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Quality issues of implied volatilities of index and stock options in the OptionMetrics IvyDB database

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Abstract

For stock and index options in the United States, OptionMetrics records prices at 3:59 p.m., not 4:00 p.m. as assumed in previous literature. The resulting 1-min time discrepancy with closing share prices creates artificial variability in implied volatility spreads and strongly affects market-wide spreads. It leads to particularly large distortions at the onset of the COVID-19 pandemic. For index options in Europe, OptionMetrics data show large deviations from put-call parity even though the original option prices match the parity exactly. Finally, the implied volatilities of stock options in Europe show clusters of exceptional deviations due to incorrect dividend information.

KEYWORDS

implied volatilities, index options, OptionMetrics, put-call parity

JEL CLASSIFICATION

G13, G14, G15

1 | INTRODUCTION

According to Battalio and Schultz (2006, p. 2085 f.), the OptionMetrics IvyDB database "is arguably the best database of option prices that is publicly available and as such it has been used by numerous researchers."[1] It provides daily option prices and the corresponding implied volatilities (IVs) and "Greeks" for index and stock options around the world. In addition, it provides end-of-day estimates of the IV surfaces of call and put options, which are derived with a proprietary methodology based on a kernel smoothing algorithm.[2] In this paper, we consider stock options in the United States and Europe as well as index options on the S&P 500, the EuroStoxx 50, and the German DAX index. The option data are from OptionMetrics' IvyDB-US and IvyDB-Europe databases (introduced in 2002 and 2008, respectively). The index data are also included (in identical form) in the IvyDB-GI database (since 2011). In this paper, we draw attention to problems with the IVs provided by OptionMetrics (OM) in all three databases.

The IVs of stock index options suggest substantial deviations from put-call parity (PCP) that are not really present. To find such deviations in the data is unexpected for two reasons. First, index options belong to the most actively traded

[1]We thank OptionMetrics for providing the option data.

[2]Some parts of the database also contain tick data, which we do not consider in this paper.

derivatives in the international financial markets. Most index options are of European type and do not include exotic elements. Moreover, long and short positions in the underlying asset can be implemented at low cost by trading in the corresponding futures contracts. Therefore, arbitrage trading to ensure PCP should function smoothly. Second, OM actually uses PCP to estimate the expected dividend yield so that the PCP relationship should at least apply to the options from which the implied dividend yield is derived. However, the IVs of puts and calls in the database often deviate over the whole range of strike prices and maturities.

For S&P 500 options, the reason for such systematic deviations is that OM uses nonsynchronous index levels (recorded at 16:00) and option quotes (recorded at 15:59) and an average dividend yield based on "3 months of option data across all strikes and expirations" (OptionMetrics, 2021b, p. 32) rather than the specific dividend yield implied in option quotes on a particular day for a specific expiration date. To our knowledge, the resulting distortions in OM's IVs of S&P 500 options have not yet been described in previous literature (except in a footnote in Wallmeier, 2021, p. 43). A more accurate and at the same time simpler estimation for the exact term of each option is available and commonly applied in prior literature (while another part of the literature uses the IVs of S&P 500 options provided by OM directly). Using this method, most of the deviations disappear, which means that the IVs of calls and puts almost perfectly fall in line. For EuroStoxx 50 and DAX options, this alignment should be guaranteed by construction because their settlement prices are usually fixed in accordance with PCP. Nevertheless, large deviations occur in OM's processed data.

The data on stock options in Europe contain clusters of exceptional spreads between the IVs of puts and calls that are related to dividends during the time to maturity. According to our analysis, these clusters are mostly artefacts of incomplete or incorrect dividend information and dividend projections. In particular, many firms suspended their dividends at the outbreak of the COVID-19 pandemic, which is often not recorded in the database in a timely manner and therefore not considered in valuing the options. In addition, there seems to be a more general problem with incorporating dividends into the valuation model. We are not aware that these concerns have been raised in prior research. So far, only a few publications have used this database (e.g., Baltussen et al., 2018; Faria et al., 2022; Gagnon et al., 2023), but it might attract more attention for international comparative studies in the future.

Although much less frequent than in European data, anomalies of implied volatilities due to outdated dividend projections also occur in US stock options data. More importantly, there is a timing mismatch of 1 min between the option quotes that are recorded at 15:59 and the closing prices recorded at 16:00. This mismatch generally increases the variability of implied volatility spreads between puts and calls, and it results in considerable distortions at the outbreak of the COVID-19 pandemic. The reason is that during this period, big market moves occurred repeatedly in the final minutes of trading. As a consequence, IV spreads in OM data falsely suggest that the PCP relationship broke down in turbulent times, giving rise to synchronous spikes of IV spreads across different stocks.

The timing mismatch problem has been highlighted by Battalio and Schultz (2006) who "show that the nonsynchronous prices and microstructure biases inherent in the OM prices can lead researchers to greatly exaggerate the frequency of put-call parity violations" (p. 2086).[3] The authors explain (Battalio & Schultz, 2006, p. 2096):

> The equity option markets cease trading at 4:02 p.m. Although some equity markets continue to trade after 4:00 p.m., specialists on the NYSE and dealers in the Nasdaq market typically cease trading at 4:00 p.m. Even if the times of closing prices in the options and stocks markets were to align perfectly, it is not clear that the prices would be meaningful. Option market makers are obligated to trade at posted quotes during the trading day. In contrast, option market makers posting closing quotes on day t are not required to trade with anyone at those quotes on day $t + 1$. Similarly, dealers and specialists in the underlying stocks have no obligation to execute incoming orders at the price of the most recent transaction. Hence, closing option quotes and closing stock prices obtained from the OptionMetrics database do not represent contemporaneous prices at which investors could have simultaneously traded.

Presumably to address this problem, OM has been recording the option quotes since July 30, 2009 at 15:59, when they are still active (OptionMetrics, 2021c, p. 19 and 38). This, however, creates a new timing mismatch. We are not aware that this specific mismatch from 15:59 to the closing auction has been analyzed (or even mentioned) in the

[3]This possibility is also an important consideration in later studies on violations of PCP (e.g., Cremers & Weinbaum, 2010).

literature. The previous literature seems to assume that OM captures option prices at 16:00 at the market close.[4] Our objective is to examine the consequences of the timing mismatch in detail, using synchronized underlying prices recorded at 15:59. We are able to separate the effect of the timing mismatch from other effects such as OM's proprietary valuation algorithm (although we do not have access to this algorithm). The reason is that the early exercise option can be ignored when interest rates are negative and no dividends are paid. In fact, our own IV spreads based on analytical models replicate OM's IV spreads (based on OM's proprietary numerical algorithm) almost perfectly when using closing prices. When replacing the closing prices by share prices at 15:59, the IV spreads (in absolute terms) decrease substantially.

The paper proceeds as follows. Section 2 examines the index options. In Section 2.1, we outline OM's estimation of the dividend-adjusted underlying index level and the alternative computation proposed in prior literature. Section 2.2 describes our index option data, and Section 2.3 compares the results of the two estimations for S&P 500 options. Section 2.4 presents similar results for the two most actively traded index options in Europe, which are the EuroStoxx50 option and the DAX option. Section 3 examines the equity options. We discuss the computation of IVs in Section 3.1 and describe the data in Section 3.2. The results for stock options in Europe and the United States are shown in Sections 3.3 and 3.4, respectively. Section 3.5 presents a case study that shows the relevance of our results for stock options in the United States. The case study examines how the timing mismatch affects measured market-wide IV spreads and comovements of individual IV spreads, which are well-known indicator variables for market inefficiency or informed trading. Section 3.6 briefly discusses how this paper relates to the work of Cremers and Weinbaum (2010), which is central to the predictability of stock returns based on deviations from put-call parity. Section 4 concludes the paper.

2 | INDEX OPTIONS

2.1 | Estimation of the dividend-adjusted underlying index level

2.1.1 | Standard method

Ignoring transaction costs, PCP for a European option implies that

$$S_t(T) + P_t(K, T) = C_t(K, T) + Ke^{-r(T-t)}, \tag{1}$$

where t is the trading day, T the maturity date, $S(T)$ the index level less the present value of dividends to be distributed during the time to maturity, K the strike price, r the risk-free rate of return and $P(K, T)$ and $C(K, T)$ are the prices of put and call options with strike K and maturity T. For given market prices of the options, a synthetic dividend-adjusted index level $A_t(K, T)$ can be computed as

$$A_t(K, T) = C_t(K, T) - P_t(K, T) + Ke^{-r(T-t)}. \tag{2}$$

If PCP holds, $A_t(K, T)$ for fixed t and T is the same for all K: $A_t(K, T) = S_t(T)$. The IVs based on this dividend-adjusted index level $S_t(T)$ will be identical for pairs of calls and puts with the same strike price. This means that the strike price profile of IVs ("smile" or "skew" pattern) will be the same for calls and puts. In contrast, if PCP does not hold, using the dividend adjusted index level $A_t(K^*, T)$ implied in options with strike K^* will result in deviations of the IVs of calls and puts for at least one strike price K' with $K' \neq K^*$ so that the skew patterns of calls and puts do not coincide.

Direct estimates of $S_t(T)$ are often imprecise because the closing prices in the options and stock markets are not perfectly synchronous and expected dividends are not known. For these reasons, researchers often use a synthetic index level derived from the most liquid options, which are typically at-the-money (ATM) options (strike K^{ATM}) (see, e.g., Aït-Sahalia & Lo, 1998; Almeida & Freire, 2021; Bardgett et al., 2019; Chen & Xu, 2014; Fan & Mancini, 2009;

[4]For example, Han and Li (2021, p. 1254) state: "[...] after March 2008, when the option prices used by OptionMetrics to calculate implied volatility change from the last transaction price at the end of the day (i.e., 4:15 PM Eastern Standard Time (EST)) to the average of best bid and offer closest to 4:00 PM EST." Similarly Jones et al. (2018, p. 6): "Typically (e.g., the IvyDB database, CBOE.com), end-of-day implied volatilities are computed from the option's closing bid-ask midpoint and the official closing price of the stock." In both studies, a timing mismatch is potentially important, because it creates commonality of IV spreads across individual firms and thus affects the variation of aggregate IV spreads; see Section 3.5.

Golez, 2014; van Binsbergen et al., 2012).[5] For fixed t and T, the implied volatilities $IV_t(K, T)$ across all strikes are then computed based on the index level $S_t(T) = A_t(K^{ATM}, T)$. Using this estimation, one cannot draw conclusions on PCP for ATM options because the PCP relationship for these options holds by definition.[6] However, violations of PCP can still be detected from deviations of IVs of in-the-money and out-of-the-money options.

