

Efficient option pricing for Rough Bergomi model

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Abstract

One of the recent rough volatility models that showed a promising potential in quantitative finance is the rough Bergomi model, introduced by [3]. This new model exhibited consistent results with the stylised fact of implied volatility surfaces being essentially time-invariant, and ability to capture the term structure of skew observed in equity markets. In the absence of analytical European option pricing methods for the model, the only prevalent option is to use Monte Carlo (MC) simulation for efficient pricing. We design a novel alternative hierarchical approach based on adaptive sparse grids quadrature, specifically multi-index stochastic collocation (MISC) as in [18], coupled with Brownian bridge construction and Richardson extrapolation. Assuming one targets prices estimates with a sufficiently small degree of error tolerance, our new designed hierarchical method demonstrates substantial computational gains with respect to the standard Monte Carlo method, across different parameters constellations.

Keywords Rough volatility, Monte Carlo, multi-index stochastic collocation, Brownian bridge construction, Richardson extrapolation.

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1 Introduction

Modeling the volatility to be stochastic, rather than constant as in Black-Scholes model, enabled the quantitative finance experts to explain certain phenomena observed in option price data, in particular the implied volatility smile. However, this family of models has a main drawback consisting in failing to capture the true steepness of the implied volatility smile close to maturity. To overcome this undesired feature, experts suggested to add jumps to stock price models, for instance modelling the stock price process as an exponential Lévy process. Unfortunately, the issue of the presence of jumps in stock price processes remains controversial [11, 2], and is one of the major critics for such models.

Motivated by the statistical analysis of realised volatility by Gatheral, Jaisson and Rosenbaum [16] and the theoretical results on implied volatility by Fukasawa [14], rough stochastic volatility has emerged as a new paradigm in quantitative finance, overcoming the limitations observed by

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diffusive stochastic volatility models. In these models, the trajectories of volatility has Hölder regularity lower than those of the standard Brownian motion [16, 3]. In fact, they are based on fractional Brownian motion (fBM), which is a centred Gaussian process, whose covariance structure depends on the Hurst parameter $0 < H < 1/2$ (we refer to [22, 12, 9] for more details regarding the fBM processes). In this case, the fBM has negatively correlated increments and "rough" sample paths. Gatheral, Jaisson, and Rosenbaum [16] prove empirically the advantages of such models. For instance, they show that the log-volatility in practice has a similar behavior as fBM with the Hurst exponent $H \approx 0.1$ at any reasonable time scale (see also [15]). These results were confirmed by Bennedsen, Lunde and Pakkanen [6], who study over a thousand individual US equities and showed that the Hurst parameter H lies in $(0, 1/2)$ for each equity. Other works showed further benefits of such rough volatility models over standard stochastic volatility ones, in terms of explaining crucial phenomena observed in financial markets. For instance, from a statistical point of view, we mention [16, 6], and from an option-pricing point of view, we mention [3].

One of the recent rough volatility models is the rough Bergomi (rBergomi) model, developed by Bayer, Friz and Gatheral [3]. This model showed consistent behavior with the stylised fact of implied volatility surfaces being essentially time-invariant. It was also proven that this model enables to capture the term structure of skew observed in equity markets. The construction of the rBergomi model was performed by moving from physical to pricing measure and simulating prices under that model to fit well the implied volatility surface in the case of the S&P 500 index with few parameters. The model's name is inspired by the Bergomi variance curve model [8], and may be seen as a non-Markovian extension of the latter.

Despite the promising features of the rBergomi model, pricing and hedging under such model, still constitutes a challenging task, due to the non-Markovian nature of the fractional driver. In fact, the standard numerical pricing methods, being efficient in the case of diffusions, such as: Monte Carlo (MC) estimators, PDE discretization schemes, asymptotic expansions and transform methods, are not easily carried over to the rough setting. Furthermore, due to the lack of Markovianity or affine structure, conventional analytical pricing methods do not apply. To the best of our knowledge, the only prevalent method for pricing options under such model is MC simulation. In particular, recent advances in simulation methods for the rough Bergomi model and different variants of pricing methods based on MC under such model have been proposed in [3, 4, 23, 7, 20]. For instance, in [23], the authors employ a novel composition of variance reduction methods. When pricing under rBergomi model, they got substantial computational gains over the standard MC method. On the other hand, more attempts to have analytical understanding of option pricing and implied volatility under this model have been achieved in [21, 5, 13]. We should point out that pricing and model calibration under rough volatility models still remains a time consuming task.

In this paper, we design a novel hierarchical fast option pricer, based on a hierarchical adaptive sparse grids quadrature, specifically multi-index stochastic collocation (MISC) as in [18], coupled with Brownian bridge construction and Richardson extrapolation, for options whose underlyings follow rBergomi model as in [3]. In order to use a variant of adaptive sparse grids quadrature for our purposes, we had to solve two main issues, that constitutes the two stages of our new designed method. In the first stage, we smoothen the integrand by using the conditional expectation trick as was proposed by [26], in the context of Markovian stochastic volatility models. In a second stage, we applied a variant of hierarchical adaptive sparse grids quadrature, specifically MISC as in [18], to solve the integration problem. In this stage, we had to apply two pre-transformations before using the MISC solver, in order to overcome the issue of facing a high dimensional integrand, due to the

discretization scheme used for simulating the rBergomi dynamics. Given that MISC profits from anisotropy, the first pre-transformation consists of applying a hierarchical path generation method, based on Brownian bridge (BB) construction, with the aim of reducing the effective dimension. The second pre-transformation consists of applying Richardson extrapolation to reduce the bias, resulting in reducing the needed number of time steps in the coarsest level to achieve a certain error tolerance, and therefore, the maximum number of dimensions needed for the integration problem.

Compared to the works that we mentioned above, mainly [23], our first contribution is that we design an alternative approach based on a variant of adaptive sparse grid quadrature. Given that the only prevalent option, in this context, is to use different variants of MC method, our work opens a new perspective for experts in this field to investigate the performance of other methods besides MC, to solve pricing and calibration problems related to rBergomi model. Our second contribution is that we reduce the computational cost not only through variance reduction, as in [23], by using the conditional expectation, but also through bias reduction through using Richardson extrapolation. Finally, assuming one targets prices estimates with a sufficiently small degree of error tolerance, our third contribution is manifested by the observed substantial computational gains over standard MC method, when pricing under rBergomi model. We show these gains through our numerical experiments for different parameters constellations. In this paper, we limit ourselves to compare our novel proposed method against standard MC. A more systematic comparison against the variant of MC proposed in [23] can be carried over but this is left for a future work. Another eventual direction of research may also investigate the performance of quasi Monte Carlo (QMC) for such problems.

The outline of this paper is as follows: We start in Section 2 by introducing the pricing framework that we are considering. We provide some details about the rBergomi model, option pricing under this model and simulation scheme used to simulate asset prices following rBergomi dynamics. Then, in Section 3, we explain the different building blocks that constitutes our proposed method, which are basically MISC solver, Brownian bridge construction and Richardson extrapolation. Finally, we show in Section 4, the results obtained through different numerical experiments, across different parameters constellations for the rBergomi model. Assuming one targets European call option prices estimates with a sufficiently small degree of error tolerance, the reported results illustrate the substantial computational gains of our novel hierarchical method over standard MC, under different settings.

2 Problem setting

In this section, we introduce the pricing framework that we are considering in this project. We start in Section 2.1 by giving some details for the rBergomi model proposed in [3]. We then derive, in Section 2.2, the formula of the price of a European call option under rBergomi model. This Section corresponds basically to the first stage of our approach, *i.e.* the analytical smoothing step. Finally, we explain in Section 2.3, some details about the hybrid scheme that we used to simulate the dynamics of asset prices under the rBergomi model.

2.1 The rBergomi model

We use the rBergomi model for the price process S_t as defined in [3], normalized to $r = 0$, which is defined by

$$(2.1) \quad \begin{aligned} dS_t &= \sqrt{v_t(\widetilde{W}^H)} S_t dZ_t, \\ v_t &= \xi_0(t) \exp \left(\eta \widetilde{W}_t^H - \frac{1}{2} \eta^2 t^{2H} \right), \end{aligned}$$

where for $0 < H < 1$ (Hurst parameter) and $\eta > 0$. We have \widetilde{W}^H is a certain Volterra process (Riemann-Liouville fBm process), defined by

$$(2.2) \quad \widetilde{W}_t^H = \int_0^t K^H(t, s) dW_s^1, \quad t \geq 0$$

where the kernel $K^H : \mathbb{R}_+ \times \mathbb{R}_+ \rightarrow \mathbb{R}_+$ reads

$$K^H(t, s) = \sqrt{2H} (t-s)^{H-1/2}, \quad \forall 0 \leq s \leq t.$$

We note that the map $s \rightarrow K^H(s, t)$ belongs to L^2 , so that the stochastic integral (2.2) is well defined.

W^1, Z denote two *correlated* standard Brownian motions with correlation $\rho \in [-1, 1]$, so that we can write

$$Z := \rho W^1 + \bar{\rho} W^\perp \equiv \rho W^1 + \sqrt{1 - \rho^2} W^\perp,$$

where (W^1, W^\perp) are two independent standard Brownian motions. Therefore, (2.1) can be written as

$$(2.3) \quad \begin{aligned} S_t &= S_0 \exp \left(\int_0^t \sqrt{v(s)} dZ(s) - \frac{1}{2} \int_0^t v(s) ds \right), \quad S_0 > 0 \\ v(u) &= \xi_0(u) \exp \left(\eta \widetilde{W}_u^H - \frac{\eta^2}{2} u^H \right), \quad \xi_0 > 0. \end{aligned}$$

The filtration $(\mathcal{F}_t)_{t \geq 0}$ can here be taken as the one generated by the two-dimensional Brownian motion (W^1, W^\perp) under the risk neutral measure \mathbb{Q} , resulting in a filtered probability space $(\Omega, \mathcal{F}; \mathcal{F}_t, \mathbb{Q})$. The stock price process S is clearly then a local $(\mathcal{F}_t)_{t \geq 0}$ -martingale and a supermartingale, therefore integrable. We shall henceforth use the notation $\mathbb{E}[\cdot] = E^\mathbb{Q}[\cdot | \mathcal{F}_0]$ unless we state otherwise.

We refer to v_u as the variance process, where $\xi_0(u) = \mathbb{E}[v_u] \in \mathcal{F}_0$ a.s. the forward variance curve. \widetilde{W}^H is a centered, locally $(H - \epsilon)$ -Hölder continuous, Gaussian process with $\text{var}[\widetilde{W}_t^H] = t^{2H}$.

2.2 Option pricing under rBergomi model

In our project, we are interested in pricing European call options under rBergomi model. Assuming $S_0 = 1$, and using the conditioning argument on the σ -algebra generated by W^1 (argument first used by [26] in the context of Markovian stochastic volatility models), we can show that the call price is given by

$$\begin{aligned}
C_{RB}(T, K) &= E[(S_T - K)^+] \\
&= E[E[(S_T - K)^+ | \sigma(W^1(t), t \leq T)]] \\
(2.4) \quad &= E\left[C_{BS}\left(S_0 = \exp\left(\rho \int_0^T \sqrt{v_t} dW_t^1 - \frac{1}{2}\rho^2 \int_0^T v_t dt\right), K = K, T = 1, \sigma^2 = (1 - \rho^2) \int_0^T v_t dt\right)\right],
\end{aligned}$$

where C_{BS} denotes the Black-Scholes price.

In fact, if we use the orthogonal decomposition of S_t into S_t^1 and S_t^2 , where

$$S_t^1 := \mathcal{E}\left\{\rho \int_0^t \sqrt{v_s} dW_s^1\right\}, \quad S_t^2 := \mathcal{E}\left\{\sqrt{1 - \rho^2} \int_0^t \sqrt{v_s} dW_s^\perp\right\},$$

where $\mathcal{E}()$ denotes the stochastic exponential, then, we obtain by conditional log-normality

$$\log S_t | \mathcal{F}_t^1 \sim \mathcal{N}\left(\log S_t^1 - \frac{1}{2}(1 - \rho^2) \int_0^t v_s ds, (1 - \rho^2) \int_0^t v_s ds\right),$$

where $\mathcal{F}_t^1 = \sigma\{W_s^1 : s \leq t\}$. Therefore, we obtain (2.4).

