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Abstract

Empirical tests of option pricing models are joint tests of the 'correctness' of the model, the efficiency of the market and the simultaneity of price observations. Some degree of nonsimultaeity can be expected in all but the most liquid markets and is therefore evident in many non-US markets. Simulation results indicate that nonsimultaneity is potentially a significant problem in empirical tests of futures option pricing models. Empirical results using Australian data show that a five-minute window for matching transactions does not remove the nonsimultaneity bias for near-the-money and out-of-the money options. A more accurate matching may therefore be required. The nonsimultaneity bias is effectively removed if a five-minute window is employed for in-the-money options.

Key Words: nonsimultaneity; futures option; mispricing

Introduction

Empirical tests of option pricing models are joint tests of three hypotheses, namely the 'correctness' of the model, the efficiency of the option market and the simultaneity of price observations. Galai (1982) states that violation of any one of these three hypotheses will bias empirical tests towards rejection of the model as the true general equilibrium model with which markets price derivative securities. Nonsimultaneity will also lead to the appearance of ex-post abnormal profits when no such opportunities exist (Galai (1982)). The first two hypotheses have provided the impetus for a large and expanding literature on the pricing accuracy of increasingly sophisticated derivative pricing models. The third hypothesis refers to the matching, in time, of the traded price of the option and the traded price of the underlying asset. Simultaneous price observations are available only if two conditions are met. First, the trades must occur at the same moment in time. Second, the data source must accurately report both trade times. The first condition is not required for a market to be efficient but is assumed to exist in pricing models. The second condition is likely to be met where trading is undertaken by electronic means but may be violated where data are gathered from pit trading.

The problem of nonsimultaneity seems to have been resolved in the US by the availability of time-stamped transaction data on highly liquid instruments. These data may enable researchers to match prices to within one minute.[1] However, there are a large number of option markets outside the US that are not sufficiently liquid to resolve fully the nonsimultaneity problem. Therefore, studies using data from these markets can still suffer from nonsimultaneity biases. Even within the US, simultaneous data are not available for all options listed on all option markets.

The importance of nonsimultaneity in empirical tests of option pricing models can be assessed via two methods. These are: (1) simulation of the theoretical consequences of nonsimultaneity and (2) empirical estimation of the effects of nonsimultaneity. This study uses both methods to investigate the effects of nonsimultaneity in futures option markets.

Empirical research on futures options in Australia has received growing attention. Brace and Hodgson (1991) focus on All-Ordinaries Share Price Index (SPI) futures call options and conduct a test of the pricing ability of the Asay (1982) model. They also examine the ability of volatility estimates implied by the model to forecast future stock price index volatility. However, they use daily closing prices and thus nonsimultaneity is potentially a problem in their study. Brace and Hodgson recommend that future research use simultaneous data and also examine the model's ability to correctly price put futures options. Twite (1996) also examines SPI futures options using daily data. To minimise the nonsimultaneity problem, Twite uses the average of the closing bid and closing ask prices.[2] Both papers report significant pricing errors, but the impact of nonsimultaneity on their results is unclear.

Empirical evidence on this question is provided by Brown and Taylor (1997) who employ time-matched transaction data on the All Ordinaries SPI futures option contract.[3] Brown and Taylor find that there is significant mispricing using the Asay model and thus they suggest that nonsimultaneity does not appear to have been a source of the mispricing errors reported in prior research. Therefore, either the markets are inefficient, or the pricing model is incorrect. In response to these results Brown and Robinson (1999) develop a more sophisticated model that accounts for skewness and kurtosis of futures prices. They use transaction data matched to within five minutes and find that pricing errors, while reduced, are still present. This result may still be affected by nonsimultaneity because of the five-minute window between price observations.

Brown (1999) examines the error structure of the Asay model in pricing SPI futures options by treating the implied volatility from market option prices as a means to quote the price of the option. Given that the implied volatility estimates should be equal across exercise prices and the term to maturity, the implied volatility estimate is used as an indication of factors not included in the Asay model. Brown finds evidence of a volatility skew and that there are risks in option trading not captured by the Asay model. She also finds that the supply and demand for institutional hedging by fund managers determines the observed volatility skew in ways consistent with the observed volatility structure.

Studies that use daily data can be subject to a large degree of nonsimultaneity. A lag of two hours is not improbable for less liquid contracts, while a rush in trading at the end of the day may cause price observations to be only minutes or seconds apart. While the use of transaction data should help to reduce the nonsimultaneity bias, studies that do not precisely match trades may still be subject to some degree of nonsimultaneity. It is the objective of this paper to quantify the effects of nonsimultaneity via simulation analyses and to investigate empirically the effects that nonsimultaneity may have had on recent studies of the Australian futures options market.

Literature Review

While the problem of nonsimultaneity was recognised in early empirical tests of option pricing models[4], the non-existence of intraday data at that time precluded a detailed examination of its effects on apparent option mispricing. Trippi (1977) attempts to control for the effects of nonsimultaneity by referencing closing prices with their opening prices the next trading day to see whether execution of trades at the closing price was feasible. Galai (1977) uses hourly option quotations to help evaluate nonsimultaneity effects while Galai (1979) finds that violations of convexity boundary conditions using daily closing price data disappear when transactions data are employed. Nonsimultaneity has also been addressed in Vijh's (1988) re-examination of the findings of Manaster and Rendleman (1982) and in Bodurtha and Courtadon's (1986) study of foreign currency options. However, the most important studies for our purposes are those that have modelled nonsimultaneity using simulation analysis. This type of analysis has been undertaken by Bookstaber (1981) and Easton (1994).

In Bookstaber's model the final stock trade of the day occurs after the final option trade.[5] To allow for this possibility, trading in options and stocks are modelled as occurring uniformly throughout the day. The number of trades above one is assumed to follow a Poisson distribution, where stock and option trades are independent random variables. Using this specification, the time between final stock and option trades is simulated and stock prices are simulated as lognormally distributed random variables. The difference between the stock price at the time of the final option trade and the final stock price of the day is evaluated relative to a preset benchmark that defines the impact of nonsimultaneity.[6] By varying the daily number of trades in both stocks and options[7], Bookstaber assesses the nonsimultaneity problem at differing degrees of liquidity, stock price variability and nonsimultaneity benchmarks. He finds that the number of option trades throughout the day is a key driver of nonsimultaneity, while the effects of nonsimultaneity also increase as the variability of stock prices increases. Furthermore, nonsimultaneity is found to decrease as the benchmark for nonsimultaneity increases (since by definition a greater degree of stock price movement is required to cause nonsimultaneity). Finally, Bookstaber applies his methodology to the study of Chiras and Manaster (1978) who examined the ability of implied variance to predict the future variability of stock returns. Bookstaber finds that, in a majority of instances, the apparent mispricing of options falls within the bounds of being explained by nonsimultaneity.

