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Article

An Open Innovation Intraday Implied Volatility for Pricing Australian Dollar Options

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Abstract: This study introduces the intraday implied volatility (IV) for pricing the Australian dollar (AUD) options. The IV is estimated using the at-the-money one-month, two-month, and three-month maturity AUD options traded in the opening, midday, and closing period of a trading day. The Mincer-Zarnowitz regression test evaluates the predictive power of IV to forecast the foreign exchange volatility for the within-week, one-week, and one-month horizon. The mean absolute error, mean squared error, and root mean squared error measures are employed to assess the performance of IV in estimating the price of currency options for the within-week, one-week, and one-month horizon. This study reveals four critical findings. First, a three-month maturity IV does not contain vital information for pricing options. Second, IV incorporated information is not relevant to compute the value of options for a horizon of less than a week. Third, IV in the closing period of Monday or Tuesday subsumes most of the essential information to estimate options price. Fourth, the shorter (longer) maturity IV provides critical information to price options for the shorter (longer) horizon. The intraday IV is a new dimension of unobservable volatility in accurately pricing currency options for researchers and practitioners.

Keywords: intraday implied volatility; realised volatility; Australian dollar options; Mincer–Zarnowitz regression



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1. Introduction

This study introduces intraday implied volatility (IV) which is an innovative approach to estimate the volatility of underlying currency for pricing currency options accurately. The intraday IV captures the market information at the opening, midday, and closing period of a trading day for pricing options with higher accuracy. If the options are mispriced, particularly overpriced options, it will increase the cost for hedging using currency options. The 2019 Bank for International Settlement (BIS) Triennial Survey results reveal that the turnover in Australian dollar (AUD) options increased by 58 percent between April 2016 and April 2019 [1], which is significant compared to other currency options. Therefore, Australian dollar options are considered to assess the capability of intraday IV to holding appropriate market information for pricing options precisely.

Foreign exchange (FX) risks are reported as one of the major risks related to foreign investments and international assets pricing [2]. Most portfolio managers have been using FX options as their primary hedging tools to manage these risks [3]. The flexibility of currency options in creating a customised risk/return profile to achieve a specific investment objective has led to the significant growth of the FX options market. Holding currency options for various investment decisions such as hedging or speculation can be costly if the options are mispriced. Options mispricing affects the selection of hedge ratio, hedging efficiency, as well as expected hedging costs [4]. For this reason, the accuracy of currency options pricing has been attracting the attention of market participants [5]. Currently, the most commonly used model to calculate European options prices is known as the Black–Scholes [6] (BS)

model [7]. The BS model assumes constant volatility. If true, this assumption would lead to a flat implied volatility curve. Observed implied volatility in practice differs across option contracts, depending on both moneyness and time to maturity. However, due to the theoretical approximation between the stochastic volatility and conditional volatility models to BS for at-the-money (ATM) options and nearest to expiration [8,9] and the rich informational content, implied volatility is still of interest [10–13] and the BS model is still widely applied [14]. Using the Merton [15] version of the BS model (BSM) to calculate prices of European currency options, all components are observable except the volatility of the underlying currency. Errors in the estimation of volatility result in the options mispricing [16–18]. The improvement of volatility estimation leads to lower errors of option prices [19]. Hence, forecasts of future volatility of underlying assets are vital for estimating and forecasting the currency options price accurately.

The literature has explored the volatility intensively. As the options prices reflect the market's expectation about the future movements of the prices of the underlying asset over the remaining life of the option contract, more research concentrates on volatility implied in options prices [20]. The implied volatility (IV) contains all available information, including historical data [10,20–25]. It is widely accepted that the IV from the market options price is a reasonable measure of the market's opinion of the volatility of the underlying asset. The forward-looking IV subsumes relevant information in terms of future volatility, and it often outperforms historical volatility in predicting future realised volatility (RV). Such superior performance was recognised in different types of assets [26]. For currency options, the majority of both previous and more current research found that IV was a reliable predictor of future volatility. IV contained valuable information for volatility forecasting and captured approximately 50 per cent of actual currency volatility [27].

However, most of the previous research used the conventional approach that was based on daily IV obtained from daily closing options prices. As the operation of financial markets during their opening trading hour are based on a continuous, high-frequency basis, the conventional method using a discrete sample of datasets on markets at a significantly lower frequency with the majority of data being extracted per day, or per week to forecast volatility is no longer relevant [28]. New technologies have been creating opportunities to obtain better, faster, and more efficient datasets to explore financial market phenomena at the finest levels of data [29]. It provides reliable intraday data to supporting financial investment decisions across different assets classes and instruments consisting of commodities, derivatives, equities, fixed income, and foreign exchange [30]. The purpose of this paper is to investigate the performance of the intraday implied volatility (IV) for pricing the Australian dollar (AUD) options. This study has three major contributions.

First, this study introduces an intraday IV approach based on the one-month, two-month, and three-month maturity options traded in the opening, midday, and closing period of a trading day, which captures the most relevant information of the FX in estimating options prices. Second, the research findings indicate that the one-month and two-month maturity intraday IV holds vital information to predict the volatility of the underlying currency of options for the one-week and one-month forecast horizon, respectively. Third, this research confirms that the information content embedded in the IV based on the one-month and two-month maturity options is appropriate to estimate the value of currency options for the one-week and one-month horizon, respectively.

The rest of the paper proceeds as follows. Section 2 discusses the literature review. The next section describes the methodology and data used in this study. Section 4 conducts the empirical analysis, followed by the discussion of the findings. The last section concludes the paper.