We insist that the analytical smoothing trick, based on conditionning, performed in (2.4) enables us to get a smooth analytic integrand inside the expectation. Therefore, applying sparse quadrature techniques becomes an adequate option for computing the call price as we will investigate later.

2.3 Simulation of the rBergomi model

One of the numerical challenges encountered in the simulation of rBergomi dynamics is the computation of the terms $\int_0^T \sqrt{v_t} dW_t^1$ and $V = \int_0^T v_t dt$ as in (2.4), mainly because of the singularity of the Volterra kernel $K(s, t)$ at the diagonal $s = t$. In fact, one needs to jointly simulate the two-dimensional Gaussian process $(W_t^1, \widetilde{W}_t^H : 0 \leq t \leq T)$, resulting in $W_{t_1}^1, \dots, W_{t_N}^1$ and $\widetilde{W}_{t_1}^H, \dots, \widetilde{W}_{t_N}^H$ along a given time grid $t_1 < \dots < t_N$. In the literature, there are essentially three possible ways to achieve this:

- i) Euler discretization of the integral (2.2), defining \widetilde{W}^H , together with classical simulation of increments of W^1 . This is horribly inefficient because the integral is singular and adaptivity probably does not help, as the singularity moves with time. For this method, we need an N -dimensional random Gaussian input vector to produce one (approximate, inaccurate) sample of $W_{t_1}^1, \dots, W_{t_N}^1, \widetilde{W}_{t_1}^H, \dots, \widetilde{W}_{t_N}^H$.
- ii) Given that $W_{t_1}^1, \dots, W_{t_N}^1, \widetilde{W}_{t_1}^H, \dots, \widetilde{W}_{t_N}^H$ together forms a $(2N)$ -dimensional Gaussian random vector with computable covariance matrix. One can use Cholesky decomposition of the covariance matrix to produce exact samples of $W_{t_1}^1, \dots, W_{t_N}^1, \widetilde{W}_{t_1}^H, \dots, \widetilde{W}_{t_N}^H$, but unlike the first way, we need $2 \times N$ -dimensional Gaussian random vectors as input. This method is exact but slow (See [3] and Section 4 in [5] for more details about this scheme). The simulation requires $\mathcal{O}(N^3)$ flops.

- iii) The hybrid scheme of [7] uses a different approach, which is essentially based on Euler discretization as the first way but crucially improved by moment matching for the singular term in the left point rule. It is also inexact in the sense that samples produced here do not exactly have the distribution of $W_{t_1}^1, \dots, W_{t_N}^1, \widetilde{W}_{t_1}^H, \dots, \widetilde{W}_{t_N}^H$, however they are much more accurate than samples produced from method *i*), but much faster than method *ii*). As in method *ii*), in this case, we need a $2 \times N$ -dimensional Gaussian random input vector to produce one sample of $W_{t_1}^1, \dots, W_{t_N}^1, \widetilde{W}_{t_1}^H, \dots, \widetilde{W}_{t_N}^H$.

In this project, we adopt the last approach for the simulation of the rBergomi asset price. We utilise the first order variant ($\kappa = 1$) of the hybrid scheme [7], which is based on the approximation

$$\widetilde{W}_{\frac{i}{N}}^H \approx \overline{W}_{\frac{i}{N}} := \sqrt{2H} \left(\int_{\frac{i-1}{N}}^{\frac{i}{N}} \left(\frac{i}{N} - s \right)^{H-\frac{1}{2}} dW_u^1 + \sum_{k=2}^i \left(\frac{b_k}{N} \right)^{H-\frac{1}{2}} \left(W_{\frac{i-(k-1)}{N}}^1 - W_{\frac{i-k}{N}}^1 \right) \right),$$

where N is the number of time steps and

$$b_k := \left(\frac{k^{H+\frac{1}{2}} - (k-1)^{H+\frac{1}{2}}}{H + \frac{1}{2}} \right)^{\frac{1}{H-\frac{1}{2}}}.$$

Employing the fast Fourier transform to evaluate the sum in (2.3), which is a discrete convolution, a skeleton $\overline{W}_0^H, \overline{W}_1^H, \dots, \overline{W}_{\frac{[Nt]}{N}}^H$ can be generated in $\mathcal{O}(N \log N)$ floating point operations.

The variates $\overline{W}_0^H, \overline{W}_1^H, \dots, \overline{W}_{\frac{[Nt]}{N}}^H$ are generated by sampling $[nt]$ iid draws from a $\kappa + 1$ -dimensional Gaussian distribution and computing a discrete convolution. We call these pairs of Gaussian random variables from now on as (W^1, W^2) .

3 Details of our approach

We recall that our goal is to compute the expectation in (2.4). In fact, as seen in Section 2.3, we need $2N$ dimensional Gaussian inputs for the used hybrid scheme (N is the number of time steps in the time grid), namely

- $\{W_i^1\}_{i=1}^N$: The N Gaussian random variables that are defined in Section 2.1.
- $\{W_j^2\}_{j=1}^N$: An artificial introduced N Gaussian random variables that are used for left-rule points in the hybrid scheme, as explained in Section 2.3.

Thus, we can rewrite (2.4) as

$$\begin{aligned} C_{RB}(T, K) &= E \left[C_{BS} \left(S_0 = \exp \left(\rho \int_0^T \sqrt{v_t} dW_t^1 - \frac{1}{2} \rho^2 \int_0^T v_t dt \right), K = K, T = 1, \sigma^2 = (1 - \rho^2) \int_0^T v_t dt \right) \right], \\ (3.1) \quad &\approx \int_{\mathbb{R}^{2N}} C_{BS} (G(W_1^1, \dots, W_N^1, W_1^2, \dots, W_N^2)) \rho_N(\mathbf{W}^1) \rho_N(\mathbf{W}^2) dW_1^1 \dots dW_N^1 dW_1^2 \dots dW_N^2 \end{aligned}$$

where G maps $2N$ independent standard Gaussian random inputs to the parameters fed to Black-Scholes formula as in (3.1), and ρ_N is the multivariate gaussian density, given by

$$\rho_N(\mathbf{z}) = \frac{1}{(2\pi)^{N/2}} e^{-\frac{1}{2}\mathbf{z}^T \mathbf{z}}.$$

Therefore, the initial integration problem that we are solving lives in $2N$ -dimensional space, which becomes very large as the number of time steps N , used in the hybrid scheme, increases.

Our approach of approximating the expectation in (3.1) is based on multi-index stochastic collocation (MISC), proposed in [18]. We describe the MISC solver in our context in Section 3.1. To make an effective use of MISC, we apply two pre-transformations to overcome the issue of facing a high dimensional integrand, due to the discretization scheme used for simulating the rBergomi dynamics. The first pre-transformation consists of applying a hierarchical path generation method, based on Brownian bridge (Bb) construction, with the aim of reducing the effective dimension as described in Section 3.2. The second pre-transformation consists of applying Richardson extrapolation to reduce the bias, resulting in reducing the maximum number of dimensions needed for the integration problem. Details about Richardson extrapolation are provided in Section 3.3.

If we denote by \mathcal{E} the total error of computing the expectation in (2.4) using MISC solver, then we have a natural error decomposition, giving by

$$(3.2) \quad \mathcal{E} \leq \mathcal{E}_Q(TOL_{\text{MISC}}, N) + \mathcal{E}_B(N),$$

where \mathcal{E}_Q is the quadrature error, function of MISC tolerance: TOL_{MISC} and N : the number of time steps, and \mathcal{E}_B is the bias, function of N or $\Delta_t = \frac{T}{N}$ (size of the time grid).

3.1 The MISC solver

Assume we want to solve the problem of approximating the expected value of $E[f(Y)]$ on a tensorization of quadrature formulae over the stochastic domain, Γ . We also assume that $f(y)$ is a continuous function (analytic) over Γ .

To introduce simplified notations, we start with the one-dimension case. Let us define $\beta \leq 1$ be an integer positive value referred to as a "stochastic discretization level", and $m : \mathbb{N} \rightarrow \mathbb{N}$ be a strictly increasing function with $m(0) = 0$ and $m(1) = 1$, that we call a "level-to-nodes function". At level β , we consider a set of $m(\beta)$ distinct quadrature points in $(-\infty; \infty)$, $\mathcal{H}^{m(\beta)} = \{y_\beta^1, y_\beta^2, \dots, y_\beta^{m(\beta)}\} \subset [-\infty, \infty]$, and a set of quadrature weights, $\omega^{m(\beta)} = \{\omega_\beta^1, \omega_\beta^2, \dots, \omega_\beta^{m(\beta)}\}$. We also let $C^0((-\infty, \infty))$ be the set of real-valued continuous functions over $(-\infty, \infty)$. We then define the quadrature operator as

$$(3.3) \quad Q(m(\beta)) : C^0((-\infty, \infty)) \rightarrow \mathbb{R}, \quad Q(m(\beta))[f] = \sum_{j=1}^{m(\beta)} f(y_\beta^j) \omega_\beta^j.$$

In our case, and following (3.1), we have a multi-variate integration problem and we have, given the previous notations, $f := C_{\text{BS}} \circ G$, $\mathbf{Y} = (\mathbf{W}^1, \mathbf{W}^2)$, and Γ is finite dimensional and given by a $2N$ tensor product of intervals. Therefore, we define, for any multi-index β

$$Q^{m(\beta)} : \Gamma \rightarrow \mathbb{R}, \quad Q^{m(\beta)} = \bigotimes_{n=1}^{2N} Q^{m(\beta_n)}$$

where the n -th quadrature operator is understood to act only on the n -th variable of f . Practically, we obtain the value of $Q^{m(\beta)}[f]$ by considering the tensor grid $\mathcal{T}^{m(\beta)} = \times_{n=1}^{2N} \mathcal{H}^{m(\beta_n)}$ with cardinality $\#\mathcal{T}^{m(\beta)} = \prod_{n=1}^{2N} m(\beta_n)$ and computing

$$Q^{\mathcal{T}^{m(\beta)}}[f] = \sum_{j=1}^{\#\mathcal{T}^{m(\beta)}} f(\hat{y}_j) \bar{\omega}_j$$

where $\hat{y}_j \in \mathcal{T}^{m(\beta)}$ and $\bar{\omega}_j$ are products of weights of the univariate quadrature rules.

Remark 3.1. We note that the quadrature points are chosen to optimize the convergence properties of the quadrature error. For instance, in our context, since we are dealing with Gaussian densities, using Gauss-Hermite quadrature points is the appropriate choice.

A direct approximation $E[f[\mathbf{Y}]] \approx Q^{m(\beta)}[f]$ is not an appropriate option due to the well-known "curse of dimensionality" effect. We use MISC as it was suggested in [18]. MISC is a hierarchical adaptive sparse grids quadrature strategy that uses stochastic discretizations and classic sparsification approach to obtain an effective approximation scheme for $E[f]$.