2.1.2 | Method applied by OptionMetrics

For dividend-paying US indices, OptionMetrics (2021b, p. 32) describes the estimation as follows:

> A put-call parity relationship is assumed, and the implied index dividend is calculated from the following linear regression model:
>
> $$C - P = b_0 + b_1 S + b_2 ST + b_3 K + b_4 KT + b_5 D_{BA}$$
>
> In this model, $C - P$ is [the] difference between the price of a call option and the price of a put option with the same expiration and strike. When calculating this difference, the bid price of the call is used with the offer price of the put, and vice versa. D_{BA} is a dummy variable set equal to 1 if the call option's bid price is used. S is the underlying security's (index's) closing price, K is the strike price of the call and put options, and T is the time to expiration in years. The regression is calculated using 3 months of option data across all strikes and expirations [...] According to the principle of put-call parity, the dividend yield on the underlying index will be approximately equal to the negative of the estimated parameter b_2.

While the idea of this estimation is similar to the standard procedure described in Section 2.1.1, it rests on two simplifying assumptions: (1) the continuously compounded interest and dividends are linearized, and (2) the dividend yield is assumed to be constant for all maturities T and for the 3 months from which the data originate. The effect of assumption (1) should be small, while assumption (2) is important. In fact, traders and market makers in index options record precisely which dividends are expected until each maturity date. Accordingly, the implied dividend yield is specific for each combination of valuation day and maturity date.

An even more important problem in OM's calculation is that the option quotes are recorded at 15:59 while the underlying index value is the closing price (OptionMetrics, 2021c, p. 19 and 38), which creates a timing mismatch of approximately 1 min. Applying PCP to ATM options on each day and maturity date as in the standard procedure (see Section 2.1.1) provides an estimate of the dividend-adjusted index level without having to decompose it into an index and a dividend component. OM's calculation, in contrast, is ultimately based on inaccurate dividend yields and nonsynchronous index levels.

The calculation is different for indices in Europe and Asia (OptionMetrics, 2021b, p. 32):

> The dividend yield for European and Asian indices is calculated based on linearized put-call parity. The present value of the dividend payments [is]:
>
> $$PV(div) = P - C + (S - K) + K(e^{rT} - 1)$$
>
> where r is interest rate to the option expiration and T is time to maturity in years. Then the implied dividend yield is: $d = PV(div)/(TS)$.

According to PCP, the last bracket term $(e^{rT} - 1)$ in the formula for $PV(div)$ should read: $(1 - e^{-rT})$. However, with the approximation $e^{rT} \approx 1 + rT$ applied by OM, both versions give the same result. The computation of the present value of dividends appears to be similar to the standard method of Section 2.1.1, but it is not clear for which strike prices K the present value $PV(div)$ is computed and how the final value is obtained if $PV(div)$ is calculated for different strike prices.

[5]For the corresponding estimation based on transaction data, see Hafner and Wallmeier (2000, 2007), and Wallmeier (2015, 2021).

[6]To run a PCP test for ATM options as well, a synchronous index level and the exact dividends until maturity are required (Kamara & Miller, 1995).

2.2 | Data

We select option records with a trading volume larger than zero and a positive IV provided by OM (Option Price file).[7] We only consider options with a moneyness (defined as the ratio of strike price and forward price)[8] between 0.90 and 1.05 and a time to maturity $T - t$ in calendar days of $14 \leq T - t \leq 91$. We match call and put options on the basis of equal date, expiration, strike and settlement.[9] We require pairs for at least five different strikes (for fixed day and expiration) to be available. For the remaining matched pairs, we define the IV spread as the difference between the IVs of puts and calls, expressed in percentage points.

To obtain our own IV estimates, we implement the standard procedure presented in Section 2.1.1 in the following way. $P(K, T)$ and $C(K, T)$ are the quotes used by OM (as indicated by "CalculationPrice"). These are mid quotes for S&P 500 options and settlement quotes for EuroStoxx50 and DAX options. The risk-free rate is interpolated from the zero curves included in the database. For fixed t and T, we compute $A_t(K, T)$ according to Equation (2) for each strike K with a moneyness between 0.95 and 1.02 and use the median value as the dividend-adjusted index level $S_t(T)$ on which the IVs of calls and puts are based.

We carry out the analysis for all years from 1996 to 2020 for S&P 500 options and from 2002 to 2020 for Eurostoxx 50 and DAX options but show results only for selected years. The results in the other years are similar.

In a part of the analysis, we use returns of the S&P 500 index in the last minute of trading from the "S&P 500 (SPX) Historical 1 Minute Dataset" provided by FirstRate Data (firstratedata.com). The last-minute return is based on the last recorded index level before 16:00:00 and the last recorded index level before 15:59:00.

2.3 | Results for S&P 500 options

Figure 1 shows examples of substantial deviations between the IVs of puts (black circles) and calls (black crosses) provided by OM.[10] In our own calculation, all deviations disappear: the blue circles and crosses for puts and calls, respectively, are practically indistinguishable. The graphs illustrate that it would be particularly problematic in these cases to consider only out-of-the-money options (puts for moneyness <1 and calls for moneyness >1) since OM's IVs do not coincide at moneyness equal to 1.

Figure 2 plots the IV spreads in 2020 over time. The OM spreads in the first panel show considerable variation and clusters of spreads in one direction (e.g., positive in March/April and negative in December), while the spreads in the second panel, which are based on the standard estimation method, are almost flat. As can be seen from Table 1, the standard deviation of the spread is 2.06 percentage points according to OM (SD OM) but only 0.13 percentage points in our calculation (SD new), which corresponds to a reduction (Diff) of 93.8%. The results are similar for ATM options and for options with different remaining terms. In the other years included in Table 1, the standard deviation of the IV spread is always reduced by at least 68%. This reduction is also economically important, as it is in the order of magnitude of transaction costs or even higher.

Our filtering rules described in Section 2.2 do not exclude weekly options (OM Expiry Indicator "w"), which account for a substantial share of all observations in recent years (48% in 2020; 40% in 2015). As a robustness check, we have reproduced Table 1 without weekly options and find very similar results (not tabulated).

To assess the significance of the timing mismatch, we determine what part of the variance of OM's IV spreads can be explained by the last-minute index return. To this end, we first compute the mean IV spread per day from the observations in the first panel of Figure 2 (mean across strike prices and times to maturity). The resulting time series of daily IV spreads is positively correlated with the last-minute index return. Indeed, the last-minute return explains 63.2% of the variation in daily IV spreads. The remaining variation is mainly due to the simplifying assumption of constant dividend yields and real deviations from PCP.[11] Other minor technical factors are the remaining timing

[7]We downloaded and installed the database IvyDB-GI, version 3.0, on July 1, 2021.

[8]We use the forward price from the Forward Price file with a corresponding date, expiration, and settlement.

[9]Variable "AMSettlement," indicating whether the option expires at the market open or close on the last trading day.

[10]Hafner and Wallmeier (2000) proposed to use this illustration to check for distorted underlying index levels.

[11]These effects cannot be neatly separated because it is not clear what dividend expectations traders actually had and how realistic therefore OM's dividend yield assumption is.

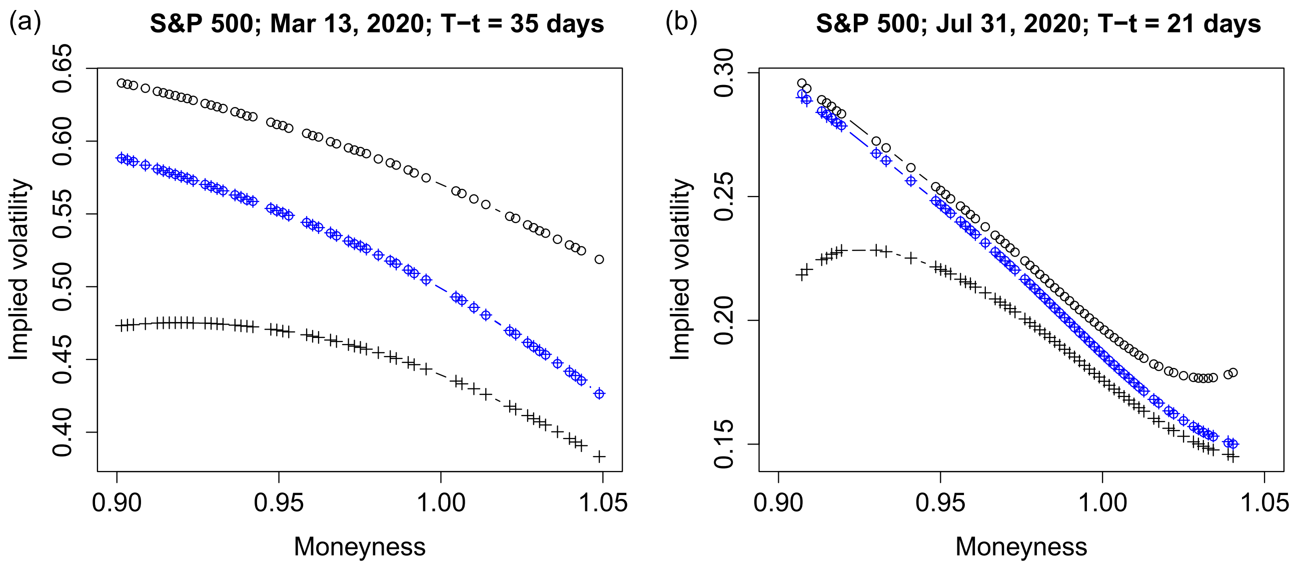

FIGURE 1 Examples of divergent put and call IVs of S&P 500 options. Circles: puts; crosses: calls. Black: IVs provided by OM; blue: our own IV calculation. The IVs provided by OM can be replicated assuming a dividend-adjusted index level of 2710.3 (a) and 3268.0 (b). The blue IVs are based on dividend-adjusted index levels of 2667.2 (a) and 3261.6 (b). IV, implied volatility; OM, OptionMetrics. [Color figure can be viewed at wileyonlinelibrary.com]

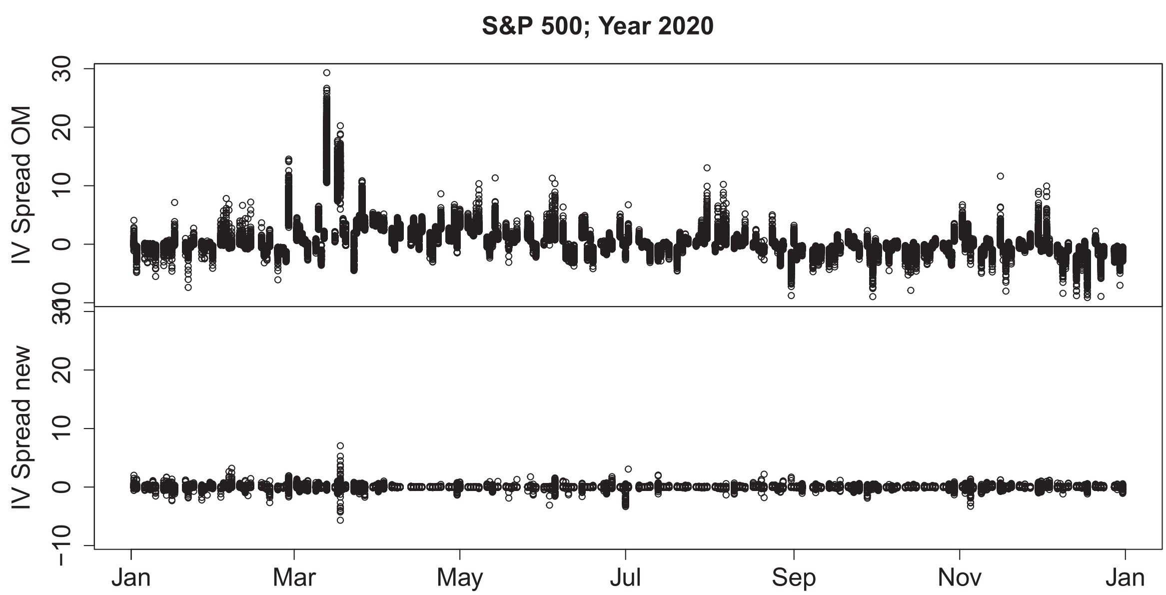

FIGURE 2 IV spreads of S&P 500 options in 2020. The IV spread is defined as the difference between the IVs of pairs of puts and calls (in percentage points). Upper panel: based on IVs provided by OM; lower panel: based on our own IV calculation. All observations with a time to maturity from 14 to 91 calendar days and a moneyness from 0.90 to 1.05 are considered. IV, implied volatility; OM, OptionMetrics.

mismatch between the close prices and the prices of the last trade before the closing auction, and the linearization of the interest rate and dividend yield mentioned in Section 2.1.2.