2. Literature Review

Xu and Taylor [31] examined the informational efficiency of the four currency options (British pound (GBP), Deutsche mark (DEM), Japanese yen (JPY), and Swiss franc (CHF) against the US dollar (USD)) from January 1985 to January 1992 and concluded that

option prices subsumed useful information about future volatilities. Likewise, Jorion [32] tested the predictive power of DEM, JPY, and CHF against the USD and found that IV contained more information content compared to statistical time-series models. Kazantzis and Tessaromatis [33] analysed the information content and predictive power of IV using six currency options (JPY, DEM, GBP, CHF, Canadian dollar (CAD), and AUD against the USD) from December 1989 to April 1997. The findings indicated that IV was more informative than historical and GARCH-based volatilities for horizons ranging from one day to three months. Kim and Kim [34] showed that the IV of the CAD, CHF, DEM, GBP, and JPY options tended to be low in the early part of the week but remain high in the last part of the week beginning on Wednesdays. Chang and Tabak [35] produced evidence that the IV of Brazilian options contained vital information that was missing in the econometric models and it provided superior foreign exchange (FX) forecasts. Busch et al. [23] explored the role of IV in predicting future volatility and found that IV was an unbiased predictor and provided helpful information for volatility forecasting in the FX market. Pilbeam and Langeland [36] recognised that the IV of CHF, EUR, GBP, and JPY provided a superior performance compared to the GARCH model in both the low and high volatility periods of the FX market. Sahoo and Trivedi [37] showed that IV outperformed historical volatilities in forecasting future RV . Wong and Heaney [38] found the knowledge of the volatility smile, which were implied from the one-month maturity of GBP/USD, EUR/USD, AUD/USD, and USD/JPY options, improved FX volatility forecast accuracy. Covrig and Low [39] used over-the-counter (OTC) data for USD per GBP, JPY per USD, and USD per AUD to examine the information of IV for different forecast horizons. They suggested that quoted IV subsumed the information content of historically based forecasts at shorter horizons (one-month and two-month horizon). Pong et al. [40] found that the IV of the DEM, GBP, and JPY options incorporated most of the relevant information for the forecast horizon of either one-month or three-month. Christoffersen and Mazzotta [41] revealed that the IV of at-the-money (ATM) options for the EUR, GBP, and JPY mostly provided the unbiased and reasonably accurate forecasts of actual volatility one month and three months out.

Until the late 1970s, using monthly data played an essential role in empirical research due to the unavailability of and access problems to higher frequency data, such as daily or intraday data. However, the development of information technology in the 1990s provided access to time-stamped observations on all quotes and transactions. These tick-by-tick data, termed as ultra-high-frequency data by Engle [42], are usually referred to as high-frequency data in current studies. High-frequency data indicated that many financial assets experienced the particular intraday patterns [20] and these patterns were significantly associated with intraday returns variations, volatility, volume, and bid-ask spreads [43]. A large number of studies suggested that intraday trading activities exhibited a U-shaped pattern with the trading volumes being extremely high at the market's opening and closing periods, such as Wood et al. [44], Gerety and Mulherin [45], Brock and Kleidon [46] for the New York Stock Exchange (NYSE); McInish and Wood [47] for the Toronto Stock Exchange; and Hamao and Hasbrouck [48] for the Tokyo stock exchange. Several studies reported the M-shaped [29,49] or J-shaped patterns [50] for the UK stock exchange. Most of the research found the importance of intraday data in improving volatility predicting. There was a significant amount of information in the five-minute returns when estimating hourly variances [51–53]. Wang and Wang [20] explored the capability of intraday IV information content using the S&P500 Index as a sample from 2005 to 2010. Their study recognised that the IV around noon contains more useful information regarding future volatility than IV at the market's closing period, which has been frequently used in the previous literature. Trading at a specific time of the trading day is motivated by specific information and risk factors, which do not remain during other times. Hence, our paper investigates the performance of IV in estimating and forecasting options prices at three different trading time periods of the trading day (opening, midday, and closing) using the AUD currency options datasets covering the period from 2010 to 2017.

Previous studies focused on the daily IV of currency options to forecast the volatility of FX. There are not many pieces of research utilising the high-frequency data and intraday IV in estimating and forecasting volatility. Furthermore, IV incorporated information has not been used for pricing options. Therefore, this paper will examine the capability of intraday IV with different time to maturity in forecasting future volatility and estimating currency options price.

3. Materials and Methods

3.1. Data Description

This study used AUD currency options provided by the Options Price Reporting Authority (OPRA) as the last-sale options quotations. We obtained data from Thomson Reuters' database through the Securities Industry Research Centre of Asia-Pacific (SIRCA). The sample period began on 01 January 2010 and ended on 31 December 2017. The options were traded on Monday to Friday, excluding public holidays from 9:30 to 16:00 (US Eastern standard time), and expired on the third Friday of each month. The options were European style, with the contract size of sample currency options being AUD 10,000 and settled in USD. The time to maturity of an option was assumed to be the number of calendar days remaining until the option matured. The sample options expired in one-month (2 to 30 days), two-month (31 to 60 days), and three-month (61 to 90 days) periods. The IV was calculated for the opening-period (9:30 to 10:00), midday-period (12:30 to 13:00), and closing-period (15:30 to 16:00) of a trading day. The time difference between "opening-period" and "midday-period" and between "midday period" and "closing period" was equal (two and half hours) enough to position them evenly in a trading day. The BSM model assumed the volatility as constant, which introduced a bias into the IV estimation. Hull and White [54] stated that the magnitude of the bias in the BS model was the smallest for near-the-money options. Therefore, the IV was calculated based on the ATM one-month, two-month, and three-month maturity options traded during the opening, midday, and closing periods of a trading day.