For the sake of concreteness, in our setting from (3.1), we are left with a $2N$ -dimensional Gaussian random inputs, which are chosen independently, resulting in $2N$ numerical parameters for MISC, which we use as the basis of the multi-index construction, reflecting the fact that W_i^1 and W_j^2 can vary independently of each other regardless of $i \neq j$ or $i = j$. Let $l \in \{1, \dots, 2N\}$ and set

$$(3.4) \quad p_l := \begin{cases} W_l^1, & 1 \leq l \leq N, \\ W_{l-N}^2, & N+1 \leq l \leq 2N. \end{cases}$$

For a multi-index $\ell = (l_i)_{i=1}^{2N} \in \mathbb{N}^{2N}$, we denote by $Q_N^\ell := Q^{N, m(\ell)}(p_\ell)$ the result of a discretized integral, using N time steps, with parameters $p_\ell := (p_{l_i})_{i=1}^{2N}$, and with a number of quadrature points $m(l_i)$ in the dimension p_{l_i} . We further define the set of differences ΔQ_N^ℓ as follows: for a single index $1 \leq i \leq 2N$, let

$$(3.5) \quad \Delta_i Q_N^\ell := \begin{cases} Q_N^\ell - Q_N^{\ell'} & \text{with } \ell' = \ell - e_i, \text{ if } \ell_i > 0 \\ Q_N^\ell & \text{otherwise} \end{cases}$$

where e_i denotes the i th $2N$ -dimensional unit vector. Then, ΔQ_N^ℓ is defined as

$$(3.6) \quad \Delta Q_N^\ell := \left(\prod_{i=1}^{2N} \Delta_i \right) Q_N^\ell.$$

For instance, when $N = 1$, then

$$\begin{aligned} \Delta Q_1^\ell &= \Delta_2 \Delta_1 Q_1^{(l_1, l_2)} = \Delta_2 \left(Q_1^{(l_1, l_2)} - Q_1^{(l_1-1, l_2)} \right) = \Delta_2 Q_1^{(l_1, l_2)} - \Delta_2 Q_1^{(l_1-1, l_2)} \\ &= Q_1^{(l_1, l_2)} - Q_1^{(l_1, l_2-1)} - Q_1^{(l_1-1, l_2)} + Q_1^{(l_1-1, l_2-1)}. \end{aligned}$$

We have the telescoping property

$$(3.7) \quad Q_N^\infty = \sum_{l_1=0}^{\infty} \cdots \sum_{l_{2N}=0}^{\infty} \Delta Q_N^{(l_1, \dots, l_{2N})} = \sum_{\ell \in \mathbb{N}^{2N}} \Delta Q_N^\ell,$$

provided that $l_1 \rightarrow \infty, \dots, l_{2N} \rightarrow \infty$, where Q_N^∞ is the biased option price, computed with N time steps.

As stated before, our goal is to approximate, Q_N^∞ , then the actual MISC estimator computed using a given a set of multi-indices $\mathcal{I} \subset \mathbb{N}^{2N}$, is given by

$$Q_N^\mathcal{I} := \sum_{\ell \in \mathcal{I}} \Delta Q_N^\ell.$$

The quadrature error in this case is given by

$$(3.8) \quad \mathcal{E}_Q(TOL_{\text{MISC}}, N) = |Q_N^\infty - Q_N^\mathcal{I}| \leq \sum_{\ell \in \mathbb{N}^{2N} \setminus \mathcal{I}} |\Delta Q_N^\ell|.$$

If we denote the computational work at level $\ell = (l_1, \dots, l_{2N})$, for adding an increment ΔQ_N^ℓ in the telescoping sum, by \mathcal{W}_N^ℓ , then the construction of the optimal \mathcal{I} will be done by profit thresholding, i.e., for a certain threshold value T , we add a multi-index ℓ to \mathcal{I} provided that

$$\log \left(\frac{|\Delta Q_N^\ell|}{\mathcal{W}_N^\ell} \right) \leq T.$$

Remark 3.2. We mention that the choice of the hierarchy of quadrature points, $m(\ell)$, is flexible in the MISC solver and can be fixed by the user, depending on the convergence properties of the problem at hand. For instance, for the sake of reproducibility, in our numerical experiments, we used a linear hierarchy: $m(l) = 4(l-1) + 1$, $1 \leq l$, for results of parameters sets 1 and 2 in table 4.1. For the remaining parameters sets in table 4.1, we used a geometric hierarchy: $m(\ell) = 2^{l-1} + 1$, $1 \leq l$.

Remark 3.3. As emphasized in [18], one important requirement to get the optimal performance of MISC solver is to check the convergence of first and mixed differences operators (See [18] for details). We checked this requirement in all our numerical experiments, and for illustration, we show in figures (3.1, 3.2), the convergence of first and second order differences for the case of parameters set 3 in table 4.1.

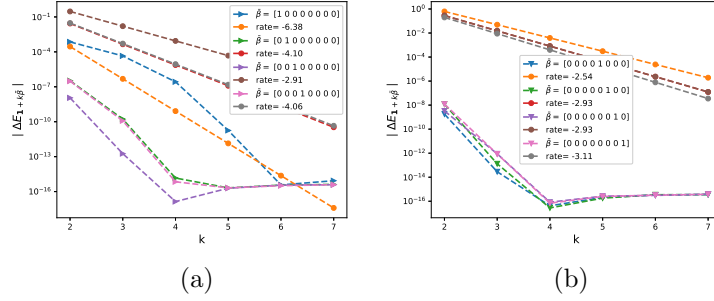


Figure 3.1: The rate of convergence of first order differences $|\Delta E_\beta|$ ($\beta = \mathbf{1} + k\bar{\beta}$), for parameters set 3 in table 4.1. The number of quadrature points used in the i -th dimension is $N_i = 2^{\beta_i - 1} + 1$. a) wrt W^1 b) wrt W^2 .

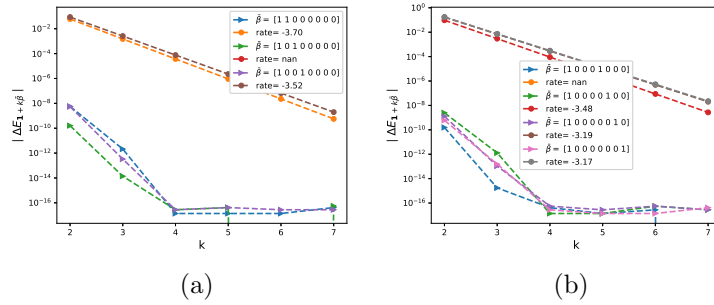


Figure 3.2: The rate of convergence of second order differences $|\Delta E_\beta|$ ($\beta = \mathbf{1} + k\bar{\beta}$), for parameters set 3 in table 4.1. The number of quadrature points used in the i -th dimension is $N_i = 2^{\beta_i - 1} + 1$. a) wrt W^1 b) wrt W^2 .

Remark 3.4. In this paper, we limited ourselves to designing a new alternative method based on hierarchical adaptive sparse grids quadrature for computing option prices under rBergomi model. Giving the significant performance of our novel designed algorithm, we expect that designing a method based on QMC can bring similar or more gains as our approach. An investigation of the performance of QMC in a similar context is left for a future work.

3.2 Brownian bridge construction

In the literature of adaptive sparse grids and QMC, several hierarchical path generation methods (PGMs) or transformation methods have been proposed to reduce the effective dimension. Among these transformations, we cite the Brownian bridge (Bb) construction [24, 25, 10], the principal component analysis (PCA) [1] and the linear transformation (LT) [19], etc ...

In our context, sampling the Brownian motion can be constructed either sequentially using a standard random walk construction or hierarchically using other hierarchical PGM as listed above. For our purposes, to make an effective use of MISC, which profits from anisotropy, we use the Bb construction since it produces dimensions with different importance for MISC (creates anisotropy), contrary to random walk procedure for which all the dimension of the stochastic space have equal

importance (isotropic). This pre-transformation reduces the effective dimension of the problem and as a consequence accelerates the MISC procedure by reducing the computational cost.

Let us denote $\{t_i\}_{i=0}^N$ the grid of time steps, then the Bb construction [17] consists of the following: given a past value B_{t_i} and a future value B_{t_k} , the value B_{t_j} (with $t_i < t_j < t_k$) can be generated according to the formula:

$$(3.9) \quad B_{t_j} = (1 - \rho)B_{t_i} + \rho B_{t_k} + \sqrt{\rho(1 - \rho)(k - i)\Delta t}z, \quad z \sim \mathcal{N}(0, 1),$$

where $\rho = \frac{j-i}{k-i}$. In particular, if N is a power of 2, then given $B_0 = 0$, Bb generates the Brownian motion at times $T, T/2, T/4, 3T/4, \dots$ according

$$(3.10) \quad \begin{aligned} B_T &= \sqrt{T}z_1 \\ B_{T/2} &= \frac{1}{2}(B_0 + B_T) + \sqrt{T/4}z_2 = \frac{\sqrt{T}}{2}z_1 + \frac{\sqrt{T}}{2}z_2 \\ B_{T/4} &= \frac{1}{2}(B_0 + B_{T/2}) + \sqrt{T/8}z_3 = \frac{\sqrt{T}}{4}z_1 + \frac{\sqrt{T}}{4}z_2 + \sqrt{T/8}z_3 \\ &\vdots \end{aligned}$$

where $\{z_j\}_{j=1}^N$ are independent standard normal variables. In Bb construction scheme given by (3.10), the most important values that determine the large scale structure of Brownian motion are the first components of $\mathbf{z} = (z_1, \dots, z_N)$.

Remark 3.5. In this paper, we chose to couple Brownian bridge construction with the MISC solver to reduce the effective dimension, since it is the less costly option in terms of computational work and the easiest to implement. We did not investigate the performance of MISC when coupling it with other hierarchical path generations method such as PCA or LT, which could be left as a future work that looks for the optimal PGM to couple with MISC in this context.

3.3 Richardson extrapolation

Another pre-transformation that we coupled with MISC is Richardson extrapolation [27]. In fact, applying level ℓ of Richardson extrapolation reduces dramatically the bias and as a consequence reduces the needed number of time steps N used in the coarsest level to achieve a certain error tolerance. This means basically that Richardson extrapolation reduces directly the total dimension of the integration problem for achieving some error tolerance.

We recall that the Euler scheme has weak order 1 so that

$$(3.11) \quad \left| \mathbb{E} \left[f(\hat{X}_T^h) \right] - \mathbb{E} [f(X_T)] \right| \leq Ch$$

for some constant C , all sufficiently small h and suitably smooth f . It can be easily shown that (3.11) can be improved to

$$(3.12) \quad \mathbb{E} \left[f(\hat{X}_T^h) \right] = \mathbb{E} [f(X_T)] + ch + \mathcal{O}(h^2),$$

where c depends on f .

Applying (3.12) with discretization step $2h$, we obtain

$$(3.13) \quad \mathbb{E} \left[f(\hat{X}_T^{2h}) \right] = \mathbb{E} [f(X_T)] + 2ch + \mathcal{O}(h^2),$$

implying

$$(3.14) \quad 2\mathbb{E} \left[f(\hat{X}_T^{2h}) \right] - \mathbb{E} \left[f(\hat{X}_T^h) \right] = \mathbb{E} [f(X_T)] + \mathcal{O}(h^2),$$

For higher levels extrapolations, we use the following: Let us denote by $h_J = h_0 \cdot 2^{-J}$ the grid sizes (where h_0 is the coarsest grid size), by K the level of the Richardson extrapolation, and by $I(J, K)$ the approximation of $\mathbb{E} \left[f(\hat{X}_T^{h_J}) \right]$ by terms up to level K (leading to a weak error of order K), then we have

$$(3.15) \quad I(J, K) = \frac{2^K [I(J, K-1) - I(J-1, K-1)]}{2^K - 1} + \mathcal{O}(h^{K+1}), \quad J = 1, 2, \dots, K = 1, 2, \dots$$

Remark 3.6. Although we report later in Section 4, some plots of the weak error (Bias) rates for cases with/without Richardson extrapolation, we emphasize that our results are pure experimental, and hence we cannot be sure what will happen in the asymptotic regime. In fact, in this work, we target prices estimates with a sufficiently small value of error tolerance, when using few number of time steps, *i.e.* in the pre-asymptotic regime.

Remark 3.7. We note that we did not apply Richardson extrapolation for all our numerical experiments. In fact, as it will be illustrated later in Section 4, for some parameters constellations, we can get a satisfactory small error tolerance even without applying a level 1 of Richardson extrapolation. Those cases basically are characterized by a sufficiently small bias in the pre-asymptotic regime.

4 Numerical experiments

4.1 Summary of the numerical results

We conduct our experiments for 5 different parameters sets as presented in tables 4.1.

In Section 4.2, we estimate the weak error (Bias) for the different parameter constellations, for 2 scenarios involving with/without Richardson extrapolation. The conclusions of this section are:

- Without Richardson extrapolation: For all cases except parameters set 4, we get a weak error of order Δt , with different constants. Interestingly, we see that the case of parameters set 4 (see table 4.1) has a weak error rate of order around 0.4 but with a small constant.
- With Richardson extrapolation: For all reported cases (sets 1, 2, 3 in table 4.1), we get an improvement for weak error in terms of the rate and constants compared to the case without Richardson extrapolation.