OM estimates volatility surfaces (Volatility Surface files) and IVs of ATM options with standardized times to maturity (Std Option Price files) separately for calls and puts. Since these calculations are based on the IVs of individual options, the artificial IV spreads carry over to the surface data.

TABLE 1 IV spreads of S&P 500 options in selected years.

Stat.	$14 \le T-t \le 91$ All	$14 \le T-t \le 91$ ATM	$T-t=30$ All	$T-t=30$ ATM	$T-t=58$ All	$T-t=58$ ATM	$T-t=86$ All	$T-t=86$ ATM
Panel A: 2020								
N	110,819	30,873	2,587	735	907	255	447	127
SD OM	2.06	1.56	2.18	1.88	2.65	2.14	1.42	1.19
SD new	0.13	0.05	0.11	0.05	0.2	0.19	0.04	0.02
Diff	−93.8	−96.6	−95	−97.4	−92.4	−91	−97	−98.7
Panel B: 2015								
N	37,797	11,237	1,308	378	299	104	121	48
SD OM	1.09	0.73	0.98	0.76	0.45	0.42	0.38	0.37
SD new	0.21	0.06	0.14	0.05	0.11	0.08	0.05	0.02
Diff	−80.4	−91.7	−86	−92.8	−75.9	−80.3	−85.7	−93.5
Panel C: 2010								
N	10,206	2,294	320	53	157	49	49	18
SD OM	0.94	0.63	0.86	0.7	0.5	0.53	0.3	0.25
SD new	0.28	0.2	0.21	0.22	0.1	0.05	0.07	0.03
Diff	−70.7	−67.4	−75.3	−68.3	−80.5	−90.1	−75.2	−86.9
Panel D: 2005								
N	6,829	1,930	235	55	111	35	28	10
SD OM	1.53	0.88	1.26	0.79	1.12	0.82	0.82	0.76
SD new	0.22	0.14	0.19	0.17	0.08	0.06	0.1	0.08
Diff	−85.9	−83.6	−84.9	−78.2	−92.6	−92.1	−88	−89
Panel E: 2000								
N	3,865	983	118	33	59	17	18	4
SD OM	3.01	2.54	2.23	1.8	1.68	1.44	0.53	0.54
SD new	0.25	0.18	0.17	0.12	0.15	0.17	0.11	0.02
Diff	−91.6	−92.9	−92.5	−93.4	−91.1	−88	−78.7	−97.1

Note: The IV spread is defined as the difference between the IVs of pairs of puts and calls and is given in percentage points. $T-t$ is the time to maturity in calendar days. “All” refers to options with a moneyness between 0.90 and 1.05, while “ATM” only includes options with a moneyness between 0.99 and 1.01. Both SD OM and SD new are given in percentage points.

Abbreviations: Diff, the difference between SD new and SD OM in percent; *N*, the number of observations; SD new, the standard deviation of IV spreads according to our own computation; SD OM, the standard deviation of IV spreads provided by OM.

2.4 | Results for EuroStoxx50 and DAX options

The IVs of EuroStoxx50 and DAX options are based on the settlement prices at Eurex Exchange (while the IVs of S&P 500 options are based on mid quotes). The settlement prices are normally set in accordance with PCP. This is why the IV spreads for both options are practically zero in our calculation (see the lower panels of Figures 3 and 4). For the EuroStoxx50 option, the spreads provided by OM are zero in most cases, but strongly negative on some days that seem to be clustered (e.g., in September and November 2020, see the upper panel in Figure 3). The IV spreads of DAX options vary substantially in both directions (upper panel of Figure 4). More details for the spreads in 2020 are given in Table 2. According to our analysis, these deviations are pure artifacts (the cause of which is unclear).

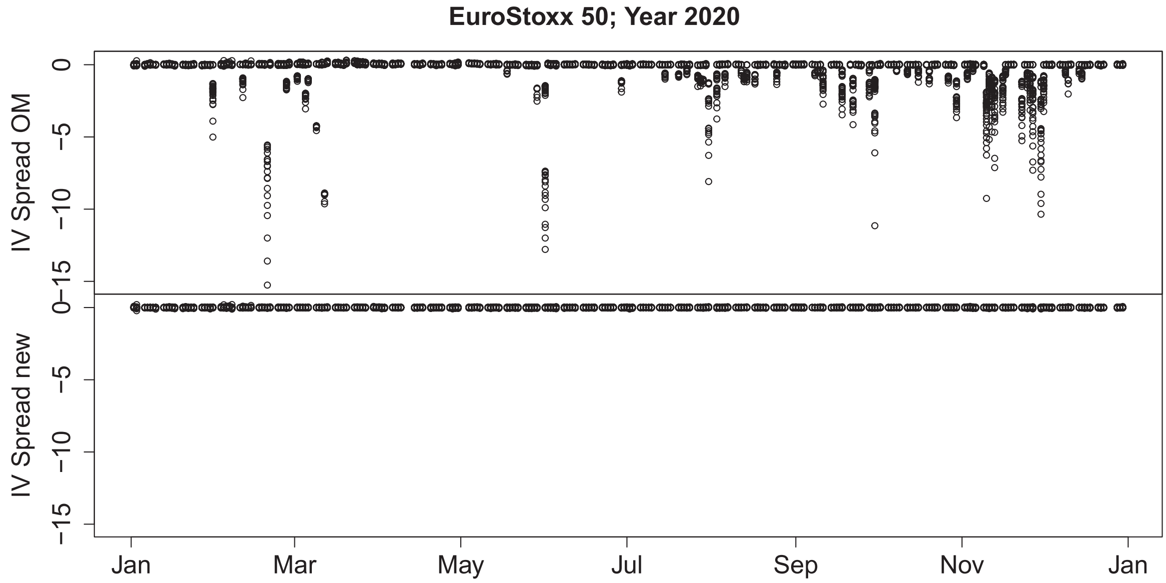

FIGURE 3 IV spreads of EuroStoxx 50 options in 2020. The IV spread is defined as the difference between the IVs of pairs of puts and calls and is given in percentage points. Upper panel: based on IVs provided by OM; lower panel: based on our own IV calculation. All observations with a time to maturity from 14 to 91 calendar days and a moneyness from 0.90 to 1.05 are considered. IV, implied volatility; OM, OptionMetrics.

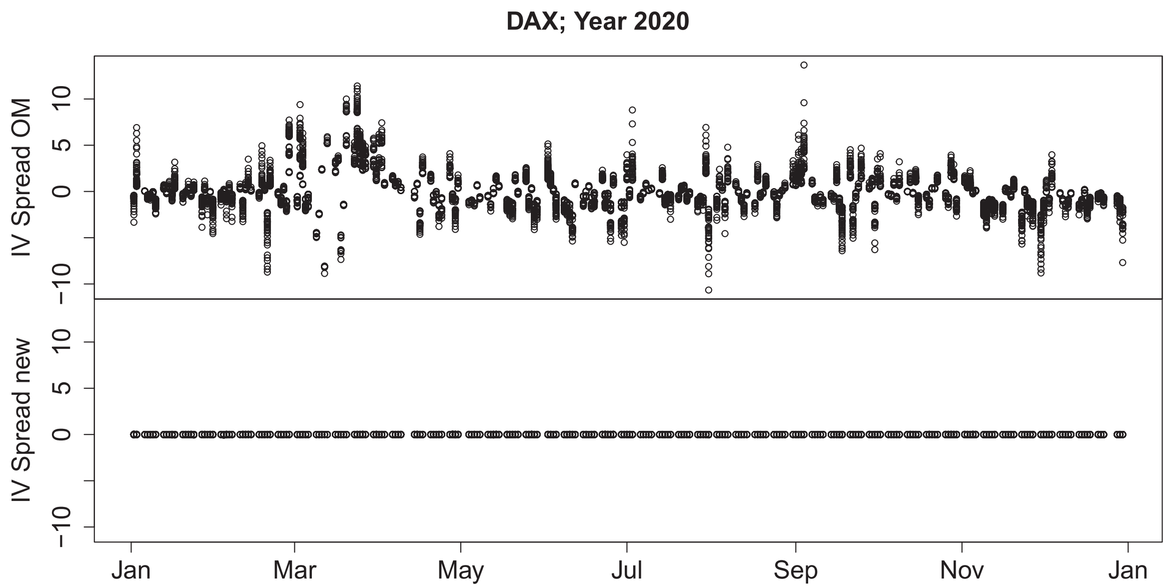

FIGURE 4 IV spreads of DAX options in 2020. The IV spread is defined as the difference between the IVs of pairs of puts and calls and is given in percentage points. Upper panel: based on IVs provided by OM; lower panel: based on our own IV calculation. All observations with a time to maturity from 14 to 91 calendar days and a moneyness from 0.90 to 1.05 are considered. IV, implied volatility; OM, OptionMetrics.

3 | EQUITY OPTIONS

3.1 | Computation of implied volatilities

3.1.1 | Method applied by OptionMetrics

To evaluate American-style stock options in Europe and the United States, OM uses a proprietary pricing algorithm based on the binomial model of Cox et al. (1979) (CRR). The binomial tree valuation is repeated

TABLE 2 IV spreads of EuroStoxx50 and DAX options in 2020.

