for intraday futures and index returns, *Journal of Applied Econometrics* 13, 245-263.

Miller, Merton H., Jayaram Muthuswamy, and Robert E. Whaley (1994), Mean reversion of Standard & Poor's 500 index basis changes: Arbitrage induced or statistical illusion?, *Journal of Finance* 49 (2), 479-513.

Neal, Robert (1996), Direct tests of index arbitrage models, *Journal of Financial and Quantitative Analysis* 31(4), 541-562.

Overdahl, James, and Henry McMillan (1998), An evaluation of the effects of NYSE Rule 80A on trading costs and intermarket arbitrage, *Journal of Business* 71 (1), 27-53.

Ricker, Jeffrey P. (1998), Breaking the eighth: Sixteenths on the New York Stock Exchange, working paper.

Ross, Katharine, and George Sofianos (1998), An analysis of price volatility October 27 and 28, 1997, NYSE Working Paper 98-04.

Stoll, Hans R., and Robert E. Whaley (1990), The dynamics of stock index and stock index futures returns, *Journal of Financial and Quantitative Analysis* 25 (4), 441-468.

Figure 1: Futures implied, Trade, Ask and Bid indices on February 10, 1997.

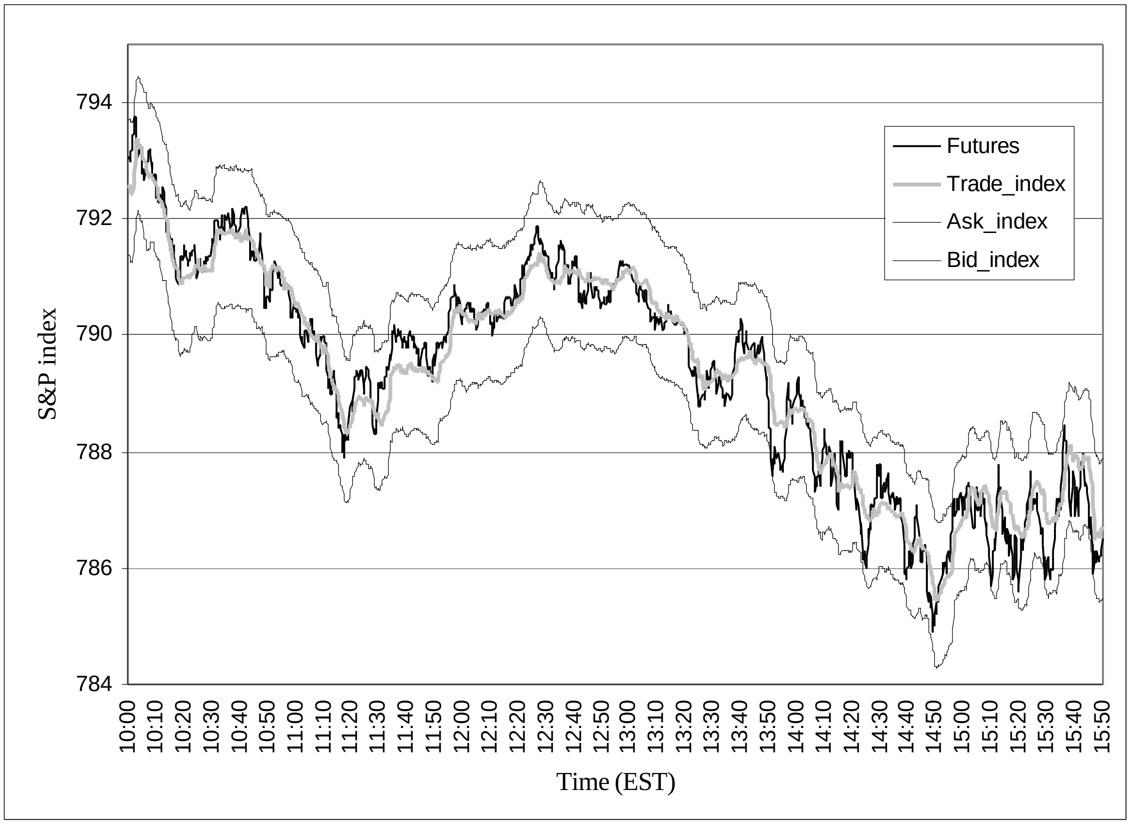

Figure 2: Percentage MPE around reported arbitrage trades before and after the introduction of sixteenths