We followed the ATM criteria in Xing et al. [55]; the ratio of the strike price to the stock price was considered between 0.95 and 1.05. The average of the close bid/ask quote of each five-minute interval was computed for each options price to mitigate problems due to bid/ask bounce [56]. The one-month, two-month, and three-month AUD and USD deposit interest rate were used as the proxy of the risk-free interest rate.

3.2. Methodology

The research methodology consists of five sub-sections, (i) calculating IV, (ii) computing realised volatility (RV), (iii) IV forecasting RV , (iv) IV estimating options model price, and (v) estimating the options pricing error.

3.2.1. Implied Volatility Calculation

The BSM model replaces the stock price with foreign currency and considers the interest gained on holding foreign currency to be equivalent to a continuously paid stock dividend. The notation of the BSM model and its descriptions are as follows:

C_t = price of call in domestic currency at time t

P_t = price of put in domestic currency at time t

S_t = spot price at time t

X_t = exercise price in domestic currency at time t

R_t^d = interest rate of domestic currency at time t

R_t^f = foreign currency interest rate at time t

T = options expiration time

σ_t = volatility of underlying currency

N = cumulative normal distribution function

In the BSM model, the European type call and put options are priced as:

$$C_t = S_t e^{-R_t^f T} N(d_{1,t}) - X_t e^{-R_t^d} N(d_{2,t}) \tag{1}$$

$$P_t = X_t e^{-R_t^d T} N(-d_{2,t}) - S_t e^{-R_t^f} N(-d_{1,t}) \tag{2}$$

where,

$$d_{1,t} = \frac{\ln\left(\frac{S_t}{X_t}\right) + \left(R_t^d - R_t^f + \frac{\sigma_t^2}{2}\right)T}{\sigma_t \sqrt{T}}, \tag{3}$$

And

$$d_{2,t} = \frac{\ln\left(\frac{S_t}{X_t}\right) + \left(R_t^d - R_t^f - \frac{\sigma_t^2}{2}\right)T}{\sigma_t \sqrt{T}} = d_{1,t} - \sigma_t \sqrt{T} \tag{4}$$

For notation convenience, let $\zeta_t = e^{-R_t^f T}$ and $\eta_t = e^{-R_t^d T}$ so that Equations (1) and (2) can be written as follows:

$$C_t^{mkt,k,l} = S_t \zeta_t N\left[d_{1,t}\left(\sigma_{c,t}^{k,l}\right)\right] - X_t \eta_t N\left[d_{2,t}\left(\sigma_{c,t}^{k,l}\right)\right] \tag{5}$$

$$P_t^{mkt,k,l} = X_t \eta_t N\left[-d_{2,t}\left(\sigma_{p,t}^{k,l}\right)\right] - S_t \zeta_t N\left[-d_{1,t}\left(\sigma_{p,t}^{k,l}\right)\right] \tag{6}$$

where ∇_{mkt} = call and put market price; ∇_k = one-month, two-month, three-month maturity options; ∇_l = opening period, midday period, closing period. Now we calculate the implied volatility $\left(\sigma_{c,t}^{k,l}\right)$ for the ATM call options market price $\left(C_t^{mkt,k,l}\right)$ and implied volatility $\left(\sigma_{p,t}^{k,l}\right)$ for the ATM put options market price $\left(P_t^{mkt,k,l}\right)$ through the Newton–Raphson [57] iterative search procedure.

Despite the numerous suggestions about weighted-average techniques for calculating IV, there is no theoretically appropriate weighting scheme in the literature to estimate IV. We used the method suggested by Jorion [32] that computes IV as the average of the call options price IV and the put options’ price IV. This study estimates IV as:

$$\hat{\sigma}_t^{k,l} = \frac{\hat{\sigma}_{c,t}^{k,l} + \hat{\sigma}_{p,t}^{k,l}}{2}, \tag{7}$$

3.2.2. Realised Volatility Calculation

The actual market volatility is unobservable, so in evaluating volatility estimating and forecasting, the usual proxy for “true volatility” is the so-called realised volatility (RV). The RV sums the squared intraday returns sampled at a particular rate of recurrence [52,58]. The optimal interval to construct the RV is not known. Based on standard practice and previous literature, there is evidence that the five-minute RV as the benchmark outperformed other measures, and it is difficult to significantly surpass the five-minute (5 min) data frequency for RV [53]. Consequently, this study used daily RV series constructed from five-minute intraday spot prices as a proxy for the unobservable variance. If S_i is the spot rate for a five-minute sampling frequency, the underlying exchange rate return in a five-minute interval was estimated as:

$$r_{i,t} = \ln\left(\frac{S_i}{S_{i-1}}\right) \tag{8}$$

where $r_{i,t}$ represents the return in interval i on day t . Equation (7) computed the realised variance of day t ,

$$v_t = \sum_{i=1}^n r_{t,i}^2, \tag{9}$$

where n denotes the total number of data points from 9:30 to 16:00 for Monday to Friday. Further, the RV is the standard deviation of the realised variance. Therefore, the RV per trading day is calculated as:

$$\hat{\sigma}_t^{RV} = \sqrt{v_t}, \tag{10}$$

As intraday data of trading days estimate the RV , when the exchange is closed, days are ignored and the RV per annum is:

$$\hat{\sigma}_t^{RV} = \sqrt{Dv_t}, \tag{11}$$

where D is considered 252 trading days per year consistent with the normal assumption of the options market.