	14 ≤ $T - t$ ≤ 91		$T - t = 30$		$T - t = 58$		$T - t = 86$	
Stat.	**All**	**ATM**	**All**	**ATM**	**All**	**ATM**	**All**	**ATM**
Panel A: EuroStoxx50; Year 2020								
N	7599	1655	159	30	122	33	71	18
SD OM	1	0.77	0.02	0.01	0.03	0.03	0.07	0.06
SD new	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0
Diff	−98.3	−98.7	−21.4	−11.8	−55.7	−69.3	−84.6	−92.8
Panel B: DAX; Year 2020								
N	8937	2054	246	49	137	33	50	13
SD OM	1.92	1.59	1.6	1.47	1.02	1.18	1.37	1.21
SD new	0.01	0.01	0.01	0	0.01	0	0.01	0
Diff	−99.5	−99.7	−99.5	−99.7	−99	−99.6	−99.2	−99.7

Note: The IV spread is defined as the difference between the IVs of pairs of puts and calls. $T - t$ is the time to maturity in calendar days. “All” refers to options with a moneyness between 0.90 to 1.05, while “ATM” only includes options with a moneyness between 0.99 and 1.01. Both SD OM and SD new are given in percentage points.

Abbreviations: Diff, the difference between SD new and SD OM in percent; N, the number of observations; SD new, the standard deviation of IV spreads according to our own computation; SD OM, the standard deviation of IV spreads provided by OM.

iteratively for different values of the stock return volatility until the resulting option value converges to the given market value. The volatility for which convergence is achieved is reported as the IV. The CRR model requires a large number of subperiods to keep the discretization error low, resulting in a high computational cost. To address this problem, OM has developed its own pricing algorithm that “uses advanced techniques to achieve convergence in a fraction of the processing time required by the standard CRR model” (OptionMetrics, 2021a, 2021c, p. 49 and 37).

If dividends have been announced for the time between the valuation date and the option maturity date, OM uses this information, which is recorded in the Distribution files, in the valuation. If dividends have not yet been announced, OM forecasts the amount and timing of future dividends and records these projections in the Distribution Projection files. Forecast dividends that fall in the period up to the option maturity date are considered in the valuation in the same way as announced dividends.

Any dividend during the option's term is converted to a dividend yield by dividing the forecast dividend amount by the share price at the option's valuation date. OM assumes that this dividend yield applies to all share prices in the binomial tree at the projected payment date (constant dividend yield assumption). Technically, this assumption has the advantage that the binomial share price tree remains recombining after the dividend payment. As a consequence, the binomial model can be applied to dividend-paying stocks without further complications. However, the constant dividend yield assumption simplifies the actual dividend policy, according to which firms will usually adhere to the announced dollar dividend rather than paying a dividend that is proportional to the share price on the payment date.

For each stock on each trading day, OM calculates separate volatility surfaces for puts and calls in the dimensions moneyness and time to maturity using a kernel smoothing technique (Volatility Surface files). OM also provides the interpolated surface values for standardized options defined as ATM options with times to maturity of 10, 30, 60, 91, 122, 152, 182, 365, 547 and 730 calendar days (Std Option Price files).

3.1.2 | Own calculation

In the valuation of puts, we ignore the possibility of early exercise, which is a good approximation for short-term options in general (Driessen et al., 2009, p. 1384f) and in particular in the low-interest phase since the financial crisis. For puts with a dividend payment during the time to maturity, we use the share price less the present value of dividends as the underlying asset value in the Black–Scholes formula

(Black, 1975).[12] For calls, early exercise is only relevant if dividend payments occur. In this case, we compute IVs from the Roll–Geske–Whaley approximate model (Geske, 1979, 1981; Roll, 1977; Whaley, 1981).

We calculate IVs both for the current share price and for an implied share price that is defined in the same way as for index options in Section 2.1.1. That is, on each day for each maturity date, we determine an implied share price such that ATM calls and puts have the same IVs. The idea is to match the general levels of the strike price pattern of calls and puts so that the remaining IV spreads are due to structural differences. In this sense, the implied share price minimizes the IV spreads across the available strike prices. In particular, this procedure prevents artificial IV spreads caused by a timing mismatch between underlying and option prices.

In our calculations, we only consider dividends that have already been announced (as recorded in OM's Distribution files) and ignore OM's dividend projections. In the vast majority of cases, dividends are known over the short-term horizon of at most 91 days that we consider. If a part of the dividend projections in OM's Distribution Projection files were relevant, leaving them out would bias the results against our calculation.

3.2 | Data

From IvyDB-Europe and IvyDB-US, we select stock options[13] over the period from 2002 to 2020 for Europe and from 1996 to 2020 for the United States.[14] We only include options that (1) have a positive IV provided by OM, (2) a positive open interest, (3) a moneyness (defined as the ratio of strike price and forward price) between 0.90 and 1.05, (4) a time to maturity $T - t$ in calendar days of $14 \leq T - t \leq 91$, and (5) that belong to an option series (fixed day and expiration) for which pairs of puts and calls for at least five strike prices in the moneyness range between 0.90 and 1.05 are available. This last condition (5) is restrictive, but necessary for a meaningful computation of IV spreads based on implied share prices because IV spreads would be zero by definition when derived from only one option pair.

Stocks are only considered in a given year if at least 250 IVs fulfill these five requirements. We match call and put options on the basis of equal date, expiration, strike, settlement[15] and, additionally in Europe, equal currency and exchange. Interest rates are interpolated rates from the currency-matched zero curves provided by OM, and dividend information comes from OM's Distribution files.

The implied share price is determined as follows. When no dividends are to be considered, for each strike K in the moneyness range from 0.95 to 1.02, we compute the share price S_K for which the IVs of puts and calls with strike K are the same. The median of these S_K values is our final estimate of the implied share price. If dividends are relevant, we apply a search algorithm to find the share price that minimizes the IV spread of the option pair with moneyness closest to 1. We consider the search to be successful only if it results in an IV spread of at most 0.2 percentage points. If no spread can be determined, we also do not include any value of OM in our analyses. This is important because the PCP deviations in OM are likely to be high in such cases.

The options data in IvyDB-Europe and IvyDB-US differ in one important respect. In IvyDB-Europe, the option prices from the major exchanges are settlement prices. These are often fixed in accordance with PCP so that the IV spreads are zero. In IvyDB-US, in contrast, the option price used for calculating IVs is set equal to the midpoint of the best bid quote and the best offer quote across all exchanges on which the option trades.[16] Since July 30, 2009, the best bid and offer quotes "are captured at 15:59 ET. The underlying price used is the official (composite) close" (OptionMetrics, 2021c, p. 38). This means that there is a mismatch of 1 min between the option quotes (15:59) and the underlying prices (from the closing auction at 16:00).[17] To explore its consequences, we collect share prices at 15:59 from the algoseek S&P 500 1 min Bars. This database contains trade-based open, high, low and close prices for every stock in the S&P 500 index for every minute of every trading day. We consider the close in the minute from 15:58:00 to

[12]This valuation is only an approximation if the dividend is not paid immediately after the valuation date (see Frishling, 2002; Veiga & Wystup, 2009; Vellekoop & Nieuwenhuis, 2006).

[13]Issue type 0 (Common Stock) for the United States and Issue type 1 (Shares) for Europe.

[14]We downloaded and installed the databases IvyDB-Europe, version 3.1, on July 1, 2021, and IvyDB-US, version 5.1, on August 31, 2021. All analyses are based on these data. In June 2023, we replicated the figures included in this paper based on data from version 3.2 of IvyDB-Europe and version 5.4 of IvyDB-US and found the same results.

[15]Variable "AMSettlement," indicating whether the option expires at the market open or close on the last trading day.

[16]Since options' trading prices are generally not the average of bid and ask quotes, using the mean introduces an error that affects implied volatility; see Hentschel (2003).

[17]For details on the closing auction, we refer to Bogousslavsky and Muravyev (2023).

15:58:59 (i.e., the share price of the last transaction in this minute) as the underlying share price that is best synchronized with the option quotes on which OM's IVs are based.

3.3 | Results for stock options in Europe (IvyDB-EU)

The IV spreads (IV put minus IV call) of stocks in Europe are typically very close to zero, which indicates that the settlement prices are often fixed in accordance with PCP. All the more striking are occasional clusters of seemingly anomalous IV spreads, often in the range of double-digit percentage points. Figure 5 shows the example of Deutsche Bank in 2020. In the upper panel of the figure, the IV spreads are based on IVs provided by OM. The anomalous cluster in April and March is due to the fact that OM took into account a dividend scheduled for May 22, 2020, although this had been suspended following the recommendation of the European Central Bank on March 27, 2020. The middle panel shows that the anomaly also appears in the standardized options data, while it is absent from our own calculations, shown in the lower panel. Similar anomalies due to suspended or deferred dividends not recorded in OM's distribution files occurred in 2020 for other stocks including ABN Amro; Adidas; Heineken; H & M; ING Group; Thyssenkrupp; AXA; Continental; Daimler; Danone; Fresenius; Fresenius Medical Care; Merck; and VW.[18]

While the anomalies are particularly prevalent in 2020 due to the many dividend changes in the course of the COVID-19 pandemic, they also occur in all other years. For the years from 2002 to 2020, Table 3 compares the standard deviation of OM's IV spreads with the standard deviation in our computation based on implied share prices. Each year, we pool the IV spreads across firms, trading days, maturities and moneyness. In 2020, 647,979 IV spreads (N) for a total of 420 firms (Ni) are available. Their standard deviation is 5.16 percentage points in OM compared to 1.18 percentage points in our computation, which corresponds to a reduction of 77.10%. The IV spreads are much higher when dividends are relevant (OM: 10.83 percentage points; our calculation: 2.66 percentage points). This is in part due to computational problems and inaccurate dividend data, but it is also important to note that PCP is only an approximation in cases with dividends. In the other years, the standard deviation of all observations in our calculation lies mostly between 1 and 1.5 percentage points, while it is mostly between 3 and 5 percentage points in OM's calculation. In all years and both with and without dividends, our calculation leads to a reduction of the standard deviation of 40% to 78%.

We also compute standard deviations of IV spreads on the firm level and report percentiles of the annual distributions across firms in Table 4. In the notation x/y of the table entries, x is the standard deviation in OM's calculation and y the standard deviation in our calculation. The OM distribution is clearly shifted towards higher IV spreads compared to our distribution. The 90% percentiles in 2020 are far apart (8.92 vs. 1.91 percentage points) because of the anomalous clusters in OM. The difference is less extreme but still substantial in most other years. With the exception of 2006, the 90% percentile is always smaller than 3 percentage points in our computation, while it is, with the exception of 2005, always larger than 4 percentage points in OM's calculation.

The possible effect of the anomalies on research studies must be examined in each individual case. Baltussen et al. (2018) use the database to measure the time variation in daily IVs, "with IV measured as the average IV of the call option and put option that are closest to being at the money (ATM)" (Baltussen et al., 2018, p. 1619). The averaging reduces the effect of potential anomalies in the sample years. It would even correct such distortions completely if they were the same for puts and calls (which is, however, not the case). In the future, researchers might draw the conclusion to only consider options from this database for which no dividends are announced or projected in the remaining time to maturity (as in Zhan et al., 2022; Ofek et al., 2004, for US data).

3.4 | Results for stock options in the United States (IvyDB-US)

In the United States, we focus on potential anomalies related to dividends and on the effect of the timing mismatch between option quotes (15:59) and underlying prices (16:00).