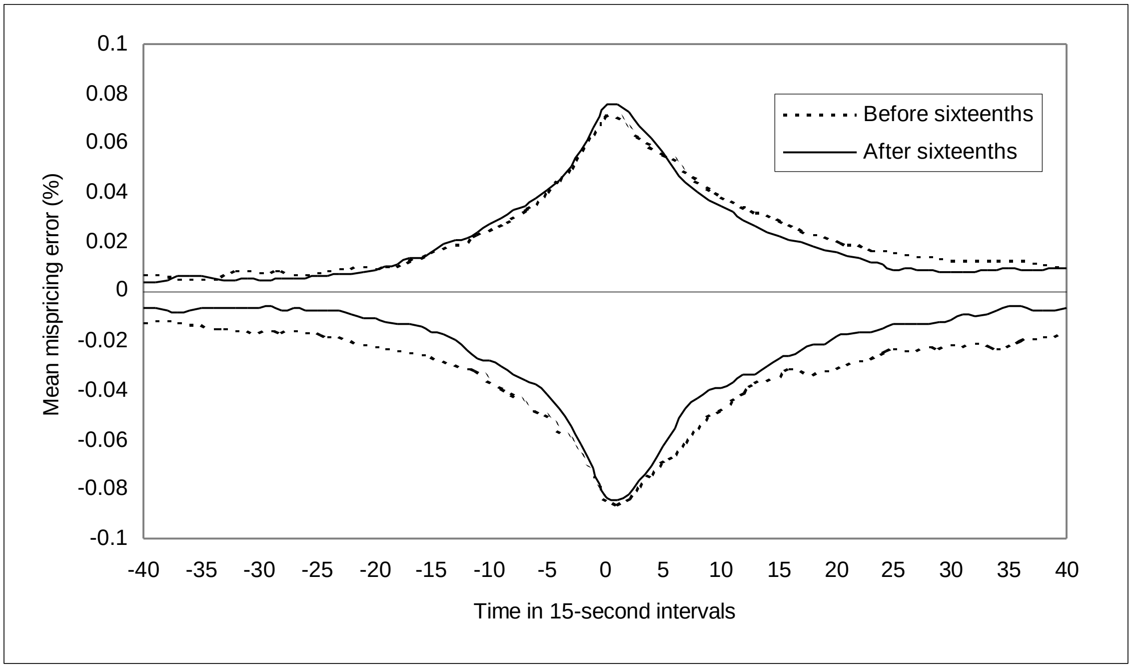

Table 1: Properties of index and futures returns, and the MPE

Series	Mean (%)	SD (%)	r_1	r_2	r_3	r_4
Panel A: Before the introduction of sixteenths at the NYSE (3 January – 23 June, 1997)						
Trade index	0.0000385	0.00818	0.314	0.320	0.287	0.255
Midpoint index	0.0000376	0.00637	0.678	0.572	0.485	0.417
Futures	0.0000469	0.0243	−0.0972	0.0167	0.0134	0.00679
MPE (cost-of-carry)	0.00813	0.0782	0.950	0.910	0.873	0.841
MPE (market-implied)	0.0000175	0.0591	0.912	0.841	0.777	0.719
Panel B: After the introduction of sixteenths at the NYSE (24 June – 23 December, 1997)						
Trade index	−0.0000000345	0.00843	0.560	0.497	0.422	0.357
Midpoint index	−0.00000133	0.00763	0.756	0.633	0.528	0.443
Futures	−0.00000796	0.0286	−0.116	−0.00167	0.0110	0.0123
MPE (cost-of-carry)	0.0258	0.0722	0.919	0.857	0.804	0.760
MPE (market-implied)	0.0000169	0.0582	0.874	0.779	0.697	0.628