Easton (1994) simulates the effects of nonsimultaneity on tests of put-call parity. In this study stock prices lag reported put and call option prices by periods of 15 minutes and 2 hours and the study therefore extends the end-of-day closing data simulation study of Bookstaber (1981) to an intraday setting. Via an arbitrage argument, upper and lower bounds for the price of an American put are determined from simultaneous observations on the underlying stock price and the call price, for given exercise price, interest rate and dividends to be paid during the life of the option. The test consists of observing and analysing violations of these boundaries. Easton hypothesises that nonsimultaneity may have led to specious violations in Australian studies of put-call parity. Earlier studies had suggested that the observed violations may have been due to transaction costs.

Easton calculates theoretically correct call and put option prices for a given set of parameters using Black-Scholes and binomial models of option pricing at a given point in time. The underlying stock price is modelled to follow a multiplicative binomial process for a period of time after the initial option prices are determined. The final stage involves using the simultaneous call and put option values and the subsequent (nonsimultaneous) stock prices, to observe the apparent violations of put-call parity. Sensitivity analysis is conducted by varying parameters such as the term to maturity of the option, the interest rate and the volatility of the underlying stock. Easton finds that nonsimultaneity can cause significant violation rates and that these violation rates are consistent with Australian empirical evidence on violations of put-call parity. His study therefore offers an alternative to transaction costs as an explanation of apparent option mispricing.

There have been a number of differing lines of research in the literature on futures options. One considers mispricing biases resulting from futures options pricing models derived in the Black-Scholes framework. In Black's (1976) model, underlying futures prices are assumed to follow geometric Brownian motion. Therefore, futures prices are log-normally distributed and returns are normally distributed. Ramaswamy and Sundaresan (1985) develop a futures option pricing model that allows for early exercise. Their model depends critically on the dividend yield of the underlying security. They find that early exercise may be optimal for futures options but by numerically assessing their model they conclude that the value of the early exercise premium is quite small.

Asay (1982) and Lieu (1990) develop models that take account of futures-style margining which is used in some exchanges, such as the Sydney Futures Exchange. Futures-style margining requires no upfront purchase price for the option contract but margin calls may be made as the market price changes. Asay shows that futures option prices under futures-style margining are similar to Black (1976) futures options prices but because the option premium no longer flows from buyer to writer at initiation of the contract, the interest rate factor falls out of the option pricing formula. Lieu proves that with futures-style margining it is never optimal to exercise American futures options early because the option premium always exceeds the option's intrinsic value. The model therefore applies to both American and European options.

Simulation Analysis and Results

We conducted a simulation of the effects of nonsimultaneity between futures prices and futures option prices. Potentially, the results of the simulation are relevant to empirical tests of option pricing models in any market where the researcher does not have access to time-stamped transaction data or where the securities are traded in imperfectly liquid markets. The results of this study quantify the potential impact of nonsimultaneity with regard to a number of characteristics, such as term to maturity, degree of 'moneyness' and the underlying futures price volatility.

The methodology employed here is similar to that of Easton (1994) and consists of three steps. In step one we use the Asay (1982) option pricing model to value a hypothetical call or put option on a futures contract. The option is priced using a given set of parameters: the underlying futures price, the exercise price, the expected return on the underlying security[8], the term to maturity, and the futures price volatility. This calculation provides a hypothetically 'correct' market price for the option when the option price and the futures price are observed simultaneously. Step two involves modelling the underlying futures price to follow a multiplicative binomial process for periods of 5 minutes, 15 minutes and 2 hours after the price calculated in step one. These periods were divided into 250 intervals. For example, the time lag of two hours is divided into intervals of approximately 29 seconds. Step three involves using the Asay model to calculate the call and put prices resulting from each possible futures price at the end of the binomial tree. To show the effect of nonsimultaneity, these option prices are compared to the option price calculated in step one. The binomial distribution gives the probability of each outcome in the final step of the binomial tree.[9] The results reported reflect the probability of achieving the specified degree of apparent mispricing resulting from nonsimultaneity between option prices and futures prices, given that the range of potential outcomes is represented by the binomial distribution. The pricing parameters are then varied, and the simulation repeated, to provide a detailed sensitivity analysis.

We measure the extent of mispricing by the percentage pricing error, which is defined as the difference between the initial ('correct') price of the option and the price of the option derived from the nonsimultaneous futures price, divided by the initial option price. The percentage pricing error depends to a large extent on the initial price of the option. For example, the same absolute (dollar) pricing error may be found for an out-of-the-money option and an in-the-money option, but because out-of-the-money options are worth less than in-the-money options, the percentage pricing error will be greater for the out-of-the-money option. For this reason the mispricing of out-of-the-money options may appear relatively large but may not be economically significant when transaction costs are taken into account. On the other hand, measuring the extent of mispricing by absolute (dollar) pricing errors is also problematic. A dollar pricing error of any given magnitude can always be achieved simply by imagining that a trader varies the number of contracts traded. Percentage pricing errors cannot be manipulated in this way.

Table 1 reports the results of using nonsimultaneous prices in pricing call options. The time lag between price observations is varied from 5 minutes to 15 minutes to 2 hours. The three panels assess the differing sensitivities of in-the-money, at-the-money, and out-of-the-money call options to mispricing from nonsimultaneity. For all simulations the initial futures price is fixed at $10, and the exercise price is varied to produce different degrees of moneyness. While the futures price lags the recorded option price the analysis also applies where the futures price is recorded before the option price. In this case the binomial tree modelling the nonsimultaneous futures prices progresses "backward" through time rather than forward. The calculations are the same.