Remark 4.1. We emphasize that the reported weak rates correspond to the pre-asymptotic regime¹³ that we are interested in. We are not interested on estimating the rates specifically but rather a sufficient precise estimate of the weak error (Bias), $\mathcal{E}_B(N)$, for different time steps N , in order to get the biased MC solution for a given discretization, that we denoted $Q^N(\infty)$ in Section 3.1. For a fixed discretization, the corresponding biased solution will be set as a reference solution to the MISC solver in order to estimate the quadrature error $\mathcal{E}_Q(TOL_{MISC}, N)$.

In Section 4.3, we show tables and plots reporting the different errors involved in MC method (bias and statistical error), related to the plots in Section 4.2, and in MISC (Quadrature error). We do this for each case of parameter set. The quadrature error (see (3.8)) is computed by subtracting the MISC solution from the biased solution, computed with sufficiently large number of samples (to kill the statistical error). Given that both methods, MC and MISC, have the same bias, the computational time of MC and MISC is compared such that the statistical error is almost equal to the stable quadrature error produced by MISC.

The conclusions of this section are:

- i) For the case of set 1 (See Section 4.3.1), MISC coupled with Richardson extrapolation is 3 times faster than MC coupled with Richardson extrapolation, to achieve a total relative error around 8% (see tables(4.8, 4.9)). This gain is improved when applying level 2 Richardson extrapolation. In fact, MISC coupled with Richardson extrapolation (level 2) is 4 times faster than MC coupled with Richardson extrapolation (level 2), to achieve a total relative error around 0.5% (see tables (4.12, 4.13)). Applying Richardson extrapolation brought a significant improvement for MISC (compare tables (4.4,4.5) (no Richardson), tables (4.8, 4.9) (Richardson (level 1)) and tables ((4.12, 4.13)) (Richardson (level 2)), also see figure 4.9).
- ii) For the case of set 2 (See Section 4.3.2), MISC coupled with Richardson extrapolation is 19 times faster than MC coupled with Richardson extrapolation, to achieve a total relative error around 8% and 4 times faster than MC, to achieve total relative error around 2% (see tables (4.20,4.21)). This gain is improved when applying level 2 Richardson extrapolation. In fact, MISC coupled with Richardson extrapolation (level 2) is 17 times faster than MC coupled with Richardson extrapolation (level 2), to achieve a total relative error below 1% (see tables (4.24, 4.25)). Applying Richardson extrapolation brought a significant improvement for MISC (compare tables (4.16, 4.17) (no Richardson), tables (4.20,4.21) (Richardson (level 1)) and tables (4.24, 4.25) (Richardson (level 2)), also see figure 4.13).
- iii) For the case of set 3 (See Section 4.3.3), MISC is 35 times faster than MC, to achieve a total relative error below 1% and 8 times faster than MC, to achieve a total relative error around 0.1% (see figure 4.15 and tables (4.29, 4.28)). Using Richardson extrapolation brought an improvement in terms of the complexity constant compared to using simple MISC (See figure 4.17 and tables (4.32, 4.33)).
- iv) For the case of set 4 (See Section 4.3.4), MISC is 141 times faster than MC, to achieve a total relative error below 1% (see figure 4.19 and tables (4.37, 4.36)).
- v) For the case of set 5 (See Section 4.3.5), MISC is 220 times faster than MC, to achieve a total relative error below 6% and 16 times faster than MC, to achieve total relative error around 2% (see figure 4.21 and tables (4.41, 4.40)).

4.2 Weak error plots

In this section, we include the results of weak errors for the different parameters sets as in table 4.1, with and without Richardson extrapolation. We considered a number of time steps $N \in \{2, 4, 8, 16\}$. The options are priced in terms of the moneyness K , where K is the strike price. The reference solution was computed with $N = 500$ time steps (reported in table 4.1). We note that the weak errors plotted here correspond to relative errors. We show in table 4.1 the different parameter constellations that we consider to report our results for MC and MISC.

Parameters	Reference solution
Set 1: $H = 0.43, K = 1, S_0 = 1, \rho = -0.9, \eta = 1.9, \xi = 0.235^2$	0.0712 ($5.7e-05$)
Set 2: $H = 0.07, K = 1, S_0 = 1, \rho = -0.9, \eta = 1.9, \xi = 0.235^2$	0.0791 ($7.9e-05$)
Set 3: $H = 0.02, K = 1, S_0 = 1, \rho = -0.7, \eta = 0.4, \xi = 0.1$	0.1248 ($1.3e-04$)
Set 4: $H = 0.02, K = 0.8, S_0 = 1, \rho = -0.7, \eta = 0.4, \xi = 0.1$	0.2407 ($5.6e-04$)
Set 5: $H = 0.02, K = 1.2, S_0 = 1, \rho = -0.7, \eta = 0.4, \xi = 0.1$	0.0568 ($2.5e-04$)

Table 4.1: Reference solution, using MC with 500 time steps and $M = 10^6$, of call option price under rBergomi model, for different parameter constellation. The numbers between parentheses correspond to the statistical errors.

4.2.1 Without Richardson extrapolation

From figures (4.1,4.2,4.3), we see that for all cases except parameters set 4, we get a weak error of order Δt , with different constants. Interestingly, we see that the case of parameters set 4 (see table 4.1) has a weak error rate of order around 0.4 but with a small constant. The upper and lower bounds are 95% confidence intervals.

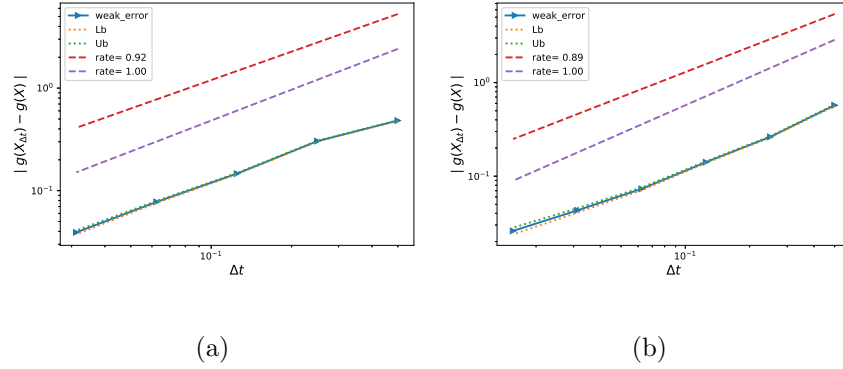


Figure 4.1: The rate of convergence of the weak error $|E[g(X_{\Delta t})] - g(X)|$ without Richardson extrapolation, using MC with $M = 10^6$: a) Set 1 parameters in table 4.1. b) Set 2 parameters in table 4.1.

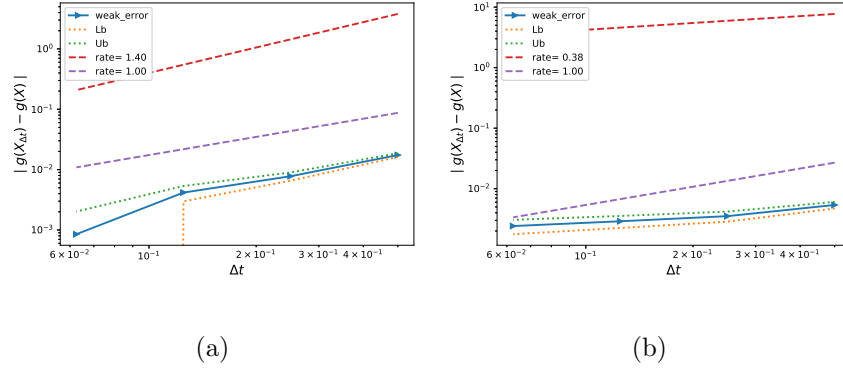


Figure 4.2: The rate of convergence of the weak error $|E[g(X_{\Delta t})] - g(X)|$ without Richardson extrapolation, using MC with $M = 5.10^6$: a) Set 3 parameters in table 4.1, b) Set 4 parameters in table 4.1.

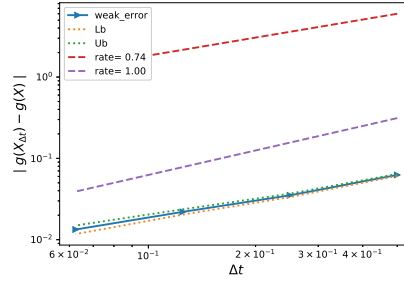


Figure 4.3: The rate of convergence of the weak error $|E[g(X_{\Delta t})] - g(X)|$, for set 5 parameters in table 4.1, without Richardson extrapolation, using MC with $M = 5.10^6$.

4.2.2 With Richardson extrapolation (level 1)

Figures (4.4, 4.5) illustrate the weak errors estimates for parameters sets 1, 2, 3 in table 4.1. The upper and lower bounds are 95% confidence intervals.

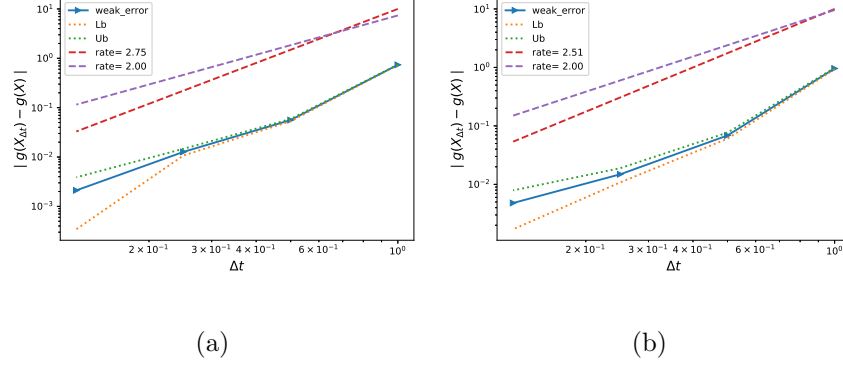


Figure 4.4: The rate of convergence of the weak error $|\mathbb{E}[2g(X_{\Delta t/2}) - g(X_{\Delta t})] - g(X)|$ with Richardson extrapolation, using MC with $M = 10^6$: a) Set 1 parameters in table 4.1. b) Set 2 parameters in table 4.1,

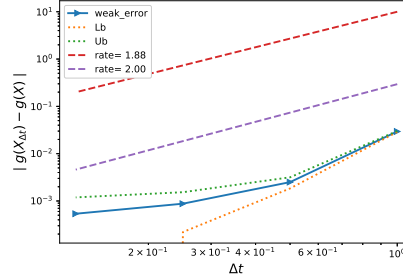


Figure 4.5: The rate of convergence of the weak error $|\mathbb{E}[2g(X_{\Delta t/2}) - g(X_{\Delta t})] - g(X)|$, for set 3 parameters in table 4.1, with Richardson extrapolation, using MC with $M = 10^7$.

4.3 Comparing different errors and complexity for MC and MISC

The results were reported for the different sets of parameters defined in table 4.1. We considered a number of time steps $N \in \{2, 4, 8, 16\}$. The options are priced in terms of the moneyness K , where K is the strike price.

For each set, we report the results for 2 scenarios: i) Without using Richardson extrapolation and ii) Using level 1 Richardson extrapolation.

In each case, we show a table of computed values using MISC with different tolerances as well the biased MC value, using large number of samples to kill the statistical error. Then, in a second table, we show the bias as well the statistical error for MC method, related to Section 4.2. After that, a plot shows the behavior of the relative quadrature error which is computed as the normalized difference between the biased MC solution and MISC solution. Then, we provide the total relative error which is the sum of the bias and statistical error for MC, and the quadrature error for MISC. We note that we used a number of samples for MC such that the statistical error is almost equal to the stable quadrature error, in order to have a fair complexity comparison between the two methods. Finally, we show the CPU time needed for each solver. We note that in all cases the

actual work (runtime) was obtained using a 40-core Intel(R) Xeon(R) CPU E5-268 architecture.¹⁷

4.3.1 Case of set 1 parameters in table 4.1

Without Richardson extrapolation

Method \ Steps	2	4	8	16
MISC ($TOL_{MISC} = 10^{-1}$)	0.1140	0.0961	0.0871	0.0802
MISC ($TOL_{MISC} = 10^{-2}$)	0.1077	0.0944	0.0838	0.0772
MISC ($TOL_{MISC} = 10^{-3}$)	0.1077	0.0921	0.0819	0.0762
MISC ($TOL_{MISC} = 10^{-4}$)	0.1079	0.0921	0.0822	—
MC method ($M = 8.10^6$)	0.1078	0.0921	0.0822	0.0767

Table 4.2: Call option price of the different methods for different number of time steps. Case of set 1 parameters in table 4.1, without Richardson extrapolation.