3.2.3. Implied Volatility Forecasting Realised Volatility

For IV from different maturities of options, the forecasting evaluation was implemented using the regression test introduced by Mincer and Zarnowitz [59], known as the Mincer–Zarnowitz (MZ) regression. In the MZ regression analysis, the RV is regressed on a constant and IV as in Equation (12):

$$\hat{\sigma}_t^{RV} = \beta_0 + \beta_1 \hat{\sigma}_{t-j}^{k,l} + \varepsilon_t, \tag{12}$$

where $\forall_j =$ within-week, one-week, and one-month horizon. The within-week horizon indicates that the IV is calculated one to four days before the date of RV is computed. Similarly, the one-week and one-month horizon imply that the IV is estimated one week and one month before the date of RV is obtained. The MZ regression allowed the evaluation of two different aspects to predict the volatility. First, the unbiasedness and efficiency of the forecast were evaluated by testing the intercept and slope through the joint hypothesis ($H_0: \beta_0 = 0$ and $\beta_1 = 1$) [60]. Second, the accuracy of the forecast was evaluated by the high goodness of fit value, R-squared (R^2). The R^2 is a statistical measure that represents the percentage of the variance for RV explained by IV. The value of R^2 compares the predictive power of IV to forecast RV for different horizons; such as, the R^2 of IV for the one-week horizon being higher than that of the one-month horizon implies that the RV can be explained well by the IV for the one-week horizon; that is, IV forecast of RV for one-week horizon outperforms its performance for the one-month horizon. The MZ regression analysis uses the OLS (ordinary least squared) method with Newey–West corrected errors for heteroscedasticity and serial correlation.

3.2.4. Implied Volatility Estimating Options Model Price

This study calculated the call options and put options model price using the estimated value of IV as the input for the BSM options pricing model. The $C_t^{mkt,k}$ and $P_t^{mkt,k}$ in Equations (5) and (6) were substituted with call options model price ($\hat{\Pi}_{c,t}^{mod,k}$) and put options model price ($\hat{\Pi}_{p,t}^{mod,k}$) as in Equations (13) and (14), respectively.

$$\hat{\Pi}_{c,t}^{mod,k} = S_t \zeta_t N \left[d_{1,t} \left(\hat{\sigma}_{t-i}^{k,l} \right) \right] - X_t \eta_t N \left[d_{2,t} \left(\hat{\sigma}_{t-i}^{k,l} \right) \right] \tag{13}$$

$$\hat{\Pi}_{p,t}^{mod,k} = X_t \eta_t N \left[-d_{2,t} \left(\hat{\sigma}_{t-i}^{k,l} \right) \right] - S_t \zeta_t N \left[-d_{1,t} \left(\hat{\sigma}_{t-i}^{k,l} \right) \right] \tag{14}$$

3.2.5. Options Pricing Error Estimation

The options pricing error (OPE) is the difference between the ATM options market price and the estimated options model price. The OPE is measured using standard statistical

accuracy criteria, including mean absolute error (MAE), mean squared error (MSE), and the root mean squared error (RMSE), as in Equations (15)–(17), respectively.

$$MAE_u^{m,k,l} = \frac{1}{n} \sum_{t=1}^n \left| \Pi_{u,t}^{ATM,k,l} - \hat{\Pi}_{u,t}^{mod,k,l} \right| \tag{15}$$

$$MSE_u^{m,k,l} = \frac{1}{n} \sum_{t=1}^n \left(\Pi_{u,t}^{ATM,k,l} - \hat{\Pi}_{u,t}^{mod,k,l} \right)^2 \tag{16}$$

$$RMSE_u^{m,k,l} = \sqrt{\frac{1}{n} \sum_{t=1}^n \left(\Pi_{u,t}^{ATM,k,l} - \hat{\Pi}_{u,t}^{mod,k,l} \right)^2} \tag{17}$$

where \forall_u = call price, put price.

4. Results

Table 1 describes the performance of IV to forecast RV for the within-week forecast horizon, one-week forecast horizon, and one-month forecast horizon. R² values from the forecasting regression in Equation (12) are reported. The IV with the highest R² is preferred.

For the within-week forecast horizon, in the opening of Tuesday, three-month (R² = 0.336) maturity IV outperformed in forecasting the RV. In the midday of Wednesday, two-month (R² = 0.335) maturity IV outperformed in forecasting the RV. In the closing period of Monday, two-month (R² = 0.379) maturity IV performed better when predicting the RV. Overall findings for the within-week horizon indicated that the two-month maturity IV (R² = 0.379) in the closing period of Monday (begin-week day) were the most superior to the forecast of RV.

For the one-week forecast horizon, in the opening period of Tuesday, one-month (R² = 0.465) maturity IV performed better in forecasting RV. Likewise, in the midday period of Tuesday, one-month (R² = 0.432) maturity IV showed better performance when predicting RV. Next, in the closing period of Monday, one-month (R² = 0.472) maturity IV was superior in predicting RV. Overall findings for the one-week horizon revealed that one-month maturity IV (R² = 0.472) in the closing period of Monday (begin-week day) held better predictive power when forecasting RV.

For the one-month forecast horizon, in the opening period of Tuesday, two-month (R² = 0.386) maturity IV performed better when forecasting RV. In the midday period of Tuesday, two-month (R² = 0.332) maturity IV held higher predictive power when predicting RV. Finally, in the closing period of Tuesday, two-month (R² = 0.393) maturity IV was superior when predicting RV. Overall findings for the one-month horizon suggested that the two-month maturity IV (R² = 0.393) in the closing periods of Tuesday (begin-week day) held higher forecasting capabilities in predicting RV.