Panel A of table 1 shows the effects of nonsimultaneity on pricing in-the-money call options. The percentage of options which display greater than a five percent degree of mispricing is at a maximum of 28 percent when a 30-day call option is considered, for which the level of underlying futures price volatility is 40 percent, and where the time lag between option and futures prices is set at two hours. The degree of mispricing increases as the volatility of the underlying futures price increases. A higher futures price volatility allows a greater dispersion of possible futures prices at the end of the time lag, and hence mispricing is greater over the range of possible outcomes. The degree of mispricing also increases as the option's term to maturity decreases. Because options become less valuable as the term to maturity decreases, a given degree of nonsimultaneity (*ie* a given futures price discrepancy), will cause a larger degree of option mispricing at shorter terms to maturity. Panel A of table 1 also shows that there are virtually no cases of mispricing of the order of 15 percent. Finally, mispricing is not present when shorter time lags of either 15 minutes or 5 minutes are considered.

Panel B of table 1 shows the mispricing observed for at-the-money call options under conditions of nonsimultaneity. Mispricing in this case is greater than is the case with in-the-money options. For example, with 10 percent volatility of the underlying futures price and 30 days to maturity of the call option, the degree of mispricing is over five percent in nearly 45 percent of all possible futures price outcomes after a two-hour time lag between futures and option prices. The corresponding result for in-the-money calls (panel A) is only 0.29 percent. Qualitatively, the results for at-the-money calls (panel B) are similar to those for in-the-money calls (panel A) in that mispricing increases with higher volatility, a shorter term to maturity and a longer time lag between price observations. Mispricing virtually disappears at a time lag of 5 minutes but is present for 30-day options when the time lag is 15 minutes.

Panel C of table 1 shows that, in the case of out-of-the-money call options, there is significantly greater mispricing than in the two prior cases. The intuition for this result is that out-of-the-money options have lower values than in-the-money options because they have only a time value. Hence, a smaller futures price change is able to cause a larger degree of relative mispricing. Consequently, high degrees of mispricing are observed. For example, in the case of a 30-day call option with underlying futures price volatility of 10 percent, there is an 84 percent probability of observing a five percent degree of mispricing when the observation lag is two hours. The effects of term to maturity and the time lag between observations are in the same direction as in the two previous cases but the direction of effect for volatility has reversed. Mispricing now decreases as the underlying futures price volatility increases. When the underlying futures price volatility increases, there are two offsetting effects. First, there is a greater dispersion of possible futures price outcomes and hence a higher probability of observing a given degree of mispricing. Second, however, the call price increases so that nonsimultaneity is less of a problem, since it takes a larger deviation from the correct futures price to cause a given percentage level of option mispricing. In panel C, the latter effect dominates the former, because out-of-the-money options have relatively low prices.

To consider further these results the analyses are repeated by decomposing the option price into its intrinsic value and time value components.[10] The effect of nonsimultaneity on the intrinsic value of an in-the-money option is straightforward. The true (simultaneous) intrinsic value is $F_T - X$, where F_T is the true (simultaneous) futures price and X is the exercise price. The observed (nonsimultaneous) intrinsic value is $F_O -$

X, where F_O is the observed (nonsimultaneous) futures price. The difference between these measures of intrinsic value shows the effect of nonsimultaneity on the intrinsic value and is just $F_O - F_T$. The effect will therefore depend (positively) on just two factors *viz* the time lag between the true and the observed futures prices and the futures price volatility during this period.

The price of an out-of-the-money option consists entirely of time value and it is therefore hypothesised that the results for the time value of in-the-money options will be similar to the results for out-of-the-money options. The effects of nonsimultaneity on call option time value are reported in table 2. As hypothesised, the results are qualitatively similar to those for out-of-the-money call options. In particular, higher volatility causes lower mispricing in both cases, whereas higher volatility causes higher mispricing for in-the-money options (table 1, panel A). The direction of effects for term to maturity (negative) and time lag (positive) are, as expected, unchanged. The magnitude of the effects is also comparable. For example, panel A of table 2 shows that the probability of 5 percent mispricing at a two-hour time lag for the time value of an in-the-money call, with 30 days to maturity and a volatility of 10 percent, is 80.07 percent. The corresponding figure for the out-of-the-money option (table 1, panel C) is 84.96 percent.

The simulation analysis is also performed for equivalent in-the-money, at-the-money and out-of-the-money put options. All parameters are identical to those used for the call option simulations. The results of this analysis are provided in table 3. The results show that mispricing of put options can arise under conditions of nonsimultaneity, especially when the degree of option moneyness is low.

Panel A of table 3 shows the results for in-the-money put options. The percentage of options which display greater than a five percent degree of mispricing is at a maximum of 21 percent when a 30-day put option is considered, for which the level of the underlying futures price volatility is 40 percent and where the time lag between option and futures prices is set at two hours. Similar to the case of in-the-money call options, put option mispricing increases with higher levels of futures price volatility for the reasons which were previously explained. Furthermore, the degree of mispricing is shown to decrease as the term to maturity of the option increases. This follows since increasing the term to maturity increases the value of options. Hence they become less sensitive to nonsimultaneity since they require a larger price discrepancy to cause the same relative degree of mispricing. Finally, it is apparent in panel A of table 3 that at any time lag there are almost no cases of mispricing of the order of 15 percent. Similarly, mispricing virtually disappears when the time lag is decreased from two hours to either 15 or 5 minutes.

Note that the mispricing results for at-the-money put options are equal to those derived for the time-value of at-the-money call options by the put-call parity relation for futures options with futures-style margining.[11] This result also holds true for in-the-money call options and out-of the money put options. Finally, results for the time value of put options are equal to those reported for the time value of call options by the same relation.

Empirical Analysis

To provide empirical evidence relevant to the simulation results provided in Section 3, we conducted an empirical analysis on SPI futures options using all trades in 1993 on the Sydney Futures Exchange. This analysis uses the transaction data employed in Brown and Robinson (1999). However our objective is not to replicate Brown and Robinson's results but rather to draw general inferences about the consequences of nonsimultaneity in relation to pricing tests. Given that the data are recorded from the open outcry system used in the Sydney Futures Exchange prior to November 1999, the actual time appended to the data may be inaccurate since it represents the time that the transaction was entered into the computerised system and not the time of the transaction. Because the time stamp may be inaccurate this is a limitation of the data used in this study.

The methodology of testing for nonsimultaneity is as follows. SPI futures option transactions are matched with the immediately preceding SPI futures transaction to a maximum time between trades of five minutes. In order to calculate theoretical option prices, the Asay (1982) option pricing model is used. The Asay model requires an estimate of the volatility of the log futures price. To estimate this parameter we use data from a five-day window preceding each option trade. The procedure used is to minimise the sum of squared pricing errors as in Whaley (1982), using all transactions in the five-day window for options with the same maturity date. Percentage pricing errors are calculated as the market price minus the model price, divided by the market price of the option, where underlying variables are measured in dollar terms (one point = $100 prior to 11 October 1993 and one point = $25 thereafter). Percentage pricing errors are examined for the impact of nonsimultaneity by regressing the absolute percentage pricing errors on the time lag between matched prices and a set of control variables.