Method \ Steps	2	4	8	16
MC Bias ($M = 8.10^6$)	0.5142 (0.0366)	0.2933 (0.0209)	0.1551 (0.0110)	0.0777 (0.0055)
MC Statistical error ($M = 8.10^6$)	8.4e-04 (6.0e-05)	4.8e-04 (3.4e-05)	3.8e-04 (2.7e-05)	3.3e-04 (2.35e-05)

Table 4.3: Bias and statistical errors of MC for computing call option price for different number of time steps. Case set 1, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors.

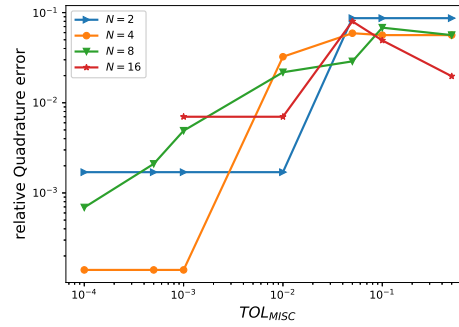


Figure 4.6: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 1 parameters, without Richardson extrapolation. See detailed values in table A.1

Method \ Steps	2	4	8	16
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.6010	0.3496	0.2232	0.1269
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.5159	0.3257	0.1769	0.0847
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	0.5159	0.2934	0.1600	0.0847
MISC ($TOL_{\text{MISC}} = 10^{-4}$)	0.5159	0.2934	0.1558	—
MC	0.5159	0.2938	0.1555	0.0817

Table 4.4: Total relative error of MISC, with different tolerances, and MC to compute call option price for different number of time steps. Case set 1 parametrs of table 4.1, without Richardson extrapolation. The values marked in red, for MISC method, correspond to the total relative errors associated with stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	2	4	8	16
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.1	0.1	0.6	6
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.2	1	9	215
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	2	11	243	4650
MISC ($TOL_{\text{MISC}} = 10^{-4}$)	6	96	5760	—
MC	50	344	637	8
Ratio of (MC/MISC)	250	31	0.1	0.04

Table 4.5: Comparison of the computational time (in Seconds) of MC and MISC, used to compute call option price of rBergomi model for different number of time steps. Case set 1 parametrs of table 4.1. The average MC CPU time is computed over 10 runs.

With Richardson extrapolation (level 1)

Method \ Steps	1 – 2	2 – 4	4 – 8
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.1357	0.0783	0.0785
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.1237	0.0781	0.0745
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	0.1224	0.0766	0.0720
MC method ($M = 10^6$)	0.1237	0.0752	0.0721

Table 4.6: Call option price of the different methods for different number of time steps. Case set 1 parameters of table 4.1, using Richardson extrapolation (level 1).

Method \ Steps	1 – 2	2 – 4	4 – 8	8 – 16
MC Bias ($M = 10^6$)	0.7378 (0.0525)	0.0561 (0.0040)	0.0127 (0.0009)	0.0021 (0.0001)
MC Statistical error ($M = 10^6$)	3.3e – 03 (2.3e–04)	1.6e – 03 (1.1e–04)	1.0e – 03 (7.1e–05)	9.0e – 04 (6.4e–05)

Table 4.7: Bias and statistical errors of MC for computing call option price for different number of time steps. Case set 1 parameters in tabel 4.1, with Richardson extrapolation (level 1). The numbers between parentheses are the corresponding absolute errors.

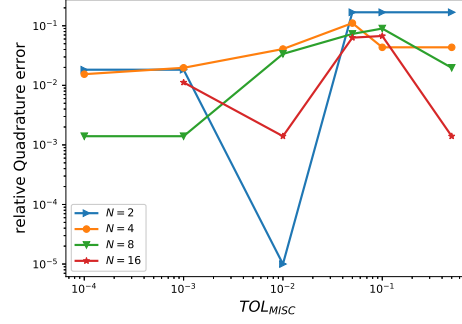


Figure 4.7: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 1 parameters, with Richardson extrapolation. See detailed values in table A.2.

Method \ Steps	1 – 2	2 – 4	4 – 8
MISC ($TOL_{MISC} = 10^{-1}$)	0.9063	0.0996	0.1026
MISC ($TOL_{MISC} = 10^{-2}$)	0.7378	0.0968	0.0464
MISC ($TOL_{MISC} = 10^{-3}$)	0.7561	0.0758	0.0141
MC	0.7561	0.0758	0.0141

Table 4.8: Total relative error of MISC and MC, with different tolerances, to compute call option price for different number of time steps. Case set 1 parameters in table 4.1, with Richardson extrapolation(level 1). The values marked in red, for MISC method, correspond to the total relative errors associated with stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	1 – 2	2 – 4	4 – 8
MISC ($TOL_{MISC} = 10^{-1}$)	0.1	0.1	0.6
MISC ($TOL_{MISC} = 10^{-2}$)	1	2	18
MISC ($TOL_{MISC} = 10^{-3}$)	4	12	520
MC	34.7	37	532
Ratio of (MC/MISC)	8.7	3.1	1

Table 4.9: Comparison of the computational time (in Seconds) of MC and MISC, using Richardson extrapolation (level 1), used to compute call option price of rBergomi model for different number of time steps. Case set 1 parameters in table 4.1. The average MC CPU time is computed over 10 runs.

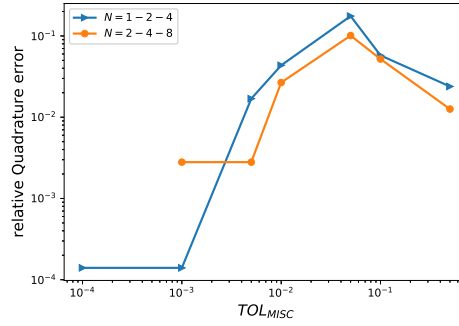
With Richardson extrapolation (level 2)

Method \ Steps	1 – 2 – 4	2 – 4 – 8
MISC ($TOL_{MISC} = 10^{-1}$)	0.0567	0.0747
MISC ($TOL_{MISC} = 10^{-2}$)	0.0639	0.0729
MISC ($TOL_{MISC} = 5 \cdot 10^{-3}$)	0.0620	0.0708
MC ($M = 3 \cdot 10^6$)	0.0608	0.0710

Table 4.10: Call option price of the different methods for different number of time steps. Case set 1 parameters in table 4.1, using Richardson extrapolation (level 2).

Method \ Steps	1 – 2 – 4	2 – 4 – 8
MC Bias ($M = 3 \cdot 10^6$)	0.1459 (0.0104)	0.0024 ($1.7e-04$)
MC Statistical error ($M = 3 \cdot 10^6$)	1.5e – 03 ($1.0e-04$)	6.8e – 04 ($4.8e-05$)

Table 4.11: Bias and statistical errors of MC for computing call option price for different number of time steps. Case set 1 parameters in tabel 4.1, with Richardson extrapolation (level 2). The numbers between parentheses are the corresponding absolute errors.



level

Figure 4.8: Quadrature error of MISC, with different tolerances, to compute call option price of the different tolerances for different number of time steps. Case set 1 parameters, with Richardson extrapolation (level 2). See detailed values in table A.3.

Method \ Steps	1 – 2 – 4	2 – 4 – 8
MISC ($TOL_{MISC} = 10^{-1}$)	0.2035	0.0544
MISC ($TOL_{MISC} = 10^{-2}$)	0.1894	0.0291
MISC ($TOL_{MISC} = 5.10^{-3}$)	0.1628	0.0052
MC	0.1628	0.0052

Table 4.12: Total relative error of MISC, with different tolerances, and MC to compute call option price for different number of time steps. Case set 1 parameters in table 4.1, with Richardson extrapolation(level 2). The values marked in red, for MISC method, correspond to the total relative errors associated with stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	1 – 2 – 4	2 – 4 – 8
MISC ($TOL_{MISC} = 10^{-1}$)	0.25	2
MISC ($TOL_{MISC} = 10^{-2}$)	2	24
MISC ($TOL_{MISC} = 5.10^{-3}$)	5	64
MC	20	231
Ratio of (MC/MISC)	4	3.6

Table 4.13: Comparison of the computational time (in Seconds) of MC and MISC, using Richardson extrapolation (level 2), used to compute call option price of rBergomi model for different number of time steps. Case set 1 parameters in table 4.1. The average MC CPU time is computed over 10 runs.

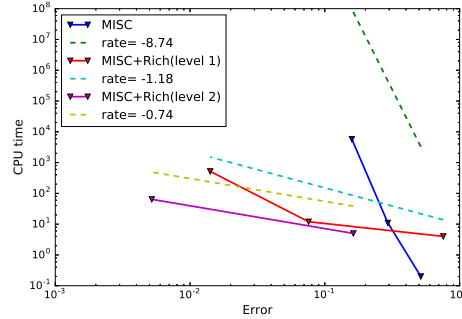


Figure 4.9: Complexity plot for MISC (with/without) Richardson extrapolation for case set 1 parameters of table 4.1.

4.3.2 Case of set 2 parameters in table 4.1

Without Richardson extrapolation

Method \ Steps	2	4	8
MISC ($TOL_{MISC} = 10^{-1}$)	0.1097	0.0926	0.0791
MISC ($TOL_{MISC} = 10^{-2}$)	0.1119	0.1023	0.0910
MISC ($TOL_{MISC} = 10^{-3}$)	0.1195	0.1023	0.0910
MISC ($TOL_{MISC} = 10^{-4}$)	0.1218	0.1023	—
MC method ($M = 8.10^6$)	0.1218	0.1024	0.0914

Table 4.14: Call option price of the different methods for different number of time steps. Case of set 2 parameters in table 4.1, without Richardson extrapolation.

Method \ Steps	2	4	8	16
MC Bias ($M = 8.10^6$)	0.5375 (0.0426)	0.2922 (0.0208)	0.1542 (0.0122)	0.0731 (0.0058)
MC Statistical error ($M = 8.10^6$)	2.5e-03 (2.0e-04)	1.3e-03 (1.0e-04)	6.3e-04 (5.0e-05)	1.33e-03 (1.1e-04)

Table 4.15: Bias and statistical errors of MC for computing call option price for different number of time steps. Case set 2 parameters in table 4.1, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors.

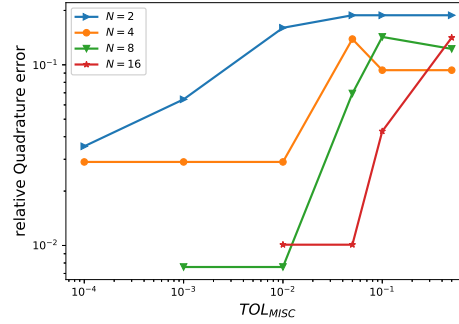


Figure 4.10: Quadrature error of MISC, with different tolerances, to compute call option price of time steps. Case set 2 parameters, without Richardson extrapolation. See detailed values in table A.4.

Method \ Steps	2	4	8
MISC ($TOL_{MISC} = 10^{-1}$)	0.6900	0.4153	0.3097
MISC ($TOL_{MISC} = 10^{-2}$)	0.6622	0.2928	0.1595
MISC ($TOL_{MISC} = 10^{-3}$)	0.6371	0.2928	0.1595
MISC ($TOL_{MISC} = 10^{-4}$)	0.5378	0.2928	—
MC	0.5400	0.2935	0.1593

Table 4.16: Total relative error of MISC, with different tolerances, and MC to compute Call option price for different number of time steps. Case set 2 parameters in table 4.1, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors. The values marked in red, for MISC method, correspond to the total relative errors associated with stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	2	4	8
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.08	0.13	0.7
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.2	5	333
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	2	73	3650
MISC ($TOL_{\text{MISC}} = 10^{-4}$)	43	1240	—
MC method	220	358	9
Ratio of (MC/MISC)	5	72	0.03

Table 4.17: Comparison of the computational time (in Seconds) of MC and MISC, used to compute Call option price of rBergomi model for different number of time steps. Case set 2 parameters in table 4.1. The average MC CPU time is computed over 10 runs.