Sample mean, standard deviation (SD), and autocorrelation (r) of trade index returns, midpoint index returns, futures returns, the mispricing error (MPE) according to the cost-of-carry model, and the market implied MPE. The data frequency is 15-second intervals, with the first 30 minutes and the last 10 minutes of each trading day excluded, leaving 1,401 observations per day (except for July 3 and November 28, where the NYSE closed at 13:00 p.m.). Overnight price changes are excluded. The 'trade index' is the index value computed from the last transaction price for each stock prior to or on the 15-second mark. The 'midpoint index' is the average of the ask and bid indices, each of which is computed based on the last (ask and bid) quotes for each stock prior to or on the 15-second mark. The 'cost-of-carry' MPE is based on the cost-of-carry model using the 3-month Eurodollar interest rate and discounting the present value of actual dividends by a factor 0.8313. The 'market-implied' MPE is constructed such that the average difference between the log futures price and log midpoint index for each trading day is equal to zero. Both MPEs are in percentage points, dividing the difference between the futures implied index and midpoint index by the midpoint index and multiplying by 100.

Table 2a: The S&P 500 index bid-ask spread

	January 3 – June 23, 1997 (before introduction sixteenths)				June 24 – December 23, 1997 (after introduction sixteenths)			
	Quoted spread	Effective spread	Quoted spread	Effective spread	Quoted spread	Effective spread	Quoted spread	Effective spread
	(index-points)		(percentage)		(index-points)		(percentage)	
Mean	2.40	1.59	0.300	0.198	2.00	1.15	0.213	0.122
Standard dev.	0.103	0.0919	0.0179	0.0122	0.194	0.179	0.0208	0.0192
Maximum	3.63	2.85	0.435	0.345	4.06	5.13	0.440	0.550
Minimum	2.06	1.19	0.240	0.142	1.43	0.802	0.156	0.0860

Sample mean, standard deviation, maximum and minimum of the S&P 500 index bid-ask spread. The quoted spread is the difference between the ask index and the bid index (in index-points) or the difference between the ask index and bid index divided by the midpoint index (relative spread). The effective spread is the market capitalization weighted effective spread of the 500 stocks comprising the index, where the effective spread for each stock is either computed as the absolute difference between the midpoint of the stock's bid and ask quotes and the stock's trading price (in index-points). The relative effective spread is the effective spread in index-points divided by the midpoint index. The data frequency is 15-second intervals, with the first 30 minutes and the last 10 minutes of each trading day excluded, leaving 1401 observations per day (except for July 3 and November 28, where the NYSE closed at 13:00 p.m.).

Table 2b: Cost of tracking the index using less than 500 stocks

	January 3 – June 23, 1997 (before introduction of sixteenths)				June 24 – December 23, 1997 (after introduction of sixteenths)			
	Quoted spread		Effective spread		Quoted spread		Effective spread	
Number of stocks	Spread in index-points	Proportion of index	Spread in index-points	Proportion of index	Spread in index-points	Proportion of index	Spread in index-points	Proportion of index
Panel A: Stocks sorted on percentage spread, include cheapest								
50	1.01	0.273	0.00	0.100	0.77	0.247	0.00	0.10
100	1.27	0.464	0.02	0.190	0.92	0.394	0.01	0.20
150	1.41	0.571	0.37	0.400	1.07	0.517	0.21	0.37
200	1.55	0.670	0.68	0.570	1.20	0.628	0.44	0.56
250	1.68	0.750	0.90	0.710	1.33	0.721	0.57	0.68
300	1.81	0.823	1.05	0.790	1.44	0.798	0.68	0.77
350	1.94	0.881	1.19	0.870	1.57	0.866	0.78	0.85
400	2.07	0.929	1.32	0.930	1.69	0.922	0.89	0.92
450	2.22	0.970	1.44	0.970	1.82	0.966	1.00	0.97
500	2.40	1.000	1.59	1.000	2.00	1.000	1.16	1.00
Panel B: Stocks sorted on market capitalization, include largest								
50	1.76	0.487	1.21	0.490	1.55	0.491	0.91	0.49
100	1.91	0.656	1.30	0.660	1.66	0.660	0.98	0.67
150	2.02	0.754	1.36	0.750	1.72	0.759	1.01	0.77
200	2.10	0.826	1.41	0.830	1.78	0.830	1.04	0.84
250	2.18	0.878	1.45	0.880	1.83	0.881	1.06	0.89
300	2.23	0.920	1.48	0.920	1.87	0.921	1.09	0.93
350	2.28	0.952	1.51	0.950	1.91	0.952	1.11	0.96
400	2.32	0.976	1.54	0.980	1.94	0.976	1.12	0.98
450	2.36	0.992	1.56	0.990	1.97	0.991	1.14	1.00
500	2.40	1.000	1.59	1.000	2.00	1.000	1.16	1.00