Options of all maturities were used and after eliminating 28 call prices and 2 put prices which violated boundary conditions, there remained 2694 call prices and 2179 put prices. Moneyness groupings are shown in table 4, while table 5 shows descriptive statistics of the implied volatility estimates employed in the model. Table 6 shows summary statistics for the pricing errors that result. On average, the Asay model appears to overprice call options and underprice put options, and the mispricing is greater for put options than for call options. Table 7 shows characteristics of the independent variable, the time between matched futures and options transactions. The sample means are 54.8 seconds for calls and 51.9 seconds for puts. The maximum time is close to the maximum allowable of 5 minutes, while the minimum is zero.

The regression model employed to analyse the pricing errors is:

$$\text{Absolute Percentage Error}_{it} = \alpha + \beta_1 \sqrt{\text{Time Between Trades}_{it}} + \beta_2 \text{ Option Moneyness}_{it} + \beta_3 \text{ Option Maturity}_{it} + \beta_4 \text{ Option Volatility}_{it} + \beta_5 \text{ Dummy}_{it} + \varepsilon_{it}$$

where Absolute Percentage Error is the absolute value of the percentage mispricing defined as the market price minus the model price, divided by the market price; Time Between Trades is the time in minutes between matching futures and options transactions; Option Moneyness is defined as the underlying futures price divided by the exercise price; Option Maturity is the option's term to maturity measured in days; Option Volatility is the volatility input used in the Asay model and Dummy is a variable which takes the value of one if the transaction was after the re-denomination of the SPI futures contract on 11 October 1993 and zero otherwise. The regression is a pooled regression since option transactions occur across exercise prices (subscript i) and through time (subscript t).

Several studies, including Whaley (1982) and more recently Bakshi, Cao and Chen (1997) and Long and Officer (1997) have used regression models to analyse option pricing errors and we have adopted a similar approach. However, our choice of explanatory variables is also motivated by the simulation results in Section 3. These results showed that a number of factors affected the option pricing errors when nonsimultaneity was present. In addition to the degree of nonsimultaneity itself, option moneyness, volatility and term to maturity were all shown to affect the degree of option mispricing due to the degree of nonsimultaneity. Further, the mathematical analysis contained in the Appendix shows that the option pricing errors due to nonsimultaneity should be proportional to the square root of the time between matching trades. Hence the functional form of the regression model is specified to include the square root of the time between trades. Evidence in Brown (2001) suggests that SPI futures volume, as measured by both contract numbers and dollar values, increased after the re-denomination of the SPI futures contract, so that market efficiency may have increased. Finally, the data are sub-grouped into moneyness categories since the model has known moneyness biases; for examples, see Brown (1999) and Shimeld and Easton (2000).

The results in table 8 show that for call options the degree of nonsimultaneity is a significant factor in explaining the pricing errors. Using all call option transactions, for each (square root of the) minute of nonsimultaneity, the absolute value of the percentage pricing error increases by 1.3% and this result is significantly different from zero at the five percent level.[12] Given that the data are predominantly from near-the-money options, grouping the data into moneyness categories may be able to show more clearly any nonsimultaneity bias. The simulation analysis showed that at-the-money and out-of-the-money options were the most affected by nonsimultaneity and the regression results in table 8 partially support this conclusion. For near-the-money options, the coefficient for the time between trades is positive and significant at the five percent level but for out-of-the-money options, the coefficient, while positive, is not statistically significant. Finally, the results show that for in-the-money options, the time between trades is not a significant variable in explaining percentage mispricing errors. This result is consistent with the simulation results which showed that a five-minute window eliminated the nonsimultaneity bias for in-the-money and at-the money options.

The other variables are also significant factors in the regression model. The percentage mispricing decreases, the greater the moneyness of the option and the estimated coefficient is significantly different from zero at the one percent level. This result holds for all option transactions and within moneyness groupings and is probably best explained by the fact that the procedure for minimising the sum of dollar square errors to find the implied volatility estimate gives greater weight to options with higher prices. Hence the more the option is in-the-money, these options, all other things being equal, will be worth more and have greater weight in determining the volatility estimate to best fit the option prices. This analysis also holds for option maturity. The longer the term to maturity, the lower is the percentage mispricing error for all categories reported with the exception of in-the-money options. Volatility displays varying impacts on the percentage mispricing but none of the coefficients is significantly different from zero.

Finally, the coefficient on the dummy variable shows that after the re-denomination of the SPI contract mispricing has decreased in all moneyness categories.

Table 9 shows the results of the regression model for put options. The coefficient for the time between trades across all transactions indicates that for each (square root of the) minute between matching trades, the absolute value of the percentage pricing errors increases by 1.15%, but this result is not significantly different from zero at the five percent level. When transactions are grouped by moneyness, for out-of-the-money options, the (square root of the) time between trades is shown to have a positive impact on the pricing errors and this result is statistically significant at the five percent level. Furthermore, the simulation results of the previous section showed that out-of-the-money options were most affected by the consequences of nonsimultaneity. This empirical result supports that conclusion.

Other variables in the analysis are also able to explain the variation in the percentage pricing errors. The results indicate that pricing errors are greater the less the option is in-the-money, which is the same result as discussed for call options.[13] Option term to maturity also has a negative impact on the pricing errors, and this result follows from the previous analysis of option moneyness and maturity and the least squares minimisation procedure used to estimate volatility. However, neither of the last two results is significant for in-the-money put options, which may be due to the small sample size. Finally, the dummy variable for the re-denomination of the SPI futures contract shows that option pricing errors using in the Asay model have decreased since the SPI contract was re-denominated and is statistically significant when transactions are categorised according to moneyness. These results suggest that for put options, since most trades for SPI options are out-of-the-money, nonsimultaneity may still cause biases even when a five-minute matching window for futures and options trades is employed.