With Richardson extrapolation (level 1)

Method \ Steps	1 – 2	2 – 4	4 – 8
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.1260	0.0756	0.0702
MISC ($TOL_{\text{MISC}} = 5.10^{-2}$)	0.1260	0.0716	0.0796
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.1456	0.0838	0.0796
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	0.1497	0.0838	—
MC method ($M = 10^6$)	0.1552	0.0846	0.0804

Table 4.18: Call option price of the different methods for different number of time steps. Case set 2 parameters of table 4.1, using Richardson extrapolation (level 1)

Method \ Steps	1 – 2	2 – 4	4 – 8	8 – 16
MC Bias ($M = 10^6$)	0.9594 (0.0760)	0.0686 (0.0054)	0.0149 (0.0012)	0.0048 (0.0004)
MC Statistical error ($M = 10^6$)	1.3e – 02 (1e–03)	4.1e – 03 (3.2e–04)	2.1e – 03 (1.7e–04)	1.6e – 03 (1.3e–04)

Table 4.19: Bias and statistical errors of MC for computing call option price for different number of time steps. Case set 2 parameters in tabel 4.1, with Richardson extrapolation (level 1). The numbers between parentheses are the corresponding absolute errors.

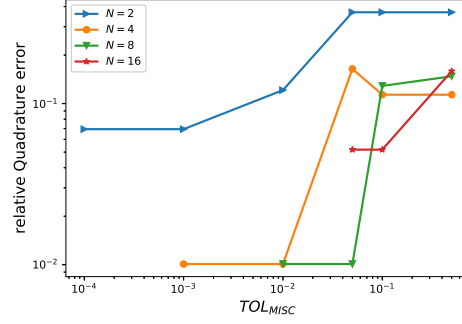


Figure 4.11: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 2 parameters, with Richardson extrapolation. See detailed values in table A.5.

Method \ Steps	1 – 2	2 – 4	4 – 8
MISC ($TOL_{MISC} = 10^{-1}$)	1.3281	0.1822	0.1437
MISC ($TOL_{MISC} = 5 \cdot 10^{-2}$)	1.3281	0.2327	0.0250
MISC ($TOL_{MISC} = 10^{-2}$)	1.0806	0.0787	0.0250
MISC ($TOL_{MISC} = 10^{-3}$)	1.0288	0.0787	—
MC	1.0288	0.0787	0.0250

Table 4.20: Total relative error of MISC, with different tolerances, and MC to compute call option price for different number of time steps. Case set 2 parameters in table 4.1, with Richardson extrapolation (level 1). The numbers between parentheses are the corresponding absolute errors. The values marked in red, for MISC method, correspond to the total relative errors associated with stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	1 – 2	2 – 4	4 – 8
MISC ($TOL_{MISC} = 10^{-1}$)	0.1	0.18	1.6
MISC ($TOL_{MISC} = 5 \cdot 10^{-2}$)	0.1	0.6	37
MISC ($TOL_{MISC} = 10^{-2}$)	1.3	6	2382
MISC ($TOL_{MISC} = 10^{-3}$)	3.5	244	—
MC	12	113	130
Ratio of (MC/MISC)	3.4	18.8	3.5

Table 4.21: Comparison of the computational time (in Seconds) of MC and MISC, using Richardson extrapolation (level 1), used to compute call option price of rBergomi model for different number of time steps. Case set 2 parameters in table 4.1. The average MC CPU time is computed over 10 runs.

With Richardson extrapolation (level 2)

Method \ Steps	1 – 2 – 4	2 – 4 – 8
MISC ($TOL_{MISC} = 10^{-1}$)	0.0587	0.0702
MISC ($TOL_{MISC} = 5 \cdot 10^{-2}$)	0.0401	0.0790
MISC ($TOL_{MISC} = 10^{-2}$)	0.0623	0.0784
MC ($M = 3 \cdot 10^6$)	0.0601	0.0787

Table 4.22: Call option price of the different methods for different number of time steps. Case set 2 parameters in tabel 4.1, using Richardson extrapolation (level 2).

Method \ Steps	1 – 2 – 4	2 – 4 – 8
MC Bias ($M = 3 \cdot 10^6$)	0.2411 (0.0191)	0.0058 (4.6e-04)
MC Statistical error ($M = 3 \cdot 10^6$)	3.5e – 03 (2.8e-04)	1.8e – 03 (1.4e-04)

Table 4.23: Bias and statistical errors of MC for computing call option price for different number of time steps. Case set 2 parameters in tabel 4.1, with Richardson extrapolation (level 2). The numbers between parentheses are the corresponding absolute errors.

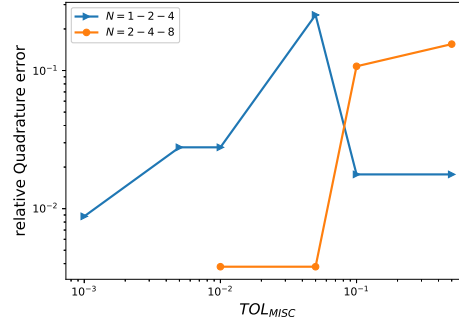


Figure 4.12: Quadrature error of MISC to compute Call option price of the different tolerances for different number of time steps. Case set 2 parameters, with Richardson extrapolation (level 2). See detailed values in table A.6.

Method \ Steps	1 – 2 – 4	2 – 4 – 8
MISC ($TOL_{MISC} = 10^{-1}$)	0.2588	0.1131
MISC ($TOL_{MISC} = 5 \cdot 10^{-2}$)	0.4936	0.0096
MISC ($TOL_{MISC} = 10^{-2}$)	0.2689	0.0096
MC	0.2689	0.0096

Table 4.24: Total relative error of MISC, with different tolerances, and MC to compute call option price for different number of time steps. Case set 2 parameters in table 4.1, with Richardson extrapolation (level 2). The values marked in red, for MISC method, correspond to the total relative errors associated with stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	1 – 2 – 4	2 – 4 – 8
MISC ($TOL_{MISC} = 10^{-1}$)	0.2	2
MISC ($TOL_{MISC} = 5.10^{-2}$)	0.5	74
MISC ($TOL_{MISC} = 10^{-2}$)	9	3455
MC	118	1274
Ratio of (MC/MISC)	13	17

Table 4.25: Comparison of the computational time (in Seconds) of MC and MISC, using Richardson extrapolation (level 2), used to compute call option price of rBergomi model for different number of time steps. Case set 2 parameters in table 4.1. The average MC CPU time is computed over 10 runs.

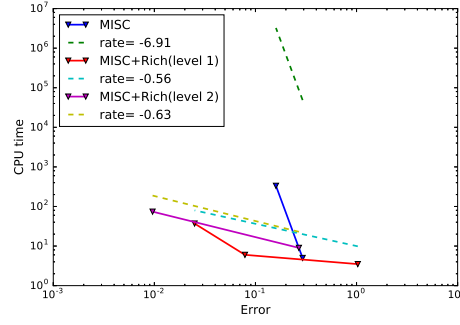


Figure 4.13: Complexity plot for MISC (with/without) Richardson extrapolation for case set 2 parameters of table 4.1.

4.3.3 Case of set 3 parameters in table 4.1

Without Richardson extrapolation

Method \ Steps	2	4	8	16
MISC ($TOL_{MISC} = 10^{-1}$)	0.1258	0.1239	0.1231	0.1229
MISC ($TOL_{MISC} = 10^{-2}$)	0.1258	0.1246	0.1248	0.1250
MISC ($TOL_{MISC} = 10^{-3}$)	0.1271	0.1259	0.1252	0.1249
MISC ($TOL_{MISC} = 10^{-4}$)	0.1270	0.1258	0.1252	—
MC method ($M = 3.10^6$)	0.1269	0.1257	0.1253	0.1249

Table 4.26: Call option price of the different methods for different number of time steps. Case of set 3 parameters in table 4.1, without Richardson extrapolation.

Method \ Steps	2	4	8	16
MC Bias ($M = 3.10^6$)	0.0174 (0.0022)	0.0078 (0.001)	0.0042 (0.0005)	0.0008 (0.0001)
MC Statistical error ($M = 3.10^6$)	5.0e-04 (6.2e-05)	4.7e-04 (5.9e-05)	4.6e-04 (5.8e-05)	4.6e-04 (5.8e-05)

Table 4.27: Bias and statistical errors of MC for computing call option price for different number of time steps. Case set 3, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors.

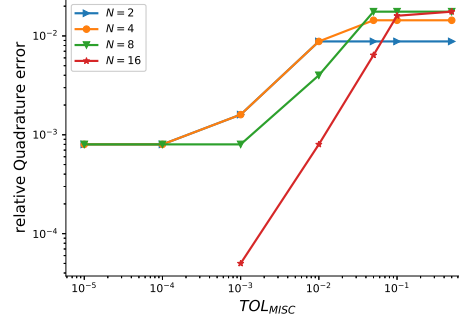


Figure 4.14: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 3 parameters, without Richardson extrapolation. See detailed values in table A.7.

Method \ Steps	2	4	8	16
MISC ($TOL_{MISC} = 10^{-1}$)	0.0262	0.0222	0.0218	0.0168
MISC ($TOL_{MISC} = 10^{-2}$)	0.0262	0.0166	0.0082	0.0016
MISC ($TOL_{MISC} = 10^{-3}$)	0.0190	0.0094	0.0050	0.0008
MISC ($TOL_{MISC} = 10^{-4}$)	0.0182	0.0086	0.0050	—
MC	0.0179	0.0083	0.0047	0.0013

Table 4.28: Total relative error of MISC, with different tolerances, and MC to compute call option price for different number of time steps. Case set 3 parameters of table 4.1, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors. The values marked in red, for MISC method, correspond to the total relative errors associated with stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	2	4	8	16
MISC ($TOL_{MISC} = 10^{-1}$)	0.1	0.1	0.2	0.8
MISC ($TOL_{MISC} = 10^{-2}$)	0.1	0.5	8	92
MISC ($TOL_{MISC} = 10^{-3}$)	0.5	3	24	2226
MISC ($TOL_{MISC} = 10^{-4}$)	1	6	80	—
MC method	122	211	427	766
Ratio of ($MC/MISC$)	122	35	18	8

Table 4.29: Comparison of the computational time (in Seconds) of MC and MISC, used to compute Call option price of rBergomi model for different number of time steps. Case set 3 parametrs of table 4.1. The average MC CPU time is computed over 10 runs.

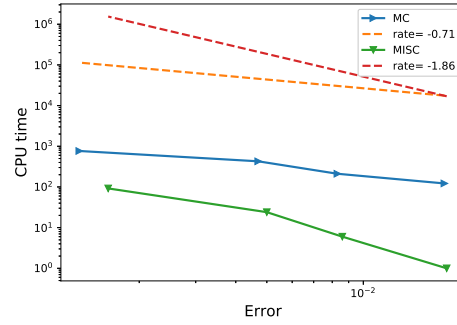


Figure 4.15: Complexity plot for MC and MISC for case set 3 parameters of table 4.1.

With Richardson extrapolation (level 1)

Method \ Steps	1 – 2	2 – 4	4 – 8	8 – 16
MISC ($TOL_{MISC} = 10^{-1}$)	0.1261	0.1220	0.1222	0.1226
MISC ($TOL_{MISC} = 10^{-2}$)	0.1267	0.1230	0.1245	0.1247
MISC ($TOL_{MISC} = 10^{-3}$)	0.1285	0.1247	0.1247	0.1247
MC method ($M = 10^7$)	0.1284	0.1251	0.1249	0.1248

Table 4.30: Call option price of the different methods for different number of time steps. Case set 3 parameters of table 4.1, using Richardson extrapolation (level 1).

Method \ Steps	1 – 2	2 – 4	4 – 8	8 – 16
MC Bias ($M = 10^7$)	0.0295 (0.0037)	0.0025 (0.0003)	0.0009 (0.0001)	0.0005 (6.2e-05)
MC Statistical error ($M = 10^7$)	3.5e-04 (4.4e-05)	3.4e-04 (4.2e-05)	3.3e-04 (4.1e-05)	3.3e-04 (4.1e-05)

Table 4.31: Bias and statistical errors of MC for computing call option price for different number of time steps. Case set 3 parameters in tabel 4.1, with Richardson extrapolation (level 1). The numbers between parentheses are the corresponding absolute errors.