Sample means of the quoted and effective spreads in index-points and the proportion (covered market capitalization divided by total market capitalization) of the index covered as a function of the number of stocks. The included stocks are either selected based on the cheapest relative spreads (Panel A) or based on the largest market capitalization stocks (Panel B).

Table 3: Sample characteristics of S&P 500 index arbitrage trades

	Buy programs (Buy stock, sell futures)			Direct sell programs (Sell stock, buy futures)			Short-sell programs (Short-sell stock, buy futures)			
Variable	All	80A	No 80A	All	80A	No 80A	All	80A	No 80A	All
Panel A: Before introduction of sixteenths at the NYSE (3 January – 23 June, 1997)										
Cost-of-carry MPE	0.102	0.132	0.0946	-0.101	-0.181	-0.0916	-0.129	-0.156	-0.0893	0.103
(%)	(0.0674)	(0.0822)	(0.0608)	(0.0828)	(0.134)	(0.0689)	(0.105)	(0.118)	(0.0658)	(0.0772)
Market-implied MPE	0.0721	0.0817	0.0696	-0.0863	-0.128	-0.0814	-0.0907	-0.100	-0.0771	0.0794
(%)	(0.0592)	(0.0742)	(0.0544)	(0.0681)	(0.127)	(0.0554)	(0.0919)	(0.106)	(0.0633)	(0.0658)
Cost-of-carry MPE	0.830	1.08	0.765	-0.790	-1.41	-0.716	-0.998	-1.21	-0.685	0.822
(index-points)	(0.551)	(0.682)	(0.492)	(0.641)	(1.04)	(0.532)	(0.808)	(0.901)	(0.508)	(0.610)
Market-implied MPE	0.578	0.666	0.555	-0.682	-1.01	-0.644	-0.709	-0.788	-0.593	0.631
(index-points)	(0.474)	(0.607)	(0.430)	(0.536)	(1.00)	(0.436)	(0.719)	(0.833)	(0.489)	(0.521)
Dollar value stocks	16.9	17.7	16.6	16.3	16.5	16.3	15.3	17.2	12.6	16.5
(millions)	(8.37)	(8.58)	(8.30)	(7.77)	(8.09)	(7.74)	(7.76)	(8.10)	(6.33)	(8.09)
Number of stocks	357	313	369	361	289	369	289	314	253	355
	(128)	(126)	(126)	(124)	(134)	(120)	(131)	(120)	(140)	(127)
Sample size	1587	326	1261	1395	146	1249	176	105	71	3158
Panel B: After introduction of sixteenths at the NYSE (24 June – 23 December, 1997)										
Cost-of-carry MPE	0.114	0.136	0.109	-0.0835	-0.136	-0.0726	-0.114	-0.122	-0.0520	0.102
(%)	(0.0578)	(0.0611)	(0.0557)	(0.0787)	(0.103)	(0.0679)	(0.100)	(0.0963)	(0.113)	(0.0708)
Market-implied MPE	0.0770	0.0741	0.0777	-0.0872	-0.109	-0.0828	-0.0905	-0.0946	-0.0555	0.0817
(%)	(0.0610)	(0.0627)	(0.0606)	(0.0718)	(0.104)	(0.0620)	(0.0949)	(0.0944)	(0.0937)	(0.0674)
Cost-of-carry MPE	1.07	1.27	1.02	-0.773	-1.26	-0.672	-1.06	-1.12	-0.474	0.947
(index-points)	(0.536)	(0.563)	(0.517)	(0.727)	(0.952)	(0.626)	(0.920)	(0.882)	(1.05)	(0.656)
Market-implied MPE	0.718	0.693	0.724	-0.809	-1.01	-0.768	-0.835	-0.873	-0.509	0.760
(index-points)	(0.562)	(0.578)	(0.558)	(0.664)	(0.967)	(0.573)	(0.871)	(0.866)	(0.869)	(0.622)
Dollar value stocks	13.4	15.9	12.7	14.2	16.1	13.8	15.2	15.9	8.71	13.8
(millions)	(6.53)	(8.01)	(5.94)	(7.54)	(9.54)	(6.98)	(9.05)	(9.02)	(6.42)	(7.09)
Number of stocks	388	344	398	377	304	392	288	300	188	379
	(124)	(133)	(119)	(128)	(149)	(117)	(140)	(134)	(153)	(128)
Sample size	2360	466	1894	1779	308	1471	172	154	18	4311