Summary and Conclusions

The simulation results of this study suggest that apparent mispricing is strongly related to the degree of nonsimultaneity between the option price and the price of the underlying asset, as measured by the time lag between price observations. The degree of apparent mispricing (measured by percentage pricing errors) in the presence of a given degree of nonsimultaneity will be related to the option's moneyness (negatively) and the option's term to maturity (also negatively). The effect of volatility on apparent mispricing in the presence of nonsimultaneity is more complex and depends on the moneyness of the option because the effect on intrinsic value can be in the opposite direction to the effect on time value. The results also suggest that a time lag as short as five minutes may not be sufficient to eliminate the bias for out-of-the-money options, whereas for in-the-money options even a lag of 15 minutes may be adequate. Accordingly, it may be advisable in future empirical studies to use a different matching rule for different options. For example, a five-minute window might be used for in-the-money options, and a shorter window for at-the-money and out-of-the money options.

The empirical results using the prices of futures options on the Sydney Futures Exchange are broadly consistent with the patterns suggested by the simulation results. Our measure of the time between trades shows a consistently positive (although not always statistically significant) relationship between the degree of nonsimultaneity and the percentage pricing error. Similarly, the relationship between pricing errors and option moneyness[14] is typically found to be negative, and the relationship between pricing errors and term to maturity is also typically negative. Finally, and also as expected, the results for the relationship between pricing errors and volatility are mixed.

Appendix

The Asay model for a call option is given by $C = FN(d_1) - XN(d_2)$

$$d_1 = \frac{\ell n\left(\frac{F}{X}\right) + \frac{1}{2}\sigma^2 T}{\sigma\sqrt{T}} \text{ and } d_2 = d_1 - \sigma\sqrt{T}$$

where F is the underlying futures price, X is the exercise price of the option, T is the term to maturity of the option, σ is the volatility of the underlying log futures price and $N(\ )$ is the cumulative Normal function.

The call option price, C, as a function of the underlying asset price, F, as measured at the point in time, t, can be expressed with a first order Taylor series approximation around a measurement at an earlier time of $(t\text{-}k)$ as follows:

$$C(F(t)) - C(F(t-k)) = \frac{\partial C(F(t-k))}{\partial F}(F(t) - F(t-k)). \qquad \text{(A1)}$$

The underlying index price, S, in the Asay model is assumed to follow a geometric Brownian motion:

$$dS = \mu S dt + \sigma S dz \text{ and } dz = \varepsilon\sqrt{dt} \text{ where } \varepsilon \sim \text{Normal } (0,1). \qquad \text{(A2)}$$

The futures price on the index, by the cost of carry model can be shown to be:

$$F = Se^{r(T-t)}. \qquad \text{(A3)}$$

Applying Ito's lemma to (A3), the stochastic process followed by the futures price, F, in (A3) can be shown to be:

$$dF = (\mu - r)Fdt + \sigma F dz. \qquad \text{(A4)}$$

Since $\dfrac{\partial C(F)}{\partial F} = N(d_1)$ and substituting (A4) into (A1) leads to the discrete approximation:

$$C(F(t)) - C(F(t-k)) = N(d_1(F(t-k))).\{(\mu - r)kF(t-k) + \sigma F(t-k)\varepsilon\sqrt{k}\} \quad \text{(A5)}$$

By risk neutrality, $\mu = r$, so that the expected return on the futures contract is zero. Taking absolute values of (A5) and substituting the previous result leads to:

$$|C(F(t)) - C(F(t-k))| = N(d_1(F(t-k))).\{\sigma F(t-k)|\varepsilon|\sqrt{k}.\} \qquad \text{(A6)}$$

Since $N(d_1), \sigma, F \text{ and } \sqrt{k}$ are positive by definition, equation (A6) leads to the following hypotheses.

The absolute value of the option pricing model error is dependent on:

The option's delta, $N(d_1)$, the underlying asset price volatility, σ, the underlying asset price, F, the square root of the time between option trades and underlying asset trades, $\sqrt{k}$ (i.e. the degree of nonsimultaneity), and the absolute value of a normally distributed random variable .

It can also be shown that for put options in the Asay model equation (A6) becomes:

$$|P(F(t)) - P(F(t-k))| = |(N(d_1(F(t-k))) - 1)|.\{\sigma F(t-k)|\varepsilon|\sqrt{k}\} \qquad \text{(A7)}$$

where P(F) denotes the put price in the Asay model.

[1] An example is Whaley (1986). See also Bakshi, Cao and Chen (1997).

[2] Twite (1996, p. 142) also suggests that because of infrequent option trading the nonsimultaneity problem will remain even if transaction data are used.

[3] The maximum time lag between futures prices and futures option prices was set at one minute. The average time between price observations was 28 seconds.

[4] Nonsimultaneity has also been recognised in other areas of finance, such as the biases incurred when using daily data as opposed to intraday data. Brooks and Chiou (1995) provide an example and review studies examining stock price behaviour around events such as stock splits.

[5] Bookstaber also recognises that the final trade of the day may be in the option market rather than the stock market. While allowing for this possibility, he concludes that the primary cause of nonsimultaneity is where the final stock trade follows the final option trade.

[6] Bookstaber suggests that a reasonable value of this benchmark might be the difference between the stock price implied by the final option trade and the last reported stock quotation.

[7] The stockmarket is modelled to have greater liquidity than the option markets. The empirical evidence supports the notion that there is greater trading activity in the underlying instruments than in the option market.

[8] Note that the expected return on the underlying security is not required to price the option. It is required only to determine the true probabilities of each ending state occurring. In general, a higher expected return on the security leads to a higher upside probability in the binomial model, all other things being equal. Because the underlying security is a futures contract the expected rate of return is set to zero. For a further discussion of the expected return on futures contracts see Hull (2000, pp. 293-4).

[9] Note that these probabilities are the true 'risk averse' probabilities for each particular outcome, which may differ from the risk neutral probabilities of each particular outcome used implicitly to price the option. However, numerical analyses not reported here show that tests of nonsimultaneity are not materially affected by using either the true risk averse probabilities or the risk neutral probabilities.

[10] The intrinsic value of a call option on futures is the futures price less the exercise price (with a minimum value of zero). Time value is the difference between the option price and the intrinsic value of the option.

[11] The put-call parity relation can be expressed for futures options with futures style margining as $P - C = X - F$, where P is put price, C is call price, X is exercise price and F is futures price.

[12] We hypothesise that the longer the time between matching trades, the greater the pricing error due to nonsimultaneity. Therefore, we use a one-tailed test.