The closing period IV better performed in forecasting RV for within-week, one-week, and one-month forecast horizons. Therefore, this study estimated the currency options price using IV based on options traded only during closing periods with a one-month, two-month, and three-month maturity. The closing period IV were used as inputs for the Equations (13) and (14) to estimate the call and put options model price, respectively. The MAE, MSE, and RMSE methods were employed in Equation (15), Equation (16) and Equation (17), respectively, to measure the options pricing error (OPE).

Table 2 describes the performance of IV to price the AUD options for the within-week forecast horizon, one-week forecast horizon, and one-month forecast horizon.

Table 1. Implied volatility (IV) forecast realised volatility (RV) for Australian dollar (AUD) options for within-week, one-week, and one-month forecast horizon.

| Time to Maturity | | Within-Week Forecast | | | | One-Week Forecast | | | | | One-Month Forecast | | | | |
|---------------------------------------|----------------|----------------------|--------------------|--------------------|------------|----------------------|--------------------|------------|------------|------------|--------------------|----------------------|------------|------------|------------|
| | | Mon to Fri | Tue to Fri | Wed to Fri | Thu to Fri | Mon to Mon | Tue to Tue | Wed to Wed | Thu to Thu | Fri to Fri | Mon to Mon | Tue to Tue | Wed to Wed | Thu to Thu | Fri to Fri |
| Panel A: Opening period (9:30–10:00) | | | | | | | | | | | | | | | |
| 1-month | Slope | 0.207 | 0.248 | 0.187 | 0.152 | 0.204 | 0.227 | 0.249 | 0.193 | 0.290 | 0.199 | 0.197 | 0.227 | 0.138 | 0.257 |
| | R ² | 0.133 | 0.195 ¹ | 0.114 | 0.102 | 0.405 | 0.465 ² | 0.307 | 0.262 | 0.305 | 0.227 | 0.228 ¹ | 0.162 | 0.092 | 0.151 |
| 2-month | Slope | 0.415 | 0.479 | 0.483 | 0.443 | 0.366 | 0.414 | 0.504 | 0.445 | 0.445 | 0.324 | 0.337 | 0.449 | 0.357 | 0.361 |
| | R ² | 0.294 | 0.228 | 0.335 ² | 0.300 | 0.308 | 0.365 ¹ | 0.321 | 0.342 | 0.238 | 0.356 | 0.386 ² | 0.263 | 0.217 | 0.177 |
| 3-month | Slope | 0.554 | 0.548 | 0.569 | 0.508 | 0.472 | 0.435 | 0.495 | 0.482 | 0.540 | 0.409 | 0.454 | 0.447 | 0.285 | 0.439 |
| | R ² | 0.221 | 0.336 ² | 0.288 | 0.270 | 0.253 | 0.284 ¹ | 0.161 | 0.183 | 0.212 | 0.249 | 0.295 ¹ | 0.162 | 0.202 | 0.170 |
| Panel B: Midday period (12:30–13:00) | | | | | | | | | | | | | | | |
| 1-month | Slope | 0.248 | 0.245 | 0.207 | 0.253 | 0.216 | 0.217 | 0.227 | 0.310 | 0.260 | 0.194 | 0.196 | 0.205 | 0.215 | 0.224 |
| | R ² | 0.198 | 0.214 ² | 0.142 | 0.172 | 0.400 | 0.432 ¹ | 0.275 | 0.349 | 0.235 | 0.224 | 0.260 ² | 0.156 | 0.159 | 0.141 |
| 2-month | Slope | 0.427 | 0.411 | 0.390 | 0.425 | 0.364 | 0.353 | 0.397 | 0.436 | 0.390 | 0.304 | 0.317 | 0.364 | 0.347 | 0.290 |
| | R ² | 0.246 | 0.280 ¹ | 0.244 | 0.257 | 0.356 | 0.375 ² | 0.274 | 0.347 | 0.218 | 0.261 | 0.332 ¹ | 0.241 | 0.232 | 0.135 |
| 3-month | Slope | 0.470 | 0.486 | 0.465 | 0.479 | 0.396 | 0.419 | 0.473 | 0.513 | 0.479 | 0.332 | 0.385 | 0.413 | 0.415 | 0.362 |
| | R ² | 0.250 | 0.262 ¹ | 0.219 | 0.240 | 0.299 | 0.317 ² | 0.189 | 0.315 | 0.191 | 0.241 | 0.327 ³ | 0.208 | 0.230 | 0.125 |
| Panel C: Closing period (15:30–16:00) | | | | | | | | | | | | | | | |
| 1-month | Slope | 0.274 | 0.247 | 0.224 | 0.272 | 0.244 | 0.221 | 0.260 | 0.287 | 0.301 | 0.228 | 0.181 | 0.200 | 0.207 | 0.247 |
| | R ² | 0.313 ³ | 0.207 | 0.160 | 0.213 | 0.472 ^{3,*} | 0.435 | 0.317 | 0.329 | 0.257 | 0.210 | 0.275 ³ | 0.146 | 0.158 | 0.144 |
| 2-month | Slope | 0.432 | 0.427 | 0.426 | 0.458 | 0.378 | 0.380 | 0.423 | 0.430 | 0.434 | 0.320 | 0.322 | 0.353 | 0.350 | 0.325 |
| | R ² | 0.379 ^{3,*} | 0.273 | 0.252 | 0.294 | 0.396 ³ | 0.379 | 0.298 | 0.353 | 0.251 | 0.285 | 0.393 ^{3,*} | 0.215 | 0.248 | 0.158 |
| 3-month | Slope | 0.513 | 0.500 | 0.489 | 0.501 | 0.438 | 0.438 | 0.517 | 0.496 | 0.512 | 0.370 | 0.394 | 0.426 | 0.420 | 0.399 |
| | R ² | 0.352 ³ | 0.258 | 0.248 | 0.292 | 0.335 ³ | 0.310 | 0.240 | 0.290 | 0.228 | 0.284 | 0.310 ² | 0.207 | 0.238 | 0.146 |