A visual inspection of the IV spreads per firm and year reveals that anomalous clusters occur much less frequently than in the European data. Nevertheless, anomalies still exist, as illustrated in Figure 6 for Boeing in 2020. Similar

[18]Figures for these companies are available on request from the author.

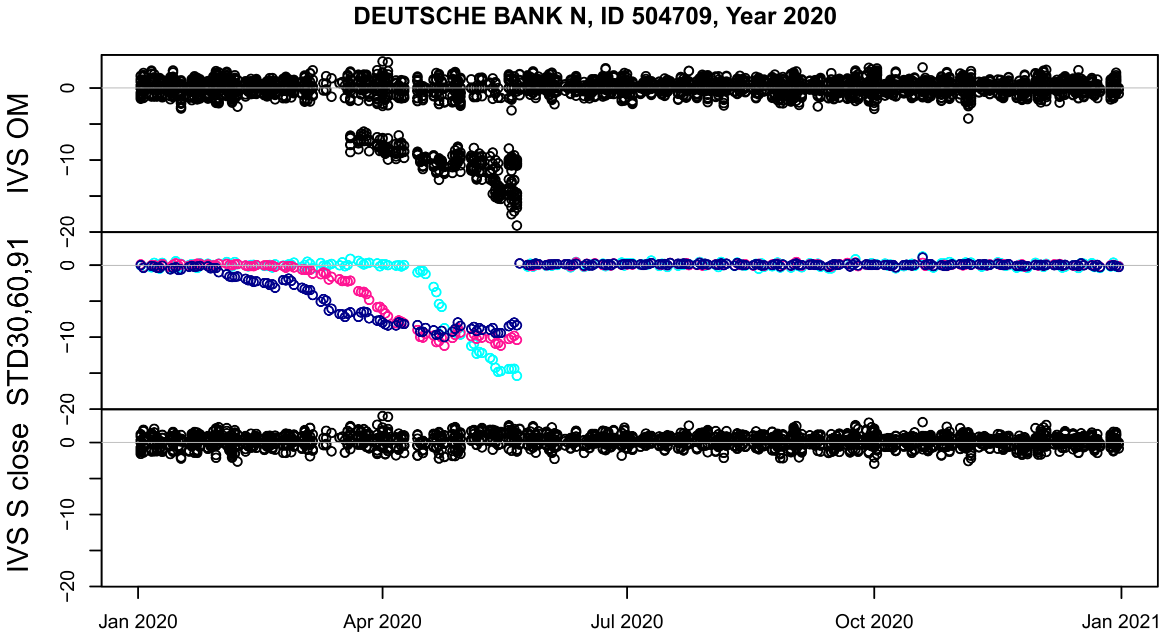

FIGURE 5 IV spreads Deutsche Bank in 2020. Upper panel: OM IV spreads in percentage points (IV put−IV call) for all pairs of puts and calls with positive open interest, a moneyness between 0.9 and 1.05 and a time to maturity between 14 and 91 calendar days. Anomaly in April/May: OM's Distribution Projection file contains a projected dividend for May 22, 2020, although the dividend had been suspended following the recommendations made by the European Central Bank to European banks on March 27, 2020. Middle panel: OM IV spreads of standardized options with a time to maturity of 30 (lightblue), 60 (pink) and 91 (blue) calendar days. Lower panel: Own calculation of IV spreads based on the underlying share prices provided by OM and taking into account the suspension of the dividend. IV, implied volatility; OM, OptionMetrics. [Color figure can be viewed at wileyonlinelibrary.com]

examples among S&P 500 stocks in 2020 include General Motors, Las Vegas Sands, Molson Coors Brewing, Walt Disney and Wynn Resorts.[19] Boeing announced early in the COVID-19 pandemic that it would suspend its dividends. However, projected dividends remained recorded in OM's Distribution Projection file. Since OM's option valuation is based on these dividend projections, the IVs of puts are too low and the IVs of calls too high, resulting in negative IV spreads (upper panel of Figure 6). The anomalies are also clearly visible in the IV spreads of standardized options shown in the middle panel. In our own calculation based on share prices at 15:59 (lower panel), the anomalies are not present because we do not take OM's dividend projections into account.

The effect of the timing mismatch is illustrated in Figure 7 for Amazon in 2020. Similar examples among S&P 500 stocks in 2020 include Alphabet, Apple, Autozone, Facebook and Netflix. The upper panel of Figure 7 for Amazon shows OM's IV spreads, which we can replicate very accurately by using closing share prices.[20] The 2020 correlation between OM's IV spreads and our IV spreads based on closing prices is greater than 0.999. This is important because it means that differences between OM's IV spreads and our IV spreads based on share prices at 15:59 are almost entirely due to the timing mismatch.

The lower panel shows IV spreads according to our calculation based on share prices at 15:59. The correlation between OM's IV spreads for Amazon shown in the upper panel and our IV spreads in the lower panel is 0.27. The variability of the IV spreads at 15:59 is much lower than in the upper panel, and the spike in March 2020 at the outbreak of the COVID-19 pandemic disappears.

The difference of 1 min was particularly important in March 2020. As the Wall Street Journal noted on Friday, March 13: "Big swings in the final minutes of trading have become a staple of the recent market tumult" (Banerji et al., 2020). This was particularly true on Friday, March 13, when the Dow Jones Industrial Average experienced the biggest gain since 2008, just 1 day after the biggest drop since 1987: "Stocks swung on Friday before making a stunning rally in the last minutes of the trading session" (Banerji et al., 2020). For this day, Table 5 reports the implied share prices (for options expiring on April 17, 2020), the

[19]Figures for companies mentioned in this section are available on request from the author.

[20]The replication is not shown because the graph is indistinguishable from the upper panel in Figure 7. This also means that early exercise does not play a role and the binomial model used by OM does not introduce relevant discretization errors.

TABLE 3 Europe: Standard deviations of pooled IV spreads per year.

				IV spreads OM			IV spreads imp			Diff (imp-OM) in %		
Year	*N*	Ni	%D	All	nD	D	All	nD	D	ΔAll	ΔnD	ΔD
2002	92,414	126	12.10	4.15	4.29	2.91	1.56	1.56	1.58	−62.40	−63.60	−45.70
2003	107,991	118	10.20	5.15	5.30	3.51	1.35	1.34	1.40	−73.80	−74.70	−60.10
2004	167,243	163	12.10	4.59	4.58	4.65	1.27	1.27	1.29	−72.30	−72.30	−72.30
2005	221,360	190	11.10	3.99	4.10	2.94	1.15	1.05	1.76	−71.20	−74.40	−40.10
2006	170,873	115	9.80	4.08	4.01	4.62	2.30	2.25	2.71	−43.60	−43.90	−41.30
2007	437,825	325	12.90	3.24	3.12	3.91	1.50	1.46	1.79	−53.70	−53.20	−54.20
2008	385,414	325	13.20	4.26	4.07	5.32	1.60	1.52	2.02	−62.40	−62.70	−62
2009	440,273	334	11.60	3.86	3.76	4.46	1.31	1.16	2.15	−66.10	−69.10	−51.80
2010	549,884	354	11.80	3.57	3.44	4.35	1.16	1.04	1.82	−67.50	−69.80	−58.20
2011	396,702	273	13.30	3.41	2.80	5.86	1.28	1.18	1.81	−62.50	−57.90	−69.10
2012	503,155	347	11.50	4.52	4.08	6.93	1.57	1.48	2.15	−65.30	−63.70	−69
2013	542,137	357	10.30	5.39	5.33	5.83	1.38	1.27	2.10	−74.40	−76.20	−64
2014	593,438	397	9.50	3.17	2.93	4.78	1.18	1.10	1.79	−62.80	−62.50	−62.60
2015	642,102	417	11.90	3.29	3.04	4.72	1.28	1.16	1.94	−61.10	−61.80	−58.90
2016	617,100	398	12.10	3.54	3.13	5.66	1.26	1.04	2.30	−64.40	−66.80	−59.40
2017	495,256	308	12.30	2.89	2.56	4.60	1.42	1.32	1.98	−50.90	−48.40	−57
2018	606,188	419	12.30	3.01	2.51	5.35	1.23	1.06	2.06	−59.10	−57.80	−61.50
2019	820,033	503	11.50	3.39	2.72	6.53	1.03	0.86	1.85	−69.60	−68.40	−71.70
2020	647,979	420	9	5.16	4.20	10.83	1.18	0.92	2.66	−77.10	−78.10	−75.40

Note: IV spreads are defined as the difference between the IVs of pairs of puts and calls (in percentage points). "N" is the number of IV spreads, "Ni" the number of stocks and "%D" the proportion (in percent) of options with a dividend during the time to maturity. "All" includes options with and without dividends; "nD" includes only options without dividends; "D" includes only options with a dividend before maturity. "IV spreads imp" are based on implied share prices; "IV spreads OM" are based on IVs as reported by OM. The columns "IV spreads OM" and "IV spreads imp" report the standard deviations of annually pooled IV spreads (in percentage points). The last three columns show the relative difference (in percent) between the standard deviation of "IV spreads imp" and the standard deviation of "IV spreads OM".

share prices at 15:59 and 16:00 (both from algoseek S&P 500 1 min Bars) and the official closing share prices of six stocks showing a spike in IV spreads on this day. The implied share prices and the prices at 15:59 are considerably lower than the share prices at 16:00 and the closing prices. Since OM combines the option quotes at 15:59 with the closing prices, the latter are too high, which leads to strongly positive IV spreads.

To assess the effect of the timing mismatch on a broader basis for S&P 500 stocks, Table 6 shows standard deviations of IV spreads pooled annually across stocks, times to maturity and moneyness. The number of available IV spreads (*N*) increases from 93,207 in 2010 to 1,483,601 in 2020. Column "OM" contains the standard deviation of OM's IV spreads; columns "Close," "15:59" and "Simp" contain the standard deviations according to our computations based on closing prices, share prices at 15:59 and implied share prices. The last three columns show the percentage difference between the standard deviations according to our computations and OM's computation.

As mentioned earlier, IV spreads based on closing prices are generally very similar to OM's IV spreads. The only substantial difference is that we do not take OM's dividend projections into account. In this way, we avoid anomalies that are caused by inappropriate dividend projections as shown in Figure 6 for Boeing. For this reason, our standard deviation in 2020 based on closing prices (3.24 percentage points) is slightly smaller than the standard deviation based on OM's IVs (3.39 percentage points). The standard deviation decreases further to 2.73 percentage points based on 15:59 share prices and to 2.53 percentage points based on implied share prices. This means that $(3.39 - 2.73)/3.39 = 19.5\%$ of the standard deviation of OM's IV spreads in 2020 can be explained by anomalous dividend projections and the timing mismatch of 1 min. Using share prices at 15:59 still does not perfectly synchronize

TABLE 4 Europe: Percentiles of the standard deviations of IV spreads for individual firms.