[13] Note that the sign of moneyness is now reversed for put options since the variable definition of moneyness is unchanged.

[14] Given that the moneyness variable is defined as F / X for both calls and puts, a negative relationship between pricing errors and moneyness shows up as a negative regression coefficient for calls and a positive regression coefficient for puts.

TABLE 1
Simulation Analysis: Pricing Errors for Call Futures Options

The Asay (1982) model is used to calculate a hypothetically 'correct' call futures option price for given futures price (F), exercise price (X), option term to maturity (T) and annualised standard deviation of the futures price (σ). The futures price is then modelled using a multiplicative binomial process for a further 5 minutes, 15 minutes or 2 hours, and the model option price is recalculated using each terminal (nonsimultaneous) futures price. The binomial tree provides the probability of each nonsimultaneous price being observed. Apparent pricing errors are calculated as the 'correct' option price, minus the nonsimultaneous price, divided by the 'correct' price. The probability of observing 5% and 15% mispricing are reported in the table.

Panel A
In-the-Money Call Option

F	F/X	X				
$10	1.1	9.09				

T	σ	Lag of Two Hours: Prob> 5% Mispricing	Lag of Two Hours: Prob> 15% Mispricing	Lag of 15 Minutes: Prob> 5% Mispricing	Lag of 15 Minutes: Prob >15% Mispricing	Lag of 5 Minutes: Prob> 5% Mispricing	Lag of 5 Minutes: Prob >15% Mispricing
30 Days	10%	0.29%	0.00%	0.00%	0.00%	0.00%	0.00%
	25%	18.40%	0.00%	0.01%	0.00%	0.00%	0.00%
	40%	28.23%	0.15%	0.29%	0.00%	0.00%	0.00%
90 Days	10%	0.19%	0.00%	0.00%	0.00%	0.00%	0.00%
	25%	7.69%	0.00%	0.00%	0.00%	0.00%	0.00%
	40%	14.56%	0.00%	0.00%	0.00%	0.00%	0.00%
180 Days	10%	0.08%	0.00%	0.00%	0.00%	0.00%	0.00%
	25%	2.67%	0.00%	0.00%	0.00%	0.00%	0.00%
	40%	5.80%	0.00%	0.00%	0.00%	0.00%	0.00%

TABLE 1 Continued

Panel B
At-the-Money Call Option

F	F/X	X					
$10	1.0	10					
		Lag of Two Hours		Lag of 15 Minutes		Lag of 5 Minutes	
T	σ	Prob> 5% Mispricing	Prob> 15% Mispricing	Prob> 5% Mispricing	Prob >15% Mispricing	Prob> 5% Mispricing	Prob >15% Mispricing
30 Days	10%	44.88%	2.79%	3.17%	0.00%	0.02%	0.00%
	25%	48.67%	2.78%	3.67%	0.00%	0.03%	0.00%
	40%	48.67%	2.78%	4.32%	0.00%	0.04%	0.00%
90 Days	10%	18.40%	0.01%	0.02%	0.00%	0.00%	0.00%
	25%	20.67%	0.02%	0.04%	0.00%	0.00%	0.00%
	40%	22.94%	0.03%	0.06%	0.00%	0.00%	0.00%
180 Days	10%	6.64%	0.00%	0.00%	0.00%	0.00%	0.00%
	25%	8.75%	0.00%	0.00%	0.00%	0.00%	0.00%
	40%	10.05%	0.00%	0.00%	0.00%	0.00%	0.00%

TABLE 1 Continued

Panel C Out-of-the-Money Call Option							
F	F/X	X					
$10	0.9	11.11					
		Lag of Two Hours		Lag of 15 Minutes		Lag of 5 Minutes	
T	σ	Prob> 5% Mispricing	Prob> 15% Mispricing	Prob> 5% Mispricing	Prob >15% Mispricing	Prob> 5% Mispricing	Prob >15% Mispricing
30 Days	10%	84.96%	48.67%	52.80%	5.15%	25.58%	0.11%
	25%	65.81%	20.67%	22.94%	0.05%	4.32%	0.00%
	40%	61.36%	12.96%	16.48%	0.00%	1.63%	0.00%
90 Days	10%	56.93%	7.69%	10.06%	0.00%	0.36%	0.00%
	25%	37.69%	0.89%	1.14%	0.00%	0.00%	0.00%
	40%	34.28%	0.41%	0.54%	0.00%	0.00%	0.00%
180 Days	10%	31.25%	0.28%	0.54%	0.00%	0.00%	0.00%
	25%	18.40%	0.01%	0.01%	0.00%	0.00%	0.00%
	40%	14.56%	0.00%	0.00%	0.00%	0.00%	0.00%

TABLE 2
Simulation Analysis: Pricing Errors for Time Value Component of Call Futures Options

The Asay (1982) model is used to calculate a hypothetically 'correct' call futures option price for given futures price (F), exercise price (X), option term to maturity (T) and annualised standard deviation of the futures price (σ). The futures price is then modelled using a multiplicative binomial process for a further 5 minutes, 15 minutes or 2 hours, and the model option price is recalculated using each terminal (nonsimultaneous) futures price. The binomial tree provides the probability of each nonsimultaneous price being observed. Apparent pricing errors for the time value component are calculated as the time value of the 'correct' price, minus the time value of the nonsimultaneous price, divided by the time value of the 'correct' price. The probability of observing 5% and 15% mispricing are reported in the table.

In-the-Money Call Option (Time Value)								
F	F/X	X						
$10	1.1	9.09						
			Lag of Two Hours		Lag of 15 Minutes		Lag of 5 Minutes	
T	σ		Prob> 5% Mispricing	Prob> 15% Mispricing	Prob> 5% Mispricing	Prob >15% Mispricing	Prob> 5% Mispricing	Prob >15% Mispricing
30 Days	10%		80.07%	44.89%	48.67%	3.44%	22.94%	0.03%
	25%		65.81%	16.49%	20.67%	0.02%	2.67%	0.00%
	40%		56.93%	10.07%	11.37%	0.00%	0.79%	0.00%
90 Days	10%		52.80%	5.16%	7.70%	0.00%	0.15%	0.00%
	25%		34.28%	0.31%	0.54%	0.00%	0.00%	0.00%
	40%		25.59%	0.08%	0.15%	0.00%	0.00%	0.00%
180 Days	10%		28.23%	0.12%	0.24%	0.00%	0.00%	0.00%
	25%		11.37%	0.00%	0.00%	0.00%	0.00%	0.00%
	40%		7.70%	0.00%	0.00%	0.00%	0.00%	0.00%

TABLE 3
Simulation Analysis: Pricing Errors for Put Futures Options

The Asay (1982) model is used to calculate a hypothetically 'correct' put futures option price for given futures price (F), exercise price (X), option term to maturity (T) and annualised standard deviation of the futures price (σ). The futures price is then modelled using a multiplicative binomial process for a further 5 minutes, 15 minutes or 2 hours, and the model option price is recalculated using each terminal (nonsimultaneous) futures price. The binomial tree provides the probability of each nonsimultaneous price being observed. Apparent pricing errors are calculated as the 'correct' option price, minus the nonsimultaneous price, divided by the 'correct' price. The probability of observing 5% and 15% mispricing are reported in the table.