Notes: IV represents implied volatility of Australian dollar (AUD) options. Equation (7) estimates IV using one-month (2 to 30 days), two-month (31 to 60 days), and three-month (61 to 90 days) maturity AUD options, for the opening (9:30–10:00), midday (12:30–13:00), and closing (15:30–16:00) a trading day. RV represents the realised volatility of Australian dollar. Equation (11) calculates the RV using the 5-min frequency AUD spot rate. The Mincer–Zarnowitz (MZ) regression analysis model, as in Equation (12), provides the slope coefficient and R² of within-week forecast horizon (Monday, Tuesday, Wednesday, and Thursday to Friday of the same week), one-week forecast horizon (Monday, Tuesday, Wednesday, Thursday, and Friday to Monday, Tuesday, Wednesday, Thursday, and Friday of next week, respectively), and one-month forecast horizon (Monday, Tuesday, Wednesday, Thursday, and Friday to Monday, Tuesday, Wednesday, Thursday, and Friday of next month, respectively) for the one-month, two-month, and three-month maturity options traded in the opening, midday, and closing of a trading day are given in panels A, B, and C, respectively. The *p*-value is zero for all cases and is not reported in the table to avoid repetition. Further, the zero *p*-values indicate that the null hypothesis is rejected at any level of significance. The superscripts 1, 2, and 3 denote the lower, mid, and higher value of R², respectively, among different trading periods (opening, midday, closing) for the maturity of each option (one-month, two-month, three-month). The * represents the highest value of R² among one-month, two-month, and three-month maturity IV that lead the performance of IV to forecast RV for within-week, one-week, and one-month forecast horizon, respectively. Monday or Tuesday, Wednesday, and Thursday or Friday are considered as begin-week day, mid-week day, and end-week day, respectively.

Table 2. Estimate options pricing error for AUD options for the within-week, one-week, and one-month horizon.

| Time to Maturity | | Within-Week Forecast | | | | One-Week Forecast | | | | | One-Month Forecast | | | | |
|---------------------------------|------|----------------------|------------|------------|------------|--------------------|------------|------------|------------|------------|--------------------|--------------------|------------|------------|------------|
| | | Mon to Fri | Tue to Fri | Wed to Fri | Thu to Fri | Mon to Mon | Tue to Tue | Wed to Wed | Thu to Thu | Fri to Fri | Mon to Mon | Tue to Tue | Wed to Wed | Thu to Thu | Fri to Fri |
| Panel A: OPE under MAE measure | | | | | | | | | | | | | | | |
| 1-month | CALL | 0.137 ³ | 0.143 | 0.154 | 0.155 | 0.142 ³ | 0.151 | 0.187 | 0.156 | 0.146 | 0.158 | 0.146 ² | 0.185 | 0.160 | 0.165 |
| | PUT | 0.067 ³ | 0.082 | 0.073 | 0.077 | 0.056 ³ | 0.064 | 0.075 | 0.076 | 0.069 | 0.091 | 0.086 ² | 0.102 | 0.091 | 0.091 |
| 2-month | CALL | 0.138 ² | 0.140 | 0.140 | 0.145 | 0.149 ² | 0.154 | 0.204 | 0.158 | 0.155 | 0.151 | 0.144 ³ | 0.180 | 0.154 | 0.154 |
| | PUT | 0.068 ² | 0.072 | 0.077 | 0.071 | 0.061 ² | 0.071 | 0.082 | 0.083 | 0.075 | 0.077 | 0.077 ³ | 0.097 | 0.087 | 0.078 |
| 3-month | CALL | 0.139 ¹ | 0.149 | 0.141 | 0.149 | 0.155 ¹ | 0.163 | 0.195 | 0.259 | 0.255 | 0.154 | 0.152 ¹ | 0.189 | 0.163 | 0.172 |
| | PUT | 0.074 ¹ | 0.075 | 0.078 | 0.077 | 0.079 ¹ | 0.082 | 0.091 | 0.090 | 0.081 | 0.098 | 0.094 ¹ | 0.111 | 0.106 | 0.098 |
| Panel B: OPE under MSE measure | | | | | | | | | | | | | | | |
| 1-month | CALL | 0.036 ³ | 0.048 | 0.055 | 0.044 | 0.044 ³ | 0.049 | 0.079 | 0.050 | 0.046 | 0.050 | 0.050 ¹ | 0.097 | 0.064 | 0.061 |
| | PUT | 0.009 ³ | 0.040 | 0.011 | 0.032 | 0.007 ³ | 0.009 | 0.015 | 0.013 | 0.010 | 0.028 | 0.020 ¹ | 0.040 | 0.021 | 0.020 |
| 2-month | CALL | 0.038 ² | 0.041 | 0.037 | 0.041 | 0.050 ¹ | 0.064 | 0.096 | 0.054 | 0.054 | 0.045 | 0.043 ³ | 0.077 | 0.048 | 0.050 |
| | PUT | 0.010 ² | 0.011 | 0.013 | 0.010 | 0.008 ² | 0.011 | 0.015 | 0.039 | 0.039 | 0.018 | 0.012 ³ | 0.024 | 0.018 | 0.013 |
| 3-month | CALL | 0.039 ¹ | 0.050 | 0.049 | 0.045 | 0.045 ² | 0.054 | 0.092 | 0.054 | 0.049 | 0.046 | 0.043 ² | 0.087 | 0.051 | 0.062 |
| | PUT | 0.012 ¹ | 0.021 | 0.021 | 0.023 | 0.017 ¹ | 0.023 | 0.026 | 0.018 | 0.024 | 0.022 | 0.017 ² | 0.027 | 0.026 | 0.020 |
| Panel C: OPE under RMSE measure | | | | | | | | | | | | | | | |
| 1-month | CALL | 0.190 ³ | 0.219 | 0.236 | 0.210 | 0.210 ³ | 0.222 | 0.282 | 0.224 | 0.222 | 0.225 | 0.223 ¹ | 0.312 | 0.254 | 0.247 |
| | PUT | 0.095 ³ | 0.201 | 0.106 | 0.180 | 0.085 ³ | 0.098 | 0.125 | 0.115 | 0.098 | 0.169 | 0.141 ¹ | 0.200 | 0.145 | 0.142 |
| 2-month | CALL | 0.195 ² | 0.204 | 0.192 | 0.203 | 0.213 ² | 0.254 | 0.310 | 0.233 | 0.254 | 0.212 | 0.207 ³ | 0.278 | 0.219 | 0.224 |
| | PUT | 0.104 ² | 0.106 | 0.114 | 0.102 | 0.091 ² | 0.106 | 0.125 | 0.197 | 0.106 | 0.134 | 0.113 ³ | 0.155 | 0.136 | 0.114 |
| 3-month | CALL | 0.197 ¹ | 0.224 | 0.297 | 0.213 | 0.224 ¹ | 0.233 | 0.304 | 0.233 | 0.233 | 0.215 | 0.208 ² | 0.296 | 0.226 | 0.249 |
| | PUT | 0.110 ¹ | 0.207 | 0.209 | 0.214 | 0.117 ¹ | 0.127 | 0.129 | 0.135 | 0.120 | 0.148 | 0.130 ² | 0.167 | 0.162 | 0.143 |