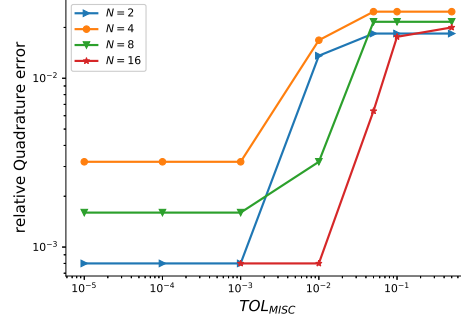


Figure 4.16: Quadrature error of MISC, with different tolerances, to compute call option price, for different number of time steps. Case set 3 parameters, with Richardson extrapolation. See detailed values in table A.8.

Method \ Steps	2 – 4	4 – 8	8 – 16
MISC ($TOL_{MISC} = 10^{-1}$)	0.0273	0.0225	0.0181
MISC ($TOL_{MISC} = 10^{-2}$)	0.0193	0.0041	0.0013
MISC ($TOL_{MISC} = 10^{-3}$)	0.0057	0.0025	0.0013
MC	0.0073	0.0025	0.0013

Table 4.32: Total relative error of MISC, with different tolerances, and MC to compute Call option price for different number of time steps. Case set 3 parameters in table 4.1, with Richardson extrapolation(level 1). The numbers between parentheses are the corresponding absolute errors. The values marked in red, for MISC method, correspond to the total relative errors associated with stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	2 – 4	4 – 8	8 – 16
MISC ($TOL_{MISC} = 10^{-1}$)	0.15	0.25	1
MISC ($TOL_{MISC} = 10^{-2}$)	0.6	10	112
MISC ($TOL_{MISC} = 10^{-3}$)	3.5	34	3150
MC	45	438	2240
Ratio of (MC/MISC)	13	13	20

Table 4.33: Comparison of the computational time (in Seconds) of MC and MISC, using Richardson extrapolation (level 1), used to compute Call option price of rBergomi model for different number of time steps. Case set 3 parameters in table 4.1. The average MC CPU time is computed over 10 runs.

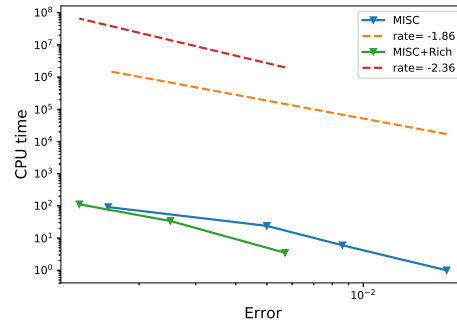


Figure 4.17: Complexity plot for MISC (with/without) Richardson extrapolation for case set 3 parameters of table 4.1.

4.3.4 Case of set 4 parameters in table 4.1

Method \ Steps	2	4	8	16
MISC ($TOL_{MISC} = 10^{-1}$)	0.2413	0.2403	0.2403	0.2397
MISC ($TOL_{MISC} = 10^{-2}$)	0.2413	0.2403	0.2409	0.2413
MISC ($TOL_{MISC} = 10^{-3}$)	0.2413	0.2411	0.2414	0.2413
MISC ($TOL_{MISC} = 10^{-4}$)	0.2421	0.2416	0.2414	—
MC method ($M = 5 \cdot 10^6$)	0.2420	0.2416	0.2414	0.2413

Table 4.34: Call option price of the different methods for different number of time steps. Case set 4 parameters in table 4.1, without Richardson extrapolation.

Method \ Steps	2	4	8	16
MC Bias ($M = 5.10^6$)	0.0054 (0.0013)	0.0035 (0.0008)	0.0029 (0.0007)	0.0024 (0.0006)
MC Statistical error ($M = 5.10^6$)	3.4e-04 (8.3e-05)	3.4e-04 (8.1e-05)	3.3e-04 (8.0e-05)	3.3e-04 (8.0e-05)

Table 4.35: Bias and statistical errors of MC for computing call option price for different number of time steps. Case set 4, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors.

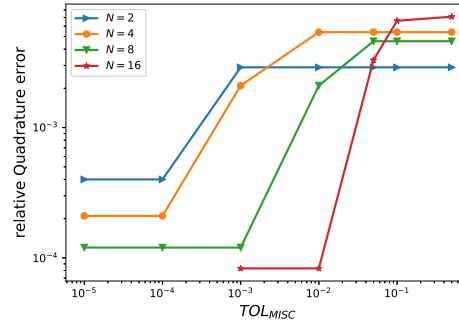


Figure 4.18: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 4 parameters, without Richardson extrapolation. See detailed values in table A.9

Method \ Steps	2	4	8	16
MISC ($TOL_{MISC} = 10^{-1}$)	0.0083	0.0089	0.0075	0.0090
MISC ($TOL_{MISC} = 10^{-2}$)	0.0083	0.0089	0.0050	0.0025
MISC ($TOL_{MISC} = 10^{-3}$)	0.0083	0.0056	0.0030	0.0025
MISC ($TOL_{MISC} = 10^{-4}$)	0.0058	0.0037	0.0030	—
MC	0.0057	0.0038	0.0032	0.0027

Table 4.36: Total relative error of MISC, different tolerances, and MC to compute call option price for different number of time steps. Case set 4 parameters of table 4.1, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors. The values marked in red, for MISC method, correspond to the total relative errors associated with stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	2	4	8	16
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.1	0.1	0.1	1
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.1	0.15	9	112
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	0.2	2	27	2226
MISC ($TOL_{\text{MISC}} = 10^{-4}$)	1	6	136	—
MC method	141	246	461	820
Ratio of ($MC/MISC$)	141	41	17	7

Table 4.37: Comparison of the computational time (in Seconds) of MC and MISC, used to compute call option price of rBergomi model for different number of time steps. Case set 4 parameters of table 4.1. The average MC CPU time is computed over 10 runs.

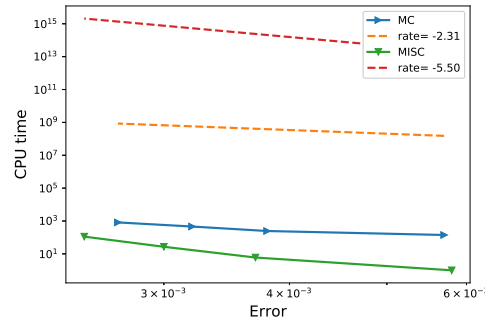


Figure 4.19: Complexity plot for MC and MISC for case set 4 parameters of table 4.1.

4.3.5 Case of set 5 parameters in table 4.1

Method \ Steps	2	4	8	16
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.0590	0.0564	0.0552	0.0546
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.0590	0.0564	0.0574	0.0572
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	0.0605	0.0587	0.0579	0.0575
MC method ($M = 5.10^6$)	0.0605	0.0587	0.0579	0.0576

Table 4.38: Call option price of the different methods for different number of time steps. Case of set 5 parameters in table 4.1, without Richardson extrapolation.

Method \ Steps	2	4	8	16
MC Bias ($M = 5.10^6$)	0.0650 (0.0037)	0.0330 (0.0019)	0.0202 (0.0012)	0.0130 (0.0007)
MC Statistical error ($M = 5.10^6$)	7.0e-04 (4.0e-05)	6.7e-04 (3.8e-05)	6.5e-04 (3.7e-05)	6.3e-04 (3.6e-05)

Table 4.39: Bias and statistical errors of MC for computing call option price for different number of time steps. Case set 5, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors.

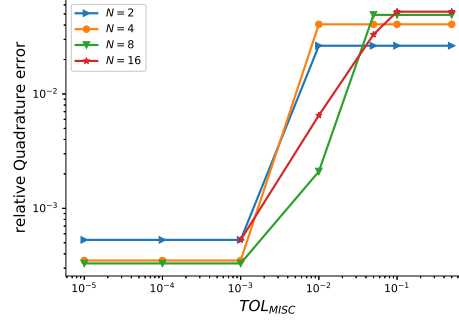


Figure 4.20: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 5 parameters, without Richardson extrapolation. See detailed values in table A.10

Method \ Steps	2	4	8	16
MISC ($TOL_{MISC} = 10^{-1}$)	0.0914	0.0736	0.0693	0.0654
MISC ($TOL_{MISC} = 10^{-2}$)	0.0914	0.0736	0.0223	0.0195
MISC ($TOL_{MISC} = 10^{-3}$)	0.0655	0.0334	0.0205	0.0135
MC	0.0657	0.0337	0.0209	0.0136

Table 4.40: Total relative error of MISC, with different tolerances, and MC to compute call option price for different number of time steps. Case set 5 parameters of table 4.1, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors. The values marked in red, for MISC method, correspond to the total relative errors associated with stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	2	4	8	16
MISC ($TOL_{MISC} = 10^{-1}$)	0.1	0.1	0.2	0.5
MISC ($TOL_{MISC} = 10^{-2}$)	0.1	0.1	8	97
MISC ($TOL_{MISC} = 10^{-3}$)	0.7	4	26	1984
MC method	154	229	420	938
Ratio of ($MC/MISC$)	220	57	16	0.5

Table 4.41: Comparison of the computational time (In seconds) of MC and MISC, used to compute Call option price of rBergomi model for different number of time steps. Case set 5 parametrs of table 4.1. The average MC CPU time is computed over 10 runs.

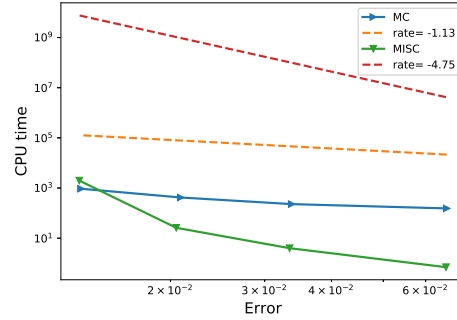


Figure 4.21: Complexity plot for MC and MISC for case set 5 parameters of table 4.1.

5 Conclusions and future work

In this work, we propose a novel hierarchical fast option pricer, based on a hierarchical adaptive sparse grids quadrature, specifically multi-index stochastic collocation (MISC) as in [18], coupled with Brownian bridge construction and Richardson extrapolation, for options whose underlyings follow rBergomi model as in [3]. In order to use a variant of adaptive sparse grids quadrature for our purposes, we had to solve two main issues, that constitutes the two stages of our new designed method. In the first stage, we smoothen the integrand by using the conditional expectation trick as was proposed by [26], in the context of Markovian stochastic volatility models. In a second stage, we applied a variant of hierarchical adaptive sparse grids quadrature, specifically MISC as in [18], to solve the integration problem. In this stage, we had to apply two pre-transformations before using the MISC solver, in order to overcome the issue of facing a high dimensional integrand, due to the discretization scheme used for simulating the rBergomi dynamics. Given that MISC profits from anisotropy, the first pre-transformation consists of applying a hierarchical path generation method, based on Brownian bridge (BB) construction, with the aim of reducing the effective dimension. The second pre-transformation consists of applying Richardson extrapolation to reduce the bias, resulting in reducing the needed number of time steps in the coarsest level to achieve a certain error tolerance, and therefore, the maximum number of dimensions needed for the integration problem.

Given that the only prevalent option, in this context, is to use different variants of MC method,

our first contribution is that we design an alternative approach based on adaptive sparse grid quadrature, which opens a new perspective for experts in this field to investigate the performance of other methods besides MC, to solve pricing and calibration problems related to rBergomi model. Our second contribution is that we reduce the computational cost not only through variance reduction, as in [23], by using the conditional expectation, but also through bias reduction through using Richardson extrapolation, which contributes also to reducing the dimension of the integration problem associated to computing the option price. Finally, assuming one targets prices estimates with a sufficiently small degree of error tolerance, our third contribution is manifested by the observed substantial computational gains over standard MC method, when pricing under rBergomi model. We show these gains through our numerical experiments for different parameters constellations.