Panel A
In-the-Money Put Option

F	F/X	X					
$10	0.9	11.11					
		Lag of Two Hours		Lag of 15 Minutes		Lag of 5 Minutes	
T	σ	Prob> 5% Mispricing	Prob> 15% Mispricing	Prob> 5% Mispricing	Prob >15% Mispricing	Prob> 5% Mispricing	Prob >15% Mispricing
30 Days	10%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%
	25%	11.37%	0.00%	0.00%	0.00%	0.00%	0.00%
	40%	20.68%	0.01%	0.03%	0.00%	0.00%	0.00%
90 Days	10%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%
	25%	3.67%	0.00%	0.00%	0.00%	0.00%	0.00%
	40%	6.64%	0.00%	0.00%	0.00%	0.00%	0.00%
180 Days	10%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	25%	0.64%	0.00%	0.00%	0.00%	0.00%	0.00%
	40%	1.14%	0.00%	0.00%	0.00%	0.00%	0.00%

TABLE 3 Continued

Panel B At-the-Money Put Option							
F	F/X	X					
$10	1.0	10					
		Lag of Two Hours		Lag of 15 Minutes		Lag of 5 Minutes	
T	σ	Prob> 5% Mispricing	Prob> 15% Mispricing	Prob> 5% Mispricing	Prob >15% Mispricing	Prob> 5% Mispricing	Prob >15% Mispricing
30 Days	10%	44.89%	2.01%	3.17%	0.00%	0.01%	0.00%
	25%	41.10%	2.01%	2.67%	0.00%	0.01%	0.00%
	40%	41.10%	1.63%	2.29%	0.00%	0.01%	0.00%
90 Days	10%	18.40%	0.01%	0.01%	0.00%	0.00%	0.00%
	25%	16.49%	0.00%	0.01%	0.00%	0.00%	0.00%
	40%	14.56%	0.00%	0.00%	0.00%	0.00%	0.00%
180 Days	10%	5.81%	0.00%	0.00%	0.00%	0.00%	0.00%
	25%	4.97%	0.00%	0.00%	0.00%	0.00%	0.00%
	40%	3.67%	0.00%	0.00%	0.00%	0.00%	0.00%

TABLE 4

Moneyness Groupings

Moneyness groupings are defined with reference to the underlying futures price (F) divided by the option exercise price (X). For call options In-the-Money-Options are defined as F/X >= 1.025, Near-the-Money options are defined as 0.975 =< F/X < 1.025 and Out-of-the-Money options are defined as F/X < 0.975. Put options groupings are defined using the opposite ordering.

	Calls	Puts
In-the-Money	261	29
Near-the Money	1612	731
Out-of-the-Money	821	1419
Total	2694	2179

TABLE 5

Daily Implied Volatility Estimates

Implied volatility estimates are calculated for each of the 254 trading days during 1993 using a five-day rolling window which employs all trades (at least one required). Following the methodology of Whaley (1982) implied volatility estimates are calculated by minimising the sum of square pricing errors of the Asay (1982) option pricing model. Options of all maturity series are included in the five-day window of transactions.

	Calls	Puts
N	250	250
Mean	15.25%	16.69%
Median	14.86%	16.43%
Maximum	18.73%	20.06%
Minimum	12.03%	13.76%
Standard Deviation	1.25%	1.23%

TABLE 6

Summary Statistics of Pricing Errors

Percentage pricing errors are defined as the market price minus the model price divided by the market price of the option.

Option Type	N	Mean Percentage Error	Median Absolute Percentage Error	Mean Absolute Percentage Error
Calls	2593	-4.47%	6.28%	11.62%
Puts	2120	14.36%	10.41%	21.44%

TABLE 7

Time between Futures and Options Trades for Call and Put Options

	Calls	**Puts**
N	2694	2179
Mean	54.8s	51.9s
Median	34.5s	30s
Maximum	4m 58.8s	4m 57s
Minimum	0s	0s
Standard Deviation	57.8s	58.1s

TABLE 8

Empirical Results: Call Options

$$\text{Absolute Percentage Error}_{it} = \alpha + \beta_1 \sqrt{\text{Time Between Trades}_{it}} + \beta_2 \text{ Option Moneyness}_{it} + \beta_3 \text{ Option Maturity}_{it} + \beta_4 \text{ Option Volatility}_{it} + \beta_5 \text{ Dummy}_{it} + \varepsilon_{it}$$

The absolute percentage error is measured as the absolute value of the market price less the model price, divided by the market price. The time between trades on futures and options is measured in minutes, option moneyness is defined as the futures price divided by the exercise price, option maturity is measured in days, option volatility is measured in in percent and is calculated using options with the same term to maturity and Dummy is a variable which takes the value of one if the transaction was on or after 11 October 1993 and zero otherwise. Note that the number of observations used in the regression differs from those reported in Table 4 because all trades in the first five trading days of the year were required to calculate the first rolling implied volatility estimate. T statistics are in parentheses and are calculated using White's heteroscedasticity-consistent standard errors and covariances. The regression is a pooled regression since option transactions occur across exercise prices (subscript i) and through time (subscript t).