Notes: IV represents implied volatility of AUD options. Equations (13) and (14) estimate call price and put price, respectively, by using closing period IV for one-month (2 to 30 days), two-month (31 to 60 days), and three-month (61 to 90 days) maturity AUD options. The mean absolute error (MAE), mean squared error (MSE), and root mean squared error (RMSE) methods were employed as in Equation (15), Equation (16), and Equation (17), respectively, to measure the closing options pricing error (OPE). The OPE under MAE, MSE, and RMSE measures are given in the panels A, B, and C, respectively, for within-week estimate horizon (Monday, Tuesday, Wednesday, and Thursday to Friday of the same week); for one-week estimate horizon (Monday, Tuesday, Wednesday, Thursday, and Friday to Monday, Tuesday, Wednesday, Thursday, and Friday of next week, respectively); for one-month estimate horizon (Monday, Tuesday, Wednesday, Thursday, and Friday to Monday, Tuesday, Wednesday, Thursday, and Friday of next month, respectively). The superscripts 1, 2, and 3 denote higher, mid, and lower pricing error for the maturity of each option (one-month, two-month, three-month) among MAE, MSE, and RMSE measures, respectively. Monday or Tuesday, Wednesday, and Thursday or Friday are considered as begin-week day, mid-week day, and end-week day, respectively.

For the within-week forecast horizon, under the MAE measure, one-month (call pricing error = 0.137 and put pricing error = 0.067) maturity IV of Monday outperformed when estimating AUD call and put options. Next, for the MSE measure, one-month (call pricing error = 0.036 and put pricing error = 0.009) maturity IV of Monday was superior to price AUD call and put options. Finally, under the RMSE measure of Monday, one-month (call pricing error = 0.190 and put pricing error = 0.095) maturity IV held appropriate information to compute AUD call and put options. Overall, the one-month maturity of Monday (begin-week day) IV contained vital information to price AUD options.

For the one-week horizon, under the MAE measure, one-month (call pricing error = 0.142 and put pricing error = 0.056) maturity IV of Monday held appropriate information to estimate the AUD call and put options. Next, for the MSE measure, one-month (call pricing error = 0.044 and put pricing error = 0.007) maturity IV of Monday was superior to price the AUD call and put options. Finally, under the RMSE measure, one-month (call pricing error = 0.210 and put pricing error = 0.085) maturity IV of Monday contained vital information to compute the AUD call and put options. Overall, the one-month maturity of Monday (begin-week day) IV held critical information to estimate the price of the AUD options.

For the one-month horizon, under the MAE measure, two-month (call pricing error = 0.144 and put pricing error = 0.077) maturity IV of Tuesday provided appropriate information to estimate the AUD call and put options. Next, for the MSE measure, two-month (call pricing error = 0.043 and put pricing error = 0.012) maturity IV of Tuesday outperformed when pricing AUD call and put options. Finally, under the RMSE measure, two-month (call pricing error = 0.207 and put pricing error = 0.113) maturity IV of Tuesday contained vital information to compute the AUD call and put options. Overall, two-month maturity of Tuesday (begin-week day) IV held critical information to estimate the price of the AUD options.