		Percentiles						
Year	**Ni**	**1%**	**10%**	**25%**	**50%**	**75%**	**90%**	**99%**
2002	126	0.16/0.06	0.39/0.17	0.8/0.31	2.04/0.62	4.1/1.15	6.36/2.57	9.82/5.48
2003	118	0.07/0.03	0.34/0.15	0.59/0.28	1.19/0.55	3.85/1.68	5.85/2.86	11.92/4.16
2004	163	0.08/0.09	0.37/0.2	0.63/0.35	1.59/0.99	2.51/1.54	4.12/2.25	8.09/3.52
2005	190	0.34/0.18	0.67/0.31	0.98/0.59	1.47/1.09	2.2/1.51	3.25/1.88	7.52/3.29
2006	115	1.7/0.79	2.61/1.06	3/1.28	3.64/1.89	4.38/2.62	5.32/3.29	7.33/5.63
2007	325	0.85/0.22	1.2/0.45	1.41/0.62	1.92/0.88	3.7/1.34	5.8/2.1	8.8/6.19
2008	325	0.49/0.14	0.92/0.23	1.51/0.36	2.71/0.72	5.38/1.49	7.33/2.25	11.84/5.65
2009	334	0.39/0.07	0.89/0.23	1.4/0.43	2.3/0.72	4.12/1.41	7.06/2.49	13.95/5.02
2010	354	0.18/0.06	0.43/0.23	1.09/0.44	1.85/0.88	3.6/1.26	5.29/1.83	10.48/3.39
2011	273	0.28/0.08	0.51/0.25	0.86/0.46	1.72/0.85	4.07/1.39	6.29/2.03	10.81/3.67
2012	347	0.23/0.05	0.64/0.22	1.46/0.38	3.17/0.83	4.87/1.55	6.6/2.54	13.47/4.96
2013	357	0.19/0.03	0.43/0.21	0.93/0.38	3.07/0.77	5.73/1.35	9.17/2.25	15.37/5
2014	397	0.04/0.01	0.28/0.18	0.53/0.32	1.65/0.65	3.7/1.26	5.12/1.97	8.31/3.37
2015	417	0.11/0.01	0.31/0.17	0.55/0.36	1.29/0.68	3.74/1.23	5.53/2.08	9.91/3.59
2016	398	0.16/0.04	0.34/0.16	0.66/0.32	1.32/0.68	3.49/1.13	5.47/1.72	9.87/4.34
2017	308	0.11/0.09	0.34/0.21	0.58/0.37	1.45/0.69	3.02/1.11	4.6/1.81	7.61/3.57
2018	419	0.08/0.06	0.31/0.17	0.5/0.31	1.19/0.58	3.17/1	4.66/1.66	8.9/3.46
2019	503	0.06/0.05	0.26/0.18	0.48/0.34	1.12/0.64	4.09/1.02	6.76/1.5	11.7/2.95
2020	420	0.06/0.03	0.45/0.12	1.07/0.33	2.99/0.71	5.6/1.16	8.92/1.91	12.72/3.75

Note: This table shows percentiles of the annual distribution of the firm-level standard deviations of IV spreads (in percentage points). The first number is the standard deviation in OM's calculation, the second number the standard deviation in our own calculation.

Abbreviation: Ni, the number of firms

option quotes and share prices. The remaining discrepancy might explain another $(2.73 - 2.53)/3.39 = 5.9\%$ of the standard deviation of OM's IV spreads, as can be seen from the results for implied share prices. The results are very similar in 2018 and 2019. In other years, the reduction in the standard deviation of IV spreads by using share prices at 15:59 lies between 7% and 8%, which is still considerable. Only in 2011, the standard deviation of OM's IV spreads is slightly smaller than the standard deviation of IV spreads based on 15:59 prices.

Our analyses so far were limited to stocks included in the S&P 500 for which share prices at 15:59 are available. For the full sample, we compare OM's IV spreads with IV spreads based on implied share prices in Tables 7 and 8, which are structured in the same way as before for European data (Tables 3 and 4). Before 2009, the number of firms (Ni) and IV spreads (N) is small. In these years, the critical requirement often is that option quotes for at least five strike prices with a moneyness between 0.9 and 1.05 are available. Table 7 shows that the annual standard deviation of IV spreads based on implied share prices is smaller by 19%–67% than the standard deviation of OM's IV spreads. The distribution percentiles in Table 8 reveal that this reduction is distributed more evenly across firms than in European data. In particular, the difference at the 90% percentile between OM's IV spreads and our spreads for implied share prices is much smaller. The reason is that anomalies occur much less frequently in the US data.

3.5 | Case study: Relevance for aggregate implied volatility spreads

Since last-minute movements in equity markets are correlated across stocks, the timing mismatch affects IV spreads not only at the individual stock level but also at the aggregate level. Aggregate IV spreads have been used for various purposes in previous research. For example, Han and Li (2021) use an aggregate IV spread as a proxy for

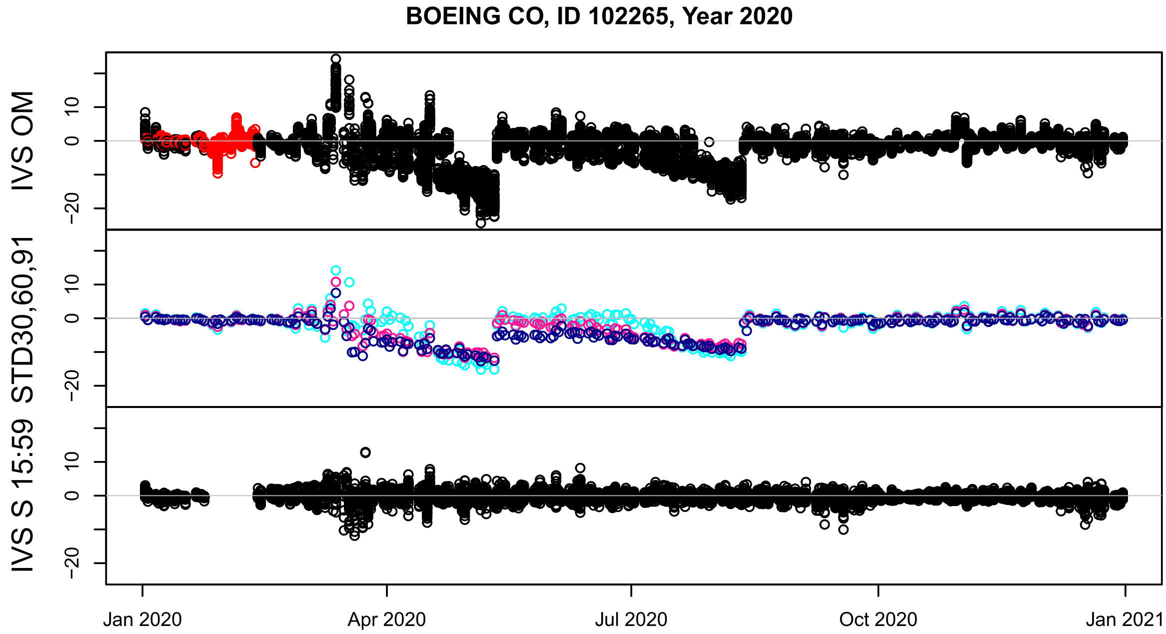

FIGURE 6 IV Spreads Boeing in 2020. Upper panel: OM IV spreads in percentage points (IV put−IV call) for all pairs of puts and calls with positive open interest, a moneyness between 0.9 and 1.05 and a time to maturity between 14 and 91 calendar days. Black: no dividend during the options' term; red: dividend during the options' term. Anomalies in April/May and July/August: In March 2020, Boeing announced to suspend dividend payments. However, projected dividends for May 12, 2020, and August 12, 2020, remained recorded in OM's Distribution Projection file. Middle panel: OM IV spreads of standardized options with a time to maturity of 30 (lightblue), 60 (pink) and 91 (blue) calendar days. Lower panel: Own calculation of IV spreads based on the price of the underlying stock at 15:59. Only cases without dividends are considered. IV, implied volatility; OM, OptionMetrics. [Color figure can be viewed at wileyonlinelibrary.com]

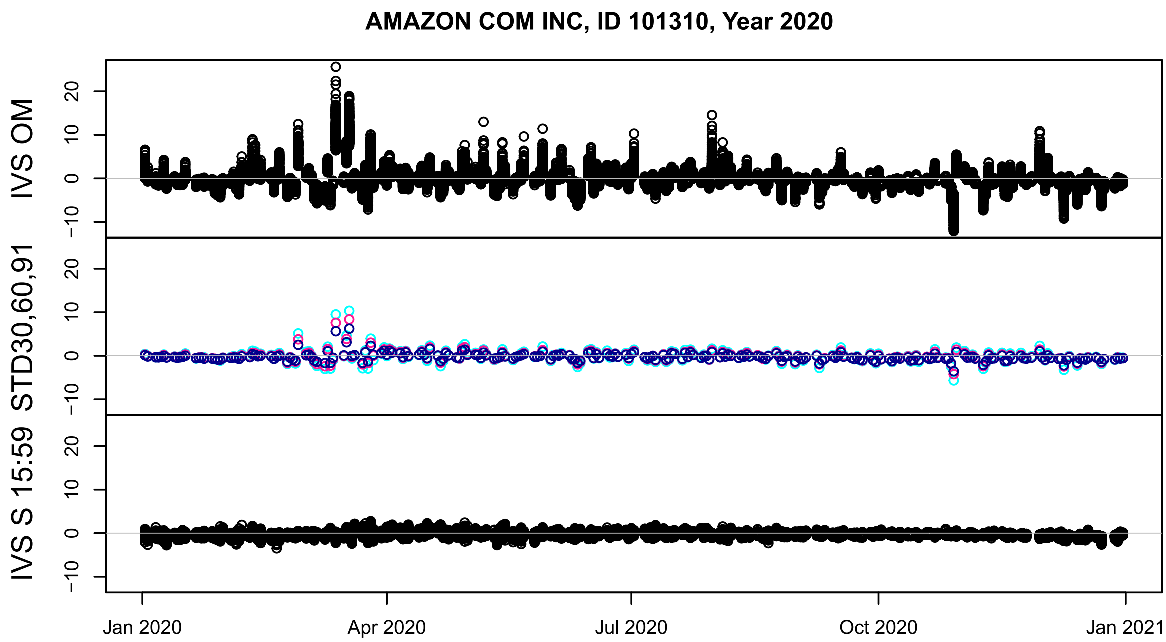

FIGURE 7 IV spreads Amazon in 2020. Upper panel: OM IV spreads in percentage points (IV put−IV call) for all pairs of puts and calls with positive open interest, a moneyness between 0.9 and 1.05 and a time to maturity between 14 and 91 calendar days. Middle panel: OM IV spreads of standardized options with a time to maturity of 30 (lightblue), 60 (pink) and 91 (blue) calendar days. Lower panel: Own calculation of IV spreads based on the price of the underlying stock at 15:59. IV, implied volatility; OM, OptionMetrics. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Share prices of selected stocks on Friday March 13, 2020.