Data	**N**	α	β_1	β_2	β_3	β_4	β_5
All Trades 1993	2593	2.3674 13.81*	0.0130 1.96**	-2.2399 -13.67*	-0.0012 -9.48*	0.1351 0.47	-0.0191 -3.14*
In-the-Money	254	0.1592 3.83*	0.0026 0.72	-0.1487 -3.82*	0.0002 2.98*	0.0903 0.59	-0.0002 -0.07
Near-the-Money	1550	2.5770 11.19*	0.0112 1.74**	-2.3972 -11.08*	-0.0015 -11.92*	-0.2526 -0.78	-0.0180 -2.97*
Out-of-the-Money	789	4.6745 8.23*	0.0244 1.51	-4.5390 -8.04*	-0.0019 -5.47*	-0.2407 -0.39	-0.0361 -2.35*

* denotes significance at the one percent level
** denotes significance at the five percent level

TABLE 9

Empirical Results: Put Options

$$\text{Absolute Percentage Error}_{it} = \alpha + \beta_1 \sqrt{\text{Time Between Trades}_{it}} + \beta_2 \text{ Option Moneyness}_{it} + \beta_3 \text{ Option Maturity}_{it} + \beta_4 \text{ Option Volatility}_{it} + \beta_5 \text{ Dummy}_{it} + \varepsilon_{it}$$

The absolute percentage error is measured as the absolute value of the market price less the model price, divided by the market price. The time between trades on futures and options is measured in minutes, option moneyness is defined as the futures price divided by the exercise price, option maturity is measured in days, option volatility is measured in in percent and is calculated using options with the same term to maturity and Dummy is a variable which takes the value of one if the transaction was on or after 11 October 1993 and zero otherwise. Note that the number of observations used in the regression differs from those reported in Table 4 because all trades in the first five trading days of the year were required to calculate the first rolling implied volatility estimate. T statistics are in parentheses and are calculated using White's heteroscedasticity-consistent standard errors and covariances. The regression is a pooled regression since option transactions occur across exercise prices (subscript i) and through time (subscript t).

Data	**N**	α	β_1	β_2	β_3	β_4	β_5
All Trades 1993	2120	-3.5522 -23.64*	0.0115 1.42	3.9956 27.56*	-0.0035 -20.80*	-1.5513 -4.94*	-0.0093 -1.26
In-the-Money	29	0.0574 0.12	0.0034 0.30	-0.0340 -0.07	0.0004 0.65	0.0896 0.16	-0.0302 -2.19**
Near-the-Money	719	-1.9281 -3.40*	0.0199 1.33	2.0621 3.64*	-0.0021 -8.42*	0.2074 0.48	-0.0296 -3.50*
Out-of-the-Money	1372	-3.7189 -36.28*	0.0159 1.71**	4.4307 53.99*	-0.0038 -22.31*	-3.3206 -8.53*	-0.0184 -1.92**

* denotes significance at the one percent level
** denotes significance at the five percent level

References

Asay, M., "A note on the design of commodity option contracts". *Journal of Futures Markets* 52, 1-7 (1982).

Bakshi, G., Cao, C., Chen, Z., "Empirical performance of alternative option pricing models". *Journal of Finance* 52, 2003-2049 (1997).

Black, F., "The pricing of commodity contracts". *Journal of Financial Economics* 3, 167-179 (1976).

Bodurtha, J.N., Courtadon, G.R., "Efficiency tests of foreign exchange currency options markets". *Journal of Finance* 41, 151-162 (1986).

Bookstaber, R.M., "Observed option mispricing and nonsimultaneity of stock and option quotations". *Journal of Business* 54, 141-155 (1981).

Brace, A., Hodgson, A., "Index futures options in Australia - An empirical focus on volatility". *Accounting and Finance* 31, 13-30 (1991).

Brooks, R.M., Chiou, S-N., "A bias in closing prices: The case of the when-issued pricing anomaly". *Journal of Financial and Quantitative Analysis* 30, 441-454 (1995).

Brown, C.A., "The volatility structure implied by options on the SPI futures contract". *Australian Journal of Management* 24, 115-130 (1999).

Brown, C.A., The successful redenomination of a futures contract: The case of the Australian all ordinaries share price index futures contract". *Pacific-Basin Finance Journal* 9, 47-64 (2001).

Brown, C.A., Robinson, D.M., "Option pricing and higher moments". Paper presented at the Asia Pacific Finance Association conference, Melbourne (1999).

Brown, C.A., Taylor, S.D., "A test of the Asay model for pricing options on the SPI futures contract" *Pacific-Basin Finance Journal* 5, 579-594 (1997).

Chiras, D.P., Manaster, S., "The information content of option prices and a test of market efficiency". *Journal of Financial Economics* 6, 213-234 (1978).

Easton, S.A., "Non-simultaneity and apparent option mispricing in tests of put-call parity". *Australian Journal of Management* 19, 47-60 (1994).

Galai, D., "Tests of market efficiency of the Chicago Board Options Exchange". *Journal of Business* 50, 167-197 (1977).

Galai, D., "A convexity test for traded options". *Quarterly Review of Economics and Business* 19, 83-90 (1979).

Galai, D., "A survey of empirical tests of option-pricing models". In Brenner, M. (Ed.), *Option Pricing: Theory and Applications*. Lexington: Lexington Books, 1982.

Hull, J.C., *Options, Futures, and Other Derivative Securities*, 4th edn. Englewood Cliffs, New Jersey: Prentice-Hall, 2000.

Lieu, D., "Option pricing with futures style margining". *Journal of Futures Markets* 10, 327-338 (1990).

Long, M.D., Officer, D.T., "The relation between option mispricing and volume in the Black-Scholes option model". *Journal of Financial Research* 20, 1-12 (1997).

Manaster, S., Rendleman, R.J., "Option prices as predictors of equilibrium stock prices". *Journal of Finance* 37, 1043-1057 (1982).

Ramaswamy, K., Sundaresan, S.M., "The valuation of options on futures contracts". *Journal of Finance* 40, 1319-1340 (1985).

Shimeld, S., Easton, S., "Smiles and the maturity effect in the SFE". Paper presented at the PACCAP/FMA conference, Melbourne (2000).

Trippi, R., "A test of option market efficiency using a random-walk valuation model". *Journal of Economics and Business* 29, 93-98 (1977).

Twite, G., "The pricing of SPI futures options with daily futures style margin payments". *Australian Journal of Management* 21, 139-157 (1996).

Vijh, A.M., "Potential biases from using only trade prices of related securities on different exchanges: A comment". *Journal of Finance* 43, 1049-1055 (1988).

Whaley, R.E., "Valuation of American call options on dividend paying stocks: Empirical tests". *Journal of Financial Economics* 10, 29-58 (1982).

Whaley, R.E., "Valuation of American futures options: Theory and empirical tests". *Journal of Finance* 41, 127-150 (1986).