5. Discussion

Our paper employed the tick data obtained from Thomson Reuters' database, an archive of historical every-minute data drawn from the real-time content. The use of big data would enable efficiency and speed to innovation. Financial innovation, such as venture capital, equity funds, and exchange-traded funds contributed positively to the financial deepening and economic growth [61,62]. The application of the information in portfolio management also allows the generation of high-frequency trading, which is considered a financial innovation, concentrating on order flow and rapidly evolving information [63]. In the derivatives market, millions of calculations need to be conducted daily to price derivative instruments to manage the risks and to determine hedge positions. However, information obtained from these computations is useful for only a limited period and will be outdated when the market moves. De Spiegeleer et al. [64] indicated that the use of real-time data and market information was mandatory in successfully running a derivative business in the present era of information explosion. As technology is increasing and the world overwhelmed by numbers and digits [65], forecasting volatility and options price based on the intraday data is crucial for the immediate investment decision making.

The empirical analysis indicated that the IV at the closing period performed better in predicting *RV* for all forecast horizons. As more intensive trading occurred at the end of the trading day, more valuable information to forecast future volatility can be extracted from the options price at the market close [66]. The within-week horizon provides a mixed picture for IV in terms of holding information to forecast *RV*. It suggests that the IV does not contain relevant information to predict the volatility of the underlying currency of options for a one- to four-day forecast horizon. Therefore, the intraday IV is not appropriate to estimate the currency options price for the within-week horizon. The one-month and two-month maturity; begin-week day and closing period of IV hold relevant information to forecast *RV* for the one-week and one-month forecast horizon, respectively. It reveals that the information content embedded in one-month and two-month maturity IV is significant in predicting the volatility of the underlying currency of options for the one-week and

one-month forecast horizon, respectively. Consequently, a one-month and two-month maturity IV is appropriate to estimate the currency options price for the one-week and one-month estimate horizon, respectively. These findings are in line with the research of Garvey and Gallagher [10] that examined the forecastability of IV using a sample of 16 FTSE-100 stocks and found that IV provided a useful volatility forecasting method, especially for the medium forecasting horizons between ten and thirty days. Although most of the previous research using data from stock market showed that the optimal forecast horizon of IV was from one day to less than thirty days [22,56], our results showed that the IV did not work well for the short forecast horizons from one day to four days, but it performed superiorly for the medium forecast horizons from one week to one month.

6. Conclusions

The accuracy of currency options pricing plays a crucial role in managing financial risk, providing a source of financial leverage for speculators, and preventing the opportunity for abnormal arbitrage profit. To calculate prices of currency options using the Merton [15] version of the BSM model, only the volatility of the underlying currency is not observable in the market. As volatility estimation errors lead to options mispricing, accurate forecasts of future volatility of underlying assets are essential for estimating and forecasting the currency options price. The IV is widely used to estimate the volatility of FX. The majority of the studies involving IV often find that the most relevant information for predicting an underlying asset's volatility can be found in the options price. Therefore, this paper was particularly interested in FX volatility prediction for pricing currency options. However, it is argued that the daily IV holds discrete information regarding the FX movement at a specific time of the trading day, which is not sufficient for estimating options prices accurately [67]. This study, therefore, introduces intraday IV through estimating IV for the price of options with different maturity during the opening, midday, and closing period of a trading day. The intraday IV approach will add a new dimension in the literature for the pricing currency option with higher accuracy.

Overall, the results suggest four key insights. First, three-month maturity IV does not hold vital information about future volatility of the underlying currency and pricing currency options. It happens because the shorter period information of one-month and two-month maturity options are useful compared to the longer period information of three-month maturity options. Second, IV incorporating all information is not relevant in computing the value of currency options for a horizon estimate that is less than a week. This is due to FX volatility following clustering, and both information content day (e.g., Monday) and forecasting day (i.e., Friday) lying in the same cluster. Third, IV for the closing period on Monday or Tuesday includes the most useful information compared to other periods of trading day and other days of the week when forecasting the volatility of the underlying currency and estimating the price of currency options. This occurs as all weekdays do not hold equally relevant information or critical information diminishes gradually from the middle of the week. Fourth, the shorter (longer) maturity IV provides essential information when pricing currency options for the shorter (longer) horizon. If the currency options are overpriced, the hedgers and speculators experience the higher cost for buying or holding currency options. However, the options become profitable for the options seller or writer. Further, the cost of hedging and speculation is less when options are underpriced. This also makes an opportunity cost loss for the options seller. The paper's results can provide valuable information to fund managers to hedge extreme risk and allow policy makers to construct a comprehensive strategy to prevent the opportunity for abnormal arbitrage profit. High-frequency traders can refer to these results to select valuable and useful intraday information for their immediate decision making. The sample data obtained for this research from the exchange-traded market is not as big as the OTC market. BIS (2019) reported that the currency options are traded not only in the exchanges, but a considerable volume of currency options are also traded in the interbank market due to the customisation benefit of OTC currency options

over options traded in exchanges. Moreover, the study limits the data sample in the AUD currency options that represent the developed market. The research findings may not be appropriate to apply to the other FX markets that experience different characteristics such as currency markets of emerging countries. The covered period of the dataset is from 1 January 2010 to 31 December 2017 due to the large volume of high-frequency data that needs to be collected. Therefore, our research captures particular economic circumstances in the context of the post Global Financial crisis period. The research results may be not suitable to apply for different economic circumstances such as before and during the crisis period. However, the information content of the IV during a crisis period is also peculiarly relevant [68,69] as it provides incremental and valuable information to hedge financial risk and to bring us a better understanding of market sentiment and behaviour. Hence, the avenue for potential further research concerns extending this research to the emerging currency options, using data from the OTC market, or testing the research results in different economic circumstances. As each type and each period of FX market contains peculiar characteristics, the investigations of intraday IV in other market conditions are necessary to provide a fully comprehensive view of its performance in forecasting the volatility of the underlying currency and estimating the value of currency options.

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