Stock	Ticker	ID	Simp	15:59	16:00	Close
Alphabet	GOOGL	121812	1197.82	1197.45	1214.37	1214.27
Amazon	AMZN	101310	1765.04	1763.88	1786.31	1785
Apple	AAPL	101594	274.35	274.41	278.06	277.97
Autozone	AZO	101806	1006.70	1008.41	1014.15	1012.73
Facebook	FB	154402	167.58	168.19	170.62	170.28
Netflix	NFLX	115422	332.27	332.50	336.30	336.30

Abbreviations: Close, official closing price; ID, the security ID used by OM; Simp, the share price implied in options with maturity date April 17, 2020. "15:59" and "16:00" are the share prices at 15:59 and 16:00, respectively, according to the algoseek S&P 500 1 min Bars.

TABLE 6 S&P 500 sample: Standard deviations of pooled IV spreads per year.

Year	*N*	Ni	OM	Close	15:59	Simp	Close-OM	15:59-OM	Simp-OM
2010	93,207	109	1.85	1.82	1.51	0.93	−1.60	−18.40	−49.70
2011	136,976	170	2.08	2.03	2.14	1.17	−2.40	2.90	−43.80
2012	155,292	169	1.67	1.64	1.55	1.02	−1.80	−7.20	−38.90
2013	263,004	236	1.72	1.67	1.49	0.96	−2.90	−13.40	−44.20
2014	698,804	282	2.65	2.62	2.44	1.94	−1.10	−7.90	−26.80
2015	1,002,313	274	3	2.99	2.77	2.19	−0.30	−7.70	−27
2016	946,396	277	2.64	2.64	2.45	2.10	0	−7.20	−20.50
2017	1,084,207	312	2.40	2.38	2.19	1.99	−0.80	−8.80	−17.10
2018	1,391,874	338	2.54	2.51	2.04	1.89	−1.20	−19.70	−25.60
2019	1,465,541	339	2.29	2.27	1.85	1.73	−0.90	−19.20	−24.50
2020	1,483,601	344	3.39	3.24	2.73	2.53	−4.40	−19.50	−25.40

Note: "OM," "Close," "15:59," and "Simp" all show the standard deviation of IV spreads. These are based on OM data, closing prices, share prices at 15:59 and implied share prices. The last three columns report relative differences (in percent) between the standard deviations.

Abbreviations: *N*, the number of IV spreads; Ni, the number of stocks.

macroeconomic information of option traders. The idea is that informed options trading drives the IVs of puts and calls apart because arbitrage is limited by transaction costs and other frictions.[21] As a result, the aggregate IV spread is informative of future market returns. Empirical data for the United States from 1996 to 2015 supports this hypothesis. Jones et al. (2018) find a similar relationship between aggregate IV spreads and future market returns. However, they view IV spreads as option-implied stock lending fees. Thus, the level of these fees is an indicator of short-selling activity. This indicator predicts market returns when short-sellers have superior information. Rösch et al. (2017) investigate the comovement of stock-level efficiency measures and the resulting dynamics of market-wide efficiency. IV spreads are included as one (of four) efficiency measures. The authors find strong comovements reflecting a systematic market-wide component of (in)efficiency. In the following, we examine whether the timing mismatch is potentially relevant to these studies.

Similar to Han and Li (2021), we define aggregate IV spreads as the equally weighted average of the IV spreads of individual stocks with a time to maturity of approximately 30 days.[22] To determine the IV spreads of individual stocks, we pre-select IV spreads with a remaining maturity of less than 45 days and a moneyness (strike/forward price) of more than 0.99 and less than 1.01. From this set of short-term ATM options, we select the IV spread whose remaining

[21]Similarly, IV spreads of individual stocks are often used as a measure of informed trading on firm-related information; see, for example, Cremers and Weinbaum (2010), Xing et al. (2010), Kang and Park (2014), Liu (2019), Park et al. (2019), Zhang (2019), Fung and Loveland (2020).

[22]Han and Li (2021) use OM's Standardized Options so that the time to maturity is exactly 30 days.

TABLE 7 US full sample: Standard deviations of pooled IV spreads per year.

Year	*N*	Ni	%D	IV spreads OM			IV spreads imp			Diff (imp-OM) in %		
				All	nD	D	All	nD	D	ΔAll	ΔnD	ΔD
1996	380	1	0	3.33	3.33		1.64	1.64		−50.80	−50.80	
1997	2083	4	45.20	2.37	1.98	2.77	1.41	1.26	1.54	−40.50	−36.40	−44.40
1998	2654	6	20.90	2.30	2.50	1.18	1.51	1.60	1.01	−34.30	−36	−14.40
1999	7243	14	12.30	2.26	2.31	1.91	1.15	1.11	1.26	−49.10	−51.90	−34
2000	12,503	23	7.90	2.36	2.34	2.52	1.04	1.01	1.32	−55.90	−56.80	−47.60
2001	749	2	0	3.05	3.05		1.08	1.08		−64.60	−64.60	
2002	422	1	17.80	1.18	1.27	0.52	0.80	0.85	0.39	−32.20	−33.10	−25
2003	230	1	23.90	0.82	0.72	0.97	0.66	0.64	0.66	−19.50	−11.10	−32
2004	1019	2	30.10	0.97	1.09	0.60	0.55	0.50	0.38	−43.30	−54.10	−36.70
2005	5573	6	22.90	1.73	1.88	1.02	0.57	0.51	0.57	−67.10	−72.90	−44.10
2006	11,056	8	32.80	1.20	1.14	1.31	0.78	0.42	1.16	−35	−63.20	−11.50
2007	20,625	22	24.80	2.15	2.16	2.15	0.86	0.59	1.25	−60	−72.70	−41.90
2008	18,671	23	27.90	2.62	2.49	2.86	0.93	0.52	1.46	−64.50	−79.10	−49
2009	118,963	124	28.60	1.84	1.80	1.93	0.79	0.71	0.95	−57.10	−60.60	−50.80
2010	251,626	228	25.70	2.24	2.39	1.77	1.25	1.15	1.49	−44.20	−51.90	−15.80
2011	394,360	354	25.80	2.83	2.93	2.54	1.70	1.68	1.77	−39.90	−42.70	−30.30
2012	427,541	344	27.90	2.56	2.71	2.12	1.45	1.40	1.57	−43.40	−48.30	−25.90
2013	650,033	443	24.10	2.47	2.57	2.13	1.23	1.13	1.49	−50.20	−56	−30
2014	1,458,088	531	19	3.66	3.79	3.06	2.27	2.20	2.50	−38	−42	−18.30
2015	1,852,639	505	19.10	3.58	3.63	3.37	2.46	2.38	2.73	−31.30	−34.40	−19
2016	1,580,092	461	20.40	3.23	3.27	3.06	2.35	2.28	2.59	−27.20	−30.30	−15.40
2017	1,857,757	542	19.50	2.81	2.79	2.87	2.19	2.09	2.57	−22.10	−25.10	−10.50
2018	2,325,355	589	18.90	2.83	2.81	2.90	2.14	2.09	2.32	−24.40	−25.60	−20
2019	2,445,912	571	18	3.10	3.14	2.89	1.98	1.88	2.35	−36.10	−40.10	−18.70
2020	2,548,711	593	15.70	3.51	3.50	3.56	2.70	2.62	3.08	−23.10	−25.10	−13.50

Note: IV spreads are defined as the difference between the IVs of pairs of puts and calls (in percentage points). "All" includes options with and without dividends; "nD" includes only options without dividends; "D" includes only options with a dividend before maturity. "IV spreads imp" are based on implied share prices; "IV spreads OM" are based on IVs as reported by OM. The columns "IV spreads OM" and "IV spreads imp" report the standard deviations of annually pooled IV spreads (in percentage points). The last three columns show the relative difference (in percent) between the standard deviation of "IV spreads imp" and the standard deviation of "IV spreads OM".

Abbreviations: %D, the proportion (in percent) of options with a dividend during the time to maturity; *N*, the number of IV spreads; Ni, the number of stocks.

maturity is closest to 30 calendar days. Finally, if this IV spread can be computed for at least 50 individual stocks on a given day, we average these spreads to obtain the aggregate IV spread for that day.

We compute aggregate IV spreads in this way from the sample of S&P 500 stocks using three different definitions of stock-level IVs: IVs provided by OM; IVs resulting from our own calculations based on closing share prices; and IVs resulting from our own calculations based on share prices at 15:59. Table 9 shows the results for each year from 2010 to 2020. As expected, our calculations based on closing prices replicate OM data well: The correlation of the two aggregate IV spreads is always higher than 0.99 (col. 3), and the ratio of the two standard deviations is close to 1 (col. 6). The results differ significantly when closing prices are replaced by share prices at 15:59. The new aggregate IV spread is much less strongly correlated with the aggregate IV spread from OM data (col. 4), and its standard deviation is significantly lower (decrease of 27% to 71%, see col. 7).

TABLE 8 US full sample: Percentiles of the standard deviations of IV spreads for individual firms.

		Percentiles						
Year	**Ni**	**1%**	**10%**	**25%**	**50%**	**75%**	**90%**	**99%**
1996	1	3.33/1.64	3.33/1.64	3.33/1.64	3.33/1.64	3.33/1.64	3.33/1.64	3.33/1.64
1997	4	1.34/1	1.45/1.07	1.62/1.17	1.97/1.3	2.55/1.51	3.12/1.78	3.46/1.93
1998	6	1.55/0.81	1.6/1.02	1.67/1.27	1.74/1.37	2.04/1.45	3.08/2.22	3.93/2.9
1999	14	1.12/0.71	1.36/0.73	1.49/0.77	1.66/1	2.01/1.33	2.49/1.38	4.86/2.06
2000	23	1.1/0.57	1.26/0.68	1.49/0.77	2/0.87	2.53/1.21	2.99/1.38	3.26/1.62
2001	2	1.81/0.84	1.98/0.88	2.28/0.94	2.77/1.04	3.26/1.15	3.55/1.21	3.73/1.24
2002	1	1.18/0.8	1.18/0.8	1.18/0.8	1.18/0.8	1.18/0.8	1.18/0.8	1.18/0.8
2003	1	0.82/0.66	0.82/0.66	0.82/0.66	0.82/0.66	0.82/0.66	0.82/0.66	0.82/0.66
2004	2	0.7/0.5	0.74/0.5	0.82/0.5	0.94/0.51	1.06/0.52	1.14/0.53	1.18/0.53
2005	6	0.69/0.48	0.75/0.48	0.83/0.49	1.03/0.54	1.29/0.61	1.95/0.64	2.5/0.66
2006	8	0.84/0.32	0.92/0.38	0.96/0.52	1.08/0.58	1.22/0.61	1.55/1.18	2.09/2.35
2007	22	0.79/0.27	0.83/0.34	1.06/0.45	1.44/0.54	2.1/0.87	3.4/1.85	3.64/2.05
2008	23	0.74/0.19	1.09/0.32	1.43/0.49	1.71/0.64	2.73/0.89	3.68/1.26	4.76/1.73
2009	124	0.97/0.19	1.08/0.49	1.17/0.58	1.33/0.68	1.69/0.81	2.15/1.22	4.77/1.81
2010	228	0.84/0.18	1.05/0.41	1.22/0.61	1.52/1.03	2.07/1.55	3.22/2.37	6.37/3.87
2011	354	0.83/0.26	1.1/0.44	1.33/0.74	1.95/1.33	3.1/2.25	4.6/3.22	7.89/4.95
2012	344	0.85/0.22	1.02/0.39	1.23/0.63	1.64/1.06	2.69/1.97	3.95/2.91	6.99/5.03
2013	443	0.95/0.35	1.22/0.65	1.44/0.88	1.76/1.18	2.23/1.61	2.94/2.15	7.07/3.27
2014	531	1.4/0.74	2.14/1.49	2.56/1.99	3.05/2.4	3.89/2.99	5.23/3.61	10.5/5.94
2015	505	1.43/0.66	2.33/1.51	2.76/2.11	3.33/2.63	4.15/3.23	5.4/3.95	10.93/5.68
2016	461	1.21/0.54	2.12/1.57	2.48/2.01	3/2.5	3.92/3.21	5.05/4.13	8.71/6.33
2017	542	1.16/0.61	1.79/1.35	2.1/1.68	2.56/2.11	3.24/2.79	4.09/3.49	7.13/5.06
2018	589	1.43/0.54	1.85/1.21	2.16/1.49	2.6/1.99	3.33/2.76	4.44/3.88	8.11/6.81
2019	571	1.18/0.47	1.58/0.96	1.92/1.28	2.38/1.78	3.28/2.69	4.7/4.07	9.04/7.48
2020	593	1.57/0.53	2.1/1.22	2.56/1.68	3.25/2.43	4.19/3.5	5.46/4.81	8.44/7.66