In this paper, we limit ourselves to compare our novel proposed method against standard MC. A more systematic comparison against the variant of MC proposed in [23] can be carried over but this is left for a future work. Another eventual direction of research may also investigate the performance of QMC for such problems. Finally, accelerating our novel designed method can be reached by coupling MISC with a more optimal hierarchical path generation method than Brownian bridge construction, such as PCA or LT transformations, etc ...

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References Cited

- [1] Peter A Acworth, Mark Broadie, and Paul Glasserman. A comparison of some monte carlo and quasi monte carlo techniques for option pricing. In *Monte Carlo and Quasi-Monte Carlo Methods 1996*, pages 1–18. Springer, 1998.
- [2] Pierre Bajgrowicz, Olivier Scaillet, and Adrien Treccani. Jumps in high-frequency data: Spurious detections, dynamics, and news. *Management Science*, 62(8):2198–2217, 2015.
- [3] Christian Bayer, Peter Friz, and Jim Gatheral. Pricing under rough volatility. *Quantitative Finance*, 16(6):887–904, 2016.
- [4] Christian Bayer, Peter K Friz, Paul Gassiat, Joerg Martin, and Benjamin Stemper. A regularity structure for rough volatility. *arXiv preprint arXiv:1710.07481*, 2017.
- [5] Christian Bayer, Peter K Friz, Archil Gulisashvili, Blanka Horvath, and Benjamin Stemper. Short-time near-the-money skew in rough fractional volatility models. *arXiv preprint arXiv:1703.05132*, 2017.
- [6] Mikkel Bennedsen, Asger Lunde, and Mikko S Pakkanen. Decoupling the short-and long-term behavior of stochastic volatility. *arXiv preprint arXiv:1610.00332*, 2016.
- [7] Mikkel Bennedsen, Asger Lunde, and Mikko S Pakkanen. Hybrid scheme for brownian semistationary processes. *Finance and Stochastics*, 21(4):931–965, 2017.

- [8] Lorenzo Bergomi. Smile dynamics ii. 2005.
- [9] F. Biagini, Y. Hu, B. Øksendal, and T. Zhang. *Stochastic Calculus for Fractional Brownian Motion and Applications*. Probability and Its Applications. Springer London, 2008.
- [10] Russel E Caflisch, William J Morokoff, and Art B Owen. *Valuation of mortgage backed securities using Brownian bridges to reduce effective dimension*. 1997.
- [11] Kim Christensen, Roel CA Oomen, and Mark Podolskij. Fact or friction: Jumps at ultra high frequency. *Journal of Financial Economics*, 114(3):576–599, 2014.
- [12] Laure Coutin. An introduction to (stochastic) calculus with respect to fractional brownian motion. In *Séminaire de Probabilités XL*, pages 3–65. Springer, 2007.
- [13] Martin Forde and Hongzhong Zhang. Asymptotics for rough stochastic volatility models. *SIAM Journal on Financial Mathematics*, 8(1):114–145, 2017.
- [14] Masaaki Fukasawa. Asymptotic analysis for stochastic volatility: martingale expansion. *Finance and Stochastics*, 15(4):635–654, 2011.
- [15] Jim Gatheral, Thibault Jaisson, Andrew Lesniewski, and Mathieu Rosenbaum. Volatility is rough, part 2: Pricing.
- [16] Jim Gatheral, Thibault Jaisson, and Mathieu Rosenbaum. Volatility is rough. *arXiv preprint arXiv:1410.3394*, 2014.
- [17] Paul Glasserman. *Monte Carlo methods in financial engineering*. Springer, New York, 2004.
- [18] Abdul-Lateef Haji-Ali, Fabio Nobile, Lorenzo Tamellini, and Raul Tempone. Multi-index stochastic collocation for random pdes. *Computer Methods in Applied Mechanics and Engineering*, 306:95–122, 2016.
- [19] Junichi Imai and Ken Seng Tan. Minimizing effective dimension using linear transformation. In *Monte Carlo and Quasi-Monte Carlo Methods 2002*, pages 275–292. Springer, 2004.
- [20] Antoine Jacquier, Claude Martini, and Aitor Muguruza. On vix futures in the rough bergomi model. *Quantitative Finance*, 18(1):45–61, 2018.
- [21] Antoine Jacquier, Mikko S Pakkanen, and Henry Stone. Pathwise large deviations for the rough bergomi model. *arXiv preprint arXiv:1706.05291*, 2017.
- [22] Benoit B Mandelbrot and John W Van Ness. Fractional brownian motions, fractional noises and applications. *SIAM review*, 10(4):422–437, 1968.
- [23] Ryan McCrickerd and Mikko S Pakkanen. Turbocharging monte carlo pricing for the rough bergomi model. *arXiv preprint arXiv:1708.02563*, 2017.
- [24] William J Morokoff and Russel E Caflisch. Quasi-random sequences and their discrepancies. *SIAM Journal on Scientific Computing*, 15(6):1251–1279, 1994.
- [25] Bradley Moskowitz and Russel E Caflisch. Smoothness and dimension reduction in quasi-monte carlo methods. *Mathematical and Computer Modelling*, 23(8):37–54, 1996.

- [26] Marc Romano and Nizar Touzi. Contingent claims and market completeness in a stochastic volatility model. *Mathematical Finance*, 7(4):399–412, 1997.
- [27] Denis Talay and Luciano Tubaro. Expansion of the global error for numerical schemes solving stochastic differential equations. *Stochastic analysis and applications*, 8(4):483–509, 1990.

A Numerical comparison between MISC and MC

A.1 Case of set 1 parameters in table 4.1

Method \ Steps	2	4	8	16
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.0868 0.0062	0.0563 0.0040	0.0681 0.0049	0.0492 0.0035
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.0017 0.0001	0.0324 0.0023	0.0218 0.0016	0.0070 0.0005
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	0.0017 0.0001	1.4e-04 1.0e-05	0.0049 3.5e-04	0.0070 0.0005
MISC ($TOL_{\text{MISC}} = 10^{-4}$)	0.0017 0.0001	1.4e-04 1.0e-05	6.9e-04 (4.9e-05)	— —

Table A.1: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 1 parameters in table 4.1, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors. The values marked in red correspond to stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	1 – 2	2 – 4	4 – 8
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.1685 (0.0120)	0.0435 (0.0031)	0.0899 (0.0064)
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	1e-05 (7e-07)	0.0407 (0.0029)	0.0337 (0.0024)
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	0.0183 (0.0013)	0.0197 (0.0014)	0.0014 (0.0001)

Table A.2: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 1 parameters in table 4.1, with Richardson extrapolation(level 1). The numbers between parentheses are the corresponding absolute errors. The values marked in red correspond to stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	1 – 2 – 4	2 – 4 – 8
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.0576 (0.0041)	0.0520 (0.0037)
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.0435 (0.0031)	0.0267 (0.0019)
MISC ($TOL_{\text{MISC}} = 5.10^{-3}$)	0.0169 (0.0012)	0.0028 (0.0002)

Table A.3: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 1 parameters in table 4.1, with Richardson extrapolation(level 2). The numbers between parentheses are the corresponding absolute errors. The values marked in red correspond to stable quadrature errors for MISC, and will be used for complexity comparison against MC.

A.2 Case of set 2 parameters in table 4.1

Method \ Steps	2	4	8
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.1525 (0.0121)	0.1231 (0.0097)	0.1555 (0.0123)
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.1247 (0.0099)	6.3e – 04 (5.0e–05)	0.0053 (0.0004)
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	0.0288 (0.0023)	6.3e – 04 (5.0e–05)	0.0053 (0.0004)
MISC ($TOL_{\text{MISC}} = 10^{-4}$)	2.5e – 04 (2.0e–05)	6.3e – 04 (5.0e–05)	–

Table A.4: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 2 parameters in table 4.1, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors. The values marked in red correspond to stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	1 – 2	2 – 4	4 – 8
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.3687 0.0292	0.1136 0.0090	0.1288 0.0102
MISC ($TOL_{\text{MISC}} = 5.10^{-2}$)	0.3687 0.0292	0.1641 0.0130	0.0101 0.0008
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.1212 0.0096	0.0101 0.0008	0.0101 0.0008
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	0.0694 0.0055	0.0101 0.0008	– –

Table A.5: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 2 parameters in table 4.1, with Richardson extrapolation(level 1). The numbers between parentheses are the corresponding absolute errors. The values marked in red correspond to stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	1 – 2 – 4	2 – 4 – 8
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.0177 (0.0014)	0.1073 (0.0085)
MISC ($TOL_{\text{MISC}} = 5 \cdot 10^{-2}$)	0.2525 (0.0200)	0.0038 (0.0004)
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.0278 (0.0022)	0.0038 (0.0004)

Table A.6: Quadrature error of MISC, with different tolerances, to compute Call option price for different number of time steps. Case set 2 parameters in table 4.1, with Richardson extrapolation(level 2). The numbers between parentheses are the corresponding absolute errors. The values marked in red correspond to stable quadrature errors for MISC, and will be used for complexity comparison against MC.

A.3 Case of set 3 parameters in table 4.1

Method \ Steps	2	4	8	16
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.0088 (0.0011)	0.0144 (0.0018)	0.0176 (0.0022)	0.0160 (0.0020)
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.0088 (0.0011)	0.0088 (0.0011)	0.0040 (0.0005)	0.0008 0.0001
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	0.0016 (0.0002)	0.0016 (0.0002)	0.0008 0.0001	0.0004 0.00005
MISC ($TOL_{\text{MISC}} = 10^{-4}$)	0.0008 (0.0001)	0.0008 0.0001	0.0008 0.0001	— —

Table A.7: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 3 parameters in table 4.1, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors. The values marked in red correspond to stable quadrature errors for MISC, and will be used for complexity comparison against MC.

Method \ Steps	1 – 2	2 – 4	4 – 8	8 – 16
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.0184 (0.0023)	0.0248 (0.0031)	0.0216 (0.0027)	0.0176 (0.0022)
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.0136 (0.0017)	0.0168 (0.0021)	0.0032 (0.0004)	0.0008 (0.0001)
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	0.0008 (0.0001)	0.0032 (0.0006)	0.0016 (0.0002)	0.0008 (0.0001)

Table A.8: Quadrature error of MISC, with different tolerances, to compute Call option price for different number of time steps. Case set 3 parameters in table 4.1, with Richardson extrapolation(level 1). The numbers between parentheses are the corresponding absolute errors. The values marked in red correspond to stable quadrature errors for MISC, and will be used for complexity comparison against MC.

A.4 Case of set 4 parameters in table 4.1

Method \ Steps	2	4	8	16
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.0029 (0.0007)	0.0054 (0.0013)	0.0046 (0.0011)	0.0066 (0.0016)
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.0029 (0.0007)	0.0054 (0.0013)	0.0021 (0.0005)	8.3e-05 2.0e-05
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	0.0029 (0.0007)	0.0021 (0.0005)	1.2e-04 3.0e-05	8.3e-05 2.0e-05
MISC ($TOL_{\text{MISC}} = 10^{-4}$)	0.0004 (0.0001)	2.1e-04 5.0e-05	1.2e-04 3.0e-05	— —

Table A.9: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 4 parameters in table 4.1, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors. The values marked in red correspond to stable quadrature errors for MISC, and will be used for complexity comparison against MC.

A.5 Case of set 5 parameters in table 4.1

Method \ Steps	2	4	8	16
MISC ($TOL_{\text{MISC}} = 10^{-1}$)	0.0264 (0.0015)	0.0406 (0.0023)	0.0491 (0.0028)	0.0524 (0.0030)
MISC ($TOL_{\text{MISC}} = 10^{-2}$)	0.0264 (0.0015)	0.0406 (0.0023)	0.0021 (0.0005)	0.0065 0.0004
MISC ($TOL_{\text{MISC}} = 10^{-3}$)	5.3e-04 (3.0e-05)	3.5e-04 2.0e-05	3.3e-04 1.9e-05	5.3e-04 3.0e-05

Table A.10: Quadrature error of MISC, with different tolerances, to compute call option price for different number of time steps. Case set 5 parameters in table 4.1, without Richardson extrapolation. The numbers between parentheses are the corresponding absolute errors. The values marked in red correspond to stable quadrature errors for MISC, and will be used for complexity comparison against MC.