Sample means for the cost-of-carry MPE (percentage or index-points), the market-implied MPE (percentage or index-points), the dollar value per arbitrage trade in millions, and the number of stocks per arbitrage trade. The sample covers all index arbitrage trades reported to the NYSE from January 3 to June 23, 1997 (Panel A) and June 24 to December 23, 1997 (Panel B) between 10:00 a.m. and 3:50 p.m. EST. '80A' ('No 80A') indicates rule 80A is (not) active and relevant for the buy or sell program at the time of the arbitrage trade. The 'cost-of-carry' MPE is based on the cost-of-carry model using the 3-month Eurodollar interest rate and discounting the present value of actual dividends by a factor 0.8313. The 'market-implied' MPE is constructed such that the average difference between the log futures price and log midpoint index for each trading day is equal to zero. MPEs in percentage points are computed by dividing the difference between the futures implied index and midpoint index by the midpoint index and multiplying by 100. The MPE in index-points is the difference between the futures implied index and midpoint index.

Table 4: Mean mispricing errors conditional upon futures volatility

	All buy and sell programs, no rule 80A			
Futures volatility range	MPE (%) (Cost-of-carry))	MPE (%) (Market-implied)	Bid-ask spread	Sample size
Panel A: Before introduction of sixteenths at the NYSE (3 January – 23 June, 1997)				
<0.015	0.0766 (0.0481)	0.0528 (0.0360)	2.34 (0.0716)	187
0.015-0.020	0.0811 (0.0537)	0.0619 (0.0447)	2.39 (0.102)	703
0.020-0.025	0.0892 (0.0632)	0.0704 (0.0508)	2.42 (0.107)	701
0.025-0.030	0.103 (0.0697)	0.0907 (0.0574)	2.44 (0.113)	409
0.030-0.035	0.108 (0.0603)	0.0941 (0.0585)	2.45 (0.105)	147
0.035-0.040	0.115 (0.0869)	0.104 (0.0884)	2.46 (0.128)	77
>0.040	0.0960 (0.0925)	0.0927 (0.0805)	2.54 (0.149)	147
Panel B: After introduction of sixteenths at the NYSE (24 June – 23 December, 1997)				
<0.015	0.0793 (0.0583)	0.0646 (0.0459)	1.88 (0.143)	106
0.015-0.020	0.0840 (0.0509)	0.0591 (0.0380)	1.93 (0.151)	625
0.020-0.025	0.0831* (0.0510)	0.0681 (0.0415)	2.01 (0.172)	670
0.025-0.030	0.0804** (0.0604)	0.0758** (0.0615)	2.03 (0.182)	501
0.030-0.035	0.0869** (0.0686)	0.0810** (0.0599)	2.04 (0.194)	333
0.035-0.040	0.100 (0.0670)	0.0900 (0.0634)	2.08 (0.177)	270
>0.040	0.114 (0.0871)	0.116 (0.095)	2.30 (0.288)	453