Note: This table shows percentiles of the annual distribution of the firm-level standard deviations of IV spreads (in percentage points). The first number is the standard deviation in OM's calculation, the second number the standard deviation in our calculation.

Abbreviation: Ni, the number of firms.

Removing the timing mismatch by using share prices at 15:59 also affects the comovements between the IV spreads of the individual stocks. To show this, we calculate the average correlation between the IV spreads of the individual stocks and the aggregate IV spreads (Table 9, cols. 8–10). Again, the results for OM data and closing prices are very similar. In contrast, using prices at 15:59 eliminates much of the correlation. It is clear from these results that the timing mismatch creates a significant amount of artificial correlation. The timing mismatch effect is so large that it is impossible to tell without recalculation whether study results based on aggregate IV spreads from OM data would be similar if aggregate IV spreads based on synchronous data were used.[23]

[23]Han and Li (2021) argue that "the predictive power of IVS remains significant [...] in the subsample after March 2008" when OptionMetrics used "the average of best bid and offer closest to 4:00 PM EST. This indicates that nonsynchronized trading between the option market and the stock market does not drive our results." This conclusion cannot be drawn because OM actually uses quotes at 3:59 p.m. and the resulting timing mismatch is important as shown here.

TABLE 9 Comparison of aggregate IV spreads based on S&P 500 sample.

		Corr		SD			Av. corr w/agg		
Year (1)	*N* (2)	OM-Close (3)	OM-15:59 (4)	OM (5)	Close/OM (6)	15:59/OM (7)	OM (8)	Close (9)	15:59 (10)
2010	237	0.998	0.690	0.005	0.979	0.602	0.427	0.429	0.332
2011	241	0.999	0.788	0.009	0.977	0.701	0.564	0.568	0.448
2012	234	0.995	0.303	0.005	0.976	0.438	0.464	0.469	0.317
2013	240	0.994	0.430	0.005	0.990	0.290	0.528	0.542	0.243
2014	249	0.996	0.843	0.006	0.981	0.725	0.495	0.505	0.413
2015	250	0.997	0.859	0.010	1.010	0.659	0.575	0.590	0.457
2016	251	0.994	0.676	0.006	1.000	0.612	0.465	0.475	0.339
2017	249	0.993	0.671	0.004	1.013	0.633	0.385	0.399	0.275
2018	248	0.999	0.709	0.010	0.997	0.423	0.564	0.582	0.389
2019	249	0.990	0.573	0.006	1.038	0.435	0.428	0.449	0.279
2020	251	0.994	0.596	0.016	0.992	0.424	0.431	0.437	0.249

Note: This table compares aggregate IV spreads based on OM data, closing prices, and share prices at 15:59. "N" is the number of days per year for which aggregate IV spreads can be computed. "Corr" is the correlation (Pearson) between aggregate IV spreads based on OM data and closing prices (col. 3), and based on OM data and share prices at 15:59 (col 4). "SD" is the standard deviation of aggregated IV spreads based on OM data (col. 5); ratio of SD based on closing prices and SD based on OM data (col. 6), and ratio of SD based on prices at 15:59 and SD based on OM data (col. 7). "Av. corr w/agg" is the mean (across firms) of correlations between a stock's IV spreads and aggregate IV spreads; the stock-level and aggregate IV spreads are based on OM data (col. 8), on closing prices (col. 9) or on share prices at 15:59 (col. 10).

3.6 | A note on Cremers and Weinbaum (CW, 2010)

The study of CW (2010) is central for stock return predictability based on deviations from put-call parity, which raises the question of how this study relates to their work. CW find that a positive (negative) spread between the IVs of calls and puts is associated with significantly positive (negative) abnormal returns over the following 4 weeks. The authors provide evidence that this result is not due to short-sale constraints, but to the presence of informed traders in the options market. The degree of predictability decreases over time, suggesting that sophisticated investors have learned to quickly incorporate the information contained in option prices into share prices.

During the sample period of CW from 1996 to 2005, option markets closed at 16:02 EST, while stock exchanges closed at 16:00 EST. CW point out that the resulting 2-min mismatch in OptionMetrics data represents a "potentially serious nonsynchronicity problem" (p. 343). The difference was in the opposite direction of the current mismatch (which has existed since 2009), as the option quotes were leading the share prices. A correction would therefore require intraday option quotes (rather than intraday share prices), which are not available for the sample period of CW.[24]

Nevertheless, there are good reasons to believe that the 2-min mismatch is not critical to the finding of CW that deviations from put-call parity predict the cross-section of stock returns. Firstly, the study design takes into account the problem of nonsynchronicity by initiating the portfolio positions only on the day following the trading signal. Therefore, the predictability cannot be due to a bias caused by looking ahead to the 16:02 option quotes. Second, the deviations from put-call parity reported by CW are so large and divergent across stocks that the 2-min mismatch can only be a minor factor. For each stock-day combination with sufficient data, CW compute IV spreads as the weighted average of the difference between the call and put IVs across all call-put pairs with the same strike price and expiry date. This results in an overall, pooled standard deviation of IV spreads of 6.95 percentage points (p. 343). In the first subperiod from 1996 to 2000, in which stock return predictability is strongest, the 20th, 40th, 60th, and 80th percentiles of IV spreads are −4.568; −1.845; −0.012; and 2.681 percentage points (CW, Table 1, p. 344). With such large

[24]CW, p. 348: "Ideally, one would like to compute volatility spreads as of 4:00 PM EST to address this [nonsynchronicity]; however, we do not have intraday options data."

differences, it is not plausible that the order of the IV spreads and the composition of the quintile portfolios, on which the performance analysis is based (CW, Table 4, p. 351), is significantly affected by the 2-min mismatch.

The cross-sectional and time-series variation of IV spreads shown in this paper is much smaller than in CW (see, e.g., Table 7), and therefore the relative importance of the 1-min mismatch is greater. An important difference is that our selection criteria are more restrictive, as described in Section 3.2. The requirement of 5 option pairs per series is crucial for estimating implied IVs in our analysis, but rarely fulfilled before 2009 (see Table 7, col. Ni). While the sample in CW includes approximately 1400 stocks per day in January 1996 and 2200 stocks in December 2005 (p. 343), only 1 stock in 1996 and 6 stocks in 2005 fulfill our selection criteria. A detailed comparison is therefore not possible.

4 | CONCLUSION

The IVs of S&P 500 options in OM's IvyDB-GI and IvyDB-US database suggest substantial deviations from PCP that do not really exist. The discrepancies mainly arise from using nonsynchronous index and option prices and an average implied dividend yield rather than the implied yield for the specific term of each option. The IVs of puts and calls of EuroStoxx 50 and DAX options also deviate substantially, even though their settlement prices are fixed in accordance with PCP. When applying the standard procedure for calculating IVs, almost all deviations disappear. This argues for not taking the IVs of index options from OM, but calculating them according to the standard procedure.

The IVs of stock options in Europe show clusters of exceptional deviations that are mostly related to inaccurate dividend information. Charts such as those shown in this paper could be used by OptionMetrics to detect and correct such data errors in the future before they enter the database. A possible conclusion for future research using the IvyDB-EU database could be to only consider options without dividends (and dividend projections) during the remaining time to maturity.

The IVs of stock options in the United States also show anomalous clusters caused by outdated dividend projections, as was illustrated for Boeing in 2020. Even though the number of these anomalies is small, they are problematic for several reasons. First, they are correlated across firms and all go in the same direction because the underlying cause–the suspension of dividends that was not correctly recorded in OM–is the same. Second, they occur at a time of market stress that might be of particular interest for researchers. Third, the size of the anomalous IV spreads is exceptionally large. They are partly lower than −20 percentage points and thus clearly stand out from the normal bandwidth of IV spreads. The IV spreads of standardized options are less extreme in absolute terms because they are taken from smoothed volatility surfaces. In relative terms, however, they are even more striking because the IV spreads of standardized options normally fluctuate narrowly around zero. Therefore, techniques like machine-learning algorithms would likely recognize these patterns. Finally, the anomalies are so large that they are relevant for the original IVs as well. These are, on average, distorted by half of the distortion in IV spreads.

The timing mismatch of 1 min between the option quotes (recorded at 15:59) and the closing share prices (recorded at 16:00) generally increases the variability of IV spreads. In addition, it caused significant distortions at the outbreak of the COVID-19 pandemic when large price changes occurred repeatedly in the last minutes of trading. As the last-minute price changes are correlated across stocks, the timing mismatch affects IV spreads also at the aggregate stock market level.

Researchers who are aware of these effects can decide whether it is appropriate to recalculate IVs based on share prices at 15:59. This might be particularly useful in studies on PCP, option mispricing, option returns and comovements of IV spreads. For longer maturities than studied in this paper, the difficulties to separate artificial IV spreads from real violations of PCP will be even greater, because trading in these options is less active and dividends are more important but less predictable.

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DATA AVAILABILITY STATEMENT

The main data that support the findings of this study are available from OptionMetrics LLC. Restrictions apply to the availability of these data, which were used under academic license for this study. Further data that support the findings of this study are available from FirstRate Data and Algoseek. Restrictions apply to the availability of these data, which were used under license for this study.

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