Mean percentage mispricing errors (MPEs), mean bid-ask spreads and standard deviations (inside parentheses) as a function of the standard deviation of 15-second futures returns in the 30 minutes prior to the arbitrage trade. Only cases are included where rule 80A did *not* inhibit the arbitrage trade. The 'cost-of-carry' MPE is based on the cost-of-carry model using the 3-month Eurodollar interest rate and discounting the present value of actual dividends by a factor 0.8313. The 'market-implied' MPE is constructed such that the average difference between the log futures price and log midpoint index for each trading day is equal to zero. MPEs in percentage points are computed by dividing the difference between the futures implied index and midpoint index by the midpoint index and multiplying by 100. ** and * indicate the mean MPE after sixteenths is significantly (at the 1% and 5% level, respectively) smaller than the mean MPE before sixteenths in the corresponding volatility range (and corresponding MPE measure).

Table 5: AR(1) coefficient in a TAR model for the percentage MPE at various price frequencies

	Before sixteenths (3 January – 23 June, 1997)			After sixteenths (24 June – 23 December, 1997)		
Frequency	Buy programs	Sell programs	No arbitrage	Buy programs	Sell programs	No arbitrage
15-seconds	0.946	0.827	0.855	0.896	0.863	0.822
	(0.0253)	(0.0230)	(0.00248)	(0.0215)	(0.0248)	(0.00241)
30-seconds	0.828	0.757	0.804	0.713	0.672	0.746
	(0.0272)	(0.0264)	(0.00248)	(0.0236)	(0.0277)	(0.00240)
45-seconds	0.650	0.593	0.724	0.540	0.554	0.666
	(0.0273)	(0.0293)	(0.00248)	(0.0233)	(0.0280)	(0.00241)
60-seconds	0.557	0.588	0.655	0.392	0.464	0.603
	(0.0271)	(0.0315)	(0.00248)	(0.0227)	(0.0280)	(0.00242)
75-seconds	0.471	0.512	0.605	0.312	0.384	0.556
	(0.0269)	(0.0321)	(0.00248)	(0.0221)	(0.0278)	(0.00242)
90-seconds	0.400	0.506	0.567	0.297	0.367	0.522
	(0.0270)	(0.0302)	(0.00249)	(0.0225)	(0.0277)	(0.00242)
105-seconds	0.428	0.483	0.534	0.294	0.378	0.491
	(0.0265)	(0.0313)	(0.00249)	(0.0220)	(0.0282)	(0.00242)
120-seconds	0.360	0.441	0.503	0.247	0.333	0.464
	(0.0266)	(0.0293)	(0.00250)	(0.0214)	(0.0275)	(0.00242)
Sample size	1483	1431	163,804	2074	1741	172,711

A threshold autoregressive model of order 5 (TAR(5)) is estimated for the market-implied percentage mispricing error (MPE). The data are divided into three regimes (buy programs, sell programs, and no arbitrage) based on the times the arbitrage trades were reported to the NYSE. The table reports the AR(1) coefficient for the lagged MPE. This lagged MPE is 15 seconds after the time the arbitrage trade was entered, as this is the time the mean mispricing error starts to decay in response to the arbitrage trade. The contemporaneous MPE, the left-hand-side variable in the TAR(5) model, is the MPE one period later than the lagged MPE, which is 15, 30, …, 120 seconds for the 15-, 30-, …, 120-second frequencies, respectively. The 'market-implied' MPE is constructed such that the average difference between the log futures price and log midpoint index for each trading day is equal to zero. MPEs in percentage points are computed by dividing the difference between the futures implied index and midpoint index by the midpoint index and multiplying by 100.